

Boron-free kornerupine from the Reynolds Range, Arunta Block, central Australia

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Abstract

Nearly boron-free kornerupine is locally abundant in pods or lenses of coarse-grained, non-foliated, Mg- and Al-rich rocks that occur at high metamorphic grades in early Proterozoic metapelitic rocks from the Reynolds Range, Northern Territory, Australia. This is the third reported occurrence of boron-free kornerupine worldwide. The samples consist almost entirely of coarse-grained kornerupine and its breakdown products sapphirine, cordierite, and gedrite or orthopyroxene. The kornerupine contains only 0.45 wt.% B₂O₃, corresponding to 0.098 B atoms per 22 (O, OH), and closely approximates 11:10:11 in terms of molar ratios of (MgO + FeO_{total}):Al₂O₃:SiO₂, with $X_{Mg} = Mg/(Mg + Fe_{total}) = 0.874$. The unusual textures and bulk compositions of the rocks in the pods are interpreted to have resulted from metasomatism and high-grade metamorphism (750 to 800° and ~ 4.5 kbar) of precursors that may have included sedimentary Mg-rich clays. Rocks containing boron-poor, and relatively boron-rich kornerupine (2.18 wt.% B₂O₃; $X_{Mg} = 0.892$) are separated in outcrop by as little as 10 m of the foliated cordierite-quartzite country rock and other rock types, suggesting that the compositions or amounts of the metasomatic fluids varied on a local scale.

KEYWORDS: kornerupine, boron, metapelite, Reynolds Range, Australia.

Introduction

This paper describes the third occurrence, worldwide, of natural boron-free kornerupine, in rocks from the Reynolds Range, Northern Territory, central Australia. Kornerupine is a relatively rare magnesium iron aluminum silicate that occurs in aluminous upper amphibolite- and granulite-facies metamorphic rocks. Most natural kornerupines contain substantial boron, with up to 4 (wt.%) B₂O₃ (Grew *et al.*, 1990). Natural boron-free kornerupine has previously been reported only from lenses of aluminous rock in or closely associated with the anorthosites of the Messina layered intrusion, Limpopo Belt, Zimbabwe, southern Africa (Schreyer and Abraham, 1976a; Windley *et al.*, 1984; Klaska and Grew, 1991; Droop, 1989; Grew *et al.*, 1990), and rocks from Fiskenaesset Harbour, Greenland (Herd, 1973; Schreyer and Abraham, 1976a).

In the Arunta Block of central Australia, kornerupine is locally abundant in large, isolated pods or lenses of aluminous rocks that crop out sporadically in high-grade, upper amphibolite- and granulite-facies portions of the Reynolds, Strangways, Harts, and Anmatjiras Ranges

(Woodford and Wilson, 1976a, b; Hensen and Warren, 1983; Warren and McCall, 1983; Goscombe, 1992; Hand, 1992 *pers. comm.*). Analyses of kornerupines from the western Harts Ranges show approximately 2–3% B₂O₃ (Hensen and Warren, 1983; Warren and McCall, 1983). Elsewhere in the Arunta Block kornerupine has usually been assumed to be boron-bearing, and thereby interpreted to suggest local increases in the activity of B₂O₃ (*e.g.* Goscombe, 1992). However, the results of the present study suggest that boron-free kornerupine may be relatively common in the Arunta Block.

Geological setting

The Reynolds Range forms a 130 km long, NW-trending belt that lies approximately 120 km to the NNW of Alice Springs, Northern Territory (Fig. 1), within the Arunta Block, a Precambrian complex of metamorphic and igneous rocks in central Australia. The Reynolds Range consists largely of metasedimentary rocks that have been intruded by large and small granite sheets. There is a strong regional metamorphic gradient parallel to

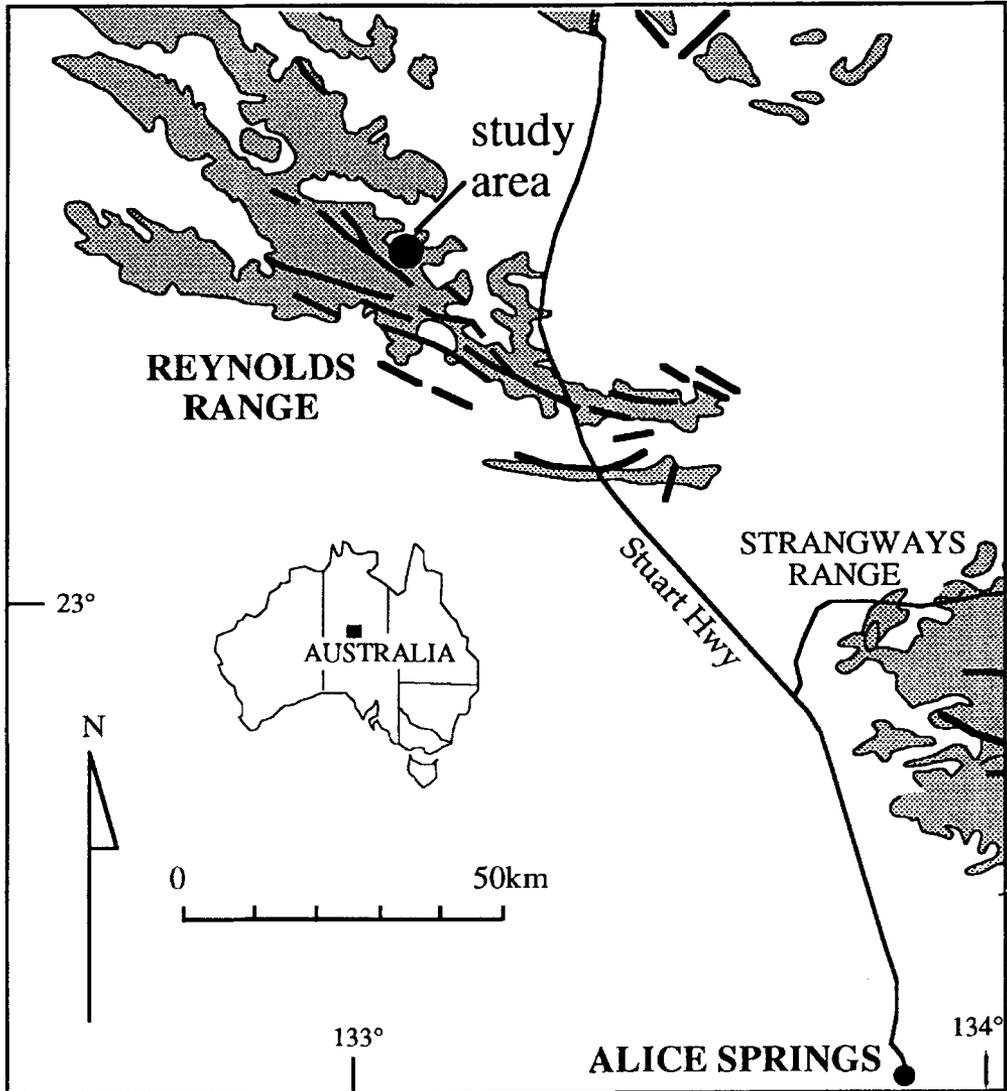


FIG. 1. Location of study area in the Reynolds Range, Northern Territory, Australia. Stippled pattern indicates Proterozoic metamorphic rocks of the Arunta block in the Reynolds and Strangways Ranges; dark lines indicate faults. (After Warren, 1979, and Stewart, 1981).

the structural-stratigraphic strike of the range, from greenschist facies (approximately 400°C) in the NW to low-pressure granulite facies in the SE ($\geq 750^\circ$, Dirks *et al.*, 1991; Clarke and Powell, 1991).

The Reynolds Range has in the past been considered a good example of an isobarically-cooled terrain (Dirks and Wilson, 1990; Clarke and Powell, 1991; Collins and Vernon, 1991; Dirks *et al.*, 1991). However, Hand *et al.* (1992) have

recently suggested that an appearance of isobaric cooling resulted from the overprinting of successive high-grade metamorphic events in the area, and that a period of decompression followed each of the two regional metamorphic peaks. This second interpretation is also in agreement with recent results from the study area. Many metamorphic reaction textures in the Mg- and Al-rich rocks from the study area appear consistent with decompression at high tempera-

tures close to the peak of the regional granulite facies metamorphism. These textures and their implications in terms of the metamorphic history of the Reynolds Range region are discussed in detail elsewhere (Vry and Cartwright, in press).

Study area

The kornerupine-bearing rock samples were collected from an area of approximately 5 × 5 m (Fig. 2) near the eastern end of a large pod or lens of Mg-rich aluminous rocks, a few tens of

metres wide and several tens of metres long, that crops out near Sandy Creek in the Reynolds Range at approximately 133°05'E and 22°27'S (Fig. 1). The samples consist almost entirely of nearly boron-free kornerupine and its breakdown products, sapphire, cordierite, and orthopyroxene or gedrite. Closely-associated rocks are composed largely of spinel, orthopyroxene, and phlogopite, ± gedrite; phlogopite and spinel; cordierite and orthopyroxene ± gedrite; kornerupine and sapphire; and cordierite ± quartz (Fig. 2). Parts of the pods are nearly monomineralic over areas of more than 1 m². This and similar smaller pods occur sporadically within low-pressure granulite-facies exposures of the early Proterozoic Lander Rock beds (750 to 800°C and approximately 4.5 kbar; Clarke and Powell, 1991; Dirks *et al.*, 1991), where they represent only a tiny part (<< 1%) of the overall outcrop area.

The Lander Rock beds are a laterally-extensive sequence of folded pelitic metasediments that are in parts highly magnesian. In the vicinity of the study area the Lander Rock beds include large amounts of cordierite-rich quartzite ($X_{Mg} \geq 0.85$), and cordierite-rich metapelitic rocks with little or no feldspar. These country rocks preserve the dominant regional metamorphic structures, which are characterized by km-scale, NW-trending, tight upright folds with a penetrative, subvertical axial planar gneissic foliation.

The Mg- and Al-rich rocks in the pods, by contrast, form a distinctive suite of non-foliated, coarse-grained (0.5 to > 15 cm) metamorphic rocks that have unusual bulk compositions and fairly simple, high-temperature mineral assemblages (Vry and Cartwright, in press). The rocks in the pods are also characterized by low- $\delta^{18}O$ values ($\delta^{18}O_{\text{whole rock}} \lesssim 2\text{--}6\text{‰}$ relative to SMOW), and high, 'igneous' deuterium values ($\delta D = -51.5$ to -65.6‰ for phlogopites). The stable isotope results will be presented in detail in subsequent papers.

Analytical methods

Whole-rock analyses of major and trace elements were obtained by XRF at the School of Earth Sciences, University of Melbourne, Parkville, Victoria, Australia. Minerals were analysed at the school of Earth Sciences, Macquarie University, North Ryde, NSW, Australia, using a fully automated ETEC electron microprobe equipped with 3 crystal spectrometers and a Link Systems EDS. The accelerating voltage was 15 kV, and the sample current was 3 nA. The electron microprobe analyses were obtained using a combination of energy-dispersive (EDS) and wavelength-disper-

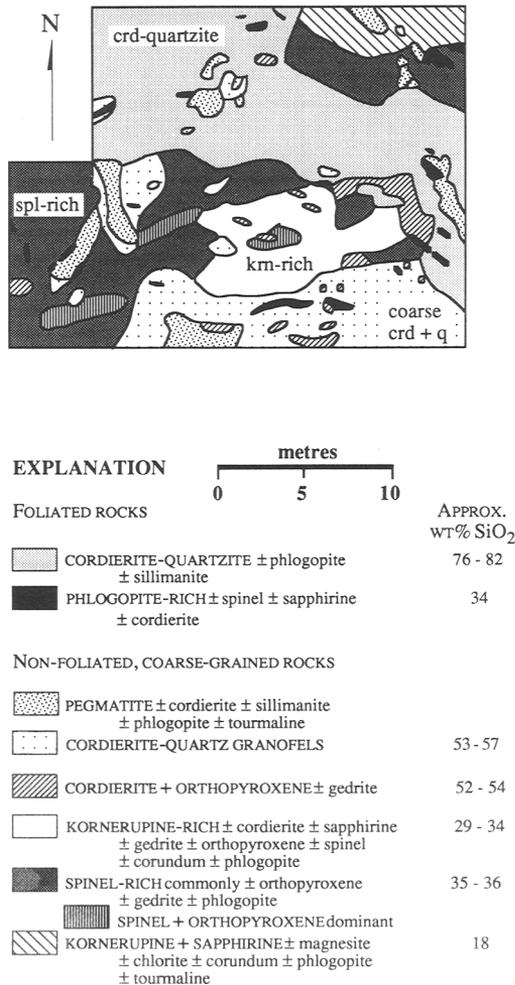


FIG. 2 Sketch map of the eastern end of the kornerupine-bearing pod, showing outcrop pattern of major rock types.



FIG. 3. Texture attributed to the breakdown of nearly boron-free kornerupine: optically-continuous relics of kornerupine cut by coarse symplectitic intergrowths of sapphirine + cordierite ± gedrite ± orthopyroxene; width of figure = 15 mm.

sive methods, with major elements analysed by EDS. Data reduction was carried out on-line using Bence-Albee (WDS) and ZAF (EDS) correction procedures. A preliminary investigation of the chemistry of fluid inclusions in the kornerupine-bearing rocks was undertaken using inductively-coupled mass spectrometry (ICPMS). This method is suitable for the detection of a wide variety of cationic species, but was not used to analyse for Ca because of chemical interferences. The rock samples were crushed in a TEMA tungsten carbide mill, leached for 2 weeks at room temperature in approximately twice their volume of deionized water, and filtered to remove particles larger than 0.45 µm in diameter. Qualitative assays of the leachate solutions were obtained using the VG Plasmaquad PQ2+ ICPMS in the Department of Earth Sciences, Monash University, Clayton, Victoria. Kornerupine was analysed for H₂O and boron according to the methods of Werdning and

Schreyer (1978) at the Institut für Mineralogie, Ruhr-Universität Bochum.

Petrography

The mineral assemblages in sample XF-4, from which the kornerupine has been analysed for boron, and a similar sample (XF-2) are shown in Table 1. Each of these rocks consists almost entirely of kornerupine and its breakdown products, sapphirine, cordierite, and gedrite ± orthopyroxene. The absence of boron-bearing minerals such as tourmaline in the product assemblages first suggested that the kornerupine in these rocks might contain very little boron; this was confirmed by chemical analysis of the kornerupine from sample XF-4.

Sample XF-4 consists of large, optically-continuous relics of faintly-pleochroic, colourless to pale blue kornerupine (Fig. 3). The kornerupine contains only 0.45 wt.% B₂O₃, corresponding to 0.098 B atoms per 22 (O, OH), and closely approximates 11:10:11 in terms of molar ratios of (MgO + FeO_{total}): Al₂O₃: SiO₂, with $X_{Mg} = Mg/(Mg + Fe_{total}) = 0.874$. This kornerupine is cut by spectacular, coarse (to > 2 cm in length) symplectitic intergrowths of colourless cordierite ($X_{Mg} = 0.94$), sapphirine ($X_{Mg} = 0.87$) that is pleochroic in blue to pale tan, and pale brown, faintly-pleochroic gedrite ($X_{Mg} = 0.835$) (Fig. 3). The gedrite contains Na, minor Ca, and F (Na ≈ 0.45 moles p.f.u.; Ca ≈ 0.07 moles p.f.u.; F ≈ 0.21 moles p.f.u.) that are not detected in electron microprobe analyses of the kornerupine. These elements were probably introduced with H₂O at the time of the kornerupine breakdown. Qualitative ICPMS analyses of water-soluble extracts of the fluid inclusions in these rocks suggest that the aqueous fluid also contained soluble species of K and Mg, ± minor Al.

TABLE 1. Mineral assemblages* of kornerupine-bearing rocks from the Reynolds Range, N.T., Australia

Sample number	krn	phl	sa	ged	crd	spl	opx	c
XF-4**	BF (1)	(1 or 2)	(2)	(1?, 2)	(2 & 3)	(3)	(2)	
XF-2**	NA(1)	(1 or 2)	(2-3)	(2)	(2 & 3)	(1 & 3)	(1, 2, 3)	(2?)

Notes: * Mineral abbreviations: crd, cordierite; c, corundum; ged, gedrite; krn, kornerupine; opx, orthopyroxene; phl, phlogopite; sa, sapphirine; spl, spinel.

** BF, boron-free; NA, not analysed for boron; (1) Texturally-early: corroded relics of coarse grains; (2) Texturally-secondary: coarse, symplectitic intergrowths of spl, ged and/or opx, and crd, replacing krn; finer c ± opaques replacing spl (1); (3) Smaller-scale intergrowths: crd + spl replacing krn; spl + opx associated with crd and coarse krn.

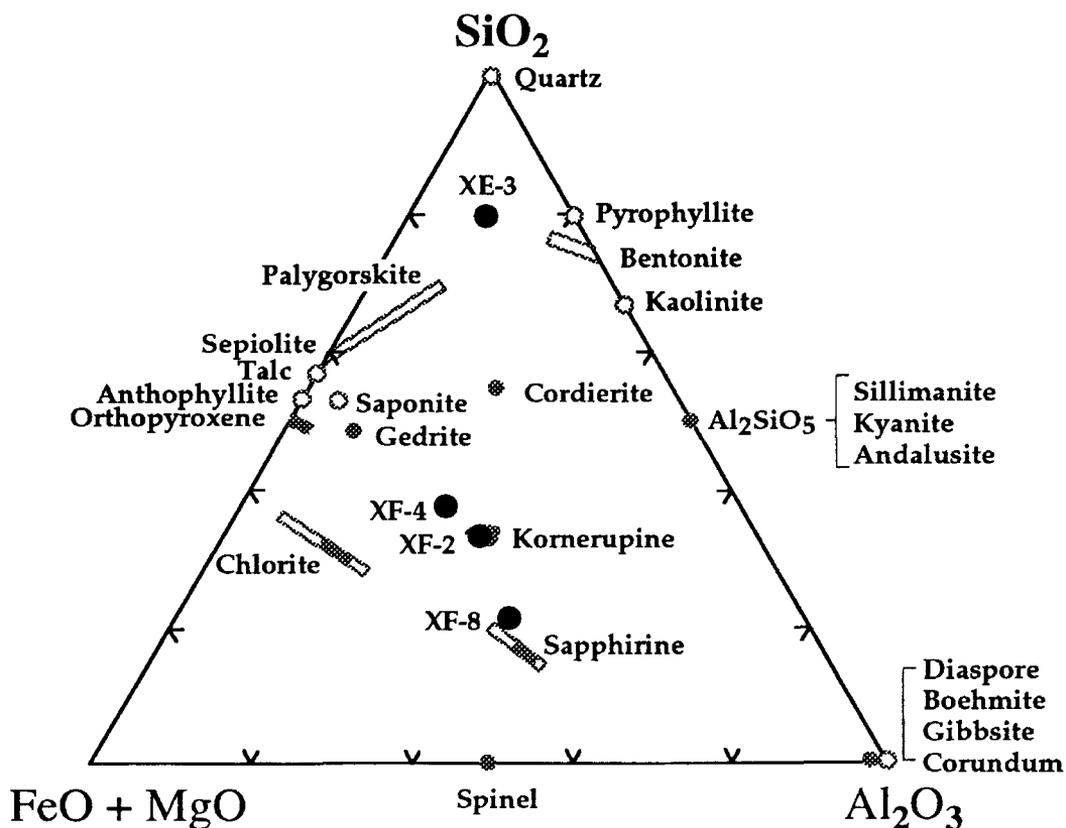


FIG. 4. Ternary plot into plane molar SiO_2 , Al_2O_3 , ($\text{MgO} + \text{FeO}$), showing whole-rock compositions (large black filled circles) of kornerupine-bearing samples (XF-2, XF-4, XF-8) and the cordierite-quartzite country rock (XE-3), and also showing mineral compositions (filled symbols, analyses of high-temperature minerals from study area; open symbols, for reference purposes).

Phlogopite is an accessory mineral in the rock, and is pleochroic from colourless to medium brown. Minor amounts of cordierite and green spinel also occur as smaller-scale intergrowths replacing kornerupine.

Sample XF-2 shows similar textures, but with much less gedrite and more orthopyroxene, probably reflecting local variability in the activities of species including H_2O and Na^+ . Local variability in fluid amounts or fluid speciation is also suggested by the presence of boron-bearing kornerupine in samples collected less than 10 m away, in rocks that are composed almost entirely of coarse crystals (to > 8 cm) of pale blue, boron-bearing kornerupine (2.18 wt.% B_2O_3 ; $X_{\text{Mg}} = 0.892$) and blue sapphirine ($X_{\text{Mg}} = 0.900$) (sample XF-8).

Kornerupine compositions

Representative electron microprobe analyses of kornerupines from the study area are shown in Table 2; an analysis of the boron-free kornerupine from the Limpopo Belt (Grew *et al.*, 1990) is included for comparison. The kornerupines from the study area are all Mg-rich, with X_{Mg} values between approximately 0.85 and 0.92.

Whole-rock geochemistry

Whole-rock analyses of kornerupine-bearing rocks from the study area are given in Table 3, and an analysis of the associated cordierite-quartzite country rock, sample XE-3, is included for

TABLE 2: Kornerupine analyses

Ref. no.*	9365	XF-4	XF-2	XF-8
	Weight percent			
SiO ₂	28.62	29.89	27.40	29.87
TiO ₂	0.13	b.d.	b.d.	b.d.
Al ₂ O ₃	48.20	46.04	45.73	43.53
Fe ₂ O ₃	0.18	-	-	-
FeO	3.06	-	-	-
FeO _{tot}	-	4.45	5.44	4.03
MnO	0.05	b.d.	b.d.	b.d.
MgO	17.23	17.36	16.96	18.61
CaO	0.07	b.d.	b.d.	b.d.
Na ₂ O	0.04	b.d.	b.d.	b.d.
BeO	0.0003	n.a.	n.a.	n.a.
B ₂ O ₃	0	0.45**	n.a.	2.18**
F	0.63	b.d.	b.d.	0.12
H ₂ O	1.52	0.96**	n.a.	0.42**
Total†	99.46	99.15	(95.53)	98.71
	Normalized to 21.5 oxygens			
Si	3.551	3.737	3.560	3.750
Al	7.049	6.786	7.004	6.442
Ti	0.012	b.d.	b.d.	b.d.
Fe ³⁺	0.017	-	-	-
Fe ²⁺	0.317	-	-	-
Fe _{tot}	-	0.465	0.591	0.417
Mn	0.005	b.d.	b.d.	b.d.
Mg	3.187	3.235	3.284	3.430
Ca	0.009	b.d.	b.d.	b.d.
Na	0.010	b.d.	b.d.	b.d.
B	0.000	0.097	n.a.	0.465
F	0.247	b.d.	b.d.	0.047
OH	1.254	0.800	n.a.	0.346

Notes: *Sample 9365, included for comparison purposes, collected by W. Schreyer at Sinyoni Claims, from lenses within the anorthosites of the Messina layered intrusion in the Limpopo Belt of Zimbabwe (Schreyer and Abraham, 1976a; Klaszka and Grew, 1991; Grew *et al.*, 1990); samples XF-4, XF-2, and XF-8 from the Reynolds Range, N.T., Australia, this study.

**Analyses provided by the Analytical Laboratory of the Institute für Mineralogie, Bochum.

†Adjusted for F.

comparison. The kornerupine-bearing rocks are both Mg- and Al-rich and extremely silica-undersaturated. The bulk compositions of samples XF-4 and XF-2 plot close to kornerupine in terms of SiO₂, Al₂O₃, and (MgO + FeO_{total}), and the composition of sample XF-8 lies between kornerupine and sapphirine (Fig. 4). Both the cordierite-quartzite country rocks and the kornerupine-bearing samples from the pods have high Mg/

(Mg + Fe) ratios and extremely low contents of Cr, Ni, and V. In addition, the kornerupine-bearing rock samples can have elevated contents of Zr, U, Th, Y, Ce, and Cl, with larger amounts in the more silica-undersaturated specimens.

Origin of the kornerupine-bearing rocks

The unusual compositions of the rocks in the pods, and their Mg-rich country rocks, could result from a variety of different processes. Worldwide, most occurrences of Mg-rich rocks such as whiteschists and cordierite-anthophyllite rocks have been explained by one of the following three general models:

(1) *nearly-isochemical metamorphism* of unusual protoliths, such as Mg-rich clays (Touret and De la Roche, 1971; Schreyer and Abraham, 1976b; Schreyer, 1977; Warren, 1979; Waters and Moore, 1985), or weathered or hydrothermally-altered basic volcanogenic materials (McKie, 1959; Chinner and Sweatman, 1968; Woodford and Wilson, 1976a; Robinson *et al.*, 1982; Windley *et al.*, 1984);

(2) *partial melting of pelitic rocks*, with subsequent removal of the anatectic granitic melt to leave a restite enriched in Al, Fe, Mg and immobile elements, and impoverished in Na, K, Ca and Si (Grant, 1968; Lal and Moorhouse, 1969; Nixon *et al.*, 1973; Clifford *et al.*, 1975; Lal *et al.*, 1978); or

(3) *metasomatism* (Hudson and Wilson, 1966; Woodford and Wilson, 1976b; Warren, 1979; Allen, 1979; Waters and Moore, 1985; Warren and Hensen, 1987).

The kornerupine-bearing rocks and the other coarse-grained rocks in the pods were probably not formed by partial melting of pelitic rocks. There is little evidence for partial melting, such as the development of granitic veins, in the bedded metapelitic and quartzose gneisses adjacent to the pods. Most of these country rocks lack feldspars, and thus would not be expected to produce large amounts of felsic melts at the conditions of metamorphism in the Reynolds Range. The limited partial melting that occurred in the uncommon feldspar-bearing pelitic country rocks did not disrupt the bedding or produce extremely aluminous, coarse-grained, Mg-rich enclaves. The kornerupine-bearing rocks are restricted to rare, isolated, large pods of coarse-grained, non-foliated rocks that have a high degree of Al-enrichment and that are not associated with large volumes of partial melts. It is improbable that large amounts of felsic melts formed in, and were effectively extracted and removed only from these pods, and

TABLE 3a. Major element compositions (wt.%) of kornerupine-bearing rocks from the study area, and cordierite-quartzite country rock.

	cordierite-quartzite	kornerupine-bearing samples		
	XE-3	XF-4	XF-2	XF-8
SiO ₂	76.53	34.01	28.98	17.77
TiO ₂	0.10	0.11	0.15	0.06
Al ₂ O ₃	13.98	38.38	46.04	54.87
Fe ₂ O ₃	1.74	5.71	5.43	4.11
MnO	0.01	0.04	0.03	0.03
MgO	5.75	19.43	17.09	17.86
CaO	0.01	0.16	0.39	0.06
Na ₂ O	0.07	0.43	0.10	0.14
K ₂ O	0.45	0.11	0.22	0.12
P ₂ O ₅	0.01	0.04	0.33	0.06
L.O.I.	1.01	0.85	0.95	2.86
Total	99.71	99.33	99.85	98.14

L.O.I. = Loss on ignition

therefore the rocks in the pods are not interpreted to be melt restites.

Neither the cordierite-rich country rocks nor the kornerupine-bearing rocks in the pods are likely to have been produced by nearly-isochemical metamorphism of basic volcanogenic materials. The rocks have extremely low contents of Cr, Ni, and V that are unlike altered mafic rocks (Reinhardt, 1987). In any case, mafic or ultramafic rocks are extremely uncommon in the quartzose and metapelitic Lander Rock beds, and the rare mafic sills have typical metabasaltic mineral assemblages.

Pelitic or quartzose sediments containing Mg-rich minerals such as sepiolite, palygorskite, or saponite (see Fig. 4) are possible precursors of the bedded cordierite-rich metapelites and cordierite-quartzites (e.g. sample XE-3, Fig. 4). The Cr-, Ni-, and V-poor bulk compositions of these rocks (Table 3b) are comparable to analyses of Mg-rich evaporitic clays (op. cit.). The Mg-rich compositions are unlike high-alumina laterites or bauxites, which form under good drainage conditions where Mg is extensively leached. If the bulk chemical compositions of the country rocks reflect the original sedimentary compositions, and not later alteration, they should provide insights into the early Proterozoic sedimentary setting. Modern deposits of magnesian clays may form especially where wind-blown aluminum-rich detrital materials from a lateritic landmass collect in nearshore settings that are characterized by alkalinity (pH

TABLE 3b. Trace element compositions (p.p.m.) of kornerupine-bearing rocks from the study area, and cordierite-quartzite country rock

	cordierite-quartzite	kornerupine-bearing samples		
	XE-3	XF-4	XF-2	XF-8
Zr	72	74	173	268
U	7	7	17	50
Th	25	27	60	131
Rb	43	13	18	18
Sr	6	6	5	10
Y	41	45	133	248
V	4	20	16	22
Cr	< 3	< 3	< 3	< 3
Ni	12	36	44	77
Nb	6	2	2	2
Zn	19	46	40	< 2
Pb	< 4	< 4	12	28
Ba	51	32	38	20
Ga	35	30	31	71
S	< 15	< 15	< 15	55
Cl	38	50	478	641
Sc	< 3	9	16	8
Ce	20	22	98	202
Nd	< 15	< 15	34	85
Co	125	107	115	67
Cu	< 3	4	< 3	< 3
As	21	6	18	9

values between approximately 7.5 and 9.5), water stagnation and evaporation, moderate salinities, and a warm climate, usually in the latitudes between about 30 and 40° north or south (Velde, 1977; Callen, 1984).

Although the country rocks are bedded pelitic metasediments, the chemical, textural, and especially the stable isotope characteristics of the coarse-grained rocks in the pods cannot be explained by isochemical metamorphism of a low-temperature, clay-rich protolith. The rocks in the pods have both low $\delta^{18}\text{O}$ values ($\delta^{18}\text{O}_{\text{whole rock}} \approx 2-6\text{‰}$ relative to SMOW) and relatively high 'igneous' deuterium values ($\delta\text{D} = -51.5$ to -65.6‰ for phlogopites). This combination of $\delta^{18}\text{O}$ - and δD -values is not typical of metamorphosed pelitic sedimentary rocks.

Clay minerals and aluminum hydroxides that form at surficial temperatures in contact with meteoric waters have δD - and $\delta^{18}\text{O}$ -values that depend on the meteoric water relationship $\delta\text{D} = 8 \delta^{18}\text{O} + 10$ (Hoefs, 1987). Thus, on a δD - versus $\delta^{18}\text{O}$ -diagram, sedimentary clays plot parallel to the meteoric water line and close to the 'kaolin line' along approximately $\delta\text{D} = 8 \delta^{18}\text{O} - 230$. Aluminum hydroxides such as gibbsite have $\delta^{18}\text{O}$ -

values approximately 10‰ lower than kaolinites formed in contact with the same meteoric waters at surficial temperatures (Savin and Lee, 1988), whereas Mg-rich clay minerals such as saponite have $\delta^{18}\text{O}$ -values approximately 8‰ higher (Kyser, 1987).

The $\delta^{18}\text{O}$ -values of the rocks from the study area are much lower than those of common sandstones, marine shales, marine carbonates, or cherts ($\delta^{18}\text{O}$ -values near 10‰; 14–19‰; 25‰; and as high as 44‰, respectively; Hoefs, 1987). Metamorphic dehydration reactions can produce only very small shifts (< 1‰) in the $\delta^{18}\text{O}$ -values of rocks (Hoefs, 1987). Thus, metamorphic dehydration of any chemically-appropriate sedimentary mixture of clays, detrital minerals, and aluminum hydroxides, \pm sedimentary magnesite, would not be expected to form the low $\delta^{18}\text{O}$ -values (\approx 3.4‰) of the kornerupine-rich rocks. Although low-temperature clay minerals formed at high latitudes could in theory have relatively low $\delta^{18}\text{O}$ -values similar to the rocks in the study area, such clays should also be characterized by extremely low initial δD -values, below approximately -140 ‰. Dehydration reactions encountered during metamorphism to high-grade conditions would cause these δD -values to become more negative, and thus even more dissimilar to the values of the rocks from the study area. Taken together, the unusual $\delta^{18}\text{O}$ - and δD -values show that the coarse-grained rocks from the pods were not formed by nearly-isochemical metamorphism of surficial sedimentary rocks.

An entirely sedimentary origin for the rocks in the pods also appears inconsistent with current interpretations of the regional metamorphic-deformation history. The rocks in the study area have undergone two separate episodes of metamorphism and deformation, the first of which probably attained granulite-facies conditions with temperatures similar to, or higher than those of the second granulite-facies metamorphism (Hand *et al.*, 1992). Any metasedimentary rocks would have undergone two episodes of high-grade metamorphism and deformation, and might be expected to preserve some evidence of at least the second high-grade deformation fabric.

The lack of foliation and coarse grain sizes of the rocks within the pods, where kornerupine crystals are typically 5–10 cm in length, and the unusual bulk compositions and nearly monomineralic nature of the kornerupine-bearing rocks in particular (see Fig. 4, samples XF-2, XF-4, and XF-8), are also atypical of metamorphosed pelitic or metapelitic rocks. The kornerupine-bearing rocks, for example, would require unlikely

sedimentary precursors substantially richer in both magnesite and aluminum hydroxides than most metamorphosed evaporitic clays, which plot between chlorite and quartz on Fig. 4. The unusual textures, mineral assemblages, and bulk chemical compositions all support the interpretation that the coarse-grained minerals in the pods grew at high temperatures in a fluid-rich environment, and largely post-date the high-grade regional metamorphic fabric.

The characteristic features of the rocks in the pods probably reflect, at least in part, the action of metasomatic fluids. The enrichment of relatively-immobile elements such as Zr, U, Th, Y, and Ce in many of the kornerupine-bearing rocks, with larger amounts in the more silica-undersaturated specimens, suggests that these rocks are residua, and the concomitant enrichment in chlorine (Table 3b) supports a model involving fluid transport. The extreme desilicification, the low- $\delta^{18}\text{O}$ values, and the preservation of highly magnesian bulk compositions in the rocks from the pods suggest that the metasomatic fluid may have been derived from a mafic or ultramafic source.

The metasomatism probably occurred after the overlying sediments of the Reynolds Range group were deposited. Rocks that are closely comparable to the orthopyroxene + spinel rocks from the study area (Fig. 2) also occur above the regional unconformity in the overlying Reynolds Range group, in association with rocks that are interpreted to reflect fluid infiltration (I. Cartwright and I. Buick, *pers. comm.*, 1992).

Although it is not possible to unambiguously determine whether the pods were produced (1) by some combination of early processes that occurred prior to the final high-grade metamorphism and deformation, or (2) by metasomatism at high temperatures, close to the peak of the final regional granulite-facies metamorphism, model (2) is considered somewhat more likely.

Early processes (1) might help explain the unusual chemical and isotopic compositions of the kornerupine-bearing rocks, and also the presence of abundant boron-free kornerupine in the study area. The unusual chemical and isotopic compositions of the kornerupine-bearing rocks could have resulted if early processes removed silica and produced relatively high-temperature concentrations of Mg-rich chlorite \pm talc \pm magnesite, and aluminum hydroxides \pm micas \pm clays. Subsequent complete breakdown of these minerals during prograde metamorphism would have released fluids, possibly promoting the local growth of large crystals in the pods.

Early processes might also help explain the presence of large amounts of nearly boron-free

kornerupine in the study area. Kornerupine is a hydrous mineral, and the coarse grain sizes strongly suggest that it grew in the presence of a fluid phase.

However, in the presence of Na^+ , boron-free kornerupine is likely to be unstable relative to assemblages involving gedrite (Schreyer and Abraham, 1976a), and most water-rich metamorphic fluids contain some NaCl. Clearly, the introduction of fluids containing Na, Ca, H_2O , and F, while the region was still at high temperatures, caused the kornerupine in the study area ($X_{\text{Mg}} = 0.874$) to undergo partial breakdown, forming the symplectitic intergrowths of sapphirine ($X_{\text{Mg}} = 0.867$), cordierite ($X_{\text{Mg}} = 0.943$), and gedrite ($X_{\text{Mg}} = 0.835$; $\text{Na} \approx 0.45$ moles per formula unit, p.f.u.; $\text{Ca} \approx 0.07$ moles p.f.u.; $\text{F} \approx 0.21$ moles p.f.u.; Vry and Cartwright, in press).

Nevertheless, prograde devolatilization of earlier mineral assemblages would not normally be expected to form nearly monomineralic rock types, which are a characteristic feature within the pods. Furthermore, the non-foliated, and in some cases radiating mineral textures of the rocks in the pods strongly suggest that the growth of the coarse-grained minerals occurred late, largely post-dating the second high-grade regional deformation. These observations support interpretation (2), that the Mg- and Al-rich rocks from the pods formed by metasomatism at high temperatures, close to the peak of the final regional granulite-facies metamorphism. High-temperature metasomatic fluids could have promoted the growth of coarse-grained, high-temperature minerals such as kornerupine, and may have caused local extensive desilicification and isotopic re-equilibration of precursors such as sedimentary magnesian clays.

P-T conditions

Figure 5 shows that previous estimates of the peak metamorphic conditions in the study area (750 to 800°C and 4.1 ± 0.3 kbar, Dirks *et al.*, 1991; 4.5 ± 1 kbar, Clarke and Powell, 1991) are generally compatible with the results of experimental studies of the stability of boron-free kornerupine by Seifert (1975). The previous pressure estimates for this part of the Reynolds Range were obtained for the metapelitic country rocks, using the quantitative, average *P-T* approach outlined by Powell and Holland (1985, 1988) with the expanded, internally consistent thermodynamic data set of Holland and Powell (1990).

The experimental studies by Seifert (1975) show that boron-free kornerupine has an extensive

stability field at $T > 735^\circ\text{C}$, $P_{\text{H}_2\text{O}} \geq 4.5$ kbar in the system $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$. Because the stability field is limited at the lowest pressures (Fig. 5), boron-free kornerupine is considered to be most likely to occur in high-grade rocks that have been metamorphosed under relatively high-pressure conditions. These samples from the Reynolds Range show that boron-free kornerupine can occur abundantly at pressures close to or slightly above 4.5 kbar.

The positions of the limiting equilibria curves shown in Fig. 5 will be affected to some degree by additional components present in natural rocks. The stability of boron-free kornerupine will be affected by the substitution of Fe for Mg in the silicates, and, perhaps more importantly in these Mg-rich rocks, by the stabilization of gedrite by Na. Schreyer and Abraham (1976a) have suggested that the addition of Na^+ could cause boron-free kornerupine to break down, within the stability field shown in Fig. 5, to form symplectitic intergrowths of sapphirine, cordierite, and gedrite that are comparable to those seen in the Reynolds Range. The positions of the limiting equilibrium curves that are labelled in Fig. 5 will also be shifted to lower temperatures and the entire stability field could be extended to somewhat lower pressures by any reduction of the activity of H_2O in a coexisting fluid phase. The presence of the additional components Na_2O , CaO, and F in the gedrites shows that the activity of H_2O was < 1 at the time that the symplectitic intergrowths formed.

Conclusions

Nearly boron-free kornerupine is locally abundant in large, isolated pods of coarse-grained, non-foliated, Mg- and Al-rich rocks from high-grade portions of the Reynolds Range, N.T., central Australia, and may also occur in other nearby areas of the Arunta Block. The samples consist almost entirely of coarse-grained, Mg-rich kornerupine ($X_{\text{Mg}} = 0.874$) that has undergone partial breakdown to produce coarse symplectitic intergrowths of sapphirine, cordierite, and gedrite or othopyroxene. The pods occur within high-temperature, low-pressure granulite-facies (750–800°C and approximately 4.5 kbar) exposures of early Proterozoic metapelitic rocks, demonstrating that Mg-rich boron-free kornerupine can occur abundantly at these relatively low pressures. The kornerupine and other coarse-grained minerals are interpreted to have formed by metasomatism and high-grade metamorphism of precursors that may have included sedimentary Mg-rich clays. The composition or amounts of these early metasomatic fluids probably varied on a local scale, such

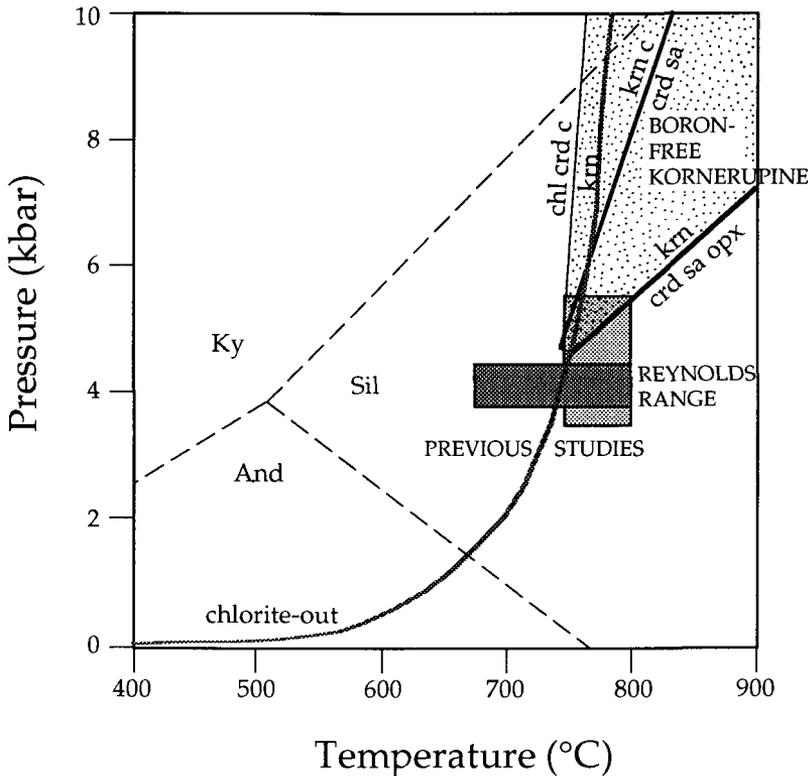


FIG. 5. Previous interpretations of the metamorphic conditions in this portion of the Reynolds Range, N.T. Australia (shaded boxes) are generally consistent with the experimentally-determined stability field of boron-free kornepine (stippled area; Seifert, 1975). The maximum stability of magnesian chlorite is shown according to the results of Jenkins and Chernosky (1986), and McPhail *et al.*, (1990). The aluminosilicate phase diagram of Holdaway (1971) is included as a reference. 1 kbar = 100 MPa.

that rocks composed largely of boron-poor kornepine (0.45 wt.% B_2O_3) occur within a few metres of rocks rich in boron-bearing kornepine (2.18 wt.% B_2O_3). The abundance of gedrite, which indicates later inputs Na, Ca, H_2O , and F, also varies locally. The pods preserve evidence that local, and possibly transient phenomena were an important feature of the high-temperature metamorphic history in this and other adjacent parts of the Arunta Block.

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