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Pan-African extension and near-isothermal exhumation of a granulite facies terrain, Dronning Maud Land, Antarctica

A. K. ENGVIK* & S. ELVEVOLD†

*Institutt for geologi og bergteknikk, Norges teknisk-naturvitenskapelige universitet, N-7491 Trondheim, Norway
†Norsk Polarinstitutt, N-9296 Tromsø, Norway

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Abstract – The Mühlig-Hofmann- and Filchnerfjella in central Dronning Maud Land, Antarctica, consist of series of granitoid igneous rocks emplaced in granulite and upper amphibolite facies metamorphic rocks. The area has experienced high-temperature metamorphism followed by near-isothermal decompression, partial crustal melting, voluminous magmatism and extensional exhumation during the later phase of the late Neoproterozoic to Cambrian Pan-African event. Remnants of kyanite–garnet–ferritschermakite–rutile assemblages indicate an early higher-pressure metamorphism and crustal overthickening. The gneisses experienced peak granulite facies temperatures of 800–900 °C at intermediate pressures. Breakdown of garnet + sillimanite + spinel-bearing assemblages to cordierite shows subsequent re-equilibration to lower pressures. An E–W foliation dominating the gneisses illustrates transposition of migmatites and leucocratic melts which evolved during the near-isothermal decompression. Occurrence of extensional shear bands and shear zones evolving from the ductile partial melting stage through semiductile towards brittle conditions, shows that the uplift persisted towards brittle crustal conditions under tectonic W/SW-vergent extension. Late-orogenic Pan-African quartz syenites intruded after formation of the main gneiss fabric contain narrow semiductile to brittle shear zones, illustrating that the extensional exhumation continued also after their emplacement. The latest record of the Pan-African event is late-magmatic fluid infiltration around 350–400 °C and 2 kbar. At this stage the Pan-African crust had undergone 15–20 km exhumation from the peak granulite facies conditions. We conclude that the later phase of the Pan-African event in central Dronning Maud Land is characterized by a near-isothermal decompression *P–T* path and extensional structures indicating tectonic exhumation, which is most likely related to a late-orogenic collapsing phase of the Pan-African orogen.

Keywords: Antarctica, extension, exhumation, granulite facies, Pan-African Orogeny.

1. Introduction

Many high-grade rocks contain evidence for near-isothermal decompression accompanied by partial melting at elevated temperature (e.g. Teyssier & Whitney, 2002). Gneiss domes cored by migmatite and granitoid intrusions are a signature of the rapid ascent of partially molten crust in exhumed orogens. Near-isothermal decompression and partial melting indicate a high geothermal gradient. High geothermal gradients can be caused by processes such as lithosphere thinning or introduction of underlying basaltic magmas (e.g. Platt & England, 1994). Late-orogenic extensional denudation can explain rapid exhumation of deeper crustal rocks (e.g. Platt, 1993). Decompression driven by surficial or tectonic processes may also trigger partial melting by crossing phase boundaries during uplift (Teyssier & Whitney, 2002). This situation will result in a positive feedback between melting and decompression involving buoyancy-driven ascent of crustal rocks.

In this paper we show that the central Dronning Maud Land, East Antarctica, underwent near-isothermal decompression and partial melting related to Pan-African extension. Mesoproterozoic rocks of the area were intruded by voluminous granitoid intrusions and underwent granulite facies metamorphism and deformation during the late Neoproterozoic (Ohta, Tørudbakken & Shiraishi, 1990; Moyes, 1993; Mikhalsky *et al*. 1997; Jacobs *et al*. 1998; Paulsson & Austrheim, 2003). Plate reconstructions suggest that late Mesoproterozoic rocks were formed during the Kibaran event, and that the late Neoproterozoic overprint of East Antarctica, corresponding to the Pan-African event, occurred during the amalgamation of Gondwana (e.g. Fitzsimons, 2000). It has been discussed whether the Pan-African amalgamation of East Antarctica was dominated by transcurrent or collisional tectonics (Wilson, Grunow & Hanson, 1997; Meert & van der Voo, 1997; Fitzsimons, 2000). Jacobs *et al*. (1998) suggested a transpressional orogenic setting for the

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* Author for correspondence: ane.engvik@geo.ntnu.no

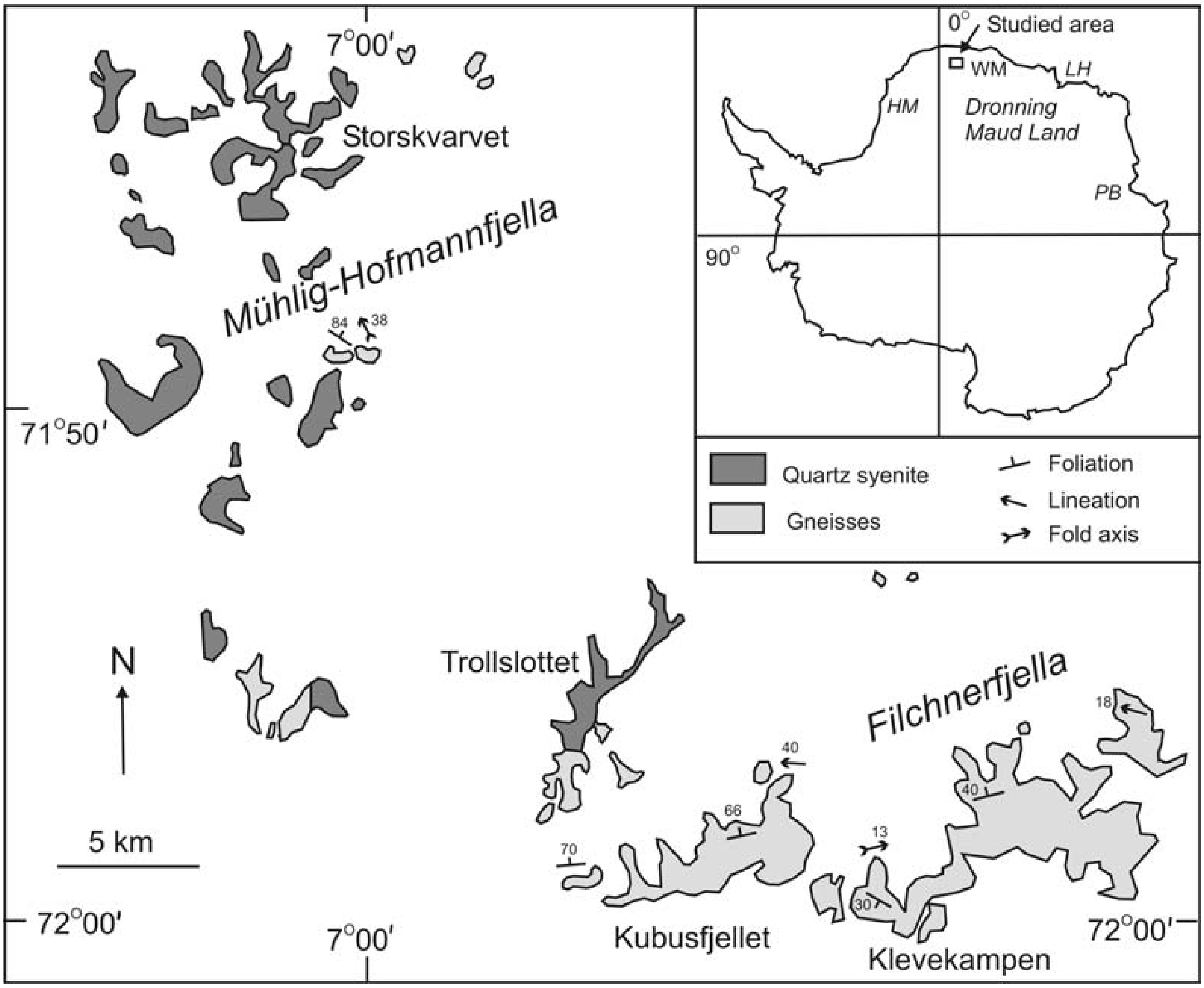

Figure 1. Geological map of eastern Mühlig-Hofmann- and Filchnerfjella, Dronning Maud Land, Antarctica. HM – Heimefrontfjella, WM – Wohlthatmassiv, LH – Lützow Holmbukta, PB – Prydz Bay.

mountain range of Dronning Maud Land. However, detailed structural mapping over continuous areas within the East Antarctic craton are difficult due to widespread ice coverage, difficult access to exposures and extreme climatic conditions. Glacial drainage patterns are likely to follow weak deformation zones and therefore cover important information for the construction of geological models.

The nunataks of eastern Mühlig-Hofmannfjella and Filchnerfjella (Fig. 1) are a hitherto poorly known part of Dronning Maud Land mountain range. In this paper we describe the tectonometamorphic evolution of a suite of granulite facies rocks in this area. The gneisses are characterized by near-isothermal decompression and partial melting. Extensional structures evolved under ductile to brittle conditions and indicate tectonic exhumation. In accordance with the work in the Wohlthatmassiv by Jacobs *et al.* (2003), we suggest that central Dronning Maud Land underwent extensional exhumation during a late-orogenic collapsing phase of the Pan-African event in Dronning Maud Land.

2. Geological setting

The mountains and nunataks of eastern Mühlig-Hofmannfjella and Filchnerfjella in central Dronning Maud Land consist of series of granitoid igneous rocks emplaced into granulite and upper amphibolite facies metamorphic rocks (Bucher-Nurminen & Ohta, 1993; Ohta, 1999). The granulite facies gneisses of Filchnerfjella (Fig. 1) are characterized by a banded sequence of mafic, intermediate and leucocratic rocks (Fig. 2a). Different rock types form layers varying in thickness from < 1 m up to several tens of metres. Migmatization has affected large parts of the metamorphic sequence.

The igneous suite includes voluminous intrusions of charnockites, granites and quartz syenites which intruded throughout the Pan-African event from 600 to 500 Ma (Ohta, Tørudbakken & Shiraishi, 1990; Moyes, 1993; Mikhalsky *et al.* 1997; Jacobs *et al.* 1998; Paulsson & Austrheim, 2003). Charnockites and granites, occurring in the neighbouring area to the

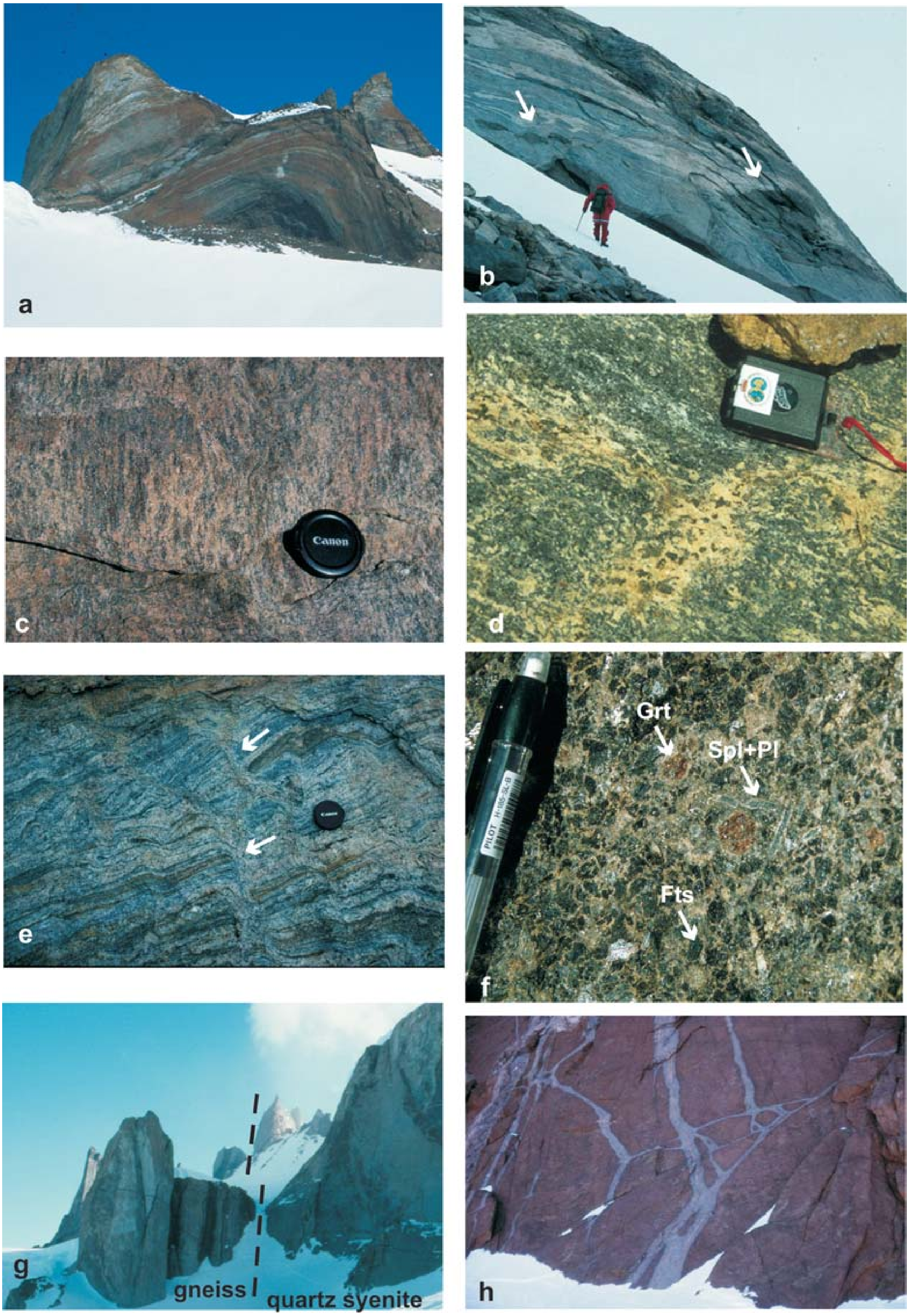

Figure 2. For legend see next page.

mapped lithologies of Fig. 1, have a local gneissic overprint. The quartz syenites which cut the gneiss structures in the area of eastern Mühlig-Hofmannfjella and Filchnerfjella belong to a large magmatic complex extending between 6° and 13° E.

3. Lithologies

3.a. Banded gneisses

3.a.1. Pelitic gneisses

Metasedimentary rocks occur as garnet–biotite migmatites, sillimanite-bearing gneisses and biotite–cordierite schists. The pelitic and semipelitic gneisses are muscovite-free and contain abundant leucocratic layers and lenses, which are interpreted as anatectic melts.

The metapelites contain variable proportions of garnet, sillimanite, cordierite, spinel, ilmenite, biotite, quartz, K-feldspar (perthite), plagioclase (antiperthite) and myrmekite. Garnet ($Alm_{73-81}Prp_{16-23}Grs_{2-3}Sps_1$) is present as subhedral to anhedral poikiloblasts with inclusions of quartz, plagioclase, biotite, sillimanite, rutile and rare kyanite. Garnet is strongly resorbed and commonly replaced by secondary cordierite–quartz or biotite–plagioclase intergrowths. Sillimanite is clustered in foliation-parallel aggregates together with green, hercynitic spinel and ilmenite (Fig. 3a). These aggregates are mantled by cordierite such that spinel and sillimanite are never in direct contact with other matrix minerals such as garnet, K-feldspar and quartz.

3.a.2. Mafic rocks

Mafic rocks contain variable amounts of orthopyroxene, amphibole, biotite, ilmenite and clinopyroxene, and are predominantly characterized by absence of garnet. The mafic rocks occur as inclusions concentrated along foliation-parallel horizons and most probably represent disrupted former dykes or sills (Fig. 2b). Garnet-bearing mafic granulites are found as inclusions in garnet-bearing leucocratic gneiss, range in size from 1 to 5 metres, and occur locally with orthopyroxene-bearing leucosomes (Fig. 2d).

The garnet-bearing mafic rocks display a granoblastic texture of ferritschermakite, garnet ($Alm_{51}Prp_{27}Grs_{20}Sps_3$), plagioclase and oxide. Garnet occurs as embayed and resorbed porphyroblasts, up to 2 cm in diameter, surrounded by a coarse intergrowth of secondary orthopyroxene + plagioclase (Fig. 3b) together with associated gedrite. The large, ferritschermakite porphyroblasts are also surrounded by a coarse, symplectitic orthopyroxene–plagioclase intergrowth (Fig. 3c). Orthopyroxene in symplectites is En_{64-70} with $Al_2O_3 = 3.0$–4.2 wt %. Matrix plagioclase is strongly zoned from An_{59} (core) to An_{92} (rim). Up to 1.5 cm long, prismatic, blue aggregates consist of symplectitic green Mg–Fe–Al–spinel ($hercynite_{52}$) + plagioclase(An_{86-91}) intergrowths (Figs. 2f, 3d). An outer corona of plagioclase surrounds the symplectitic intergrowths. The prismatic outline of the intergrowths suggests that they represent a pseudomorph after an earlier Al-rich phase.

3.a.3. Leucocratic gneisses

Migmatites are formed in metasediments, gneisses of intermediate composition and, more rarely, in mafic rocks. Granite sheets and diatexites with schlieric structure are commonly interlayered with the migmatites and gneisses. The leucocratic gneiss is commonly garnet ± sillimanite ± cordierite bearing, and massive to weakly foliated. We interpret the leucocratic gneiss to be the product of substantial melting of metasediments. Irregular biotite-rich schlieren considered to represent melanosome (restite) are commonly observed.

3.b. Quartz syenite

The quartz syenite is characterized by its massive appearance and reddish brown colour and the texture is coarse grained to pegmatitic. The major constituent of the syenite is short-prismatic, euhedral perthite, up to 5 cm long. Plagioclase, quartz, biotite, hastingsite, grunerite and minor orthopyroxene form interstitial grains. The quartz syenite commonly contains xenoliths and rafts of mafics, granites and layered gneisses/migmatites. The size of the xenoliths varies from 10 cm up to several hundreds of metres. Intrusive relationships are exposed at Trollslottet (Fig. 2g), where the massive quartz syenite clearly post-dates the regional fabric in the layered gneisses.

4. Metamorphic evolution

The metamorphic evolution of the Filchnerfjella gneisses is recorded by four stages (Fig. 4). The first

Figure 2. (a) Layered gneisses of Kubusfjellet with large-scale syn- and antiform pair. Height above the ice is *c.* 400 m. (b) Competent lenses (white arrows) in gneiss formed by disruption of a former layer by shear zones. (c) Early L–S fabric preserved in a competent lens tectonically enclosed in gneiss; lens cap diameter is 6 cm. (d) Orthopyroxene-bearing leucosomes cutting the foliation of mafic rocks; length of black case is 7 cm. (e) Leucosomes cutting the foliation of migmatite (white arrows). Extensional shear bands (Type I) in gneiss showing syn-tectonic migration of leucocratic melts along the shear planes; lens cap diameter is 6 cm. (f) Relics after an early higher-pressure garnet + ferritschermakite + kyanite assemblage found in garnet amphibolite (abbreviations after Kretz, 1983). Visible length of pen is 8 cm. (g) Intrusive contact of the quartz syenite into the gneisses exposed in the nunatak of Trollslottet. Left cliff is approximately 100 m high. (h) Conspicuous late-magmatic fluid infiltration zones causing a light alteration of the dark quartz syenite around pegmatitic veins. Height of visible wall is approximately 50 m.

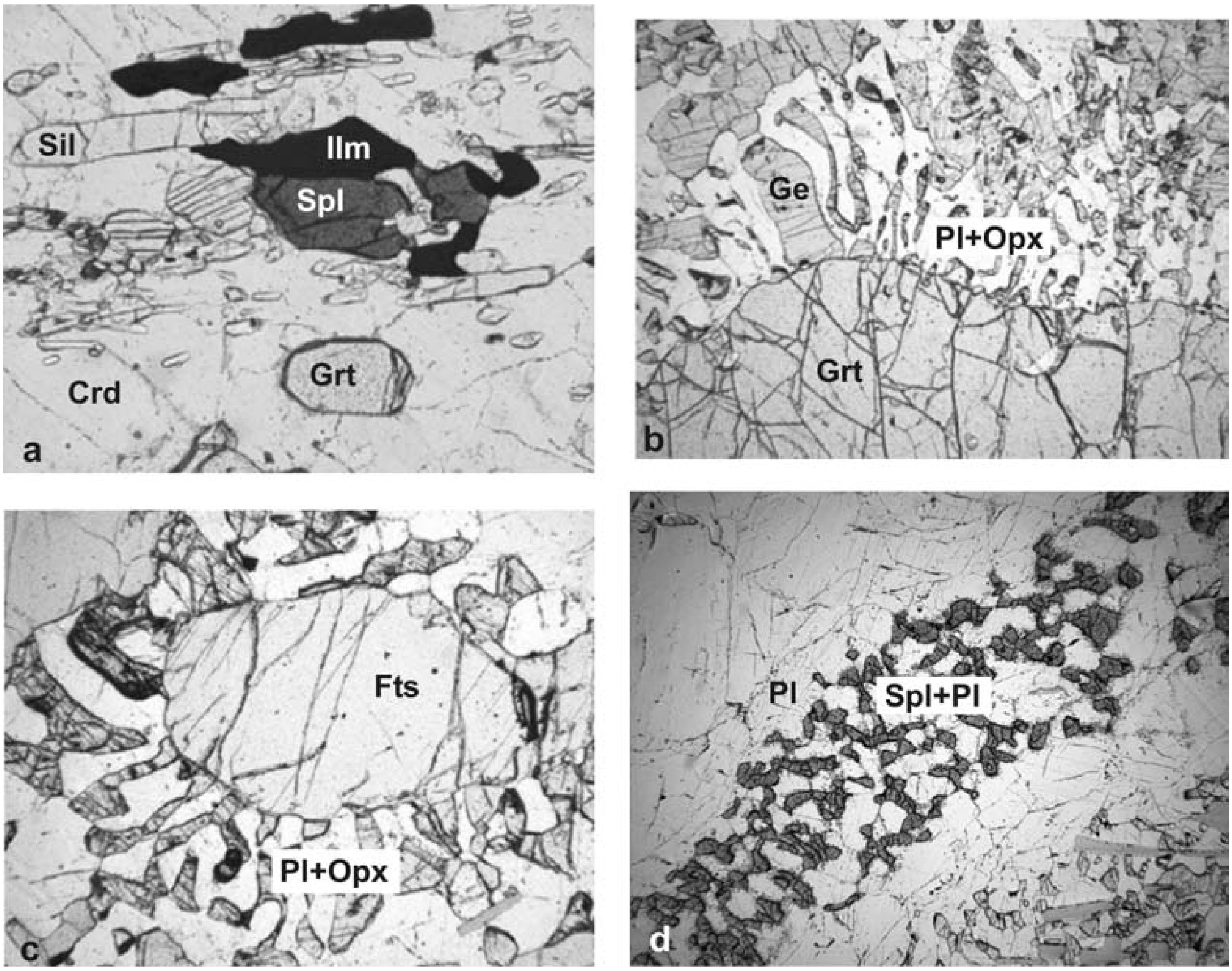

Figure 3. Photomicrographs (abbreviations after Kretz, 1983). (a) Sillimanite clustered in foliation-parallel aggregates together with spinel and ilmenite. The aggregates are mantled by cordierite. Sample dml40a; width of image is 1.65 mm. (b) Garnet in garnet-amphibolite replaced by symplectites of plagioclase + orthopyroxene or plagioclase + orthoamphibole (Ge). Sample dml27b; width of image is 2.64 mm. (c) Ferritschermakite in garnet-amphibolite replaced by plagioclase + orthopyroxene-symplectite. Sample dml27b; width of image is 1.98 mm. (d) The prismatic, blue aggregates of garnet-amphibolite interpreted to represent former kyanite (see Fig. 2f) consist of spinel + plagioclase intergrowths, again surrounded by a plagioclase corona. Sample dml27a; width of image is 3.3 mm.

stage exhibits signs of early higher pressure conditions (Stage 1). The prismatic intergrowth of spinel + plagioclase occurring in the mafic rocks suggests that they represent a pseudomorph after an earlier Al-rich phase (Figs 2f, 3d). Formation of spinel + plagioclase intergrowths as reaction products after kyanite is a common feature in decompressed high-pressure rocks (Johansson & Möller, 1986; Elvevold & Gilotti, 2000). We interpret the prismatic spinel–plagioclase intergrowths in the mafic rocks of Filchnerfjella to be breakdown products after kyanite. The gneisses display indications for early higher pressure conditions in the form of the garnet + ferritschermakite + kyanite assemblage in the mafic rocks. The inclusions of kyanite and rutile in garnet of metapelitic rocks are also indications of the early higher pressure conditions. The breakdown of kyanite into spinel + plagioclase and the occurrence of sillimanite as the Al-phase in metapelitic and leucocratic lithologies, indicate a prograde evolution of the Filchnerfjella gneisses from the kyanite (Stage 1) into the sillimanite field (Stage 2).

The peak metamorphism (Stage 2) is constrained by the presence of orthopyroxene in mafic rocks and by the assemblage garnet + sillimanite + ternary feldspar + spinel + quartz in metapelites. Garnet-bearing leucosomes in metapelites suggest that anatexis occurred through biotite dehydration melting which starts at temperatures above 800 °C (Le Breton & Thompson, 1988). The absence of orthopyroxene in pelitic compositions suggests an upper temperature limit of 900–915 °C (Harley, 1998). The presence of sillimanite as the stable aluminosilicate limits the peak pressure below 10 kbar at 800 °C. This leads to the interpretation that the gneisses have experienced peak granulite facies conditions of 800–900 °C at intermediate pressures.

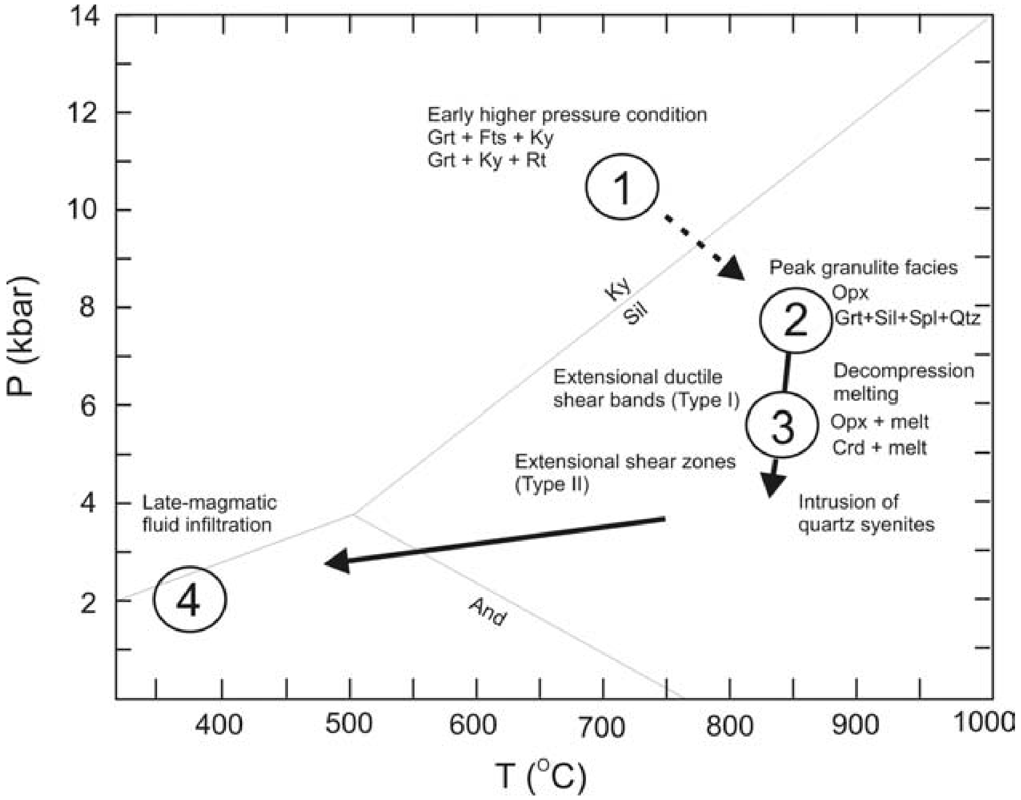

Figure 4. *P–T* evolution for the rocks of eastern Mühlig-Hofmann- and Filchnerfjella. The diagram illustrates the four recorded main metamorphic events of an early higher pressure condition (Stage 1), peak granulite facies (Stage 2), near-isothermal decompression and partial melting (Stage 3), and late-magmatic fluid infiltration (Stage 4). (Abbreviations after Kretz, 1983. Al_2SiO_5 triple point after Holdaway, 1971.)

The granulites contain abundant reaction textures recording partial re-equilibration to lower pressures (Stage 3). The replacement of garnet and ferritschermakite in mafic rocks by orthopyroxene–plagioclase symplectites (Fig. 3b, c) suggests decompression while the granulites remained at elevated temperatures (Harley, 1989). In pelitic granulites, garnet + sillimanite + spinel-bearing assemblages break down to cordierite (Fig. 3a). Late, nebulous leucosomes in pelitic granulites contain aggregates of cordierite, whereas mafic rocks contain melt patches with euhedral orthopyroxene (Fig. 2d). The reactions responsible for the partial replacement of garnet-bearing assemblages by cordierite in metapelites have a shallow dP/dT and are commonly taken as indicative of decompression. The late leucosomes are interpreted to have formed by decompressional melting, and this together with the recorded mineral reactions above, indicates that the granulite facies rocks of Filchnerfjella underwent a steep and near-isothermal unloading *P–T* path. This interpretation involving a clockwise *P–T* path including isothermal decompression has been suggested in many studies of granulites in East Antarctica (Harley, 2003).

Late-magmatic fluid infiltration occurs conspicuously and extensively as light-coloured alteration haloes around pegmatitic and aplitic veins cutting both gneisses and quartz syenite in the studied area (Fig. 2h; Stage 4). The fluid was primarily a granitoid melt rich in H_2O and CO_2 (Engvik *et al*. 2003). The colour change is caused by textural and mineral transformations including orthopyroxene breakdown to biotite, perthite to microcline, and sericitization of plagioclase. Studies of mineral transformations and fluid inclusions of the alteration zones show that the late-magmatic fluids infiltrated at crustal conditions of 350–400 °C around 2 kbar (Engvik *et al*. 2003).

5. Structures

The gneisses are foliated and show compositional banding (Fig. 2a). The banding represents transposed primary layered sequences as seen by tight isoclinal fold hinges and intrafolial folds (Fig. 5a). The regional foliation of the banded gneisses in Filchnerfjella generally strikes E–W with variable southern or northern dips (Fig. 6a) and has locally a strong subhorizontal E–W-trending lineation (Fig. 6b). Conspicuous large-scale folding is visible both as open and tight folds (Fig. 2a). The variance of the foliation dip indicates a main regional folding with subhorizontal E–W-trending fold axes. Intrafolial isoclinal folds (Fig. 6c) show some variation in fold axis orientation; however, they are in accordance with the main fold axis direction interpreted from the foliation measurements. The E–W foliation is

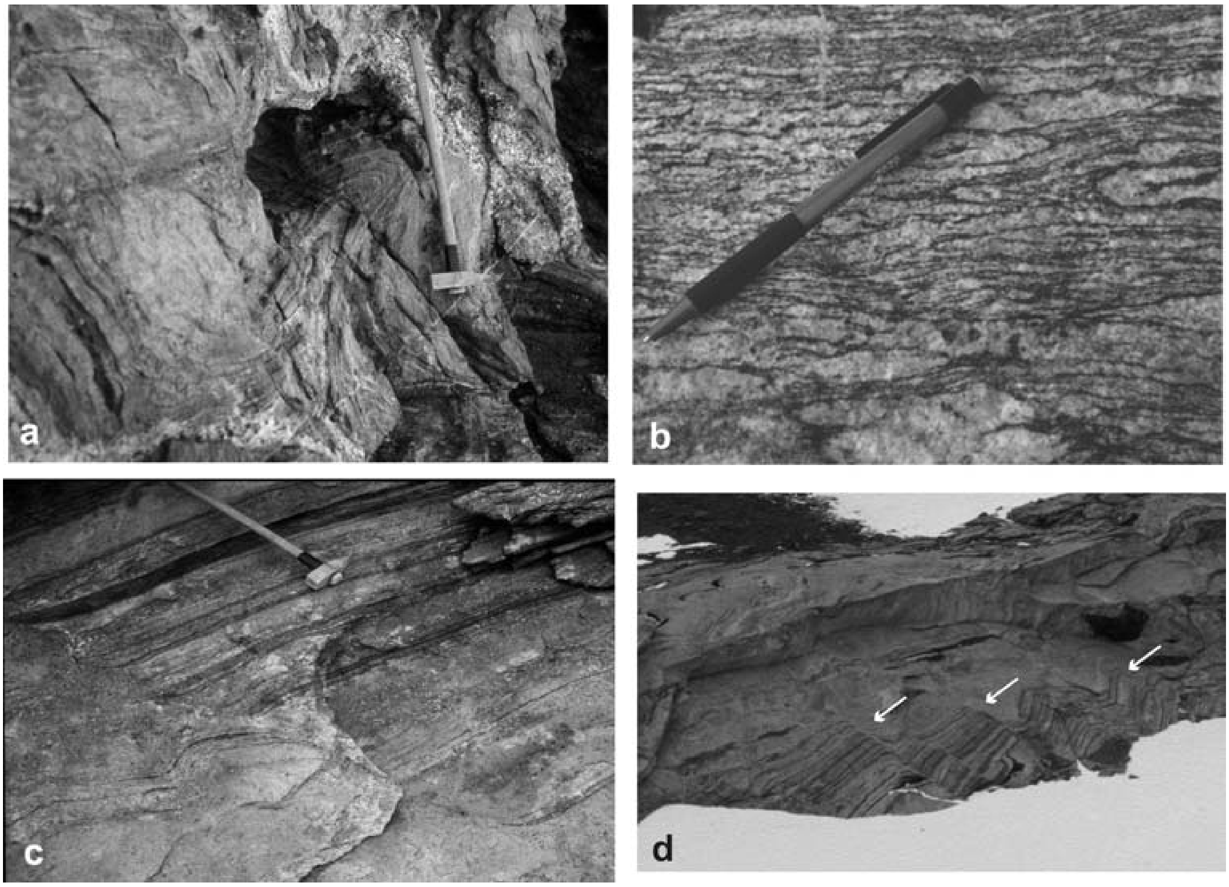

Figure 5. (a) Isoclinal fold hinge in leucocratic gneiss; length of hammer is 60 cm. (b) Strong transposition of early formed leucosomes in migmatite; length of pen is 15 cm. (c) Type II extensional shear zone cutting the gneiss; length of hammer is 60 cm. (d) Type II extensional shear zones showing rotation of gneiss lenses (white arrows); width of field of view is approximately 15 m.

accompanied with strong transposition of leucosomes, melanosomes and restites showing that it has evolved during the near-isothermal decompressional stage (Fig. 5b). Due to the high-temperature metamorphism accompanied by strong flattening, early structures are only preserved as intrafolial folds and older fabric locally found within a few competent layers tectonically enclosed in the gneisses (Figs 2b, c). Leucosomes occurring as nebulous patches and as veins cross-cutting the foliation show that the partial melting occurred over a longer period (Figs 2d, e).

Two types of extensional structures distinguished in the Filchnerfjella gneisses illustrate a progressive evolution from ductile through semiductile to brittle conditions during exhumation. Ductile normal sense shear bands (Type I) are frequently observed internally in the gneiss foliation (Fig. 2e). In the migmatitic gneisses, locally derived melts are observed migrating along the shear planes (Fig. 2e). This illustrates that the partial melting of the decompressional Stage 3 (Fig. 4) was accompanied by tectonic extension. The ductile shear bands show both sinistral and dextral movement, indicating a flattening of the rocks in this stage. Only a few observed ductile reverse sense shear bands are found developed coeval to, and with the same orientation as, the normal sense shear bands. The reverse sense shear bands are interpreted to have evolved in local shortening fields of the strain ellipse.

Succeeding the decompressional melting of Stage 3, extensional normal shear zones (Type II) evolving from ductile through semiductile towards brittle condition cut the banding and foliation of the gneisses and show displacement up to tens of metres (Figs 5c, d, 7). The shear zones have been studied both at reachable outcrops (Fig. 5c, d) and in the north-side wall of Klevekampen (Fig. 7). The north-side wall of Klevekampen gives an overview of the extensional structures where a large central shear zone shows an offset of about 50 m (Fig. 7a). The shear zones show dominantly top-to-the-W to -SW movement, but shear zones with top-to-the-E to -NE movement have evolved as back-rotation of smaller fault blocks (Fig. 7b–d). The shear zones recrystallize the quartzofeldspatic assemblage, indicating movement at temperatures above 400–500 °C (Voll, 1976; Gapais, 1989; Passchier & Trouw, 1996). The thickness of the shear zones varies from a few decimetres to one centimetre, and the grain size of the recrystallized mineral assemblage varies from 0.5 down to 0.01 mm (Fig. 8). The recrystallized mineral assemblage of the shear zones shows a dominantly

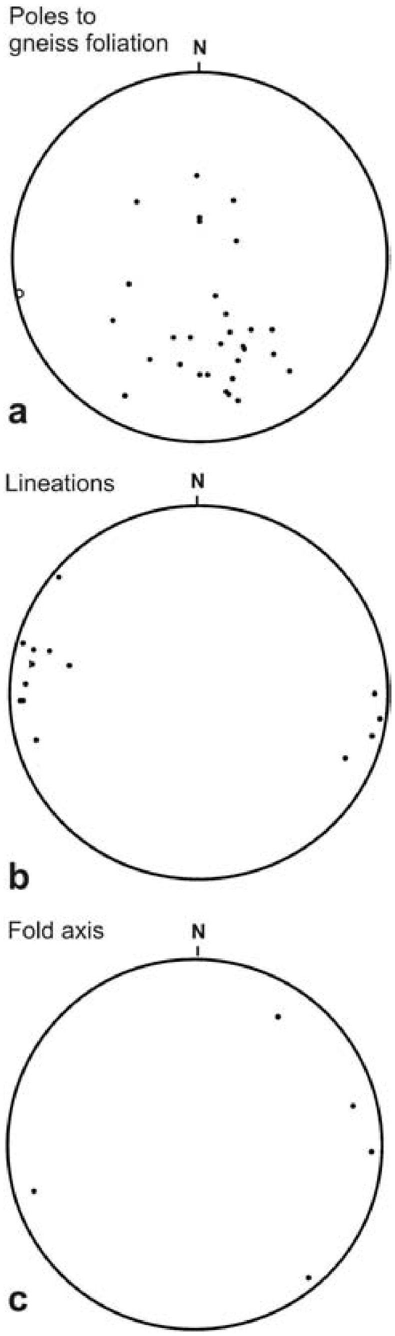

Figure 6. Lower hemisphere equal area projections of structures in the eastern Mühlig-Hofmann- and Filchnerfjella. (a) Poles to gneiss foliations. Pole of best fit great circle to the foliation poles (open circle) indicates a main subhorizontal E–W-trending fold axis of the gneisses. (b) Orientation of lineations in the gneisses showing subhorizontal E–W trend. (c) Orientation of fold axis.

fine- to very fine-grained quartzofeldspatic mineral assemblage with oriented biotite, flattened grains and rods of quartz, and porphyroclasts of feldspars, myrmekite and hastingsite.

The gneiss structure is cut by quartz syenite intrusions (Fig. 2g). The quartz syenites show locally syn-magmatic structures and a faint foliation defined by parallel-oriented K-feldspar crystals, lenses of oriented xenoliths and restites of older material and mafic minerals. Shear zones are also observed in the quartz syenite as more narrow zones of 1–3 cm thickness. They contain a recrystallized feldspar + biotite + quartz assemblage as in the gneiss, with a very fine grain size down to 0.01 mm (Fig. 8). The conspicuous late-magmatic alteration zones (Stage 4) are both cut by and cutting the shear zones. Where the pegmatites and alteration zones are cut, they show brittle offset. The semiductile to brittle nature of the shear zones, evolving coevally with the late-magmatic fluid infiltration zones, illustrates that the crust towards Stage 4 has been exhumed into the brittle–ductile transition zone. In addition, late brittle faults are clearly visible in the mountain walls in both gneiss and quartz syenite massifs.

6. Discussion

6.a. Pan-African near-isothermal uplift during tectonic extension

High-pressure metamorphic rocks such as eclogites, which indicate subduction of crust to great depths during orogenesis, are not found in central Dronning Maud Land. However, remnants of a kyanite + garnet + ferritschermakite assemblage found in Filchnerfjella indicate an early higher-pressure metamorphism. Rutile and kyanite found as inclusions in garnet are also indicative of higher pressures. This early stage event indicates significant crustal thickening during Pan-African continent collision. However, we cannot rule out that the higher-pressure mineral parageneses are remnants left after the Mesoproterozoic Kibaran orogeny.

Although Mesoproterozoic ages are reported, central Dronning Maud Land is thoroughly overprinted by the Pan-African high-temperature metamorphism and voluminous magmatism which continued through the period of 600–485 Ma (Ohta, Tørudbakken & Shiraishi, 1990; Moyes, 1993; Mikhalsky *et al*. 1997; Jacobs *et al*. 1998; Paulsson & Austrheim, 2003). As discussed in Section 4, peak granulite facies metamorphism occurred at *c*. 800–900 °C at mid-crustal levels followed by a near-isothermal decompression. The high-temperature uplift was accompanied by partial melting of the crust now represented by migmatitic and leucocratic horizons in the gneiss sequences, as well as by larger magmatic intrusions. Some of the earlier Pan-African intrusions show various degrees of deformation (Mikhalsky *et al*. 1997; Jacobs *et al*. 1998), while the later quartz syenites are only deformed by the later semiductile shear zones and brittle faults. The E–W foliation dominating the gneisses shows transposition of migmatites and leucocratic melts, and is interpreted to have evolved during the near-isothermal decompression. Because of the high-temperature metamorphism accompanied by strong flattening, structures from the prograde evolution of the gneisses are preserved only locally

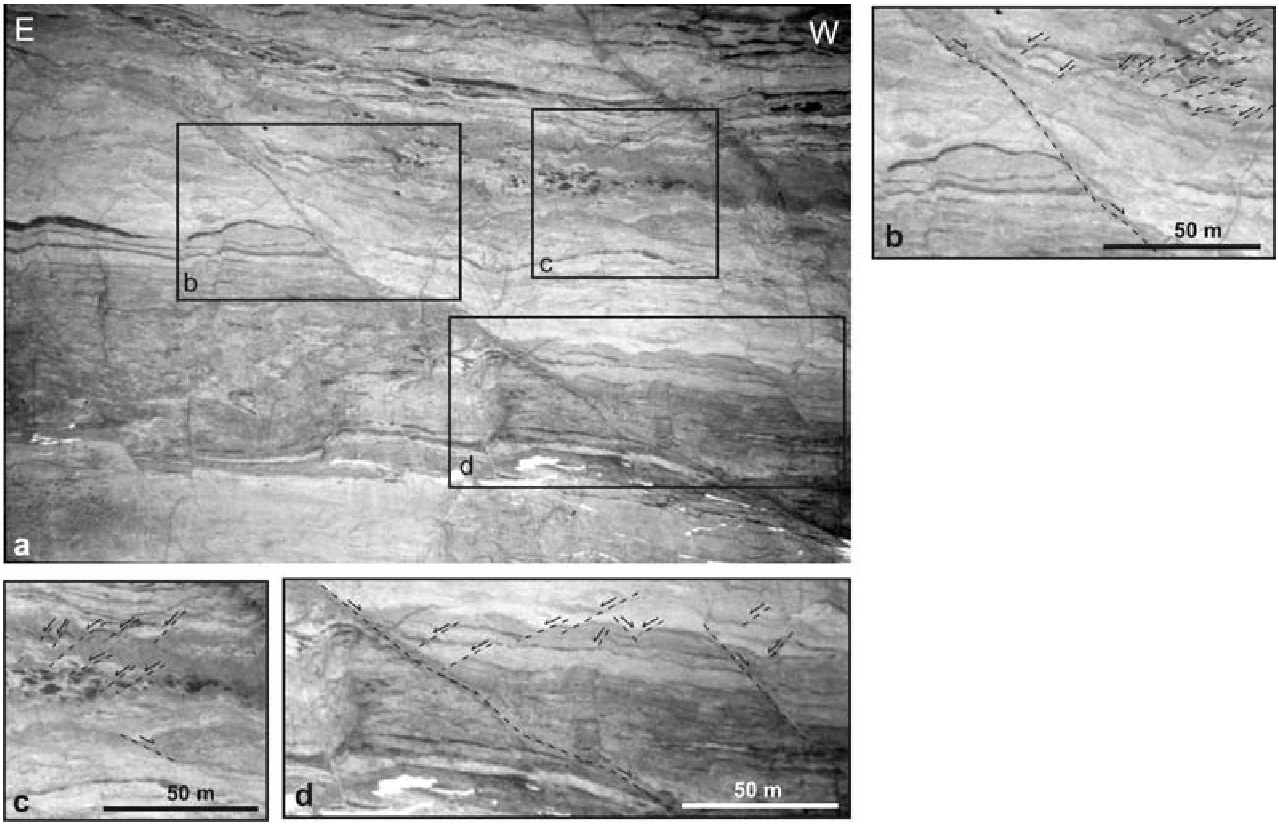

Figure 7. (a) Part of north-side wall of Klevekampen showing the gneiss structure including banded horizons, foliation and extensional ductile to brittle normal shear zones. The central main shear zone shows an offset of about 50 m. The height of the imaged area is about 250 m. (b–d) Enlarged parts of the mountain wall of Klevekampen (see Fig. 7a). Stippled lines indicate shear zones. The shear zones show a dominantly top-to-the-W to -SW movement, but shear zones with top-to-the-E to -NE movement have evolved as back-rotation of smaller fault blocks.

and without original structural relationships to their surroundings. Transposition of early formed leucosomes in migmatites, in addition to the occurrence of leucosomes cutting the foliation or migrating along extensional ductile shear bands, illustrates that the high-temperature partial melting continued over a longer period during exhumation. The occurrence of extensional shear bands and shear zones, which evolved from the ductile partial melting stage through semiductile towards brittle conditions, shows that the exhumation persisted towards brittle crustal conditions under tectonic top-to-the-W/SW-vergent extension. Although less obvious than in the gneiss, the presence of semiductile shear zones in the quartz syenite shows that the extensional exhumation continued into the brittle–ductile transition zone after the intrusion of the voluminous quartz syenitic magmas. This illustrates that quartz syenite, dated to *c*. 520–510 Ma by U–Pb geochronology on zircons (Mikhalsky *et al.* 1997; Paulsson, 2003), was emplaced when the country rocks were at higher crustal levels than they were during peak metamorphism.

The latest metamorphic record of the Pan-African event is the late-magmatic fluid infiltration around 2 kbar (Engvik *et al.* 2003). The fluid infiltration is dated around 485 Ma by U–Pb on zircons and titanites (Paulsson, 2003), giving the time where the crust was exhumed to about 2 kbar and the tectonic activity was decreasing. This shows that the Pan-African exhumation from peak granulite facies (7–8 kbar; Bucher-Nurminen & Ohta, 1993; Piazolo & Markl, 1999) was about 15–20 km. Later exhumation, brittle faulting and intrusion of mafic dykes are related to Permo-Triassic removal of crustal material and break-up of Gondwana around 200 Ma (e.g. Groenewald *et al.* 1995; S. Meier, unpub. Ph.D. thesis Alfred-Wegener-Institute, 1999).

6.b. Late-orogenic collapse of the Pan-African East Antarctic orogen

Plate reconstructions suggest that the Neoproterozoic overprint of East Antarctica formed during the amalgamation of Gondwana (e.g. Fitzsimons, 2000). It is not clear whether the belt was dominated by transcurrent or collisional tectonics (Wilson, Grunow & Hanson, 1997; Meert & van der Voo, 1997; Fitzsimons, 2000). For Dronning Maud Land, Jacobs *et al.* (1998) suggest a transpressional orogenic setting correlated to the Mozambique belt of southeastern Africa. If the

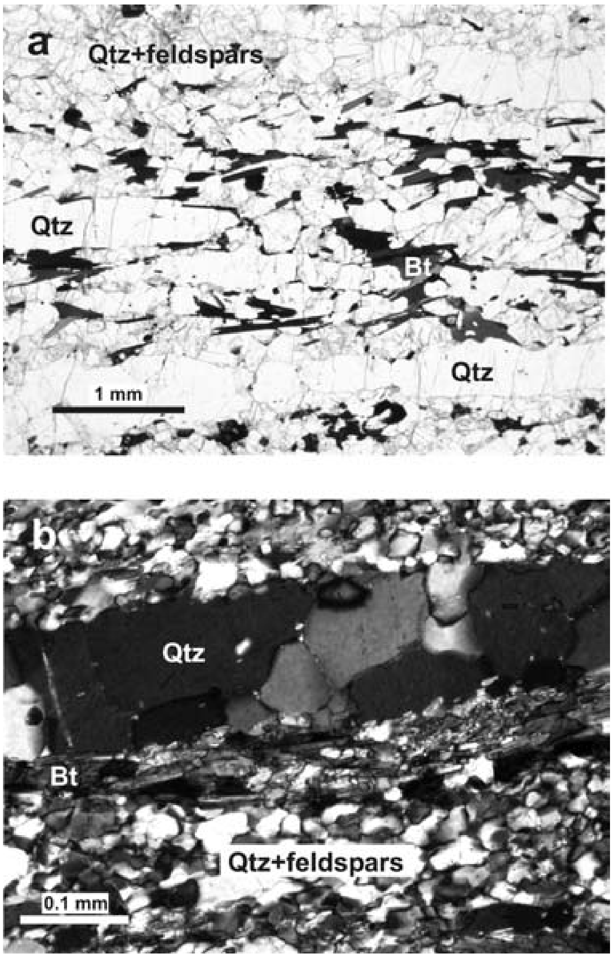

Figure 8. Photomicrographs showing recrystallized quartzofeldspatic mineral assemblage in Type II extensional shear zones (abbreviations after Kretz, 1983). (a) Large flattened quartz grains oriented parallel to the fine-grained matrix minerals of quartz, plagioclase, microcline and oriented biotite. From ductile shear zone in gneiss of Klevekampen, sample AN28. (b) Very fine-grained recrystallized quartz, feldspars and horizons with oriented biotite and coarser quartz grains in a quartz rod. From a semiductile shear zone cutting the quartz syenite of Trollslottet, crossed nicols, sample AHA202.

high-pressure mineralogical parageneses recorded from Filchnerfjella represent an early stage of the Pan-African event, crustal thickening during a convergent orogeny is evident, in accordance with the model by Meert & van der Voo (1997). The chemical signature of the syenites in central Dronning Maud Land is also in accordance with an overthickened crust during continent–continent collision (Paulsson, 2003).

Evidence of rapid exhumation combined with tectonic extension is widespread in areas of East Antarctica. In the area around Prydz Bay (70° E, 70° S) tectonic extension resulted in an uplift of 10–15 km around 514 Ma (Thost, Hensen & Motoyoshi, 1994; Carson *et al*. 1995; Fitzsimons, Kinny & Harley, 1997; Zhao *et al*. 1997). In Lützow Holmbukta (*c*. 40° E, 69° S) the crust was uplifted from *c*. 11 to 4 kbar under near-isothermal decompression for a period of 20 ± 10 Myr during the late Pan-African event (Fraser *et al*. 2000). In western Dronning Maud Land, a major shear zone near Heimefrontfjella (10° W) separates the little-affected Mesoproterozoic crust of western Dronning Maud Land (Groenewald *et al*. 1995; Jacobs *et al*. 1996) from the Pan-African overprinted central Dronning Maud Land. In this area Groenewald *et al*. (1995) reported a major uplift and exhumation around 500 Ma. Jacobs *et al*. (2003) reported Pan-African extensional structures in the Wohlthatmassiv of central Dronning Maud Land (12° E) and suggested that orogenic collapse had occurred. Late Pan-African extension is also reported from the East African orogen of Madagascar (Collins, Razakamanana & Windley, 2000; De Wit *et al*. 2001) and in the Arabian–Nubian Shield in Egypt (Blasband *et al*. 2000).

Near-isothermal decompression is commonly recorded by migmatites in gneiss areas. Teyssier & Whitney (2002) suggested a genetic link and a dynamic relationship between decompression and partial melting. Partial melting weakens the crust and facilitates orogenic collapse and crustal thinning. Decompression driven by surficial or tectonic processes may also trigger partial melting by crossing the phase boundaries during isothermal exhumation. Melt will remain mobile because the decompression path remains in the stability field of the melt. Ascent of hot orogenic crust creates low-density and low viscosity regions that rise sufficiently fast and retain enough melt to maintain near-isothermal conditions. Teyssier & Whitney (2002) have suggested density inhomogeneities in thickened orogenic crust as a driving force for buoyancy uplift and partial melting during decompression.

The high geotherm under the Pan-African event is recorded by metamorphic studies over large areas of the East Antarctic craton (Bucher-Nurminen & Ohta, 1993; Thost, Hensen & Motoyoshi, 1994; Piazolo & Markl, 1999). In addition, the late Pan-African syenitic magmas are voluminous in central Dronning Maud Land. Syenitic magmas may originate from crustal partial melting at high temperatures, and their formation requires a supply of heat from the underlying mantle (Wyllie, 1977; Philpotts, 1990). Stüwe & Sandiford (1993) have assumed underplating of basaltic, asthenosphere-derived melts to explain the high temperatures and crustal uplift recorded over the large East Antarctic craton. According to Stüwe & Sandiford (1993), such hot underplating melts can trigger partial melting of the crust, which is consistent with the occurrence of crustal melts as pegmatites, granites and charnockites. However, in an orogenic cycle, high temperatures can also be caused by delamination or convective removal of mantle lithosphere being replaced by hotter asthenosphere (England & Houseman, 1988). The removal of the mantle lithosphere can induce orogenic collapse (Dewey, 1988), and the high temperature source below combined with rapid exhumation will result in a near-isothermal decompression triggering partial melting and post-tectonic intrusions as found in central Dronning Maud Land. Extensional structures as reported in this work from the Filchnerfjella, and also in the Wohlthatmassiv by Jacobs *et al*. (2003), show that the exhumation was accompanied by tectonic extension over a larger part of central Dronning Maud Land. We conclude that the late phase of the Pan-African event in central Dronning Maud Land is characterized by a near-isothermal decompression *P*–*T* path and extensional structures indicating tectonic exhumation, which most likely is related to a late-orogenic collapsing phase of a Pan-African orogen.

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