

Mineralogy and metamorphic history of norite dykes within granulite facies gneisses from Sand Mata, Rajasthan, NW India

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Abstract

Metanorite dykes intrude the Banded Gneiss Complex at various places in Rajasthan, N.W. India. They show neither chilled margins nor gradational contacts with the country rock amphibolite or granulite facies gneisses. They have ophitic to subophitic texture with strongly zoned subcalcic clinopyroxene and orthopyroxene, olivine and plagioclase, with subsidiary biotite. During slow cooling a series of reaction coronas developed with garnet forming round biotite, ilmenite and orthopyroxene; hornblende round pyroxenes and orthopyroxene, hornblende \pm spinel round olivine, which may be totally replaced. It is inferred that the dykes crystallised from a tholeiitic magma at about 1100–1150 °C and were intruded during the waning stages of granulite facies metamorphism. The corona minerals grew at about 650–700 °C. A series of reactions to account for the development of the coronas is proposed using measured mineral compositions. Although these reactions do not balance for individual corona formation, metamorphism was probably isochemical with Ca, Na, K, Ti, Si and H₂O only mobile on the scale of a thin section. Si and H₂O were possibly mobile on a larger scale.

KEYWORDS: norites, dykes, gneisses, granulite facies, Rajasthan, India.

Introduction

METANORITE dykes of uncertain age intrude the upper amphibolite to granulite facies rocks of the Banded Gneiss Complex (BGC) at various places in Rajasthan, NW India (Fig. 1; Gupta, 1934; Heron, 1953). Where the dykes intruded granulite facies gneisses they have partially re-equilibrated to granulite facies conditions and where they cut amphibolite facies gneisses they are hornblende-rich. The BGC is older than 2.58 Ga (Crawford, 1970) and possibly as old as 3.5 Ga (McDougall *et al.*, 1983).

At Sand Mata, olivine-bearing, unfoliated metanorite dykes crosscut the high-pressure granulites and interlayered garnet amphibolites and metapelites of the BGC (Sharma *et al.*, in prep.). The dykes are 10–15 m wide and show neither chilled margins nor gradational contacts with the country rock. They are distinct in texture and mineral assemblage from the garnet amphibolites and granulites. They have ophitic to subophitic texture, but at Sand Mata also contain garnet, recrystallised

amphibole and subordinate biotite which indicate that the basic intrusions have been partially metamorphosed.

The gneisses from Sand Mata generally trend NW and have suffered three phases of deformation. The earliest recognisable phase (F₁) comprises rootless folds. The second deformation (F₂) produced N–NW-trending isoclinal or reclined folds whose axes parallel the regional folds. It is thought that F₂ was coeval with the upper amphibolite to granulite facies metamorphism related to the Aravalli Mountain Orogeny (1.6–0.94 Ga). F₃ deformation is heterogeneous but trends NE–SW and probably occurred during the waning stages of the main metamorphism (Sharma *et al.*, in prep.). The metanorite dykes trend SW and cut the regional foliation, indicating emplacement prior to or during F₃.

The aim of this paper is to describe the sequence of textural and compositional changes occurring in the dykes and to determine the conditions of metamorphism.

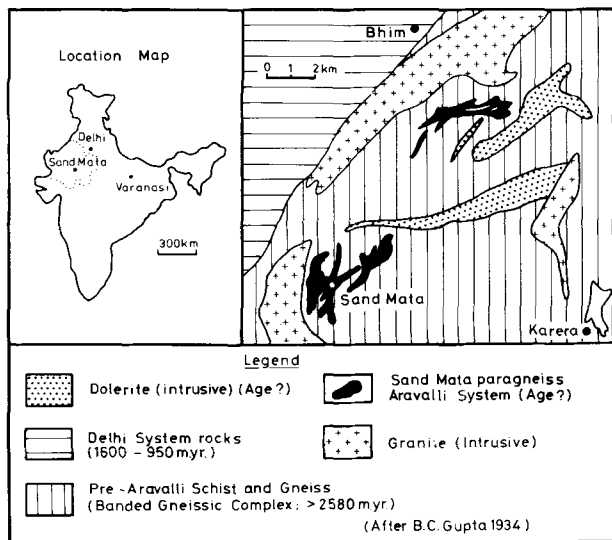


FIG. 1. General geology of the Sand Mata area, Rajasthan.

Petrography and mineral chemistry

Modes are given in Table 1 and representative mineral analyses are given in Table 2. Most analyses were obtained using a LINK systems 860 energy dispersive detector with a current of about 3 nA on cobalt. Wavelength dispersive analyses were obtained using a Cambridge Instruments Microscan V electron microprobe with a current of about 20 nA on copper. Full ZAF corrections were applied using the computer programme FRAME. A range of natural and synthetic minerals and pure metal standards were used.

As the intrusive metanorite has only partially re-equilibrated, the primary igneous mineralogy is

TABLE 1. Modes (vol.%) of the Sand Mata dykes.

	ol	opx	cpx	plag	ilmt	hb	hb	bi	gt
	(pyx) (bi+opq)								
589	0.5	20.7	19.7	45.9	0.7	9.8	1.1	0.9	0.7
539	4.0	26.5	10.1	46.9	1.5	8.2	0.7	1.2	1.1
582	1.7	22.6	16.6	46.6	1.1	9.3	1.2	0.9	-
537	-	34.2	8.0	45.6	0.9	10.0	0.7	0.6	-
614	0.6	4.6	-	46.0	0.3	48.5	-	-	-

distinguishable from the metamorphic assemblage. The primary phases are olivine (ol), orthopyroxene (opx), clinopyroxene (cpx), plagioclase (plag) and ilmenite (ilmt). The ophitic texture due to pyroxene-plagioclase intergrowths is largely preserved.

Igneous assemblage. Olivine (1-5 vol.%) is occasionally present as inclusions within either ortho- or clinopyroxene and is extensively altered to serpentine and magnetite-hematite. It is generally about Fe_{71} but a few grains are Fe_{57} . NiO is below the detection limit of the energy dispersive system (about 0.25 wt. %). It is consistently more Fe-rich than coexisting cpx, but has a similar mg (100Mg/(Mg + Fe)) to enclosing opx.

Orthopyroxene (20-30 vol.%) occurs as ophitic intergrowths with plagioclase. Large grains are strongly zoned with pinkish-brown cores and colourless rims (Fig. 2a). Clinopyroxene (10-20 vol.%) is zoned from a homogeneous pinkish-brown centre to a colourless to pale green rim. Both pyroxenes frequently show marginal alteration against plagioclase to a pale green hornblende, but occasionally only a relic of pyroxene is seen in the core of secondary hornblende grains. Analyses are plotted in Fig. 3. Both pyroxenes show pronounced zoning, reflecting both primary igneous zoning and partial re-equilibration to the metamorphic conditions. The zoning, from core to rim, for one typical clinopyroxene grain is shown in fig. 4. Clinopyroxene cores (brown in colour) have up to 1.2 wt. % Cr_2O_3 , 0.6 wt. % TiO_2 and 14-18 wt. % CaO. Rims (colourless) have 0.2 or less wt. % Cr_2O_3 , 0.2

wt. % TiO_2 and about 22 wt. % CaO . Al_2O_3 ranges from 2–4 wt. % and *mg* ranges from 85–78 but with no systematic variation from core to rim. Orthopyroxene is also zoned from core to rim (Table 2) with about 2.2 wt. % CaO in the core and a fairly narrow colourless rim with about 0.5 wt. % CaO . TiO_2 ranges from about 0.5 wt. % in the centre to below detection in the rim, *mg* ranges from 73 to 56, that is considerably more iron-rich than the co-existing cpx. Small recrystallised opx aggregates have a similar composition to the rims of large grains. The TiO_2 and Al_2O_3 contents of the pyroxenes suggest crystallisation from a tholeiitic magma (Kushiro, 1960; Nisbet and Pearce, 1977).

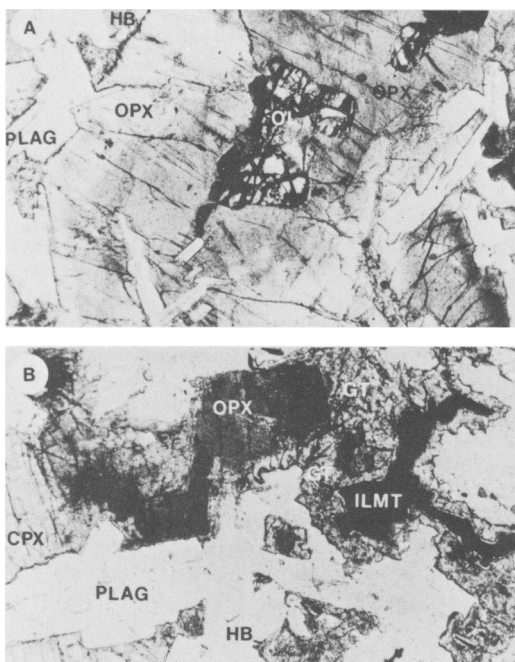


FIG. 2. (A) Photomicrograph showing ophitic plagioclase and olivine enclosed in strongly zoned orthopyroxene. (B) Development of garnet around orthopyroxene and ilmenite. Hornblende replaces pyroxene. Fields of view 3.2 mm.

Plagioclase (45–47 vol. %) is often intergrown with pyroxene and is normally zoned. It is generally fairly calcic in grain centres, *c.* An_{84-85} , but near hornblende or garnet fringes it reduces to about An_{50} . Grains poikiloblastically enclosed in pyroxene are zoned from about An_{85} to about An_{72} . This wide range reflects both primary igneous zoning and the participation of the anorthite

molecule in the hornblende and garnet-forming reactions. Small amounts of reddish-brown hornblende could be primary.

Metamorphic effects are marked by the presence of garnet (gt), hornblende (hb), biotite (bi), reaction coronas around olivine and blastophitic texture.

Metamorphic assemblage. Hornblende occurs mostly as tiny granules forming rims 100–250 μm thick around both ortho- and clinopyroxene. It generally shows bright green to colourless pleochroism but hornblende rimming biotite is yellowish. Thicker rims may contain quartz grains. Where replacement has been more extensive, e.g. sample 614, pyroxenes may be completely pseudomorphed by pale green to colourless fibrous mats of tremolitic hornblende, with rims, again 100–250 μm thick, consisting of granules of green hornblende. Sometimes the centre is composed of colourless fibrous anthophyllite. Anthophyllite is only present when the pyroxene has been completely replaced. These textures suggest that the brighter green, more aluminous rims formed by a reaction between pyroxene and plagioclase, but where alteration has been more extensive, there has been simple hydration of opx to form anthophyllite. The composition of the hornblende is extremely variable depending on the mineral being replaced and on the degree of replacement. Calcic amphiboles range in composition from actinolitic hornblende to pargasite (Leake, 1978; Fig. 5). Where replacement of pyroxene is nearly complete the hornblende has much lower Al_2O_3 and alkali contents. In any one sample, hornblende rimming biotite is more aluminous and has a higher TiO_2 content than hornblende rimming pyroxene. Cr_2O_3 and MnO are below detection, TiO_2 ranges from 2.5 to 0.25 wt. %, Na_2O from 2.5 to 0.45 wt. % and K_2O from 1.4 to 0.2 wt. %. Hornblende tends to be more magnesian than the pyroxene it is replacing and contains tiny opaque inclusions. Fe_2O_3 estimates (Robinson *et al.*, 1982) give maximum $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratios of about 0.22.

In addition to the obvious pyroxene replacement textures, mosaics of colourless, sometimes fibrous opx occur intergrown with opaque oxides \pm biotite. This is in turn rimmed by bright green vermicular intergrowths of hornblende \pm spinel \pm plagioclase. A thin rim of biotite may intervene between the opx and hb, and in one example, garnet occurs, instead of hornblende, between the opx and plag. Some of these coronas (e.g. 539) are cored by olivine, suggesting that they represent the former presence of olivine and are the result of olivine + plagioclase breakdown reactions. The texture suggests the former presence of plagioclase between the olivine and cpx and it is thought that the corona-forming

Table 2. Representative analyses from the Sand Mata dykes. gt(opx) is adjacent to opx (edge) and gt(ilmt) rims ilmenite. The other garnet point is enclosed by the biotite (bi). hb(opx) and hb(cpx) rim opx and cpx respectively. Analyses quoted to two decimal places are wavelength dispersive analyses and those to one decimal place are energy dispersive analyses, blanks mean the element was below detection.

	589 cpx centre	589 cpx edge	589 opx centre	589 opx edge	589 gt (opx)	589 gt (ilmt)	589 gt	589 bi	589 hb (opx)	589 hb (cpx)	614 opx	614 anth	614 hb	614 hb edge	539 ol	539 opx edge	539 gt	539 cpx	539 plag
SiO ₂	52.16	52.38	52.05	51.90	38.39	37.73	38.3	36.0	43.3	41.8	53.1	55.5	54.7	48.1	37.4	51.6	39.1	52.1	51.3
TiO ₂	0.36	0.24	0.50	0.13	-	0.11	-	5.0	1.0	1.0	-	-	-	-	-	-	-	-	-
Al ₂ O ₃	3.53	2.37	1.89	0.55	21.36	21.06	21.6	14.9	12.8	15.2	1.8	1.7	2.2	10.3	-	0.8	19.2	1.1	30.1
Cr ₂ O ₃	1.22	0.18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
FeO	7.38	5.84	22.43	27.27	27.92	30.71	27.8	15.8	11.3	9.6	17.3	15.5	7.0	9.1	26.3	28.4	29.2	10.8	-
MnO	0.17	0.14	0.22	0.17	0.57	0.34	0.6	-	-	-	0.3	0.5	-	-	0.4	-	0.6	-	-
MgO	17.33	16.00	21.91	20.07	4.83	2.89	5.2	13.3	13.3	13.7	26.2	23.1	19.8	15.9	36.2	18.3	4.8	11.8	-
CaO	17.57	22.58	2.09	0.37	7.60	8.40	7.9	-	12.2	12.5	1.0	0.7	12.7	12.1	-	0.4	7.5	23.1	13.2
Na ₂ O	0.34	0.45	-	-	-	-	-	-	1.5	2.4	-	-	0.3	1.2	-	-	-	0.6	4.1
K ₂ O	-	-	-	-	-	-	-	9.8	1.2	1.2	-	-	-	0.3	-	-	-	-	-
TOTAL	100.06	100.18	101.09	100.46	100.66	101.24	101.4	94.8	96.6	97.4	99.7	97.0	96.7	97.0	100.3	99.5	100.4	99.5	98.7
mg	80.7	83.0	63.5	56.8	23.6	14.4	25.0	60.0	67.7	71.8	73.0	72.6	83.4	75.7	71.1	53.2	23.6	66.0	-
o	6	6	6	6	12	12	12	22	23	23	6	23	23	23	4	6	12	6	8
Si	1.910	1.928	1.926	1.967	2.997	2.976	2.970	5.457	6.412	6.127	1.840	7.852	7.739	6.904	0.990	1.988	3.080	1.977	2.359
Al	0.090	0.072	0.074	0.025	1.965	1.957	1.973	2.543	1.588	1.873	0.060	0.148	0.261	1.096	-	0.012	1.783	0.023	1.631
Al	0.062	0.031	0.008	-	-	-	-	0.118	0.645	0.752	0.017	0.135	0.106	0.646	-	0.024	-	0.026	-
Ti	0.010	0.007	0.014	0.004	-	0.006	-	0.570	0.111	0.110	-	-	-	-	-	-	-	-	-
Cr	0.038	0.005	0.000	0.000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fe	0.226	0.180	0.694	0.864	1.823	2.026	1.803	2.003	1.400	1.177	0.528	1.834	0.828	1.092	0.582	0.915	1.925	0.343	-
Mn	0.005	0.004	0.007	0.005	0.038	0.023	0.039	-	-	-	0.009	0.060	-	-	0.009	-	0.040	-	-
Mg	0.946	0.878	1.209	1.134	0.362	0.340	0.601	3.004	2.935	2.993	1.426	4.871	4.175	3.401	1.428	1.039	0.564	0.667	-
Ca	0.689	0.890	0.083	0.015	0.636	0.711	0.657	-	1.939	1.966	0.039	0.106	1.926	1.864	-	0.016	0.634	0.941	0.651
Na	0.024	0.032	-	-	-	-	-	-	0.431	0.682	-	-	0.082	0.334	-	-	-	-	0.365
K	-	-	-	-	-	-	-	1.895	0.226	0.224	-	-	-	0.055	-	-	-	-	-

reaction ceased when the plagioclase was consumed. In general these coronas develop against larger plagioclase grains or aggregates of grains and corona development proceeds until the olivine has been consumed. Similar coronas have been described from many gabbros (e.g. Grieve and Gittins, 1975). The hb in the olivine breakdown coronas has lower Ti and K than hb rimming pyroxenes.

Garnet occurs in several ways: (a) at plagioclase-

ilmenite grain boundaries, sometimes with an intervening rim of plagioclase (Fig. 2b); (b) at opx-plag interfaces (Fig. 2b) as in the country rock granulites (Sharma *et al.*, in prep.). In one occurrence (sample 539, Table 2) there is a very thin rim of cpx between the garnet and the plagioclase; (c) small elongate garnet grains occur isolated in plagioclase. These grains have the same form and composition as those rimming ilmenite and are thus thought to have formed in the same way. Garnet grains may

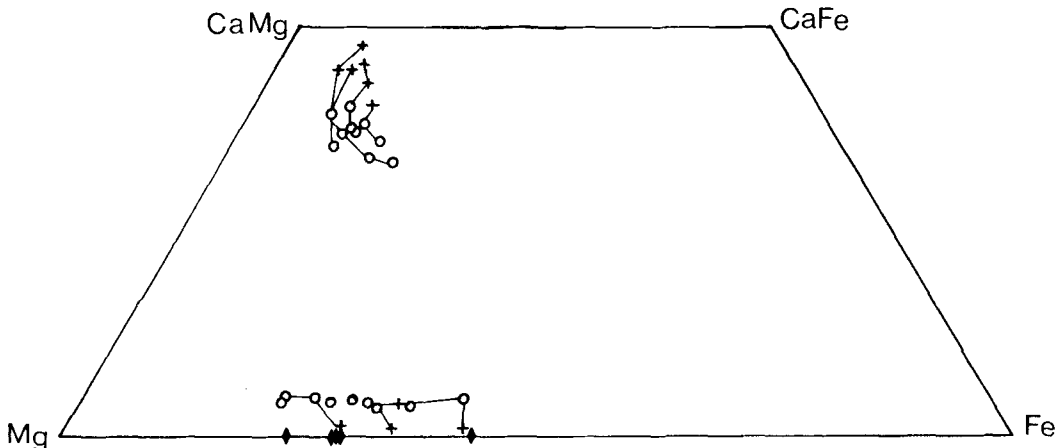


FIG. 3. Pyroxene quadrilateral. Open circles represent grain cores and crosses grain rims. Lines join points from the same grain. Diamonds are olivines.

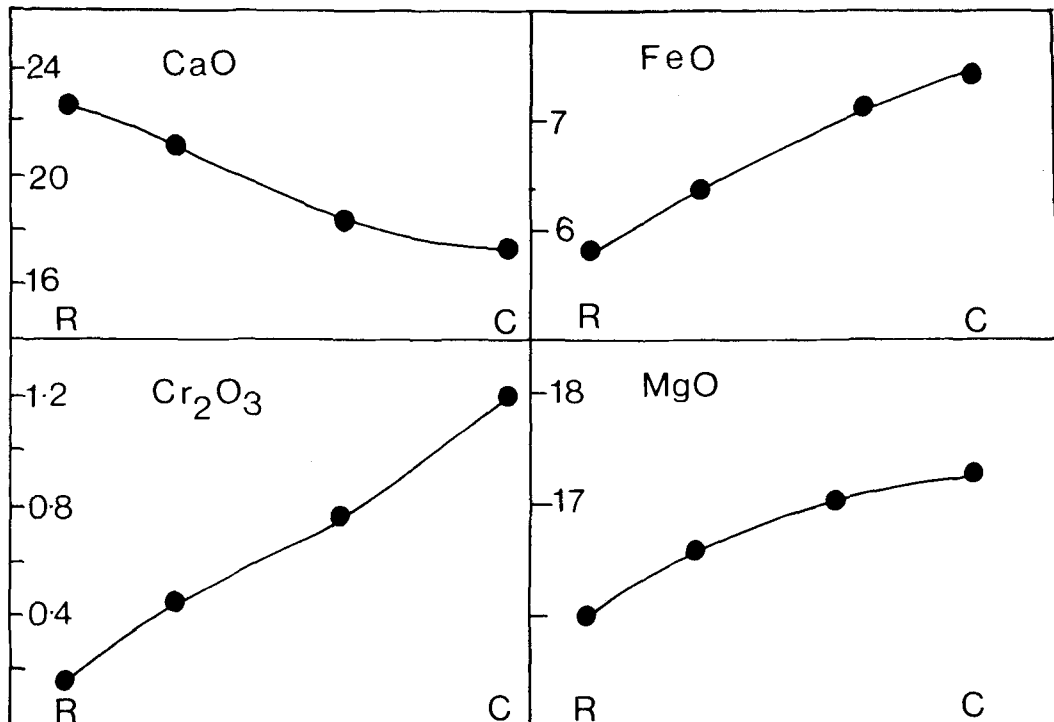


FIG. 4. Zoning from core (C) to rim (R) of a typical clinopyroxene grain, adjacent to plagioclase. Scale is in wt. % oxide and the core to rim distance is about 5 mm.

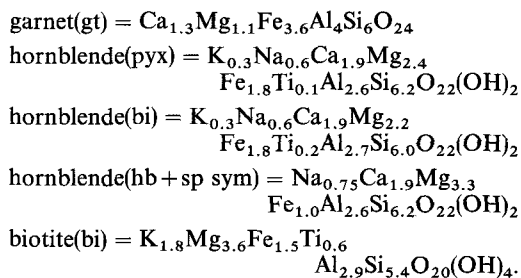
contain brown inclusions of either rutile or biotite. It is not always completely isotropic and is sometimes being replaced by biotite. Occasionally there is simultaneous development of garnet and hornblende around opx. From Table 2 it can be seen that garnet around ilmenite is slightly more Fe-rich and more calcic than that rimming opx or biotite. Garnet rimming opx has about 21 mol. % grossular, 16–19 mol. % pyrope and 54–61 mol. % almandine, whereas rims around ilmenite have only 11 mol. % pyrope and about 61–66 mol. % almandine and 24–27 mol. % grossular. Fe^{3+} contents, estimated from charge balance, are fairly low ($\text{Fe}^{3+}/\text{Fe}^{2+}$ is about 0.04). Garnet only occurs in the samples with the most Fe-rich pyroxenes.

Biotite occurs as discrete grains, rimming opaque oxides and occasionally garnet and is itself often rimmed by hornblende. Some may be primary igneous biotite. It contains about 5.5 wt. % TiO_2 and less than 0.5 wt. % Na_2O . Hornblende rimming biotite usually contains opaque oxide inclusions and may contain rutile. Ilmenite is fairly pure apart from about 0.65 wt. % MgO, MnO, Cr_2O_3 and NiO are below detection. Plagioclase against biotite

may be altered, resulting in an isotropic mass (kaolinite?) and is also locally replaced by white mica.

Mineral reactions

In addition to the igneous mineralogy displaying ophitic texture, the Sand Mata dykes are characterised by localised re-equilibration at grain boundaries. A series of reactions are now proposed to account for the textural relationships described above. The following mineral compositions were used (Table 2):



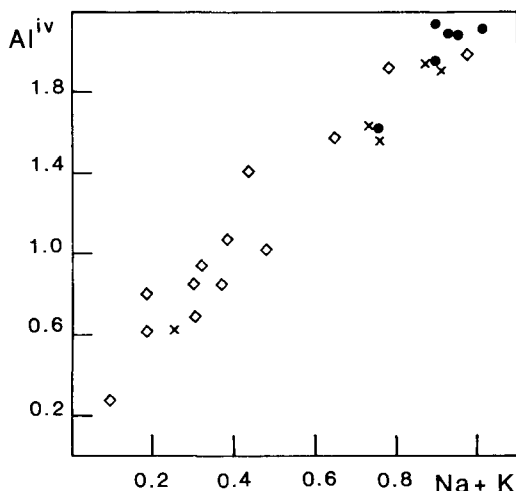


FIG. 5. Hornblende analyses plotted on an Al^{iv} versus $\text{Na}+\text{K}$ diagram (cations based on 23 oxygens in the water-free formula).

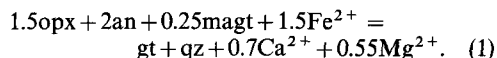
Other minerals used are: opx— $(\text{Mg},\text{Fe})_2\text{Si}_2\text{O}_6$; cpx— $\text{Ca}(\text{Mg},\text{Fe})\text{Si}_2\text{O}_6$; ol— $(\text{Mg},\text{Fe})_2\text{SiO}_4$; anth— $(\text{Mg},\text{Fe})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$; act(actinolite)— $\text{Ca}_2(\text{Mg},\text{Fe})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ and anorthite(an), albite(ab), magnetite(magt) and ilmenite(ilmt) which are treated as pure end members. Magnetite may occur in solid solution with ilmt.

It is not possible to write completely balanced reactions for the formation of the various coronas. A great variety of reactions have been proposed for similar coronas (Grieve and Gittins, 1975; van Lamoen, 1979; Whitney and McLelland, 1983 and Mongkoltip and Ashworth, 1983) all of which make certain assumptions, which, in turn, raise further problems. Following Whitney and McLelland (1983) and Mongkoltip and Ashworth (1983) we have chosen to write the reactions assuming that Al and Si are effectively immobile and that other ionic species are free to move, at least locally. Many authors (e.g. Fisher, 1973) have suggested that Al diffuses slowly and the lack of quartz in the Sand Mata dykes suggests excess SiO_2 was neither produced or consumed in the reactions. Chemical species assumed to be mobile have been written in an ionic form. Under dry conditions it is likely that oxygen diffusion is also very slow (Freer, 1981), and most of the reactions presented below are written assuming conservation of oxygen (see also Mongkoltip and Ashworth, 1983).

Another problem is that the composition of the reactant plagioclase is not known. Plagioclase grains completely enclosed in pyroxene range from An_{85} to An_{72} which is believed to be primary

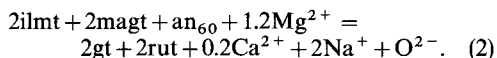
igneous zoning, but grains adjacent to garnet or hornblende fringes may only be An_{50} , which suggests that the anorthite molecule has been preferentially included in the corona minerals, suggesting that Al and Si can diffuse within the plagioclase lattice and that the assumption above is not strictly valid.

Formation of garnet. Garnet fringes occur around both opx and ilmenite. Around opx, tiny opaque granules intergrown with garnet suggest the former presence of opaque oxides which have mostly been consumed in the reaction. A possible reaction might be:



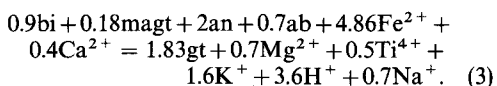
This reaction is written assuming Al, Si and O are conserved, and results in a more sodic plagioclase forming. The reaction produces a small amount of quartz. As noted above, the garnet might be intergrown with another phase causing the observed anisotropy. If no product quartz is formed, there must be the introduction of an unacceptably large amount of material, making the likely ideal of constant volume impossible.

However, garnet occurs more frequently as rims to opaque oxides with no opx, where it is more Fe-rich and slightly more calcic (Table 2). In this case, all the Si and Al for the garnet must come from the plagioclase, so a reaction can only be written if the plagioclase fortuitously has an Al/Si ratio of $\frac{2}{3}$ (i.e. An_{60}), which is in the range of plagioclase compositions found. A possible reaction might be:



This reaction assumes some of the iron comes from magnetite in solid solution with ilmenite. As noted above, rutile needles sometimes occur intergrown with the garnet. If this reaction were written to conserve oxygen, large amounts of Fe^{2+} must be introduced.

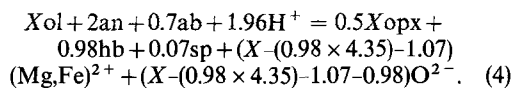
Garnet also occurs rarely as rims to biotite, a possible reaction being:



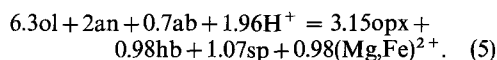
This reaction, as written, involves quite large additions of material and therefore may not take place at constant volume. However, it is possible to rewrite the reaction so that it consumes a greater amount of magnetite, in which case the oxygen will not be conserved. In hydrous conditions the diffusion of oxygen is likely to be much faster (Mongkoltip and Ashworth, 1983), so that oxygen diffusion has probably occurred.

Olivine-plagioclase coronas: In the most simple and common case, the coronas comprise a core of low-Al opx with an outer rim of hb + sp symplectite against plagioclase. There is no observed qz and the amounts of spinel are small.

If it is assumed that the Si and Al for the hb + sp symplectite are inherited from the reactant plagioclase and that the Si for the opx is inherited from the olivine, so that diffusion of Al and Si is very limited, we can write the following reaction:



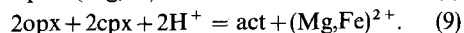
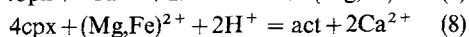
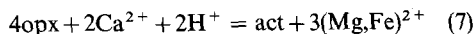
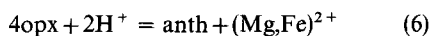
It is not possible to balance this reaction, unless one knows the exact proportions of each of the phases in the coronas. Unfortunately, these data are not available, partly because in some coronas the olivine has been completely consumed. However, we can assume that the reaction occurred at approximately constant volume, which can be roughly approximated by constant oxygen (Mongkoltip and Ashworth, 1983). Reaction (4) now reduces to:



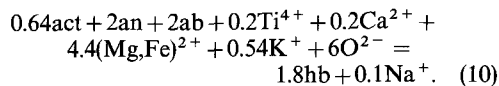
This reaction produces the correct Fe/Mg ratios in the product phases and consumes plagioclase of composition An_{74} which is slightly less calcic than the original plagioclase grains (An_{85} - An_{72}). Some coronas contain plagioclase which may be relics of the original igneous plagioclase.

Formation of hornblende. Hornblende fringes occur around both pyroxenes, which are strongly zoned such that the cpx is depleted in the opx molecule (i.e. becomes more calcic) towards the grain margins and opx is depleted in the cpx molecule (i.e. becomes less calcic). This could indicate that both the opx and cpx molecules are consumed in the hornblende-forming reaction. The replacement of pyroxenes by actinolite or anthophyllite with an outer rim of hornblende represents an addition of Al (from reactant plagioclase) which was not able to diffuse to the core. Where pyroxenes are extensively replaced, the entire opx is replaced by anthophyllite, with a fringe of actinolite hornblende and a rim of hornblende. This implies very restricted movements of Al.

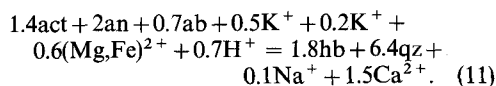
The formation of the amphibole fringes can be modelled in two stages (a) the formation of actinolite or anthophyllite from pyroxene and (b) the formation of hb from actinolite. The core reactions, modelled at constant Si and zero Al would be:



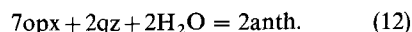
The rim reaction can be modelled as follows:



This reaction requires addition of large amounts of material, i.e. a volume increase. To avoid such an increase while strictly conserving Si and Al requires the production of quartz, as is observed in a few fringes. The above reaction rewritten, again with constant oxygen, becomes:

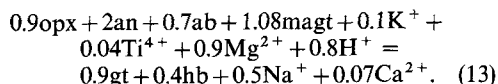


Anthophyllite may form from opx as in reaction (6) or by the addition of silica:



This reaction requires a much larger increase in volume than (6) so we suggest that the amphibole fringes formed from pyroxene by a combination of reactions (6)-(9) and reaction (11) which will allow formation of anthophyllite from opx and actinolite from cpx with a rim of actinolite and an outer rim of hornblende against plagioclase. The amphibole is zoned rather than occurring as discrete layers, which indicates limited mobility for Si and Al within the hornblende layer. The $(\text{Mg,Fe})^{2+}$ required for reaction (11) is provided by the breakdown of pyroxenes to form Al-free amphiboles in the centre of the fringes.

Hb also occurs near opx-garnet contacts, possibly resulting from the following reaction:



Hornblende of a slightly different composition occurs as fringes to biotite, some of which may be of igneous origin. Using plagioclase of the composition found, it is impossible to produce hb from biotite without excess Al, so either albite is preferentially consumed or Al must in this case be mobile.

It is interesting to consider whether the growth of coronas was isochemical but to do this one must make quantitative estimates of the volume of reactants and products. This is not possible, as in some cases the olivine has been completely consumed so that the original proportions of ol, opx and plag cannot be estimated. However, in a qualitative way, it can be seen that although

reactions to produce individual corona minerals e.g. gt around opx, do not balance, excess components produced in one reaction are consumed by another, e.g. Ca is produced by garnet-forming reactions (e.g. reaction (1)) and is consumed by hornblende-forming reactions (e.g. reaction (7)) and (Mg,Fe) released from the formation of anthophyllite is consumed by the formation of hornblende. It seems that there is no need for the introduction or removal of significant amounts of material during formation of the various coronas, so that metamorphism was more or less isochemical, although Ca, Ti, Na, K, Mg, Fe and H₂O appear to have been mobile on the scale of a thin section, with Si and Al relatively immobile. Si and Al are mobile to a limited extent within plagioclase and hornblende layers. Where replacement of pyroxene by amphibole is extensive, H₂O may have been added. It is not possible from textural data to produce an order of reactions, but as all the reactions appear to be inter-related, it is possible that they were approximately simultaneous, as the excess components from one reaction drive another.

Metamorphic conditions

The Sand Mata dykes intruding the garnet granulites possess both igneous and metamorphic features. The latter are documented by the development of ol+plag reaction textures and by the development of garnet and hornblende fringes. The restriction of metamorphic events to grain boundaries rather than complete re-equilibration suggests that the dykes were emplaced towards the end of a metamorphic event.

The composition of pyroxene cores (Table 2; Fig. 3), with low-Ca clinopyroxene and high-Ca orthopyroxene suggest that igneous compositions have been preserved. This is reflected in the calculated two-pyroxene temperatures (Table 3) which give a range of values from 1050–1220 °C. The Lindsley

(1983) geothermometer is likely to be the most accurate as it is based on recent experimental data and the assumption of ideal mixing in the Wood and Banno (1973) and Wells (1977) thermometers is incorrect (see discussion in Lindsley, 1983). Using the Lindsley model, a best estimate of the emplacement temperature is 1175 ± 50 °C. It is possible that these temperatures are an over estimate if some of the zonation observed in the cpx (Figs. 4, 5) has resulted from the diffusion of Ca from the centre to the edges of the grains leaving Ca-depleted cores. Temperatures calculated from grain edges are very variable, depending on the degree of re-equilibration (Table 3). Temperatures calculated from the Wood and Banno (1973) and Wells (1977) models are higher than those calculated from Powell (1978) and Lindsley (1983) models. The cpx with the highest Ca content gives a temperature of about 750 °C (Lindsley, 1983) and orthopyroxene gives about 650–600 °C. Similar low opx temperatures have been recorded from other areas (Lindsley, 1983) and could be the result of various factors, including imprecise Ca analyses or low blocking temperatures in opx.

Garnet-clinopyroxene temperatures of about 700 °C were obtained from a gt-cpx pair occurring between opx and plag (Ellis and Green, 1979; sample 539, Tables 2, 3). Temperatures in the range 700–800 °C were also obtained from gt-cpx pairs in enclosing garnet amphibolites. This model is thought to give reasonable estimates (Johnson *et al.*, 1983). Gt-bi temperatures are in the range 550–700 °C (Ferry and Spear, 1978; Table 3). Hb-plag temperatures (Spear, 1981) are between 480 and 550 °C.

It is concluded that the dykes were emplaced with liquid temperatures of 1100 °C and that the growth of gt ± hb took place at about 700 ± 50 °C. The pyroxenes have only partially re-equilibrated to lower temperatures, so a wide range of intermediate temperatures can be calculated. Other mineral equilibria, such as gt-bi and hb-plag, seem

Table 3. Calculated temperatures. core and edge refer to the centres and edges of opx and cpx grains. W&B refers to Wood and Banno (1973), Wells to Wells (1977), Powell to Powell (1978), Lindsley to Lindsley (1983), E&G to Ellis and Green (1979) and F&S to Ferry and Spear (1978)

sample	cpx - opx		Lindsley	Powell	gt-cpx E&G	gt-bi F&S
	W&B	Wells				
589						
core	1055	1180	1190-1210(cpx) 1050-1120(opx)	1144		550-650
edge	875	926	ca 750 (cpx) ca 600 (opx)	744		
582						
centre	1131	1182	1200-1220(cpx) 1150-1220(opx)	1145		
edge	1004	1047	1000-1050(cpx) 600-700 (opx)	797		
539					670-734	650-680

to have re-equilibrated at still lower temperatures, possibly as a result of slow cooling.

There are no geobarometers which can be applied to these rocks as no garnet-bearing samples have positively identified quartz.

Conclusions

The textures and spatial occurrence of hornblende and garnet in the Sand Mata dykes suggest that metamorphism took place in a static environment, unlike the Kangamiut dyke swarm of West Greenland (Windley, 1970) which has similar mineralogy but was metamorphosed during shearing with preferential growth of hornblende and garnet in shear zones.

The formation of hornblende in the Sand Mata dykes was presumably a consequence of varying $a_{\text{H}_2\text{O}}$ during metamorphism and cooling. Hydration of pyroxenes to form narrow fringes of hornblende also occurs in the adjacent pyroxene granulites (Sharma *et al.*, in prep.) where there is no deformation accompanying retrogression. This is in contrast to the Lewisian of NW Scotland where large scale retrogression of granulites is accompanied by the development of vertical structures which act as channelways for the fluids (Beach and Tarney, 1978).

It is possible that the water needed for the hydration of pyroxenes in the Sand Mata dykes was derived internally from the breakdown of early brown hornblende and biotite, so that $a_{\text{H}_2\text{O}}$ was internally buffered. The presence of a low variance assemblage with both reactants and products is consistent with internal buffering (Powell, 1983).

The evolution of the dykes can be summarised as follows:

(i) subcalcic clinopyroxene, orthopyroxene, olivine and plagioclase (with subsidiary biotite) crystallised from a tholeiitic magma and were emplaced into hot country rocks during the waning stages of granulite facies metamorphism.

(ii) the above igneous assemblage partially re-crystallised, without major changes in bulk composition to form garnet around ilmenite, biotite and orthopyroxene, to form hornblende around pyroxenes and orthopyroxene \pm spinel \pm hornblende coronas around olivine. These coronas, similar to those developed in the country rock granulites, formed at about 650–700 °C.

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