

Partial melting of metapelites at ultrahigh-pressure conditions, Greenland Caledonides

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ABSTRACT Eclogite, orthogneiss and, by association, metapelite from an island at 78°N in North-East Greenland experienced ultrahigh-pressure (UHP) metamorphism at approximately 970 °C and 3.6 GPa, at the end of the Caledonian collision, 360–350 Ma. Hydrous metapelites contain abundant leucocratic layers and lenses composed of medium-grained, anhedral, equigranular quartz, antiperthitic plagioclase and K-feldspar with minor small garnet and kyanite crystals. Leucosomes are generally parallel to the matrix foliation, are interlayered with residual quartz bands, anastomose around residual garnet and commonly cross-cut micaceous segregations. Textures suggest that the leucosomes crystallized from a syntectonic melt, but crystallized at the end of local high-grade deformation. The metapelite outcrop is < 1.5 km from kyanite eclogites with confirmed coesite, but the metapelites lack coesite and palisade textures diagnostic of coesite pseudomorphs. They do contain highly fractured garnet megacrysts with polycrystalline quartz inclusions (some surrounded by radial fractures) and Ti-rich phengite inclusions that suggest the former presence of coesite. Polyphase inclusions in garnet contain reactants and products of the inferred dehydration melting reaction: $\text{Phe} + \text{Qtz} = \text{Ky} + \text{Kfs} + \text{Rt} + \text{melt}$. The reactants are thought to have been early inclusions of hydrous phases within garnet that melted and then crystallized new phases. Garnet surrounding these inclusions has patchy zoning with elevated Ca, consistent with experiments that produced similar patchy microstructures in garnet around inclusions with an unequivocal melt origin. The peak UHP metamorphic assemblage in these rocks is inferred to have been phengite, coesite, garnet, kyanite, rutile, fluid $\pm$ omphacite $\pm$ epidote. Phase diagrams indicate that dehydration melting of phengite in this assemblage would have occurred after decompression from peak pressure, but still above the coesite to quartz transition. Unusual crown- and moat-like textures in garnet around some polycrystalline quartz inclusions are also consistent with the inference that melting took place at UHP conditions.

Key words: Caledonides; Greenland; metapelites; partial melting; ultrahigh-pressure.

INTRODUCTION

Ultrahigh-pressure (UHP) metamorphic rocks commonly evolve under nominally anhydrous conditions and have been examined mainly in terms of phase relationships among solid phases, but the important possibility of generation of a supercritical melt/fluid phase by dehydration melting of hydrous phases is increasingly being examined (Chopin, 2003, and references therein). Demonstrating that partial melting took place in UHP rocks, especially metapelites, is difficult because of extensive reaction and re-equilibration of assemblages along the decompression and cooling path (Perchuk *et al.*, 2005, in press). Extensive migmatites and other evidence of partial melting, which occurred during exhumation from UHP conditions, have been documented in the Dabieshan of China (Faure *et al.*, 1999; Zhong *et al.*, 2001) and the Western Gneiss region of Norway (Labrousse *et al.*, 2002). Investigators working on diamondiferous rocks

of the Saxonian Erzgebirge and the Kokchetav massif have even found polyphase inclusions in garnet that are interpreted to represent crystallized trapped melt (Hwang *et al.*, 2001; Stöckhert *et al.*, 2001; Massonne, 2003; Korsakov *et al.*, 2004; Korsakov & Hermann, 2006). Similar textures have been reproduced in novel experiments on garnet with hydrous and carbonate mineral inclusions, supporting an origin by partial melting (Perchuk *et al.*, 2005, in press).

Peak conditions of UHP metamorphism in the North-East Greenland Caledonides are estimated to have been as high as 970 °C and 3.6 GPa (Gilotti & Ravana, 2002). At these conditions, dehydration melting of hydrous minerals such as phengite and clinozoisite is possible in otherwise dry rocks (e.g. Hermann & Green, 2001; Chopin, 2003; Perchuk *et al.*, 2005, in press). Phengite-bearing pelitic rocks, from the small island where coesite has been found, are particularly good candidates for partial melting. In this paper, we describe the complex textures and

mineral assemblages that are preserved in these metapelites and examine them for evidence of partial melting. We present documentation of the mineralogy and texture of a polyphase inclusion, interpreted as having formed from partial melting and crystallization of the melt within a garnet megacryst. To our knowledge, this is the first documented instance of a trapped former melt inclusion in diamond-free UHP rocks. Ca zoning in garnet is also presented as evidence in favour of melt origin for leucosomes and the polyphase inclusions. Examination of mineralogy and textures of crystallized partial melts in these rocks relative to experimental phase relations indicates that the melting occurred after peak pressure but still at UHP conditions.

Partial melting of rocks containing hydrous minerals will dramatically affect the rheologic properties of subducted crust and is thought to play a crucial role in the initiation of rapid exhumation of UHP terranes, although the exact mechanism is still poorly understood (Faure *et al.*, 1999; Hermann *et al.*, 2001; Zhong *et al.*, 2001; Labrousse *et al.*, 2002; Chopin, 2003). Understanding the extent, conditions and timing of partial melting in UHP rocks in as many individual terranes as possible will provide important constraints on tectonic models for exhumation of UHP metamorphic rocks.

GEOLOGICAL SETTING

Caledonian UHP metamorphism has long been known from the Western Gneiss region of Norway (e.g. Smith, 1984; Wain, 1997), but has only recently been reported from North-East Greenland (Gilotti & Ravna, 2002; McClelland *et al.*, 2006). The Norwegian UHP terrane is part of the continental crust of Baltica that was subducted beneath Laurentia during the Caledonian orogeny. Metamorphism in the diamond stability field (Dobrzhinetskaya *et al.*, 1995; van Roermund *et al.*, 2002) attests to subduction down to 150 km. UHP metamorphism of Baltica occurred at approximately 410–400 Ma (Terry *et al.*, 2000; Carswell *et al.*, 2003; Root *et al.*, 2004; Tucker *et al.*, 2004). The Norwegian UHP terrane is exposed in three discrete E-trending culminations that may be over 40 000 km³ if they are a continuous folded sheet (Root *et al.*, 2005). The UHP rocks in Greenland are found on a small island (Fig. 1), informally known as Rabbit Ears Island. The island lies at 78°N in Jøkelbugt at the exposed eastern margin of the larger North-East Greenland eclogite province (Gilotti, 1993). As is typical of many UHP areas around the world, we expect that the documented area of UHP metamorphism in Greenland will increase with further study; however, this will take time due to the remote location of the area. HP and UHP

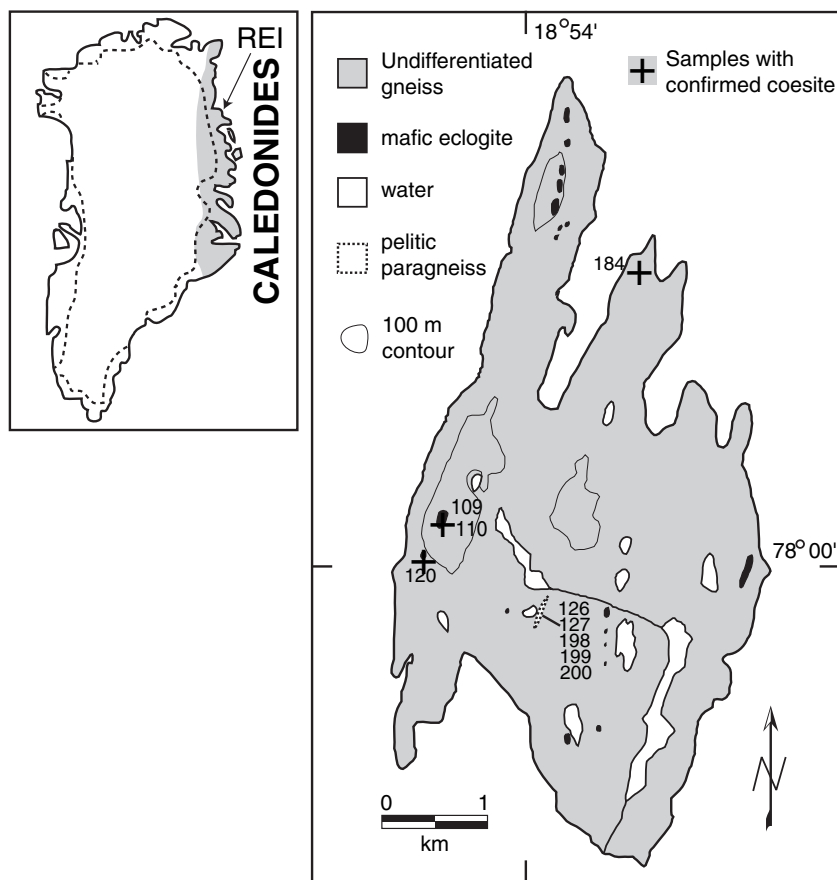


Fig. 1. Map of Rabbit Ears Island showing lithologies and sample locations. The shaded area on the inset shows the extent of the Greenland Caledonides and the approximate location of Rabbit Ears Island (REI). All sample numbers are preceded by 03-.

metamorphism in Greenland occurs in the continental crust of the Laurentian margin, in the upper plate of the continent–continent collision. HP metamorphism in North-East Greenland has been dated at 410–390 Ma (Gilotti *et al.*, 2004), while UHP metamorphism is *c.* 360–350 Ma (Gilotti *et al.*, 2004; McClelland *et al.*, 2006).

Palaeoproterozoic quartzofeldspathic orthogneisses comprise the majority of the rocks on Rabbit Ears Island. The gneisses contain variable amounts of quartz, K-feldspar, plagioclase, garnet, clinopyroxene, amphibole, biotite, rutile, ilmenite, titanite and zircon depending on their original bulk composition and their degree of retrogression. Clinopyroxene is abundant in the orthogneisses, and its presence is a good indicator of a preserved high grade history. In the least retrogressed gneisses, garnet and zircon contain inclusions of eclogite facies phases (e.g. phengite, kyanite, omphacite and rutile) and coesite was found in a zircon from sample 03-184 (Fig. 1) (McClelland *et al.*, 2006). Gneissosity is steep and strikes approximately 015° (i.e. parallel to the peninsulas on the north side of the island that resemble a rabbit's ears). The gneisses contain strings of blocky eclogite boudins; one such boudinaged layer runs the length of the western side of the island (Fig. 1). The eclogites are compositionally banded on a decimetre scale suggesting that their protolith was a layered mafic intrusion. Coesite has been found as inclusions in zircon in three different kyanite eclogite samples (03-110, 03-109 & 03-120 on Fig. 1, McClelland *et al.*, 2006). Polycrystalline quartz inclusions with palisade texture and radial fractures are common in garnet of the kyanite eclogite, and are interpreted to be pseudomorphs after coesite (Gilotti & Ravna, 2002); they are found to a lesser extent in omphacite and kyanite. Pressures and temperatures in the range of 3.6 GPa and 970 °C were calculated from the peak assemblage garnet + omphacite + kya-

nite + coesite/quartz + phengite (Gilotti & Ravna, 2002), using the Ravna & Terry (2004) calibration based on net transfer reactions among these six phases. The estimated peak temperature is unusually high for UHP terranes (Liou *et al.*, 2004), and may be an important cause of the partial melting inferred for the metapelites.

In addition to eclogites, the orthogneisses contain rare lenses of metasedimentary rocks. One distinctive outcrop of purple pelitic paragneiss is located on the east side of a small lake in the south-central part of Rabbit Ears Island (Fig. 1). Similar purple paragneiss float is found in *felsenmeer* all over the island. Garnet gives the rock its characteristic purple hue. The outcrop on Rabbit Ears Island consists of a 10–15 m thick layer of rusty weathering, purple garnet–biotite gneiss concordant with the regional foliation in the surrounding orthogneiss. Gneissosity is defined by cm-scale compositional layering between reddish-weathering quartzofeldspathic leucosomes and biotite-rich layers. The largest single lens of garnet-bearing leucosome is 15–20 cm thick and parallel to the foliation (Fig. 2; sample 03-198), while the smallest lenses are wispy layers on the order of 1 mm thick. The leucocratic lenses and layers appear to be the products of partial melting of the pelites, because they commonly cross-cut gneissic banding, are roughly granitic in composition, are equigranular and lack internal foliation.

SAMPLE DESCRIPTIONS

Metapelitic rocks of this outcrop range from dark finely banded garnet, phengite, biotite, kyanite gneiss with a limited proportion of dispersed quartzofeldspathic leucosome (samples 03-200 and 03-199) to a sample of the segregated leucosome lens (sample 03-198) with residual garnet and only minor biotite. In the



Fig. 2. Photograph of the pelitic paragneiss outcrop. The pencil is 14 cm long. The garnet-bearing leucosome (sample 03-198) is 15–20 cm thick and lies parallel to the near-vertical foliation. Typical pelitic rocks are best viewed in the upper portion of the photograph.

sample descriptions, the term leucosome is used to refer to light-coloured quartzofeldspathic layers and lenses, and micaceous segregation (rather than melanosome) to refer to dark micaceous layers that consisted mainly of phengite at HP/UHP conditions and were not really dark. Palaeosome refers to portions of the rock that have been least affected by melting, and neosome refers to products of melt crystallization. Descriptions of five metapelitic samples collected from this outcrop are presented in order of those with least leucosome and least evidence of partial melting to those with the most leucosome and most extensive evidence of partial melting.

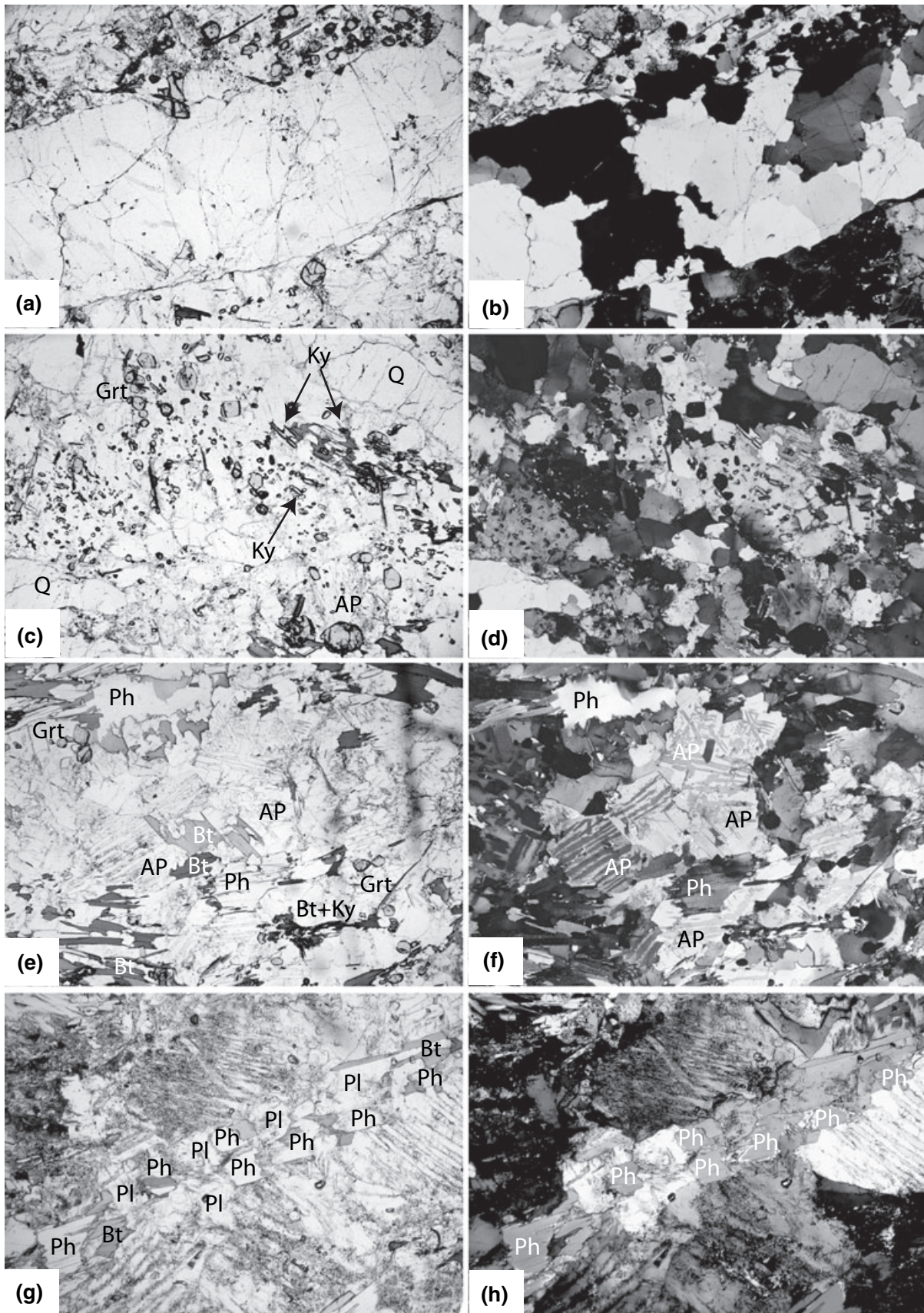
Sample 03-200 is a well foliated garnet, phengite, biotite, kyanite gneiss. The hand specimen is finely laminated (< 2 mm thick layers) with white quartzofeldspathic layers alternating with dark layers rich in biotite, phengite, garnet and kyanite. In thin section, the light layers contain patches of dusty-appearing plagioclase, K-feldspar and quartz with minor white mica, biotite, small subhedral garnets (some have unusual doughnut shapes and quartz inclusions in their cores), and minor kyanite, dispersed among matrix grains of quartz, white mica (partially altered to biotite), biotite and kyanite. The leucosome patches, which comprise 10–15 vol.% of the rock, are interpreted as crystallized partial melt, but they apparently did not coalesce or travel far from their place of origin. In this sample, it is still possible to make a rough distinction between matrix quartz, which occurs as isolated single grains, and nearly monomineralic bands of quartz grains that are sutured together (Fig. 3a,b). These quartz bands, which are thicker and more abundant in more thoroughly migmatized samples, are associated with fine grained, quartzofeldspathic layers and lenses inferred to have crystallized from melt. The abundance of phengite in the matrix (with some grains rimmed or partially replaced by biotite), especially in association with patches inferred to have crystallized from melt, indicates that it may have been abundant in the peak mineral assemblage and dehydration melting of phengite may have given rise to the leucosomes (Indares & Dunning, 2001). Individual dark and light layers that define the foliation are less than 2 mm thick. Dark layers in the matrix are composed of biotite, phengite, quartz, fairly abundant kyanite, and garnet porphyroblasts, 5–9 mm in diameter, which

contain large, polyphase inclusions ($\text{Qtz} \pm \text{Bt} \pm \text{Ky}$) in their interiors. The direct association of kyanite with biotite suggests a reaction with $\text{Bt} + \text{Ky}$ as products.

Sample 03-199 shows limited evidence of partial melting. It is similar to 03-200, but contains a larger proportion (≈ 20 vol.%) of localized leucosome pods and lenses and is highly altered with biotite commonly replaced by green chlorite and highly sericitized K-feldspar. Garnet porphyroblasts up to 7 mm in diameter are altered to $\text{Bt} + \text{Chl}$ along fractures. Isolated leucocratic lenses contain K-feldspar, plagioclase, quartz, biotite, phengitic white mica (commonly partially replaced by biotite), small garnet and kyanite dispersed within a quartz-rich matrix, in which quartz grains are separated by mica and do not form bands. Kyanite is intimately associated with biotite in the dark matrix layers. The foliation in this sample is weaker than that of 03-200, having been disrupted by post-kinematic biotite and chlorite growth.

Sample 03-126 contains a substantial proportion of leucocratic layers and lenses (up to 5 mm in thickness) that anastomose throughout the matrix and commonly surround large garnet porphyroblasts. The leucosome, which makes up about 35% of the sample volume, consists of intergrown quartz bands (Fig. 3a,b) and fine-grained, dusty lenses of K-feldspar, plagioclase (some single twinned grains and some antiperthite, Fig. 3c–h), quartz, white mica, minor biotite and very fine euhedral crystals of garnet. Minor kyanite is observed as small isolated crystals (Fig. 3c) and associated with biotite in the leucosome. The micaceous segregations contain quartz, phengite (some partially rimmed by biotite), biotite, K-feldspar, plagioclase and kyanite. Thin micaceous layers containing aligned phengite are commonly surrounded by leucosome inferred to have crystallized from melt. In some cases, trains of isolated phengite grains that are optically continuous occur in the leucosome of this sample (Fig. 3g,h). Kyanite is most abundant in biotite-rich micaceous segregations. Large garnet porphyroblasts appear to have originated as metamorphic garnet and been modified by additional growth as a result of melt crystallization (see discussion of garnet zoning). Garnet megacrysts are anhedral, highly fractured and contain abundant inclusions; inclusions are most commonly monomineralic and contain quartz or white mica or are biminerally with both. Garnet grains are larger than those in

Fig. 3. Photomicrographs of leucosome textures. Mineral abbreviations are after Spear (1993) unless otherwise indicated. The field of view is 3 mm wide except in (g) and (h). (a) Quartz bands (sample 03-127) are sharply bounded segregations entirely composed of quartz grains containing trails of fluid inclusions. Plane-polarized light (PPL). (b) The same field as (a) in cross-polarized light (XPL). Individual grains have serrated boundaries and undulose extinction. The quartz bands are interpreted as residual, but the deformation features are late. (c) Sample 03-127, typical fine grained leucosome with quartz (Q), K-feldspar, antiperthitic alkali feldspar (AP), small garnet and kyanite, and minor biotite. PPL. (d) Same as (c), in XPL. (e) Sample 03-126, a coarser grained leucosome with characteristic rod-like antiperthite. Phengite (Ph) is rimmed and partially replaced by biotite. Small garnet is located in the upper left and lower right of the image. Small kyanite is associated with biotite. PPL. (f) Same as (e), in XPL. (g) Optically continuous phengite (Ph) that is common in the antiperthitic leucosomes of sample 03-126. The phengite is partially replaced by plagioclase (not antiperthitic) and biotite. Adjacent leucosome consists mostly of coarse-grained antiperthitic alkali feldspar. PPL; field of view is 2.5 mm. (h) Same as (g), in XPL.



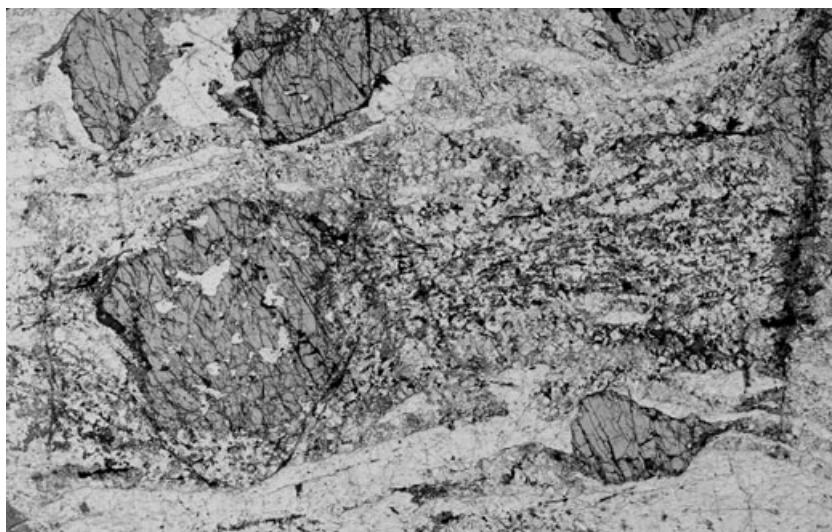


Fig. 4. A high resolution scan of an entire 4 cm wide thin section, 03-127a, in PPL. Megacrystic garnet shows various relationships with the leucosomes and micaceous segregations. The clear areas are quartz bands and dusty layers and lenses interlayered with them are leucosomes, i.e. crystallized matrix melt. Thin micaceous segregations occur to the right of the largest garnet porphyroblast.

03-200 and 03-199 (up to 1 cm in diameter) and are commonly clustered together when they occur in or adjacent to the leucosome. In garnet porphyroblasts adjacent to leucosomes, large (and small) quartz inclusions may be surrounded by a moat that consists of plagioclase and K-feldspar. Rutile, zircon and monazite are present as accessory minerals.

Sample 03-127 contains thicker, more abundant leucosome layers than 03-126, and leucosome commonly surrounds large garnet or clusters of garnet (individual grains up to 12 mm). Leucosome layers and lenses are up to 1 cm thick and comprise 40–50% of the sample volume. Figure 4 shows the overall texture of this sample in which leucosome dominates the upper left and lower right portions of the image and surrounds several garnet porphyroblasts. The leucosome contains recrystallized quartz bands interspersed with dusty layers and lenses that contain antiperthitic plagioclase, K-feldspar, quartz, minor myrmekite and fairly abundant small subhedral crystals of garnet and kyanite (Fig. 3a–d) and minor biotite. In the leucosome, kyanite is small and varies in abundance; it is commonly associated with biotite. Garnet megacrysts, whether surrounded by leucosome or in micaceous segregations, are similar in size, are ovoid and anhedral, contain abundant inclusions (monomineralic to polymineralic), and are highly fractured. Rutile is present in the leucosome matrix, commonly in association with biotite, and as inclusions in garnet; zircon is an accessory mineral. Biotite-rich micaceous segregations in this sample contain abundant kyanite.

A 15–20 cm thick lens of segregated, garnet megacryst-bearing leucosome within the pelitic paragneiss (Fig. 2, sample 03-198) was sampled for this study. This sample has a moderate foliation defined by alternating parallel layers and lenses of fine-grained leucosome and quartz bands. The leucosome (approximately 85% of the sample volume) is composed of equal proportions of recrystallized quartz

bands and leucocratic material interpreted to have crystallized from melt. The leucosomes are composed mainly of patchy K-feldspar, antiperthitic plagioclase, and quartz with minor white mica, minor biotite, and small subhedral grains of garnet and kyanite. K-feldspar and antiperthitic plagioclase in the leucosome patches appear dusty as they are variably altered to sericite; however, some zoned grains of plagioclase are twinned and relatively unaltered. This sample contains approximately 15% scattered garnet megacrysts up to 1 cm in diameter (slightly smaller than garnet in 03-126 and 03-127). Garnet megacrysts are interpreted to be modified residual garnet from the palaeosome because of their much larger size than the neosome garnet (< 0.5 mm) in leucosome, and the large, complex quartz $\pm$ feldspar inclusions and fracture textures that they retain. Minor retrograde biotite rims some of the large garnet porphyroblasts.

EVIDENCE FOR UHP METAMORPHISM IN PELITIC PARAGNEISS

The primary evidence that pelitic paragneiss from Rabbit Ears Island experienced UHP metamorphism comes from its proximity to samples of other lithologies that have been shown to contain coesite (McClelland *et al.*, 2006) and coesite pseudomorphs for which peak conditions of $\sim 970^\circ\text{C}$ at 3.6 GPa were estimated (Gilotti & Ravna, 2002). The presence of coesite in zircon from garnet-bearing host orthogneiss sample 03-184, which comes from a locality 3.3 km along-strike from the metapelite outcrop (Fig. 1), demonstrates that the country rocks experienced the same UHP conditions as the nearby kyanite eclogite pods. The schistosity in the metapelites is concordant with gneissosity and no structural discontinuities have been identified around the outcrop. At UHP conditions, much or all of the free SiO_2 in the metapelites would have been coesite.

Evidence presented below demonstrates that the pelitic paragneisses experienced partial melting early on their decompression path from peak pressure. The temperatures estimated for the Greenland UHP eclogites are much higher than the average for UHP terranes (Liou *et al.*, 2004), but approach those determined for the diamondiferous Saxonian Erzgebirge and the Kokchetav massif, Kazakhstan, where evidence for melting has been recognized (Hwang *et al.*, 2001; Stöckhert *et al.*, 2001; Dobrzynetskiy *et al.*, 2003; Massonne, 2003; Korsakov *et al.*, 2004; Korsakov & Hermann, 2006). The presence of partial melt (as a supercritical fluid) would enhance kinetics and contribute to rapid conversion of coesite to quartz, changes in metamorphic assemblage and annealing of textures characteristic of the coesite-quartz transition such as radial fractures and coesite pseudomorphs. This may explain why

definitive UHP textures have not been observed in the pelitic paragneisses. Some garnet megacrysts in samples 03-126 and 03-127 contain abundant monomineralic and bimineralic inclusions and are highly fractured (Figs 4 & 5a). Although no diagnostic palisade-textures have been observed after coesite (Chopin & Sobolev, 1995; Hacker & Peacock, 1995), polycrystalline quartz inclusions (Fig. 6a,b) are common in the garnet megacrysts. Monocrystalline quartz inclusions, phengite inclusions and Qtz + Phe inclusions are also common (Figs 5 & 6). The dominant fractures in garnet megacrysts, which are late and are probably related to exhumation, occur in a single parallel set (Figs 4, 5a & 7a) oblique to the rock foliation. Finer fractures, which are less obvious because they are partially annealed and overprinted by the later set, commonly radiate outward from small mono- and polycrystalline quartz

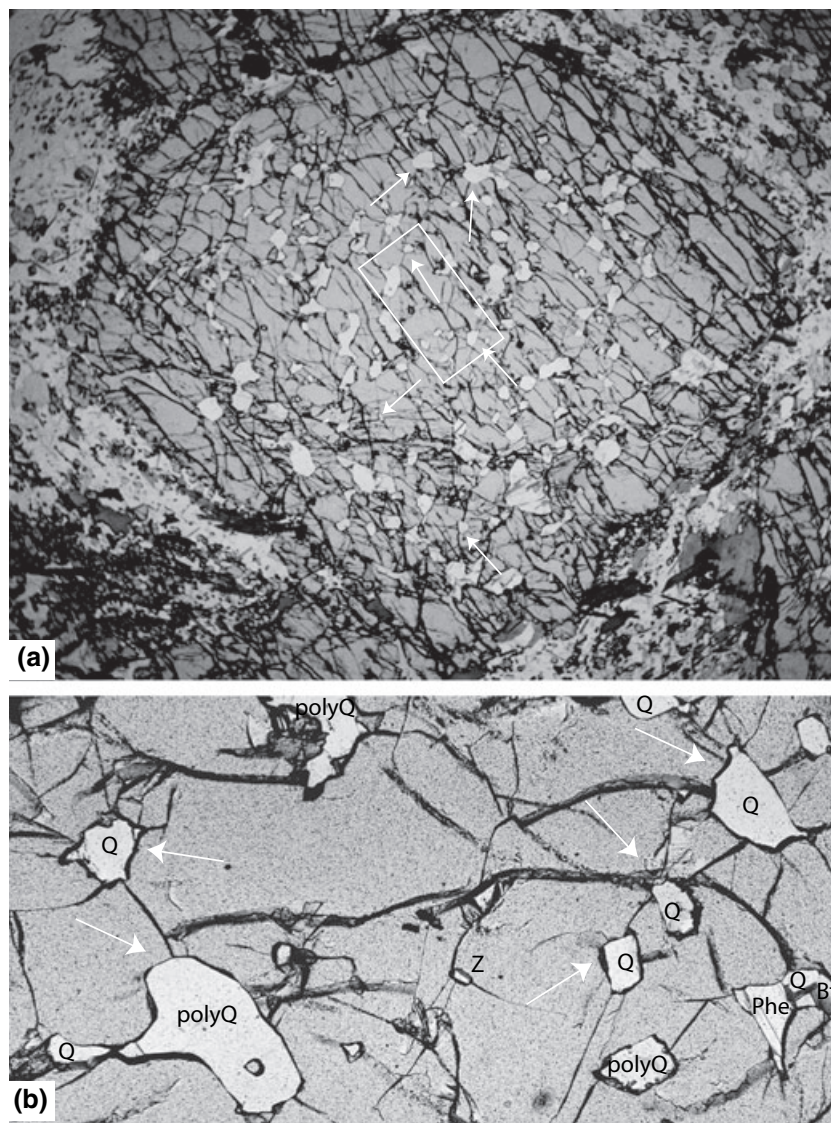


Fig. 5. Photomicrograph of an inclusion-rich garnet megacryst, sample 03-127, PPL. Field of view in (a) is 12 mm wide. The garnet contains inclusions of mono- or polycrystalline quartz, phengite or quartz + phengite. In the dominant set, fractures are parallel and late, but some of the finer, earlier fractures are radial to the margins of mono- and poly-crystalline quartz inclusions (arrows). (b) Inset from (a) is 2 mm wide and shows the finer fractures that radiate from the margins of many of the quartz inclusions, indicative of the former presence of coesite (Q = quartz, polyQ = polycrystalline quartz, Phe = phengite, Bt = biotite, and Z = zircon).

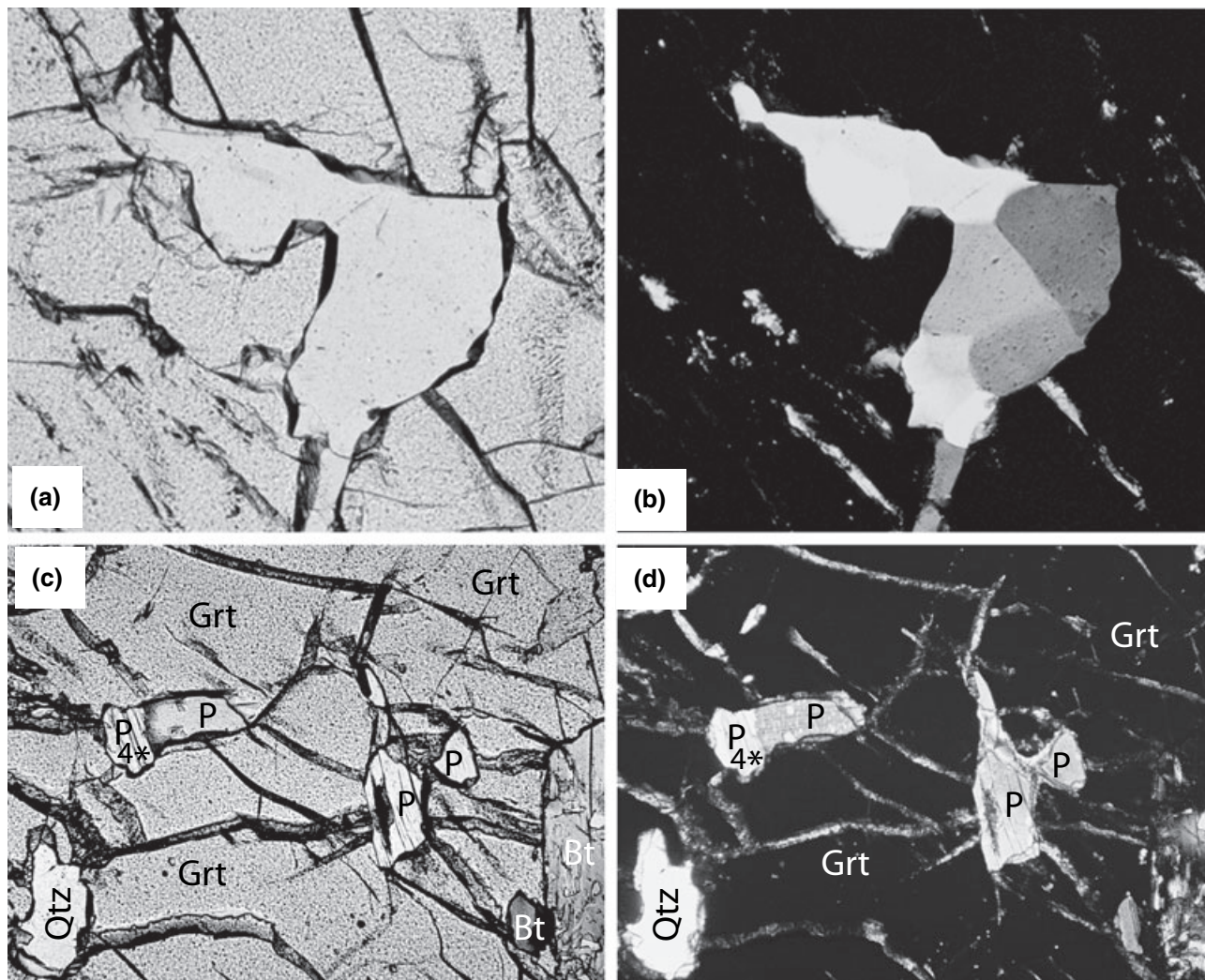


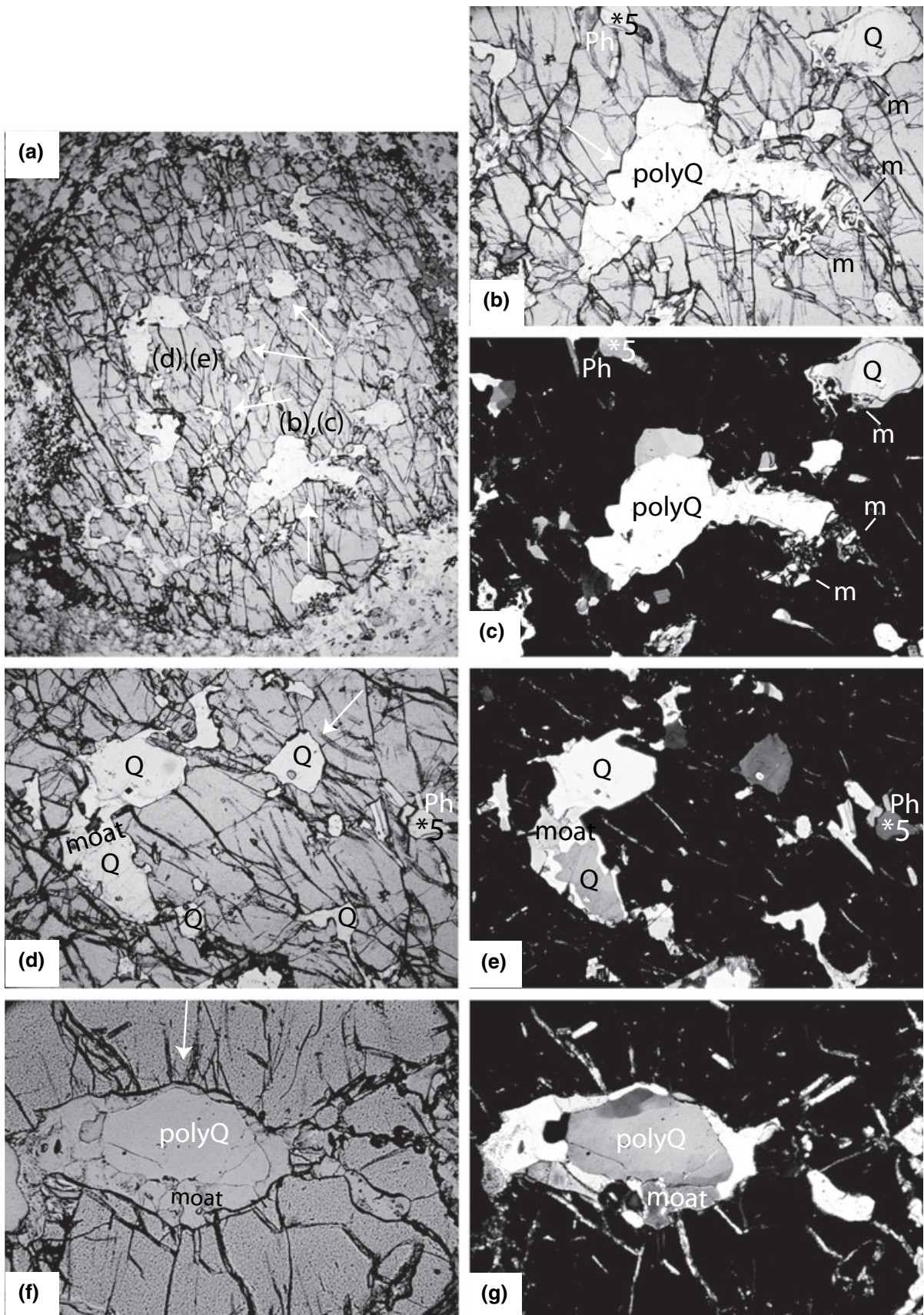
Fig. 6. (a, b) A polycrystalline quartz inclusion in a garnet megacryst, sample 03-127; (a) in PPL; (b) in XPL. Several fractures extend from the inclusion, but they are not exactly radial. The width of the field of view is 0.75 mm. (c) Phengite inclusions (P) in a garnet of sample 03-126. The location of Analysis no. 4 in Table 1 is shown by an asterisk. The field of view is 1.6 mm wide; (d) in XPL.

inclusions (arrows in Fig. 5a,b; arrows in Fig. 7a,b, d,f). These radial fractures are evidence of expansion at the coesite to quartz transition. Ti-rich phengite inclusions in garnet, even without the full assemblage of the garnet–clinopyroxene–kyanite–phengite–coesite/quartz geothermobarometer (Ravna & Terry, 2004), are evidence of high to ultrahigh pressure.

MINERAL CHEMISTRY

Minerals were analysed using standard techniques on the JEOL 733 Superprobe and the CAMECA SX-100 electron microprobe in the Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy, New York. Back-scattered electron (BSE) images were used for characterization of tex-

Fig. 7. (a) Photomicrograph of a garnet poikiloblast from sample 03-127 with larger polycrystalline quartz inclusions than the garnet in Fig. 5. Inclusions surrounded by radial fractures are indicated by white arrows. Many of the inclusions seem to have been in communication with the matrix via fractures, and have plagioclase + K-feldspar rims (moats) around the inclusions that are interpreted as melt related features. Field of view is 12 mm wide. (b) Detail in PPL and (c) XPL of a feldspar-rimmed quartz inclusion. The feldspar rim or moat (m) is localized along fractures that extend into the garnet at lower right of the photograph. The quartz inclusion at the upper right has an almost continuous moat around it. Field of view is 3 mm wide. (d) Detail in PPL and (e) XPL of another two-lobed feldspar-rimmed quartz inclusion. Asterisks indicate probe analysis spots. Field of view is 3 mm wide. (f) Detail in PPL and (g) XPL of a thick feldspar moat around a polycrystalline quartz inclusion that is surrounded by radial fractures. Field of view is 1.6 mm wide.



tural relationships. Semi-quantitative X-ray element maps were obtained by programming the microprobe stage to move in a rectangular grid pattern under a fixed beam with high current, collecting X-ray intensity data for Ca, Mg, Fe, Mn and Na at each spot. Representative mineral analyses are given in Table 1; locations of probe analyses are shown on the figures. In addition to the analysed minerals, phengite, biotite, plagioclase, K-feldspar and garnet (Table 1), all samples contain quartz, kyanite and rutile, which are essentially pure minerals, along with accessory zircon and monazite. All analysed minerals occur in different settings or generations and, therefore, have a range of compositions.

Phengite occurs with biotite in the foliated micaceous segregations and as isolated grains in the leucosome; in both settings it is commonly rimmed or partially replaced by biotite $\pm$ plagioclase. Phengite is also found as isolated inclusions in the large porphyroblastic garnet (Figs 6c,d & 7b–e). In some inclusions white mica is pristine and isolated, and in others it is partially replaced by biotite. Phengite is present in the polyphase inclusion in garnet from 03-127 (Fig. 8) in which it is inferred to have reacted with adjacent quartz during dehydration melting. White mica in all settings is phengitic with Si per 11-oxygen formula unit ranging from 3.138 to 3.300 (Table 1). White mica with the highest phengite content is found as isolated inclusions in garnet porphyroblasts (Fig. 6, Anal. no. 4; Fig. 7, Anal. no. 5; Fig. 8, Anal. no. 7) and in the matrix, which is inferred to have contained partial melt. All phengite is relatively high in Ti with Ti per formula unit varying from 0.087 to 0.131.

Biotite commonly rims and replaces white mica, but also occurs as separate grains in the matrix and in the micaceous segregations. Fe/Fe + Mg in biotite varies from 0.424 to 0.502. Biotite in all settings is Ti-rich with Ti per formula unit varying from 0.125 to 0.267 (Table 1).

Plagioclase and K-feldspar vary in grain size and may occur as antiperthite or as separate grains in the leucosome. Plagioclase also occurs with biotite as a replacement of phengite. The matrix feldspar is interpreted to have crystallized from a melt and exsolved over a range of conditions, and has a range of compositions. Plagioclase is albite rich with the following range of compositions (mean $\pm$ standard deviation): Ab = 0.760 ± 0.048 , An = 0.223 ± 0.049 and Or = 0.018 ± 0.004 . Or-content of K-feldspar is 0.871 (± 0.018) and Ab-content is 0.123 (± 0.019), and the An-content averages only 0.001 (Table 1).

Garnet is almandine (60–72 mol.%)–pyrope (17–34 mol.%) with significant and variable grossular content (8–19 mol.%). The spessartine content is extremely low (< 1 mole%) and shows no discernable pattern. The details of garnet zoning, particularly of Ca, in these metapelites are discussed below in relation to partial melting.

Quartz was also analysed for Ti (Wark & Watson, 2006) and rutile for Zr for thermometry following the technique developed by Watson *et al.* (2006) that uses long count times on several spectrometers on the SX-100 simultaneously. Values of Ti in quartz in sample 03-126 range from 16 to 73 ppm with a mean of 27 ppm; in sample 03-127 Ti in quartz ranges from 17 to 116 ppm with a mean of 35 ppm. Zr in rutile in sample 03-126 ranges from 577 to 658 ppm with a mean of 620 ppm; in sample 03-127 Zr ranges from 541 to 675 ppm with a mean of 634 ppm.

EVIDENCE FOR PARTIAL MELTING IN METAPELITES

Leucosomes and residues

Leucocratic layers and lenses are present in the pelitic paragneiss on Rabbit Ears Island at all scales from the 15–20 cm thick lens in outcrop (Fig. 2) to millimetre-size wisps in thin section (Fig. 4). The samples show a strong variation in the proportion and distribution of leucosome. In the more thoroughly migmatized samples, 03-126 and 03-127, leucosomes cross-cut foliation at all scales (Fig. 4) and show evidence of coalescence and migration to form centimetre to decimetre-scale segregations. Leucocratic layers and lenses are comprised of sutured quartz bands alternating with dusty, medium-grained, equigranular, pods and layers (Fig. 4) that contain quartz, K-feldspar, antiperthitic plagioclase, small, euhedral garnet and kyanite, and minor biotite (Fig. 3). The dusty, quartzofeldspathic layers and lenses (but not the quartz bands) are interpreted to have crystallized from melt, because their constituent quartz, K-feldspar and antiperthitic plagioclase are anhedral and have an allotriomorphic equigranular, granitoid texture (Fig. 3). Small euhedral to subhedral garnet and kyanite crystals (Fig. 3a,c), which are abundant in these quartzofeldspathic layers, are also interpreted to have crystallized from melt. The similar proportion of K-feldspar and antiperthitic plagioclase and lower proportion of quartz in the quartzofeldspathic layers is consistent with crystallization of a granitic melt produced by partial melting of pelite (Winter, 2001). The presence of antiperthitic feldspar in the leucosomes indicates crystallization of Or-rich plagioclase from a melt at relatively high temperature (Spear, 1993; Godard *et al.*, 1996; Gilotti & Elvevold, 2002) and subsequent exsolution. Some leucosomes of sample 03-126 contain optically continuous remnants of phengite, partially replaced by biotite + plagioclase and surrounded by leucosome comprised of quartz, antiperthitic feldspar and other components of the inferred crystallized melt (Fig. 3g,h). This observation is consistent with the inference (see below) that dehydration melting of phengite + quartz produced the melts in these samples. Together these macroscopic and microscopic observations indicate that the metapelites experienced extensive partial melting.

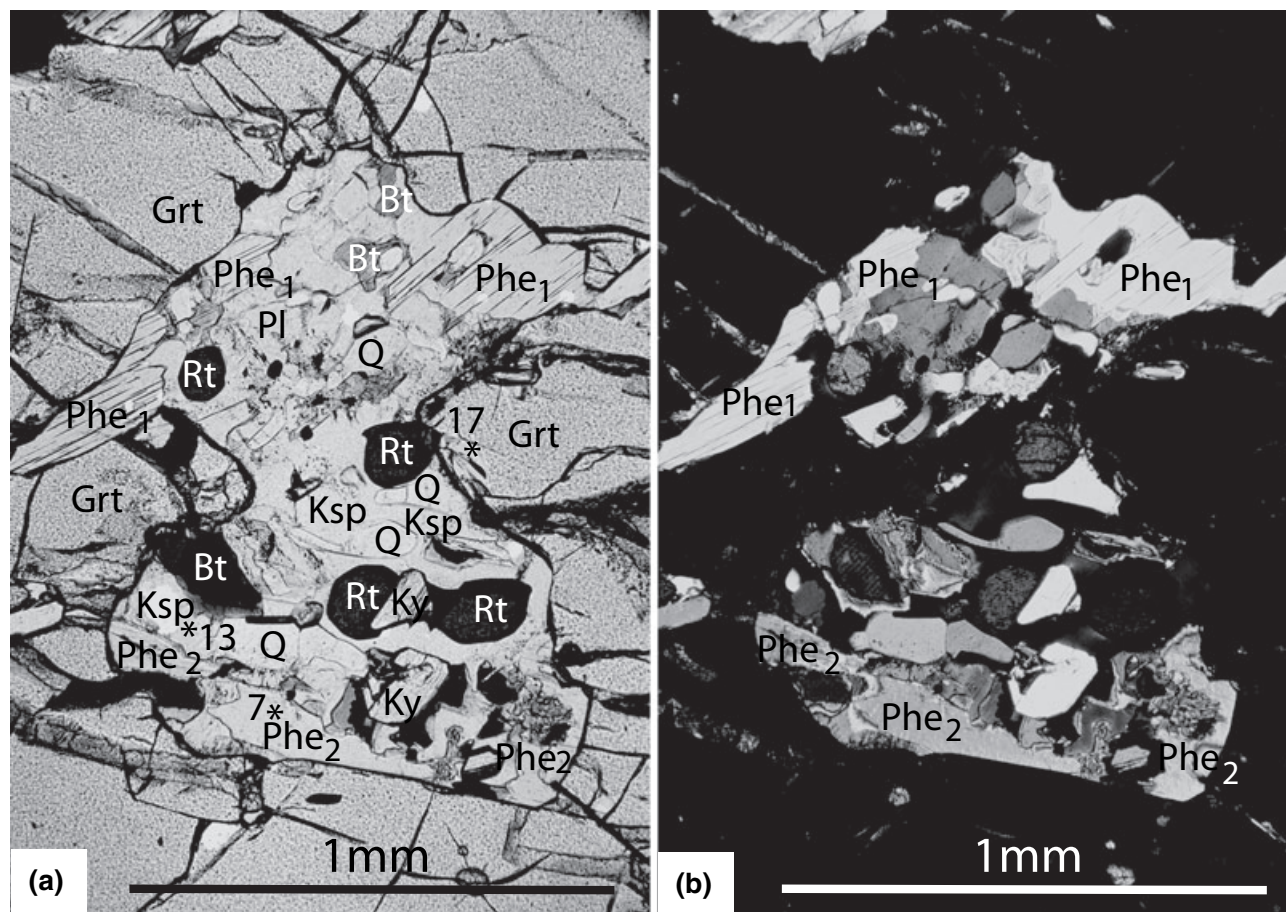


Fig. 8. Photomicrographs of a polyphase inclusion in a garnet from sample 03-127. The two optically continuous phengite grains (Phe₁ & Phe₂) are interpreted as relicts of phengite that reacted with intervening coesite or quartz (Q) to form melt + Ky + Rt + Ksp. The melt is inferred to have crystallized, entirely within the inclusion, to produce plagioclase, kyanite, biotite and other phases. (a) in PPL, and (b) in XPL. Locations of analysis points are shown for Grt-17, Phe-7 and Ksp-13.

Sutured bands of nearly pure quartz (Fig. 3a,b) interlayered with the quartzofeldspathic leucosome patches are interpreted as residual excess quartz, which was surrounded by partial melt, but was not melted. Indares & Dunning (2001) interpreted similar coarse-grained quartz-rich domains in a high-pressure granulite as residual. The sample inferred to be least affected by partial melting (03-200) shows incipient development of quartz bands from matrix quartz, supporting our interpretation that they are excess unmelted quartz. The large (to 1.5 cm) poikiloblastic garnet in all samples is interpreted as modified residual metamorphic garnet.

Polyphase inclusions in garnet

Evidence of partial melting of original hydrous mineral inclusions inside garnet is preserved in a few large polyphase inclusions. Figure 8 shows a complex polyphase inclusion from sample 03-127 that contains phengite and quartz (interpreted to be reactants), and kyanite, rutile, K-feldspar, biotite and plagioclase

(interpreted to be products of the melting reaction or melt crystallization). Remnants of two large phengite crystals inside the inclusion are optically continuous, suggesting that the two phengite grains and intervening coesite or quartz formed a large composite inclusion in the garnet porphyroblast prior to melting. Melt is inferred to have formed and crystallized entirely inside the garnet, as there is no evidence of melt or fluid having escaped from the inclusion. Kyanite and rutile in the inclusion are subhedral, and may have formed as solid products of the melting reaction or upon melt crystallization.

Similar polyphase inclusions in garnet, interpreted as having crystallized from trapped melt or volatile-rich supercritical fluid (which are indistinguishable at UHP conditions), have been described from other HP and UHP terranes (Hwang *et al.*, 2001; Stöckhert *et al.*, 2001; Massonne, 2003; Korsakov *et al.*, 2004; Korsakov & Hermann, 2006). The difference is that these inclusions contain diamond, pointing to the formation of diamond in the presence of a supercritical fluid at unequivocal UHP conditions. Polyphase in-

clusions that include quenched melt have been produced in experiments that subjected garnet with pre-existing hydrous inclusions, such as clinozoisite, amphibole and chlorite, to UHP/UHT conditions (Perchuk *et al.*, 2005, in press). The experimentally produced inclusions have regular and irregular shapes and are mostly composed of glass, but some contain new crystals of kyanite and garnet. Many more new phases would have crystallized from the included melt if the experiments had been slowly cooled instead of quenched. The polyphase inclusions in garnet from the Greenland metapelites contain residual phases, such as phengite, as well as new phases inferred to have crystallized from a former melt.

Additional evidence for melting in these metapelites is that many of the mono- and polycrystalline quartz inclusions in the large porphyroblastic garnet are surrounded by a discontinuous moat of plagioclase plus K-feldspar (Figs 7 & 9). The moats are thicker and more common around large polycrystalline quartz inclusions that are near garnet rims or in communication with the leucocratic matrix surrounding the garnet.

Such feldspar rims are interpreted to have crystallized from a melt that invaded/infiltrated the garnet along cracks or grain boundaries. The most dramatic example of this texture is shown in Fig. 9. At the lower centre of the photograph, an embayment extends into the garnet from the inclusion. This embayment has a matrix of feldspar continuous with feldspar of the moat, but also contains biotite and white mica, which might have produced melt *in situ* like the inclusion shown in Fig. 8. Another compelling texture [Fig. 9b (white arrows) and Fig. 10e,f] consists of small apophyses of two-feldspars $\pm$ biotite that extend into the garnet from the feldspar-rimmed polycrystalline quartz inclusion. This texture may result from melt invasion into the garnet as a result of expansion during the coesite to quartz transition. Korsakov & Hermann (2006) observed similar features associated with carbonate melt inclusions in UHP rocks of the Kokchetav Massif and referred to them as a 'crown-like' texture. Similar apophyses commonly occur at the corners of melt inclusions in garnet produced experimentally (Perchuk *et al.*, in press).

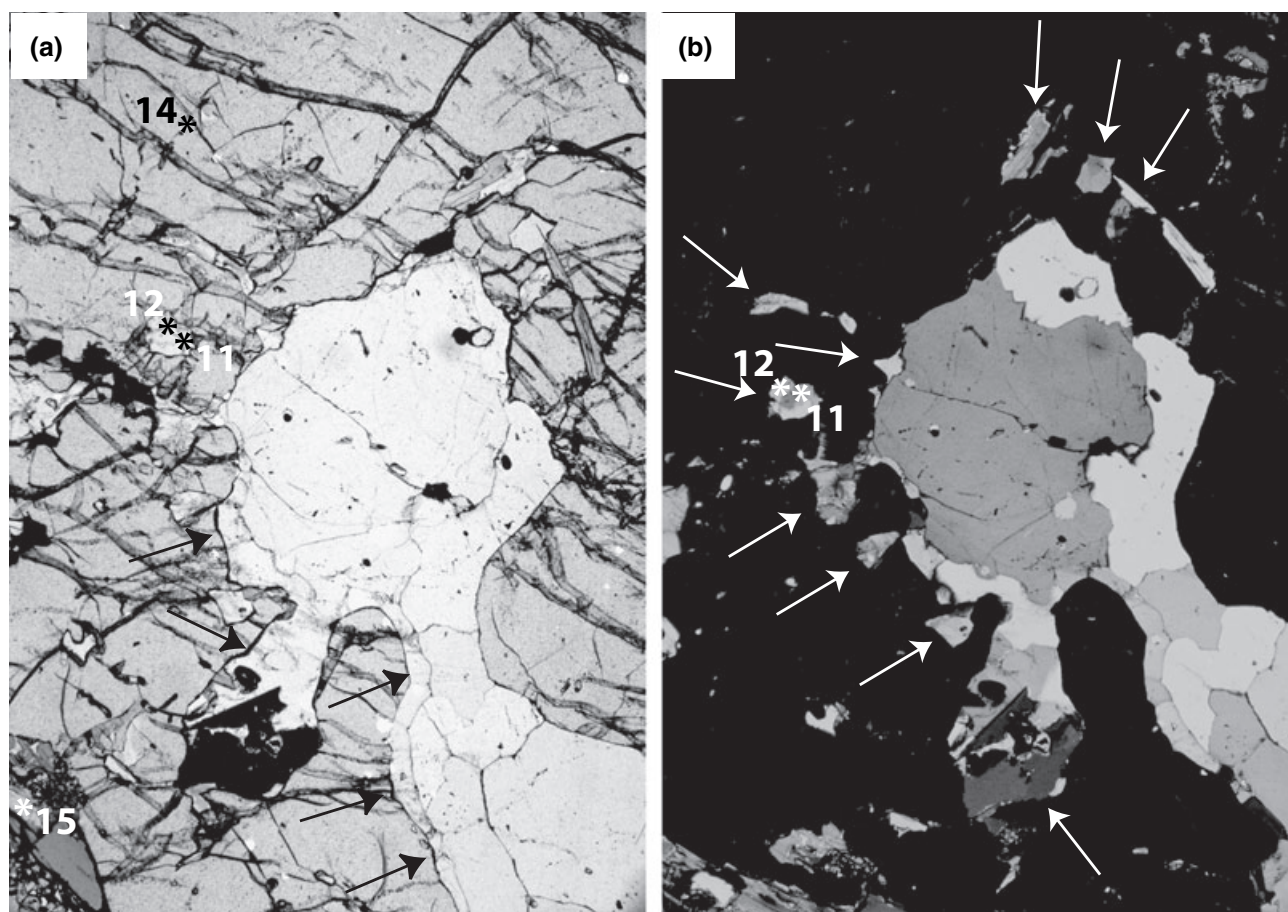
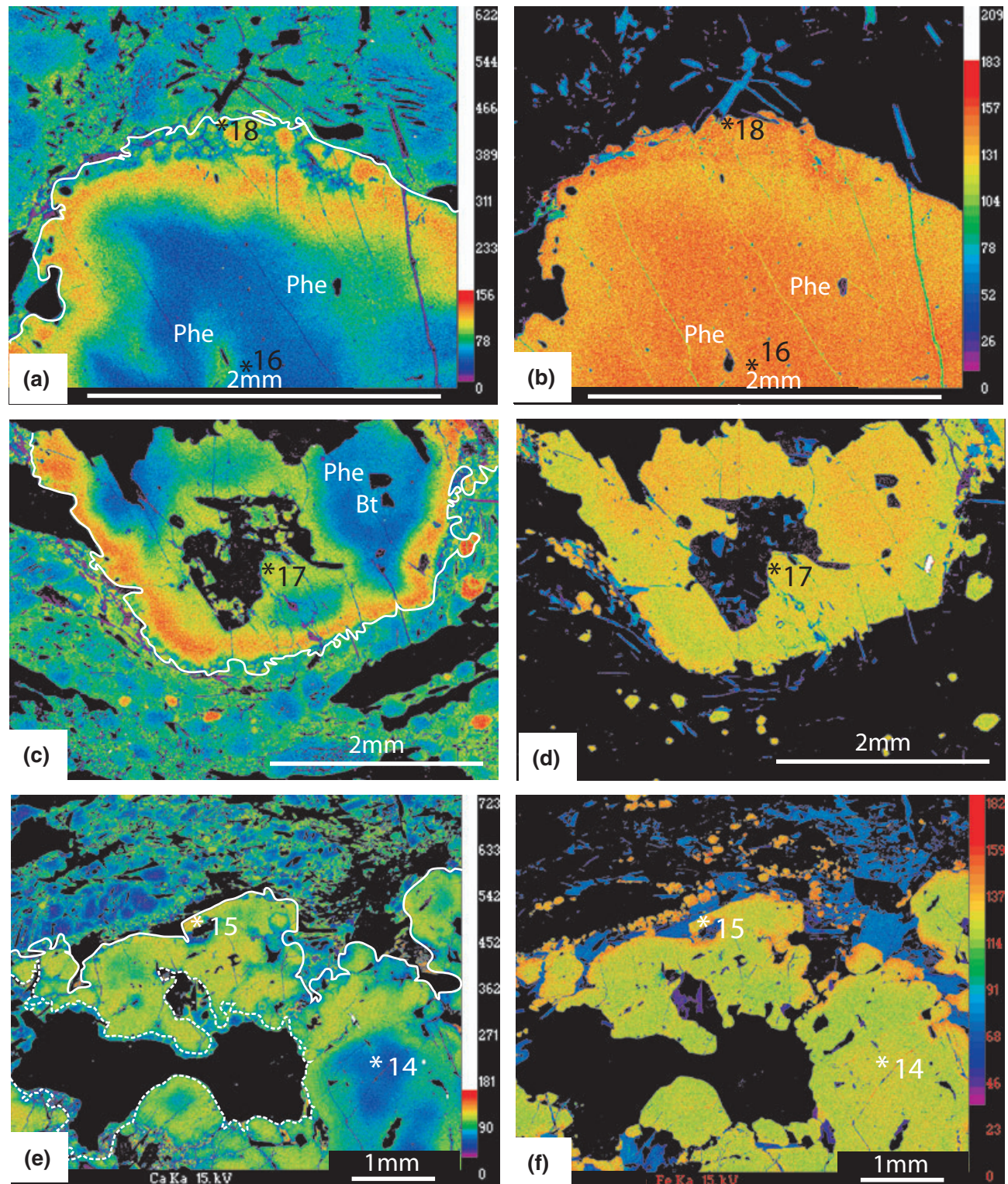


Fig. 9. Photomicrograph of a large polycrystalline quartz inclusion in a garnet of 03-126 that displays crown-like texture; (a) in PPL; (b) XPL. The lower right portion of this inclusion is in contact with the partially melted rock matrix (not shown). The quartz is partially rimmed by a moat of K-feldspar plus plagioclase (indicated by black arrows in (a)). Apophyses (indicated by white arrows in (b)) of two feldspars $\pm$ biotite form the crown-like texture that is interpreted as injection of melt during radial fracturing and subsequent crystallization. Field of view is 3 mm wide. Asterisks show analysis locations.

Garnet zoning

Colour X-ray maps of Ca and Fe zoning in three garnet megacrysts from two of the Rabbit Ears Island samples are shown in Fig. 10. Mn and Mg X-ray maps

are not shown, because Mn is extremely low (< 0.6 wt%) and uniform in all of the garnet and Mg zoning is very similar to that of Fe. The garnet of Fig. 10(a,b) is relatively simple and free of inclusions with a zoning pattern that is typical for the garnet



megacrysts. This garnet is weakly zoned in Fe (and Mg) with both being slightly higher and uniform in the interior, lower in an inner rim, and slightly higher and patchy in the outermost rim (Fig. 10b). It, like other garnet megacrysts, has low Ca ($X_{\text{Grs}} = 0.09$) in its interior, high Ca in the inner rim (up to $X_{\text{Grs}} = 0.20$), and high-to-low, very patchy Ca in the outermost rim (Fig. 10a). Given the high peak temperature of metamorphism ($\leq 970^\circ\text{C}$), any prograde zoning in the garnet cores is likely to have been destroyed by diffusion (Yardley, 1977; Spear & Florence, 1992). Compositions of garnet cores and inclusions in the cores should, therefore, reflect peak metamorphic conditions (Sobolev & Shatsky, 1990; Shatsky *et al.*, 1995). Fe, Mg and Mn profiles in the garnet cores are indeed relatively flat (e.g. Fig. 10b,d); however, Ca is somewhat variable (Fig. 10a). Although the high-Ca zones in garnet cores could be relict prograde growth zoning (e.g. Chernoff & Carlson, 1997), they are irregularly distributed and seem to be related to phengite (Phe in Fig. 10a) and polyphase inclusions (Fig. 10c), which may have reacted with surrounding garnet. Garnet megacrysts typically have a continuous inner rim with uniformly high Ca content (Fig. 10a,c). The composition of these rims is similar to that of small matrix garnet (isolated high Ca, high Fe grains in lower part of Fig. 10c,d) that are inferred to have crystallized from partial melt. We favour an interpretation where the rims of megacrystic garnet also crystallized in equilibrium with the partial melt. The Ca content of the outermost rim of the garnet in Fig. 10(a) and some other garnet is very patchy, and appears to have coalesced from many small garnet grains that have high Ca cores and low Ca rims and resemble neosome garnet of the adjacent leucosome (note isolated high Ca, high Fe grains in the matrix of Fig. 10c,d). The patchy rim is indeed garnet, as indicated by the high Fe zone of the Fe X-ray map in Fig. 10(b). The Fe in the outer garnet rim also shows weak patchy zoning (Fig. 10b). Once formed, the patchy garnet rim must have cooled quite quickly to preserve such intricate zoning in Fe as well as Ca. A complete understanding of zoning, especially of Ca, in garnet megacrysts of Rabbit Ears Island metapelites requires further detailed investigation, which is currently under way. Near rim changes in garnet megacryst composition will

help us to reconstruct the decompression portion of the P - T path (e.g. Spear *et al.*, 1999).

Figure 10(c,d) shows zoning in the garnet that surrounds the polyphase, partial melt inclusion of Fig. 8. It, like the garnet of Fig. 10(a,b), has a high Ca inner rim, a patchy high-to-low Ca outermost rim, and is surrounded by quartzofeldspathic leucosome (which in this case contains high Ca neosome garnet). In addition to its high Ca rim, this garnet has a patchy, irregular zone of slightly elevated Ca around the large central inferred melt inclusion. In their UHP/HT experiments, Perchuk *et al.* (2005, in press) observed patchy microfabrics in BSE images of garnet surrounding melt inclusions, which correlate with variations in Ca content. These authors suggest that such patchy microfabrics are strong evidence of partial melting in garnet inclusions, but anticipate that diffusion would smooth similar zoning in natural samples. Although the patchy microfabrics were not observed in BSE images, patchy zones of high Ca in garnet around the polyphase inclusion (Fig. 10c) may similarly have formed due to partial melting.

The large garnet shown in Fig. 10(e,f) is surrounded by leucosome and appears to have interacted extensively with melt. It contains a large polycrystalline quartz inclusion (Ca-free area inside the dashed white line in Fig. 10e), which is in communication with the matrix and is surrounded by a feldspar moat (patchy blue-green rim just inside the white dashed line of Fig. 10e). The moat is interpreted as crystallized melt that invaded from adjacent, partially melted matrix; melt or fluid may also have escaped into apophyses and cracks that cross-cut the garnet. Ca is slightly elevated (relative to blue area near analysis point no. 14 in Fig. 10e) and has a very patchy distribution in garnet all around the large quartz inclusion, especially adjacent to apophyses and fractures that extend into the surrounding garnet. This garnet does not display the patchy-Ca outermost rim, because it is largely surrounded by biotite.

POSSIBLE MELTING REACTIONS

Mineral assemblages preserved in the Rabbit Ears Island paragneiss are a combination of relict minerals containing inclusions that were formed up to and at

Fig. 10. Colour X-ray maps of garnet megacrysts and surrounding matrix. Figure (a), (c), (e) are Ca X-ray maps with high to low Ca represented by the colour scale duplicated on the right sides of Fig. 10(a,e). Figure (b), (d), (f) are corresponding Fe X-ray maps. (a), (b) Ca and Fe X-ray maps of a garnet rim from sample 03-127, which is adjacent to leucosome that contains antiperthite, quartz, biotite and small garnet, and is interpreted to have crystallized from a melt. The white line on the Ca map outlines the garnet boundary defined by the high-Fe region on Fig. 10(b). The Ca X-ray map (a) shows an outer rim with variable, patchy Ca, composed of many small garnet with high-Ca cores and low-Ca rims that have coalesced with the garnet porphyroblast. This texture is common at the rims of garnet porphyroblasts in contact with leucosome (e.g. Fig. 10c). (c, d) Ca and Fe X-ray maps of the garnet surrounding the polyphase inclusion in Fig. 8, sample 03-127. Note especially the elevated, but patchy Ca zoning around the inferred melt inclusion and the very high Ca in the garnet rim and matrix garnet. (e, f) Ca and Fe X-ray maps of the garnet in Fig. 9. The solid white line in (e) marks the outer margin of garnet; the dashed white line represents the inner margin of garnet against the moat-rimmed polycrystalline quartz inclusion. The feldspar moat is the mottled blue and green area between the dashed white line and the black area (quartz) on the Ca map. The patchy, elevated Ca in garnet surrounding the moat-rimmed inclusion, apophyses and fractures is consistent with interaction of garnet with a melt according to Perchuk *et al.* (in press).

the peak of UHP metamorphism, plus assemblages that are the solid products of partial melting, and, finally, mineral assemblages that resulted from crystallization of the partial melt. Although major changes, including melting and extensive crystallization and recrystallization of garnet took place in these samples on their decompression path, the effects of very low pressure, low temperature, retrograde metamorphism (e.g. involving chlorite and ilmenite) are relatively limited and will be ignored in this discussion. Because of the complexity of the preserved assemblages, determination of the equilibrium paragenesis at any stage of metamorphism is an uncertain process that must be based on inclusions in garnet porphyroblasts, textures in inferred melt inclusions in garnet and in the leucocratic matrix, and experimental and calculated phase relations (e.g. Spear *et al.*, 1990, 1995). The lack of appropriate assemblages, complex garnet zoning and disequilibrium among existing assemblages limit opportunities for traditional geothermobarometry.

One problem is to infer the assemblage in the metapelites at the peak of UHP metamorphism. The best estimate of peak conditions of ≤ 970 °C at 3.6 GPa (Gilotti & Ravna, 2002) comes from thermobarometry on the assemblage Grt + Omp + Ky + Coe + Phe in a kyanite eclogite located approximately 1.3 km west of the metapelite outcrop. These kyanite eclogites contain coesite inclusions in zircon (McClelland *et al.*, 2006). Massonne & Willner (2004) calculated pseudosections from 1.0 to 4.0 GPa and 600–1000 °C for a variety of melt-free pelitic and semipelitic compositions. Their calculations predict that at 970 °C and 3.6 GPa, the equilibrium paragenesis will be potassic white mica, kyanite, clinopyroxene, fluid, coesite, garnet, magnetite and rutile + epidote in some compositions. There is no evidence of magnetite in these rocks and it is inferred that low oxygen fugacity prevented its formation. Ilmenite that rims and partially replaces a few rutile grains is a late retrograde product. None of the metapelites contains clinopyroxene or epidote, and there is no textural evidence that either was ever present, even at the highest temperatures and pressures experienced by these rocks. For example, there are no clinopyroxene or epidote inclusions in garnet, nor are there textures in the matrix that suggest replacement of clinopyroxene or epidote by other minerals; however, some Ca-bearing phase (besides garnet) must have been present to contribute to the inferred melt, which crystallized An₂₀ plagioclase and grossular-rich garnet. It is possible that a small amount of clinopyroxene or epidote was consumed in the post-peak dehydration melting reaction. We infer that the peak UHP metamorphic assemblage in these rocks was phengite, coesite, garnet, kyanite, rutile, supercritical fluid and possibly minor clinopyroxene or epidote.

Although a small amount of fluid-present melting of muscovite and/or biotite (limited by fluid availability) may have occurred prior to the peak of UHP meta-

morphism (e.g. Spear *et al.*, 1999), substantial melting like that observed in the Rabbit Ears Island metapelites could only have been produced by fluid-absent (dehydration) melting. Experiments and analysis of phase relations at UHP and UHT (Fig. 11; Hermann & Green, 2001; Indares & Dunning, 2001; Massonne & Willner, 2004) indicate that phengite is the most likely hydrous phase in pelitic bulk compositions at or near peak UHP conditions. Its presence is supported by inclusions of phengite in the interiors of residual garnet porphyroblasts (Fig. 6c,d).

Figure 11 shows the limiting reactions for assemblages in the KCMASH system without excess fluid based on the UHP/HT experiments of Hermann & Green (2001). Estimated peak UHP conditions for the Rabbit Ears Island metapelites are shown on the phase diagram, along with the locations of the quartz to coesite transition and the reaction of albite to jadeite + quartz (Spear, 1993). Because clinopyroxene may not have been present in the metapelites, we have added the Cpx-absent reaction determined from Schreinemakers analysis. As the Greenland UHP terrane

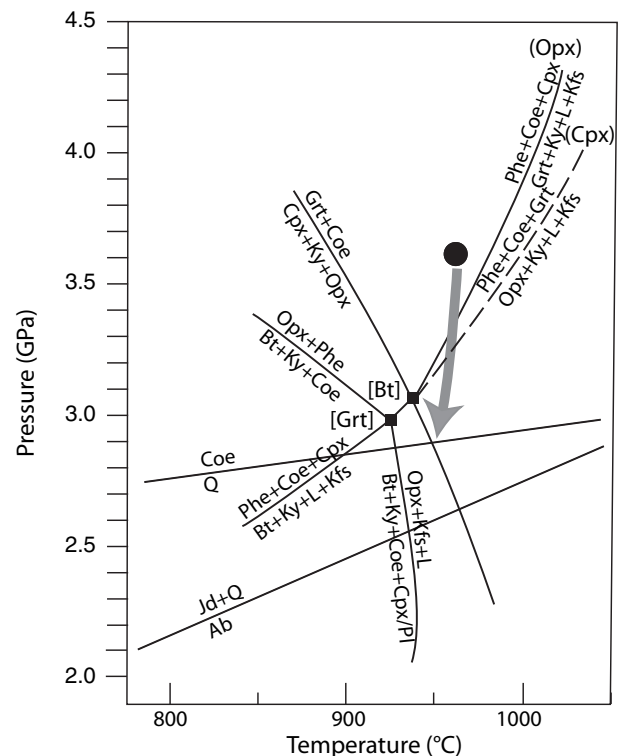
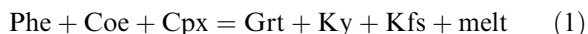
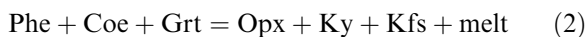


Fig. 11. Pressure–temperature grid for ‘fluid absent’ melting at ultrahigh-pressure and ultrahigh-temperature after Hermann & Green (2001). The Cpx-absent reaction was added to the Bt-absent invariant point based on Schreinemakers analysis and the fact that Liquid (L) must be on the high temperature side. The locations of the quartz = coesite and albite = jadeite + quartz reactions were taken from Spear (1993). The broad shaded arrow indicates a likely, initial decompression path for the UHP rocks on Rabbit Ears Island based on *P*–*T* paths for similar terranes (Hermann *et al.*, 2001; Chopin, 2003).

was exhumed, the rocks must have experienced decompression along a P – T path that would have crossed the dehydration melting reaction:



If the phase relations of Fig. 11 apply to these metapelites, and they contained clinopyroxene at peak UHP conditions, they would have begun to melt by reaction (1) before crossing the coesite to quartz transition. If they did not contain clinopyroxene, Reaction 2:



would have taken place at slightly higher temperature and/or lower pressure. If a reaction similar to Reaction 1 or Reaction 2 produced melt, then kyanite, K-feldspar, and garnet or orthopyroxene would have formed as solid products with melt collecting in layers and lenses. In the isolated polyphase inclusion in Fig. 8, two large grains of phengite apparently reacted with intervening coesite (or quartz) to produce melt, subhedral grains of kyanite, rutile, and K-feldspar, and grow new garnet or change the composition of the existing garnet. Neither Reaction 1 nor Reaction 2 is entirely consistent with observed assemblages. There is no evidence of clinopyroxene in these pelites to serve as a reactant in Reaction 1 or of orthopyroxene as a product of Reaction 2 (except a few tiny pinkish, low birefringence grains in leucosome patches; not analysed). It is possible that all clinopyroxene was consumed by melting Reaction 1 (most likely, because some Ca-bearing phase must have been involved) or that melting took place as a result of dehydration of $\text{Phe} + \text{Coe}$ with little or no involvement of ferromagnesian phases. The mineralogy of the inferred trapped melt inclusion (Fig. 8) indicates that the reaction in the inclusion was $\text{Phe} + \text{Coe} = \text{Ky} + \text{Kfs} + \text{Rt} + \text{melt}$. Phengite was apparently never completely consumed by the melting reaction because phengitic white mica (partially replaced by biotite $\pm$ plagioclase) is present in the leucosome matrix and the melt inclusion.

DECOMPRESSION AND COOLING HISTORY OF UHP METAPELITES

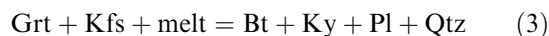
A detailed P – T path for UHP rocks in the Greenland Caledonides is under construction, but it is anticipated that the decompression trajectory involved near-isothermal decompression followed by cooling at moderate pressure like other UHP terranes (e.g. Hermann *et al.*, 2001; Chopin, 2003). Insights into the decompression history can be gained by carefully examining assemblages and textures in the metapelites in which we have demonstrated partial melting.

Early on the decompression path, coesite, which was abundant in the matrix and as inclusions in garnet, would have transformed to quartz, expanded and caused fracturing of garnet. If melting preceded con-

version of coesite to quartz as suggested by the phase diagram (Fig. 11), the presence of melt/fluid may have enhanced the kinetics of the coesite to quartz transition and contributed to the annealing of any diagnostic textures of the coesite to quartz reaction.

The feldspar rim (inferred to represent crystallized melt that invaded from the matrix) and the unusual crown-like texture surrounding the large polycrystalline quartz inclusion shown in Fig. 9 may provide evidence for whether melt formed before or after the conversion of coesite to quartz, and attendant fracturing of garnet. If melting took place before conversion of coesite to quartz as indicated by the phase diagram (Fig. 11), melt would have entered weak zones in the coesite–phengite ($+\text{Grt} + \text{Ky} + \text{Rt} \pm \text{Cpx}$) gneiss. At the coesite to quartz transition, the conversion of matrix coesite to quartz would be quite rapid, especially because fluid (or in this case melt) enhances the kinetics of the transition (Mosenfelder *et al.*, 2005). Volume expansion of SiO_2 by approximately 9% would have fractured garnet and forced the melt into the fractures and any other zones of weakness. This may explain the crown texture and other instances of two-feldspar moats between polycrystalline quartz inclusions and surrounding garnet (Figs 7 & 9).

Crystallization of the melt took place below the $\text{Jd} + \text{Qtz} = \text{Ab}$ reaction (Fig. 11), but still in the kyanite field, because plagioclase, K-feldspar, quartz and kyanite have textures typical of crystallization from a melt. Crystallization produced the assemblage biotite + kyanite, so must have occurred when the biotite dehydration melting reaction



was crossed in the down-temperature direction below the intersection of the muscovite dehydration melting reaction with the biotite dehydration melting reaction (at $[\text{Grt}]$ in Fig. 11; see also LeBreton & Thompson, 1988; Spear, 1993; Spear *et al.*, 1999; Vielzeuf & Schmidt, 2001). The matrix contains quartz bands indicating excess SiO_2 and some phengite (now partially replaced by biotite $\pm$ plagioclase pseudomorphs), which apparently did not completely melt. Preliminary results based on recently calibrated geothermometers for Ti in quartz (Wark & Watson, 2006) and Zr in rutile (Watson *et al.*, 2006) indicate temperatures of 600–700 °C. These temperatures likely represent final equilibration of these minerals on the exhumation path, perhaps when the melt crystallized. Future work on these rocks will focus on determination of a detailed P – T path for decompression.

CONCLUSIONS

1. Rare metapelitic rocks on Rabbit Ears Island exhibit macroscopic and microscopic evidence of partial melting. From the outcrop to the thin section scale, they contain leucocratic layers and lenses composed of medium-grained, anhedral, equigranular quartz, anti-

perthitic plagioclase and K-feldspar with minor small garnet and kyanite crystals. The leucocratic segregations anastomose around garnet porphyroblasts, are interlayered with quartz bands and commonly cross-cut micaceous segregations. These textures suggest that the melt segregated during deformation, but crystallized near the end of local deformation. The leucosomes did not experience the strong amphibolite facies deformation partitioned into the surrounding orthogneiss.

2. The metapelite outcrop lies < 1.5 km from coesite-bearing kyanite eclogites and is concordant with the surrounding coesite-bearing orthogneiss. The metapelites lack coesite and palisade quartz inclusions diagnostic of coesite pseudomorphs. Megacrystic garnet does, however, contain polycrystalline quartz inclusions, in some cases surrounded by radial fractures, and Ti-rich phengite inclusions, which are suggestive of metamorphism in the coesite stability field.

3. Polyphase inclusions in garnet are interpreted as reactants and products of arrested partial melting of original hydrous mineral inclusions in garnet. One inclusion examined in detail contains minerals, which indicate that the dehydration melting reaction: $\text{Phe} + \text{Coe/Qtz} = \text{Ky} + \text{Kfs} + \text{Rt} + \text{melt}$ and subsequent melt crystallization took place entirely within the garnet inclusion. Garnet in contact with the crystallized melt inclusion shows patchy zoning with elevated Ca content. This zoning is similar to the patchy microstructures produced during melting experiments on hydrous inclusions in garnet at UHP/HT conditions (Perchuk *et al.*, 2005, in press). High Ca, patchy rims on garnet megacrysts in contact with leucosome are also interpreted to have crystallized from melt, along with small idioblastic new garnet.

4. We infer that the peak UHP metamorphic assemblage in the metapelites was phengite, coesite, garnet, kyanite, rutile, fluid $\pm$ clinopyroxene $\pm$ epidote. Interpretation of our samples based on experimental phase equilibrium (Hermann & Green, 2001) indicates that dehydration melting of phengite occurred in the coesite stability field after peak pressure. The unusual crown- and moat-like textures in garnet around some polycrystalline quartz inclusions are also consistent with the inference that melting took place before or during the conversion of coesite to quartz.

5. Melt crystallization assemblages and textures yield important information about the decompression/cooling path, but the construction of a detailed P - T path for exhumation of the UHP rocks of the North-East Greenland Caledonides requires further analysis of applicable phase equilibria.

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