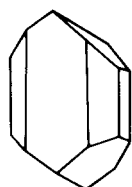# A petrologic and fluid inclusion study of charnockites from the Lützow-Holm Bay region, East Antarctica: Evidence for fluid-rich metamorphism in the lower crust

M. Santosh and M. Yoshida

Faculty of Science, Osaka City University, Osaka 558, Japan

(Received June 25, 1991; revised and accepted May 7, 1992)

LITHOS

ABSTRACT

Santosh, M. and Yoshida, M., 1992. A petrologic and fluid inclusion study of charnockites from the Lützow-Holm Bay region, East Antarctica: Evidence for fluid-rich metamorphism in the lower crust. Lithos, 29: 107–126.

The Proterozoic terrain of Lützow-Holm Bay in East Antarctica comprises an amphibolite- to granulite-facies progression from north to south, exposing an oblique section of the lower crust. The granulite terrain is represented dominantly by orthopyroxene-bearing anhydrous granulites (charnockites), garnet- and biotite-bearing gneisses (leptynites), and garnet, sillimanite and graphite bearing aluminous metapelites (khondalites). Thus it is petrographically identical with its Gondwanian counterparts in Sri Lanka and southern India. Charnockite formation is characterized by the consumption of garnet, biotite and quartz to produce orthopyroxene, alkali feldspar and plagioclase under isothermal conditions and at reduced water activities. A number of mineral-reaction textures, including orthopyroxene–plagioclase symplectites around clinopyroxene relics in intermediate charnockites and spinel rims between adjacent garnet and sillimanite in khondalites, suggest near-isothermal conditions of equilibration. Mineral phase equilibria barometry traverse across the granulite terrain indicates an increase in pressure from c. 5 kbar in the north to c. 8–9 kbar in the south. The temperature gradient of c. 100°C is less pronounced. Fluid inclusion studies indicate abundant CO_2 trapped within the charnockite minerals. The systematic variation in fluid densities with a garnet→feldspar→quartz succession within individual samples argues against post-metamorphic fluid infiltration and fits a scenario of mineral equilibration during near-isothermal uplift following a clockwise pressure–temperature–time path. Along the pressure gradient, the fluid densities show an increase from c. 0.98 to c. 1.10 g/cm³. This strengthens other evidence of a synmetamorphic entrapment of CO_2. Preliminary carbon isotope measurements of CO_2 extracted from inclusions yield $\delta^{13}C$ values of c. −5 to −6‰, suggesting a sub-continental mantle source. The Gondwanan Lützow-Holm Bay terrain had undergone substantial extension during the late Proterozoic, with displacement along megafaults and emplacement of several alkaline–subalkaline granite and syenite plutons, and also K-basalts. It is therefore envisaged that the abundant CO_2 in the charnockites could have been derived from an attenuated continental lithosphere, and transferred through magmatic conduits.

Correspondence to: M. Santosh, Centre for Earth Science Studies, Trivandrum 695 031, India.

Introduction

The East Antarctic Shield comprises the Archaean Napier Complex and the Proterozoic Rayner and Lützow-Holm Complexes (Fig. 1). The Napier Complex is marked by uncommonly high pressures and temperatures at c. 10 kbar and 1000°C (e.g., Grew, 1980; Sheraton et al., 1980; Harley, 1983; Sandiford and Powell, 1986). The Lützow-Holm Bay (LHB) region, in contrast, is characterized by a continuous transition from amphibolite facies in the north to granulite facies in the south along the Prince Olav Coast (Hiroi et al., 1983; Motoyoshi et al., 1989). The LHB region exposes garnet–biotite-, upper-amphibolite facies, gneisses (leptynites), intermediate to felsic charnockites (orthopyroxene-bearing anhydrous granulites), garnet-, sillimanite- and graphite-bearing aluminous granulites (khondalites), metabasites, gneissose granites and subordinate amounts of calcsilicate and ultramafic rocks. Being a fragment

of the Gondwana supercontinent, this terrain has several features in common with granulite terrains in the other Gondwana continents. Thus geological and structural history of the Lützow-Holm Bay region is comparable to that of the leptynite–khondalite–charnockite sequences in Sri Lanka and southern India. In the latter case, several recent studies have focussed attention on the charnockites (e.g., Touret and Hansteen, 1988), with particular emphasis on the intimately associated gneiss–charnockite reaction fronts (e.g., Hansen et al., 1987; Raith et al., 1989; Burton and O'Nions, 1990; Santosh et al., 1990). The unbroken amphibolite- to granulite-facies progression in this crustal domain, together with the regional association of anhydrous granulites and gneisses, provide an opportunity for studying the nature of lower continental crust in general, and the processes attending charnockite formation in particular.

Granulite petrogenesis has been debated ever since the concept of metamorphic facies was first
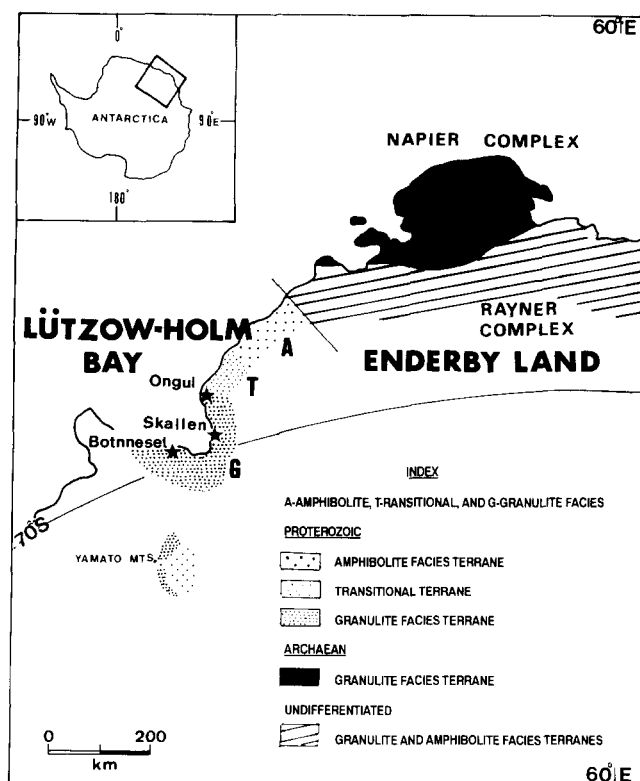

Fig. 1. Geology of East Antarctica. The Proterozoic terrain of Lützow-Holm Bay shows a progressive increase in metamorphic grade from an amphibolite-facies segment in the north (A) to a granulite-facies segment in the south (G) along a transitional zone (T). Ongul, Skallen and Botnneset, the localities of present study, are shown.

proposed. Central to any model for granulite formation is the stability of anhydrous mineral phases such as orthopyroxene. Recent debates on granulite petrogenesis consider three principal mechanisms which may depress water activities during lower crustal metamorphism. These are, (i) dilution or expulsion of pore-fluids through the external influx of a non-aqueous fluid, generally CO_2, a process popularly known as "carbonic metamorphism" (Touret, 1971; Newton et al., 1980; Santosh, 1986), (ii) metamorphism of anhydrous lithologies (Lamb and Valley, 1984) and (iii) dehydration by the extraction of a hydrous partial melt (Waters, 1988; Burton and O'Nions, 1990). Evidence from different granulite terrains provides examples of all these three mechanisms, either operating independently or in conjunction, (e.g., Frost et al., 1989; Touret and Hartel, 1990).

The objectives of this study are to examine mineral phase equilibria from representative gneiss and charnockite assemblages in the LHB region, and to assess the role of fluids from fluid inclusion studies. The results are evaluated in the context of granulite formation mechanism and probable source of fluids.

Geologic background

Over the past three decades, the Japanese Antarctic Research Expeditions (JARE) have carried out several scientific investigations in the LHB region. The pioneer works on the geology, structure and metamorphism of this high-grade terrain, summarised in Yoshida (1978, 1979) and Yoshida et al. (1983), have identified a framework of a granite-gneiss terrain in the north and a granulite facies terrain in the south, and documented the tectono-metamorphic history ranging from Early Proterozoic to Early Paleozoic. Widespread intermediate to acid charnockites have been identified from Ongul, Skallen and Botnneset, in a north–south traverse (cf. Fig. 1). Charnockites and garnet–biotite gneisses constitute the dominant litho-units in Ongul. Charnockites, gneisses, aluminous metapelites (khondalites), calcareous rocks and quartzites are represented in Skallen. The occurrence of charnockites and khondalites continue into the southernmost terrain of Botnneset. Field and microstructural studies suggest a polyphase metamorphic history for the LHB lithounits (Yoshida, 1978), comparable,

in some respects, to their counterparts in southern India.

Patch and vein-type incipient charnockites have not been recorded from Antarctica, probably due to the absence of freshly exposed quarry faces that aided in their identification in southern India and Sri Lanka. However, orthopyroxene-bearing pegmatitic veins and in situ transformation of gneiss to charnockite on a local scale have been observed in the LHB area. For example, coarse grained charnockitic rocks are found cutting the gneissic fabric without disturbing the structural fabric (Yoshida, 1978). Comprehensive field and microstructural studies presented in Yoshida (1978) indicate that charnockite formation in the LHB area resulted from the prograde transformation of gneisses, and post date the main regional penetrative events. Previous studies identified the general $P-T$ conditions of the major granulite metamorphism at 7–8 kbar and 760–830°C (Motoyoshi et al., 1989). Some unusually high pressure values (> 10 kbar) have been recorded from relict minerals in some metabasite assemblages (e.g., Yoshida, 1979) although the regional significance of this remains unknown. In the aluminous metapelites, the sporadic occurrence of relict kyanite, staurolite and rarely sapphirine, has been interpreted as indicating prograde metamorphism accompanied by decrease in pressure, since the documented reactions suggest a transition from kyanite stability field to the sillimanite stability field (Motoyoshi et al., 1989). A clock-wise $P-T$ path is inferred from the decompression textures preserved by the LHB rocks, as exemplified by orthopyroxene–plagioclase symplectites surrounding garnet. Relict kyanite is also indicative of a clockwise $P-T$ path (J. Touret, pers. commun., 1991).

Geochronologic studies have attributed a possible Proterozoic age for the region, although it is uncertain whether the dates constrain granulite-facies, or the subsequent upper amphibolite-facies metamorphism (cf. Yoshida, 1979). Rb–Sr data of Shibata et al. (1985) ascribe late Proterozoic ages (700–1100 Ma). More recently, Shiraishi and Kagami (1989) provided Sm–Nd mineral isochron ages (hornblende–biotite–plagioclase) of 620 ± 20 Ma from enderbitic charnockites. Model ages cluster around 1000 Ma, precluding any prolonged crustal residence history.

Recent studies have demonstrated that solid–fluid

equilibria on a detailed scale in a single hand-specimen (e.g., Touret and Hansteen, 1988) or closely spaced decimeter-scale traverses (e.g., Burton and O'Nions, 1990; Santosh et al., 1990) yield valuable information on the mechanism of granulite formation. In this study, we have analysed a suite of seven representative samples for mineral thermobarometric estimates, namely, three charnockites, two garnet–sillimanite metapelites (khondalites) and two garnet–biotite gneisses (leptynites). The fluid inclusion studies have been undertaken on the charnockite samples and associated gneisses. Previous petrologic investigations in LHB have identified a gradual increase in temperature from north to south. This study is the first attempt to document solid and fluid phase equilibria in a north–south traverse across the LHB terrain.

Analytical techniques

Representative analyses of gneiss and granulite mineral assemblages were carried out on polished thin sections using a JEOL JXA 733 wave length-dispersive electron microprobe at the National Institute of Polar Research, Tokyo, operating at 20 kV and 30 nA with a 15 μm defocussed beam. Fluid inclusion studies were carried out on doubly polished thin rock wafers prepared at the Osaka City University. Microthermometric experiments were undertaken at the Geological Survey of Japan Laboratory using U.S.G.S. adapted gas-flow heating-

freezing system. Temperature calibrations are based on natural and synthetic standards and the quoted values have a precision of $\pm 0.3\,°C$. Laser-excited Raman spectra analyses of representative inclusions were made at the Institute of Physics and Chemistry (Tokyo), using Jobin-Yvon RAMA-NOR U-1000 Raman microprobe.

Phase equilibria

The mineral assemblage in the charnockite is characterized by alkali feldspar, plagioclase, quartz, garnet and orthopyroxene with accessory biotite, apatite, zircon and ilmenite/magnetite. Intermediate varieties, as observed at Botnneset, contain clinopyroxene. The garnet–biotite gneisses have a similar assemblage, except that orthopyroxene is absent. Garnet in the gneisses form relatively large megacrysts with sharp linear contacts with subhedral laths of biotite. In the charnockite, adjacent garnet and biotite grains show irregular and sutured grain boundaries, suggesting that both are reactant phases. The aluminous metapelites are characterized by an assemblage of garnet–sillimanite–K-feldspar–quartz–plagioclase ± spinel, with accessory graphite and Fe–Ti oxides. Cordierite is conspicuously absent, unlike in some of their khondalite counterparts in Sri Lanka and southern India. The mineralogy of the three dominant rock types described above are summarised in Table 1 and represented in Fig. 2. From textural criteria, we
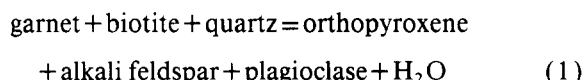
TABLE 1

Mineral assemblages of charnockites, khondalites and leptynites from Lützow-Holm Bay region, East Antarctica

| Locality	Ongul	Skallen			Botnneset		
	ON/CH	SK/CH	SK/KH	SK/LP	BT/CH	BT/KH	BT/LP
Sample No.	2402	615	618	614	1502	2931-A	2932
Garnet	×	×	×	×	×	×	×
Orthopyroxene	×	×	–	–	(×)	–	–
Clinopyroxene	–	(×)	–	–	×	–	–
Plagioclase	×	×	×	×	×	×	×
K-feldspar	×	×	×	×	×	×	×
Quartz	×	×	×	×	×	×	×
Hornblende	–	–	–	–	(×)	–	–
Sillimanite	–	–	×	–	–	×	–
Biotite	(×)	(×)	×	×	(×)	×	×
Spinel	–	–	×	–	–	×	–
Fe–Ti Oxides	×	×	×	×	×	×	×

"×" indicates sporadically present; "–" indicates absent.

identify the following reactions as critical to the LHB rocks:

garnet + biotite + quartz = orthopyroxene

$\quad$ + alkali feldspar + plagioclase + H_2O $\qquad$ (1)

This reaction characterizes the conversion of paragneisses to charnockites. If Ti is added as a component, ilmenite will also be a product phase, as commonly observed in these charnockites (cf. Table 6). The reactants are stable phases in the gneiss assemblage. The consumption of biotite, garnet and quartz and the growth of orthopyroxene and alkali feldspar require a decrease in X_{H_2O} in order to drive the dehydration reaction. Charnockite formation in the LHB, as in several other localities (e.g., Touret, 1989) occurred at T-f_{O_2} conditions outside the stability field of graphite (cf. Lamb and Valley, 1984). Hence, influx of CO_2 from an external source, as discussed below, will not result in the precipitation of graphite. Yoshida (1978) identified fresh biotite and hornblende laths in the LHB charnockites as products of a retrogressive phase during the amphibolite-facies overprinting. In such cases, the early biotite and hornblende which participated in the prograde reaction occur as fine grained xenocrysts, often as inclusions within garnet and pyroxenes. The phenomenon of amphibolite-facies retrogression subsequent to the main granulite event has been identified in the granulites of southern India and Sri Lanka, where the resultant field textures have been described as "charnockite in the breaking" (Yoshida and Santosh, 1987).

In the quartz-bearing mafic granulite sample from Skallen, another potential decompression texture is recorded by the growth of orthopyroxene–plagioclase symplectites adjacent to relic garnet and clinopyroxene (Fig. 2d), suggesting the reaction:

garnet + clinopyroxene + quartz

$\quad$ = orthopyroxene + plagioclase $\qquad$ (2)
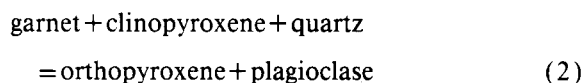
This reaction serves as one of the important indicators for a near-isothermal decompression history for LHB (cf. Harley, 1989).

In Botnneset, hornblende also participates in the charnockite-forming reaction in the garnet-hornblende-gneisses. The appearance of clinopyroxene may be related to the breakdown of calcic amphibole. Harley (1989) suggested a potential de-compression reaction in mafic granulites involving amphibole:

hornblende + plagioclase

$\quad$ = garnet + clinopyroxene + quartz + liquid $\qquad$ (3)
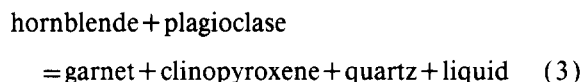
The pegmatitic pools sometimes surrounding metabasites (cf. Yoshida, 1978) may indicate the generation of water-undersaturated melts through this reaction. In the LHB rocks, although conversion of hornblende to pyroxene is recorded by the xenocrystic laths, Yoshida (1978) considers that some of the amphiboles which surround or cut pyroxenes are secondary, developed during retrogressive metamorphism.

The metapelite assemblages which often show partial melt seggregates, could be represented by vapor-absent melting along a decompression path according to the reaction:

biotite + sillimanite + plagioclase + quartz

$\quad$ = K-feldspar + garnet + liquid $\qquad$ (4)
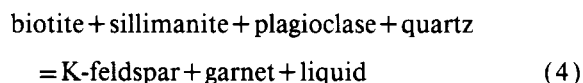
Earlier studies have noted that plagioclase sometimes occurs only as relics, in the form of minor laths, as in the Skallen khondalites (e.g., Yoshida, 1979), indicating the virtual consumption of plagioclase through the decompression reaction (4). It is inferred that vapor-absent melting of a thick pile of pelitic and psammitic sediments during prograde metamorphism resulted in migmatization and compositional layering in the gneisses and khondalites, analogous to that observed in the Kerala Khondalite Belt of southern India (cf. Chacko et al., 1987).

Further evidence for retrograde metamorphism along an isothermal path is indicated by reaction rims of spinel between garnet and sillimanite, suggesting the reaction:

garnet + sillimanite = spinel + quartz $\qquad$ (5)
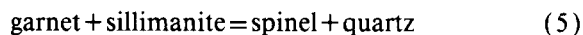
This continuous reaction is indicative of de-compression and might suggest initial high temperatures for the metapelites (cf. Harley, 1989). Prograde metamorphism in the LHB has been deduced from the rare assemblage kyanite, staurolite and sapphirine found as inclusions in garnet porphyroblasts (Motoyoshi et al., 1989).

Representative mineral analyses are presented in Tables 2–6. Garnet grains in the LHB rocks show compositional zoning with an increase in pyrope
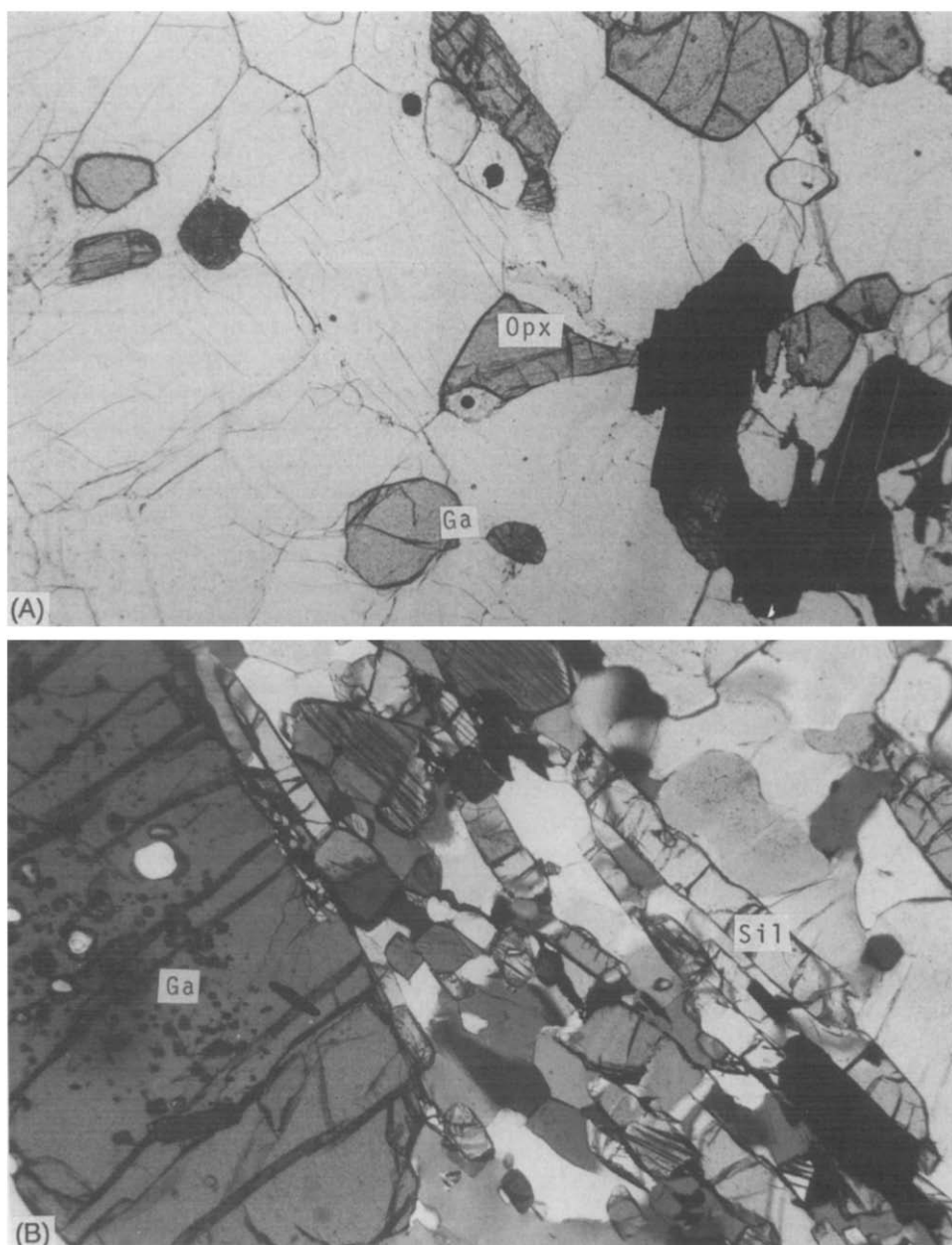
Fig. 2. Photomicrographs of representative mineral assemblages in Lützow-Holm Bay rocks. (A) Garnet–orthopyroxene char-nockite (sample 2402, Ongul); (B) garnet–sillimanite assemblage in khondalite (sample 618, Skallen); (C) garnet–biotite as-semblage in leptynite (sample 2932, Botnneset); (D) decompression texture with orthopyroxene–plagioclase symplectites sur-rounding garnet (sample 615, Skallen). The length of photographs measure 2.6 mm. Mineral abbreviations: *Ga* – garnet, *Opx* –orthopyroxene, *Sil* – sillimanite, *Bt* – biotite.

content towards the core (Yoshida, 1979). Garnet analyses presented in this study represent the core compositions. A detailed treatment of mineral chemistry from more exhaustive data-base will be

presented elsewhere. The main objective of this study is to constrain the P–T gradients from exper-imental mineral phase equilibria thermobarome-ters, as summarised in Tables 7 and 8. The results
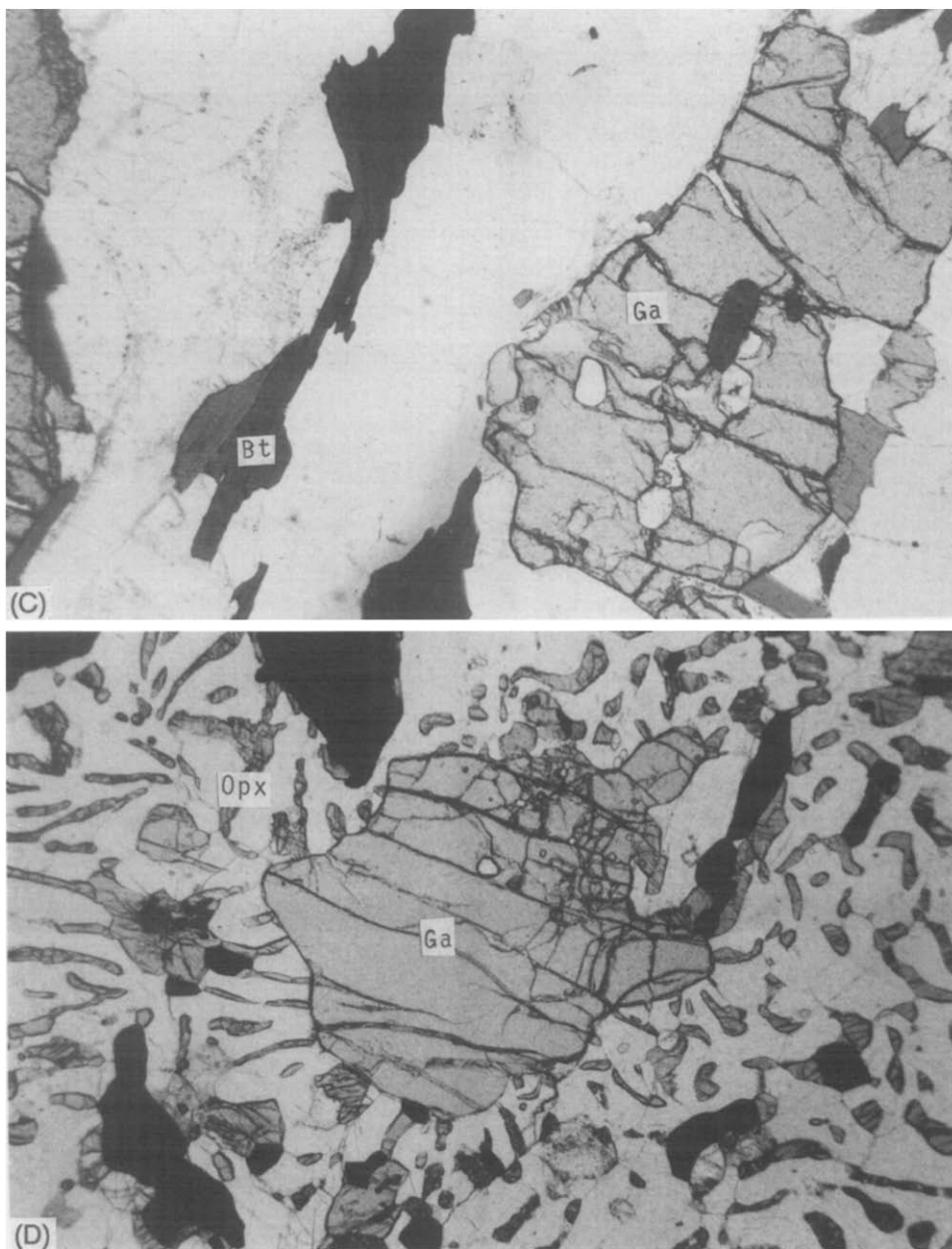
of $P-T$ estimates from different computations for the three areas are compiled in Fig. 3.

The Fe–Mg distribution between coexisting garnet and biotite, and between garnet and orthopyroxene/clinopyroxene provides thermometers for gneisses and charnockites, respectively. Considering that retrograde Fe–Mg exchange can occur in granulite facies rocks (Frost and Chacko, 1989), the temperature estimates are minimum constraints.

From the analyses of garnet cores and non-contiguous biotite pairs, thermometric computations for the gneiss and khondalite assemblages are summarised in Table 7, where the results from three approaches are compared. The Thompson (1976) and Perchuk and Lavrent'eva (1983) calibrations yield comparable ranges, while the Ferry and Spear (1978) method gives consistently higher values. In the leptynite sample from Botnneset, the three ther-

TABLE 2

Garnet analyses

Sample No.	ON/CH	SK/CH	SK/KH	SK/LP	BT/CH	BT/KH	BT/LP
SiO_2	36.77	37.71	38.10	38.29	36.66	38.18	37.75
TiO_2	0.04	0.10	0.05	0.00	0.03	0.06	0.04
Al_2O_3	19.78	20.37	21.13	21.50	19.98	20.66	19.91
Cr_2O_3	0.00	0.03	0.00	0.03	0.00	0.03	0.00
FeO*	31.33	28.86	28.66	31.77	32.91	30.99	34.06
MnO	2.34	1.22	0.49	0.54	1.70	0.64	1.56
MgO	1.71	3.40	8.53	7.24	0.56	6.43	2.96
CaO	6.23	7.92	1.82	2.55	7.38	1.92	3.29
Na_2O	0.08	0.09	0.00	0.07	0.00	0.03	0.00
K_2O	0.00	0.00	0.01	0.00	0.02	0.00	0.02
Total	98.28	99.70	98.72	101.99	99.24	98.94	99.59
On the basis of	12(O)						
Si	3.021	3.008	3.011	2.960	2.963	3.031	3.050
Al	1.916	1.915	1.968	1.959	1.957	1.933	1.896
Ti	0.002	0.006	0.003	0.000	0.002	0.004	0.002
Cr	0.000	0.002	0.000	0.002	0.000	0.002	0.000
Fe	2.153	1.925	1.828	2.054	2.287	2.058	2.302
Mn	0.163	0.083	0.033	0.035	0.120	0.043	0.107
Mg	0.209	0.404	1.005	0.834	0.069	0.762	0.356
Ca	0.548	0.677	0.154	0.211	0.657	0.164	0.285
Na	0.013	0.014	0.000	0.010	0.000	0.004	0.000
K	0.000	0.000	0.001	0.000	0.002	0.000	0.002

'*' indicates total Fe calculated as FeO in all the cases.

TABLE 3

Biotite analyses

Sample No.	SK/KH	SK/LP	BT/KH	BT/LP
SiO_2	36.63	35.70	35.89	34.53
TiO_2	6.39	4.29	5.29	6.23
Al_2O_3	14.54	16.15	15.15	13.81
Cr_2O_3	0.06	0.04	0.03	0.03
FeO*	11.20	16.36	16.86	26.06
MnO	0.00	0.10	0.00	0.00
MgO	14.34	12.84	11.74	5.77
CaO	0.05	0.00	0.00	0.02
Na_2O	0.39	0.20	0.02	0.15
K_2O	8.80	9.03	9.34	8.70
Total	92.40	94.71	94.32	95.30
On the basis of	22(O)			
Si	5.541	5.405	5.478	5.465
Ti	0.567	0.489	0.607	0.742
Al	2.459	2.882	2.726	2.577
Cr	0.006	0.005	0.004	0.004
Fe	1.418	2.071	2.152	3.450
Mn	0.000	0.013	0.000	0.000
Mg	3.234	2.897	2.672	1.362
Ca	0.009	0.000	0.000	0.003
Na	0.113	0.059	0.004	0.046
K	1.698	1.745	1.818	1.757

TABLE 4

Pyroxene analyses

Sample No.	ON/CH	SK/CH	BT/CH
	Opx	Opx	Cpx
SiO_2	47.49	49.06	47.83
TiO_2	0.03	0.07	0.17
Al_2O_3	0.58	0.92	0.91
Cr_2O_3	0.03	0.03	0.00
FeO*	39.67	32.95	26.58
MnO	0.85	0.72	0.32
MgO	8.57	13.85	2.26
CaO	0.80	0.69	19.33
Na_2O	0.11	0.08	0.46
K_2O	0.00	0.00	0.01
Total	98.13	98.34	97.87
On the basis of	6(O)		
Si	1.983	1.969	1.985
Ti	0.001	0.002	0.005
Al (iv)	0.017	0.031	0.015
Al (vi)	0.011	0.013	0.030
Cr	0.001	0.001	0.000
Fe	1.385	1.106	0.923
Mn	0.030	0.024	0.011
Mg	0.533	0.829	0.140
Ca	0.036	0.030	0.860
Na	0.008	0.006	0.037
K	0.000	0.000	0.001

TABLE 5

Plagioclase analyses

Sample No.	ON/CH	ON/CH	SK/CH	SK/KH	SK/LP	BT/CH	BT/CH	BT/KH	BT/KH	BT/LP
	(Core)	(Rim)				(Core)	(Rim)	(Core)	(Rim)	
SiO₂	59.46	60.01	58.16	58.57	61.06	63.35	62.76	60.84	59.36	60.56
TiO₂	0.01	0.02	0.00	0.03	0.04	0.03	0.01	0.03	0.04	0.04
Al₂O₃	24.18	23.82	26.86	23.92	23.59	22.67	22.33	23.96	24.04	24.04
FeO*	0.09	0.03	0.11	0.00	0.04	0.23	0.19	0.07	0.00	0.11
MnO	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.01
MgO	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.03
CaO	6.21	6.16	7.79	6.95	6.12	4.33	4.26	6.33	6.18	6.31
Na₂O	7.91	7.59	6.45	7.71	7.69	9.29	9.34	7.84	8.41	7.80
K₂O	0.36	0.47	0.23	0.09	0.22	0.26	0.27	0.40	0.49	0.34
Total	98.21	98.10	99.63	97.27	98.76	100.16	99.16	99.48	98.52	99.24
On the basis of	8(O)									
Si	2.698	2.721	2.603	2.686	2.743	2.803	2.8806	2.722	2.693	2.716
Al	1.293	1.273	1.417	1.293	1.249	1.182	1.177	1.263	1.285	1.271
Ti	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.001	0.001	0.001
Fe	0.003	0.001	0.004	0.000	0.001	0.008	0.007	0.003	0.000	0.004
Mn	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.002
Ca	0.302	0.299	0.374	0.341	0.294	0.205	0.204	0.303	0.300	6.303
Na	0.696	0.667	0.561	0.685	0.669	0.797	0.810	0.680	0.740	0.679
K	0.021	0.027	0.013	0.005	0.013	0.015	0.016	0.023	0.028	0.020

mometers read three different scales, with a discrepancy of more than 200°C. However, importantly, all the three thermometers bring out an increase in temperature from Skallen to Botnneset. Excluding the two anomalously high readings from the Ferry and Spear formulation in the leptynites, a general temperature gradient from ca. 650–700°C to 700–800°C is inferred, with the individual calibrations showing a shift of 150–200°C from the northern to southern segments of LHB.

The Fe-Mg distribution between garnet and pyroxene provides a potential charnockite thermometer. For the orthopyroxene-garnet assemblage in Ongul and Skallen, the Powell (1978) calibration based on Ca/Mg exchange, the semi-empirical calibration of Sen and Bhattacharya (1984) and the Harley and Green (1982) method were applied. These methods yield temperatures in the range of 616–670°C for Ongul and 641–744°C for Skallen, with the Sen and Bhattacharya calibration reading the highest values in both localities. The garnet–clinopyroxene assemblage in Ongul charnockite yields a range of 774–881°C based on the calibrations of Powell (1985), Ellis and Green (1979) and Saxena (1979). The temperature increase from northern to southern terrains (> 100°C) compares with a sim-

ilar trend recorded from garnet–biotite thermometry.

The four phase charnockite assemblage of garnet–orthopyroxene/clinopyroxene–plagioclase–quartz represents a potential geobarometer (Perkins and Newton, 1981). The endmember equilibrium in the system $CaO-MgO_3-Al_2O_3-SiO_2$ is given by the reaction,

1 grossular + 2 pyrope + 3 quartz

$$= 3 \text{ enstatite} + 3 \text{ anorthite} \qquad (6)$$
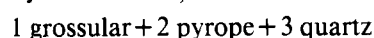
Pressures derived from this reaction provide 5.0 kbar for Ongul and 6.8 kbar for Skallen (cf. Table 8). The garnet–clinopyroxene–plagioclase–quartz assemblage in a rock from Kaname-jima, a locality north of Botnneset, indicates pressures of 8.6 kbar. A pronounced increase in pressure from Ongul through Skallen to Botnneset is thus recorded, with a difference of more than 3 kbars while passing from north-east to south-west in the LHB region.

The assemblage garnet–sillimanite–plagioclase quartz provides a useful geobarometer for pelitic assemblages, especially the khondalites. The endmember equilibrium for this geobarometry is given by the reaction,
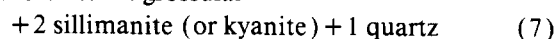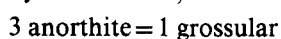
3 anorthite = 1 grossular
$$+ 2 \text{ sillimanite (or kyanite)} + 1 \text{ quartz} \qquad (7)$$

TABLE 6

Fe–Ti oxide analyses

Sample No.	ON/CH	ON/CH	SK/CH	BT/CH	BT/CH
	1	2		1	2
SiO$_2$	0.02	0.08	0.03	0.00	0.00
TiO$_2$	48.70	47.65	8.77	49.13	48.73
Al$_2$O$_3$	0.03	0.02	0.52	0.02	0.00
Cr$_2$O$_3$	0.01	0.04	0.31	0.00	0.02
FeO*	47.22	47.09	80.38	48.35	47.58
MnO	0.63	0.67	0.32	0.40	0.41
MgO	0.11	0.17	0.05	0.13	0.02
CaO	0.02	0.00	0.03	0.00	0.01
ZnO	0.00	0.00	0.00	0.00	0.00
Total	96.75	95.72	90.21	98.03	96.77
Recalculated					
Fe$_2$O$_3$	4.75	5.70	47.78	5.33	4.68
FeO	42.95	41.96	37.38	43.56	43.36
Total	97.23	96.28	95.17	98.56	97.23
R$_2$O$_3$	4.70	5.71	0.00	5.18	4.60
Usp	0.00	0.00	26.45	0.00	0.00
On the basis of	6(O)	6(O)	4(O)	6(O)	6(O)
Si	0.001	0.004	0.001	0.000	0.000
Ti	1.905	1.882	2.63	1.896	1.908
Al	0.002	0.001	0.024	0.001	0.000
Cr	0.000	0.001	0.010	0.000	0.001
Fe (3+)	0.186	0.225	1.437	0.206	0.183
Fe (2+)	1.868	1.843	1.249	1.870	1.888
Mn	0.028	0.030	0.011	0.017	0.018
Mg	0.009	0.013	0.003	0.010	0.001
Ca	0.001	0.000	0.001	0.000	0.001
Zn	0.000	0.000	0.000	0.000	0.000

The Newton and Haselton (1981) calibration provides pressures of 6.5 kbar for Skallen and 8.9 kbar for Botnneset (cf. Table 7). Hodges and Spear (1982) selected an empirical anorthite activity of 2.0, which reduces pressure readings by 1–2 kbar; in the present case, 5.2 and 6.8 kbar were obtained by this method. Ganguly and Saxena (1984) computed activities for both feldspar and garnet from Margules parameters, the resultant pressures are ca. 0.5 kbar lower than those computed by the Newton and Haselton method. More recently, Koziol and Newton (1988) redetermined the breakdown reaction (7) above, and the resultant barometer increases the pressures computed by Newton and Haselton (1981) by ca. 1 kbar. In the present case, the Koziol and Newton barometry provides the highest pressures, of the order of 7.4 kbar for Skallen and 9.8 kbar for Bottneset. We note the increase in pressures in the metapelites from Skallen to Botnneset, comparable with results from charnockite geobarometry.

Fluid phase equilibria

The involvement of a fluid phase during mineral equilibrium may be identified by different means. (1) Solid-phase equilibria and the identification of mineral assemblages which equilibrated with a fluid phase (e.g., Ferry, 1986). (2) From fluids trapped within inclusions in different minerals (e.g., Touret, 1987). The significance of metamorphic fluid phase equilibria as inferred from fluid inclusion characteristics have become a topic of debate (e.g., Lamb et al., 1987). Nevertheless, it has been convincingly demonstrated that synmetamorphic fluids may be preserved and they provide information on the role of fluids in granulite petrogenesis (e.g., Schreurs, 1984; Touret and Hansteen, 1988; Newton, 1990; Touret and Hartel, 1990; Santosh et al., 1990, 1991a; Santosh, 1991).

Fluid inclusions were studied in the three charnockite samples and associated gneisses, from Ongul, Skallen and Botnneset.

Phase-types and distribution patterns

Fluid inclusions were studied in garnet, feldspar (generally perthitic K-feldspar) and quartz, all of which showed the presence of inclusions (Fig. 4). Those in garnet and feldspar are generally of a single generation, whereas quartz shows cross-cutting trials. The dominant category (shown as type-I in Fig. 4c), comprises monophase carbonic inclusions. In garnet, such inclusions are abundant along partly resorbed grain boundaries. In feldspar, they are azonal and scattered, and are generally more abundant towards the grain core. In quartz they define short trials, pinching out within individual grains. These apparently monophase carbonic inclusions contain only a single fluid phase, which completely fill the cavities at room temperature.

The type-II inclusions are bi-phase at room temperature (c. 22°C), and develop a third phase upon slight cooling, consistent with the composition, CO_2 (liquid)+CO_2 (vapor)+H_2O (liquid). They occur along narrow trials which cross-cut the type-I inclusions, or at junctions where type-III (see below) inclusions cut across type-I. Such mixed carbonic aqueous inclusions, occurring along late trials, have been reported from charnockites in other terrains also (e.g., Hansen et a., 1984; Santosh, 1986), and could represent either unmixing of water in an
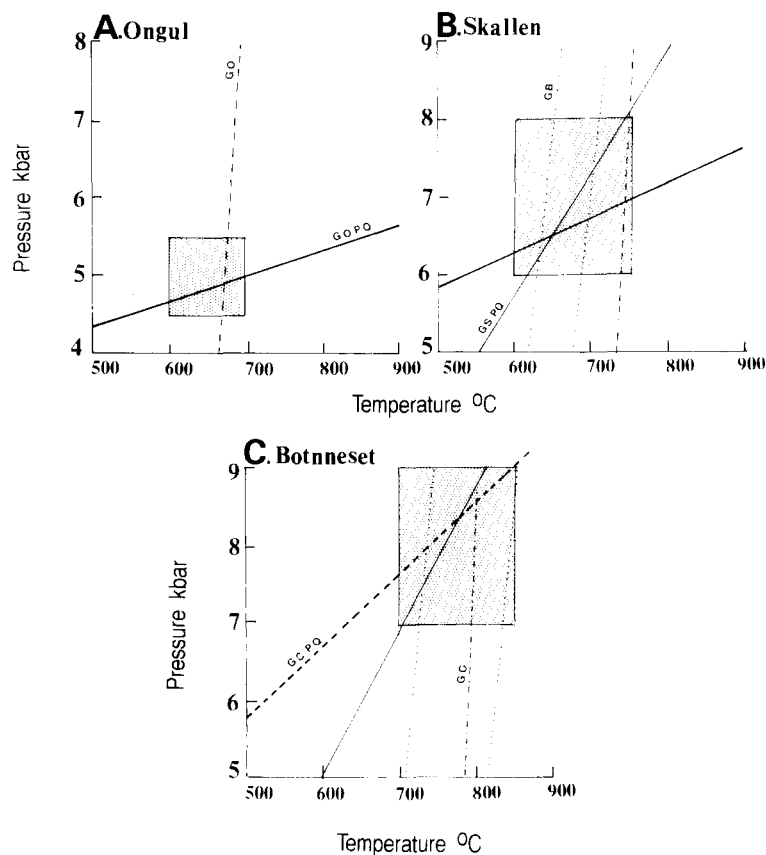
Fig. 3. Pressure–temperature ranges for the three localities shown in Fig. 1, using mineral phase equilibria computations. The thermometers are, *GO*: garnet–orthopyroxene, *GB*: garnet–biotite and *GC*: garnet–clinopyroxene. The barometers are, *GOPQ*: garnet–orthopyroxene–plagioclase–quartz, *GSPQ*: garnet–sillimanite–plagioclase–quartz and *GCPQ*: garnet–clinopyroxene–plagioclase–quartz. The probable *P-T* range for each locality is shown by shaded regions.

TABLE 7

Summary of temperature estimates in Lützow-Holm Bay rocks

	HG	SB	P(1)	S	EG	P(2)	T	FS	PL
Ongul									
Charnockite	618	670	616						
Skallen									
Charnockite	671	744	641						
Khondalite							642	705	639
Leptynite							706	799	682
Botnneset									
Charnockite				881	792	774			
Khondalite							716	814	689
Leptynite							826	986	758

Temperatures in degree centigrade. Charnockite thermometer is garnet–orthopyroxene/clinopyroxene (HG – Harley and Green, 1982; SB – Sen and Bhattacharya, 1984; P(1) Powell, 1978; S – Saxena, 1979; EG – Ellis and Green, 1979; P(2) – Powell, 1985. Gneiss garnet–biotite thermometers are T – Thompson (1976); FS – Ferry and Spear (1978); PL – Perchuk and Lavrent'eva (1983).

TABLE 8

Summary of pressure estimates in Lützow-Holm Bay rocks

	PN	NH	HS	GS	KN
Ongul Charnockite	5.0				
Skallen Charnockite	6.8				
Khondalite		6.5	5.2	7.0	7.4
Botnneset Charnockite	8.6				
Khondalite		8.9	6.8	8.1	9.8

Pressures in kilobars. The geobarometer for charnockites is garnet-orthopyroxene/clinopyroxene–plagioclase–quartz, and for khondalites, garnet–aluminosilicate–plagioclase–quartz. PN – Perkins and Newton (1981); NH – Newton and Haselton (1981); HS – Hodges and Spear (1982); GS – Ganguly and Saxena (1984); KN – Koziol and Newton (1988).

originally heterogeneous fluid, or mixing of late aqueous fluids with pure carbonic fluids trapped earlier.

Type-III inclusions comprise aqueous fluids which occur along trails cutting across several grains. From textural criteria, they appear to have been entrapped at a late stage. At room temperature, they contain a vapour bubble occupying 15–30% of the inclusion cavity volume, and the remaining portion is filled with an aqueous liquid.

Type-I inclusions are well represented in all the three minerals, and their abundance far exceeds those of the other categories. Types-II and III are generally restricted to quartz, where sometimes, type-I inclusions coexist with type-II, although in such cases they yield distinctly high homogenization temperatures and hence low densities than those in early arrays (see later section).

The associated gneisses show a marked difference in their fluid characteristics, the most striking feature being the lower abundance of carbonic (type-I) inclusions as compared to the charnockites. The gneisses also contain transposed brine inclusions, as in the metapelite sample from Skallen, with a large, leaked cavity and a tiny halite cube, probably representing a pre-metamorphic brine-rich fluid regime. Lower abundances of carbonic inclusions and the presence of brine inclusions have been described from metapelites in Sri Lanka (De Maesschalck et al., 1991) and the Kerala Kondalite Belt in southern India (Santosh et al., 1991b). Since type-I inclusions constitute the most abundantly

represented category in the charnockite minerals, information on their composition and density is fundamental to the interpretation of role of fluids in granulite formation in the LHB area.

Fluid composition

Melting temperatures of carbonic inclusions in garnet, feldspar and quartz from the three localities are shown in Fig. 5 (A–C). In all cases, the peak melting occurred close to $-56.6°C$, the triple point for pure CO_3. Inclusions in garnet and feldspar show a sharply defined peak, indicating that the trapped fluid phase is pure CO_2. Those in quartz define a broader peak, with some of the inclusions showing lower melting temperatures. The melting point of pure CO_2 will be depressed by dilutants such as CH_4 and/or N_2. CH_4 could be invoked only under low f_{O_2} conditions (cf. Lamb and Valley, 1984). Even where graphite is present in the charnockite, mass balance considerations show that its oxidation will result in the production of 20 times more methane (by volume) relative to CO_2 (Santosh et al., 1990). Evidence for such large volumes of CH_4 are absent. Klatt et al. (1988) recorded significant quantitites of N_2 from incipient charnockites at Kottavattom in southern India. We analysed representative inclusions by laser-excited Raman spectroscopy. Results show the characteristic peaks for CO_2 (Fig. 5d) in the absence of CH_4 and N_2 peaks. It is concluded that the fluids in LHB charnockites are dominantly pure CO_2. Moreover, the melting temperatures are found to be largely independent of homogenization temperatures (see next section), with no systematic correlation between T_h and T_m (Fig. 5e); hence fluid densities can be calculated assuming a pure CO_2 system.

Density of fluids

The density of the trapped carbonic fluid can be deduced from the temperature of phase transition. For these samples, all the homogenization occurs into liquid phase, by the dissolution of gaseous CO_2 into liquid CO_2. Homogenization temperatures of
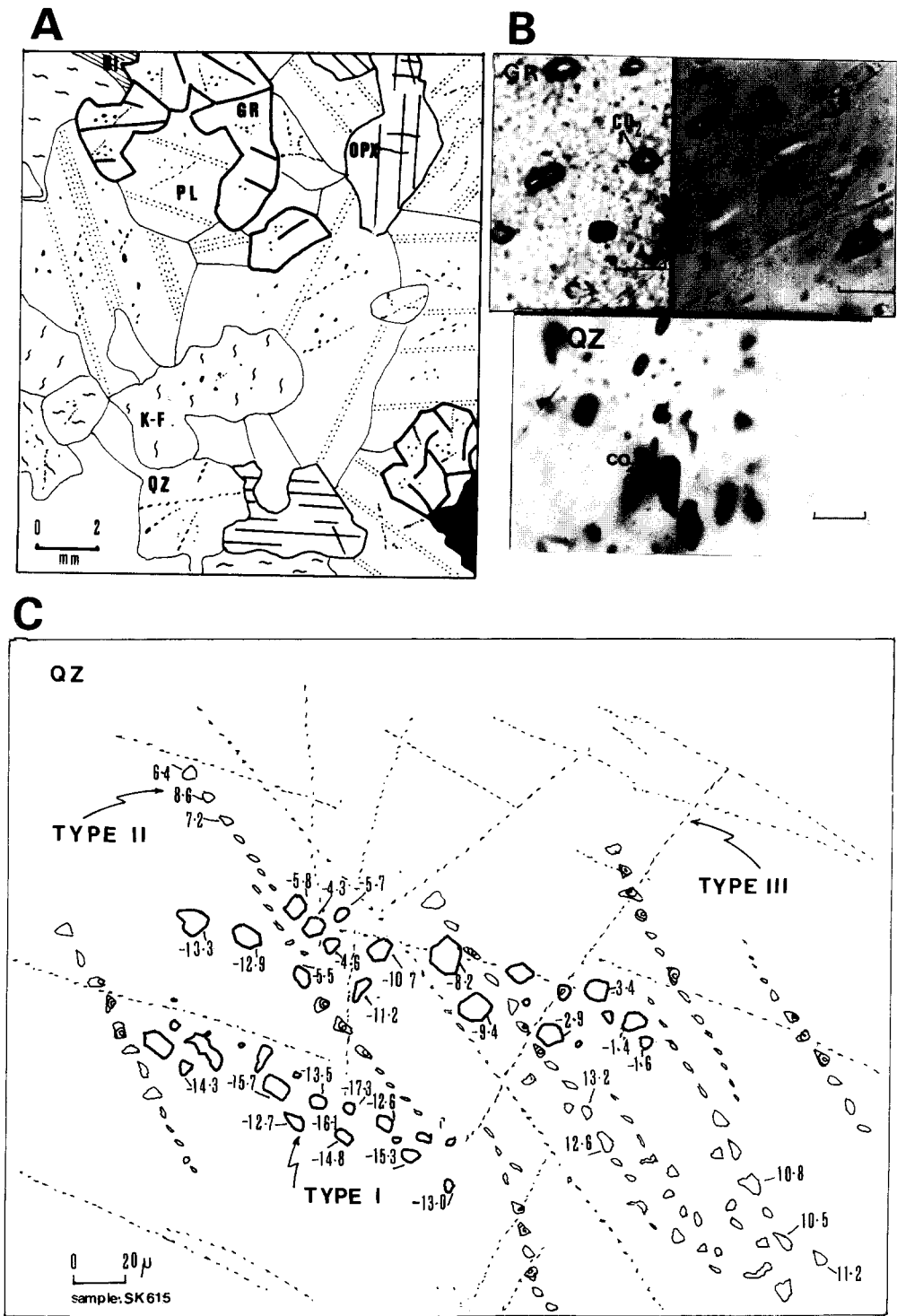
Fig. 4. (A) Sketch showing charnockite mineral assemblage and fluid inclusion distribution. (B) Photomicrographs of carbonic inclusions in garnet (*GR*), K-feldspar (*K-F*) and quartz (*Qz*). (C) Distribution pattern of different inclusion types in quartz. The numerical values indicate CO_2 homogenization temperatures. See text for discussion.
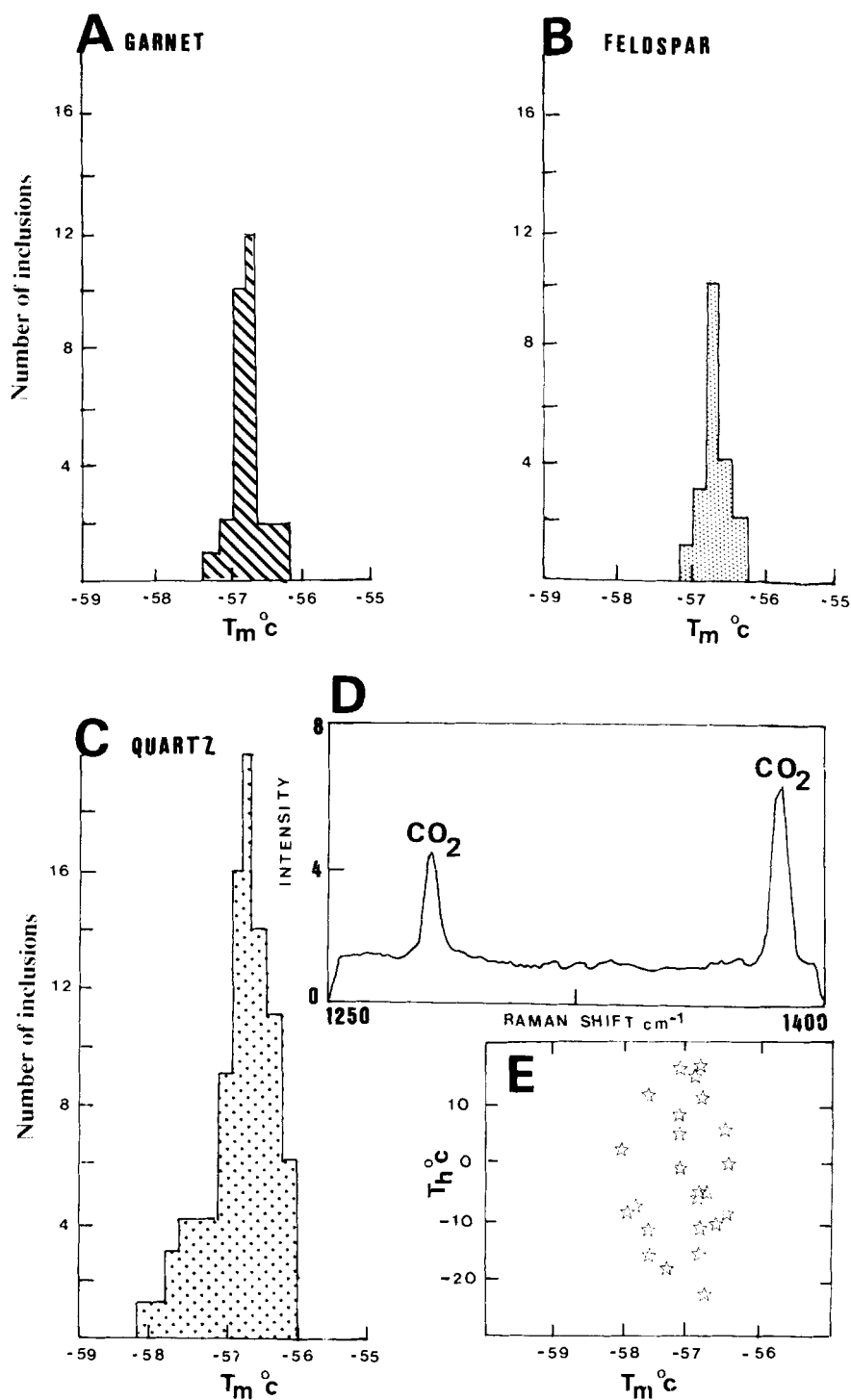
Fig. 5. (A), (B) and (C) Histograms of CO_2 melting temperatures in garnet, feldspar and quartz. (D) Raman spectra of a representative inclusion showing CO_2 peaks. (E) Plots of homogenization vs. melting temperature of representative carbonic inclusions. See text for details.

type-I inclusions in the different minerals from the three localities are compiled in the form of histograms in Fig. 6. In all cases, inclusions in garnet show lowest homogenization temperature, with T_h garnet < feldspar < quartz. Coexisting type-I and II along late trials in quartz yield the highest T_h values (open histograms in Fig. 6). The most important observation is the distinct shift in T_h towards lower values from north to south in LHB. The lowest homogenization temperatures in each locality, when translated into densities (cf. Touret and Bottinga, 1979), show lowest value for Ongul (0.98 g/cm³), intermediate for Skallen (1.05) and highest for Botnneset (1.1).

Isotopic composition

Pre-cleaned quartz grains from two charnockites (samples 615 and 1502) were thermally decrepi-

tated in a vacuum-backed glass line to extract the trapped fluids. Acid treatment of the grains did not yield any effervescence, precluding the possibility of carbonate contamination. Gases evolved below 400°C were discarded, as contribution from surficial organic contaminants is likely (cf. Santosh et al., 1991b). Visual decrepitation in doubly polished wafers using a microscope and heating-stage attachment revealed that the type-I carbonic inclusions in these samples explode in the range of 400–800°C. Hence, CO_2 liberated in the 400–800°C range was collected from the grains and its carbon isotopic composition was analysed using a mass spectrometer. $\delta^{13}C$ values of -5.2 and $-6.4‰$ were obtained for the Skallen and Botnneset charnockites, respectively.

Discussion

The LHB region provides an unbroken succession from amphibolite-facies rocks in the north to granulite-facies rocks in the south, and a continuous increase in pressure (~ 3 kbars) is consistant with an oblique section of the deep crust. The regional gneiss–granulite transition is indicated by the breakdown of garnet and biotite in the paragneisses and growth of orthopyroxene in the charnockite. Where the precursor is an orthogneiss, consumption of hornblende, and sometimes clinopyroxene, is also observed. Pre-metamorphic baking by shallow intrusives and subsequent vapor-absent metamorphism, as demonstrated for the contact-aureole granulites of Adirondacks in N. America (Lamb and Valley, 1984) may not explain the granulite formation in LHB, where the geologic setting is more similar to that of the amphibolite–granulite transition in southern India. It is also unlikely that the LHB charnockites represent the anhydrous residue after removal of a partial melt. Neither large ion lithophile element depletion, nor field evidence for significant melt segregation is observed (Yoshida, 1978).

The highest density isochores (calculated following the CO_2 equation of state of Touret and Bottinga, 1979) for carbonic inclusions in charnockites from each terrain in LHB transect the $P-T$ windows derived from phase equilibria (Fig. 7). This is a necessary, although by itself not conclusive, condition for fluid entrapment occurring during meta-
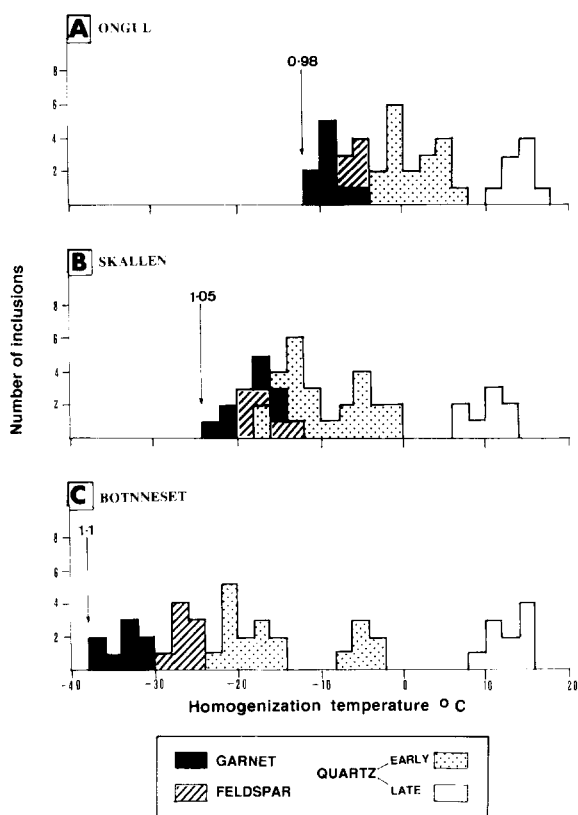

Fig. 6. Homogenization temperatures of carbonic inclusions in garnet, feldspar and quartz from the three localities. The values with arrows denote the maximum density recorded in each case.
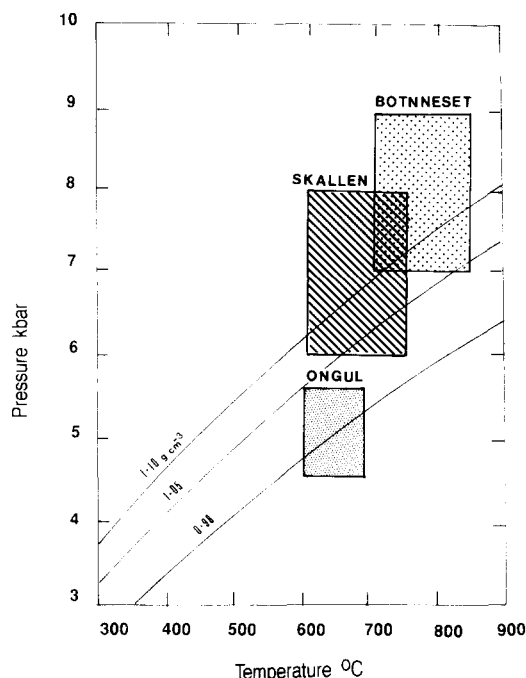
Fig. 7. $P-T$ diagram showing representative CO_2 isochores for each locality (numerical values indicate corresponding densities) and the $P-T$ regime from mineral phase equilibria (shaded box). The data show a concomitant increase in density with pressure and temperature, suggesting synmetamorphic entrapment of CO_2 in Lützow-Holm Bay charnockites.

morphism. Conversely, the observation of contrasting fluid densities from three localities argues against a large scale post-metamorphic fluid influx, which would result in either uniform densities or random fluid densities unrelated to mineral $P-T$ gradients, as proposed by Lamb et al. (1987) for the Adirondack granulites.

We have attempted a detailed homogenization study of adjacent inclusions in one sample (specimen 615 from Skallen). The type-I inclusions record a range of T_h values, between -1.4 to $-13.3°C$, along a single array, suggesting a range of densities (Fig. 4c). This reflects the change in the inclusion volume after entrapment, as borne out by experimental studies (Sterner and Bodnar, 1989). Where the rocks have undergone a rapid and virtually isothermal uplift history, as in the present case (see later section), the inclusions are prone to density modifications (cf. Santosh et al., 1991a). The late trials of carbonic and mixed carbonic-aqueous inclusions define distinctly lower isochores in $P-T$

space, unrelated to the peak metamorphic conditions. In most cases, they define a narrow range of homogenization temperatures, especially those along a single array, suggesting that they were entrapped when the dP/dT path was more shallow, hence subjected to no major post-entrapment volume changes. The transition from CO_2-H_2O to CO_2 dominated fluids while passing from gneiss to granulite, and the concomitant increase in CO_2 densities with metamorphic grade observed in LHB area are comparable with the similar features described from southern Norway (Touret, 1971) and southern India (Hansen et al., 1984). Further evidence for synmetamorphic fluid entrapment is provided by the systematic density variations of fluids in garnet, feldspar and quartz (Fig. 8). In each locality, garnets captured the highest density fluids, followed by feldspar and finally quartz, which entrapped even the late-stage fluids. Such millimeter-scale density variations among different minerals, and within single arrays in quartz, preclude post-metamorphic fluid influx and strongly suggest a relationship between entrapment and tectonics.

Two types of uplift mechanisms are commonly recognized for granulite terrains (Fig. 9, inset); isothermal uplift (ITU) and isobaric cooling (IBC). Harley (1989) illustrated the distinct mineral re-
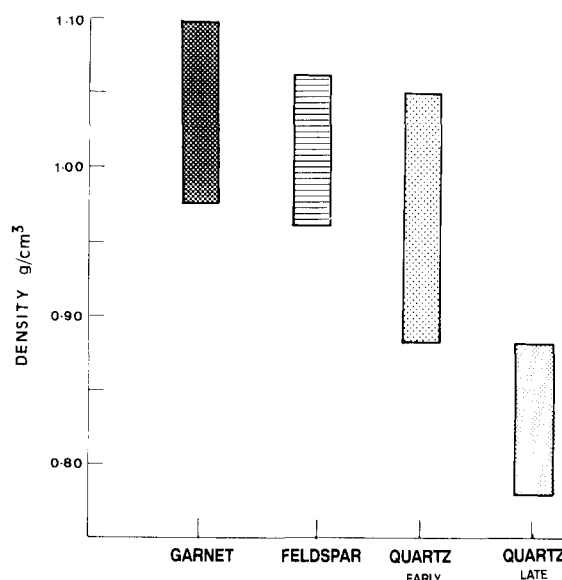

Fig. 8. CO_2 density gradients within adjacent minerals. The decrease in density from garnet through feldspar to quartz in these rocks suggest fluid entrapment under an isothermal uplift regime.
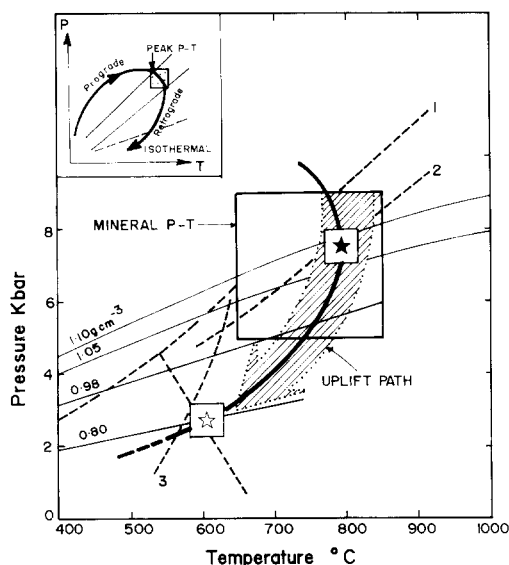
Fig. 9. Combined mineral reaction, $P-T$ domain, fluid inclusion and geochronologic data for the Lützow-Holm Bay region, converging to indicate a near-isothermal uplift history (the trace of which is shown as thick line enclosed within shaded arrow). Broken lines: 1 – alumino-silicate polymorphs and triple point (after Salje, 1986); 2 – the charnockite forming reaction, 1 grossular + 2 pyrope + 3 quartz = 3 enstatite + 3 anorthite discussed in the text; 3 – muscovite + quartz = aluminosilicate + potash feldspar + vapour (Kerrick, 1972), correlated with retrogression accompanying granite and pegmatite emplacement (c. 500 Ma, box with open star; after Motoyoshi et al., 1989). Box with filled star represents the main charnockite-forming metamorphic event (> 700 Ma) in Lützow-Holm Bay (Shibata et al., 1986). Thin lines are CO_2 isochores, with corresponding densities. The inset schematically shows the mineralogic $P-T$ box and fluid inclusion isochores, with the prograde, peak and retrograde trace of the clockwise $P-T$ path followed by the LHB rocks.

actions and textural associations in high-grade terrains derived by ITU and IBC. Touret (1987) and Touret and Hartel (1990) described the fluid evolution characteristics resulting from two uplift paths. Several of the reaction textures documented in this study conform with an initial isothermal decompression along an ITU path (cf. Harley, 1989). The development of orthopyroxene–plagioclase symplectites around relict clinopyroxene (reaction 2) and the garnet-consuming reaction for the gneiss–granulite transition (reaction 1) dictate that the charnockite assemblage equilibrated under a decompression regime. In the aluminous granulites (khondalites), decompression is recorded by spinel replacing sillimanite (reaction 5) and melt segre-

gations rich in K-feldspar and garnet derived by reaction 4.

Data from solid and fluid phases, together with geochronologic information from LHB are compiled in Fig. 9. The high density isochores for the three localities ($0.98-1.10\,g/cm^3$) pass through the $P-T$ region defined by mineral phase equilibria. Quartz-bound late carbonic and mixed-carbonic aqueous inclusions define a distinctly lower isochore ($0.80\,g/cm^3$). The Rb–Sr whole-rock isochron (closed star, 700–1000 Ma ascribed for granulite metamorphism) and Rb–Sr mineral + whole rock isochron and K–Ar biotite age (open star, 500 Ma, subsequent amphibolite facies conditions cf. Yoshida, 1978) are also shown. An ITU-type post-metamorphic trajectory is indicated. The clock-wise nature of the prograde path (inset in Fig. 9) is also supported by the occurrence of relict kyanite.

Fluid source

Solid and fluid phase data presented in this paper argue in favour of fluid-rich metamorphism in LHB. Models for CO_2 sources have been broadly classified into internal and external. CO_2 can be internally generated by the rupturing of preexisting mixed carbonic-aqueous inclusions (Raith et al., 1989), oxidation of biogenic graphite (Hansen et al., 1987) and selective extraction of H_2O or diffusion of H_2 through various mechanisms (Hollister, 1990, and references therein). Proximal external sources include decarbonation of interlayered impure carbonate horizons (Glassley, 1983). A variety of processes operating in the deep crust and upper mantle release potential fluxes of CO_2. Among these are subcrustal passage of dry magmas or exsolution from mafic magmas (Touret, 1986; Frost et al., 1989), metacarbonates sinking into underplated basaltic magmas (Wickham, 1988), degassing of attenuated continental lithosphere, and bleeding of alkaline magmas (Newton, 1990). It has been argued that in a generally fluid-absent lower crust, episodic bursts of fluid activity can occur related to compressional or extensional tectonics and associated diverse magmatic and metamorphic phenomena (Newton, 1990). Touret (1989) suggested that fluid-rich and fluid-free domains exist side by side in the lower crust, at scales yet unknown.

A detailed evaluation of the possible fluid source

for LHB metamorphism is beyond the scope of the present discussion, although some preliminary considerations can be made. None of the internal CO_2 generation mechanisms appear suitable for the LHB charnockites. Graphite is generally absent in these charnockites. Although Lamb and Valley (1984) raised the absence of graphite in many granulites as a potential argument against large-scale external influx of CO_2, it has been shown that many granulites equilibrated in T-f_{O_2} conditions outside the graphite stability limit (cf. Touret, 1989; Newton, 1990), including the LHB, as indicated by the oxide mineral assemblages. CO_2 influx in such cases will not be borne out by the precipitation of graphite. Internal CO_2 generation by strain-induced leakage of H_2O from pre-existing mixed carbonic-aqueous inclusions (Hollister, 1990) is unlikely to cause the observed density variations of fluids.

An external source of CO_2 is favoured by this study. The $\delta^{13}C$ composition of CO_2 extracted from inclusions in two charnockite samples lie in the range of ca. -5 to $-6‰$, which is comparable with a similar range obtained from a larger data-base from southern Indian charnockites (Jackson, 1990), where a sub-lithospheric source has been proposed. The occurrence of calcareous rocks in LHB, especially marble horizons in Skallen which could have acted as local sources of CO_2 through decarbonation reactions may be assessed by stable isotopic investigations. Yoshida (1978) has described graphite-rich charnockites overlying marble beds from a locality in Skallen, which could indicate copious infiltration of CO_2 by decarbonation, and resultant graphite precipitation from fluids. Hence the possibility of local CO_2 sources, at least on a limited scale, is not excluded.

The tectonic environment of Antarctica within Gondwanaland during the ca. 1000–600 Ma period of charnockite formation may be related to the transfer mechanism of fluids. Charnockites of different ages ranging from 2.6 Ga at the southern margin of Karnataka craton in South India, through 1 Ga in Antarctica to 0.5 Ga in Sri Lanka and the Kerala Khondalite Belt in southern India suggest that multiple charnockite formation events occurred in this region of the Gondwana. The 0.5 to 1.0 Ga period coincides with large scale distensional regime and opening up of megashears/faults of continental scale. Alkalic–subalkalic granite and syenite plutons, and K-basalts of Pan-African age

are distributed throughout the reactivated crustal fragments (cf. Kröner, 1980; Santosh and Drury, 1988; Santosh et al., 1989). Such a tectonic scenario is consistent with the derivation of CO_2-rich volatiles through the degassing of an attenuating continental lithosphere, and their transfer through magmatic conduits. The preliminary carbon isotope results for the LHB rocks, and the larger dataset for the southern Indian granulites are in accord with a sub-lithosperic source for CO_2.

References

Burton, K.W. and O'Nions, R.K., 1990. The timescale and mechanism of granulite formation at Kurunegala, Sri Lanka. Contrib. Mineral. Petrol., 106: 66–89.

Chacko, T., Kumar, G.R.R. and Newton, R.C., 1987. metamorphic P–T conditions of the Kerala (S. India) Khondalite belt, a granulite facies supracrustal terrain. J. Geol., 95: 343–358.

De Maesschalck, A.A., Touret, J.L.R., Maaskant, P. and Dahanayake, K., 1991. Petrology and fluid inclusions in garnetiferous gneisses and charnockites from Weddagala (Ratnapura district, Sri Lanka). J. Geol., 99: 443–456.

Ellis, D.J. and Green, D.H., 1979. An experimental study of the effect of Ca upon garnet–clinopyroxene Fe–Mg exchange equilibria. Contrib. Mineral. Petrol., 71: 13–22.

Ferry, J.M., 1986. Reaction progress: a monitor of fluid-rock interactions during metamorphic and hydrothermal events. In: J.V. Walther and B.J. Wood (Editors), Fluid–Rock Interactions during Metamorphism. Springer-Verlag, Berlin, pp. 60–88.

Ferry, J.M. and Spear, F.S., 1978. Experimental calibration of the partitioning of Fe and Mg between biotite and garnet. Contrib. Mineral. Petrol., 66: 113–117.

Frost, B.R. and Chacko, T., 1989. The granulite uncertainty

principle: limitations on thermobarometry in granulits. J. Geol., 97: 433–450.

Frost, B.R., Frost, C.D. and Touret, J.L.R., 1989. Magmas as a source of heat and fluids in granulite metamorphism. In: D. Bridgwater (Editor), Fluid Movements-Element Transport and the Composition of the Deep Crust. Kluwer, Dordrecht, pp. 1–18.

Ganguly, J. and Saxena, S.K., 1984. Mixing properties of aluminosilicate garnets: constraints from natural and experimental data, and applications to geothermobarometry. Am. Mineral., 69: 88–97.

Glassley, W.E., 1983. Deep crustal carbonates as CO_2 fluid sources: evidence from metasomatic reaction zones. Contrib. Mineral. Petrol., 84: 15–24.

Grew, E.S., 1980. Precambrian basement at Molodezhnaya station, East Antarctica. Bull. Geol. Soc. Am., 89: 801–813.

Hansen, E.C., Newton, R.C. and Janardhan, A.S., 1984. Pressures, temperatures and metamorphic fluids across an unbroken amphibolite facies to granulite facies transition in southern Karnataka, India. In: A. Kröner, A. Goodwin and G.N. Hanson (Editors), Archaean Geochemistry, the Origin and Evolution of the Archaean Continental Crust. Springer, Berlin, pp. 161–181.

Hansen, E.C., Janardhan, A.S., Newton, R.C., Prame, W.K.B.N. and Kumar, G.R.R., 1987. Arrested charnockite formation in southern India and Sri Lanka. Contrib. Mineral. Petrol., 96: 225–244.

Harley, S.L., 1983. Regional geobaromemtry-geothermometry and metamorphic evolution of Enderby Land, Antarctica. In: R.L. Oliver, P.R. James and J.B. Jago (Editors), Antarctic Geoscience. University Press, Cambridge, pp. 25–30.

Harley, S.L., 1989. The origins of granulites: a metamorphic perspective. Geol. Mag., 126: 214–247.

Harley, S.L. and Green, D.H., 1982. Garnet-orthopyroxene barometry for granulites and peridotites. Nature, 300: 697–701.

Hiroi, Y., Shiraishi, K., Nakai, Y., Kano, T. and Yoshikura, S., 1983. Geology and petrology of Prince Olav Coast, East ANtarctica. In: R.L. Oliver, P.R. James and J.B. Jan (Editors) Antarctic Earth Science. Australian Academy of Science, Canberra, pp. 32–35.

Hodges, K.V. and Spear, F.S., 1982. Geothermometry, geobarometry and the Al_2SiO_5 triple point at Mt. Moosilauke, New Hampshire. Am. Mineral., 67: 1118–1135.

Hollister, L.S., 1990. Enrichment of CO_2 in fluid inclusions in quartz by removal of H_2O during crystal-plastic deformation. J. Struct. Geol., 12: 895–901.

Jackson, D.H., 1990. Charnockite formation in southern India. Ph.D. Thesis, Open University, U.K., 223 pp, (unpublished).

Kerrick, D.M., 1972. Experimental determination of muscovite + quartz stability with $P_{H_2O} > P_{TOTAL}$. Am. J. Sci., 272: 946–958.

Klatt, E., Hoernes, S. and Raith, M., 1988. Characterisation of fluids involved in the gneiss-charnockite transformation in southern Kerala (India). J. Geol. Soc. India, 31: 57–59.

Koziol, A.M. and Newton, R.C., 1988. Redetermination of

anorthite breakdown reaction and improvement of the plagioclase-garnet-Al_2SiO_5-quartz geobarometer. Am. Mineral., 73: 216–223.

Kröner, A., 1980. Pan-African crustal evolution. Episode, 2: 3–8.

Lamb, W.M. and Valley, J.W., 1984. Metamorphism of reduced granulites in low-CO_2 vapour-free environment. Nature, 312: 56–58.

Lamb, W.M., Valley, J.W. and Brown, P.E., 1987. Post-metamorphic CO_2-rich fluid inclusions in granulites. Contrib. Mineral. Petrol., 96: 485–495.

Motoyoshi, Y., Matsubara, S. and Matsueda, H., 1989. *P–T* evolution of the granulite-facies rocks of the Lützow-Holm Bay region, East Antarctica. In: J.S. Daly, R.A. Cliff and B.W.D. Yardley (Editors), Evolution of Metamorphic Belts. Geol. Soc. Spec. Publ., 43: 325–329.

Newton, R.C., 1990. Fluids and shear zones in the deep crust. Tectonophysics, 182: 21–37.

Newton, R.C. and Haselton, H.J., 1981. Thermodynamics of the garnetplagioclase-Al_2SiO_5-quartz geobarometer. In: R.C. Newton, A. Navrotsky and B.J. Wood (Editors), Thermodynamics of Minerals and Melts. Springer-Verlag, New York, pp. 125–145.

Newton, R.C., Smith, J.V. and Windley, B.F., 1980. Carbonic metamorphism, granulites and crustal growth. Nature, 288: 45–50.

Perchuk, L.L. and Lavrent'eva, I.V., 1983. Experimental investigation of exchange equilibria in the system cordierite–garnet–biotite. In: S.K. Saxena (Editor), Kinetics and Equilibrium in Mineral Reactions. Springer-Verlag, New York, pp. 199–239.

Perkins, D. and Newton, R.C., 1981. Charnockite geobarometers based on coexisting garnet-pyroxene-plagioclase-quartz. Nature, 292: 144–146.

Powell, R., 1978. The thermodynamics of pyroxene geotherms. Philos. Trans. R. Soc. London, Ser. A, 288: 457–469.

Powell, R., 1985. Regression diagnostics and robust regression in geothermometer/geobarometer calibration: the garnet–clinopyroxene geothermometer revisited. J. Metamorph. Geol., 3: 231–243.

Raith, M., Hoernes, S., Klatt, E. and Stahle, H.J., 1989. Contrasting mechanisms of charnockite formation in the amphibolite to granulite grade transition zones of southern India. In; D. Bridgwater (Editor), Fluid Movements-Element Transport and the Composition of the Deep Crust. Kluwer. Dordrecht, pp. 29–38.

Salje, E., 1986. Heat capacities and entropies of andalusite and sillimanite: the influence of fibrolitization on the phase diagram of the Al_2SiO_5 polymorphs. Am. Mineral., 71: 1366–1371.

Sandiford, M. and Powell, R., 1986. Pyroxene exsolution in granulites from Fyfe Hills, Enderby Land, Antarctica: evidence for 1000°C metamorphic temperatures in Archaean continental crust. Am. Mineral., 71: 946–954.

Santosh, M., 1986. Carbonic metamorphism of charnockites in the southwestern Indian Shield: a fluid inclusion study. Lithos, 19: 1–10.

Santosh, M., 1991. Role of CO_2 in granulite petrogenesis: evi-

dence from fluid inclusions. J. Geosci. Osaka City Univ.,
34: 1–56.

Santosh, M. and Drury, S.A., 1988. Alkali granites with Pan-
African affinities from Kerala, south India. J. Geol., 96:
616–622.

Santosh, M., Iyer, S.S., Vasconcellos, M.B.A. and Enzweiler,
J., 1989.

Late Precambrian alkaline plutons in southwest India: geo-
chronologic and rare-earth element constraints on Pan-
African magmatism. Lithos, 24: 65–79.

Santosh, M., Harris, N.B.W., Jackson, D.H., Mattey, D.P.,
1990. Dehydration and incipient charnockite formation:
a phase equilibria and fluid inclusion study from South
India. J. Geol., 98: 915–926.

Santosh, M., Jackson, D.H., Harris, N.B.W. and Mattey, D.P.,
1991a. Carbonic fluid inclusions in south Indian granu-
lites: evidence for entrapment during charnockite forma-
tion. Contrib. Mineral. Petrol., 108: 318–330.

Santosh, M., Yoshida, M. and Nanda-Kumar, V., 1991b. Fluid
characteristics across a gneiss–incipient charnockite re-
action front in Sri Lanka: implications for granulite for-
mation in Gondwanaian deep crust. J. Mineral. Petrol.
Econ. Geol., 86: 27–44.

Saxena, S.K., 1979. Garnet–clinopyroxene geothermometer.
Contrib. Mineral. Petrol., 70: 229–235.

Sen, S.K. and Bhattacharya, A., 1984. An orthopyroxene–
garnet thermometer and its application to the Madras
charnockites. Contrib. Mineral. Petrol., 88: 64–71.

Schreurs, J., 1984. Prograde metamorphism of metapelites,
garnet–biotite thermometry and prograde changes of bio-
tite chemistry in high-grade rocks of the West Uusimaa,
southwestern Finland. Lithos, 18: 69–80.

Sheraton, J.W., Offe, L.A., Tingey, R.J. and Ellis, D.J., 1980.
Enderby Land, Antarctica- an unusual Precambrian high
grade metamorphic terrain. J. Geol. Soc. Aust., 27: 305–
317.

Shibata, K., Yanai, K. and Shiraishi, K., 1985. Rb–Sr mineral
isochron ages of metamorphic rocks around Syowa Sta-
tion and the Yamato Mountains, East Antarctica. Mem.
Natl. Inst. Polar Res., Spec. Iss., 37: 164–171.

Shiraishi, K. and Kagami, H., 1989. Preliminary geochron-
ological study of granulites from the Sor Rondane moun-
tains, East Antarctica – a comparison of Rb–Sr and Sm–
Nd ages. Proc. Symp. Antarct. Geosci., Natl. Inst. Polar
Res., 3: 152 (Abstr.).

Sterner, S.M. and Bodnar, R.J., 1989. Synthetic fluid inclu-
sions-VII. Re-equilibration of fluid inclusions in quartz
during laboratory-simulated metamorphic burial and
uplift. J. Metamorph. Geol., 7: 243–260.

Thompson, A.B., 1976. Mineral reactions in pelitic rocks:
calculation of some $P-T-X$ (Fe–Mg) phase relations. Am.
J. Sci., 276: 425–454.

Touret, J.L.R., 1971. La facies granulite en Norwege meri-
dionale. II. Les inclusions fluides. Lithos, 4: 423–435.

Touret, J.L.R., 1986. Fluid inclusions in rocks from the lower
continental crust. In: J.B. Dawson, D.A. Carswell, J. Hall
and K.H. Wedepohl (Editors), The Nature of the Lower
Continental Crust. Geol. Soc. Spec. Publ., 24: 161–172.

Touret, J.L.R., 1987. Fluid inclusions and pressure-tempera-
ture estimates in deep-seated rocks. In: H.C. Helgeson
(Editor), Chemical Transport in Metasomatic Processes.
NATO ASI Series, C-218, Reidel, Dordrecht, pp. 91–121.

Touret, J.L.R., 1989. Fluid control in the lower crust. Nied-
ersachs. A.K. Wiss., Heft 1 "Festeinfluide", pp. 57–68.

Touret, J.L.R. and Bottinga, Y., 1979. Equation d'etat pur le
CO_2: application aux inclusions carboniques. Bull. Min-
eral., 102: 635–649.

Touret, J.L.R. and Hansteen, T.H., 1988. Geothermometry
and fluid inclusions in a rock from the Doddabeta char-
nockite complex, southwest India. Rend. Soc. Ital. Min-
eral. Petrol., 43: 65–82.

Touret, J.L.R. and Hartel, T.D.H., 1990. Synmetamorphic
fluid inclusions in granulites. In: D. Vielzeuf and Ph. Vi-
dal (Editors), Granulites and Crustal Evolution. Kluwer,
Dordrecht, pp. 397–417.

Yoshida, M., 1978. Tectonics and petrology of charnockites
around Lützow-Holmbukta, East Antarctica. J. Geosci.
Osaka City Univ., 21: 65–152.

Yoshida, M., 1979. Metamorphic conditions of the polyme-
tamorphic Lützow-Holmbuka region, East Antarctica. J.
Geosci. Osaka City Univ., 22: 97–140.

Yoshida, M. and Santosh, M., 1987. Charnockite "in the
breaking" and "making" in Kerala, South India: tectonic
and microstructural evidences. J. Geosci. Osaka City
Univ., 30: 23–49.

Yoshida, M., Suzuki, M., Shirahata, H., Kojima, H. and Ki-
zaki, K., 1983. A review of the tectonic and metamorphic
history of the Lützow-Holm Bay region, East Antarctica.
In: R.L. Oliver, P.R. James and J.B. Jago (Editors), Ant-
arctic Earth Science. Australian Acad. Sci., Canberra, pp.
44–47.

Waters, D.J., 1988. Partial melting and the formation of
granulite facies assemblages in Namaqualand, South Af-
rica. J. Metamorph. Geol., 6: 387–404.

Wickham, S.M., 1988. Underplating, anatexis, and assimila-
tion of metacarbonate: a possible source for large CO_2
fluxes in the deep crust. J. Geol. Soc. India, 31: 162
(Abstr.).