Kornerupine in metasomatic zones, Strangways Range, Central Australia

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SUMMARY. The first known occurrence of kornerupine in Australia is described. The mineral is a minor component of a phlogopite-rich garnet–corundum–spinel metasomatic zone, which cuts mafic and ultramafic spinel–plagioclase–orthopyroxene–hornblende rocks. The kornerupine-bearing assemblage was formed during the second major metamorphic episode that affected the terrain, probably under low-grade granulite or upper amphibolite facies conditions. Kornerupine appears to have formed at significantly lower levels of P–T than those reached in the terrain during the peak of the second granulite metamorphism.

Geological setting. The Strangways Range is located approximately 70 km north-east of Alice Springs, in the Precambrian Arunta Complex of central Australia. During an investigation of the high-grade metamorphic rocks in the north-eastern sector of the range, small metasomatic zones transecting the high-grade metamorphic rocks were recognized. Within one of these zones the mineral kornerupine was identified, representing the first known recorded occurrence of this mineral in Australia.

The geochronology and geochemistry of the Strangways Range has been investigated by Rb/Sr and $^{40}Ar/^{39}Ar$ incremental heating techniques (Iyer, 1974; Iyer *et al.*, 1975; Woodford *et al.*, 1976), and by petrographic and geochemical methods (Woodford, 1974). Four major events, two of which are temporally and petrographically distinct granulite-facies metamorphisms, have been identified. The major-element composition of many rocks has been extensively modified by K metasomatism on at least three main occasions: during the first granulite event (M1), dated as 1860±80 Myr; during the second granulite event (M2), dated as 1430±60 Myr; and during the final metamorphic event, a retrogression, dated as 320 to 350 Myr. Another metamorphic event to affect the area, a mild reheating of the terrain at 700 to 800 Myr, effected only minor petrographic modification in the north-eastern regions where this work was done, and no change in bulk rock chemical composition, nor of Sr isotopic equilibrium, has been recognized.

The metasomatic zones formed during M1 are dominated by coarsely mesoperthitic K-feldspar with lesser amounts of quartz and phlogopite, and, in some rocks, garnet.

Metasomatic zones with kornerupine. Of more direct relevance to the present report, however, are the metasomatic zones developed during the M2 event. Chemical analyses both of representative M2 zone samples 356 and 692 and of the dominant coexisting minerals are presented in Table I. In contrast to the M1 metasomatic

zones, the mineralogy of the M2 metasomatic zones is dominated by phlogopite, with lesser amounts of garnet, spinel, and corundum. One large prismatic crystal of korne-rupine (8 mm in cross-section), and very rare, smaller, allotriomorphic grains (average dimension 1·3 mm) of kornerupine have been identified in one zone, sample 692, and in mineral concentrates separated from sample 356.

The coarse kornerupine grain displays a well-developed prismatic cleavage and is weakly pleochroic from colourless (α and β) to pale blue-green (γ). The optic axial angle $2V_\alpha$ is small ($< 5°$) and in several sections of associated grains the mineral appears uniaxial. Absorption is $\alpha \sim \beta < \gamma$. Refractive index data could not be obtained. Marginally the kornerupine is replaced by fine-grained, feathery tourmaline crystals, which are pleochroic from colourless to pale blue.

The kornerupine is set in a matrix of fine-grained phlogopite, which also contains coarse colourless garnet, fine-grained corundum, and green spinel. This spinel fre-quently contains variable amounts of exsolved magnetite. Ilmenite is an additional associated mineral.

An electron-microprobe analysis of kornerupine from sample 692 is presented in Table I. The analysis is an average composition calculated from twenty-four closely comparable probe analyses at various points from a cross-section of the coarse kor-nerupine crystal. Although the kornerupine crystal was analysed systematically, no compositional zoning was detected. The low oxide total (97·38 %) reflects both the presentation of total iron as FeO and lack of estimation of B and H_2O+ in the analyses. Similar low summations have been recorded by Herd (1973), and are to be expected when the normal levels of water and B from other kornerupines are considered. The high total FeO content (9·36 %) indicates that the kornerupine is iron-rich, reflecting the iron-rich composition of sample parent rock 692, Table I (compare the analysis of this kornerupine with the selected analyses assembled in Knorring et al., 1969).

The garnet coexisting with the kornerupine and phlogopite is an almandine–pyrope typical of granulites, and contains less than 3 % combined spessartine–andradite—grossular components (i.e. pyrope 40 %, almandine 57 %).

F was not measured in phlogopite from sample 692, the kornerupine rock. However, a similar phlogopite from sample 356 from a related metasomatic zone contains low F (0·29 %), suggesting F was not a significant component of the kornerupine-forming metasomatizing fluids.

Utilizing the distribution data of Perchuk (1968, 1970), the Fe–Mg partition between garnet and phlogopite suggests an equilibration temperature between 620 and 640 °C. Although textural evidence, which indicates equilibrium coexistence of the garnet, phlogopite, and kornerupine, is unambiguous, the reliability of this temperature estimate, an Fe–Mg equilibration temperature, cannot yet be established.

Oxide minerals in sample 692 consist of trace green spinel. In sample 356 there are both ilmenite and green spinel with exsolved magnetite. The green spinel is hercynite and commonly contains some Zn (e.g. $\approx$ 0·6 % Zn in sample 356 spinel).

The relationship between the kornerupine-bearing metasomatic zones and the host granulites is clearly evident in the field. Sample 356 is a phlogopite zone that cuts a metamorphosed layered mafic–ultramafic body. An analysis of a representative

TABLE I. *Chemical analyses of kornerupine-bearing metasomatic zones cutting ultramafic granulites*

	1*	2†	3†	4†	5†	6*	7*	8*‡	9§	10*
SiO_2	36·68	29·00	38·30	38·19	0·30	34·48	36·43	39·38	—	45·97
TiO_2	0·41	—	1·06	—	—	2·55	2·65	0·03	—	0·20
Al_2O_3	25·33	44·54	17·98	22·78	61·15	24·11	18·15	23·01	57·84	13·60
Fe_2O_3	2·94	NA	NA	NA	NA	3·62	3·08	0·53	NA	3·86
FeO	15·28	9·36	7·77	26·72	23·22	13·29	9·26	26·25	33·52	7·87
MnO	0·18	—	—	0·33	—	0·11	0·01	0·33	—	0·19
MgO	13·83	14·48	19·72	11·53	12·01	12·87	16·14	10·34	8·62	18·55
CaO	0·04	—	—	0·29	—	0·14	0·09	0·67	—	7·14
Na_2O	0·08	—	—	—	—	0·30	0·57	0·01	—	0·76
K_2O	4·11	—	9·70	—	—	5·63	9·44	0·01	—	0·24
P_2O_5	0·02	—	—	—	—	NA	NA	NA	NA	0·05
F	NA	NA	NA	NA	NA	NA	0·29	NA	NA	NA
Cl	NA	NA	NA	NA	NA	0·03	0·03	NA	NA	NA
H_2O^+	1·20	NA	NA	NA	NA	3·14	3·81	NA	NA	1·23
H_2O^-	0·10	NA	NA	NA	NA	0·21	0·24	NA	NA	0·23
Total	100·20	97·38	94·52	99·84	96·68¶	100·48	100·06	100·56	99·98	99·89

Recalculated on the basis of:

	21(O)||	22(O)	24(O)	32(O)	24(O, OH, F)	24(O)	32(O)
Si	3·67	5·54	5·85	0·07	5·329	5·964	—
Al^{iv}	}6·64	}3·07	}4·11	}15·79	2·671	0·036	}15·161
Al^{vi}					0·459	4·068	
Ti	—	0·12	—	—	0·292	0·003	—
Fe^{3+}	NA	NA	NA	NA	0·339	0·060	
Fe^{2+}	0·99	0·94	3·52	4·26	1·133	3·325	6·232
Mn	—	—	0·04	—	0·001	0·042	—
Mg	2·73	4·25	2·63	3·92	3·518	2·334	2·856
Ca	—	—	0·05	—	0·014	0·109	—
Na	—	—	—	—	0·162	—	—
K	—	1·79	—	—	1·762	—	—
OH	—	—	—	—	3·718	—	—
F	NA	NA	NA	NA	0·138	—	—

* XRF analyses, with FeO by titration and Na_2O by flame photometry.

† Microprobe analyses; total Fe expressed as FeO.

‡ Almandine 57·2, pyrope 40·2, andradite 1·5, spessartine 0·7, grossular 0·3.

§ Major analysis by electron microprobe, with total Fe expressed as FeO; trace analysis by XRF.

|| Formula calculated for 21(O) for a quarter of the unit cell as is appropriate for an analysis lacking H_2O^+ determination (Moore and Bennett, 1968).

¶ Contains Zn, but not measured.

—: not detected; NA: not analysed.

Trace-element analyses (in ppm):

	6	7	8	9	10
Rb	346	567	1	NA	9
Sr	4	4	—	NA	7
Zr	543	7	57	25	15
Cu	229	136	—	183	10
Ni	184	170	2	108	624
Co	98	45	78	984	77
Cr	391	223	136	1204	1732
V	356	424	33	1303	87
Pb	7	50	3	14	4
Zn	299	89	68	5971	122
Ba	934	1210	27	38	40

1. Sample 692, kornerupine-bearing garnet–phlogopite rock.

2, 3, 4, and 5 are kornerupine, phlogopite, garnet, and spinel, respectively, from sample 692, 5·8 km SSW of Woolanga Bore.

6. Sample 356, kornerupine-bearing garnet–phlogopite rock, a metasomatic zone cutting sample 355, 5·0 km WSW. of Woolanga Bore.

7, 8, and 9 are phlogopite, garnet, and spinel, respectively, from sample 356.

10. Sample 355, pleonaste–bronzite–hornblende granulite.

ultramafic rock, sample 355, is included in Table I. The mineralogy of this ultramafic granulite is dominated by tschermakitic hornblende and orthopyroxene with minor spinel, all of which are in textural equilibrium. Since the layered mafic-ultramafic body is largely inhomogeneous, there is no certainty that sample 355 represents the host rock of the zone prior to its metasomatism. However, there can be little doubt that the pre-metasomatism chemical composition would have been similar to that shown by sample 355.

Comparison of the analyses of the zone samples 356 and 692 with the ultramafic granulite analysis 355 indicates markedly different major element levels between the metasomatic zones and the pre-metasomatized parent rock. In the metasomatic zone samples K_2O and Al_2O_3 are much higher, reflecting the growth of phlogopite and garnet and the modal increase of spinel; TiO_2 is greater in sample 356, reflecting the development of ilmenite; SiO_2 is lower in the metasomatic zones, reflecting the elimination of orthopyroxene from the mineral assemblage. Major modification has also occurred in the trace-element levels as seen by comparison of samples 355 and 356. Rb, Zr, Cu, Zn, and Ba are significantly greater in the metasomatic zones; the increase of V in the zone sample 356 reflects the increasing abundance of ilmenite; the increase in Cu reflects the development throughout the area of minor Cu mineralization associated with the metasomatizing fluids; the elements Ni and Cr, high in the ultramafic granulite, are correspondingly decreased in the metasomatic zone.

Trace-element distribution in the coexisting minerals both from the metasomatic zones and from the granulite terrain has been investigated in detail (Woodford, 1974). In the metasomatic zone sample 356 the dominant minerals are garnet, phlogopite, and spinel. The trace elements Rb and Ba are concentrated in phlogopite, whereas spinel contains particularly high Zn and high Co, Cr, and V. Cu and Ni are preferentially incorporated into phlogopite and spinel rather than garnet. Garnet contains no significant concentration of any of the trace elements here investigated.

In contrast to the assemblage in the rocks here described, numerous workers have recorded kornerupine from sapphirine- and orthopyroxene-bearing assemblages (Haapala et al., 1971; Herd, 1973; Herd et al., 1969; Knorring et al., 1969). Herd et al. (1969) attributed the formation of kornerupine in Greenland to upper amphibolite facies conditions, as is also indicated by the assemblage described by Balasubrahmanyan (1965) from India. Schreyer and Seifert (1969), utilizing experimental techniques, have investigated possible fields of stability for kornerupine-bearing assemblages. However, the Fe-rich composition here encountered, and the greater chemical complexity of the natural system (an open system) minimize specific use of the stability fields experimentally determined on closed systems.

The absence of orthopyroxene from the kornerupine assemblages in the Strangways Range does not permit unequivocal classification of the assemblages as belonging either to the granulite facies or to the upper amphibolite facies. Petrographic evidence from adjacent rock types strongly suggests coeval formation of a petrogenetically similar phlogopite rock containing sapphirine. The phlogopite–sapphirine assemblage post-dates the formation of the sillimanite–orthopyroxene–quartz assemblage diagnostic of the maximum P–T conditions reached during the M2 event. Sapphirine,

however, has not been observed in the most highly phlogopitic zones, and its absence is attributed to a lack of SiO_2 required to react with spinel in the reaction 2 spinel+ I silica → I sapphirine. Samples from the metasomatic zones, mineralogically dominated by phlogopite ($SiO_2 \approx 38 \cdot 30$ %), have been found to contain less SiO_2 than adjacent sapphirine-bearing rocks. Formation of the Strangways Range kornerupine is attributed to low granulite or upper amphibolite facies conditions prevailing during a waning phase of M2.

Fluorine does not seem to be a significant component of the metasomatizing fluids. Since CO_2 has been recorded as bubble inclusions in kornerupine (Roedder, 1965), CO_2 may have been an important volatile component of the parent fluids, as Touret (1970) suggests.

Conclusions. Kornerupine has been developed in metasomatic zones within the high-grade metamorphic terrain of the north-east Strangways Range. Growth has occurred during the second high-grade metamorphic episode to affect the terrain. The level of *P–T* controlling kornerupine formation was probably significantly lower than the maximum reached during the second granulite metamorphic event. The formation probably occurred during a waning stage low-grade granulite or upper amphibolite episode. The extreme rarity of boron-bearing minerals in the unmetasomatized granulites indicates that B contained in the kornerupine was probably introduced into the host granulites in association with a predominantly aqueous fluid.

Experimental technique. Electron-microprobe analyses were conducted on the TNO electron probe at the Australian National University, Canberra. Details of the technique were outlined by Reed and Ware (1973) and Ware and Reed (1973). The XRF major and trace analyses were undertaken at the University of Queensland on fused and pressed discs, respectively, using a Phillips PW 1410 X-ray spectrometer. Details of the technique are similar to those given in Norrish and Chappell (1967) and Norrish and Hutton (1969).

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