GNEISSES OF THE PORTHOS AND ATHOS RANGES, NORTHERN PRINCE CHARLES MOUNTAINS, EAST ANTARCTICA: CONSTRAINTS ON THE PROGRADE AND RETROGRADE $P$-$T$ PATH

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Abstract: The Northern Prince Charles Mountains (NPCM) are composed of upper amphibolite to granulite facies metamorphic rocks. The most common rock type in the Porthos Range is felsic orthogneiss, which hosts lenses and layers of ultramafic and mafic granulite, metapelitic gneiss, and calc-silicate gneiss. In the Athos Range, north of the Porthos Range, metapelitic rocks predominate. Intrusive charnockites are common in the Porthos Range. The rocks of the NPCM record a complex history of deformation. Evidence for the earliest events ($D_1$ and $D_2$) is only preserved in ultramafic granulite boudins. $D_3$ produced the regional foliation which was folded during $D_4$. A later regional event ($D_5$) produced upright structures. Localised but abundant shear zones, mylonites ($D_6$, $\gamma$), and late pseudotachylites are believed to be related to exhumation of the terrane. Geothermobarometry indicates maximum $P$-$T$ conditions ($D_1$–$D_3$) of $800 \pm 50^\circ$C and $7 \pm 1$ kbar, using grt+$\text{opx}+\text{qtz}+\text{pl}$ assemblages in the felsic granulites and charnockites, and grt+$\text{sil}+\text{qtz}+\text{pl}$ and grt+$\text{rt}+\text{sil}+\text{ilm}$ assemblages in the metapelites. Coarse-grained garnets in metapelites contain inclusions of cordierite and sillimanite, suggesting a prograde development of heating during burial. Reaction textures in calc-silicate and mafic gneisses suggest a retrograde development initially characterised by near isobaric cooling. The antclockwise $P$-$T$ path derived for this area contrasts with $P$-$T$ paths for southeastern Prydz Bay. If these areas are all part of the same late Proterozoic mobile belt, our observations indicate that different portions of the belt have distinct tectonic histories.

Key words: granulites, Northern Prince Charles Mountains, $P$-$T$ path, petrology

Abbreviations Used in Text:
All mineral abbreviations after Kretz (1983).
$X_{\text{Mg}} = \text{Mg}/(\text{Mg} + \text{Fe}^*)$.
$X_{\text{Fe}^*} = \text{total Fe as Fe}^{2+}$.
$X_{\text{AI}} (\text{opx}) = \text{molecular AI}/2$ (cations normalised to 6 oxygens).
$X_{\text{Cs}} (\text{cpx}) = \text{Ca} - \text{Cr}/2 + \text{Na}/2 - \text{Al}/2$ (cations normalised to 6 oxygens) = Ca in M2 site.
$X_{\text{An}} (\text{scp}) = \text{equivalent anorthite content} = 100(\text{Al}/3)/3$ (cations normalised to Si + Al = 12).

$X_{\text{i}} (\text{f}) = \text{mole fraction of component i in phase f (under discussion)}$

Introduction
Textural features preserved in metamorphic rocks are vital in providing constraints on their tectonic history. Such features as early-formed minerals preserved as inclusions within minerals stable at the peak metamorphic conditions, and coronas and symplectites, developed as break-down products of the high $P$-$T$ (pressure-temperature) phases, allow qualitative to quantitative estimation of the prograde and retrograde path that the terrane has followed during its evolution.

In this paper we describe the geology of the Porthos and Athos Ranges in the Northern Prince Charles Mountains (NPCM), and give detailed petrographic data on relevant rock types. Peak metamorphic conditions are estimated by geothermobarometry, and textural features are used to constrain the possible $P$-$T$ path followed by the NPCM. Field work was undertaken during the 1988–89 austral summer in association with the Australian National Antarctic Research Expeditions (ANARE), and concentrated in the Porthos Range. Carter Peaks and Farley Massif were visited in the Athos Range.

Geological Setting
The NPCM (Fig. 1) are located in an extensive late Proterozoic terrane composed of upper amphibolite to granulite facies metamorphic rocks, which extends from south-eastern Prydz Bay to the southern PCM and north to the Rayner Complex of Enderby Land. Previous work in the PCM includes that of Tingey (1982), McKelvey and Stephenson (1990), Fitzsimons and Thost (1992) and Munksgaard et al. (1992).

The rock types of the NPCM can be divided into three groups:
(i) Basement gneisses, which pre-date the regional $D_3$ deformation. This group includes granulites of mafic to felsic composition, calc-silicate gneisses, metapelitic gneisses and ultra-mafic granulites.
(ii) Deformed intrusive rocks, which postdate $D_3$ but are affected to varying degrees by later deformation episodes. This group includes charnockites, leucogneisses and metamorphosed dykes.
(iii) Undeformed intrusive rocks, which postdate the last deformation in the area, including pegmatites and rare alkaline basaltic and syenitic dykes.

Outcrop is dominated by the basement gneiss lithologies and charnockites, with the other lithologies accounting for less than 5% of total outcrop area. More complete lithological descriptions are given by Fitzsimons and Thost (1992). The lithologies and their constituent mineral assemblages are

summarised in Table 1.

In the Porthos Range, the most common rock types are felsic to mafic orthogneiss. In contrast, the Athos Range contains abundant metapelite. Large intrusive bodies of charnockite occur throughout the Porthos Range, and account for approximately 5% of the outcrop. These rock types are described in greater detail in the following section. Dykes, sheets and lenses of leucogneiss are common in all the major rock types. At least two generations of deformed and metamorphosed mafic dykes occur in the Porthos Range, but were not seen at Carter Peaks or Farley Massif in the Athos Range. Their occurrence disproves earlier work stating that metamorphosed mafic dykes were restricted to the Archaean and lower Proterozoic rocks of the SPCM, and were absent from the upper Proterozoic rocks of the NPCM (Sheraton and Black, 1981; Tingey, 1982; Sheraton, 1983).

**Structure**

To varying degrees, most rock types have been affected by a number of deformation events. These are summarised schematically in Fig. 2. $D_1$ is expressed as a moderate to strong foliation, only preserved in the ultra-mafic and mafic gneiss pods and boudinaged layers. $D_2$ is recognised as a series of low amplitude, disharmonic folds ($F_2$), with wavelengths generally less than 50 cm, again preserved only within ultra-mafic and mafic gneiss bodies. $D_3$ has produced the dominant gneissic foliation in the region ($S_3$) in both the felsic and pelitic gneisses, and rare intrapolial $F_3$ folds. $D_3$ (this work; Fitzsimons and Thost, 1992) is equivalent to $D_1$ of other workers in the region (McKelvey and Stephenson, 1990; G. T. Nichols, I. Scrimgeour: personal communication, 1991). $D_1$–$D_3$ may represent a deformational progression during a single tectonic event. However, the fabrics

![Location map and simplified geology of the Porthos and Athos Ranges, NPCM. Location of samples discussed in the text are also shown. “Dovers Base” is only occupied during the summer season, and was established by ANARE during 1988.](image)

**Table 1.** Lithologies and mineral assemblages in the Porthos Range.

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Percentage of outcrop</th>
<th>Mineral assemblage</th>
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</thead>
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<tr>
<td>Granulites</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Felsic orthogneiss</td>
<td>70%</td>
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<tr>
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<tr>
<td></td>
<td></td>
<td>fo+di+pl+phl+cal</td>
</tr>
<tr>
<td>Metapelites</td>
<td>&lt;1*</td>
<td>grt+sil+cd+qtz+Kfs+pl+bt</td>
</tr>
<tr>
<td>Deformed intrusive rocks</td>
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<td></td>
</tr>
<tr>
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<td>5%</td>
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<tr>
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<td>Dykes</td>
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<td>hbl+opx+cpx+pl+bt+qtz</td>
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<tr>
<td>Undeformed intrusive rocks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pegmatites</td>
<td>&lt;1%</td>
<td>qtz+Kfs+pl+grt+bt+mag</td>
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<tr>
<td>Dykes</td>
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<td></td>
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</table>

*Dominant rock type in the Athos Range. Abbreviations after Kretz (1983).
preserved in the ultra-mafic and mafic gneiss bodies must have formed during the earliest stages of that event, certainly pre-boudining and rotation. D₄ folds S₃ but does not produce a penetrative foliation, and results in steep easterly plunging fold hinges. F₄ folds are tight to isoclinal, with wavelengths generally less than 5 m. During D₄, calc-silicate gneiss layer displaying F₄ folds. CHK intrusive charnockite; MTD metamorphosed and deformed dyke; BD undeformed, unmetamorphosed basaltic dyke; PEG planar pegmatite vein. S₃ is the dominant gneissic foliation in the area. See text for explanation of structural features.

University, operating with an accelerating voltage of 15 kV and a beam width of approximately 10 µm.

Granulites
This group encompasses a broad range of gneissic rocks, from felsic to mafic in composition. They are grouped together because they are interlayered, with gradational to well defined contacts, and thicknesses ranging from centimetres to several metres.

The granulites are predominantly of felsic composition (70% of outcrop) consisting of qtz + pl + Kfs with minor orthopyroxene, hornblende and biotite, and rare garnet. Their fabric varies from massive granular to well foliated and/or lineated in zones of high strain, with quartz ribbons and preferred orientation of ferromagnesian minerals.

Variation to intermediate and mafic gneisses occurs through an increase in the amount of ferromagnesian minerals, the appearance of clinopyroxene and ilmenite, and the disappearance of K-feldspar. Mafic and intermediate gneisses do not contain garnet as a part of the peak metamorphic assemblage.

The origin of the felsic to mafic granulites is not clear. They are host to other lithologies with which they are locally intimately interleaved, suggesting a sedimentary or volcanic protolith. Other more massive felsic lithologies show little compositional variation, and perhaps reflect an original igneous origin, with any enclaves representing intrusives or entrained xenoliths (Fitzsimons and Thost, 1992). Geochemistry suggests derivation from original igneous precursors, possibly generated in a subduction zone environment (Munksgaard et al., 1992).

A typical example is DT058 which is a medium-grained gnt + opx + bt felsic gneiss from Crohn Massif, with a well developed S₂ foliation defined by trails of xenoblastic garnet 2–3 mm in diameter, xenoblastic orthopyroxene grains

Lithologic and Petrographic Descriptions
In this section we describe the principal lithologies exposed in the Porthos and Athos Ranges, and give petrographic descriptions of specific samples which are subsequently used to constrain the P-T path. Probe analyses were performed on the ETEC electron microprobe at Macquarie University.
up to 1 mm in long dimension, and ragged biotite flakes. $X_{\text{Mg}}$ for garnet ranges from 0.36 to 0.37, and for orthopyroxene from 0.58 to 0.61. $X_{\text{Al}}$ for orthopyroxene ranges from 0.09 to 0.11. $X_{\text{an}}$ for plagioclase is from 0.19 to 0.20.

**Calc-silicate gneisses**

Calc-silicate gneisses occur sporadically throughout the NPCM as discontinuous layers up to 2 m thick, and isolated pods within the felsic granulites. They are conspicuous by their milky-grey colour and saccharoidal texture. An internal banding or zonation is commonly developed, defined by the concentration of minerals such as calcite, diopside, scapolite, wollastonite and quartz. Other primary metamorphic minerals include forsterite ($F_{090}$), spinel ($X_{\text{Mg}} = 80$), phlogopite, K-feldspar, hornblende and accessory sphene. The banding alternates on a centimetre scale and possibly reflects original differences in bulk composition, modified during high-grade metamorphism (Fitzsimons and Thost, 1992). Retrograde reaction textures include the breakdown of wollastonite to calcite + quartz and the development of grossular-rich scapolite.

The calc-silicate gneisses are commonly boudinaged or folded along with the enclosing host gneiss. Locally they have been mobilized, apparently due to their less competent nature, and cross-cut the foliation ($S_3$) of their host. Pegmatites containing abundant calc-silicate phases occur as 2–5 m wide irregular veins at Mt. Tarr, and as narrower discordant veins at Corry Massif and Mt. Gavaghan.

DT032 (Fig. 3a) is a medium-grained saccharoidal-textured calc-silicate from a tightly folded ($F_3$) layer at Corry Massif. It consists of primary qtz + wq + scp + cpx + Kfs in a calcite-dominated matrix. Scapolite is mantled by 0.05–0.1 mm thick rims of secondary garnet, and wollastonite is mantled by secondary quartz. Quartz, K-feldspar, clinopyroxene and scapolite occur as rounded to lobate, isolated grains in calcite, up to 1 mm in long dimension, although aggregates of these minerals exhibit polygonal grain boundaries.

Scapolite contains 0 to 0.17 wt % Cl, with EqAn$_{70-76}$. Wollastonite contains 0.3–0.5 wt % FeO, and 0.4–0.5 wt % Cr$_2$O$_3$. Garnet is grandite, with $X_{\text{grs}} = 0.676–0.755$ and $X_{\text{an}} = 0.184–0.262$. K-feldspar is Or$_{84-87}$Ab$_{14.9}$An$_{12-6}$.N.

**Metapelitic gneisses**

Pelitic lithologies are extremely rare in the Porthos Range. A highly deformed grt + sil (+ altered crd?) gneiss occurs as

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**Fig. 3.** Photomicrographs of rocks used to constrain the P-T path: (a) Calc-silicate gneiss. Wollastonite (wq), scapolite (scp), clinopyroxene (cpx) and K-feldspar (Kfs) in a calcite-rich (cal) matrix. Wollastonite contains rounded inclusions of cpx and cal, and is rimmed by secondary quartz (qtz, outlined in black). Scapolite is rimmed by secondary garnet (grt). Where minerals occur as aggregates, they exhibit polygonal grain boundaries. Scale bar 0.5 mm. Sample DT032. (b) Metapelitic migmatite. A coarse-grained grt porphyroblast containing inclusions of cordierite (crd), biotite (bt), ilmenite (ilm) and rutile (rt). The matrix contains coarse-grained sillimanite (sil), Kfs and qtz. Scale bar 1 mm. Sample NM41. (c) Mafic gneiss. Aggregates and larger individual grains of plagioclase (pl) are separated from opx, cpx and bt by a secondary grt moat. Pl-grt contacts outlined in black. Scale bar 0.5 mm. Sample PK6. (d) As for (c), taken with crossed nicols. Note the pronounced zonation in the plagioclase crystals towards the upper right and left.
an inclusion within a coarse-grained garnet-leucogneiss at Corry Massif. Pelitic gneisses are abundant in the Athos Range to the north, and gtr + crd = sil + bt gneisses outcrop at Carter Peaks. The Carter Peaks pelites are medium to coarse-grained, well-layered to migmatitic gneisses, with large (up to 3 cm) garnet porphyroblasts and fresh cordierite in a qtz + Kfs + bt ± pl matrix. Sillimanite constitutes less than 5% of the rock mass, occurring as 5 to 10 mm long prismatic crystals in the matrix, and less commonly as smaller inclusions in garnet. Garnet also contains inclusions of cordierite, biotite, abundant quartz, and rutile. Other accessory minerals include ilmenite and zircon.

Both of the samples used in the following section for P-T estimates were collected from the Carter Peaks area in the Athos Range. NM41 (Fig. 3b) is a coarse-grained migmatitic gneiss containing large garnet porphyroblasts (up to 2 cm in diameter) and prismatic sillimanite crystals in a Kfs + qtz dominated matrix. Garnet porphyroblasts are xenoblastic to sub-idiomorphic, occasionally exhibiting well developed crystal faces. Contacts between garnet and matrix sillimanite are generally straight, and the garnet contains inclusions of sillimanite, as well as rutile, ilmenite, biotite, quartz and rounded cordierite grains. The cordierite inclusions are up to 2 mm in diameter. Biotite occurs as isolated inclusions in both garnet and sillimanite, and as ragged secondary grains associated with matrix ilmenite, and along cracks in garnet. A coarse-grained sillimanite crystal was noted containing lamellar inclusions of plagioclase and K-feldspar (N. C. Munksgaard, personal communication, 1990).

The garnet in NM41 is pyrope-rich almandine, with $X_{\text{Mg}}$ ranging from 0.34 to 0.37, zoned to the more Fe-rich compositions at grain boundaries. $X_{\text{ans}}$ ranges from 0.01 to 0.02, and $X_{\text{grs}}$ ranges from 0.03 to 0.04. Cordierite has a nearly constant $X_{\text{Mg}}$ of 0.80. $X_{\text{Mg}}$ for biotite ranges from 0.68 for inclusions in sillimanite, to 0.75 for inclusions in garnet. Secondary (i.e. matrix) biotite has $X_{\text{Mg}}$ ranging from 0.75 to 0.77. $X_{\text{ilmn}}$ in ilmenite is zero.

NM49 is from a well-layered (S1) sequence, and is composed of xenoblastic garnet grains 2-3 mm in diameter, but occasionally up to 8 mm, in a qtz + Kfs + pl + opx + bt + crd matrix. Coarse-grained qtz + Kfs layers are common. Resorbed sillimanite grains, less than 1 mm in length, occur sporadically throughout the matrix, and sillimanite was also noted as 0.1 mm prismatic grains included in garnet. Rounded biotite and cordierite grains, quartz, rutile and ilmenite are also common inclusions in garnet. Cordierite also occurs in the matrix as xenoblastic grains up to 5 mm in length, including rounded quartz grains. Biotite, as well as being included in garnet, occurs as ragged matrix grains.

Garnet in NM49 is fairly homogeneous in composition, with $X_{\text{Mg}}$ ranging from 0.35 at the grain rim to 0.38 in the core. $X_{\text{ans}}$ is low, ranging from 0-0.014, and $X_{\text{grs}}$ ranges from 0.024–0.036. Matrix cordierite has $X_{\text{Mg}}$ values ranging from 0.772 in the core of the large grains to 0.797 at their rim. Cordierite included in garnet has slightly higher values, with $X_{\text{Mg}} = 0.815$. Biotite inclusions in garnet have $X_{\text{Mg}}$ ranging from 0.794 (near an ilmenite inclusion) to 0.757, whereas matrix biotite has much lower values, around $X_{\text{Mg}} = 0.68$. Matrix plagioclase has values of $X_{\text{an}}$ ranging from 0.33 to 0.36.

**Mafic gneisses**

Orthopyroxene-rich gneisses occur as large boudinaged layers (up to 10 m in length) within felsic granulites at Crohn Massif and Mt. Kirkby, and as smaller boudinaged pods at Corry Massif. They are well layered on a centimetre scale, defining the earliest fabric recognised in the area (S1) which is generally oblique to that of the host rock foliation. In the plane of this S1 foliation are developed large (up to 15 cm), randomly oriented orthopyroxene crystals. Accessory minerals are plagioclase, hornblende, biotite and opaques.

Medium-grained mafic gneiss from the western end of Mt. McCarthy (sample PK6, Figs. 3c and d) is composed of opx + bt + pl + opx. It was collected from a thick (tens of metres) mafic unit adjacent to sheared felsic gneiss (P. Kinny, personal communication, 1991). Biotite defines a moderate foliation. Plagioclase occurs as discrete aggregates 1–3 mm long, isolated by the ferromagnesian minerals. These plagioclase zones are surrounded by garnet coronas where orthopyroxene or clinopyroxene is the adjacent mineral, but plagioclase is also commonly in direct contact with biotite.

Orthopyroxene has $X_{\text{Mg}}$ ranging from 0.55 to 0.57, and $X_{\text{Al}}$ from 0.03 to 0.05. Clinopyroxene has a nearly constant $X_{\text{Mg}}$ around 0.68. Garnets are almandine-pyrope, with $X_{\text{Mg}}$ ranging from 0.29 to 0.33. Plagioclase exhibits pronounced zonation, with calcic-rich cores ($X_{\text{an}} = 0.66$) and more sodic margins adjacent to garnet coronas ($X_{\text{an}} = 0.53$).

**Charnockites**

Coarse-grained qtz + Kfs + pl + opx ± hbl ± bt ± gtr charnockite intrusions occur throughout the Porthos Range, but appear to be absent from the Athos Range. They have a distinctive dark green-brown colour and greasy lustre, with large simply twinned K-feldspar phenocrysts up to 3 cm across. Accessories include opaques, apatite and zircon. Geochemically, they have affinities with the Mawson Charnockite, 300 km to the north (Munksgaard et al., 1992).

The fabric varies from weak (in areas of low $D_3$ strain, e.g. Crohn Massif) to well linedated (areas of high $D_3$ strain, e.g. Mt. McCarthy), but none of the pre-$D_3$ structures seen in the other lithologies are present. Strong fabrics are defined by quartz ribbons and the alignment of the long axes of K-feldspar augen.

The charnockite contains enclaves of older gneisses as xenoliths and schlieren. Intrusive contacts with the host gneisses are clearly preserved at Crohn Massif, whereas at other localities (e.g. Mt. Gavaghan) the contact is concordant with adjacent gneisses, and somewhat gradational. Original intrusive relationships may have been obscured during later deformation ($D_4$) or by chemical interaction between the country gneiss and the charnockite.

The coarse-grained Mt. McCarthy charnockite (DT013) contains xenoblastic garnet grains 2–3 mm in diameter, in a highly tectonised matrix consisting of medium to coarse-grained K-feldspar, plagioclase, quartz, orthopyroxene and minor biotite. Grain-size reduction, kinking and recrystallisation at larger grain boundaries due to tectonism is a common feature. Simply twinned K-feldspar grains up to 3 cm are common, and quartz ribbons and trails of xenoblastic orthopyroxene define the well developed $L_3$
X\textsubscript{Mg} for garnet ranges from 0.22 at the rim of a grain in contact with orthopyroxene, to 0.24 in the core. Orthopyroxene in contact with garnet is more magnesian (X\textsubscript{Mg} = 0.50) than matrix orthopyroxene (X\textsubscript{Mg} = 0.45). X\textsubscript{Al} for orthopyroxene ranges from 0.03 to 0.05. X\textsubscript{An} for plagioclase ranges from 0.37 to 0.38.

**P-T Estimates**

Estimates of the metamorphic conditions, calculated using various geothermometers and geobarometers, are presented in Table 2 and Figs. 4 and 5. Calculations were performed and diagrams plotted using the program “Thermobarometry” (Spear and Peacock, 1990).

**Peak metamorphic conditions**

Samples DT058 and DT013 were used to calculate the maximum conditions of metamorphism using barometers based on the (generalised) reaction:

\[
\text{pl} + \text{opx} = \text{grt} + \text{qtz} \quad \text{(GOPS)}
\]

(e.g. Newton and Perkins, 1982; Bohnen et al., 1983a), and on the solubility of alumina in orthopyroxene co-existing with garnet (Harley and Green, 1982). These estimates are combined with garnet-orthopyroxene thermometers (Sen and Bhattacharya, 1984; Harley, 1984; Lee and Ganguly, 1988), providing P-T estimates in the range 7 ± 1 kbar, 750–850°C (Figs. 4a and b).

Rutile and ilmenite are present as inclusions within garnet in both samples NM41 and NM49, allowing the application of the GRAIL and GRIPS barometers (Bohleb et al., 1983b; Bohlen and Liotta, 1986), based on the reactions:

\[
\text{alm} + \text{rt} = \text{ilm} + \text{sil} + \text{qtz} \quad \text{(GRAIL)}
\]

\[
\text{grt(grs,alm)} + \text{rt} = \text{ilm} + \text{an} + \text{qtz} \quad \text{(GRIPS)}
\]

This yields pressures of between 6.5–7 kbar at a chosen temperature of 800°C. Comparable results are obtained using the barometers based on the reaction:

\[
\text{grs} + \text{sil} + \text{qtz} = \text{an} \quad \text{(GASP)}
\]

Pressures of between 4 (Hodges and Spear, 1982) and 7 (Koziol, 1989) kbar are obtained, with the Newton and Haselton (1981), Ganguly and Saxena (1984) and Hodges and Crowley (1985) calibrations all converging at ~6 kbar and 825°C. Garnet-cordierite and garnet-biotite thermometer applied to NM41 and NM49 (our unpublished data) yield lower temperature estimates than garnet-orthopyroxene thermometers applied to DT058 and DT012. This is thought to reflect continued Fe-Mg re-equilibration during cooling, and does not constrain the P-T history.

The occurrence of primary wollastonite in calc-silicate gneisses implies low a\textsubscript{CO\textsubscript{2}}: at a temperature of 780°C at 7 kbar, X\textsubscript{CO\textsubscript{2}} ≤ 0.25 for wollastonite to be stable, based on the results of Greenwood (1967).

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**Fig. 4.** P-T diagrams for various rock types from the Porthos Range, data and symbols from Table 2. The preferred estimate for each rock is indicated by the patterned region. (a) DT058, a grt + opx felsic gneiss, and (b) DT013, a grt-bearing charnockite. (c and d) PK6, using the assemblage (c) grt + opx + pl, and (d) grt + cpx + pl.
Table 2. Summary of mineral compositional data and thermobarometry for samples discussed in text.

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<tr>
<th>Sample</th>
<th>Assemblage</th>
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<th>PI</th>
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<td>$X_{\text{Ca}}$</td>
<td>$X_{\text{Mn}}$</td>
<td>$X_{\text{Mg}}$</td>
<td>$X_{\text{Al}}$</td>
</tr>
<tr>
<td>NM49</td>
<td>GASP, GRAIL, GRIPS</td>
<td>0.379</td>
<td>0.030</td>
<td>0.010</td>
<td>0.355</td>
<td>800</td>
</tr>
<tr>
<td>NM41</td>
<td>GRAIL</td>
<td>0.362</td>
<td>0.030</td>
<td>0.012</td>
<td>800</td>
<td>6.8</td>
</tr>
</tbody>
</table>

Fig. 5. Compilation diagram of preferred $P$-$T$ estimates derived from the metapelite gneisses and the felsic and mafic gneisses in the Porthos and Athos Ranges. The numbered and ornamented lines are $P$ estimates for the metapelite gneisses: (1) GASP (Hodges and Spear (1982)), (2) Koziol (1989), (3) GRIPS, Bohlen and Liotta (1986), (4) GRAIL, Bohlen et al. (1983b); (5) NM41, GRAIL. The following explanation refers to the high $P$ side of lines A and B: (A) garnet “in” in quartz tholeiite composition “A”, Green and Ringwood (1967), (B) garnet “in” in peridotite, Saxena and Eriksson (1985). The stippled arrow shows the preferred $P$-$T$ trajectory. Aluminosilicate triple-point from Holdaway (1971).

**Prograde $P$-$T$ path**

Textural evidence for the prograde path is provided by inclusions within garnets in metapelitic rocks from Carter Peaks. Prismatic sillimanite inclusions imply initial conditions in the sillimanite stability field. Evidence for the “up-pressure” attainment of peak conditions is suggested by the rounded cordierite inclusions, as the reaction:

$$\text{crd} = \text{grt} + \text{sil} + \text{qtz}$$  \hspace{1cm} (5)

has a relatively flat $dP/dT$ slope, with cordierite on the low-pressure side.

**Retrograde $P$-$T$ path**

Reaction textures in calc-silicate and mafic gneisses suggest a retrograde development for the NPCM initially characterised by near isobaric cooling. The formation of grossular rims on scapolite implies progress of the reaction:

$$\text{scp} + \text{wo} + \text{cal} = \text{grs} + \text{CO}_2$$  \hspace{1cm} (6)

from left to right, which occurs in response to a decrease in either temperature or $a_{\text{CO}_2}$ (Fitzsimons and Harley, 1991; Harley and Buick, 1991). Similarly, quartz rims on wollastonite can be explained by the reaction:

$$\text{wo} + \text{CO}_2 = \text{cal} + \text{qtz}$$  \hspace{1cm} (7)

also proceeding from left to right on cooling. Similar textures are reported for calc-silicate gneisses from the Aramis Range, immediately south of the Porthos Range (Fitzsimons and Harley, 1991).

The development of garnet coronas on plagioclase in PK6 suggests the reactions:

$$\text{pl} + \text{opx} = \text{grt} + \text{qtz}$$  \hspace{1cm} (1)

$$\text{pl} + \text{cpx} = \text{grt} + \text{qtz} \hspace{0.1cm} \text{(GCPS)}$$  \hspace{1cm} (8)

proceeded from left to right on cooling. Such textures can result from an increase in pressure, however strong plagioclase zonation (Fig. 3d) suggests that reaction took place during cooling, as progress of reactions 1 and 8 at elevated temperatures would tend to homogenise the plagioclase.

Quantitative estimation of the retrograde conditions recorded in PK6 (Table 2, Figs. 4c and d) suggest slightly higher-than-peak pressure conditions, at lower temperatures (700–750 $\pm$ 50°C). Estimates straddle the garnet-in curves for the quartz-tholeiite composition “A” of Green and Ringwood (1967) and the peridotite of Saxena and Eriksson (1985; Fig. 5).

**Discussion**

The textural features preserved in both metapelitic gneisses from the Athos Range and mafic orthogneisses from the Porthos Range suggest that the NPCM evolved along a $P$-$T$ path with heating prior to and during tectonic loading, followed by initial near isobaric cooling from peak conditions (i.e. an anticlockwise $P$-$T$ path). Similar $P$-$T$ paths have been derived for a number of other granulite terranes, for example, the Willyama Complex (Corbett and Phillips, 1981), the Adirondacks and Nilgiri Hills (as summarised by Bohlen, 1987), Namaqualand (Waters, 1988), the Napier Complex of Enderby Land (Motoyoshi and Hensen, 1989), and the Arunta Block (Warren and Hensen, 1989).

The $P$-$T$ path derived here for the NPCM contrasts with $P$-
paths from south-eastern Prydz Bay. There, textural evidence in metapelitic and mafic rocks indicates decompression to be the dominant retrograde feature (e.g. Harley, 1988; Stüwe and Powell, 1989; Thost et al., 1991; Nichols and Berry, 1991). However, metapelitic rocks from the Mawson coastline preserve retrograde assemblages that are in accord with the retrograde P-T path derived here, with corona development during essentially isobaric cooling (Clarke et al., 1989). Clarke et al. (1989) suggest that such a retrograde path is not inconsistent with the isothermal decompressive histories proposed for south-eastern Prydz Bay, followed by isobaric cooling. However, the occurrence of low-pressure minerals (cordierite) as inclusions in garnet in the NPCM suggests that the sense of the P-T path was anticlockwise, and is incompatible with an earlier high pressure event preceding isobaric cooling. This difference is significant as all three areas have previously been considered to be part of the same extensive late Proterozoic mobile belt. If they are, it means that different portions of the belt have distinct P-T histories.

Bohlen (1987, 1991) proposed that anticlockwise-isobaric cooling paths of granulites may be related to magmatic underplating beneath existing continental crust and intrusion and crystallisation of substantial volumes of igneous material within the crust. This is likely to occur in areas of initial rifting or extension followed by compression, in continental rift environments or above hot spots (Sandiford and Powell, 1986; Bohlen, 1991). In environments such as these an abundance of metagneous rocks should occur at depth as a result of extensive plutonism, marking the transition between previously existing crust and the igneous underplate (Bohlen, 1991). This is, perhaps, what we see exposed in the NPCM, and other areas in Prydz Bay: alternating areas dominated by either orthogneiss (e.g. the Porthos Range) or paragneiss (e.g. the Athos Range). Resolution of this scenario awaits detailed geochronological studies to determine if the orthogneiss-dominated areas represent older basement (e.g. Thost et al., 1991) or younger additions to previously existing crust.

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REFERENCES


McKELVEY, B. C. and STEPHENSON, N. C. N. (1990): A geological reconnaissance of the Radok Lake area, Amery Oasis, Prince Charles


