Chemographic Relationships in Sapphirine-Bearing Rocks From Sonapahar, Assam, India

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Abstract. Silica-deficient rocks in which sapphirine coexists with cordierite, gedrite, chondrodite, spinel, corundum and phlogopite in various parageneses, occur in association with cordierite-garnet-sillimanite-bearing granulitic gneisses in a Precambrian metamorphic terrain displaying amphibolite-granulite transition facies. Brucite coexists with spinel and corundum and its unusual stability in this environment has been attributed to its significant fluorine content. Kornerupine occurs as armoured relics within cordierite in one sample of the sapphirine-spinel-cordierite-phlogopite-bearing rock. Sapphirines (X Mg 0.77 to 0.92) plot near the 7:9:3 composition. X Mg varies in the order: chondrodite and brucite > gedrite > cordierite > phlogopite > sapphirine > spinel.

The consistent topology of the observed mineral assemblages with reference to the system $MgO - FeO - Al_2O_3 - SiO_2 - H_2O$, systematic partitioning of Mg and Fe in the coexisting phases, and textural relations are in accord with attainment of chemical equilibrium during the regional metamorphism. The sequence of metamorphic reactions has been deduced as a function of changing $MgO/(MgO + FeO)$ ratio in the bulk composition and it has been shown that the topology in the $SiO_2 - (FeO + MgO) - Al_2O_3$ diagram for more magnesian compositions is consistent with experimental data in the system $MgO - SiO_2 - Al_2O_3 - H_2O$. The stable occurrence of the spinel-cordierite and spinel-sillimanite joins in less magnesian bulk compositions suggests that these tie lines are stable to higher pressures and lower temperatures respectively as compared to the Fe-free synthetic system.

Using experimental and theoretical data on garnet-cordierite, garnet-biotite, garnet-plagioclase and orthopyroxene-clinopyroxene equilibria, PT conditions have been estimated to be $750° \pm 50°$ C/ 5 ± 0.5 Kb for the thermal peak of metamorphism.

It is suggested that the unusual bulk composition of the sapphirine-bearing rocks viz. higher Al_2O_3, MgO and $MgO/(MgO + FeO)$ and lower SiO_2, Na_2O and CaO compared to the parent cordierite-bearing granulitic gneisses may be attributed to partial melting and removal of granitic melt. This is in agreement with the variation of oxides in the 'restites' and parent rock. The 'restites' consisted of the assemblage cordierite-spinel – corundum which then reacted to form sapphirine. This reaction, which in the synthetic Fe-free system is confined to extremely low-pressures (~ 300 bars), is likely to occur at higher pressures with MgFe substitution.

Introduction

Sapphirine-bearing rocks have attracted the attention of many geologists on account of the complex petrological problem they display. Experiments in the system $MgO - SiO_2 - Al_2O_3 - H_2O$, demonstrate that sapphirine is stable over a wide PT range from upper amphibolite to granulite facies conditions (e.g., Seifert, 1974; Ackermand et al., 1975) which is in agreement with the natural occurrence of sapphirine-bearing rocks. However, such rocks are relatively rare in nature presumably because of the restricted bulk composition in which sapphirine is able to form.

The area around Sonapahar, Assam, is well known for its classic sillimanite-corundum economic deposit. Although Dunn (1929) first mapped the area in detail, sapphirine bearing rocks have been recognised only in the last 25 years or so in this locality (Ghosh and Saha, 1954). However, to date, no detailed miner-

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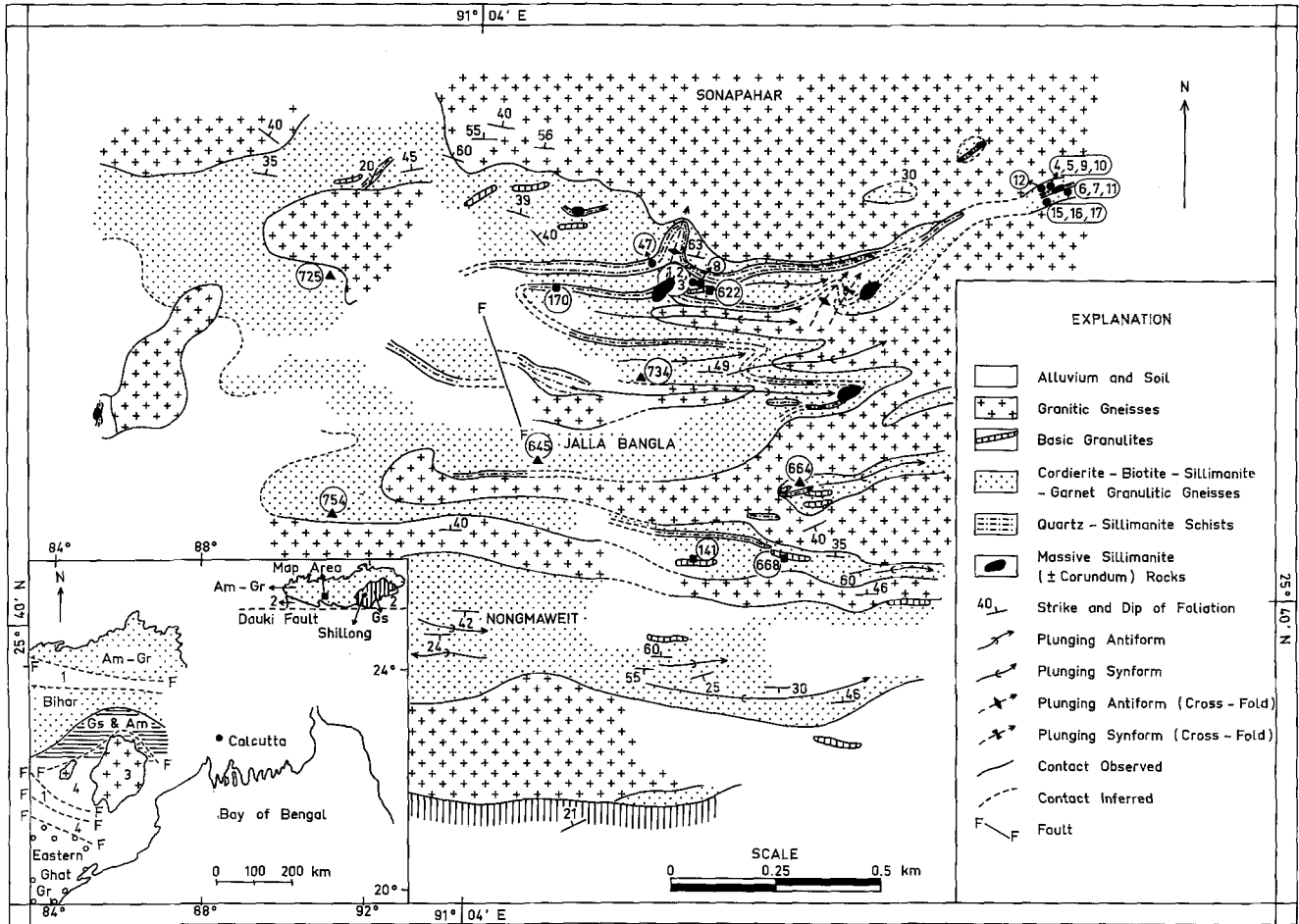
Fig. 1. Geological map of the area around Sonapahar. Solid circle-location and sample reference numbers (Tables 1, 2, 3, and 5) of the sapphirine bearing- and other silica deficient rocks. Solid triangle-location and sample numbers of cordierite-bearing granulitic gneisses (Table 4). Solid square-location and sample number of the basic granulites (Table 4). Inset shows the location of the area and distribution of regional metamorphic facies in adjoining regions. 1: Permocarboniferous Gondawana coal seams and associated sedimentary rocks. 2: Sedimentary rocks and basic volcanics of Cretaceous age. 3: Singhbhum granite. 4: Sedimentary rocks of the Iron-ore Group. Stippled—Amphibolite—granulite transition facies (*Am-Gr*). Horizontal ruled—Greenschist and amphibolite facies (*Gs & Am*) vertical ruled—Greenschist facies (*Gs*). Open circles—Granulite facies (*Gr*). F: F-Faults

alogical and petrological investigations have been carried out on these rocks.

During these investigations of the rocks several new assemblages were found, some of which have not been hitherto reported. The purpose of this paper is to discuss the mineral chemistry, phase petrology, and genesis of sapphirine-bearing and associated silica-deficient rocks and to throw light on some of the current petrological problems displayed by them, viz. (1) the effect of $Mg \rightleftharpoons Fe$ substitution on mineral stability in comparison to the synthetic Fe-free system; (2) the origin of the unusual bulk composition of these rocks which does not correspond to normal igneous or sedimentary rocks; (3) attainment of equilibrium; and (4) PT conditions of metamorphism with reference to various models of geothermometry and geobarometry.

Geological Setting

The area around Sonapahar constitutes a part of the Shillong Plateau which represents the northeastern wedge of the Peninsular Shield of India, uplifted and moved to the east over a distance of about 250 Km along the E-W trending transcurrent Dauki Fault during the Himalayan Orogeny (Evans, 1964). The Precambrian rocks of the Plateau have been variously interpreted as part of the Eastern Ghats charnokitic terrain (Crawford, 1974) or a continuation of the Satpura Belt of Bihar prior to the eastward movement. The Plateau consists essentially of rocks of upper amphibolite to granulite facies, flanked on the east by greenschist facies rocks belonging to the Shillong Series of precambrian age and to the south by sedimentary rocks and basic volcanics of cretaceous age (Fig. 1, Inset).

The metamorphic rocks of the area consist mainly of medium- to coarse-grained granitic gneisses, cordierite-garnet-biotite-sillimanite granulitic gneisses (henceforth designated cordierite-bearing gneisses in the text), quartz-sillimanite schists, and pyroxene-hornblende granulites (Fig. 1). Quartzofeldspatic veins ramify these

rocks, and where they occur in cordierite-bearing gneisses they contain coarse cordierite porphyroblasts. The contact between cordierite gneisses and quartz-sillimanite schists is usually sharp and well defined although locally the former grades imperceptibly to the latter. The axial-plane foliation (S_2) which pervades the area, has a general E-W strike, dipping northerly (sometimes to the south also) between 20 to 80°. The rocks are affected by doubly plunging E-W trending tight folds (F_1) with low plunges (6–15°). These folds of the first generation are later superposed by northerly trending later folds (F_2) with development of crenulation cleavage (S_3).

Massive sillimanite-corundum rocks occur in the cores of minor folds in the quartz-sillimanite schists, and consist predominantly of coarse radiating aggregates of sillimanite with frequent blebs of corundum as inclusions within it. Rocks with only sillimanite or corundum also occur. Along fractures and joints in these rocks coarse veins of sillimanite are common and sometimes coarse biotite segregations intergrown with sillimanite have been observed. The sapphirine-bearing rocks and associated silica-deficient assemblages occur as impersistent lenticular bodies (their dimension could not be established due to poor outcrops) in the cordierite-bearing gneisses in close proximity to massive sillimanite-corundum rocks in the extreme northeast of the area and to the south of Sonapahar (Fig. 1). The mineral assemblages of the associated rocks are summarized as follows:

Cordierite-Bearing Granulitic Gneisses

1. Gt-cd-bio-sill-qz-kf ± plag- (sp) ⎫   + Ilm + mag + pyrr/py
2. Cd-bio-sill-kf-qz ± plag- (± sp) ⎬   + tour and zirc
3. Cd-bio-sill-qz- (± sp) ⎭

Spinel is always rimmed by cordierite or sillimanite and is never in contact with quartz. Sometimes small blebs of corundum occur within sillimanite. In a few thin sections cordierite shows retrogression to andalusite, chlorite/biotite and muscovite and the textural relations are similar to those described by Lal (1969). The An-content of the plagioclase ranges between 18 and 46% (based on microprobe data).

Basic Granulites

4. Hbl-cpx-opx-plag ± bio   7. Hbl-plag ± bio ± kf
5. Hbl-opx-plag ± cumm ± bio   8. Cpx-opx-plag-qz ± bio (± hbl)
6. Hbl-cpx-plag ± bio

Minor amounts of magnetite, ilmenite, pyrrhotite/pyrite, apatite, sphene are often present in the above assemblages. In the paragenesis (8) hornblende is present only as inclusion in the pyroxenes. An content of plagioclase ranges from 41 to 57%.

Quartz-Sillimanite Schists

9. Qz-sill ± bio ± ru ± sph ± ap ± zirc

Coarse retrograde muscovite is sometimes present.

Granite Gneisses

10. Qz-kf-hbl ± plag ⎫   Minor constituents include
11. Qz-kf-plag-bio ± hbl ⎬   sphene, apatite, epidote, zoisite,
12. Qz-kf-bio-gt ± sill ⎭   clinozoisite, allanite and retrograde chlorite and muscovite.

Mineral abbreviations: Hbl-hornblende, cumm-cummingtonite, ru-rutile, sph-sphene, ap-apatite, zirc-zircon, ilm-ilmenite, mag-magnetite, pyrr-pyrrhotite, py-pyrite, tour-tourmaline, korn-kornerupine, oam-orthoamphibole, ta-talc. For the other abbreviations refer to Figures 8 and 13.

Mineral Assemblages and Textural Relations in Sapphirine-Bearing and Associated Silica-Deficient Rocks

Petrographic and microprobe studies have revealed the presence of following mineral assemblages[1] in the area:

A. Sapphirine-Bearing Assemblages

A-1   Sa-sp-cd-phl-ilm-ru   A-4   Sa-sp-co-phl
A-1-1 Sa-sp-cd-phl-ilm- (korn)   A-5   Sa-sp-co-phl-ru-
A-1-2 Sa-sp-cd-phl-plag (An 95)-   ilm-(chl)
       ilm-ap   A-6   Sa-sp-phl
A-2   Sa-chond-phl-sp-ilm-ru   A-7   Sa-phl-ru-ilm
A-3   Sa-sp-chond-ge-rul-ilm   A-8   Sa-oam-cd-bytow-
                                                 nite

B. Sapphirine-Free Assemblages

B-1   Sp-br-phl-ru-ilm ± co   B-6   Oam-en
B-2   Sp-co-phl-ru-ilm ± ap   B-7   En-phl-sp
B-3   Sp-phl-ru   B-8   Sill-ru ± phl
B-4   Co-phl-ru-ilm   B-9   sill-co-ru
B-5   Anth ± phl ± ta ± ap

In the assemblage A-1-1 kornerupine is present only as inclusions within cordierite and in A-5 chlorite is probably retrograde. Paragenesis A-8 has been reported by Ghose and Saha (1954) and B-6 and B-7 by Dunn (1929). In B-7 colourless phlogopite seems to have been misidentified as muscovite by Dunn (1929).

Sapphirine from the cordierite-bearing assemblages is typically idioblastic to subidioblastic, coarse-grained (1 to 8 mm long) and strongly pleochroic (X = pale yellow, Y = light bluish green, Z = sapphirine blue, $X < Y < Z$). On the other hand, in rocks that are devoid of cordierite, sapphirine is colourless or pale greenish blue in colour, feebly pleochroic, generally medium-grained and xenoblastic to subidioblastic (1 to 2 mm long). Herd (1973) suggested that pleochroism in sapphirine increases with rise in Fe-content and this is in agreement with our analytical data (see below). Spinel, cordierite, phlogopite and ilmenite occur as inclusions within sapphirine. Sapphirine also occurs as inclusions in cordierite and in the phlogopite matrix. Spinel and sapphirine symplectic intergrowths are present within plagioclase and cordierite in a few samples (paragenesis A-1-2, for example). Although commonly randomly oriented, in a few specimens sapphirine mimics the foliation of the matrix defined by phlogopite.

Cordierite typically occurs as porphyroblasts or in coarse granular aggregates (2 to 17 mm in diameter) which overprint the fabric of the matrix. It is often poikiloblastic, containing inclusions of corundum, spinel and phlogopite. The textural relations suggest that the crystallisation of cordierite post-dates these minerals. On the other hand, the presence of inclusions of cordierite in sapphirine and vice versa indicates that their crystallisation is broadly coeval.

Kornerupine was observed in only one sample (A-1-1) in which it occurs as elongated prisms defining S_i (internal schistosity) within cordierite porphyroblasts. It is accompanied by spinel, sapphirine and phlogopite. The textural relations suggest that the kornerupine is an armoured relic of an earlier metamorphic episode.

Spinel is commonly xenoblastic to subidioblastic and grain size ranges from 0.5 to 4.5 mm in diameter. Inclusions of magnetite,

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[1] The assemblages listed include minerals that are in mutual grain contact except those given in parentheses

rutile and phlogopite are sometimes present. Besides occurring as inclusions in cordierite and sapphirine, it is also found within aggregates of phlogopite and along grain borders of cordierite and sapphirine, apparently in textural equilibrium with these minerals.

Phlogopite occurs as coarse flakes (4–12 mm long), rarely as poikiloblasts, and is either feebly pleochroic (Z=colourless or light yellow, $X=Y$ brown or pale brown) or colourless and nonpleochroic with high birefringence as in the spinel-phlogopite rock (paragenesis B-3), in which phlogopite can easily be mistaken for muscovite.

Orthoamphibole. Anthophyllite occurs as coarse prismatic crystals (up to 28 mm long) in the assemblage B-5. Alteration to talc occurs along grain borders and cracks. Gedrite has been found in assemblage A-3 where it coexists with sapphirine, chondrodite and spinel. It occurs as coarse prismatic crystals, 2.5 to 8 mm long, and is colourless and non-pleochroic. Both anthophyllite and gedrite have been found only in K_2O-deficient rocks in which phlogopite, the sole potash-bearing mineral, is either absent or present in minor amounts.

Sillimanite is the major constituent of the assemblages B-8 and B-9 in which it occurs as coarse radiating needles (9 to 17 mm long). Sillimanite needles are intergrown with phlogopite, where present, in the fashion described by Chinner (1961).

Corundum usually occurs as small granular aggregate and rarely as coarse prismatic crystals up to 15 mm in length. In the cordierite-bearing sapphirine assemblages, corundum, although rare, has been found in mutual grain contact with spinel, sapphirine and cordierite. It is, however, present in significant amount in the cordierite-free assemblages B-1, B-2, B-4, A-4 and A-5. In the massive sillimanite rocks (B-9) corundum occurs as fine granular aggregate within sillimanite.

Chondrodite is pleochroic from yellow to dark golden yellow and has high birefringence. It is present in assemblages A-2 and A-3 as subidioblasts (1–2 mm in diameter) and is in textural equilibrium with sapphirine, gedrite, spinel and phlogopite.

Brucite has been identified in a few samples in which it coexists with spinel, corundum and phlogopite; there is no textural evidence of its formation from retrogression of periclase.

Coarse porphyroblasts of unaltered *plagioclase* (An 95%) occur in one sample of cordierite-sapphirine rock (assemblage A-1-2). It shows sharp grain contacts with cordierite, and contains inclusions of spinel, sapphirine, phlogopite and cordierite.

Time relations between the phases of deformation and metamorphic crystallization, as revealed by the fabric of these rocks, indicate that the regional metamorphism began during the first phase of deformation (D_1) and outlasted the second phase of deformation (D_2). In the sapphirine-cordierite-spinel-bearing rocks, S_3 is the prominent S-surface, and relics of crenulated S_2 (both S_2 and S_3 defined by alignment of phlogopite) are commonly preserved, suggesting that the crystallization of phlogopite began during D_1. That its formation outlasted D_2 is indicated by the occurrence of coarse cross-cutting phlogopite flakes overprinting the fabric of the matrix and containing inclusions of sapphirine, spinel, corundum, and rutile comparable to the grain size of these minerals present in the matrix. On the other hand, random orientation of cordierite, sapphirine, spinel, chondrodite, brucite and corundum with respect to the general fabric of the rocks and common presence of linear trails of S_i's defined by phlogopite within them and traceable into the matrix external schistosity ($S_e = S_3$) suggest that their crystallization is post-kinematic with respect to the D_2-

phase of deformation. Anthophyllite, gedrite and sillimanite-bearing rocks are massive and their formation probably also took place after D_2. Kornerupine may have crystallised during the syn-to late kinematic phase of the D_2 deformation as revealed by its linear alignment parallel to S_3 of the matrix, and thus its formation predates those of sapphirine, spinel and cordierite.

Mineral Chemistry

Sapphirine. Microprobe analyses of sapphirine are presented in Table 1. No zoning has been detected and the composition remains uniform from grain to grain in individual samples. The recalculated formulae correspond to the general formula M_7 (M) O_2 [T_6O_{18}] derived by Moore (1969). The sapphirine shows solid solution by the substitution Mg, Si$\rightleftharpoons$Al, Al between the compositions 2 MgO·2 Al_2O_3·SiO_2 (2:2:1) and 7 MgO·9 Al_2O_3·3 SiO_2 (7:9:3) (Gossner and Mussgnug, 1928) and most of those analysed plot close to the latter (Fig. 2). The plot of the analyses, however, lies below the 2:2:1–7:9:3 substitution join. A similar feature has been observed by Schreyer and Abraham (1976a) and the apparent excess of M-cations has been attributed by them to the presence of some Fe^{3+}. This is evident in one of analysed sapphirine of Sonapahar area (sample Ref. No. 2) in which Fe^{3+} has been determined by Mössbauer analysis (Fig. 2). The sapphirine from assemblage A-5 plots towards the aluminous side of the composition 7:9:3 and lies about midway between this composition and the most peraluminous sapphirine reported by Schreyer and Abraham (1975). Similar peraluminous sapphirine has been recently described by Meyer and Brookins (1976) and experimentally synthesized by Bishop and Newton (1975). The analytical data of the sapphirine of Sonapahar area suggest that its Al-content is controlled, besides other factors, also by mineral paragenesis. Maximum and minimum Al occur in the sapphirine coexisting with corundum and gedrite respectively (Fig. 2).

Kornerupine. The analysis of kornerupine (except for B and H_2O) from the cordierite-spinel-sapphirine rock is given in Table 1, and projects along the solid solution join between 4 MgO·3 Al_2O_3·4 SiO_2 (4:3:4) and 3.5 MgO. 3.5 Al_2O_3·3.5 SiO_2 (1:1:1). X Mg in the kornerupine is less than in sapphirine and cordierite.

Cordierite. The analyses of cordierites coexisting with sapphirine are given in Table 2. The X Mg is nearly constant (0.88 to 0.89) and is higher than coexisting sapphirine and spinel. This is consistent with the analytical data from other metamorphic terrains (Clifford et al., 1975; Hermans et al., 1976; Nixon et al., 1973). The structural formulae show slight excess of Si and minor deficiency of Al and octahedral sum compared to the ideal formula. The low total in the analysed cordierite suggests significant amounts of "gaseous" species along the structural channel.

Spinel. The microprobe analyses of spinel (Table 3) show a wide range of solid solution from spinel ($MgAl_2O_4$) to hercynite ($Fe^{2+}Al_2O_4$), and X Mg ranges from 0.14 to 0.78. A few samples contain significant amounts (up to 7 mol%) of gahnite (Zn Al_2O_4). Although only total iron as FeO has been determined, the Al-values close to 2.0 atoms per formula unit (based on 4 oxygen) and the analytical total of 99–100% indicate insignificant amount of Fe^{3+} in the analysed spinels. However, spinel (X Mg=0.14) from a cordierite-bearing gneiss shows low Al_2O_3 and low analytical sum (Table 3, Ref. No. 19). It is associated with magnetite. These features suggest that a significant amount of total iron is present as Fe^{3+} in the spinel. The ubiquitous rims of cordierite around the spinel, when the latter occurs in the matrix of quartz or feldspar

Table 1. Representative microprobe analyses and structural formulae of sapphirine and kornerupine

Reference nos.	1a	1b	2	3	4	5	6a	6b	7	8	2
Parageneses nos.	A-1	A-1	A-1-1	A-1-2	A-2	A-3	A-5	A-5	A-6	A-7	A-1-2
Sample nos.	A-16	A-16[b]	67	68	21	32	755	755	31	28	67

Oxides wt %	Minerals										
	Sapphirine										Kornerupine
SiO_2	13.1	11.8	12.9	12.5	12.8	13.9	12.7	11.6	13.9	12.6	28.8
TiO_2	—	0.02	—	0.02	0.03	0.05	0.06	—	—	0.06	—
Al_2O_3	61.7	65.1	62.1	61.2	64.9	61.8	64.2	66.1	63.4	63.9	44.0
Cr_2O_3	0.04	0.02	—	0.05	0.06	—	0.07	—	0.01	0.02	—
FeO^a	7.01	6.36	7.16[c]	8.3	2.77	3.37	3.21	3.14	3.72	3.21	6.81
MnO	0.12	0.12	0.05	0.11	0.02	0.02	0.04	0.02	0.08	0.04	0.26
MgO	16.7	16.3	16.5	15.5	18.8	20.2	18.8	17.6	19.4	19.0	15.6
Anhydrous total	98.7	99.7	98.7	97.7	99.4	99.3	99.1	98.5	100.5	98.8	95.47
$Mg/(Mg+Fe)^a$ (X Mg)	0.81	0.82	0.80	0.77	0.92	0.91	0.91	0.91	0.90	0.91	0.80

[a] Total Fe as FeO or Fe^{2+}
[b] The sapphirine occurs as an inclusion in cordierite
[c] $Fe^{3+}/Fe^{2+}+Fe^{3+}$ ratio is 0.13, based on Mössbauer analysis

CaO lower than 0.01%, K_2O less than 0.01% and Na_2O lower than 0.02% (all in weight%) in sapphirine. Kornerupine also contains 0.02% CaO
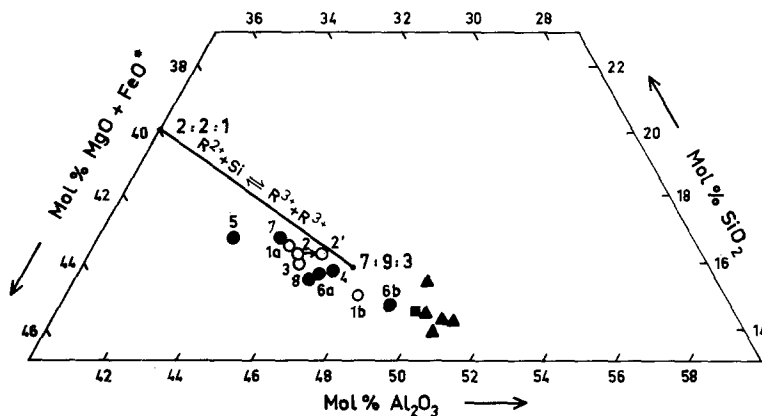
Fig. 2. A part of the system SiO_2-$(MgO+FeO)$-Al_2O_3-H_2O on the water free base plane showing the plots of analyses of sapphirine from Sonapahar area. Numbers 2:2:1 and 7:9:3 give molar proportions for the ternary composition in the order $(MgO+FeO)$-Al_2O_3-SiO_2. Open and solid circles represent sapphirines with X Mg 0.77–0.82 and 0.90–0.92, respectively. The numbers correspond to the reference numbers given in Table 1. The arrow from sample ref. no. 2 to 2′ shows shift of the plot with correction for Fe^{3+} (Table 1) in sapphirine. Solid triangles and solid squares are plots of the peraluminous sapphirines as given by Schreyer and Abraham (1975) and Meyer and Brookins (1976) respectively. FeO*-Total iron as FeO

(Fig. 3), may be ascribed to a reaction: Fe^{2+}-Fe^{3+}-Mg-spinel$_{ss}^-$ +quartz⇌cordierite + magnetite.

Phlogopite. The phlogopites (Table 3) contain rather low amounts of TiO_2, ranging from 0.15 to 2.08 wt%, which is in marked contrast with high TiO_2-contents reported for phlogopites from sapphirine-bearing rocks from other areas (Nixon et al., 1973; Clifford et al., 1975; Hermans et al., 1976). However, low TiO_2-contents in phlogopite is reported from sapphirine rocks from Waldheim, Saxony by Schreyer et al. (1975). The phlogopites show full octahedral occupancy ($R^{2+} \sim 6$) and correspond closely to the ideal formula. X Mg ranges from 0.77 to 0.98. In the chondrodite and brucite-bearing rocks the phlogopite contains 3.5 wt% of fluorine.

Anthophyllite and Gedrite. The analysed anthophyllites (Table 2) correspond closely to the ideal formula $\square^A$ $Mg_2^{M(4)}Mg_5^{VI}Si_8^{IV}O_{22}$

$(OH)_2$ (Robinson et al., 1971). X Mg varies from 0.78 to 0.87. Na increases concomitantly with the increase in Al in the anthophyllite (substitution, $Na_{0.5}+3.5$ Al⇌2 Si+1.5 (Mg, Fe^{2+}), Robinson et al., 1971).

The analysed gedrite (Table 2) has high Al_2O_3 and Na_2O and X Mg is 0.89. The analysis of gedrite from Sonapahar area closely approximates the ideal formula proposed by Robinson et al.: $Na_{0.5}$ (Mg, $Fe^{2+})_2$ (Mg, $Fe^{2+})_{3.5}Al_{1.5}Si_6Al_2O_{22}(OH)_2$.

Talc. The talc from the anthophyllite rock contains significant amount of Al_2O_3 and Na_2O (Table 2) indicating mainly the substitution Na, Al^{IV}⇌Si (Schreyer and Abraham, 1976b) and to a lesser extent Mg, Si⇌Al^{VI}, Al^{IV} as in aluminous talc (Fawcett and Yoder, 1966a). The former substitution is, however, unlikely on crystal structure grounds and the analysed talc might represent a mixed layer phyllosilicate with talc and small amounts of soda

Table 2. Representative microprobe analyses and structural formulae of minerals

Ref. nos.	1	2	3	19	19	15	16	17	5	15	17	4	5	9
Parag. nos.	A-1	A-1-1	A-1-2	—	—	B-5	B-5	B-5	A-3	B-5	B-5	A-2	A-3	B-1
Sampl. nos.	A-16	67	68	734[b]	734[b]	1	3	9	32	1	9	21	32	23
Oxides wt% Minerals	Cordierite				Garnet	Anthophyllite			Gedrite	Talc		Chondrodite		Brucite
SiO_2	50.4	49.2	49.3	48.5	37.3	55.7	59.3	56.6	47.4	58.1	57.9	28.4	34.1	0.03
TiO_2	–	–	–	–	0.04	0.04	0.03	0.04	0.17	0.03	0.02	1.26	1.95	0.01
Al_2O_3	32.8	32.8	32.3	31.4	20.8	1.93	0.35	2.16	14.9	3.01	1.89	–	–	–
Cr_2O_3	–	–	–	–	0.09	0.02	–	–	–	0.01	–	–	–	–
FeO^a	2.45	2.51	2.7	8.41	32.9	11.2	7.99	12.2	5.82	2.33	2.21	1.25	4.71	1.51
MnO	0.06	0.04	0.04	0.22	4.02	0.29	0.30	0.38	0.14	–	0.02	0.03	0.04	0.14
MgO	11.3	11.3	11.2	8.29	3.40	25.5	29.2	24.5	26.5	29.1	28.3	56.1	54.3	60.3
CaO	0.05	0.04	0.05	0.02	0.79	0.50	0.44	0.48	0.54	0.09	0.05	–	–	0.25
K_2O	–	–	–	–	–	0.01	–	–	–	0.04	0.01	–	–	–
Na_2O	0.06	0.03	0.08	0.06	–	0.32	0.06	0.32	1.67	1.01	0.88	–	–	–
F	nd	nd	nd	nd	nd	nd	nd	nd	tr	nd	nd	11.2	4.5	5.0
Anhydrous total	97.12	95.92	95.67	96.90	99.34	95.51	97.67	96.68	97.14	93.68	91.2	98.24	99.6	67.24
$Mg/(Mg+Fe)^a$	0.89	0.89	0.88	0.64	0.16	0.80	0.87	0.78	0.89	0.96	0.96	0.99	0.95	0.99

[a] Total Fe as FeO or Fe^{2+}
[b] from cordierite-bearing gneiss, cordierite rims spinel, and garnet enclosed in cordierite, corundum occurs as enclave in cordierite
[c] The name chondrodite, in the table and the text, has been used in a general sense for the humite group of minerals. The F-contents of the sample ref. nos. 21 and 32 suggest that they may be norbergite and humite respectively

nd = not determined; tr = traces

Table 3. Representative microprobe analyses and structural formulae of spinel and phlogopite

Ref. nos.	2a	2b	3	5	6	7	9	10	11	12	19	2	3	4	9
Parag. nos.	A-1-1	A-1-1	A-1-2	A-3	A-5	A-6	B-1	B-1	B-2	B-3	—	A-1-1	A-1-2	A-2	B-1
Sample nos.	67	67[b]	68	32	755	31	23	59	72	754	734	67	68	21	23
Oxid. wt% Minerals	spinel – hercynite											phlogopite			
SiO_2	—	0.02	0.03	—	—	—	0.04	—	—	0.04	—	39.7	37.5	43.6	42.1
TiO_2	0.02	—	—	—	—	0.02	0.02	0.03	0.02	0.01	0.03	1.05	2.08	0.15	0.28
Al_2O_3	61.8	61.3	61.9	66.8	66.6	66.6	64.8	61.5	63.0	66.4	54.8	16.2	16.6	12.6	13.1
Cr_2O_3	0.19	0.03	0.15	0.05	0.10	0.06	0.1	0.09	0.03	0.03	0.99	0.01	—	—	—
FeO^a	24.1	23.6	24.1	10.7	13.2	12.0	19.2	22.7	17.7	13.9	36.4	6.78	9.02	1.10	1.76
MnO	0.38	0.48	0.25	0.03	0.06	0.17	0.21	0.52	0.32	0.09	0.42	0.03	0.02	—	0.03
MgO	10.5	11.9	13.4	21.6	19.6	19.4	15.8	11.7	15.0	18.8	3.28	20.9	18.8	26.9	26.5
ZnO	3.61[c]	2.10	nd	nd	nd	nd	nd	3.20	2.89	nd	—	nd	nd	nd	nd
CaO	0.01	—	—	—	—	—	—	0.01	—	—	0.01	—	0.02	—	—
K_2O	—	—	—	—	—	—	0.01	—	—	—	0.02	8.95	9.28	8.78	9.48
Na_2O	0.12	—	—	0.02	—	0.10	0.05	0.15	0.12	0.01	0.11	0.47	0.33	1.09	0.69
F	—	—	—	—	—	—	—	—	—	—	—	nd	nd	3.4	3.5
Anhydrous total	100.73	99.43	99.83	99.20	99.56	98.35	100.23	99.90	99.08	99.28	96.06	94.09	93.73	97.62	97.44
$Mg/(Mg+Fe)^a$	0.44	0.47	0.50	0.78	0.73	0.74	0.59	0.48	0.60	0.71	0.14	0.85	0.79	0.98	0.96

[a] Total Fe as FeO or Fe^{2+}
[b] occurs as inclusion in sapphirine
[c] rim contains 4.85% ZnO and 22.8% FeO
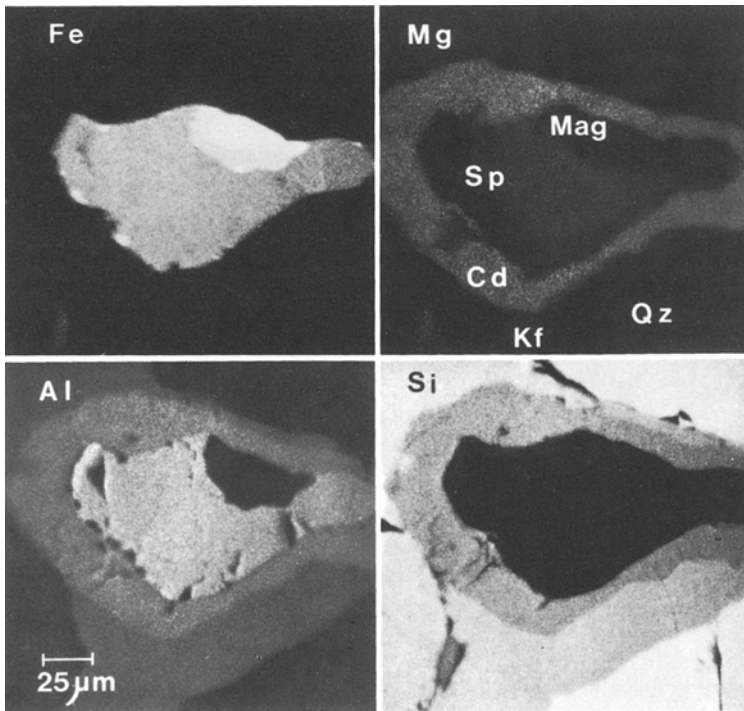[d] $Fe^{3+}/Fe^{3+}+Fe^{2+}=0.14$ based on Mössbauer analyses

Fig. 3. X-ray K_α picture showing the relative elements concentration in spinel-hercynite (Sp), rimmed by cordierite (Cd), within potash feldspar (Kf) and quartz (Qz). Mag: Magnetite; Garnet-cordierite-sillimanite-biotite granulitic gneiss, sample no. 734
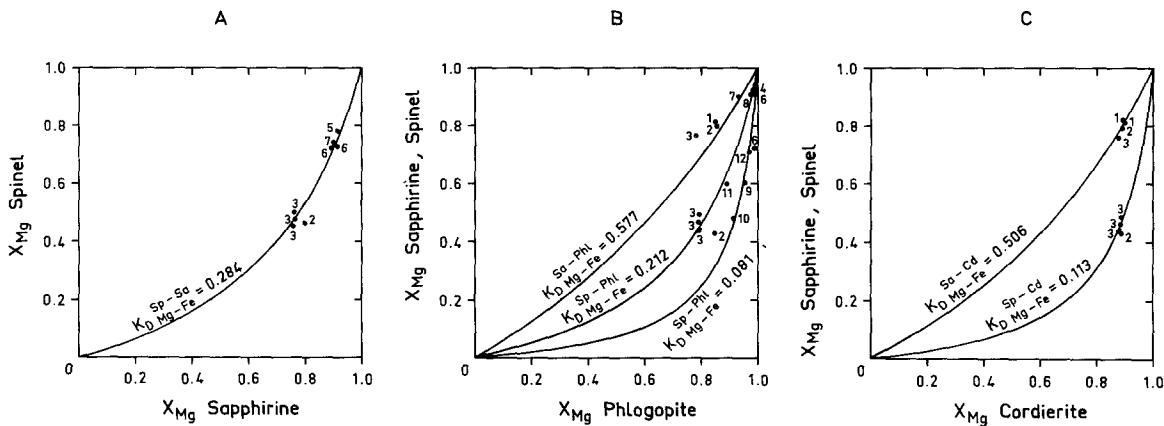

Fig. 4A–C. A, B, and **C**: Magnesium-iron (total iron as FeO) distribution diagram for the mineral pairs in sapphirine-cordierite-spinel-phlogopite parageneses of Sonapahar area. Analytical data and structural formulae are given in Tables 1, 2, and 3. X Mg = Mg/(Mg + Fe). $K_{DMg-Fe}^{A-B} = (Mg/Fe)^A/(Mg/Fe)^B$

phlogopite (Na Mg$_3$ (Al Si$_3$)O$_{10}$ (OH)$_2$ as proposed by Schreyer and Abraham. In light of the recent discovery of structurally ordered and disordered phases which are intermediate between amphiboles and micas (Veblen et al., 1977) it is also possible that the "talc" may have a mixed structure between talc and orthoamphibole (J.B. Thompson, personal communication, 1978).

Other Minerals. Chondrodite contains a significant amount of TiO$_2$ and exhibits high X Mg (0.95, 0.99) and brucite has also very high X Mg and contains about 5 wt% fluorine (Table 2). Corundum from the parageneses A-5, B-1 and B-4, contains 0.48 to 1.87 wt% total iron as Fe$_2$O$_3$ and traces of Cr$_2$O$_3$. Rutile is essentially TiO$_2$ and total Fe as FeO varies from 0.44 to 0.73% in the parageneses B-3 and B-4. Plagioclase from cordierite-sapphirine-spinel rock (paragenesis A-1-2) contains 1.968 Ca, 0.001 K and 0.107 Na based on 16 oxygens. In sillimanite from the sillima-

nite-corundum rocks (paragenesis B-8), Fe$_2$O$_3$ ranges from 0.24 to 0.66%, and traces of Cr$_2$O$_3$ and Mn$_2$O$_3$ ($\sim$0.2 wt%) have been detected. The analyses of ilmenite from the assemblage A-1-2 and A-2 show 0.12–0.14% Cr$_2$O$_3$, MnO 1.14–1.15%, and MgO 0.23–0.51 wt%.

Distribution of Mg and Fe Between Coexisting Minerals

Distribution of Mg and Fe^{2+} between mineral pairs in the sapphirine-cordierite-spinel-phlogopite parageneses is shown in Figure 4. In these calculations it has been assumed that all Fe is in the ferrous state.

This is certainly a good approximation for cordierite and spinel (see above). However, the two Mössbauer analyses performed show that the sapphirine and phlogopite have in fact, 13 and 14% respectively of the total Fe in the ferric state (cf. Tables 1 and 3). Coexisting sapphirine-spinel plot close to the line defined by $K_D^{Sp-Sa} = 0.284$ (Fig. 4A). Sapphirine-phlogopite, spinel-phlogopite, sapphirine-cordierite, spinel-cordierite also plot along the curves defined by K_D 0.577, 0.212–0.081, 0.506, and 0.113 respectively (Fig. 4B and C). The systematic distribution of $Mg-Fe^{2+}$ in the coexisting phases strongly suggests that chemical equilibrium was attained during the regional metamorphism, at least with respect to these elements, which is consistent with the textural relations already described. Such equilibrium conditions seems to be rather uncommon in sapphirine-bearing rocks, as in most localities disequilibrium or only mosaic equilibrium is revealed by textural features (e.g., Nixon et al., 1973; Clifford et al., 1975; Hermans et al., 1976).

Phase Relations

The microprobe analytical data of the coexisting minerals (Tables 1 to 3) from the sapphirine-bearing and associated silica-deficient rocks of Sonapahar area are plotted in a SiO_2-($MgO+FeO$)-Al_2O_3 diagram (Fig. 5). Many assemblages from the area contain four phases in this system, suggesting that MgO and FeO must be treated as two components. Gedrite is plotted near the anthophyllite − Al-anthophyllite join but due to its Na, Al⇌Si substitution it lies at somewhat lower SiO_2 values. It is of interest to note the presence of chondrodite and brucite in the sapphirine-spinel ± gedrite, and spinel-corundum-bearing assemblages respectively. The stability of these minerals may be attributed to the presence of fluorine. Although chondrodite has been reported from granulite facies in calcsilicate rocks or marbles (Dobretsov et al., 1973, p. 70), this is the first report of its occurrence in sapphirine-bearing rocks.

The phase relations are better depicted with the $SiO_2 − FeO − MgO − Al_2O_3$ tetrahedron, in which the minerals coexisting with corundum or sapphirine are projected onto the $SiO_2 − FeO − MgO$ plane, viz. corundum projection (Fig. 6) and sapphirine projection from the 7:9:3 composition (Fig. 7). The corundum-bearing associations, viz. brucite-spinel and cordierite-spinel-sapphirine, are nicely represented in the corundum projection. The assemblage garnet-cordierite-spinel-corundum in which spinel and corundum are present as enclaves within cordierite (and also sillimanite) in the cordierite-bearing gneisses, plots toward
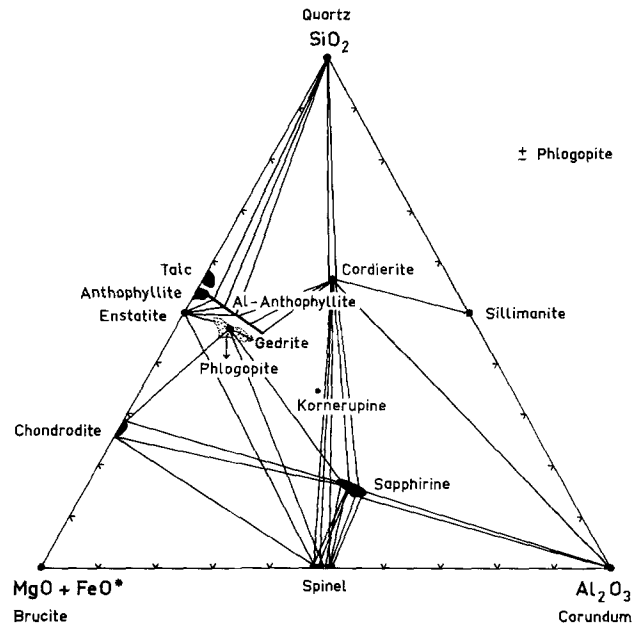

Fig. 5. The system SiO_2-($FeO+MgO$)-Al_2O_3 (mol%) showing plots of mineral analyses (solid dots and solid fields) given in Tables 1–3 and tie lines of the coexisting phases. FeO*-total iron as FeO. Stippled-composition field of the analysed phlogopite

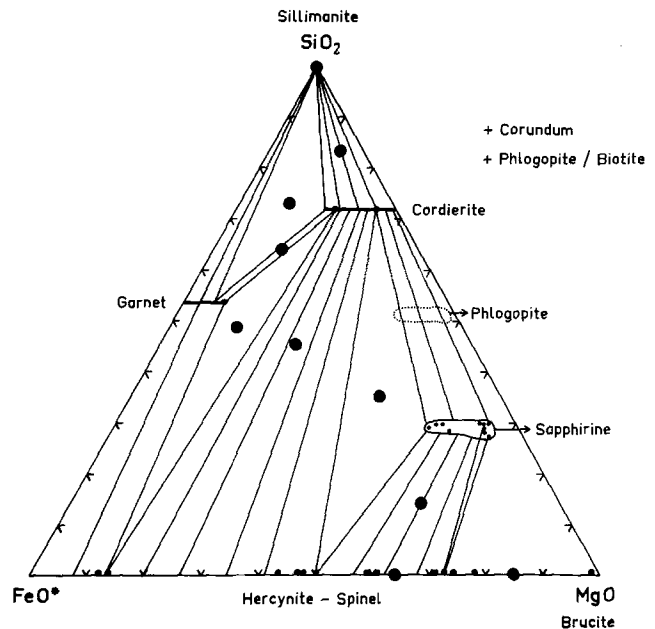**Fig. 6.** Projection from corundum onto the SiO_2-MgO-FeO plane in the system SiO_2-MgO-FeO-Al_2O_3 (H_2O) (Robinson and Jaffe, 1969). Mineral composition (small solid dots) and tie lines for the corundum-bearing assemblages are shown. Solid circles − observed mineral assemblages in the area. The mineral assemblages shown towards the lower Mg/Fe side of the cordierite-spinel$_{ss}$-sapphirine field occur as enclaves within cordierite in the cordierite-bearing granulitic gneisses. In order to depict the Mg/Fe range of the spinel-hercynite and sapphirine series all the analyses of these minerals given in Tables 1 and 3 respectively are plotted, only those joined with tie lines are coexisting with corundum. FeO*-total iron as FeO

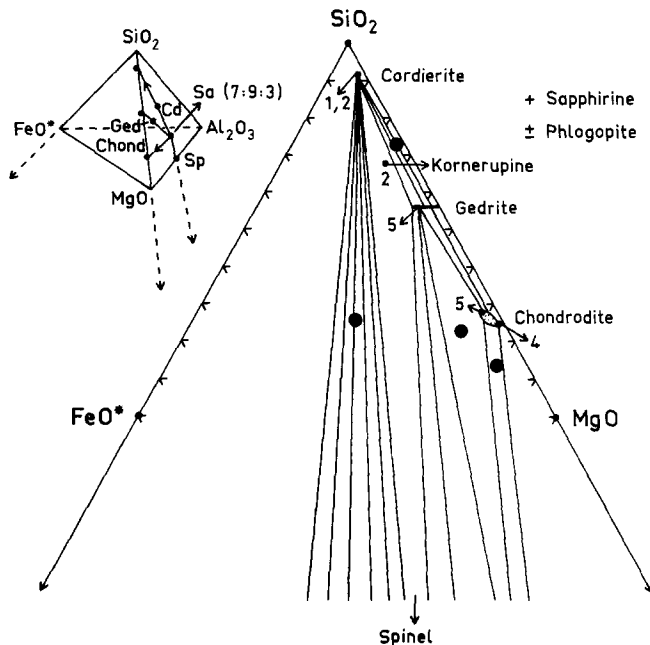Fig. 7. Projection from sapphirine (7:9:3) onto the SiO_2-FeO-MgO plane in the system SiO_2-FeO-MgO-Al_2O_3 (H_2O). Minerals are first plotted on a ternary SiO_2-(MgO + FeO)-Al_2O_3 diagram and then projected from the sapphirine on the SiO_2-(MgO + FeO) join which is then expanded into ternary diagram by plotting Mg and Fe separately (see inset). Mineral composition (small solid dots, numbers correspond to the ref. nos. given in Tables 1 and 2) and tie lines for the sapphirine-bearing assemblages (devoid of corundum) are shown. Solid circles-observed mineral assemblages in the area

the lower Mg/Fe side of the cordierite-spinel field. The topology of the diagram clearly shows the restriction of sapphirine-bearing assemblages to the higher Mg/Fe side of the cordierite-spinel field, in agreement with Seifert (1974).

The sapphirine projection diagram (Fig. 7) shows the three phase-fields of gedrite-chondrodite-spinel and cordierite-gedrite-spinel and the two-phase fields cordierite-spinel, chondrodite-spinel, gedrite-spinel and gedrite-cordierite. Because kornerupine occurs as armoured relic within cordierite and it plots in the cordierite-spinel-gedrite (sapphirine) field, its later breakdown to this assemblage is suggested. The rocks are, however, rich in potash, and phlogopite is, therefore, likely to be present in the breakdown product instead of gedrite. The absence of garnet from the sapphirine rocks may be attributed to the relatively Mg-rich bulk compositions, and the moderately low-pressure of metamorphism (see below) which restricts the garnets to compositions rich in almandine.

The consistent topology of the observed mineral assemblages and lack of intersecting tie lines in Figures 6 and 7 clearly reveal equilibrium condition as indicated by textural relations and distribution of ele-

ments in coexisting minerals described already. We shall return to the discussion of the phase relations and mineral reactions responsible for the development of the topology shown in Figures 5, 6 and 7 in the later part of this paper after critically evaluating the metamorphic conditions and commenting on the genesis of unusual bulk composition of the sapphirine-bearing rocks.

Discussion

Metamorphic Conditions

The mineral parageneses suggest metamorphism within amphibolite-granulite transition facies of Turner (1968).

Mg—Fe relationships and other relevant data for coexisting garnet-cordierite-biotite-plagioclase and orthopyroxene-clinopyroxene, and the estimated PT conditions are presented in Table 4. Thompson's (1976) ln K_D (Cd-Gar) and (Bio-garnet) vs 1/T plot have been preferred here as these are in agreement with the recent experimental data (Holdaway and Lee, 1977; Ferry and Spear, 1977) and are generally consistent with the known geological relationships (Tracy et al., 1976). The calculated pressures and temperatures range from 5.6 to 6 Kb and 500 to 700° C. As the analysed garnets contain 6 to 16 mol% of spessartite molecule the pressure estimate could be overestimated by 0.5 to 0.8 Kb according to the data of Weisbrod (1973). Furthermore using the X Mg values of cordierite only, pressure conditions can be evaluated from PT curves determined experimentally by Holdaway and Lee (1977). This suggests pressures in range 4.5 to 4.8 Kb assuming $P_{H_2O} < P_{total}$ at 700° C. That P_{H_2O} was probably less than P_{total} during the formation of cordierite- and sapphirine-bearing rocks is evident from the association of all the reactants and products of the univariant reaction: biotite + sillimanite + quartz⇌cordierite + garnet + potash feldspar + H_2O (Holdaway and Lee, 1977). Experimental data of Seifert (1976) suggest that a water-deficient environment is required for the formation of cordierite-potash feldspar—quartz-bearing assemblages at these elevated total pressures. With the development of granitic melt and under the condition $P_{H_2O} < P_{total}$ the above reaction curve shifts to lower temperatures and pressures (Holdaway and Lee, 1977) and thus cordierite and potash-feldspar may crystallise under the PT conditions given above.

On the basis of the arguments presented above, it is likely that the pressure condition may have been around 5 ± 0.5 Kb which is consistent with the widespread occurrence of sillimanite and partial retrogres-

Table 4. Mg-Fe relationships in the coexisting garnet-cordierite-biotite and derived temperatures and pressures of metamorphism

Sample nos.	Gt X_{Mg}	Cd X_{Mg}	Bio X_{Mg}	Cd-K_D	Gt[a] ln K_D	Bio-K_D	Gt[a] ln K_D	T°C[a] (Cd-Gt)	[a]P in Kb (Cd-Gt)	T°C[a] (Bio-Gt)	T°C[a] (Bio-Gt)
725	0.141	0.628	0.433	10.365	2.338	4.650	1.537	575	6.0	625	635
645	0.135	0.603	0.523	9.667	2.269	7.063	1.955	600	5.9	525	506
664	0.170	0.616	0.443	7.862	2.062	3.874	1.354	660	5.8	680	694
754	0.123	0.571	0.436	9.453	2.246	5.536	1.711	600	5.6	575	578

Mg-Fe relationships in coexisting orthopyroxene-clinopyroxene and derived temperatures of metamorphism

	opx X_{Mg}	cpx X_{Mg}	opx a_{Ag}	cpx a_{Ag}	K_D	ln K_D	T°C[c]	T°C[d]	T°C[e]	T°C[f]
668	0.537	0.668	0.268	0.036	0.134	−2.007	822	860	719	794
622	0.655	0.761	0.405	0.034	0.084	−2.478	829	827	678	715
141	0.556	0.686	0.289	0.028	0.097	−2.333	794	811	664	712

Garnet-plagioclase geothermometer based on Ghent (1976)

	Plag X_{An}	Gt X_{Gr}	Log K_D	T°C at $P=5\pm0.5$ Kb
725	0.223	0.016	−3.434	740–820
645	0.309	0.023	−3.385	735–810
664	0.184	0.017	−3.118	680–720

[a] based on model of Thompson (1976)
[b] based on model of Ferry and Spear (1977)
[c] based on Wood and Banno (1973)
[d] based on Wells (1977)
[e] based on Stormer and Whitney (1977) recalibrated model of Wood and Banno using their equation T_2
[f] based on Stormer and Whitney (1977) recalibrated model of Wood and Banno using their equation T_3
[g] $A = Mg_2Si_2O_6$

sion of cordierite to andalusite + chlorite/phlogopite as observed in a few samples of cordierite-bearing gneisses of the area, indicating a PT path of metamorphism that crossed the sillimanite-andalusite field boundary as determined by Richardson et al. (1969) (Fig. 8).

On the other hand, coexisting clinopyroxene-orthopyroxene from the basic granulites of the area indicates temperatures in the range 800 to 860° C based on the models proposed by Wood and Banno (1973) and Wells (1977). These temperature estimates are probably 50 to 100° C too high (Stormer and Whitney, 1977). Stormer and Whitney have recalibrated Wood and Banno's model. The temperature estimates by their equations nos. T_2 and T_3 yield temperatures between 664 and 794° C (Table 4). The garnet-plagioclase model of Ghent (1976) suggests temperatures in the range of 700 to 800° C assuming a pressure of 5 ± 0.5 Kb (Table 4, Fig. 8).

Bracketing the errors and discrepancies in the PT estimates from the different models of mineral equili-

bria, it is reasonable to assume $750\pm50°$ C/ 5 ± 0.5 Kb as probable metamorphic conditions during the thermal peak of regional metamorphism in the area. This is consistent, considering the probable reduced activity of water, with the lower temperature stability of sapphirine (Seifert, 1974) and boron-free kornerupine (Seifert, 1975); and breakdown of enstatite to anthophyllite (cf., upper thermal stability of anthophyllite, Fig. 8) as revealed by relicts of earlier enstatite in anthophyllite rock from the area reported by Dunn (1929). Furthermore temperatures of <700° C (500 to 700° C) obtained from garnet-cordierite and garnet-biotite equilibria probably suggest that these coexisting minerals equilibrated with respect to Mg—Fe even with decreasing temperatures[2] during which cordierite partially altered to andalusite, chlorite/phlogopite, muscovite; and feldspars to

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[2]   It is also likely that the low temperatures obtained may be partly due to appreciable Mn-content of the garnet, as this compositional variable is not sufficiently taken into account in the models of mineral equilibria so far
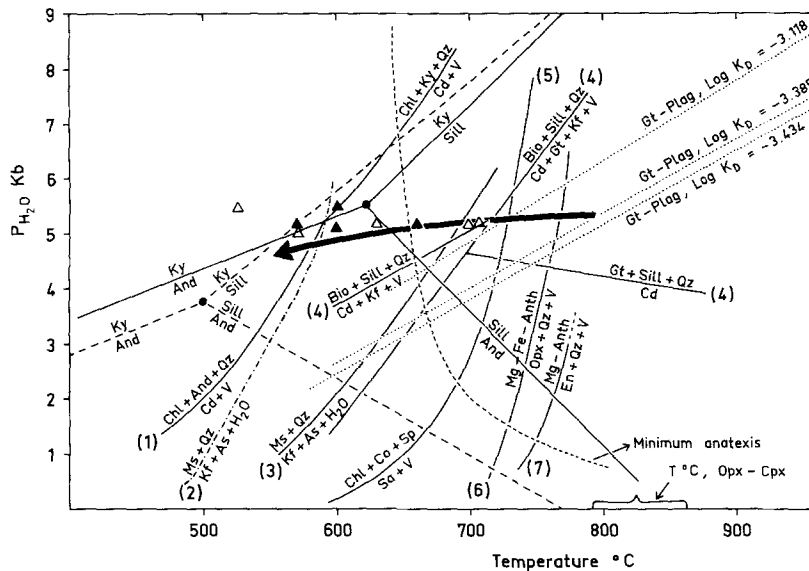
Fig. 8. PT-diagram showing experimentally determined mineral equilibria and geothermometry-geobarometry data. Aluminosilicate triple points at higher and lower PT are from Richardson et al. (1969) and Holdaway (1971) respectively. The curves of the mineral equilibria are: (1) from Seifert and Schreyer (1970), (2) Kerrick (1972) for $P_{H_2O} = 0.4\ P_{total}$, (3) Chatterjee and Johannes (1974), (4) Holdaway and Lee (1977) for $P_{H_2O} = 0.4\ P_{total}$. Gt + Sill + Qz⇌Cd and Bio + Sill + Qz⇌Cd + Kf + V curves are for X Fe (= Fe/Fe + Mg) Cd ∼ 0.40, and ∼ 0.30 respectively, (5) Seifert (1974), (6) Ravior and Hinrichsen (1975), (7) Greenwood (1963). Minimum anatexis curve for An = 26% from Winkler (1974). Solid triangles and open triangles are calculated PT conditions based on garnet-cordierite and garnet-biotite models of Thompson (1976) in which pressure has been corrected for Mn-content of the garnets after Weisbrod (1973). Garnet-plagioclase log K_D lines are based on Ghent's model (1976). T °C orthopyroxene-clinopyroxene is based on Wood and Banno (1973) and Wells (1977). Solid arrow depicts the probable path of regional metamorphism in the area. Abbreviations: Ky: Kyanite, Sill: sillimanite, And: andalusite, Chl: chlorite, Qz: quartz, Cd: cordierite, Ms: muscovite, Kf: potash-feldspar, As: aluminosilicate, V: vapour, Bio: biotite, Gt: garnet, Co: corundum, Sp: spinel, Sa: sapphirine, Anth: anthophyllite, Opx: orthopyroxene, Cpx: clinopyroxene, En: enstatite, Plag: plagioclase

coarse flakes of muscovite. These features are in accord with the experimental data on the low-temperature stability of cordierite and the upper stability of muscovite + quartz as given by Seifert and Schreyer (1970); Chatterjee and Johannes (1974) and Kerrick (1972).

Genesis of the Unusual Bulk Composition

The bulk compositions of the sapphirine-cordierite-spinel-corundum-bearing rocks are unusual because they do not correspond to any normal igneous or sedimentary rocks (Table 5). In general, sapphirine-bearing rocks are very rich in Al_2O_3, MgO, and poor in SiO_2, Na_2O, CaO and commonly K_2O. Thus they pose the problem of the nature of parent rock from which they are derived and the causes of development of unusual composition.

Several views have been proposed which may be summarized as follows:

(1) Isochemical metamorphism of unusual sedimentary bulk composition, viz. chert-bearing saponitic bentonite produced by in situ weathering of basic pyroclastics (McKie, 1959), bentonitic sediments

(Chinner and Sweatman, 1968), magnesia-rich clay (Touret and De la Roche, 1971), sedimentary mixture of kaolinite, montmorillonite and chlorite including minor quartz (Woodford and Wilson, 1976), high-alumina laterite or bauxite (Meng and Moore, 1972) and mudstone associated with evaporites (Schreyer, 1977).

(2) Alteration of basic lavas under low-temperature hydrous conditions which appear to result in almost complete loss of alkalies, CaO and relative enrichment of Al_2O_3, FeO and MgO (Vallance, 1967; Wilson, 1971).

(3) Mg-metasomatism of pelites (Muthuswami, 1949).

(4) Recrystallisation of ultramafic rocks (Lensch, 1971) or spinel-bearing bronzite (Sørensen, 1955) with accompanying Si, Ca and K-metasomatism (Herd et al., 1969). Metasomatic reaction between Al-rich inclusions and Mg-rich ultramafic host (Østergaard, 1969), or metasomatism of mafic complex (Chekirda and Entin, 1969) or chlorite + phlogopite "blackwall" reaction zone between ultramafic inclusions and country rock, later metamorphosed in the granulite facies conditions (Evans, 1977).

(5) Partial melting of pelitic rocks and subsequent

Table 5. Chemical compositions and modal analyses of rocks

Ref. nos.	1	2	3	4	5	6	7	8	9	12	Qz-sill schists		Sill-Co rocks		Cd-bearing[b] granulitic gneisses	
Paragenesis nos.	A-1	A-1-1	A-1-2	A-2	A-3	A-5	A-6	A-7	B-1	B-3	—	—	B-8	B-8	Mean[c]	s[d]
Oxides wt%	Sample nos.															
	A-16	67	68	21	32	81/755	31	28	23	81/754	49[b]	170[b]	37/50[e]	37/54[e]		
SiO_2	34.0	33.4	37.4	33.2	33.0	19.1	35.1	34.1	29.9	27.1	70.53	85.19	35.70	10.26	65.64	1.42
TiO_2	0.6	0.8	1.5	0.4	0.1	0.3	0.2	1.2	1.5	1.8	0.41	0.13	0.18	0.27	0.58	0.05
Al_2O_3	30.5	28.0	31.9	27.6	25.9	48.6	26.8	28.6	32.0	31.1	27.64	13.70	62.28	88.25	17.26	0.72
FeO^a	6.4	6.8	8.4	1.7	4.8	5.1	3.9	2.4	2.2	5.7	0.45	0.23	1.57	1.41	5.98	0.38
MnO	0.1	0.02	0.1	0.01	0.1	0.03	0.04	0.03	0.04	0.03	0.07	0.06	0.13	0.58	0.11	0.03
MgO	19.1	19.4	13.7	26.5	32.8	21.8	23.5	24.6	21.8	24.0	0.15	—	—	—	3.42	1.06
CaO	0.01	—	1.1	—	0.2	tr	tr	tr	tr	tr	0.07	0.15	tr	tr	0.45	0.25
K_2O	5.4	6.4	3.3	5.5	tr	3.1	6.6	6.1	6.7	6.1	0.15	—	—	—	3.85	1.02
Na_2O	0.3	0.3	0.2	0.7	0.7	0.4	0.4	0.7	0.5	0.6	—	—	—	—	1.56	0.73
H_2O	2.8	3.3	2.3	1.3	0.8	1.6	3.1	2.8	3.9	2.6	nd	nd	—	—	0.95	0.21
Total	99.21	98.42	99.9	96.91[f]	98.40	100.03	99.64	100.53	98.54	99.03	99.52	99.48	99.86	100.77	99.80	
	Mode vol.%															
Sapphirine	19.2	19.6	4.0	26.0	30.6	38.9	18.2	24.8	—	—	—	—				
Spinel	0.9	0.5	7.9	+	1.0	19.5	0.9	—	2.3	25.7	—	—				
Phlogopite	64.3	74.7	35.3	67.6	—	40.0	80.9	74.3	76.1	73.1	—	—				
Corundum	—	—	+	—	—	0.4	—	—	15.3	—	—	—				
Brucite	—	—	—	0.2	—	—	—	—	5.3	—	—	—				
Chondrodite	—	—	—	6.0	28.0	—	—	—	—	—	—	—				
Gedrite	—	—	—	—	40.4	—	—	—	—	—	—	—				
Rutile	—	—	—	0.1	—	0.1	—	0.4	0.8	—	0.6	—				
Ilmenite	—	0.1	0.9	0.1	—	0.1	—	0.5	0.2	1.2	—	0.8				
Chlorite	—	—	—	—	—	1.0	—	—	—	—	—					
Cordierite	15.6	5.0	46.4	—	—	—	—	—	—	—	—					
Plagioclase	—	—	5.5	—	—	—	—	—	—	—	—					
Sillimanite	—	—	—	—	—	—	—	—	—	—	58.0	13.9				
Quartz	—	—	—	—	—	—	—	—	—	—	41.4	85.1				
Kornerupine	—	0.2	—	—	—	—	—	—	—	—	—	—				
$MgO/(MgO+FeO)^a$ (Mol. Prop.)	0.84	0.84	0.74	0.97	0.92	0.88	0.92	0.95	0.95	0.88	—	—	—	—	0.50	0.06

[a] Total iron as FeO
[b] Chemical analyses by methods of Shapiro and Brannock (1962) and Hounslow and Moore (1966)—Analyst.—S.K. Haldar and R.K. Lal
[c] Arithmetic mean of 15 analyses

[d] S = Standard deviation
[e] Analyses from Dunn (1929). All other analyses are calculated from mode and microprobe data of coexisting minerals given in Tables 1–3
[f] Analysis also includes 2.7% of fluorine

removal of the anatectic granitic melt to form 'restite' enriched in Al, Fe, Mg and impoverished in Na, K, Ca and Si (Grant, 1968; Lal and Moorhouse, 1969; Nixon et al., 1973; Clifford et al., 1975).

Many features of the sapphirine-bearing rocks are inconsistent with their formation from altered mafic rocks as proposed by Vallence (1967) and Wilson (1971): (a) The bulk composition of these rocks plot outside the field of altered basalt in the SiO_2-Al_2O_3-

(MgO + FeO) diagram (Fig. 9), (b) lack of inhomogeneous mineral distribution with patchy development of calcareous rocks recorded by Vallance (1967) and (c) absence of rocks gradational in chemical composition between mafic and aluminous rocks. A high ZnO and a low Cr_2O_3-contents in the spinel from the silica deficient rocks (Table 3) and the absence of metarodingites associated with these rocks suggest that the sapphirine-bearing rocks are not derived from
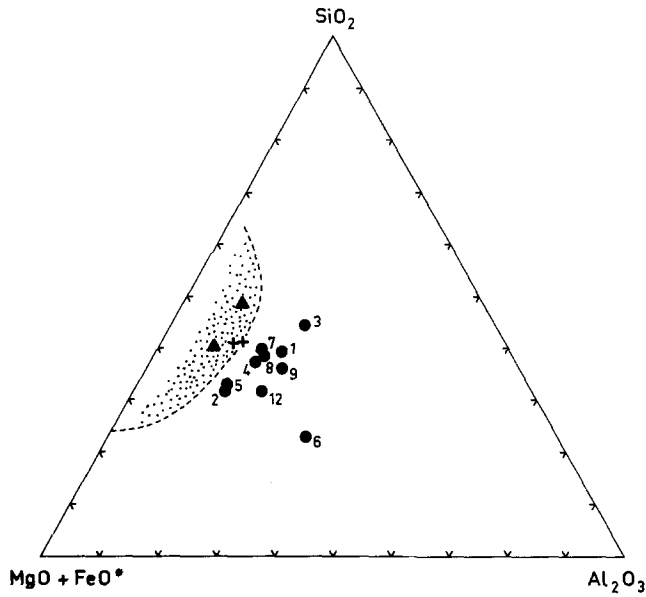
Fig. 9. Plot of bulk composition of sapphirine-bearing- and other silica-deficient rocks (solid dots, the numbers correspond to the reference numbers given in the Table 5) on a SiO_2-$(MgO + FeO)$-Al_2O_3 diagram (mol%). Stippled area denotes field of altered mafics from Vallance (1967). Crosses-altered mafics (Vallance, 1967). Solid triangles-evaporite mudstone (Schreyer, 1977). FeO*-total Fe as FeO

Fig. 10. A variation diagram in which wt% oxides is plotted against wt% $MgO + FeO$ (total iron as FeO). Solid dots- the cordierite-bearing granulitic gneisses (the analyses taken from unpublished data of Lal and Haldar, in preparation; Mean value and standard deviation are given in Table 5). Crosses- the sapphirine-bearing-and other silica-deficient rocks from Sonapahar area (for the chemical analyses refer to Table 5). Solid and open triangles-average peralkaline and alkali granites from Nockolds (1954), respectively. Solid square-average pelite, recalculated anhydrous from Shaw (1956). $MgO/(MgO + FeO)$ in mol. proportion ($= X$ Mg)

ultramafic rocks or metamorphism of the "blackwall" reaction zone. Furthermore, although isochemical metamorphism of pelitic rocks of unusual bulk composition is feasible, the systematic relationships of the oxide-content in these rocks and the associated cordierite-garnet-sillimanite-gneisses (Fig. 10) suggests an alternative hypothesis. The similar K_2O-content and higher Al_2O_3 of the sapphirine-bearing rocks and associated cordierite gneisses (Table 5) is not in agreement with extensive Mg-metasomatism only. Furthermore the latter possibility is unlikely also because of the problem of the source of Mg-rich solutions and complex chemical losses that would have to be invoked.

The field association of these rocks, with anatectic quartzofeldspatic veins makes a restite origin (5) feasible:

(1) The regional metamorphism took place at PT conditions where extensive partial melting is most likely as summarized by Winkler (1974). If a melt of granitic composition is removed from the rocks undergoing anatexis, a relative enrichment of Al, Fe, Mg and $\pm$Ca may occur in the 'restite'. Similar restite' rocks, deficient in Si and containing spinel, cordierite, corundum, sillimanite, etc. occur where pelitic rocks at the contact of mafic or ultramafic intrusives have undergone extensive anatexis and removal of granitic melt during high grade thermal metamorphism
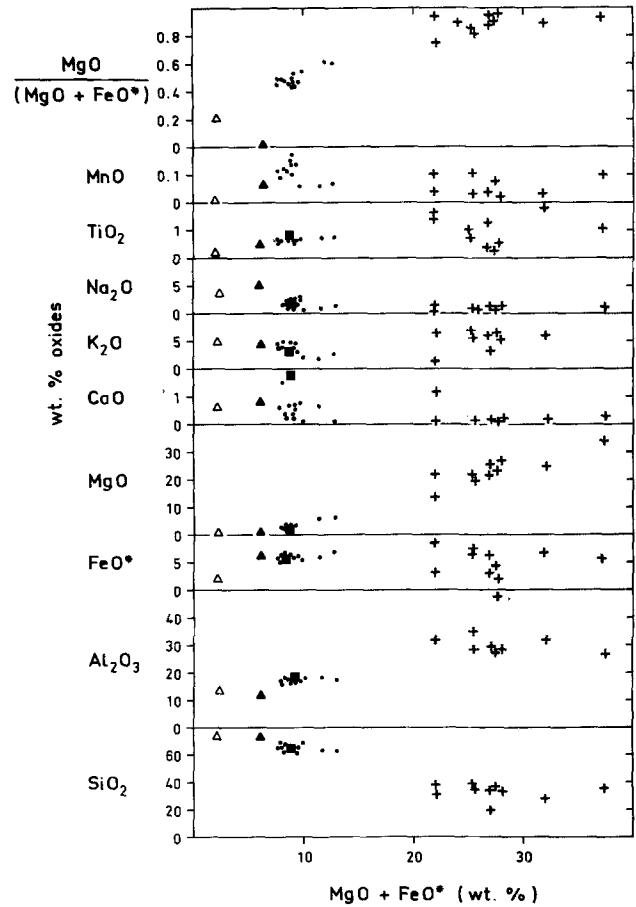
(Evans, 1964; Smith, 1965). The compatibility of granitic melts with cordierite and corundum has been demonstrated experimentally by Ackermand (unpublished data, 1978).

(2) The variation in the oxides in the sapphirine-bearing and silica-deficient rocks, cordierite-bearing gneisses and average granite (Nockolds, 1954) is depicted in Figure 10. Compared to the cordierite bearing gneisses of the area the sapphirine-bearing rocks are richer in Al_2O_3, MgO and poorer in SiO_2, Na_2O and CaO, which is consistent with removal of melt of granitic composition. The K_2O-contents of these rocks are similar or higher than those of the associated cordierite gneisses. In most areas the abstraction of granitic melt leaves behind a potash-deficient 'restite' as shown by Lal and Moorhouse

(1969). This is especially evident in the gedrite-sapphirine-bearing rocks of Sonapahar which are deficient in potash, resulting in the formation of gedrite and complete absence of phlogopite. The anomalously high value of potash in most of the sapphirine-bearing rocks may be attributed to the initial high K_2O-content of the cordierite gneisses. Thus, although potash is removed in the granitic melt, its relative amount remains similar or even becomes slightly higher in the 'restite'.

An interesting feature observed is the high X Mg value of the sapphirine-bearing and associated silica-deficient rocks (Fig. 10). Such a behaviour with progressive anatexis would be expected with partial melting since it is known that granitic melt has a considerably lower X Mg than the 'restite' (Brown and Fyfe, 1970).

(3) The high An-content of plagioclase in some of the 'restite' rocks, viz. sapphirine-cordierite-spinel-corundum-anorthite (assemblage A-1-2) and sapphirine-gedrite-cordierite-bytownite rock reported by Ghosh and Saha (1954) is consistent with experimental anatexis of pelitic rocks, in which it has been clearly demonstrated by Winkler (1974) that removal of albite component in granitic melt during partial melting results in an increase in An-content in the plagioclase of the 'restite'.

Although the data presented above are consistent with a restite origin of the sapphirine-bearing rocks, this hypothesis has still to tested by trace element geochemistry.

On the assumption that the hypothesis of removal of granitic melt from the associated cordierite-bearing gneisses and relative enrichment of Al_2O_3 and MgO in the silica-deficient 'restite' is applicable in the area, the obvious next step is to consider the amount of granitic melt which was removed to leave the 'restite'. In order to semiquantitively evaluate the partial melting process and to estimate the amount of material removed, the bulk composition of the restite rocks and average peralkaline granite (Nockolds, 1954) were mixed together in different proportions so that the synthesized composition is comparable to the average cordierite-bearing gneisses. Except for Na_2O, the calculated average compositions of the mixed rocks are well within the standard deviation for the mean of the cordierite-bearing gneisses. These calculations indicate that approx. 75 to 85% of granitic melt must be abstracted during anatexis to produce the 'restite' rocks (Fig. 11). The discrepancy in the Na_2O contents might be due to a different Na_2O/K_2O ratio of the granitic melt produced compared to the average peralkaline granite. The bulk composition of the average cordierite-bearing gneisses of the area is projected into a quartz-albite-orthoclase diagram (Fig. 12). It

plots close to the temperature minimum on the cotectic line P-E$_5$. Considering the standard deviation for the mean composition in the gneisses (Table 5) it is evident that for bulk compositions which plot above the P-E$_5$ cotectic curve cordierite-biotite-sillimanite-quartz 'restite' would develop, after abstraction of the anatectic granitic melt, while for bulk compositions lying below the cotectic curve silica-deficient residual rocks would be produced. Assuming that sufficient H_2O was available during anatexis, a considerable amount of melt would be developed at temperatures somewhat above the temperature minimum. Winkler (1974) has shown that in a paragneiss consisting of quartz, plagioclase (An$_{29}$), potash-feldspar and biotite, 84% of the original gneiss melted at 800° C/ 2 Kb P_{H_2O}. Similarly in the gneiss containing quartz-plagioclase (An$_{13}$)-potash-feldspar-cordierite-biotite-sillimanite, 73% melt formed at 770° C/2 Kb. These temperatures are likely to be lowered significantly at pressures of 5 Kb (estimated for Sonapahar) and also by the presence of fluorine (Winkler, 1974) which occurs in chondrodite, brucite and phlogopite in the 'restite' rocks. Such high temperature conditions may have prevailed during the thermal peak of metamorphism as indicated by the PT conditions estimated previously.

In light of the above hypothesis, the genesis of the massive corundum-sillimanite deposits which are associated with the quartz-sillimanite schists along the 'noses' of minor folds, may be considered. The former is richer in Al_2O_3 and poorer in SiO_2 than the latter (Table 5). If it is assumed that the quartz-sillimanite schists also contained muscovite in the earlier phase of metamorphism, a relative concentration of muscovite and removal of SiO_2 may have taken place along the closures of the minor folds during differential movement as proposed by Tuominen and Mikkola (1950) and Kerrich et al. (1977). In such zones of muscovite enrichment this mineral would disappear on increase in temperatures (Lambert et al., 1969), and form corundum or sillimanite or both, besides liquid, depending upon the availability of SiO_2.

Mineral Reactions

Assuming the maximum PT conditions of metamorphism to be $750 \pm 50°$ C/5 ± 0.5 Kb and the partial melting hypothesis to be applicable to the parageneses described, an attempt has been made to trace out the sequence of mineral reactions as a function of increasing X Mg in the bulk composition due to abstraction of anatectic granitic melt (Fig. 13):
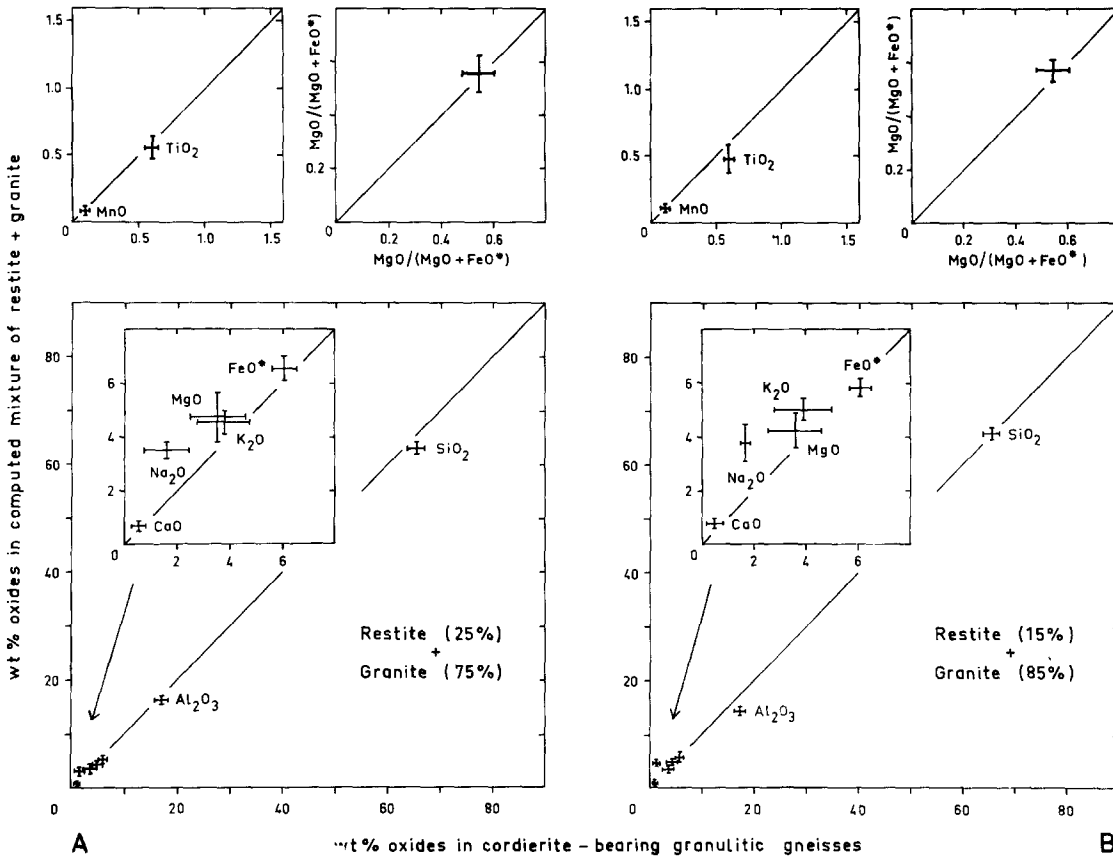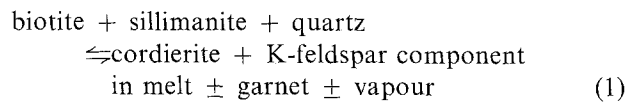
Fig. 11A and B. A Plot of the different oxides in the computed mixture of 25% restite (average of sample ref. nos. 1, 2 and 3, Table 5) plus 75% average peralkaline granite (Nockolds, 1954) against those of the average (Table 5) of cordierite-bearing granulitic gneisses (assumed parent rock of the 'restites'). The vertical and horizontal bars represent standard deviations for the arithmetic mean value of bulk composition of the computed 'restite' + granite 'mixture' and later rocks respectively. Range of MgO/(MgO+FeO) ratio in the computed mixture and cordierite-bearing granulitic gneisses and the standard deviation is shown in the Figure towards the upper right. Inset in the lower part of the diagram depicts enlarged portion of the area shown by the arrow.
B Same for the computed mixture of 15% 'restite' (average of sample ref. nos. 4, 5, 6, 7, 8, 9, and 12, Table 5) plus 85% of the peralkaline granite
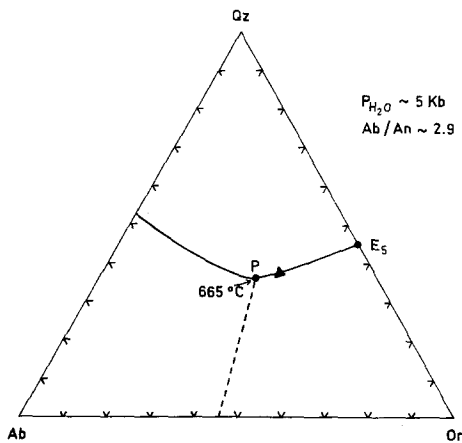
Fig. 12. Normative plot for the average cordierite-bearing granulitic gneisses (solid triangle) on the quartz (Qz): potash feldspar (Or): albite (Ab): diagram. The cotectic lines and temperature minimum (P) are for P_{H_2O} ~5 Kb and Ab/An ~2.9, and are based on data given in Winkler (1974, p. 283). Norm calculation is done by the modified method proposed by James and Hamilton (1969)

(1) From the textural evidence one of the most important reactions by which melt has been formed, is considered to be (Fig. 13b)

biotite + sillimanite + quartz
  $\leftrightharpoons$ cordierite + K-feldspar component
 in melt ± garnet ± vapour   (1)

as indicated by the ubiquitous presence of coarse poikiloblasts of cordierite and potash-feldspar overprinting the fabric of the gneisses. In many samples of these cordierite-bearing rocks potash-feldspar and plagioclase are completely absent and only minor quartz is present occurring as inclusions in cordierite. This indicates that these are also 'restites' after the removal of granitic melt. Although in many cordierite-bearing rocks idioblasts of garnet are present, its common occurrence as xenoblasts rimmed by cordier-
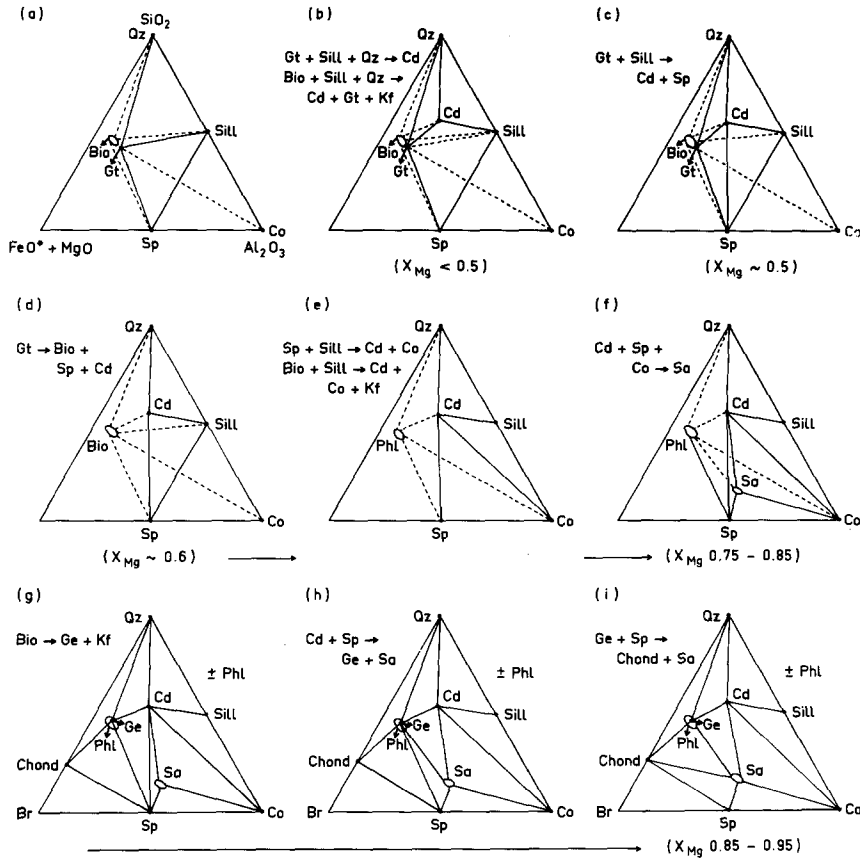
Fig. 13 a–i. The system
SiO_2-(MgO + FeO)-Al_2O_3 (H_2O)
showing the sequence of reactions
(assumed to be isobaric and isothermal)
as a function of changing X Mg
(= MgO/(Mg + FeO)) of the bulk
composition for the sapphirine-bearing
and other silica-deficient rocks of
Sonapahar area. Each diagram
represents a plane through the
SiO_2-MgO-FeO-Al_2O_3 tetrahedron,
with each plane intersecting the Al_2O_3
and SiO_2 apices but cutting the
MgO-FeO join at progressively more
Mg-rich intersections. Tie lines
connected to phlogopite/biotite are
shown by dotted lines. In g, h, and i
the tie line connecting with phlogopite
is not shown for the clarity of
representation. Phlogopite, however,
coexists with the silica-deficient phases
viz. sapphirine, spinel, corundum,
cordierite, chondrodite and brucite.
Abbreviations: Phl: phlogopite, *Qz:*
quartz, *Cd:* cordierite, *Bio:* biotite, *Gt:*
garnet, *Sill:* sillimanite, *Sp:* spinel$_{ss}$,
Co: corundum, *Sa:* sapphirine, *Ge:*
gedrite, *Chond:* chondrodite, *Br:*
brucite

ite indicates its instability presumably due to a reaction such as (Fig. 13 b).

garnet + sillimanite + quartz⇌cordierite.   (2)
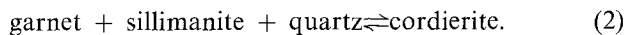
This divariant reaction will proceed to the right on increase of X Mg.

(2) With progressive removal of granitic melt from the rocks the effective bulk composition gradually moves towards the silica-deficient side of the SiO_2-(FeO + MgO) -Al_2O_3 diagram and away from the garnet compatibility field on an AFM diagram because of increasing X Mg in the 'restite'. The garnet-sillimanite join now becomes unstable and the reaction (Fig. 13c).

garnet + sillimanite⇌cordierite + spinel   (3)
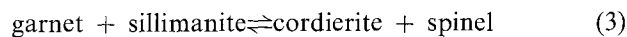
occurs as revealed by the common presence of spinel with cordierite, and relics of earlier garnet and associated sillimanite pseudomorphed by cordierite and spinel, as observed in many samples of the cordierite-garnet-bearing gneisses. The reaction given in Figure 13d is not evident from the textures observed but must be postulated from a comparison of Figure 13c and e.

Biotite is still compatible with sillimanite and oc-

curs in massive quartz-free sillimanite rocks with X Mg ~ 0.75. With X Mg > 0.75, as in all the silica-deficient 'restites', biotite/phlogopite is now incompatible with sillimanite evidently due to a reaction such as (Fig. 13 e)

biotite + sillimanite
    ⇌cordierite + corundum
    + potash-feldspar component in melt
   ± vapour.   (4)
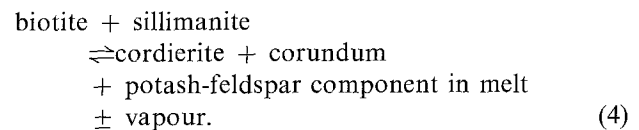
This reaction probably marks the end of partial anatexis as phlogopite has been found to be in textural equilibrium with all the silica-deficient phases. With removal of different proportions of granitic melt, 'restites' of variable X Mg result. The reactions given in Figure 13e–i do not necessarily represent reactions which may have taken place in the rocks but rather describe the changes in the topology with increasing X Mg in the bulk composition.

(3) The ubiquitous presence of spinel inclusions in sapphirine, presence of corundum as corroded blebs within cordierite, etc., are supporting evidences for a sapphirine-forming reaction:

cordierite + spinel + corundum
    ⇌sapphirine + H_2O.   (5)
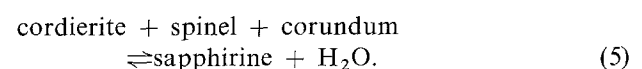
This reaction is confined to extremely low pressures (below ~ 300 bars) in the system $MgO - Al_2O_3 - SiO_2 - H_2O$ accordint to Seifert (1974). It is suggested here that the reaction curve continues to higher pressures with $Mg\rightleftharpoons Fe$ substitution in natural minerals. The reaction

chlorite + corundum + spinel
$\qquad \rightleftharpoons$ sapphirine + H_2O \hfill (6)
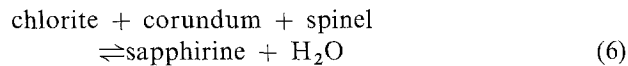
which plays an important role in the Fe-free system, cannot be held responsible for the formation of sapphirine in these rocks. In K_2O-rich bulk compositions, chlorite would breakdown, prior to the beginning of partial melting, in the presence of quartz + muscovite (cf., Seifert, 1970).

The reaction (5) is divariant in an iron-bearing system. Divariant assemblages containing all the reactants and products have been observed in one sample, while commonly the product mineral sapphirine is accompanied by two of the reactants, i.e., the assemblages sapphirine-cordierite-spinel, and sapphirine-spinel-corundum.

The formation of cordierite-spinel-corundum 'restite' and complete removal of granitic melt prior to the crystallisation of sapphirine by the reaction (5) are consistent with the argument of Yoder (in Clifford et al., 1975) that sapphirine is incompatible with granitic melt.

(4) Experimental work in the $MgO-Al_2O_3-SiO_2$-H_2O system by Seifert (1974) shows that cordierite and spinel coexist at low-pressures only and that at pressures above about ~ 3.5 Kb they react to form enstatite + sapphirine. On the other hand the sapphirine-bearing rocks of Sonapahar show that the cordierite and spinel coexist in rocks with X Mg up to ~ 0.85 but the assemblage is changed to gedrite + sapphirine in bulk composition with higher X Mg (Fig. 13 h) which is consistent with the experimental data of Seifert (1974) and estimated PT conditions of metamorphism. The stable occurrence of cordierite-spinel in the 'restites' with low X Mg suggests that with $Mg\rightleftharpoons Fe$ substitution the reaction cordierite + spinel $\rightleftharpoons$ enstatite/gedrite + sapphirine shifts to relatively higher pressures as compared to the Fe-free system.

Furthermore, the tie line spinel-aluminium silicate is restricted to extremely high temperatures ($\sim 1450°$ C) in the synthetic Fe-free system (Seifert, 1974). Coexisting spinel and sillimanite have been observed in the cordierite-bearing gneisses of the area with X Mg 0.4 to 0.6. Spinel occurs as inclusion within sillimanite because of its incompatibility with quartz present in the matrix. This observation also suggests that the presence of Fe^{2+} in natural rocks stabilizes the pair to considerably lower temperatures.

The textural relations of the sapphirine-bearing rocks and associated cordierite gneisses of the area clearly demonstrate that the presence of Fe^{2+} can drastically affect the phase relations and thus experimental data in the system $FeO-MgO-Al_2O_3-SiO_2$-H_2O may help to evaluate these assemblages in terms of physicochemical parameters.

(5) Although kornerupine is present as an armoured relic in one of the sample of the cordierite-sapphirine-spinel rocks, its general rarity needs explanation because experimental studies in the MgO-Al_2O_3-SiO_2-H_2O system have shown that boron-free kornerupine is stable above about $740°$ C and 4.5 Kb P_{H_2O} (Seifert, 1975). Presence of Fe^{2+} substituting for Mg might stabilize kornerupine to lower temperatures as proposed by Seifert. The bulk compositions of rocks in which kornerupine may form lie within the compatibility field cordierite-gedrite-sapphirine in the SiO_2-$(MgO+FeO)$-Al_2O_3 diagram (Fig. 5). Although the bulk compositions of the sapphirine-bearing rocks plot close to this field (Fig. 9), the presence of high modal phlogopite (Table 5) in most parageneses shifts the effective bulk composition in terms of the SiO_2-$(MgO+FeO)$-Al_2O_3 system towards the high alumina side of the diagram. The most likely rock which may have contained kornerupine is the sapphirine-cordierite-gedrite-bytownite rock reported by Ghosh and Saha (1954) from the area. The absence of kornerupine in this paragenesis may be attributed to the significant Na_2O-content of the bulk composition revealed by the presence of gedrite and plagioclase, which is likely to inhibit the crystallization of kornerupine as proposed by Schreyer and Abraham (1976a). Thus, lack of appropriate bulk composition rather than suitable PT conditions may have been responsible for the general rarity of kornerupine from the 'restite' rocks of the Sonapahar area.

Rarity of Sapphirine in Gneisses Involved in Anatexis

If partial melting of the cordierite gneisses is responsible for the formation of the sapphirine-bearing silica-deficient restites, it is difficult to account for the scarcity of such rocks in other areas of granulite facies where anatexis may have occurred very widely. Several factors would individually or collectively mitigate against the development of such restite rocks:

(1) Common pelitic gneisses plot on the quartz-rich portion in a normative Qz-Ab-Or diagram and therefore partial melting and the removal of the granitic melt would result in the formation of the cordierite-garnet-sillimanite-quartz-bearing restites. On the other hand silica-deficient restites would form if the

normative Qz-Ab-Or ratio in the bulk composition is poorer in quartz so as to plot below the cotectic curve and the temperature minimum.

(2) The development of the sapphirine-bearing restites requires a high X Mg value in the bulk composition and this condition is fulfilled only when a considerable amount of melt of the granitic composition ($>75\%$) containing a significant proportion of FeO (>5 wt%) is removed leaving behind the restite. Assuming significant amounts of H_2O present during the partial melting, this would require (a) either the normative Qz-Ab-Or ratio close to the temperature minimum composition or temperatures far above the minimum anatexis. (b) low Ab/An ratio, (c) presence of volatiles such as F, Cl, etc., and (d) a granitic melt composition with high FeO similar to the average peralkaline granites of Nockolds (1954).

(3) Formation of the sapphirine-bearing restites is dependent on the virtually complete removal of the anatectic melt from the restite prior to the crystallisation of sapphirine.

(4) Granitisation and feldspathisation are common in many high-grade regional metamorphic terrains, and would tend to destroy sapphirine-bearing parageneses.

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