A retrogressive sapphirine-cordierite-talc paragenesis in a spinel-orthopyroxenite from southern Karnataka, India

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Abstract

Within amphibolite facies Peninsular gneisses in the south of the Dharwar craton, units of Sargur supracrustal rocks contain ultrabasic enclaves. One of these enclaves is an orthopyroxenite which comprises bronzite, spinel and minor phlogopite preserving coarse-grained, relic textures of probable igneous origin. After incorporation into the gneisses the enclave evolved through several distinct stages, elucidation of which allow an assessment of its metamorphic history.

Firstly, deformation during closed system, anhydrous recrystallisation caused the coarse-grained textures to be partially overprinted by similar mineral assemblages but with a granoblastic texture. Secondly, open system hydration caused retrogression of the bronzite to alumino-gedrite at the margins of the enclave. Subsequently, the penetration of these fluids along grain boundaries caused reactions between spinel and bronzite to produce reaction pockets carrying assemblages of per-aluminous sapphirine associated with cordierite and talc. The differences in the mineral assemblages in each pocket coupled with slight variations in their chemistry, suggest that equilibrium did not develop over the outcrop. Because sapphirine + magnesite is present in some pockets, it is evident that CO_2 was also a component of the fluid.

Phase relations from the MASH portion of the FMASH system, to which the chemistry of the reaction pockets approximates, suggest that the hydrous metamorphism causing the changes depended upon the assemblage enstatite + spinel + vapour which exists at *PT* conditions above the position of I_{16}, ~760 °C at 3 kbar and below I_{21} at ~765 °C at 5.6 kbar (Seifert, 1974, 1975), where sapphirine is replaced by kornerupine. The suggested path of reaction occurred between I_{18} and I_{21}. Subsequent reactions related to I_{20} cause the formation of cordierite. Talc formation has to be modelled in a different reaction grid.

The metamorphism recorded by these reactions is thus at a maximum of amphibolite facies and is interpreted to have formed during the uplift and cooling history of the gneiss complex when hydrous fluids were free to migrate. Given the complex high-grade metamorphic history of this part of the Dharwar craton this event is likely to be late Archaean or Palaeoproterozoic in age.

KEYWORDS: per-aluminous sapphirine, FMASH, spinel-orthopyroxenite, India, Sargur supracrustal rocks.

Introduction

THE widespread occurrence of sapphirine-bearing rocks of several different origins and ages in the southern part of India has been known for many years (see summary in Grew, 1982, 1983, 1984; Kamineni and Rao, 1988). The majority of the occurrences reported from southern India are in silica-saturated rocks or rocks that began as silica-saturated (Grew, 1982). Silica-deficient sapphirine-bearing rocks are known from both northern (Lal *et al.*, 1978) and southern India (e.g. Lal *et al.*, 1984); this together with more

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recent work has begun to clarify some of the chemographic relationships in individual occurrences (e.g. Mohan *et al.*, 1986).

The discovery of the first occurrence of sapphirine in the Mysore region (Fig. 1) was described by Janardhan and Shadakshara Swamy (1982) from an orthopyroxenite body associated with units of Sargur supracrustal rocks. This occurrence was unlike the others previously reported which are associated with undoubted granulites (e.g. Leake *et al.*, 1974; Grew, 1982; Lal *et al.*, 1984; Mohan *et al.*, 1986). Instead, the rocks appear to be at amphibolite facies and have a strong resemblance to a sapphirine occurrence described from Namaqualand (Clifford *et al.*, 1975).

The metamorphic evolution of the region is complicated because of its proximity to the now famous charnockite region (see summary in Newton, 1992) and the orthopyroxene isograd. The *PT*-sensitive sapphirine-forming reactions might help to unravel this history. This contribution describes, in more detail, the nature of this body, the textures and assemblages present, its mineral chemistry and the implications for the regional metamorphism.

Geological setting

The Dharwar craton, of which southern Karnataka forms a part, comprises two distinct portions. Firstly there is an older high-grade terrain comprising the dominant quartzo-feldspathic gneisses, the Peninsular gneisses, components of which go back to about 3400 Ma (e.g. Beckinsale *et al.*, 1980). These gneisses contain a number of supracrustal horizons and enclaves which are collectively called the Sargur supracrustal rocks. The general geology of these units has been described by Swami Nath *et al.* (1981) whilst more detailed studies of the geology of the Sargur supracrustal rocks south of Mysore (Fig. 1) have been presented by Janardhan *et al.* (1978, 1979, 1981) and Srikantappa *et al.* (1985). Secondly, this high-grade complex is overlain unconformably (Viswanatha *et al.*, 1982) by greenstone belt successions which in part may be contemporaneous with, or younger than components of the high-grade complex (e.g. Taylor *et al.*, 1984, 1988; Chadwick *et al.*, 1981).

The craton has a southerly increase in metamorphic grade from low amphibolite facies in the north to granulite facies in the south (e.g. Pichamuthu, 1965), though this is probably the result of different metamorphic events. The area has also been divided into western and eastern blocks which are characterised by different metamorphic histories (Viswanatha and Ramakrishnan, 1975; Rollinson *et al.*, 1981). This divide, interpreted as a thrust, is a feature that has also been picked out from analysis of remote sensing imagery (Drury *et al.*, 1983). Field mapping places the boundary as a belt of mylonitic rocks (Chadwick *et al.*, 1989). Recent isotopic and dating studies have revealed that different crustal slices were assembled to form parts of the Peninsular gneiss complex (e.g. Krogstad *et al.*, 1988). The idea of eastern and western blocks may thus yet be more fully substantiated.

The area south of Mysore is similarly polymetamorphic and was subjected to multiple deformation, to yield numerous complex interference patterns (Fig. 1). The area is situated to the north of the Moyar Shear Zone which separates it from the massif granulites in the Nilgiri Hills and to the southwest and west of the areas of arrested charnockite formation (e.g. Janardhan *et al.*, 1982; Newton, 1992). The quartzo-feldspathic gneisses mainly record amphibolite facies conditions, though there have been reports of orthopyroxene-bearing assemblages in the supracrustal rocks (Devaraju *et al.*, 1983; Raith *et al.*, 1983; Srikantappa *et al.*, 1985). In nearby supracrustal units *PT* conditions calculated at c. 700 ± 30 °C and 8.6 ± 0.8 kbar were obtained from ultramafic rocks, gabbroic anorthosites and basic sheets—interpreted as dykes. These are suggested to relate to a Late Archaean, high-grade metamorphic event which in some instances produced granulite facies assemblages (Srikantappa *et al.*, 1985). However, they note that no granulite facies mineralogies were found either in host amphibolites, attributing this to more hydrous recrystallisation, or in the adjacent quartzo-feldspathic gneisses. In a detailed study of the nearby amphibolite–granulite facies transition zone, *PT* estimates between 635–864 °C and 7.3–12.1 kbar were obtained from a variety of basic rocks dominated by granulite facies assemblages (Raith *et al.*, 1983). Whilst the Gundlupet area is closer to the charnockitic region to the southeast (Fig. 1), a similar situation exists with the host quartzo-feldspathic gneisses recording only amphibolite facies conditions. Orthopyroxene does not occur in the amphibolites but has been reported from the manganiferous metasediments occurring in the vicinity and to the west of Gundlupet (Fig. 1). Because of the very high contents of MnO (up to *c.* 3 wt.%) in iron-rich orthopyroxene, its metamorphic status is uncertain (Janardhan *et al.*, 1981).

Near the village of Terakanambi, some 10 km east of Gundlupet (Fig. 1), ultramafic bodies are associated with horizons of amphibolite and manganiferous metasediments (Janardhan *et al.*,

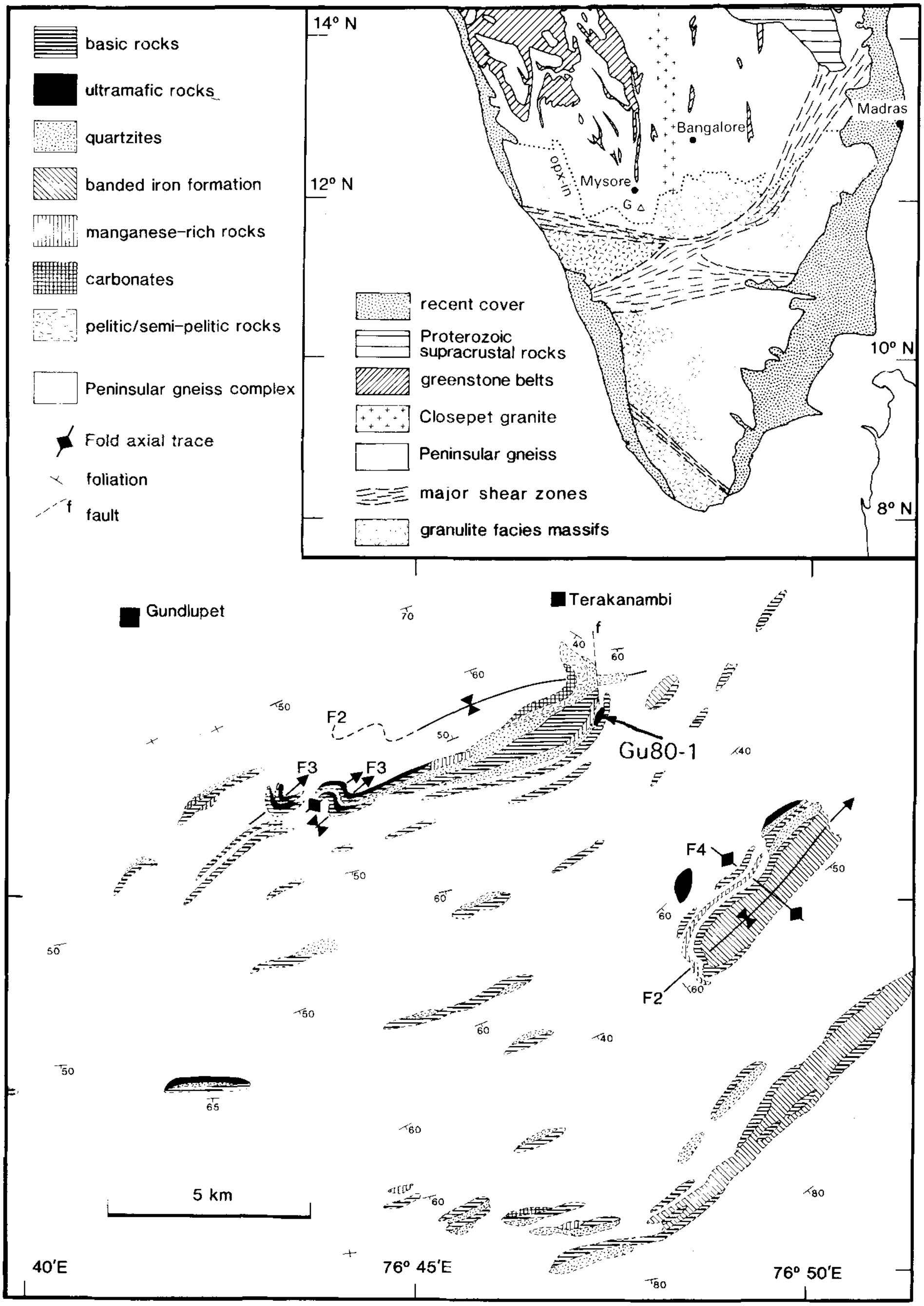

FIG. 1. Geological sketch map of the Gundlupet-Terakanambi area, south of Mysore. Main axial traces are shown indicating the polyphase nature of the deformation. Early isoclinal structures (F1) are omitted as they are largely internal to the supracrustal units, for more details see Janardhan *et al.*, (1979, 1981). Arrow indicates the location of the ultramafic enclave with the sapphirine-bearing reaction pockets from which Gu80-1 was taken. Inset shows the general disposition of the major lithotectonic units of southern peninsular India, the open triangle labelled G indicates the location of the Gundlupet area.

1981). Within the amphibolite units, trains of ultramafic enclaves occur which define crude horizons. One of these enclaves is a spinel-rich orthopyroxenite which contains a relic, coarse-grained assemblage comprising buff-coloured, stubby orthopyroxene up to several centimetres across which encloses and is separated by subhedral to euhedral dark, greenish-black spinel. Within some of the larger orthopyroxene crystals intergrowths of spinel and orthopyroxene occur which often have a euhedral spinel at the centre (Fig. 2). Internal to the enclave area areas of anhydrous recrystallisation where the coarse-grained texture has been destroyed and the present texture is a granular aggregate of dark spinel and buff orthopyroxene. Along the margins of the body the effects of hydration are observed with the development of a prismatic, buff-coloured orthorhombic amphibole up to 10 cm long which grows across both of the earlier textures. This would suggest that a reaction such as

$$\text{orthopyroxene} + \text{quartz} + \text{water} \rightleftharpoons \text{ortho-amphibole} \quad (1)$$

(e.g. Ravior and Hinrichsen, 1975) could be responsible.

Petrography and mineral assemblages

Petrographic evidence from 13 thin sections from different parts of the spinel-bearing orthopyroxenite (Gu80-1) indicates that there are several mineral assemblages. These can be divided into early and secondary types which are interpreted as representing primary and metamorphic events respectively. First, there is an essentially anhydrous assemblage comprising plates of bronzite and coarse-grained, dark green spinel with very minor interstitial phlogopite. Accessory phases are closely associated dark yellow-coloured rutile and titano-magnetite. The intergrowths of spinel and bronzite (Fig. 2) are sporadic and no petrographic evidence was found to suggest that they are a replacement phenomenon. These early textures and structures were then recrystallised and deformed in an anhydrous state to produce polygonal, sub-granoblastic aggregates of bronzite and spinel. As a precursor to this texture, mortar texture developed along some of the boundaries of the larger bronzite grains. Occasional remnants of the larger plates of bronzite are preserved as partially recrystallised, bent and kinked grains which show undulose extinction within the polygonal aggregates.

FIG. 2. General texture of part of the spinel-rich orthopyroxenite enclave showing a spinel-bronzite intergrowth enclosed within a bronzite plate.

After this anhydrous recrystallisation fluid conditions changed to those where water became freely available. The evidence for this is the idioblastic to sub-idioblastic, buff-coloured orthorhombic amphibole which was developed, particularly at the margins of the body, which overgrew the earlier textures. This general restriction of extensive amphibole development to the margins is interpreted to indicate that the retrogressive fluids were derived externally and thus the fluid system in the enclave moved from essentially closed to open behaviour. The amphibole may also be bent and commonly has undulose extinction, demonstrating that deformation occurred after growth. The amphibole and bronzite are frequently intergrown which suggests a simple replacement relationship as per reaction (1). Normally, orthorhombic amphibole contains some Al and there are two likely sources for this. First, Al may have been brought in with the externally derived fluids whilst a second possibility would be to involve the spinel. A more widespread hydration development within the body is the formation of small grains of talc scattered in many of the bronzite crystals. This development may indicate the very first stages of hydration with the fluids penetrating along grain boundaries and cleavage planes.

In the green spinel there are two responses to recrystallisation. Firstly, there is usually a bleached rim of colourless spinel developed around the still green core. The impression gained is that the green colour gradually fades towards the grain rim such that in spinel aggregates there is commonly a blotchy appearance with the bleaching following individual grain boundaries leaving coloured cores. Corundum has been reported associated with the spinel from this body (Grew, 1982) but this phase was not found in any of the 13 sections examined in this study. The second response, also due to the open system hydration, was the formation of small, hydrous reaction pockets which are sapphirine-bearing (Janardhan and Shadakshara Swamy, 1982; Grew, 1982). In the sections examined, the sapphirine-bearing pockets occur either along grain boundaries between spinel and bronzite or, in the plane of the section, are wholly contained within spinel (Fig. 3). Within these pockets, hydrous assemblages have developed which in the least complicated instances contain sapphirine, cordierite and talc. In a few reaction pockets chlorite may be present, in some instances apparently being replaced by talc. In other reaction pockets a carbonate is present which upon partial microprobe analysis is found to be an iron-rich magnesite. Sapphirine partially or, in one example, completely contained within magnesite may occur, though the significance of this assemblage is difficult to establish. Along some sapphirine–magnesite contacts there may be fine-grained, low birefringent reaction products (possibly chlorite?). Pleochroic sapphirine (α = grey, β = pale blue, γ = bright blue) occurs as scattered, idioblastic to xenoblastic grains within the pockets and may be found around the margins of spinel suggesting that the simplest possible reaction may have been:

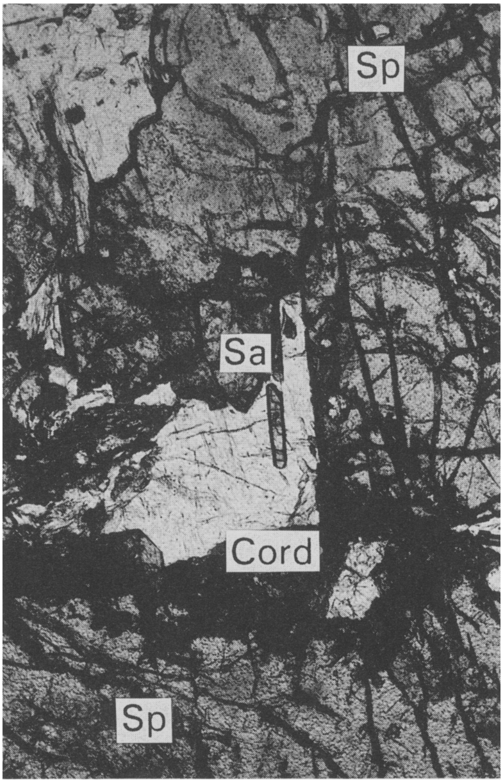

FIG. 3. Photomicrograph of a sapphirine-bearing reaction pocket developed between spinel and bronzite. Height of photo 2.5 mm.

$$\text{spinel} + \text{silica} \rightleftharpoons \text{sapphirine}. \qquad (2)$$

In some instances sapphirine may be in contact with either the spinel or the bronzite, although in most pockets cordierite usually surrounds sapphirine. Because the spinel and bronzite appear to be stable in the anhydrous system, reaction (2) requires an external source for the additional silica. Hydrous fluids from an external source explain the progressive hydration observed towards the margins of the body and adequately provide for this reaction with small amounts of fluid penetrating along the grain boundaries. Further, the externally-derived fluids would have been in contact with rocks more silica-rich than the orthopyroxenite enclave and could provide the required silica. Whilst the fluid itself is not represented in the product of reaction (2), the hydrous vapour could have been responsible for either the production of talc from the orthopyroxene, or have been consumed in the formation of orthorhombic amphibole or otherwise could have been used up in the later formation of the other hydrous phases cordierite and talc. Even though the amounts of talc are small it is considered unlikely that the necessary water required was internally derived.

The assemblage most likely to control the development of sapphirine is enstatite + spinel + vapour and one of the reactions related to I_{16}, I_{18} and I_{21} (Seifert, 1974, 1975) would be attractive (see also Fig. 6 below):

$$\text{enstatite} + \text{spinel} + \text{vapour} \rightleftharpoons \text{sapphirine} + \text{chlorite}. \qquad (3)$$

However, in most of the pockets, one of the products, chlorite (e.g. reaction (3)), is largely missing from the observed assemblage.

Talc in some instances appears to be a later replacement of sapphirine since examples of idioblastic plates of sapphirine are found cut by blades of talc. This contention is supported by the optical continuity of the sapphirine fragments. Further, talc also appears to be replacing some of the chlorite and therefore, appears petrographically to be of at least two distinct origins and probably generations: first, that replacing bronzite; second, that replacing sapphirine and chlorite. It is thus possible that some of the chlorite produced by a reaction such as (3) is eliminated.

Table 1. Representative microprobe analyses of the primary mineral assemblage orthopyroxene - spinel - phlogopite from the Terakanambi ultrabasic enclave.

	Bronzite				
	1	2	3	b	v
SiO2	53.50	55.00	55.70	54.19	54.79
TiO2	nd	0.12	0.15	0.11	0.05
Al2O3	4.40	3.69	2.89	4.86	3.35
Cr2O3	nd	nd	nd	nd	nd
FeO*	10.50	10.00	9.68	9.74	9.66
MnO	n	0.23	0.20	0.23	0.20
MgO	30.60	31.30	31.70	32.29	32.67
ZnO	nd	0.37	0.38	nd	nd
total	99.00	100.71	100.70	101.42	100.72
	structural formula 6(O)				
Si	1.898	1.916	1.937	1.830	1.906
ivAl	0.102	0.084	0.063	0.170	0.094
viAl	0.082	0.067	0.055	0.028	0.044
Cr					
Fe2+	0.310	0.305	0.281	0.281	0.281
Mn		0.007	0.006	0.007	0.006
Mg	1.617	1.626	1.643	1.663	1.693
Zn		0.01	0.01		
Xmg	0.839	0.842	0.854	0.855	0.858

	Spinel								
	2	3	5	6	7	8	ag rim	ah	ai core
SiO2	nd	nd	nd	0.28	0.19	0.23	0.03	0.00	0.00
TiO2	nd	nd	nd	nd	0.14	n	0.00	0.00	0.02
Al2O3	66.20	66.10	67.00	65.60	65.70	66.10	67.42	67.50	66.99
Cr2O3	nd	0.11	nd	0.12	nd	0.17	nd	nd	nd
FeO*	15.80	16.40	15.80	20.00	17.00	17.30	15.10	14.93	15.05
MnO	nd	nd	nd	0.12	n	0.15	0.11	0.05	0.09
MgO	18.50	17.90	17.80	14.90	16.90	16.90	18.75	19.35	19.36
total	100.50	100.51	100.60	101.02	99.93	100.85	101.41	101.83	101.51
	structural formula 32(O)								
Si				0.057	0.040	0.046	0.006		
Ti					0.022				0.0030
Al	15.815	15.834	15.966	15.878	15.878	15.845	15.900	15.841	15.793
Cr		0.018		0.02		0.019			
Fe3+	0.185	0.148	0.034	0.102	0.122	0.136	0.100	0.159	0.207
Fe2+	2.499	2.639	2.642	3.343	2.793	2.817	2.427	2.327	2.310
Mn				0.020		0.027	0.019	0.008	0.015
Mg	5.592	5.434	5.373	4.572	5.144	5.132	5.590	5.741	5.770
Xmg	0.691	0.673	0.670	0.578	0.648	0.646	0.697	0.712	0.714

	phlogopite	
	p1	p2
SiO2	40.74	39.19
TiO2	1.28	1.41
Al2O3	18.17	18.02
FeO	4.18	5.21
MnO	0.03	0.01
MgO	23.80	22.98
ZnO	nd	nd
CaO	nd	nd
Na2O	0.46	0.30
K2O	8.95	8.94
total	97.61	96.06
structural formula 22(O)		
Si	5.578	5.492
Aliv	2.422	2.508
Alvi	0.511	0.469
Ti	0.138	0.149
Fe	0.479	0.611
Mn	0.003	0.001
Mg	4.856	4.800
Zn		
Ca		
Na	0.122	0.082
K	1.563	1.599
Xmg	0.910	0.887

All Fe analysed as FeO. Fe3+ in spinel calculated to satisfy stoichiometry for R3+ ions.
nd: not detected.

Mineral Chemistry

Representative analyses of the coexisting phases are presented in Tables 1 to 4 and are plotted in the system (MgFe)O-Al_2O_3-SiO_2-H_2O (FMASH) in Fig. 4. There is a significant change in the composition of the reactants as compared with the products. The starting materials have X_{Mg} phlogopite > bronzite > spinel, and the highly magnesian nature of the products with X_{Mg} talc > cordierite > sapphirine is evident (Tables 1–4). The minerals are described in their approximate order of appearance, the primary minerals bronzite and spinel are discussed first.

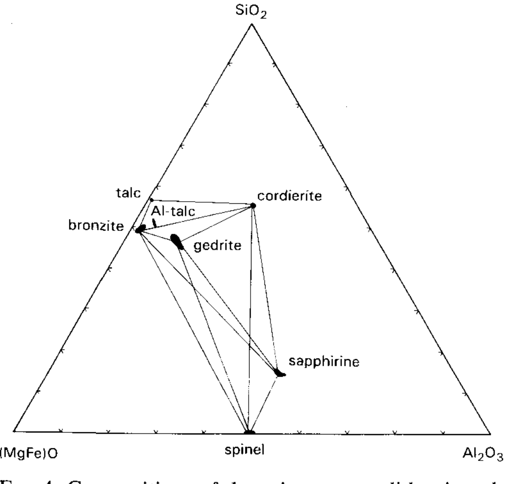

FIG. 4. Compositions of the primary protolith minerals and the reaction products from the sapphirine-bearing pockets from the Terakanambi pyroxenite enclave (sample GU80-1) plotted in the system SiO_2–(MgFeO)–Al_2O_3 (mol.%).

Bronzite. In general, bronzite appears to be relatively homogeneous in terms of X_{Mg} and is somewhat aluminous with 3–4 wt.% Al_2O_3 (Table 1). The data plot along the $MgSiO_3 \rightleftharpoons Al_2O_3$ substitution line with, in addition, Mg $\rightleftharpoons$ Fe also operating (e.g. Boyd and England, 1960; Windley *et al.*, 1984).

Spinel. The spinels approximate to a pleonaste in composition with Mg/Fe ratios around 2, very little to no detectable Cr and resemble the ceylonites described by Clifford *et al.* (1975). Their chemistry is complicated by effects attributed to metamorphism. The distinct green cores are more magnesian and less iron-rich than the colourless, bleached rims and X_{Mg} values vary between about 0.57 and 0.71 (Table 2). Further there is a small but noticeable decrease in the calculated Fe^{3+} from core to rim. It is thus possible that the bleaching is a response to change in oxidation state which could be induced by the influx of the externally-derived fluid. Because the bleaching is found along the grain boundaries, the most likely path for introduced fluids, this must be considered a strong possibility. The spinels consistently have much lower X_{Mg} values than the coexisting bronzite and phlogopite. Whilst total

Table 2. Representative microprobe analyses of orthorhombic amphiboles replacing orthopyroxene from the ultrabasic enclave .

	1	2	3	4	5	6	7	8	9
SiO2	45.80	45.00	47.10	44.99	42.35	44.89	46.13	45.64	45.09
TiO2	0.41	0.41	0.15	0.31	0.31	0.33	0.33	0.24	0.26
Al2O3	19.20	19.90	15.54	18.97	21.21	18.77	18.39	17.93	18.79
FeO*	8.38	8.53	8.82	8.20	8.85	8.47	8.45	8.10	8.97
MnO	0.15	0.22	0.18	0.15	0.20	0.19	0.27	0.24	0.26
MgO	23.30	22.60	23.69	23.15	22.05	23.81	24.04	24.21	24.12
ZnO	nd	nd	0.32	nd	nd	nd	nd	nd	nd
CaO	0.86	0.59	0.36	0.64	0.67	0.65	0.52	0.59	0.57
Na2O	1.48	1.67	1.50	1.74	1.48	1.55	1.56	1.65	1.68
K2O	nd	nd	nd	nd	nd	0.05	0.05	0.04	0.02
total	99.58	98.92	97.66	98.15	97.12	98.71	99.74	98.64	99.76
					structural formula to 23(O)				
Si	6.183	6.115	6.494	6.164	5.839	6.130	6.223	6.224	6.110
ivAl	1.817	1.885	1.506	1.836	2.107	1.870	1.777	1.776	1.890
viAl	1.234	1.309	1.020	1.227	1.373	1.152	1.147	1.106	1.112
Ti	0.042	0.042	0.015	0.031	0.032	0.034	0.033	0.025	0.026
Mg	3.724	3.649	3.965	3.742	3.595	3.814	3.820	3.869	3.862
Mg	0.964	0.927	0.902	0.985	0.979	1.032	1.013	1.051	1.009
Fe	0.947	0.97	1.017	0.939	1.021	0.967	0.953	0.924	1.017
Mn	0.019	0.026	0.022	0.019		0.022	0.031	0.028	0.030
Zn			0.033						
Ca	0.007	0.077	0.026			0.001			
Ca	0.120	0.009	0.026	0.092	0.10	0.094	0.075	0.086	0.083
Na	0.387	0.440	0.401	0.464	0.398	0.410	0.408	0.436	0.441
K						0.009	0.009	0.007	0.003
Xmg	0.832	0.825	0.827	0.834	0.818	0.834	0.835	0.842	0.827

nd: not detected

iron was analysed as FeO the stoichiometry appears to be good, with Al closely approaching 16 atoms per 32 oxygens; therefore, on the basis that there are small amounts of Cr and Si present in most samples, Fe_2O_3 is in most intances less than 0.2 per formula unit.

Phlogopite. Analyses are given in Table 1 and are magnesian, with X_{Mg} around 0.9 and have low TiO_2, resembling those reported by Lal *et al.* (1978) rather than high Ti varieties reported by Clifford *et al.* (1975). However, the phlogopites reported here are more aluminous than those given by Lal *et al.* (1978), with R^2 totalling at least 5.6 cations.

Alumino-gedrite. Orthorhombic amphibole analyses are normalised to 23(O) and have less than 7.0 Si atoms per unit formula (Table 3). They are thus gedritic and because of their high Al contents (Fig. 4), with $Al^{iv} > 0.5$, are termed alumino-gedrites after Leake (1978). Because there is approximately 1.5% Na_2O the substitution $NaAl^{iv} \rightleftharpoons \blacksquare\, Si$ is deemed to have operated. In terms of Fe–Mg substitution the chemistry is essentially constant, no obvious zonation being detected. X_{Mg} is high, at about 0.82–0.84, and is only slightly lower than that for the bronzite ($X_{Mg}{}^{opx}$ 0.84–0.85) which it is replacing. The replacement, which produced complex intergrowths with bronzite, cannot be a simple hydration approximated by adding an externally derived hydrous fluid because of the high Al content of the amphibole (compare Tables 1 and 2). An addition of aluminium must be involved which could have been derived from two possible

Table 3. Representative microprobe analyses of cordierite and talc from the reaction pockets.

	cordierite									talc				
	1	2	3	4	5	6	7	8	9	1	2	11	3	4
SiO2	49.37	49.50	48.96	49.48	49.54	49.77	50.26	49.93	50.74	60.55	60.77	61.17	55.10	52.61
Al2O3	34.07	33.26	33.06	33.88	33.44	33.88	33.03	33.98	33.93	1.79	0.92	1.34	5.64	8.82
FeO	1.74	1.92	1.88	1.68	1.90	1.83	2.40	1.83	1.44	1.82	2.07	2.31	9.73	9.63
MnO	nd	nd	0.10	nd	nd	nd	nd	0.05	0.05	nd	nd	nd	0.21	0.20
MgO	11.92	12.2	12.26	12.2	12.12	11.94	11.84	12.60	12.60	29.33	29.41	29.66	26.45	25.79
CaO	nd	nd	nd	nd	nd	nd	nd	0.03	0.03	nd	0.41	nd	0.16	0.32
Na2O	nd	0.40	nd	nd	nd	0.32	0.40	0.48	0.49	nd	0.41	nd	0.57	0.48
total	97.10	97.28	96.26	97.24	97.00	97.74	97.93	98.90	99.28	93.49	93.99	94.48	97.86	97.85
	Structural formula 18(O)									structural formula 24(O)				
Si	4.987	5.004	4.999	4.991	5.014	5.002	5.055	4.970	5.016	8.574	8.601	8.593	7.825	7.503
Al	4.056	3.964	3.979	4.029	3.989	4.015	3.916	3.987	3.954	0.299	0.153	0.222	0.945	1.483
Fe	0.147	0.163	0.160	0.142	0.161	0.154	0.202	0.152	0.119	0.215	0.245	0.272	1.155	1.149
Mn			0.008					0.004	0.004				0.024	0.024
Mg	1.794	1.839	1.865	1.983	1.829	1.788	1.774	1.869	1.856	6.188	6.204	6.201	5.599	5.482
Ca								0.003	0.003		0.062		0.024	0.048
Na		0.078				0.063	0.078	0.093	0.094		0.113		0.161	0.134
Xmg	0.924	0.919	0.921	0.933	0.919	0.921	0.898	0.925	0.940	0.966	0.962	0.958	0.829	0.827

nd: not detected

sources, either externally or internally by involving spinel. Because there has to be the addition of small amounts of other components such as Na, which were clearly externally derived, an unequivocal origin is difficult to determine. It is considered from the petrographic relations that the spinel and the fluids derived from the host amphibolites and gneisses could adequately account for the extra components.

Sapphirine. Analytical data of the sapphirines are presented in Table 4. Their composition field is shown in Fig. 4 and the individual data points are plotted in the enlarged portion of the system SiO_2-(MgFe)O-Al_2O_3 (Fig. 5*a*). The analysed sapphirines are magnesian with a relatively narrow range of X_{Mg} between 0.899 and 0.917. They are peraluminous, plotting as a relatively tight cluster to the right of the composition point 7:9:3 (Schreyer and Abraham, 1975) and agree with the composition reported earlier by Grew (1982). Tschermak substitution in the form R^{2+} Si = = $2R^{3+}$ accounts for the deviation from the ideal composition 2:2:1. The majority of analyses have very small amounts of Fe^{3+}, >0.1 Fe^{3+} per 20 oxygen (Table 4), calculated following the method of Higgins *et al.* (1979). One analysis (10, Table 4) is however, significantly more Si-rich and plots off of the main R^{2+} Si $\rightleftharpoons 2R^{3+}$ substitution line (Fig. 5*a*). Whilst the analysis requires no calculated Fe^{3+}, and the total cations per 20 oxygens is close to 14, the deviation is difficult to explain (apart from experimental error). A plot of Si against ΣR^{3+} atoms (Fig. 5*b*) shows that the analyses fall on a continuous trend sub-parallel to those of other peraluminous sapphirines. Analysis 10 plots at the extreme end of the substitution line and thus appears to be rational and not a spurious value. A strong negative correlation between Mg and Al^{vi} suggests that Mg is the main R^{2+} participant in the substitution (Fig. 5*c*), though there is little correlation with Fe^{2+} which plots as a roughly constant band, as found individual sapphirine assemblages by Lal *et al.* (1984). Analysis 10 falls off of the Mg trend and the Fe^{2+} scatter is difficult to rationalise. Two possible explanations are either that some other form of substitution was operational or, given the very small amounts of Fe^{2+} in the highly magnesian reaction pockets, equilibrium has not been attained.

Cordierite. Cordierites are fresh, generally unaltered and are rather magnesian with a consistently high X_{Mg} ~0.92, which is higher than the associated sapphirine (Tables 3 and 4). Whilst sector twinned, they appear unzoned and their slightly low totals are taken to suggest a volatile content (H_2O and/or CO_2) of about 2–3%, which is in agreement with their proposed origin. However, given that the reaction pockets are very small it has not been possible to extract mineral concentrates to test this. Na_2O was detected in some grains up to *c.* 0.6%.

Talc. Inspection of the chemical data (Table 3) and the plot of the data (Fig. 4) shows that talc has a variable composition, but may be broadly divided into two groups. Firstly, that plotting at the ideal composition with low Al and secondly, that with high Al. This suggests that either some form of substitution was operating or that the talc has been deried from two different sources. Schreyer and Abraham (1975) have suggested that $NaAl \rightleftharpoons 2Si$ substitution may operate, whilst an alternative of $MgSi \rightleftharpoons 2Al$ has been proposed by Fawcett and Yoder (1966). On the basis of the data presented here, the aluminous talc carries higher Na than the ideal composition talc, therefore, the former substitution is the more attractive. The part played by Mg is more difficult to assess because in addition there is some change in the Fe content which is not controlled by the apparent textural origin of the talc so $Mg \rightleftharpoons Fe$ exchange cannot be evaluated properly. The importance of understanding the role of talc may be ascertained from Fig. 4. Whilst it would be convenient if the ideal talc were associated with breakdown of bronzite and the aluminous talc with the breakdown of sapphirine and chlorite, this appears not to be the case. It is again emphasised that the two compositions are neither optically nor texturally distinct, for both compositions are associated with bronzite, cordierite and sapphirine. Since the only ready source of alumina in the primary assemblage is the spinel, it may suggest that the talc external to the reaction pockets has formed by involvement of the spinel. A possibility is that this was associated with the bleaching of the spinels, forming the rather more Fe-rich rims, but proof is lacking because there is no significant drop of Al content. That the talc is of very variable chemistry tends to support the contention that equilibrium was not attained.

The production of sapphirine is favoured by high oxygen fugacity (Mohan *et al.*, 1986; Herd *et al.*, 1987) and may link with the bleaching of the margins of the spinels and a change in the oxidation state of the iron (Table 1). Further, this observation is consistent with the concept that increasing water content will stabilise gedrite and cordierite. From textural evidence the sapphirine appears to coexist stably with cordierite and there appears to be some chemical evidence that in any one reaction pocket there was an approach to equilibrium between these two phases. $K_D{}^{sa\text{-}cd}{}_{Mg\text{-}Fe}$ appears to be consistent though the values vary from pocket to pocket in the range 0.5–0.98. Chemical equilibrium is regarded as a rare phenomenon (e.g. Lal *et al.*, 1978), more usually only a localised equilibrium being reached (e.g. Clifford *et al.*, 1975), as is suggested to be the case here. Because there is a

Table 4. Representative microprobe analyses of sapphirines from within reaction pockets

	Grain 1							Grain 2		Grain 3					Grain 4	Grain 5
	1	2	3	4	5	5	6	10	11	12	13	14	15	16	17	18
SiO2	12.0	12.1	12.3	12.6	12.6	12.3	11.7	14.5	11.2	11.6	12.1	11.4	12.5	11.7	12.0	12.7
Al2O3	66.0	65.7	66.8	66.6	65.5	67.0	67.5	64.4	67.0	67.3	66.5	67.0	63.7	66.4	65.4	65.5
Cr2O3	nd	nd	nd	nd	0.13	nd	nd	nd	nd	0.11	nd	nd	nd	0.17	0.16	nd
FeO*	3.58	4.00	4.12	3.93	4.08	3.92	3.87	3.79	3.87	3.56	3.58	3.73	4.01	3.68	4.09	4.06
MgO	17.20	18.00	18.10	18.50	18.20	18.00	17.90	17.70	17.90	17.40	17.90	17.40	18.10	17.80	17.85	18.40
ZnO	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0.19	nd	0.26	nd	nd
V2O5	0.11	0.11	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
total	98.89	99.91	101.32	101.63	100.51	101.22	100.97	100.39	99.97	99.97	100.08	99.72	98.31	100.01	99.51	100.66
structural formula to 20(O)																
Si	1.413	1.418	1.416	1.448	1.465	1.416	1.354	1.68	1.315	1.353	1.406	1.336	1.484	1.373	1.418	1.473
ivAl	4.587	4.582	4.584	4.552	4.535	4.584	4.646	4.32	4.685	4.647	4.594	4.664	4.516	4.627	4.582	4.527
viAl	4.595	4.495	4.552	4.487	4.461	4.535	4.571	4.491	4.565	4.616	4.555	4.603	4.429	4.533	4.494	4.454
Cr					0.012					0.01				0.016	0.01	
Fe3+		0.087	0.062	0.065	0.062	0.029	0.075		0.04	0.021	0.039	0.061	0.087	0.078	0.078	0.073
Fe2+	0.345	0.305	0.337	0.313	0.336	0.349	0.299	0.367	0.339	0.327	0.31	0.305	0.313	0.282	0.325	0.323
Mg	3.032	3.141	3.109	3.166	3.161	3.097	3.091	3.056	3.116	3.035	3.115	3.045	3.214	3.108	3.132	3.187
Zn												0.017		0.023		
V	0.01	0.01														
Xmg	0.8978	0.911	0.902	0.910	0.904	0.899	0.912	0.893	0.902	0.903	0.909	0.909	0.911	0.917	0.933	0.908

* Fe is determined as FeO and recalculated in the structural formula to balance the ideal formula following the method of Higgins et al. (1979).

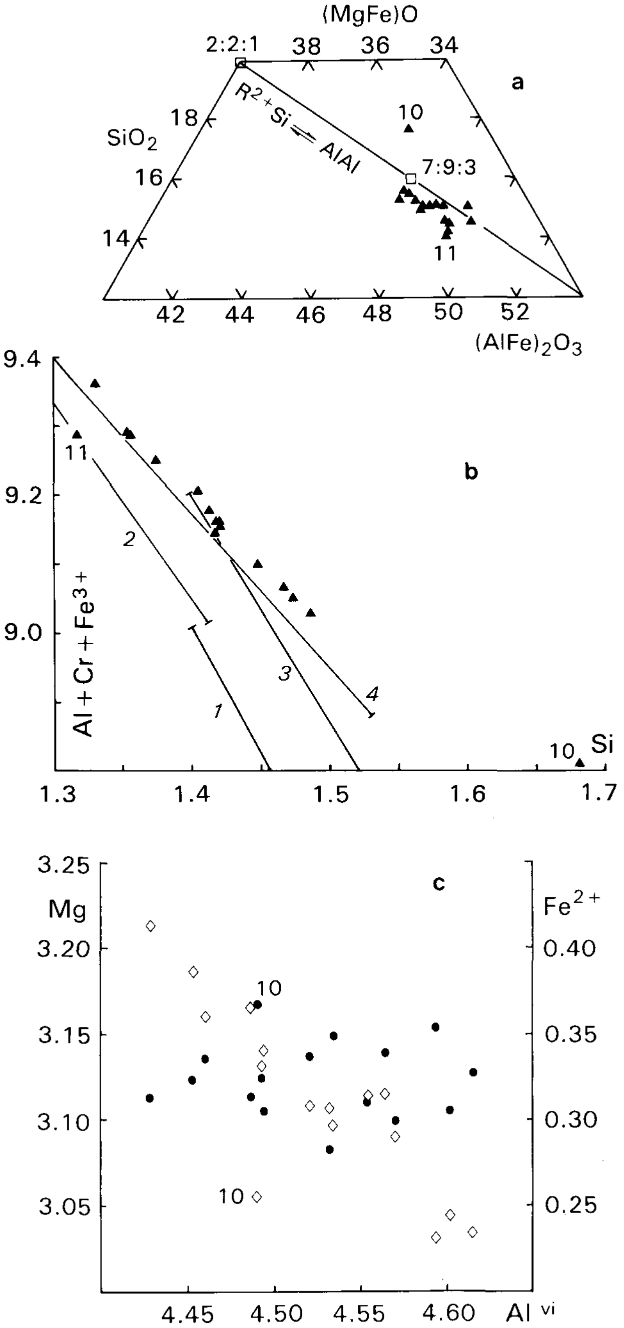

FIG. 5(*a*) Sapphirine data plotted in the relevant portion of the system SiO_2–(MgFeO)–$(AlCrFe)_2O_3$ (mol.%). The ideal substitution line R^{2+} Si $\rightleftharpoons$ 2Al extends from the composition 2:2:1 to 7:9:3. (*b*) Composition of the sapphirines showing the linear relationship between Si atoms and Al + Cr + Fe^{3+}. Points 10 and 11 are discussed in the text. Ranges for other peraluminous sapphirines are included for comparison, numbers in italics: 1, Ellis *et al.* (1980); 2, Warren and Hensen (1987); 3, Schreyer and Abraham (1975); 4, Friend (1982). (*c*) Composition of the sapphirines in terms of Mg (diamonds) and Fe^{2+} (dots) plotted against octahedrally co-ordinated Al.

large number of mineral phases involved which are divisible into three different groups of assemblages, chemical equilibrium clearly has not been attained. This may be due to several reasons. The original coarse-grained nature of the protolith could have impeded the processes of recrystallisation and introduced fluid movement. Further, it would seem that much of the fluid was consumed near the margins in the conversion of orthopyroxene to ortho-amphibole. In addition, the externally derived volatile phase, which had only just initiated the hydration reactions, was probably not of constant composition. This possibility is, for example, suggested by the development of carbonate within some reaction pockets and not others.

Phase relations and metamorphism

The mineral assemblages in Gu80-1 can, because of the relatively simple rock chemistry, be reduced to the FMASH system and, because the minerals all have high Mg/Fe ratios, they approximate to the MASH system for which there is much experimental and theoretical data (e.g. Seifert, 1974, 1975; Lal *et al.*, 1984; Mohan *et al.*, 1986). The small amounts of di- and trivalent Fe present would tend to depress the position of the various reactions in *PT* space, so the MASH system represents maximum conditions. In this study phlogopite has been ignored because it forms only a minor component of the original protolith assemblage and no potassic phases were found in the reaction pockets. In this instance it is considered unlikely that K-loss has occurred during sapphirine formation as suggested for the Namaqualand occurence (Clifford *et al.*, 1975). Therefore, any possible contribution of K is considered to be negligible. Further, the presence of magnesite in some pockets has also been ignored because of the lack of data concerning the stability of sapphirine and a carbonate phase, though from the petrographic evidence here and its earlier record from Naxos (Buick, 1988) this assemblage is clearly possible.

The rock system represented by Gu80-1 begins in an essentially anhydrous state to which hydrous volatiles are added and with the production of gedrite, chlorite, cordierite and talc the recrystallisation is taken to be retrogressive. To explain the main hydrated product around the margins of the enclave, alumino-gedrite, a possible reaction would be to involve the breakdown of some spinel to provide the required aluminium (Table 2). However, it is evident that the bleached rims of the spinels are more aluminous than the cores. Therefore, it is probable that the additional components were externally-derived.

The reactions within the enclave took place under conditions of more restricted hydration and the appearance of the sapphirine-bearing, hydrous assemblages can be made with reference to reactions beginning with the assemblage orthopyroxene + spinel + V (Fig. 6*a*). This occurs along two of the possible reaction lines arrayed around I_{18} (Seifert, 1974, 1975) and takes an essentially anhydrous assemblage into the hydrous field. This arrangement of reactions would suggest that they resulted from falling *PT* conditions. The products, cordierite + chlorite or chlorite + sapphirine are formed depending whether the reaction is above or below I_{18} in *PT* space. However, it cannot be at a lower *P* than about 3 kbar, because the reaction between enstatite and spinel to give cordierite and forsterite (Fig. 6*a,b*) is not observed.

The main problem in Gu80-1 is interpreting the timing of the appearance of sapphirine and thus the sequence of reactions. The arrangement of sapphirine-forming reactions is shown in Fig. 6*a*. In most sections of the reaction pockets chlorite is absent. Only in one or two examples, totally enclosed within spinel in the plane of section, was the assemblage chlorite + sapphirine observed. Otherwise, idioblastic sapphirine is most commonly found towards the centres of the pockets, often surrounded by cordierite and in some instances, separated from spinel. Therefore, it is possible that more than one reaction may have been responsible for the appearance of sapphirine, the path of reaction lying either above or below I_{18} (Fig. 6*a*). A possible path could have been:

$$\text{enstatite} + \text{sapphirine} + \text{vapour} \rightleftharpoons \text{chlorite} + \text{sapphirine} \quad (4)$$

rather than

$$\text{enstatite} + \text{sapphirine} + \text{vapour} \rightleftharpoons \text{chlorite} + \text{cordierite} \quad (5)$$

which produces cordierite first. This places the starting position above I_{18} and is controlled by the assemblage enstatite + spinel + vapour which runs essentially up *P* at an approximate *T* of 760–770 °C to I_{21} (Seifert, 1975; Fig. 6*b*). Here the formation of sapphirine + chlorite is terminated, as sapphirine is replaced by kornerupine, thus placing a maximum *PT* condition on the enclave. The path of reaction could then intersect reaction (5), to give the petrographic evidence of sapphirine inside cordierite. Reaction (5), which commences at I_{18}, terminates at I_{20} and so determines the maximum *P* for the cordierite-bearing

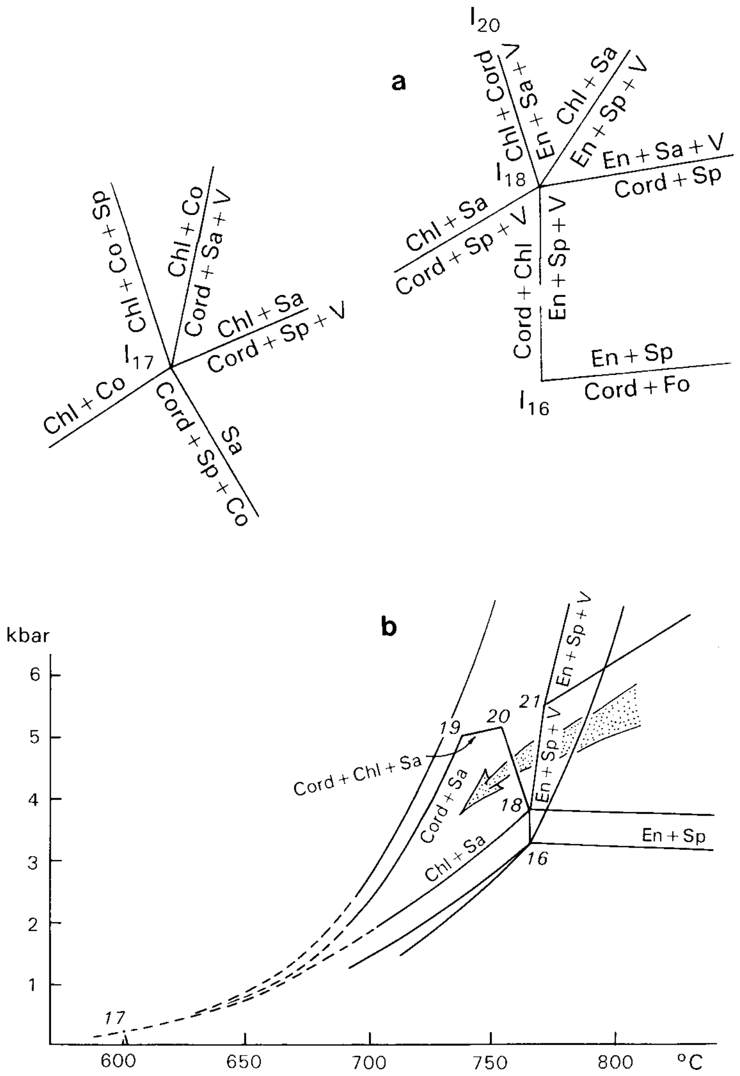

FIG. 6(*a*) Schematic arrangement of reaction relationships around I_{16}, I_{17} and I_{18} of MASH (after Seifert, 1974) involving the phases chlorite (Chl), cordierite (Cord), corundum (Co), enstatite (En), forsterite (Fo), sapphirine (Sa), spinel (Sp) and vapour (V). (*b*) PT grid with the relevant reactions and inveriant points (Seifert, 1974, 1975) located. A possible path of Gu80-1 is indicated by the arrow.

assemblage, about 5 kbar (Seifert, 1975). An approximation of the possible path associated reactions is presented in Fig. 6*b*. The lower limits of this reaction are also constrained by I_{16} because the assemblage forsterite + cordierite is not observed.

The involvement of talc means that the next stages require a modification of the grid. Because there is no indication of equilibration it is difficult to assess the contribution of the primary bronzite + spinel assemblage relative to the retrogressive alumino-gedrite + talc assemblage. Whilst hypothetical grids have been explored their value is limited for two main reasons: first, it has been demonstrated that there are additional, externally-derived components; second, because of the two different compositions of the talc (Fig. 4). However, examining the initial reactions involving the primary assemblage and using only the talc closest to the ideal composition, a possible path can be deduced. This follows the simple hydration and explains the initiation of the scattered talc in the general groundmass of the rock by

$$\text{enstatite} + \text{spinel} + \text{vapour} \rightleftharpoons \text{gedrite} + \text{talc}. \quad (7)$$

Following this path the appearance of cordierite could be explained by enstatite–gedrite reactions. However, because the reactions are not very extensive and have not gone to completion, there is the additional problem that metastable extensions were intersected.

Present in these rocks is the two-phase assemblage cordierite + spinel which is important with respect to the metamorphic evolution of the area as it is restricted to low pressures (Seifert, 1974). It is bounded by the two invariant points I_{17} and I_{18} and the reactions:

$$\text{enstatite} + \text{sapphirine} + \text{vapour} \rightleftharpoons \text{cordierite} + \text{spinel}$$

$$\text{chlorite} + \text{sapphirine} \rightleftharpoons \text{cordierite} + \text{spinel} + \text{vapour}$$

$$\text{chlorite} + \text{corundum} \rightleftharpoons \text{cordierite} + \text{spinel} + \text{vapour}$$

(Schreyer, 1970; Schreyer and Seifert, 1969). Seifert (1974) suggests that the maximum pressure for this assemblage in the pure MgO + H_2O system is 3.8 kbar. From petrographic evidence no corundum is present and the mineral assemblages observed are not related to the reaction involving corundum.

The observed sapphirine-bearing assemblages can be explained largely by reference to the reaction (4), but this produces a problem in that chlorite is a very minor component of the mineral assemblages observed. Talc could possibly be presumed to take its place since the chlorite (not present in analysed sections) would have to be highly magnesian.

To further constrain the metamorphic conditions, Seifert (1974) cites the limiting pressure for enstatite + sapphirine as *c.* 3 kbar. However, in this assemblage sapphirine would not be encountered until it had first been formed by reaction (4), or by silica addition to spinel (2). This evidence initially seems incompatible with the observed two phase assemblage of sapphirine + alumino-gedrite, taken to be equivalent to aluminous anthophyllite, (Schreyer and Seifert, 1969; Seifert, 1974) which forms in excess of 7 kbar. Again, petrographic evidence suggests that the orthorhombic amphibole has formed from the breakdown of the primary bronzite and is breaking down where it becomes involved in the reaction pockets. The addition of small amounts of Na and Fe to the MASH system will reduce the required pressures and so the values indicated by the experimental work represent maxima. Chemographic work shows that μFeO also has a limiting effect upon the presence of sapphirine (Mohan *et al.*, 1986).

Discussion and conclusions

The spinel–bronzite enclave associated with the Sargur supracrustal unit preserves early, coarse-grained textures and structures. These have a close resemblance to those in similar, coarse-grained spinel-rich, olivine- and orthopyroxene-bearing ultramafic rocks from West Greenland, interpreted to represent primary igneous textures (Friend and Hughes, 1977). Because of this textural similarity it is suggested that the Terakanambi orthopyroxenite could also be interpreted as preserving relics of its primary igneous mineralogy. These primary textures then show the effects of grain-size reduction under anhydrous, closed system conditions to yield bronzite-spinel aggregates with a granoblastic texture. The next stage in the tectono-metamorphic history is retrogressive hydration to form alumino-gedrite, an event which marks the change in the fluid phase from closed to open system behaviour. Following this first hydration effect sapphirine-bearing, hydrous pockets, restricted to grain boundaries between spinel and bronzite developed. Because each pocket has a slightly different mineralogy it is probable that there was no attainment of equilibrium between each pocket. It would seem that there were only restricted links between the pockets, such that there was fluid access but no major diffusion of components.

The sapphirine data demonstrate a dominantly per-aluminous chemistry and such compositions have been regarded previously as being metastable, formed prior to the attainment of a stable assemblage comprising corundum + cordierite (Schreyer and Abraham, 1975, 1976). Given that corundum + cordierite has been reported from the locality (Grew, 1982), it is a plausible explanation that the per-aluminous sapphirines represent metastable compositions. The metastable appearance of some of the phases is in agreement with the petrographic and mineralogical suggestions of non-equilibrium assemblages. However, there is some experimental work at low pressures suggesting that per-aluminous sapphirine can be a stable phase (Smart and Glasser, 1981), but in this example such a situation would seem to be unlikely. On the basis that the reaction pockets have slightly different assemblages, it is suggested that in individual cases a pocket may have approached equilibrium, but over the body as a whole equilibrium was clearly not attained.

It is possible that the changes under anhydrous conditions reflect the initial emplacement of the pyroxenite into the Sargur rocks, whilst the hydration and formation of low pressure assemblages reflects subsequent equilibration with its new surroundings and uplift. The work of Raith *et al.* (1983) and Srikantappa *et al.* (1985) has led to the suggestion that a late Archaean high-grade metamorphic event occurred in the region. This may link with the event which caused anatexis of the Peninsular gneiss complex and the formation of the Closepet granite at *c.* 2513–2528 Ma (Friend and Nutman, 1991, 1992) and the establishment of an amphibolite–granulite facies transition across the southern peninsula (see Newton, 1992). The introduction of fluids in association with minor amounts of carbonate has been equated with the transformation of other ultramafic bodies elsewhere in the region to carbonate-bearing, sagvanditic assemblages (Janardhan and Srikantappa, 1977; Janardhan and Shadakshara Swamy, 1982). Since there is carbonate (now identified as magnesite) present in this enclave, it would not be unreasonable to equate the events. It is this transformation which was considered by Srikantappa *et al.* (1985) to have occurred in the late Archaean at or near granulite facies conditions, associated with the formation elsewhere of arrested charnockites. Given that in the Gundlupet area there are many carbonate horizons within the supracrustal rocks (Fig. 1) it is evident that carbonate or carbon dioxide could have been transported short distances by a migrating hydrous fluid at any stage of the metamorphic history. The simplest source for the externally-derived carbonate in the reaction pockets is the associated carbonate-rich metasediments nearby and it is unlikely that it is related to the CO_2-induced arrested charnockite formation. Given that the maximum *PT* conditions, ~3–5.5 kbar at ~765 °C for the first reactions preserved in the enclave, they were the product of metamorphism at lower grade, and are more likely to be associated with retrogression during uplift and cooling.

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