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Gondwana Research 13 (2008) 30–44
www.elsevier.com/locate/gr

GR Focus

On charnockites

B. Ronald Frost *, Carol D. Frost

Department of Geology and Geophysics, University of Wyoming, Laramie, WY 82071, USA

Received 4 June 2007; received in revised form 20 July 2007; accepted 24 July 2007
Available online 7 August 2007

Abstract

Charnockitic rocks form extensive orthogneiss plutons in many granulite terranes and are less commonly found in unmetamorphosed plutons, which have formed in various tectonic regimes. Geochemically, clearly igneous charnockites cover nearly the whole range of granite chemistry, from magnesian to ferroan and from calcic to alkalic. Pyroxenes from unmetamorphosed charnockitic rocks have compositions ranging from magnesian to very iron-rich and record temperatures as high as 1000 °C. Oxygen fugacities for these plutons range from below FMQ to Δ log FMQ$>+2$, values that cover nearly the whole range found in other granitic rocks.

This range in bulk chemistry and intensive parameters is a reflection of the many mechanisms that produce charnockites. They may form in rifting environments, where they are ferroan, alkali-calcic to alkalic and metaluminous. Many of these ferroan charnockites are isotopically primitive, suggesting that they have been derived largely or entirely from differentiation or melting of tholeiitic melts. Charnockites are also found in deeply eroded arcs, where they are magnesian, calcic to calc-alkalic and metaluminous. Some charnockitic magmas may form by crustal melting or have incorporated a large component of crustal melt; these plutons tend to be weakly to moderately peraluminous and to have intermediate values of FeO/(FeO+MgO).

In this paper we suggest several changes to charnockite terminology. First, we suggest that the term "charnockite" should be a general term that is applied only to Opx (or Fay)-bearing igneous rocks or to Opx-bearing granitic orthogneisses in granulite terranes. The names for the rocks in the "charnockite series" (such as "opdalite" or "enderbite") are not necessary (Opx-granodiorite or Opx-tonalite would serve instead) and should not be used. Finally, the word "charnockite" should not be a synonym for "granulite" and terms such as "mafic charnockite", "charnockitization", "incipient charnockite" and "C-type granite" should be banned from the petrologic lexicon.

Keywords: Charnockite; Granite; Pyroxene thermometry; Oxygen fugacity; Nd-isotopes; Sr-isotopes; Granulite metamorphism

Contents

* Corresponding author. Tel.: +1 307 766 4290; fax: +1 307 766 6679.
E-mail address: rfrost@uwyo.edu (B.R. Frost).

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doi:10.1016/j.gr.2007.07.006

1. Introduction

Charnockites, Opx-bearing (or more rarely fayalite-bearing) granitic rocks, make up only a tiny fraction of the granitic rocks worldwide. Despite their comparative rarity, over the past twenty-five years these rocks have been the subject of a significant number of papers. This is probably because charnockites commonly occur in high-pressure regimes and, as such they provide us with a window into the processes that occur in the deep crust or deep within granitic plutons (Janardhan et al., 1982; Frost et al., 2000). In addition, because charnockitic rocks contain Opx or fayalite and commonly Cpx, they have assemblages that are appropriate for the calculation of intensive parameters, such as temperature, pressure, and oxygen fugacity (Frost et al., 1988; Lindsley and Frost, 1992; Frost and Lindsley, 1992). The great interest in charnockitic rocks has, unfortunately, led to considerable variation in the use of the term “charnockite” and the geologic significance one can apply to it. This paper is a summary of what we know about charnockites and provides suggestions on how the term should be used.

2. The charnockite rock series

The name “charnockite” was proposed by Holland (1900) to describe hypersthene-bearing granitic rocks of the Madras area. As noted by Howie (1955), it wasn’t long before the term became controversial. Washington (1916) introduced the term “basic charnockites” and by 1942, Gevers and Dunne were condemning the use of the term for anything but pyroxene-bearing granitic rocks (Gevers and Dunne, 1942). Howie (1955) argued that the Madras charnockites represent an Opx-bearing igneous suite, but he admitted that it was impossible to determine whether the pyroxene in the charnockitic rocks crystallized directly from a melt or formed as the result of granulite metamorphism. Pichamuthu (1960) proposed that at least some of the charnockite terrane of southern India formed due to CO_2 metasomatism. This leads to a spate of papers (*e.g.* Janardhan et al., 1982; Newton, 1989, 1992 — see summary by Santosh and Omori, 2008-this issue) which implied that most, if not all of the charnockites of South India are metamorphic rocks that were dehydrated by interaction with CO_2 which was probably liberated by underplated basalts or from metamorphosed carbonates.

Part of the confusion about charnockites is caused by the fact that the term “charnockite” refers both to a series of igneous rocks and a mineral assemblage that is similar to a metamorphic facies. Charnockites are characteristic of granulite terranes, just as the highest-grade portions of amphibolite facies are often associated with biotite or hornblende granites. As a result, for many workers the word “charnockite” has become synonymous with “granulite”, producing a wealth of terminological imprecision.

Over time a suite of Opx-bearing granitoids have been recognized that have been called the charnockite series (Le Maitre, 1989) (Fig. 1). Most of the terms for individual rock types belonging to this series, including enderbite (Opx-bearing tonalite), opdalite (Opx-bearing granodiorite), mangerite (Opx-bearing monzonite) and jotunite (Opx-bearing monzodiorite), are obscure and not widely used. The terminological monstrosity charno-enderbite, a term synonymous with opdalite, has recently crept into the literature. We are not aware of terms for Opx-bearing quartz diorite. Many authors tend to apply the term “charnockite” to both Opx-bearing granites and granodiorites, obviously implying without stating directly that

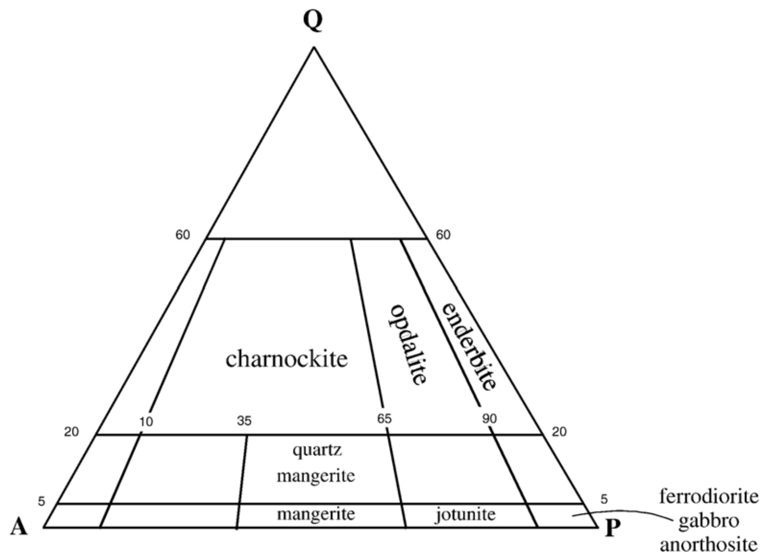

Fig. 1. QAP diagram showing the names of rocks in the charnockite series of igneous rocks.

they are talking about charnockite *sensu lato*, rather than *senso stricto*. Many authors also consider fayalite-granite to be part of the charnockite series because fayalite + quartz is chemically equivalent to Fe-rich Opx.

3. Geochemistry

Geochemical characteristics of charnockitic rock suites are given in Figs. 2–5, using the classification scheme for granitic rocks established by Frost et al. (2001a). These figures are based upon a compilation of twenty charnockite plutons from the literature that range in age from Archean to Cretaceous (Table 1). In selecting these data we considered only those charnockites that were clearly igneous (even though many of them have been metamorphosed) and in which the authors had not recognized any metasomatic alteration. Where possible, for each pluton, we included in the plots only those rocks that had the assemblage orthopyroxene + quartz (or fayalite + quartz). Included in this database are two unmetamorphosed plutons, Ballachulish and Ironside Mountain, that are not usually considered charnockitic, but which do contain pyroxene-bearing units.

3.1. FeO/(FeO + MgO)

Charnockitic plutons cover a wide range in FeO/(FeO + MgO) from fairly magnesian to very iron-rich (Fig. 2a, b, c). Many charnockitic plutons, such as Bjerkreim (Duchesne and Wilmart, 1997), Sherman (Frost et al., 1999), and the Thor Range (Bucher and Frost, 2006) are ferroan. Others, such as Amaravathi (Ramaswamy and Murty, 1973), Desliens (Percival et al., 2003), Louis Lake (Frost et al., 2000) and Mawson (Young et al., 1997) are highly magnesian. A third population of intrusions, including Ardery (Kilpatrick and Ellis, 1992), Kabbaldurga (Battacharya and Sen, 2000), and Utsalik (Percival and Mortensen, 2002) bridge the ferroan–magnesian boundary (regardless of whether one uses the Miyashiro, 1974 or Frost et al., 2001a version of the boundary). It was these intermediate plutons that Kilpatrick and Ellis (1992) considered to be examples of charnockitic, or “C-type” magmas.

Several of the ferroan charnockitic plutons contain fayalite + quartz either in addition to or to the exclusion of low Ca pyroxene. Fig. 3 shows that for two major suites, Lofoten (Malm and Ormaasen, 1978) and Bjerkreim (Duchesne and Wilmart, 1997), the transition between low-Ca pyroxene-bearing and fayalite + quartz-bearing granitoids occurs at whole rock Fe-numbers around 0.90. The transition from Opx-bearing to Fay-bearing takes place at the same Fe-values in the Sherman batholith (Frost et al., 1999), the analyses of which were not plotted in Fig. 3 because, unlike Lofoten and Bjerkreim, ferrous and ferric iron were not distinguished in the analyses of the Sherman. That the low Ca pyroxene to fayalite + quartz transition occurs at nearly the same bulk Fe-number for all three of these plutons suggests that these plutons were emplaced at nearly the same pressure. The transition would slide to higher Fe-numbers with increasing pressure. This is evident from samples of the Hopen charnockite (which is part of the Lofoten suite). After emplacement, the charnockite of Hopen underwent high-pressure metamorphism, which converted fayalite + quartz to orthopyroxene (Ormaasen, 1977). Ormaasen (1977) thus recognizes two types of charnockites in the Hopen. Charnockite I retains primary Opx, whereas in Charnockite II Opx forms pseudomorphs after fayalite.

3.2. Modified alkali lime index (MALI)

As with the Fe-number, the charnockitic plutons have a modified alkali lime index (MALI) that covers the whole range found in other granitic plutons (Fig. 4) (compare Frost et al., 2001a). Many charnockitic plutons, such as Ardery

(Kilpatrick and Ellis, 1992), Louis Lake (Frost et al., 2000) and Ustalik (Percival and Mortensen, 2002) form tight arrays similar to granitic plutons described by Frost et al. (2001a). Others, such as Dindigul (Suresha and Srikantappa, 2005), and Desliens (Percival et al., 2003) form clusters that range across one or more of the classifications. Because many of the charnockitic plutons that show these excursions have been metamorphosed, we interpret that these excursions either reflect the effect of previously unrecognized metasomatism or that the sampling involved more than one intrusion within a orthogneiss massif. The MALI number for our charnockite database tends to increase with Fe-number. The most magnesian plutons (such as Mawson) tend to be calcic or calc-alkalic whereas the ferroan ones (for example, Lofoten) tend to be alkalic or alkali-calcic.

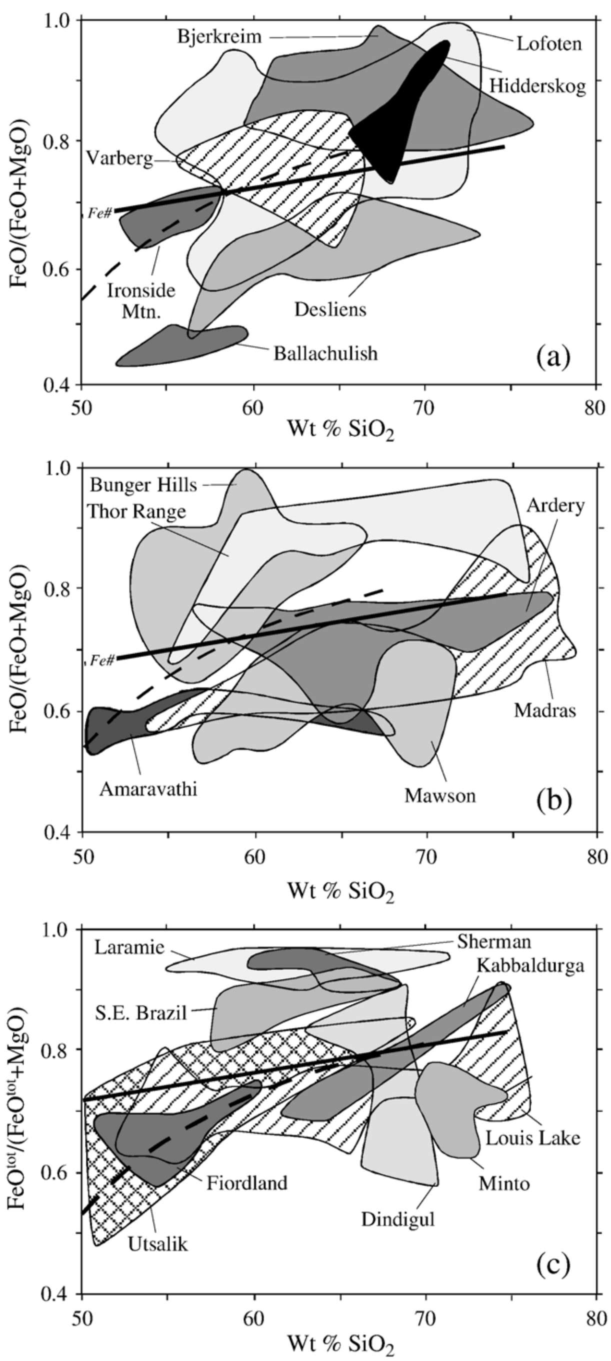

Fig. 2. Iron–magnesium variations in charnockitic plutons. a) Charnockitic plutons from North America and Europe for which both FeO and Fe_2O_3 have been analyzed. Data from Table 1: solid line = boundary after Frost et al. (2001a); dashed line = boundary after Miyashiro (1974).

3.3. Alumina saturation index (ASI)

Typical of other igneous suites, the ASI of charnokitic plutons increases with increasing silica (Fig. 5). Most charnockitic plutons remain metaluminous throughout their range in silica contents. Many of these tend to be the ferroan alkalic to alkali-calcic plutons such as Bjerkreim (Duchesne and Wilmart, 1997), Sherman (Frost et al., 1999), and the fayalite monzonites associated with the Laramie anorthosite complex (Kolker and Lindsley, 1989; Scoates et al., 1996; Anderson et al., 2003). Most of the charnockitic plutons that are peraluminous, such as Kabbaldurga (Battacharya and Sen, 2000) become so only at the most silica-rich compositions. One charnockitic pluton, Desliens (Percival et al., 2003), is distinctive in that it is peraluminous throughout its range of silica contents (apart from one outlier point). Some suites, such as Mawson (Young et al., 1997), Madras (Howie, 1955), and Dindigul (Suresha and Srikantappa, 2005) show an irregular distribution of points with some points lying well out of the range defined by most analyses in the suite. We suggest that the outlying points represent rocks that were subject to metasomatism or rocks that were not part of the original magmatic suite.

Some peraluminous samples contain garnet along with Opx, for example Amaravathi (Ramaswamy and Murty, 1973), Desliens (Percival et al., 2003), and Mawson (Young et al., 1997). This is probably a reflection of the reaction:

$$\underset{\text{orthopyroxene}}{3(\mathrm{Fe,Mg})\mathrm{SiO_3}} + \underset{\text{melt}}{\mathrm{Al_2O_3}} = \underset{\text{garnet}}{(\mathrm{Fe,Mg})_3\mathrm{Al_2Si_3O_{12}}} \quad (1)$$

wherein increasing Al_2O_3 in a melt will favor the formation of garnet over Opx. Some of the garnet in the Mawson intrusion may be primary (Young et al., 1997), but because all three of the charnockite complexes mentioned above have undergone high-pressure metamorphism, it is also possible that the garnet formed solely due to metamorphic reactions. Garnet is also present in the metaluminous Hopen charnockites (Ormaasen, 1977). The Hopen charnockites have been subjected to metamorphism at approximately 12 kbar and it is likely that garnet in these rocks has been stabilized by the breakdown of calcic plagioclase.

4. Intensive parameters

The quartz–pyroxene (or fayalite) — Fe–Ti oxide assemblage is ideal for determining intensive parameters for charnockites (Frost et al., 1988; Lindsley and Frost, 1992; Frost and Lindsley, 1992). The assemblage Opx–Cpx, which is common in many charnockites, is a well-calibrated thermometer. Inverted pigeonite is even a better thermometer because, unlike Opx and Cpx, the composition of the primary pigeonite is locked in by exsolution and is not prone to subsolidus ion-exchange re-equilibration. In addition, the breakdown of Opx (or pigeonite) to fayalite + quartz is strongly pressure dependent so that rocks with low Ca pyroxene + olivine + quartz are good barometers. Furthermore, the assemblage Opx (or Fay or Pig)–Q–Mag–Ilm, which is found in most charnockites is a QUIlF-type assemblage (Frost et al., 1988). This means the oxygen fugacity of this assemblage can be determined without having to analyze the Fe–Ti oxides, the composition of which in most plutonic rocks has re-equilibrated to low T (Frost and Lindsley, 1992).

4.1. Pyroxene thermometry in charnockites

To discuss pyroxene thermometry in charnockites we have chosen five plutons that show the complete range of pyroxene compositions found in charnockitic rocks. We have concentrated on unmetamorphosed plutons or metamorphosed pluton that still retain igneous pyroxene compositions, because these pyroxenes are likely to record emplacement conditions. In contrast, pyroxenes in deformed, metamorphosed charnockites are likely to record the conditions of metamorphism.

The charnockitic rocks of the Sherman batholith and of the Thor Range contain samples that bridge the transition from pigeonite to fayalite + quartz. This assemblage records the pressures of 2.5 ± .5 kbar for the Sherman batholith (Frost et al., 1999) and 3.6–5.4 kbar for the Thor Range (Bucher and Frost, 2006). The pigeonite is more Ca-rich and the augite less calcic in the Thor Range than in the Sherman batholith. This probably reflects the fact that the Sherman had a more extensive period of cooling than the Thor Range,

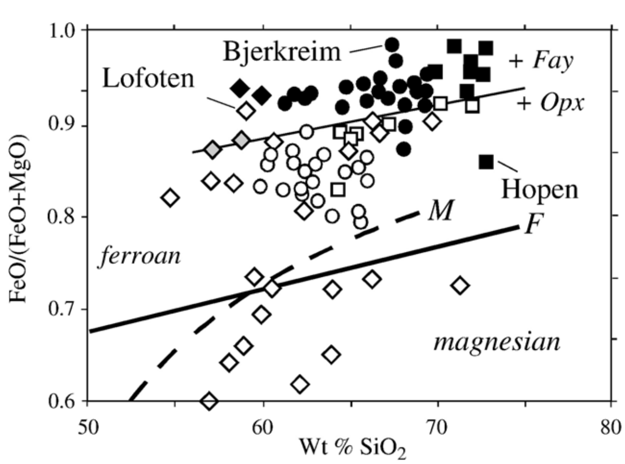

Fig. 3. Iron–magnesium variation in charnockites showing the transition from Opx-bearing to fayalite bearing. Open symbols = Opx bearing, black symbols = Fay bearing, Gray symbols = both Opx + Fay. Sources of data as in Table 1.

something that is evidenced by the higher proportion of hydrated granite in the Sherman than in the Thor Range. Both plutons record temperatures in excess of 900 °C. The high T in the Thor Range is recorded in the pigeonite in the charnockite, whereas the high T in the Sherman batholith comes from pigeonite in a ferrodiorite inclusion within the granite (Frost et al., 1999). The high-T pyroxenes from the Sherman are not shown in Fig. 6 because they do not come from a quartz-bearing rock.

The lowest-temperature pyroxene pairs come from the Louis Lake batholith (Frost et al., 2000) and from the Utsalik plutons (Percival and Mortensen, 2002). The Louis Lake batholith pyroxenes record temperatures of 775 to 800 °C and pyroxene pairs from the Utsalik record temperatures of 650–750 °C. These temperatures are surely not magmatic, rather they record the temperatures at which inter-grain Ca–Fe–Mg diffusion ceased. The low-T re-equilibration of the pyroxenes in these two plutons is a reflection of the "granulite uncertainty principle" (Frost and Chacko, 1989), in which, because of the slower cooling rate in deep-level rocks, deeper level granulites (and charnockites) will record lower temperatures than shallow ones. The most iron-rich samples of the Desliens complex contain highly exsolved Opx, which is probably relict inverted pigeonite (J. Percival, personal communication). The minimum temperature for pigeonite in these rocks is 808–967 °C, with the temperature range reflecting the variation in Fe/(Fe + Mg) in the pyroxenes.

Pyroxenes from the Ballachulish pluton (Weiss and Troll, 1989) record temperatures of 900 ± 50 °C. This is almost certainly the temperature of the solidus, for Weiss and Troll (1989) estimate a liquidus temperature in excess of 1100 °C. Such extreme temperatures are not unusual for charnockites. Liquidus temperatures of 1000 °C or higher are also suggested for Mawson (Young et al., 1997) and for the monzonitic plutons associated with the Laramie Anorthosite (Fuhrman et al., 1988; Kolker and Lindsley, 1989).

4.2. Oxygen fugacity

The oxygen fugacity of charnockitic plutons ranges from below FMQ to Δ log FMQ>+2 (Fig. 7). The huge range of oxygen fugacity and temperature for the Utsalik pluton reflects the large temperature uncertainty for these rocks (see Fig. 6) and the range in Fe/(Fe + Mg) of their pyroxenes. Because of limitations in the solution model for ilmenite, the exact oxygen fugacity values for the most oxidized rocks in Fig. 8 are uncertain (Andersen et al., 1993). Despite this uncertainty, because oxygen fugacity of the assemblage Opx–Q–Mag–Ilm will increase with increasing $\mu_{MgFe_{-1}}$, it is clear that the oxygen fugacity of the more magnesian rocks (*i.e.* the Ballachulish, Louis Lake, and the most magnesian portions of the Utsalik pluton) will be higher than that of the rocks with the more iron-rich pyroxenes. This range of oxygen fugacity recorded in the unmetamorphosed charnokitic plutons covers the range found in most felsic igneous rocks (Frost and Lindsley, 1992), which is further evidence that charnockites do not form from a unique magma type.

5. Phase relations

5.1. Solid-state phase relations

The question of whether a granitic rock crystallizes to a charnockitic assemblage is determined by the following equilibria:

$$\underset{\text{biotite}}{K(Mg,Fe)_3AlSi_3O_{10}(OH)_2} + 3\ \underset{\text{quartz}}{SiO_2} = 3\ \underset{\text{orthopyroxene}}{(Fe,Mg)SiO_3} + \underset{\text{K-feldspar}}{KAlSi_3O_8} + \underset{\text{fluid}}{H_2O} \qquad (2)$$

$$2\ \underset{\text{biotite}}{K(Mg,Fe)_3AlSi_3O_{10}(OH)_2} + 3\ \underset{\text{quartz}}{SiO_2} = \underset{\text{olivine}}{3(Fe,Mg)_2SiO_4} + 2\ \underset{\text{K-feldspar}}{KAlSi_3O_8} + 2\ \underset{\text{fluid}}{H_2O} \qquad (3)$$

Equilibria (2) and (3) have been written as if they occur in the solid state, but in both of them SiO_2, $KAlSi_3O_8$, and H_2O may occur as components in the melt, rather than as solid phases. If the melt is rich enough in iron, biotite stability will be governed by reaction (3), otherwise it will be controlled by reaction (2). Because Mg favors biotite over either Opx or Fay, increasing $\mu_{MgFe_{-1}}$ will stabilize biotite relative to either Opx or Fay (Fig. 8).

Fig. 8a shows that the dehydration of phlogopite, the Mg-end member of biotite, occurs at temperatures that are nearly 200 °C higher than does the dehydration of Fe-end member or annite. Thus, at 5 kbar, biotite would be 100 °C more stable in rocks with the composition of Ballachulish than it would be in the Sherman batholith. Fig. 8b shows that at a fixed temperature a progressive decrease in water activity will be needed to stabilize Opx with increasing $\mu_{MgFe_{-1}}$.

5.2. Phase relations in granitic and granodioritic melts

Experiments by Nany (1983) show that Opx is stable in both granitic and granodioritic melts, and that its stability decreases with decreasing T, increasing P, and increasing abundance of water in the melt (Fig. 9). In none of the experiments was Opx stable on the solidus. The Opx in Naney's experiments was quite magnesian ($X_{Fe}^{Opx}=0.14$ to 0.16 in the granite and 0.23–0.31 in the granodiorite). As noted above, increasing $\mu_{FeMg_{-1}}$ will stabilize Opx relative to biotite and, thus the stability fields for Opx (shaded areas in Fig. 9) will be larger in more iron-rich rocks. Fig. 8, however, shows that in the most Fe-rich rocks the maximum stability of biotite (at 5 kbar) still lies above 700 °C. This should still be well above the wet solidus of granites and granodiorites,

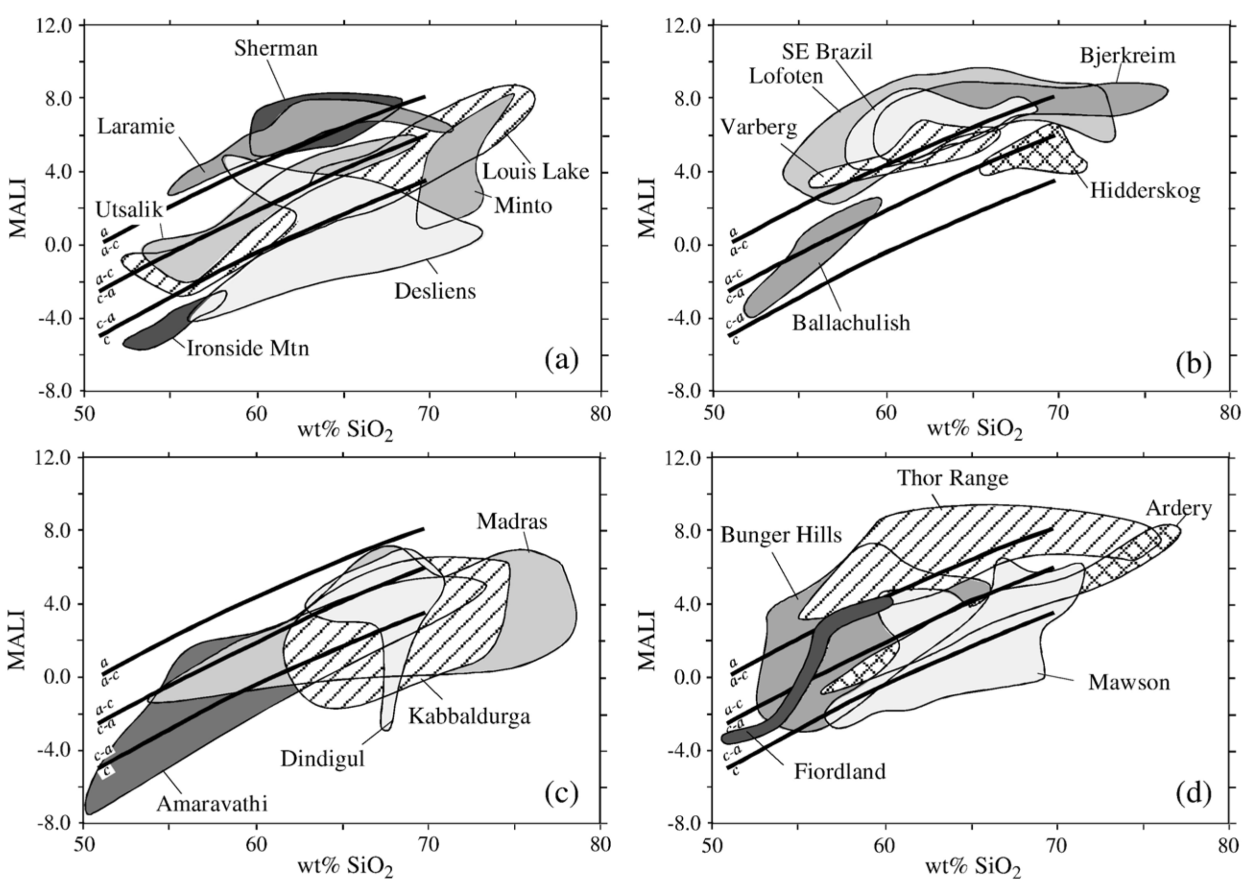

Fig. 4. Diagram showing the variation of the modified alkali lime index (MALI) with silica for charnockites. a = Charnockites of North America, b = charnockites of Europe and South America, c = charnockites from India, d = charnockites from Antarctica and New Zealand. *a* = alkalic, *a-c* = alkali-calcic, *c-a* = calc-alkalic, *c* = calcic. Boundaries after Frost et al. (2001a). Sources of data as in Table 1.

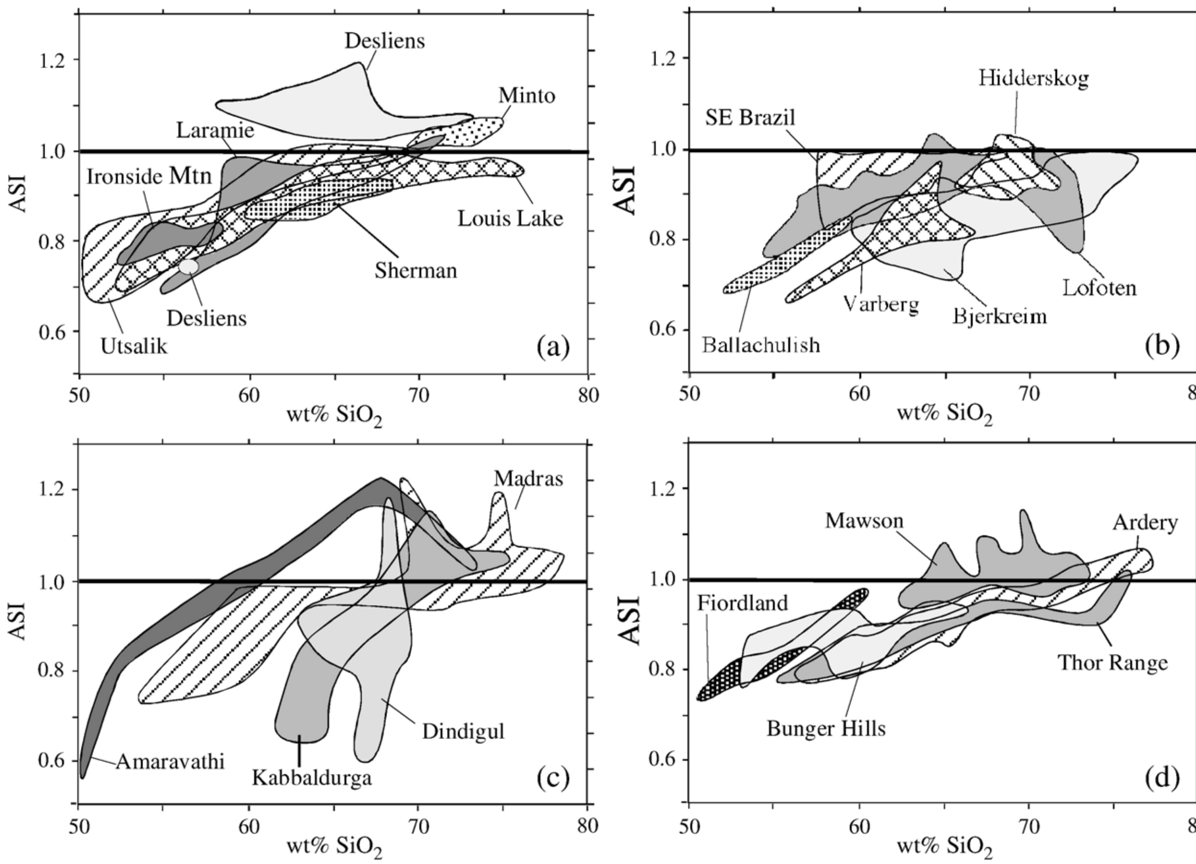

Fig. 5. Variation of the aluminum saturation index (ASI) with silica for charnockites. a = Charnockites of North America, b = charnockites of Europe and South America, c = charnockites from India, d = charnockites from Antarctica and New Zealand. Source of data as in Table 1.

indicating that even in fayalite-granites the anhydrous assemblage cannot form from wet magmas.

From Figs. 8 and 9 we can infer that the stability of charnockite is controlled by three features, high $\mu_{FeMg_{-1}}$, low water activity (or high P_{CO_2}), and high T. The tendency for high FeO/(FeO + MgO) contents of a melt to stabilize Opx or Fay at the expense of biotite explains why charnockites are so commonly ferroan. Fig. 9 shows that, if water abundance is low enough, Opx is likely to begin crystallizing in granitic and granodioritic melts at temperatures above 1000 °C — a fact that is consistent with the thermometry of the shallower Opx-bearing granitoids (Fig. 8). This low water activity is manifested in a thin section by the presence of abundant CO_2 fluid inclusions, a feature that is characteristic of charnockitic rocks (Konnerup-Madsen, 1977; Frost and Touret, 1989; Frost et al., 2000).

It is evident from Fig. 9 that, even in very water-poor melts, Opx will react to biotite before the melt reaches the solidus, which explains why the biotite-bearing Closepet granite could have CO_2-rich inclusions (Santosh et al., 1991). Many granitic melts crystallize pyroxene or fayalite as early phases, as witnessed by the many Opx- or Fay-bearing rhyolites and dacites (see a compilation by Frost and Lindsley, 1992). Fig. 9 also shows that, if pyroxenes are to survive in a plutonic granitoid they must not interact with fluids emitted by later, more hydrated melts. This means that many charnockitic plutons, such as the Louis Lake batholith or the Utsalik pluton, must be cumulates that formed early in the crystallization of a pluton and which were isolated from later, more hydrous portions of the batholith (Frost et al., 1989).

6. Isotope geochemistry

The Nd and Sr isotopic compositions of charnockites are as variable as their geochemistry and intensive parameters. Some suites, including the Leaf River plutonic suite and Opx-granite of the Minto block (Stern et al., 1994), the Louis Lake batholith (Frost et al., 1998), the Ironside Mountain batholith (Barnes et al., 2006) and Fiordland (McCulloch et al., 1987) have initial Sr and Nd isotopic compositions that suggest derivation from mantle or juvenile crustal sources, with no significant input of evolved continental crust (Fig. 10). Others, such as the David Island pluton in the Bunger Hills (Sheraton et al., 1992), Mawson (Young et al., 1997) and the Sao Pedro de Caldas and Divinolandia suites of SE Brazil (Janasi, 2002), have radiogenic initial $^{87}Sr/^{86}Sr$ ratios and pronounced negative initial ε_{Nd} consistent with the involvement of old continental crust. An origin by partial melting of anhydrous lower-crustal rocks has been invoked for these charnockites.

The Nd and Sr initial isotopic compositions of the Sherman batholith and Red Mountain pluton (Frost et al., 1999, 2001b; Anderson et al., 2003) are intermediate between these two

Table 1
Data set of Opx-bearing granitic rocks used in this study

Charnockite body	Location	Age	Ref.
Amaravathi	Eastern Ghats, South India	Unspecified	1
Ardery	Windmill Islands, Antarctica	Unspecified	2
Ballachulish	Western Scottish Highlands	412 Ma	3
Bjerkreim	Southern Norway	930 Ma	4
Bunger Hills	East Antarctica	Proterozoic	5
Desliens	Northern Quebec, Canada	2723 Ma	6
Dingdigul	South India	Unspecified	7
Fiordland	South Island, New Zealand	Early Cretaceous	8
Hidderskog	SW Norway	1160 Ma	9
Ironside	Klamath Mountains California, USA	170 Ma	10
Kabbaldurga	Mysore, South India	Late Archean	11
Laramie	Laramie Range, Wyoming, USA	1435 Ma	12–14
Lofoten	Lofoten Islands, Northern Norway	1950 Ma	15, 16
Louis Lake	Wind River Range, Wyoming, USA	2630 Ma	17
Madras	Madras area, South India	2.5 Ga	18, 19
Mawson	Mawson Coast, Antarctica	Meso–Neo Proterozoic	20
Minto	Northern Quebec, Canada	2725, 2688 Ma	21
S.E. Brazil	Southeastern Brazil	625 Ma	22
Sherman	Laramie Range, Wyoming, USA	1435 Ma	23
Thor Range	Queen Maud Land, Antarctica	500 Ma	24
Varberg	Southwest Sweden	1400 Ma	25, 26
Utsalik	Northern Quebec, Canada	2725 Ma	27

1. Ramaswamy and Murty (1973); 2. Kilpatrick and Ellis (1992); 3. Weiss and Troll (1989); 4. Duchesne and Wilmart (1997); 5. Sheraton et al. (1992); 6. Percival et al. (2003); 7. Suresha and Srikantappa (2005); 8. McCulloch et al. (1987); 9. Zhou et al. (1995); 10. Barnes et al. (2006); 11. Battacharya and Sen (2000); 12. Kolker and Lindsley (1989); 13. Scoates et al. (1996); 14. Anderson et al. (2003); 15. Ormaasen (1977); 16. Malm and Ormaasen (1978); 17. Frost et al. (2000); 18. Howie (1955); 19. Santosh et al. (2003); 20. Young et al. (1997); 21. Stern et al. (1994); 22. Janasi (2002); 23. Frost et al. (1999); 24. Bucher and Frost (2006); 25. Hubbard and Whitley (1979); 26. Christoffel et al. (1999); 27. Percival and Mortensen (2002).

groups. These plutons were emplaced across a suture juxtaposing Proterozoic rocks in the south against Archean rocks in the north. The isotopic compositions of the charnockitic rocks mimic the regional variations but are displaced from the country rock isotopic compositions towards depleted mantle values. These plutons are considered to have formed by partial melting or fractional crystallization of underplated tholeiitic basalts and crustal contamination during magma ascent.

The charnockites in our isotopic database come from a variety of tectonic environments including continental arc magmatism (Louis Lake batholith), arc collision (Fiordland, Ironside Mountain), and extension (Sherman and Red Mountain). The isotopic compositions of these rocks reinforce the conclusions based upon geochemistry and intensive parameters, namely that no single tectonic setting or magma source can account for the formation of all charnockites.

7. Discussion

7.1. The nature of charnockite magmas

It is obvious that charnockitic plutons have a wide range of geochemical characteristics. We can recognize at least three groups. First, and most obvious are the ferroan alkali-calcic to alkalic rocks. These commonly are called A-type granites but in this paper we refer to these as ferroan granitoids. Another group includes magnesian, calcic to calc-alkalic, mostly metaluminous granites that are compositionally similar to Cordilleran batholiths. Finally there is a third group that appears to straddle the transition from ferroan to magnesian granites. These plutons tend to be calc-alkalic to alkali-calcic and metaluminous. As noted above, this range of tectonic environments and petrologic processes explains the huge chemical range of charnokitic rocks (see also Rajesh and Santosh, 2004).

Petrologists recognize four tectonic environments for the formation of pyroxene-bearing granitoids: 1) rift-related, ferroan magmatism, 2) deeply eroded cordilleran-type plutons, 3) Caledonian-type plutons, and 4) deep crustal melting related to granulite metamorphism or to the emplacement of hot ferroan magmas.

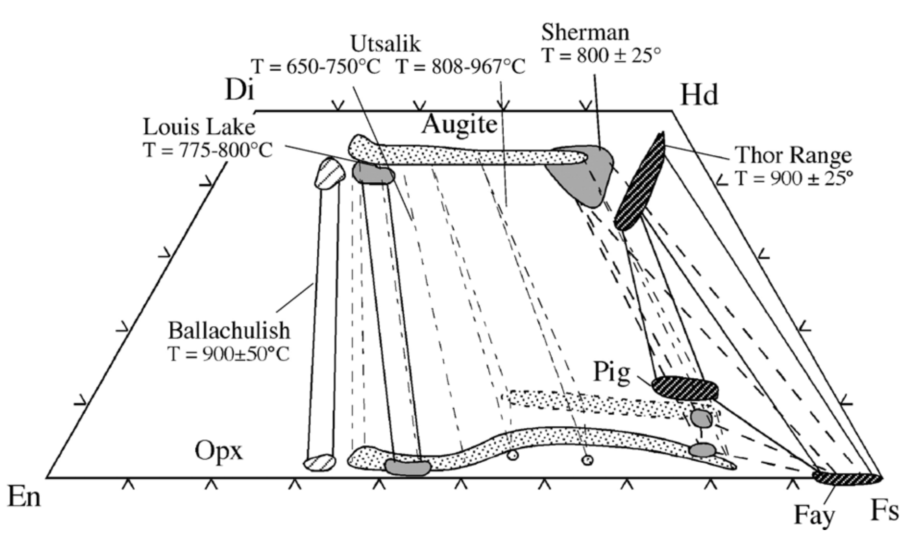

Fig. 6. Pyroxene quadrilateral showing the compositions of pyroxenes from some unmetamorphosed charnockitic plutons. Sources of data as in Table 1.

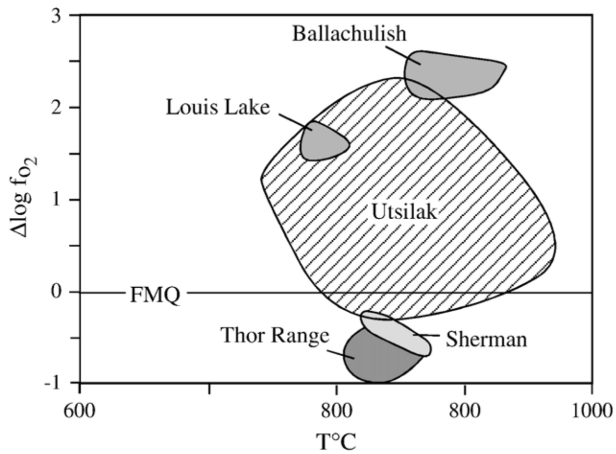

Fig. 7. Variation of temperature and oxygen fugacity for some unmetamorphosed charnockitic plutons. Sources of data as in Table 1.

7.1.1. Ferroan magmatism

Charnockitic plutons (both Opx-bearing and Fay-bearing) are a characteristic component of the AMCG (anorthosite–mangerite–charnockite–granite) suite (Emslie, 1991). These plutons tend to be ferroan alkali-calcic to alkalic metaluminous granitoids. Many of these plutons (for example the Sherman batholith, Thor Range and Fay-bearing monzonites associated with the Laramie anorthosite complex) are unmetamorphosed. Some of these plutons are interpreted to be direct differentiates of tholeiitic melts with virtually no crustal component (*e.g.* the Red Mountain pluton associated with the Laramie anorthosite complex, Anderson et al., 2003) whereas others are dominantly differentiates with minor amounts of crustal components (Bjerkreim, Duchesne and Wilmart, 1997; Sherman, Frost et al., 1999, 2001b), Thor Range (Mikhalsky et al., 2006).

7.1.2. Cordilleran type magmatism

It is clear that Opx-bearing granitoids can form in magmatic arcs, as evidenced by the presence of pyroxene in the Ironside Mountain batholith in the Klamath Mountains (Barnes et al., 2006) and Cretaceous charnokitic plutons from deep crustal levels in Fiordland (Bradshaw, 1989). These rocks tend to be magnesian calcic to calc-alkalic, metaluminous granitoids. Based upon its composition, and association with coeval thrusting of juvenile greywackes, the Louis Lake batholith, the structurally deeper parts of which are charnokitic, is proposed to be an Archean example of arc magmatism (Frost et al., 2000). Other charnockitic plutons that are proposed to represent deeply eroded magmatic arcs include Utsalik (Percival and Mortensen, 2002), Desliens (Percival et al., 2003), and Mawson (Young et al., 1997).

It is important to note that the Archean calc-alkalic magmatism need not be subduction-related. Bédard (2006) recently put forth a model tying this magmatism to melting of delaminated eclogitic crust. Such a process would be unique to the Archean and could produce the unusually hot calc-alkalic magmatism that is commonly found in Archean granulite terranes.

7.1.3. Caledonian-type magmatism

Caledonian-type granites are small, magnesian, alkali-calcic to alkalic plutons that are inferred to form during delamination of thickened continental crust after a collisional orogeny. We have identified only one example of a Caledonian-type granitoid with Opx, and that is Ballachulish. This occurrence is important because it reinforces our conclusion that, many granitoids can potentially contain Opx if they were hot enough. That being said, we are not aware of any charnockitic pluton in a granulite terrane that is compositionally similar to these types of granites.

7.1.4. Deep crustal melting

The whole rock elemental and isotopic compositions of many charnockitic plutons suggest participation of a crustal component (Young et al., 1997; Battacharya and Sen, 2000; Battacharya et al., 2001; Kar et al., 2003; Percival et al., 2003). Many of these charnockitic plutons also tend to have intermediate values of FeO/(FeO+MgO) and to be weakly to

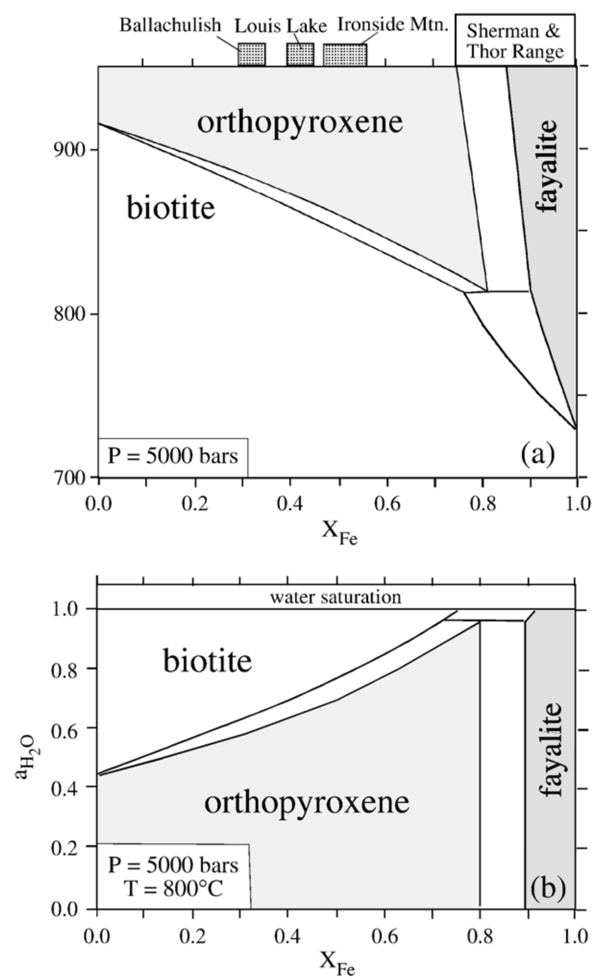

Fig. 8. Figures showing the stability relations of biotite, Opx, and fayalite in granitic rocks (*i.e.* rocks oversaturated with respect to quartz and K-feldspar). a. T–X_{Fe} projection at 5 kbar, b. a_{H_2O}–X_{Fe} slice at 5 kbar and 800 °C. Light shaded areas show stability of charnockite, darker shaded areas show the stability of fayalite-granite. Ruled boxes show the range of Opx composition in Ballachulish, Louis Lake, Ironside Mountain, Sherman, and Thor Range batholiths (see Fig. 6). Modified after Frost et al. (2000).

moderately peraluminous. Some of these charnockitic plutons with crustal components may originate as ferroan magmas in a rift setting, such as with the Bjrekreim charnockites (Duchesne and Wilmart, 1997) or arc-derived magmas (Frost et al., 2000). However, some charnockitic plutons appear to have been formed *in situ* by dry crustal anatexis (Battacharya and Sen, 2000; Kar et al., 2003; Rajesh and Santosh, 2004). Granulite terranes have been subjected to such high metamorphic temperatures that crustal melting would be expected. Indeed, Guernina and Sawyer (2003) estimate that during granulite metamorphism 20 to 40% of the original bulk composition of the paragneisses in the Ashuanipi Subprovince in Quebec (home to the Desliens, Minto and Utsalik charnockites) was extracted as granitic melt.

7.2. Charnockitic magmas as the driving force for the formation of granulite terranes

The observation that shallow-level charnockitic plutons are CO_2 bearing and were emplaced at temperatures of 1000 °C or greater reinforces the suggestions that charnokitic plutonism is a major driving force for granulite metamorphism (Frost and Frost, 1987; Frost et al., 1989; Bédard, 2003). Fig. 11 shows

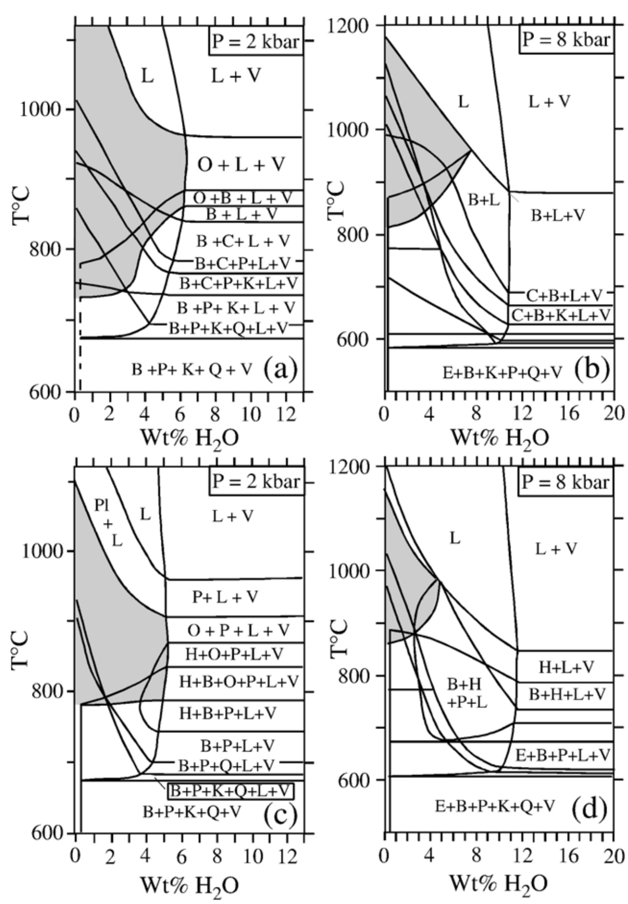

Fig. 9. Effect of water content on the crystallization sequence of granites (a and b) and granodiorite (c and d) modified after Nany (1983). Shaded area gives the fields where Opx is stable in the melt. Abbreviations: b = biotite, C = augite, E = epidote, H = hornblende, K = K-feldspar, L = liquid, P = plagioclase Q = quartz, V = vapor.

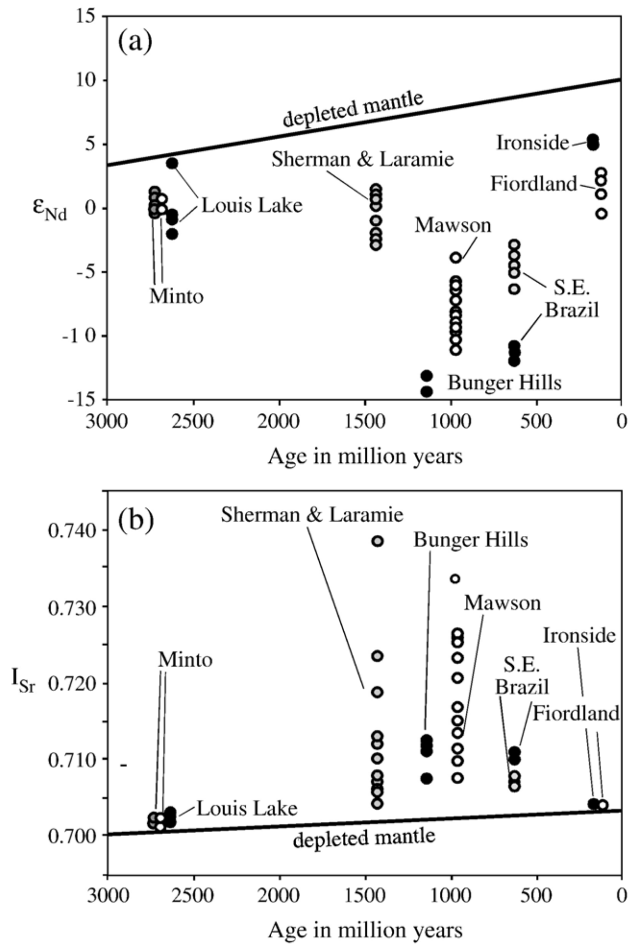

Fig. 10. a. Initial Nd isotopic compositions of charnockites as a function of intrusive age. b. Initial $^{87}Sr/^{86}Sr$ isotopic compositions of charnockites as a function of intrusive age. Data from Anderson et al. (2003), Barnes et al. (2006), Frost et al. (1999, 2001b), Janasi (2002), McCulloch et al. (1987), Sheraton et al. (1992), Stern et al. (1994) and Young et al. (1997).

schematic diagrams for two possible environments where charnokitic magmatism appears to be associated with granulite metamorphism. In neither of these models do we necessary imply that plutons move through the crust as a single blob of magma. These figures could just as well apply to the process in which individual dikes coalesce into large batholiths (Glazner et al., 2004). Indeed, relations in the Thor Range and Louis Lake batholith, which record the transition from anhydrous to hydrous granitoids, we find evidence of multiple injections of magma; some of which hydrated and some dehydrated the surrounding granitic rocks (Frost et al., 2000; Bucher and Frost, 2006).

Fig. 11a is a model for an extensional environment. In this environment heat and fluids released from mafic magma that has ponded at the base of the crust have produced granulite metamorphism in the lower crust. High-pressure differentiates of these under plated magmas will lead to ferroan magmas that are both hot and CO_2-rich (Whitaker et al., 2007). Upward movement of these magmas will be an effective process for transporting heat and fluids into the middle and upper crust. Because these magmas are hot and under saturated with respect to water, they are also likely to transport water-bearing granitic melts out of granulite terranes in the lower crust. The early cumulates of these magmas will be charnokitic, whereas the residual melts will produce typical biotite (or biotite + hornblende) granites. The transition from dry Opx- or Fay-bearing cumulates to the biotite granites is complex, because the cumulates are commonly hydrated by fluids that have either moved into the magma from the country rock or been released by the residual melts (Bucher and Frost, 2006).

The Sherman batholith (which was emplaced around 2.5 kbar) shows relations typical of a relatively shallow emplacement in a regime like this. The dry Opx- and Fay-bearing portions of the Sherman occur only as isolated outcrops in a sea of hydrated biotite granite (Frost et al., 1999). The Thor Range, which was emplaced around 4 kbar, contains abundant dry cumulates (both Fay- and Opx-bearing) that are cut through by numerous veins and dikes of biotite–hornblende granite. Lofoten and Bjerkreim also were emplaced at around 4 kbar, but they appear to lack the spectacular association of hydrous and anhydrous rocks seen in the Thor Range. A possible example of a deeply emplaced ferroan charnokitic pluton are the Bunger Hill charnockites (Sheraton et al., 1992), which were emplaced into granulite-grade country rocks at pressures around 6 kbar and yet which still retain relict igneous textures.

Pyroxene-bearing assemblages are also found in magnesian calc-alkalic and calcic granitoids (Fig. 11b). In modern environments these rocks are characteristic of arc environments. Most workers believe that the Archean examples were likely to also have been of an arc source (Frost et al., 2000; Percival and Mortensen, 2002), although Bédard (2006) suggests that they may have formed instead by melting of delaminated eclogite. Regardless of the origins, at least portions of these magmas were derived from the mantle and are likely to be hot and CO_2-laden. As with ferroan granites, these magnesian magmas are conduits for the transport of fluids and heat into the middle crust. In addition, the lower portions of these plutons are likely to have been pyroxene bearing. The pyroxene-bearing horizons in arc environments will probably be deeper than in rift environments, where the crust has been tectonically thinned (compare Fig. 11a and b).

A good example of a charnockitic magnesian calc-alkalic pluton is the Louis Lake batholith. It is exposed in an 80-kilometer long section that grades from pressures of ca. 6 kbar in the north to 3 kbar in the south (see heavy line in Fig. 11b). Pyroxenes are absent in most of the batholith but in the deepest levels of exposure the rocks are charnockitic and show little evidence of hydration. As one moves from the deeper to the shallower levels, hydration becomes increasingly common until the charnockites are represented simply by isolated blocks in biotite granite and biotite–hornblende granodiorite (Frost et al., 2000). The Ironside Mountain batholith lies at shallower depth than the Louis Lake batholith but lacks the dehydration seen in the Louis Lake batholith. This is probably because the Ironside Mountain rocks are considerably more iron-rich than the Louis Lake and in such rocks, as noted above, Opx should be more stable relative to biotite. The Utsalik and Mawson plutons (Young et al., 1997; Percival and Mortensen, 2002) were emplaced at a somewhat higher pressure. The Fiordland charnockites in New Zealand were emplaced deep in a Cretaceous island arc (Bradshaw, 1989).

7.3. The question of "charnockitization"

As noted above, the term charnockite, which engendered confusion almost as soon as it was introduced, became more confused when Pichamuthu (1960) proposed that at least some of the charnockite terrane of southern India was produced by a flux of CO_2. It was later suggested that this could have been a regional process that was driven by fluids emitted from under plated basalts (Janardhan et al., 1982). This has led to the common use of the term "charnockitization" and the assumption that the charnockites of South India were typical biotite or hornblende-bearing granitoids that were dehydrated by a massive flux of CO_2. It is true that dehydration rims are clearly present on the margins of dikes (Frost and Frost, 1987) and shear zones in some high-grade terranes (Stahle et al., 1987) but the key question is the scale of the dehydration. Is it regional-

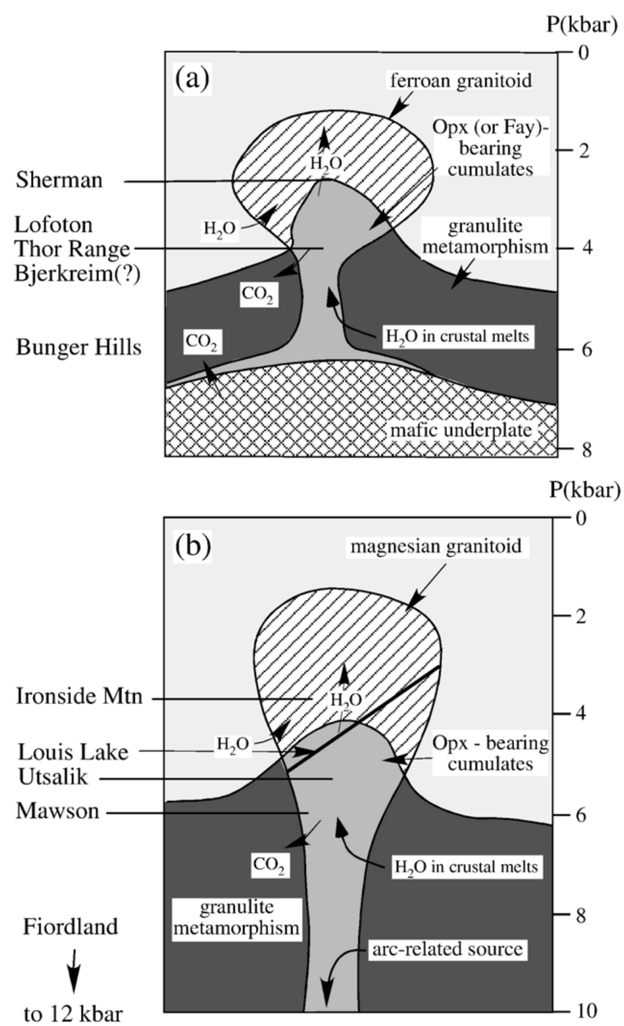

Fig. 11. Schematic cross sections showing the relation between charnockitic magmatism and granulite metamorphism. a. magmatism in rifting environments. b. Magmatism associated with arc environments. Sources of Pressure data Lofoten (Markl et al., 1989), Fiordland (Bradshaw, 1989), data for other plutons come from references in Fig. 2.

scale (Janardhan et al., 1982; Newton, 1989, 1992; Santosh and Omori, 2008-this issue) or is it a local process that is found marginal to charnokitic plutons (Frost and Frost, 1987; Frost et al., 1989; Santosh et al., 1991, Battacharya and Sen, 2000)?

Because there is ample evidence for the presence of hot, CO_2-rich magmas in the lower crust, and because the sources of heat and fluid required to dehydrate huge areas of granite are cryptic, we believe that many of the charnockite gneiss massifs had a magmatic origin (Frost and Frost, 1987). However, we also admit that CO_2-fluxing is a viable process (see Santosh and Omori, 2008-this issue) and that the question of how a charnockite orthogneiss formed must be solved in each field area. Whatever the answer, it is clear that Opx-bearing granites that have formed by solid-state dehydration are metamorphic, not igneous rocks, and as such, they should not have an igneous name (see below).

7.4. Some suggested changes to charnockite terminology

Terminology in any field of science should be designed to facilitate communication of information. Unfortunately terminology of charnockitic rocks is anything but clear and certainly fails this test. Below are a few suggestions that we hope will clear up some of the confusion.

7.4.1. The word charnockite should be applied only to igneous rocks

We propose that the term "charnockite" should be applied only to igneous rocks for two reasons. First, an igneous origin to charnockite is certainly implied by the inclusion of the term "charnockite" in the igneous classification of Le Maitre (1989). Admittedly, when Howie (1955) showed that the Madras charnockite was clearly an igneous suite he could not prove whether the suite originally crystallized with pyroxenes or had been dehydrated by a later process. However, since then petrologists have come up with a significant number of clearly igneous charnockites (*e.g.* Bradshaw, 1989; Young et al., 1997; Frost et al., 2000; Percival and Mortensen, 2002; Barnes et al., 2006). As we noted above, pyroxene-bearing granitoids are found at deep levels in typical calc-alkalic batholiths such as the Louis Lake (Frost et al., 2000), the Minto terrane (Percival and Mortensen, 2002), and in Fiordland (Bradshaw, 1989). Furthermore igneous charnockites are an important member of the AMCG association (Emslie, 1991; Duchesne and Wilmart, 1997*)*. Second, because petrologists gain nothing by using "charnockite" as a synonym for "granulite", it seems reasonable not to confuse matters with this unnecessary terminological redundancy.

7.4.2. The word "charnockite" should be applied a general sense

In igneous rock classification the word "charnockite", like the word "granite", can have a specific meaning (*i.e.* Opx (or Fay)-bearing granite) or a general meaning (*i.e.* Opx-bearing granitoid). In this paper we suggest that the simplest way to handle the problem of how to define the word "charnockite" is to restrict the term to in the general sense as below.

7.4.3. A definition for the word charnockite

We recognize that in many terranes there is an irreducible ambiguity about whether charnockitic plutons crystallized with Opx or had Opx imposed on them by later dehydration. These rocks clearly must be included in the definition of charnockite, since the type locality is one such pluton. Recognizing this ambiguity, we propose the definition below.

Charnockite: *an Opx-(or Fay-) bearing granitic rock that is clearly of igneous origin or that is present as an orthogneiss within a granulite terrane.*

We do not wish to imply by this definition that charnockite orthogneisses must be of igneous origin. We merely wish to enlarge the definition so that it included Opx-bearing granitoids that are clearly igneous and those where the origin of the Opx is uncertain.

7.4.4. Eliminate the terms enderbite, opdalite, mangerite, jotunite, and charno-enderbite

Accepting the definition above allows us to eliminate the terms enderbite, opdalite, jotunite, and mangerite (as well as charno-enderbite, a word that should never have been introduced in the first place). A major reason for eliminating these terms is that the IUGS classification scheme works perfectly well for igneous rocks. It is simple, easy to use, and its terms are well understood by the petrological community. There is no logical reason to have a parallel classification schemes for granitoids with wet and dry assemblages. By using the definition above we can classify charnockites by adding the appropriate modifier to the IUGS igneous rock classification. For example, an "opdalite" would better be termed a "granodioritic charnockite" or an "Opx-bearing granodiorite".

There are several other reasons we make this suggestion. First, the authors of the AGI Glossary of Geology (Bates and Jackson, 1980) obviously recognized that terms such as opdalite, enderbite, and jotunite are obscure and they suggested against their use. Very few petrologists would know what an opdalite is — the authors who introduced the term charno-enderbite certainly did not! If the reader has to go to a glossary to look for a term in your paper then you are not doing a good job of conveying information. Second, the terms do not add anything to our vocabulary. As noted above the IUGS classification works perfectly well. Describing a rock as a monzonitic charnockite or Opx-monzonite conveys the same information as the term mangerite, without producing yet another igneous rock name to memorize. Finally, these terms are mostly dead anyway. In the vast majority of the papers studied for this compilation, the authors did not use these obscure terms but used Opx (or Fay) as a hyphenated prefix to the IUGS classification.

7.4.5. Use fayalite prefix for fayalite-bearing rocks

Because, depending on the depth of emplacement, an iron-rich melt can crystallize either Opx or fayalite, we think that fayalite-granites must be included into the charnockite family. However, if a granite contains fayalite, we contend that it is better to call a fayalite-granite than a charnockite. This is because the term "fayalite-granite" conveys more information than the term "charnockite". When one calls a rock a charnockite it tells the reader that the rock is a granitic rock that contains Opx (or rarely Fay). The term fayalite-granite tells the reader that the rock is a dry, ferroan granite.

7.4.6. Do not use the terms such as "charnockitization", "incipient charnockite", or "C-type magma"

A key feature of terminology is that it should be as descriptive as possible. Terms such as "charnockitization", "incipient charnockite", and "charnockite in the making" carry the implication that charnockites are metamorphic (or more properly metasomatic rocks). While Opx-bearing granite may be metasomatic at a given locality, it is best not to use prejudicial terminology before one has proven the fact. We would suggest that authors substitute the terms "dehydration" or "hydration" for the words "charnockitization" or "decharnockitization". An Opx-granitic gneiss that had clearly formed by dehydration should be called "granitic granulite" rather than "charnockite" to clearly distinguish that the mineral assemblage it carries is of metamorphic as opposed to igneous origin. Finally, as we have clearly shown in Figs. 2–5, charnockites have an extreme range in composition. There is no clearly distinguishable C-type magma and this term should be dropped.

7.4.7. Abandon the terms intermediate or felsic charnockites

Recently Rajesh and Santosh (2004) divided charnockites into intermediate and felsic charnockites. We advise against these terms for two reasons. First, the terms are incredibly misleading. "Intermediate" and "felsic" have distinct connotations in petrology. According to the AGI Glossary of Geology (Bates and Jackson, 1980), intermediate rocks have silica contents that lie "intermediate between mafic and felsic" rocks. Thus one would expect intermediate rocks should have lower silica contents (~55–65 wt.% SiO_2) than felsic rocks. A quick glance at the figures in Rajesh and Santosh (2004) show that a significant number of the "intermediate" charnockites have the same silica content (68–75 wt.% SiO_2) as the felsic charnockites.

Second, the term is unnecessary, Rajesh and Santosh (2004) themselves note that the intermediate rocks are dominantly calc-alkaline and ferroan to magnesian granitoids, whereas the felsic charnockites are alkali-calcic and ferroan. In other words they can be distinguished by the same geochemical classification system that distinguishes other granitic rocks (Frost et al., 2001a). We suggest that future authors use the granitic geochemical classification for charnockites, rather than getting the reader confused over the silica content of these rocks.

8. Conclusions

Despite the confusion their name engenders, charnockites are extremely valuable rocks petrologically. Because they contain pyroxenes (and sometimes fayalite) they have low-variance assemblages that allow petrologists to calculate their intensive parameters (T, $\log f_{O_2}$, and sometimes pressure) with a much greater precision than is possible in most other granitic rocks. We have noted in this paper that charnockites can form in a wide range of geologic environments. For most granitic melt compositions Opx is stable only early in their crystallization history. Thus, charnockites give important clues to the intensive parameters present in a variety of magma compositions in the early stages of the evolution of granitic batholiths.

Charnockitic orthogneisses are important constituents of many granulite terranes. Like their unmetamorphosed relatives, they contain low-variance assemblages that allow petrologists to calculate intensive parameters that governed large portions of these terranes. In addition, if one can determine whether the Opx-bearing assemblage in a given charnockitic orthogneiss formed by magmatic or igneous processes, this information will provide important clues to the formation of the granulite terrane in which the gneisses occur.

We hope that this paper clarifies some of the confusion that surrounds charnockite terminology. We also hope that this paper has provided a framework showing the petrologic significance of charnockites in various environments so that future workers in the field will have a context into which they may place their research.

Acknowledgements

The authors want to thank the editor M. Santosh for asking us to write this paper. It gave us an opportunity to place much of the research we have done over the past 20 years into a broader context. We want to thank HM Rajesh and an anonymous reviewer for helpful reviews of the original version of this paper.

References

Andersen, D.J., Lindsley, D.H., Davidson, P.M., 1993. QUILF a PASCAL program to assess equilibria among Fe–Mg–Mn–Ti oxides, pyroxenes, olivine, and quartz. Computers & Geosciences 19, 1333–1350.

Anderson, I.C., Frost, C.D., Frost, B.R., 2003. Petrogenesis of the Red Mountain pluton, Laramie anorthosite complex, Wyoming: implications for the origin of A-type granites. Precambrian Research 124, 243–267.

Barnes, C.G., Mars, E.V., Swapp, S., Frost, C.D., 2006. Petrology and geochemistry of the Middle Jurassic Ironside Mountain batholith: evolution of potassic magmas in a primitive arc setting. Special Paper - Geological Society of America 410, 199–221.

Bates, R.L., Jackson, J.A., 1980. Glossary of Geology. American Geological Institute, Falls Church, Va.

Battacharya, S., Sen, S.K., 2000. New insights into the origin of Kabbaldurga charnockites, Karnataka, South India. Gondwana Research 3, 489–506.

Battacharya, S., Kar, R., Misra, S., Teixeira, W., 2001. Early Archean continental crust in the Eastern Ghats granulite belt, India: isotopic evidence from a charnockite suite. Geological Magazine 138, 609–618.

Bédard, J.H., 2003. Evidence for regional-scale pluton-driven high-grade metamorphism in the Archean Minto block, Northern Superior Province, Canada. Journal of Geology 111, 183–205.

Bédard, J.H., 2006. A catalytic delamination-driven for coupled genesis of Archean crust and sub-continental lithospheric mantle. Geochimica et Cosmochimica Acta 70, 1188–1214.

Bradshaw, J.Y., 1989. Origin and metamorphic history of an Early Cretaceous polybaric granulite terrain, Fiordland, Southwest New Zealand. Contributions to Mineralogy and Petrology 103, 346–360.

Bucher, K., Frost, B.R., 2006. Fluid transfer in high-grade metamorphic terrains intruded by anorogenic granites: the Thor Range, Antarctica. Journal of Petrology 47, 567–593.

Christoffel, C.A., Connelly, J.N., Åhåll, K.-I., 1999. Timing and characterization of recurrent pre-Sveconorwegian metamorphism and deformation in the Varberg-Halmstad region of SW Sweden. Precambrian Research 98, 173–195.

Duchesne, J.-C., Wilmart, E., 1997. Igneous charnockites and related rocks from the Bjerkreim-Sokndal layered intrusion (southwest Norway): a Jotunite (hypersthene monzodiorite)-derived A-type granitoid suite. Journal of Petrology 38, 337–369.

Emslie, R.F., 1991. Granitoids of rapakivi granite–anorthosite and related associations. Precambrian Research 51, 173–192.

Frost, B.R., Chacko, T., 1989. The granulite uncertainty principle: limitations on thermobarometry in granulites. Journal of Geology 97, 435–450.

Frost, B.R., Frost, C.D., 1987. CO_2, melts, and granulite metamorphism. Nature 327, 503–506.

Frost, B.R., Lindsley, D.H., 1992. Equilibria among Fe–Ti oxides, pyroxenes, olivine, and quartz: Part II. Application. American Mineralogist 77, 1004–1020.

Frost, B.R., Touret, J., 1989. Magmatic CO_2 and highly saline brines from the Sybille Monzosyenite, Laramie Anorthosite Complex, Wyoming. Contributions to Mineralogy and Petrology 103, 178–186.

Frost, B.R., Lindsley, D.H., Andersen, D.J., 1988. Fe–Ti oxide–silicate equilibria: assemblages with fayalitic olivine. American Mineralogist 73, 727–740.

Frost, B.R., Frost, C.D., Touret, J.L.R., 1989. Magmas as a source of heat and fluids in granulite metamorphism. In: Bridgwater, D. (Ed.), Fluid Movements — Element Transport and the Composition of the Deep Crust, NATO ASI series, V.C-281, pp. 1–18.

Frost, C.D., Frost, B.R., Chamberlain, K.R., Hulsebosch, T.P., 1998. The Late Archean history of the Wyoming province as recorded by granitic magmatism in the Wind River Range, Wyoming. Precambrian Research 89, 145–173.

Frost, C.D., Frost, B.R., Chamberlain, K.R., Edwards, B.R., 1999. Petrogenesis of the 1.43 Ga Sherman batholith, SE Wyoming: a reduced rapakivi-type anorogenic granite. Journal of Petrology 40, 1771–1802.

Frost, B.R., Frost, C.D., Hulsebosch, T.P., Swapp, S.M., 2000. Origin of the charnockites of the Louis Lake batholith, Wind River Range, Wyoming. Journal of Petrology 41, 1759–1776.

Frost, B.R., Arculus, R.J., Barnes, C.G., Collins, W.J., Ellis, D.J., Frost, C.D., 2001. A geochemical classification of granitic rocks. Journal of Petrology 42, 2033–2048.

Frost, C.D., Bell, J.M., Frost, B.R., Chamberlain, K.R., 2001. Crustal growth by magmatic underplating: isotopic evidence from the northern Sherman batholith. Geology 29, 515–518.

Fuhrman, M.L., Frost, B.R., Lindsley, D.H., 1988. The petrology of the Sybille Monzosyenite, Laramie Anorthosite Complex, Wyoming. Journal of Petrology 29, 699–729.

Gevers, T.W., Dunne, J.C., 1942. Charnockitic rocks near Port Edward in Alfred County, Natal. Transactions of the Geological Society of South Africa 45, 183–214.

Glazner, A.F., Bartley, J.M., Coleman, D.S., Gray, W., Taylor, R.Z., 2004. Are plutons assembled over millions of years by amalgamation from small magma chambers? GSA Today 14, 4–11.

Guernina, S., Sawyer, E.W., 2003. Large-scale melt-depletion in granulite terranes: an example from the Archean Ashuanipi Subprovince of Quebec. Journal of Metamorphic Geology 21, 181–201.

Holland, T.H., 1900. The charnockite series, a group of Archean hypersthenic rocks in Peninsular India. Memoirs of the Geological Survey of India 28, 119–249.

Howie, R.A., 1955. The geochemistry of the charnockite series of Madras, India. Transactions of the Royal Society of Edinburgh 82, 725–769.

Hubbard, F.H., Whitley, J.E., 1979. REE in charnockite and associated rocks, southwest Sweden. Lithos 12, 1–11.

Janardhan, A.S., Newton, R.S., Hansen, E.C., 1982. The transformation of amphibolite facies gneiss to charnockites in southern Karnataka and northern Tamil Nadu, India. Contributions to Mineralogy and Petrology 79, 130–149.

Janasi, V. de A., 2002. Elemental and Sr–Nd isotope geochemistry of two Neoproterozoic mangerite suites in SE Brazil: implications for the origin of the mangerite–charnockite–granite series. Precambrian Research 119, 301–327.

Kar, R., Bhattacharya, S., Sheraton, J.W., 2003. Hornblende-dehydration melting in mafic rocks and the link between massif-type charnockite and associated granulites, Eastern Ghats granulite belt, India. Contributions to Mineralogy and Petrology 145, 707–729.

Kilpatrick, J.A., Ellis, D.J., 1992. C-type magmas: igneous charnockites and their extrusive equivalents. Transactions of the Royal Society of Edinburgh. Earth Sciences 83, 155–164.

Kolker, A., Lindsley, D.H., 1989. Geochemical evolution of the Maloin Ranch pluton, Laramie Anorthosite Complex, Wyoming, Petrology and mixing relations. American Mineralogist 74, 307–324.

Konnerup-Madsen, J., 1977. Composition and microthermometry of fluid inclusions in the Kleivan Granite, South Norway. American Journal of Science 277, 673–696.

Le Maitre, R.W. (Ed.), 1989. A Classification of Igneous Rocks and Glossary of Terms. Blackwell Scientific Publications, Oxford.

Lindsley, D.H., Frost, B.R., 1992. Equilibria among Fe–Ti oxides, pyroxenes, olivine, and quartz: Part I. Theory. American Mineralogist 77, 987–1003.

Malm, O.A., Ormaasen, D.E., 1978. Mangerite–charnockite intrusives in the Lofoten-Vesterålen Area, North Norway: petrography, chemistry, and petrology. Noges Geologiske Undersökelse 338, 83–114.

Markl, G., Frost, B.R., Bucher, K., 1989. The origin of anorthosites and related rocks from the Lofoten Islands, Northern Norway: I. Field relations and estimation of intrinsic variables. Journal of Petrology 39, 1425–1452.

McCulloch, M.T., Bradshaw, J.Y., Taylor, S.R., 1987. Sm–Nd and Rb–Sr isotopic and geochemical systematics in Phanerozoic granulites from Fiordland, Southwest New Zealand. Contributions to Mineralogy and Petrology 97, 183–195.

Mikhalsky, E.V., Sheraton, J.W., Hahne, K., 2006. Charnockite composition in relation to the tectonic evolution of East Antarctica. Gondwana Research 9, 379–397.

Miyashiro, A., 1974. Volcanic rock series in island arcs and active continental margins. American Journal of Science 274, 321–355.

Nany, M.T., 1983. Phase equilibria of rock-forming ferromagnesian silicates in granitic systems. American Journal of Science 283, 993–1033.

Newton, R.C., 1989. Metamorphic fluids in the deep crust. Annual Reviews in Earth Science 17, 385–412.

Newton, R.C., 1992. Charnokitic alteration: evidence for CO_2 infiltration in granulite facies metamorphism. Journal of Metamorphic Geology 10, 383–400.

Ormaasen, D.E., 1977. Petrology of the Hopen mangerite–charnockite intrusion, Lofoten, north Norway. Lithos 10, 291–310.

Percival, J.A., Mortensen, J.K., 2002. Water-deficient calc-alkaline plutonic rocks of northeastern Superior province, Canada: significance of charnockitic magma. Journal of Petrology 43, 1617–1630.

Percival, J.A., Stern, R.A, Rayner, N., 2003. Archean adakites from the Ashuanipi complex, eastern Superior province, Canada: geochemistry, geochronology and tectonic significance. Contributions to Mineralogy and Petrology 145, 265–280.

Pichamuthu, C.S., 1960. Charnockite in the making. Nature 188, 135–136.

Rajesh, H.M., Santosh, M., 2004. Charnockitic magmatism in southern India. Proceedings of the Indian Academy of Sciences. A Earth and Planetary Sciences 113, 565–585.

Ramaswamy, A., Murty, M.S., 1973. The charnockite series of Amaravathi, Gunter District, Andhra Pradesh, South India. Geological Magazine 110, 171–184.

Santosh, M., Omori, S., 2008. CO_2 flushing: a plate tectonic perspective. Gondwana Research 13, 86–102 (this issue).

Santosh, M., Jayananda, M., Mahabaleswar, B., 1991. Fluid evolution in the Closepet Granite: a magmatic source for CO_2 in charnockite formation at Kabbaldurga? Journal of the Geological Society of India 38, 55–65.

Santosh, M., Yokoyama, K., Biju-Sekhar, S., Rogers, J.J.W., 2003. Multiple tectonothermal events in the granulite blocks of Southern India revealed from EPMA dating: implications on the history of supercontinents. Gondwana Research 6, 29–63.

Scoates, J.S., Frost, C.D., Mitchell, J.N., Lindsley, D.H., Frost, B.R., 1996. Residual-liquid origin for a monzonite intrusion in a mid-Proterozoic anorthosite complex: the Sybille intrusion, Laramie anorthosite complex, Wyoming. Geological Society of America Bulletin 108, 1357–1371.

Sheraton, J.W., Black, L.P., Tindle, A.G., 1992. Petrogenesis of plutonic rocks in a Proterozoic granulite-facies terrane — the Bunger Hills, East Antarctica. Chemical Geology 97, 163–198.

Stahle, H.J., Raith, M., Hoernes, S., Delfs, A., 1987. Element mobility during incipient granulite formation at Kabbaldurga, Southern India. Journal of Petrology 28, 803–834.

Stern, R.A., Percival, J.A., Mortensen, J.K., 1994. Geochemical evolution of the Minto block: a 2.7 Ga continental magmatic arc built on the Superior protocraton. Precambrian Geology 65, 115–153.

Suresha, K.J., Srikantappa, C., 2005. Igneous charno-enderbites and charnockites (C-type magmas) around Dindigul, Tamil Nadu. Journal of the Geological Society of India 65, 403–410.

Washington, H.S., 1916. The charnockite series of igneous rocks. American Journal of Science 41, 323–338.

Weiss, S., Troll, G., 1989. The Ballachulish Igneous Complex, Scotland: petrography, mineral chemistry and order of crystallization in the monzodiorite–quartz diorite suite and in the granite. Journal of Petrology 30, 1069–1115.

Whitaker, M.L., Nekvasil, H., Lindsley, D.H., DiFrancesco, N.J., 2007. The role of pressure in producing compositional diversity in intraplate basaltic magmas. Journal of Petrology 48, 365.

Young, D.N., Zhao, J.-X., Ellis, D.J., McCulloch, M.T., 1997. Geochemical and Sr–Nd isotopic mapping of source provinces for the Mawson charnockites, east Antarctica: implications for Proterozoic tectonics and Gondwana reconstruction. Precambrian Research 86, 1–19.

Zhou, X.Q., Bingen, B., Demaiffe, D., Liegois, J.-P., Hertogen, J., Weis, D., Michot, J., 1995. The 1160 Ma Hidderskog meta-charnockite: implications of this A-type pluton for the Sveconowegian belts in Vest Agder (SW Norway). Lithos 36, 51–66.

B. Ronald Frost is a Professor in the Department of Geology and Geophysics at the University of Wyoming. He received his Ph.D. from the University of Washington in 1973 and worked at the University of Minnesota-Duluth and Michigan Technical University before joining the faculty at Wyoming in 1978. He has served on the editorial board of the *Journal of Metamorphic Geology* and *Geochimica Cosmochimica Acta* and is currently an associate editor for *Journal of Petrology*. He was a recipient of an *Alexander von Humboldt Research Award* in 1992. His major fields of research include Precambrian geology, the geology and geochemistry of granitic rocks, the formation and metamorphism of serpentinites, the stability of Fe–Ti oxides in igneous and metamorphic environments, and the effect of metamorphism on the melting of massive sulfide ore bodies. In addition to his studies on the Precambrian basement in the Wyoming mountains, he has also conducted research on Precambrian rocks in Siberia, Canada, and Australia. He recently participated in the IODP expedition 304, which drilled an oceanic core complex on the Mid-Atlantic Ridge, where he studied the reactions governing modern seafloor alteration.

Carol D. Frost (no relation to B. Ronald Frost) is Professor of Geology and Geophysics at the University of Wyoming. She is an isotope geologist whose research interests range from the evolution of the continental crust to isotopic tracing of ground and surface water interactions. Frost received her A. B. degree from Dartmouth College in 1979 and her Ph.D. from Cambridge University in 1984. She was MSA Lecturer for 1997–1998, has served on the editorial board of *Geology* (1991–1993), *GSA Bulletin* (1994–1996), and *Geospheres* (2005–present), and has been guest editor for a number of special issues of *Lithos*, *Canadian Journal of Earth Sciences* and *Rocky Mountain Geology*. She served on the Geochemistry and Petrology and Graduate Research Fellowship panels at the National Science Foundation, and on the Solid Earth Sciences and Major Equipment for Solid and Environmental Earth Sciences panels at the Canadian National Science and Engineering Research Council. She has been honored with several teaching awards, including the University of Wyoming's highest award, the Ellbogen Meritorious Classroom Teaching Award, and was the CASE Professor of the Year for Wyoming in 2001. At the University of Wyoming Frost was Interim Director of the newly established School of Energy Resources 2006–2007, an interdisciplinary entity dedicated to teaching, research and outreach in energy-related disciplines including geosciences, engineering and economics.