CHAPTER - IV

PELITIC GRANULITES

CHAPTER -IV

PELITIC GRANULITES

Pelitic granulites are characterized by a gneissic foliation and well segregated alternate bands of quartzo-feldspathic phases with minor sillimanite and biotite and garnet - sillimanite - cordierite - biotite - orthopyroxene - spinel and very sporadic sapphirine. Augens of perthitic feldspar are common in the quartzo-feldspathic layers. The strike of the gneissosity in pelitic granulite varies from NNW-SSE, N-S, NE-SW and E-W in a traverse from north to south (Fig.2.1, Chapter-II).

The symplectitic textures shown by these rocks are discussed in Chapter-IX. On careful examination of chemical analyses (Tables-IV A-G) it will be revealed that these are dominantly iron-rich except in the northern part where these are magnesium-rich. Thus they can be referred to as iron-rich and magnesium-rich pelites. This terminology is not adopted for the purpose of description. However, the relevance of their iron and magnesium rich character in relation to metamorphism has been discussed at length in the Chapter-VII on "Metamorphic History".

IV.1 Petrography

Pelitic granulites in the study area contain the following mineral assemblages : garnet - sillimanite - cordierite - K feldspar - quartz - plagioclase - biotite - orthopyroxene - spinel - ilmenite - sapphirine and staurolite/kyanite. Important petrographic features of the individual constituents are described as under.

Garnet :

Mauvish-pink porphyroblastic garnets are abundant in the rock and their size ranges from small grains (less than 0.5mm) occurring as aggregates to large rounded porphyroblasts (upto 8mm). In the outcrops it is seen that the largest size of garnet is from the hinge of mesoscopic folds and their size diminishes towards the limbs. Locally porphyroblastic garnets yield fractures by brittle deformation and produce pulled apart texture (**Plate IV.1A**) where the fractures (with chloritoid rarely) are mostly transverse to length of the porphyroblasts. Garnet is nearly always poikilo-porphyroblastic with inclusions of sillimanite, cordierite, quartz, plagioclase, biotite, rutile, spinel and occasionally sapphirine (**Plate-IV.1B**). Generally the central portion of porphyroblastic garnets contains larger cordierite and is devoid of sillimanite (**Plate-IV.2A**). The included phases especially sillimanite, define an internal schistosity (S_i) which appears to be at an angle to external foliation (S_e) defined by sillimanite (Plate-IV.1B). S_e warps against garnet porphyroblasts **(Plate-IV.2B)**. A variety of sillimanite consisting of mats of fibrolite along with patchy biotite are present at its grain boundary **(Plate-IV.3A)** of (S_i) which appears to be at a low angle with the external schistosity (S_e) also defined by longer sillimanite needles. Garnet is also seen to include spinel, sapphirine and chloritoid and thus may be considered to be the younger than these phases **(Plate-IV.3B)**.

Sillimanite

Aluminosilicates are represented mostly by sillimanite which occurs in several modes :

(i) As included phases in the form of fibrolite within porphyroblastic garnet.

(ii) As large sillimanite needles define an external schistosity **(Plate-IV.4A)**. Such sillimanite show cross fractures as well. These are possibly peudomorphs after kyanite.

(iii) Mats of sillimanite fibrolite along with biotite present at the grain boundary of garnet and k-feldspar. These appear to have been deflected by the growth of the garnet porphyroblast suggesting that sillimanite is older than garnet. Formation of sillimanite needles (fibrolite) on biotite flakes **(Plate-IV.4B)** may be ascribed to the ease of nucleation. The material for the growth of fibrolite may have been derived from kyanite undergoing decomposition in the same rock (Chinner, 1961, has described such features in Scottish highlands). Fibrolite rim or moat is seen around spinel. **(Plate-IV.5A)**.

(iv) As "herringbone" like linear clusters of fibrolite possibly defining two phases of superposed deformation with low angle of interference **(Plate-IV.5B)**.

Cordierite :

All the outcrops of pelitic granulites in the study area owe their dark bluish grey colouration to cordierite. Presence of cordierite in large proportion renders these rocks very hard and difficult to break. Due to the resistance to weathering, both chemical and mechanical, the pelitic cordierite bearing units, stand out as conspicuous, sinuous ridge and all the higher elevations are located on this unit.

Cordierite commonly occurs as dark blue pods or segregations ortrains of rounded grains and has a tendency to form regular, elongated grains conformable to the foliation. In thin sections, it is entirely clear, except for inclusions of spinel and minute sillimanite needles and is distinguished with its characteristic sector twinning and pinitisation along the margins and fractures. Sometimes the whole grain is pinitized leaving only a few remnants of unaltered cordierite. Polysynthetic twinning also occurs only in isometric

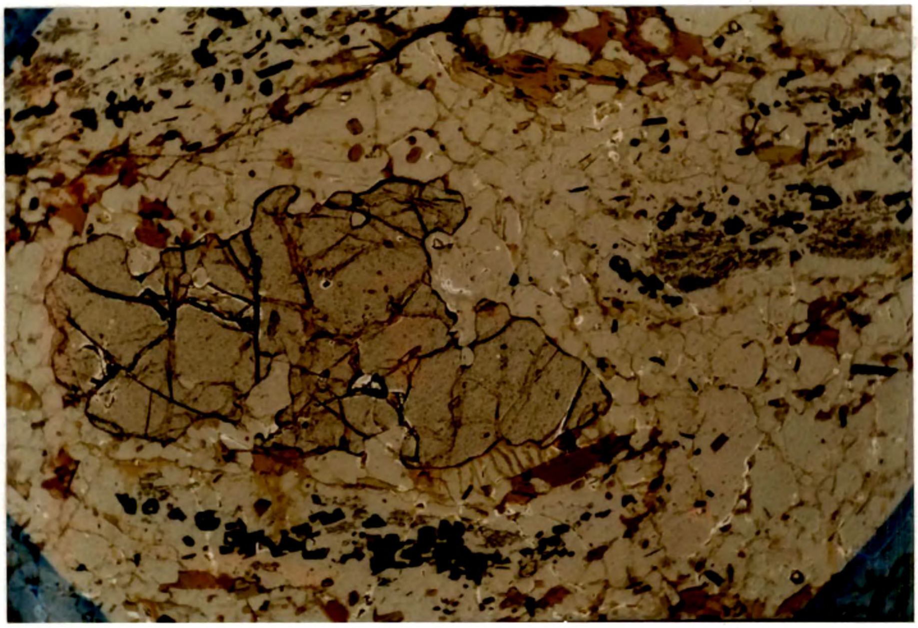


Plate -IV.1A Porphyroblastic garnets showing fractures by brittle deformation and produce pulled apart texture) where the fractures are mostly transverse to length of the porphyroblasts (PPL, 40X).

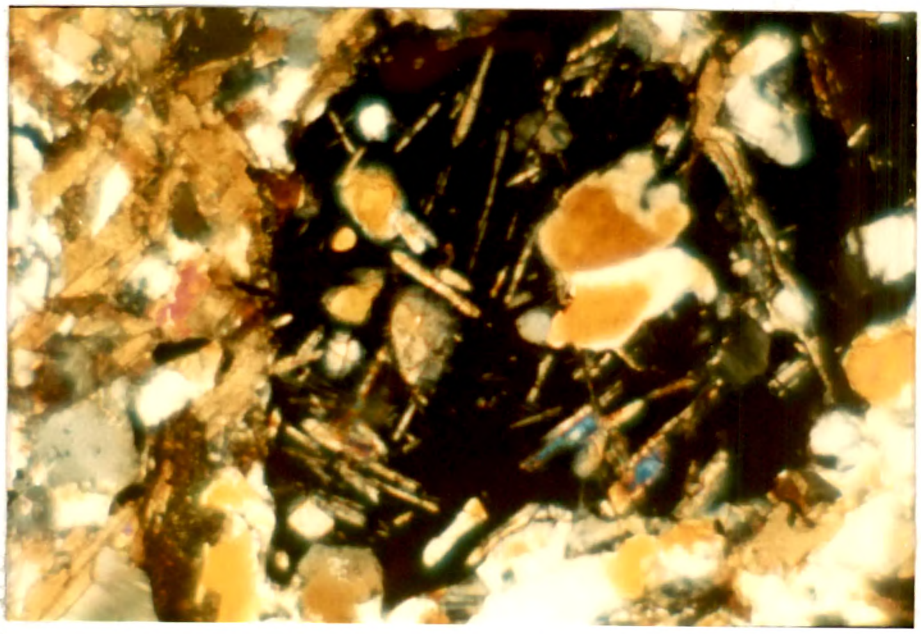


Plate-IV.1B. Nearly always poikilo-porphyroblastic garnet with inclusions of sillimanite, cordierite, quartz, plagioclase, biotite, rutile, spinel (XPL, 80X).

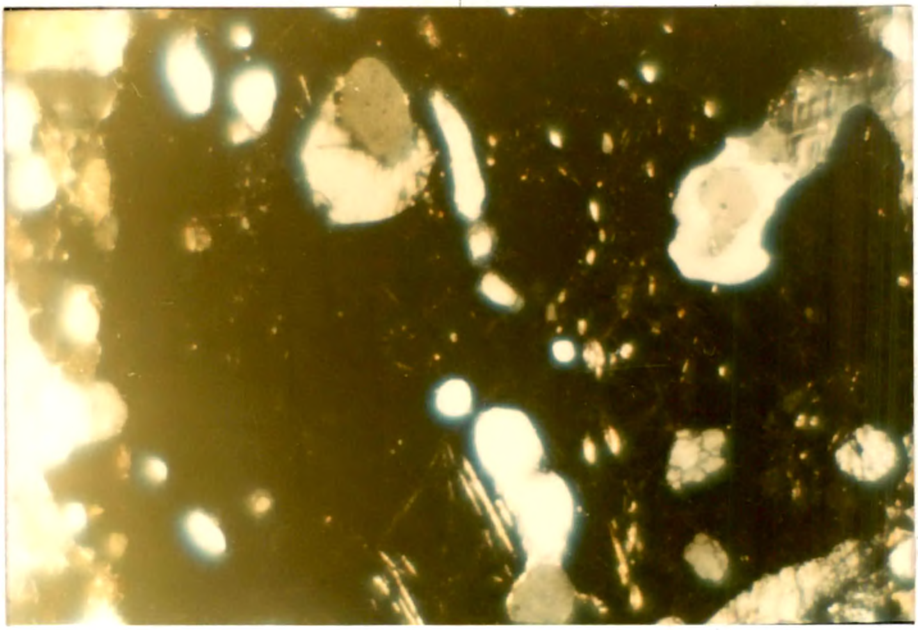


Plate -IV.2A Central portion of porphyroblastic garnets contains larger cordierite and is devoid of sillimanite (XPL, 80X).

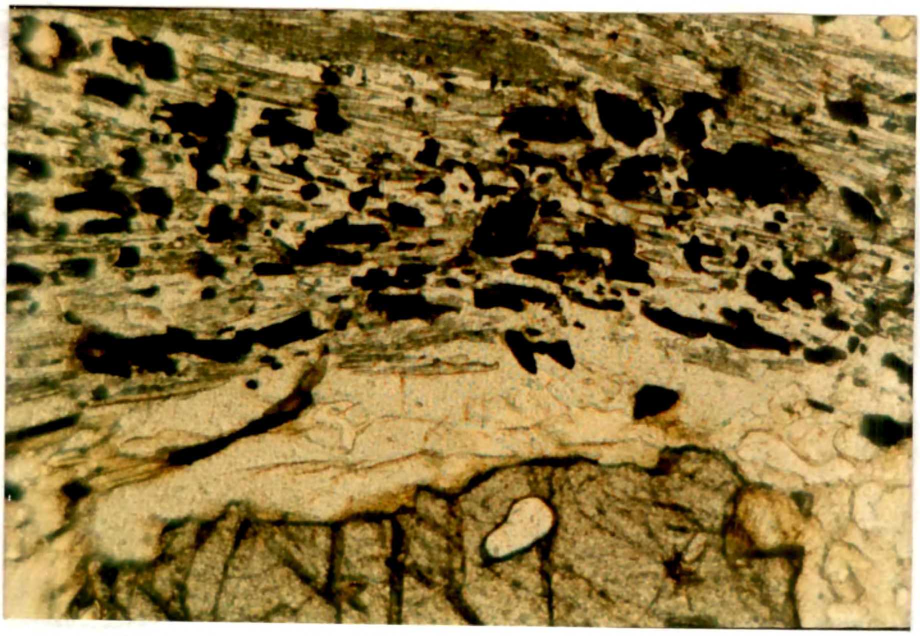


Plate-IV.2B. Photomicrograph showing S_e warps against garnet porphyroblasts (PPL, 80X).

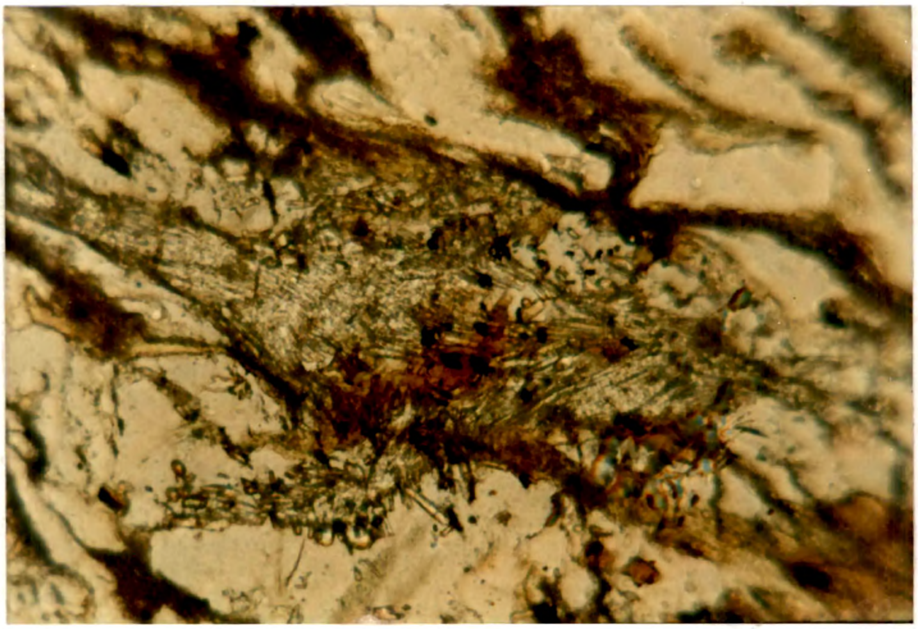


Plate -IV.3A Fibrolitic variety of sillimanite showing mats along with patchy biotite at its grain boundary (PPL, 80X).

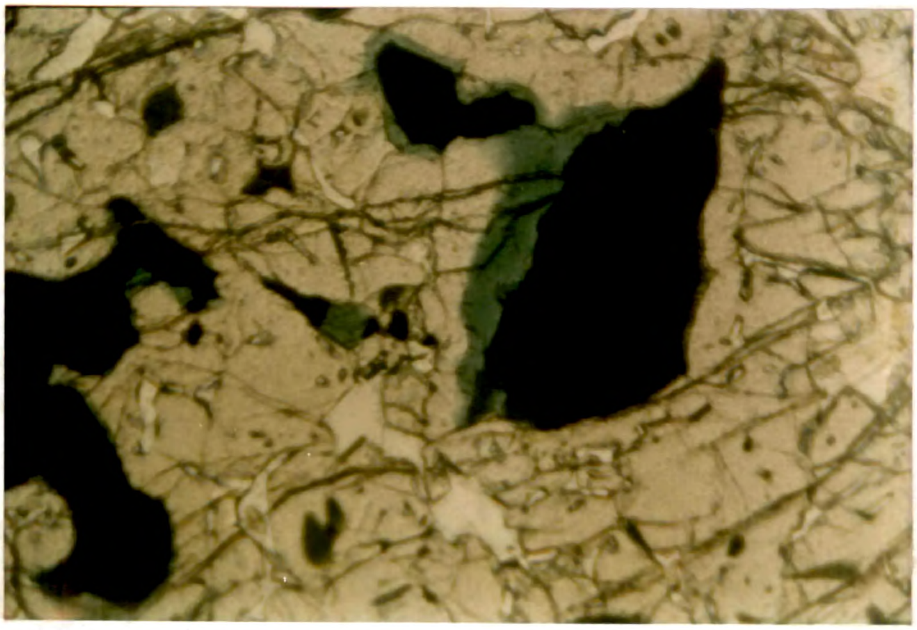


Plate-IV.3B. Garnet showing inclusions of spinel and sapphirine (PPL, 80X).

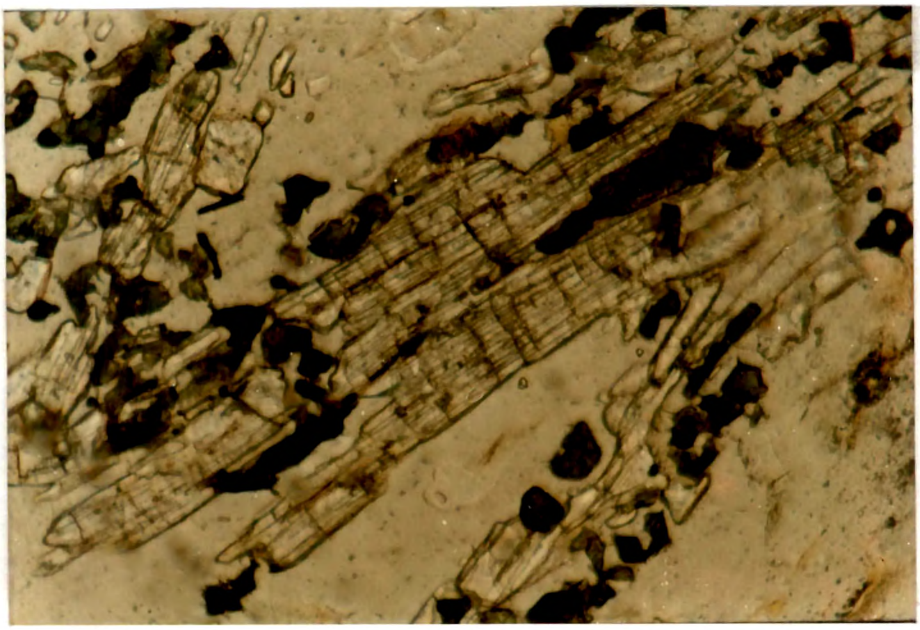


Plate -IV.4A Stout sillimanite pseudomorphous after kyanite in pelitic granulites (PPL, 40X).

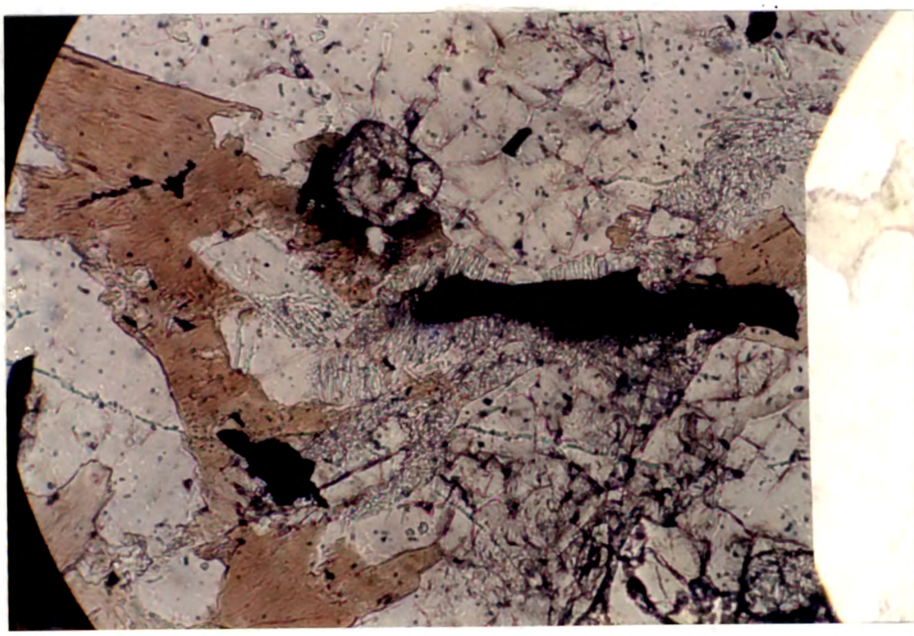


Plate-IV.4B. Formation of sillimanite needles (fibrolite) on biotite flakes may be ascribed to the ease of nucleation (PPL, 80X).

Plate-IV.5A Fibrolite rim or moat seen around spinel (PPL, 80X).

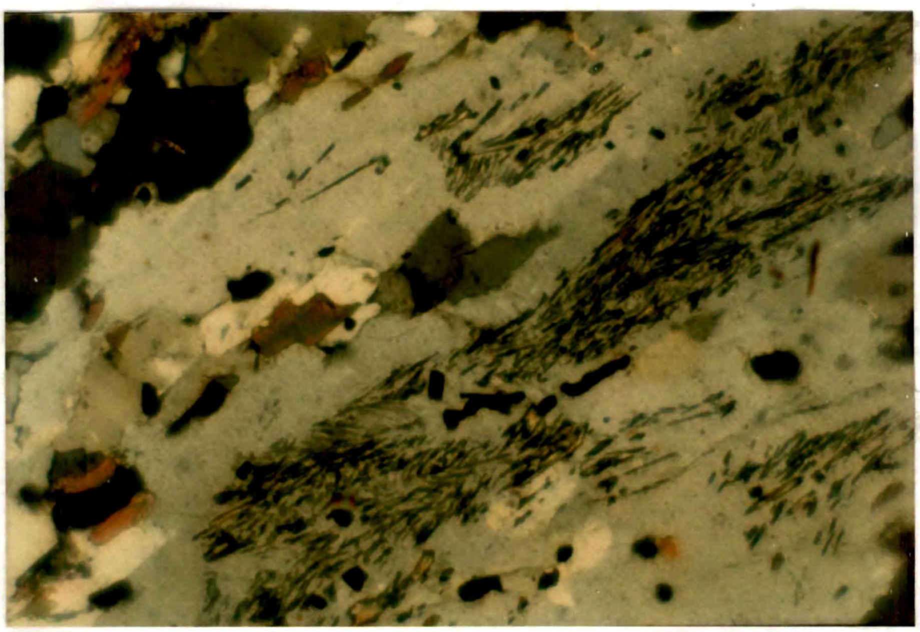


Plate-IV.5B. "Herringbone"like linear clusters of fibrolite defining two phases of superposed deformation in pelitic granulites (PPL, 80X).

grains **(Plate-IV.6A)**. Customary pleochroic haloes are confined to the central part. It also occurs as symplektitic intergrowth with quartz where it occurs as vermicular / elongated drops or as plumose symplektites with the characteristic cauliflower like growths **(Plate-IV.6B)**. It also occurs as inclusions within porphyroblasts of garnet which implies an earlier metamorphic event **(Plate-IV.1B)**. A noteworthy character is the optically +ve sign.

Cordierite appears to be of two generations : (i) The early generation cordierite occurs as pods or segregations of elongated grains and contains inclusions of fibrolitic sillimanite and spinel. Fibrolite is confined to the central part of the grain. (ii) Cordierite of later generation forms distinct metablasts that have grown across the foliation and carry inclusions of quartz and biotite. Some of the cordierite metablasts have a margin with abundant, quartz and biotite inclusions. The microcline metablasts also contain quartz and biotite inclusions in a similar fashion to these younger cordierite and obviously formed during the same period of recrystallisation.

Cordierite alters to various minerals, like chlorite and biotite especially along grain borders and along cracks within grains. In some cases, cordierite has been observed within a few mm of , but not in contact with, K-feldspar, where the two minerals are in separate layers. Biotite and chlorite occur as alteration products along the margins.

K-feldspar :

Majority of K-feldspar grains, of porphyroblastic nature, bear imprints of deformation in the forms of undulose extinction and extensive subgrain formation along the grain boundaries. These include sillimanite, biotite and quartz. Sillimanite (fibrolitic) and biotite develop along the grain boundary of k-feldspar.

Quartz :

It is either clear or has small patches of dust like inclusions. Quartz contains fine rutile (?) needles (in cross section these look like particles) which are similar to those reported by Holland (1900) in the granulites of Madras State. It is often poikiloblastic with inclusions of feldspar, biotite, rutile, garnet, zircon and sillimanite. Strain shadows and cracks are generally perpendicular to the elongation. Quartz occurs in three modes.

(i) Quartz grains occur in diverse size range. Often quartz grains are flattened, associated with feldspar and forms elongate ribbons. These quartz ribbons along with sillimanite form a foliation which warps around porphyroblastic garnet **(Plate-IV.2B)**.

(ii) Inclusion of quartz occurs within porphyroblastic garnet and K-feldspar **(Plate-IV.1B)**.

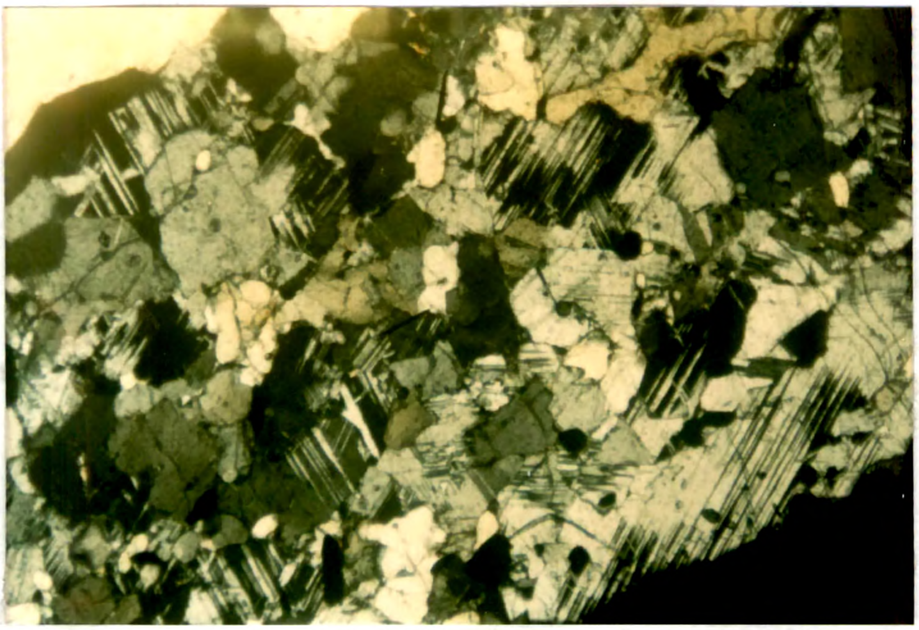


Plate-IV.6A Cordierite with inclusions of spinel and minute sillimanite needles and its characteristic polysynthetic twinning and pinitisation along the margins and fractures (XPL, 40X).

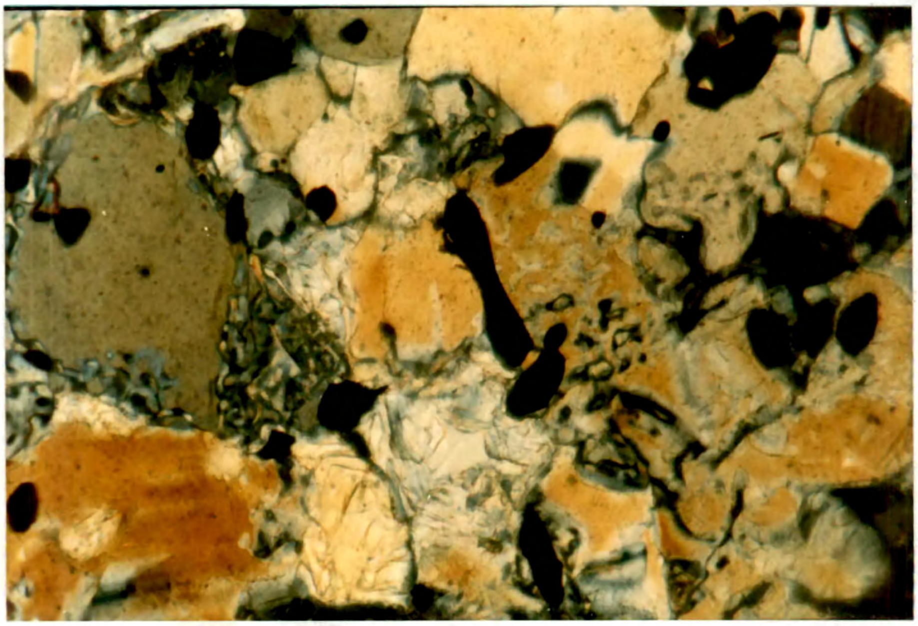


Plate-IV.6B. Cordierite showing symplektitic intergrowth with quartz where it occurs as vermicular/ elongated drops or as plumose symplektites with the characteristic cauliflower like growths (XPL, 80X).

(iii) Quartz also occurs as symplectitic intergrowth with cordierite, biotite and feldspar **(Plate-IV.6B)**.Its significance has been subsequently discussed in Chapter-IX.

Plagioclase :

Only small amount of plagioclase is present in these rocks. Relatively large porphyroblastic plagioclase grains show bending of twin lamellae and marginal subgrain formation. Myrmekitic intergrowth at the grain boundaries of K-feldspar and plagioclase feldspar is common.

Biotite :

Biotite also occurs in three modes :

(i) It occurs as included phases within garnet and k-feldspar porphyroblasts.

(ii) With quartz it forms biotite-quartz symplektite.

(iii) Mats of biotite occur along with fibrolitic sillimanite and the former one develops along the fracture of garnet porphyroblast. Often undigested garnet and sillimanite prisms are found to float in these biotite mats **(Plate-IV.3A)** which are the evidence of arrested retrogression of granulite facies to amphibolite facies.

Ortho-pyroxene

It either forms large tattered plates, riddled with inclusions of quartz, biotite and opaques or small anhedral grains. In the sapphirine bearing rocks, it is sometimes seen to rim spinel **(Plate-IV.7A)** and more often as thin bands **(Plate-IV.7B)**. It is characterised by its straight extinction and pale reddish brown to pale greenish brown pleochroism X = pale to bright pink, Y = bright yellow and Z = bright apple green or bluish green and its partings and appears to be aluminous, having been developed as a result of metamorphism of argillaceous sediments.

Ilmenite :

Most of the grains of ilmenite in pelitic granulites are present within the matrix along with quartz, sillimanite and biotite. It is rather difficult to distinguish it from other opaques.

Spinel :

It occurs as small green anhedral grains either in the groundmass or as inclusions in cordierite and garnet. It has not been seen in direct contact with quartz or feldspar. Greenish black spinels are hercynite (SH/D, 1D3), others are green-black spinel, (SM97/1) and titaniferous magnetite (SM97/1). Alteration of green black spinels to a greenish material is seen at places. Rarely spinel is seen to have inclusion of staurolite/ kyanite (Plate-IV.8A). Sometimes (rarely) spinel (the green-black variety) shows

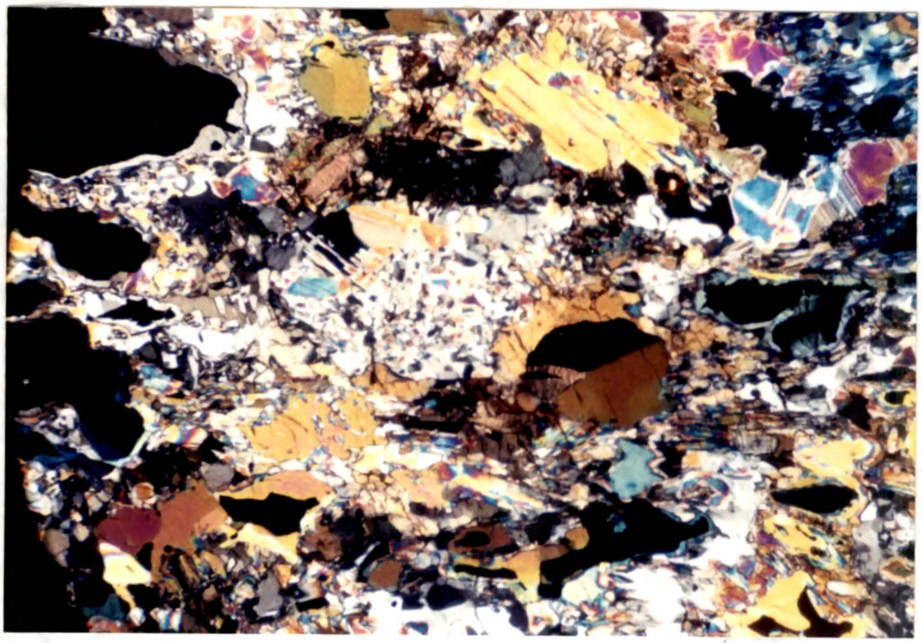


Plate-IV.7A Ortho-pyroxene forming large tattered plates, riddled with inclusions of quartz, biotite and opaques or small anhedral grains (XPL, 40X).

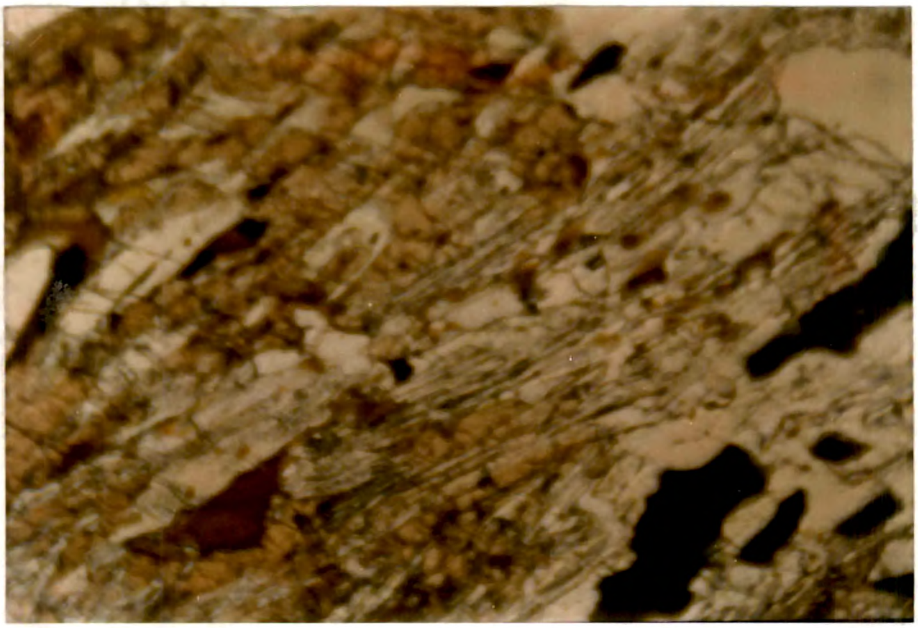


Plate-IV.7B. Sapphirine bearinng rocks with thin orthopyroxenen bands and spinel (the green-black variety) showing development of sapphirine around it (PPL, 80X).

development of sapphirine around it **(Plate-IV.3B, IV.7B)**. Spinel is often seen to have a very thin moat of fibrolite around it **(Plate-IV.8A)**. In the sapphirine bearing rock it is symplectitic with garnet. Spinel is sometimes seen to to have a rim of orthopyroxene.

Zircon :

It occurs as inclusions in the porphyroblastic garnet.

Sapphirine :

Very sporadic occurrence of sapphirine around spinel has been noticed. It is always associated with spinel around which it develops. Distinguished by its characteristic lavender blue colour and pleochroism from pale to deep lavender blue **(Plate-IV.3B)**.

Osumilite:

It is similar in appearance to quartz and cordierite and is commonly replaced by cordierite, quartz, k-feldspar symplectite that could be confused with other cordierite rich symplectites. In polarised light this mineral is colourless, non-pleochroic and is chracterised by low birefringence and optically +ve sign with no cleavage. It exhibits Ist order grey to yellowish grey interference colours. In some cases it shows rectangular outlines **(Plate-IV.8B & IV.9A)** and optically continuous intergrowth and meandering vein like habit throughout the rock. There are very few places where cordierite and osumilite are in direct contact and in most of the cases osumilite is separated from polycrystalline cordierite knots by a zone of finger like quartz, feldspar, cordierite symplectites. Osumilite bearing rocks are generally free of alteration such as sericite replacing feldspars or pinite replacing cordierite. In most of the sections,it is observed that osumilite is replaced by a very fine plumose symplectitic intergrowth of cordierite, K-feldspar and quartz. The symplectite forms along the margins of grains or forming thin veinlets. Symplectite commonly coarsens into cordierite, vermicular quartz and discrete k-feldspar grains.

Staurolite :

A few euhedral grains of staurolite are preserved within the spinel (hercynite) which in turn are enclosed within almandine garnet porphyroblasts in pelitic granulites **(Plate-IV.10A, B)**. Staurolite is distinguished by its colourless to golden yellow pleochroism and parallel extinction.

Modal analysis of pelitic granulites of four samples is given below (after Desai and Patel, 1992) :

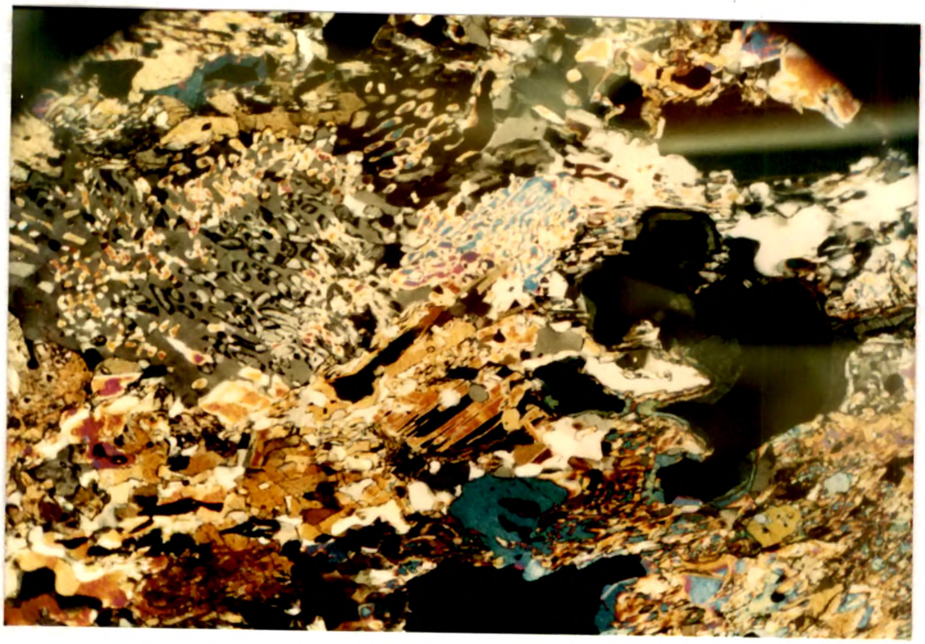


Plate-IV.8A Spinel is often seen to have a very thin moat of fibrolite around it . In the sapphirine bearing rock, it is symplectitic with garnet. Spinel is sometimes seen to to have a rim of orthopyroxene (XPL, 40X).

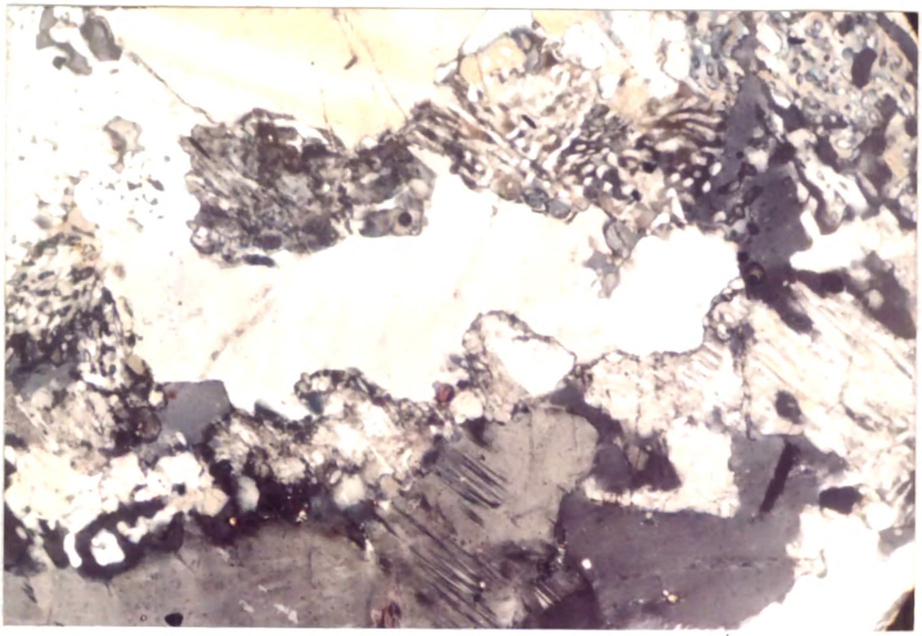
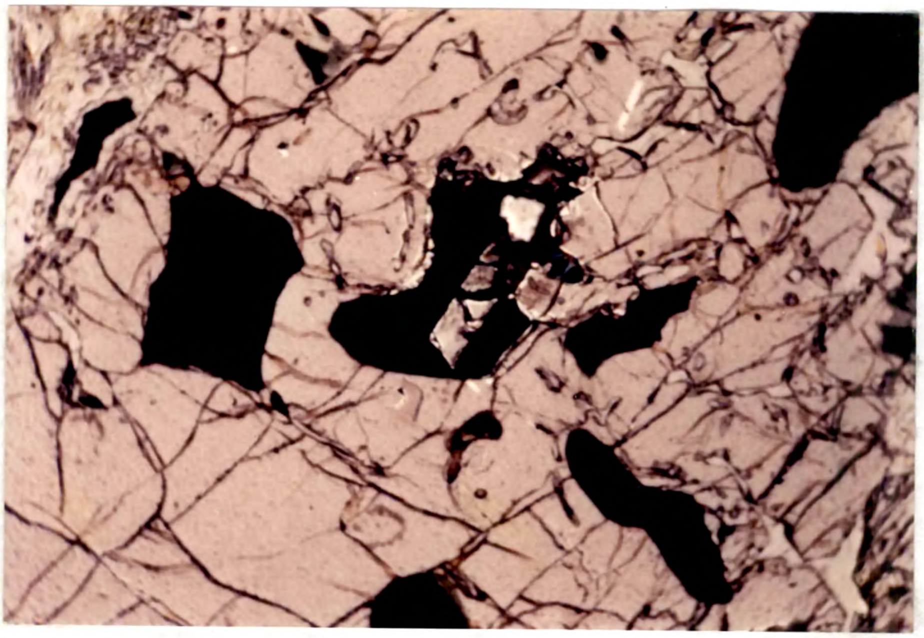
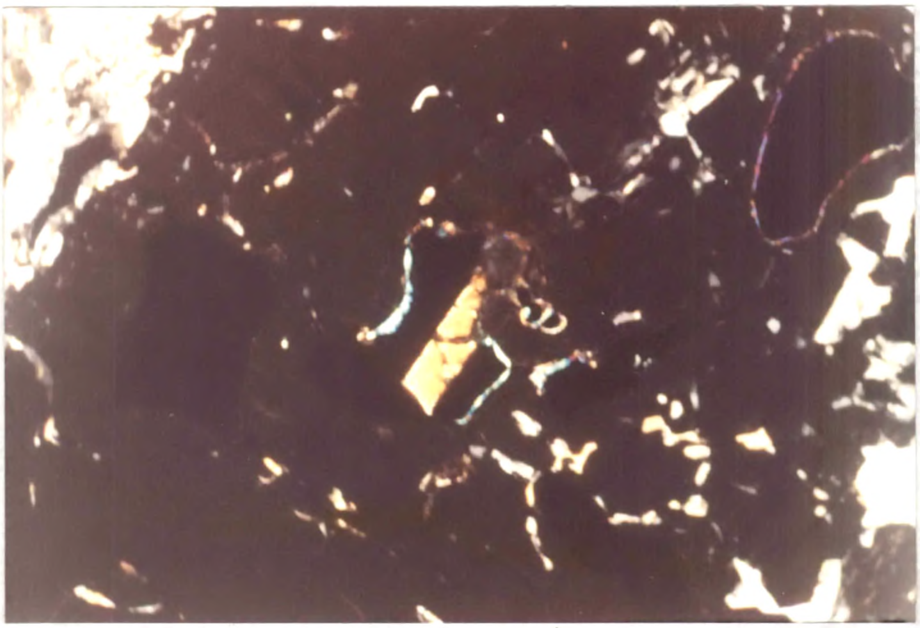


Plate-IV.8B. Osumilite showing rectangular outlines and optically continuous intergrowth and meandering vein like habit throughout the rock. Symplectites due to breakdown of osumilite (XPL, 80X).

Plate-IV.9A Symplectite forms along the margins of grains or forming thin veinlets Symplectite commonly coarsens into cordierite, vermicular quartz and discrete k-feldspar grains (XPL, 80X).



A



B

Plate-IV.10A & B Subhedral grains of staurolite within the spinel (hercynite) which in turn are enclosed within almandine garnet porphyroblasts in pelitic granulites (A- PPL, B- XPL, 80X)

	1	2	3	4
Sillimanite	01.30	01.01	-	-
Cordierite	48.43	47.54	54.38	31.85
Quartz	34.30	27.45	14.93	38.11
Garnet	12.71	08.80	02.47	06.73
Biotite	0.46	0.50	20.82	0.38
Feldspars	-	14.60	5.21	21.43
Spinel	2.80	-	-	-
Hypersthene	-	-	2.01	-
Opaques	-	0.10	0.13	0 48
Total	100.00	100.00	99.95	98.98

The somewhat rare association of cordierite and garnet with hypersthene as in the present case has been reported from the Westport Map area, Canada (Wynne-Edwards, 1967), In Western Australia (Prider, 1945) and in the Lapland area (Eskola, 1952). Devraju and Sadasivaiah (1967) have reported a similar assemblage from Mysore, which they consider to be arenaceous shale. Plumose symplektites of quartz, cordierite, k-feldspar and hypersthene have also been reported by Grew (1982b) from Paderu area, Andhra Pradesh, S.India and by Nixon et al. (1973) from Uganda. The significance of plumose symplektite is discussed later

IV.2 Mineral Chemistry

Chemical composition of minerals were determined by a Jeol Super EPMA operated at 15 KV accelerating voltage and 2μm beam diameter. Natural standards were used and some representative ZAF corrected analyses are given in Table-IVA to Table-IVG.

Garnet :

Representative garnet analyses are given in Table-IVA. Garnet in plagioclase free pelitic granulites is iron-rich with molar end member proportions 77.7 - 86 % almandine, 8 - 19 % pyrope, 2 - 3 % grossular and 1 to 2 -4 % Spessartine. Garnet from the plagioclase-bearing pelitic granulites is also iron-rich 70 - 75 % almandine, pyrope 0.12-0.18 %, grossular 2 - 3 % and 3 - 4 % Spessartine. The garnets in sapphirine bearing pelitic granulites contain 45 % almandine, 49 % pyrope, 3 % grossular and 3 % spessartine.

Cordierite :

Representative analyses of cordierite are given in Table-IVB. SiO2 ranges from 48 - 49.63%, Al2O3 30.5 - 31.5%, FeO 10.847 -12.56%, MgO 6.5 - 7.65%, MnO 0.06 - 0.21%, CaO 0 - 0.21%, K2O 0 - 0.009%, Na2O 0 - 0.23%, TiO2 0 - 0.027%. These data clearly indicate that it is a Fe rich cordierite. X_{Fe} varies from 0.44 - 0.57 while X_{Mg} ranges from 0.48 to 0.56. SiO2, Al2O3, FeO and K2O decrease from core to rim while CaO, Na2O are seen to increase from core to rim of the grains.

Biotite :

Biotite analyses are given in Table-IVC. X_{Fe} ($=Fe^{+2}/Fe^{2}+Mg$) of biotite in cordierite-rich pelitic granulites ranges between 0.29 to 0.35 (SH12) which is less than X_{Fe} biotite 0.45 - 0.5 in cordierite-poor pelitic granulites (SM96/3). In sapphirine bearing pelitic granulites X_{Fe} varies from 0.199 to 0.211. In others it varies from 0.53-0.60. In pelitic granulites biotite included in garnet has the composition X_{Fe} = 0.32 - o.35, Al^{IV} = 2.33 - 2.43, TiO_2 = 6.41 - 6.68 wt% (SH12). In plagioclase - bearing pelitic granulite (granitoid SM96/3), included biotite in garnet has the composition X_{Fe} = 0.45, TiO_2 = 0.049 - 0.199 wt%, Al^{VI} = 0.71 - 0.92. while matrix biotites are richer in X_{Fe}~ 0.5 and TiO_2~ (.074 - 0.104 wt%), Al^{VI}~ 0.96 - 1.22. Biotites in contact with garnets have X_{Fe}~ 0.46-0.49, TiO_2~ (4 - 6.6 wt%), Al^{VI} (0.3-0.7). In general there is slight increase in TiO2, MgO, K2O, Na2O and MnO form core to rim while SiO2 and Al2O3 are seen to decrease from core to rim but these are not consistent and depend on the mineral in the vicinity.

Feldspars :

Composition of feldspars from pelitic granulites are given in Table-IV D.

K-feldspar :

All the oxides wt% in are seen to decrease from core to rim. Mole fractions of X_{Or} varies from 0.89 - 0.91, X_{Ab} 0.102 - 0.088 and X_{An} .001 - 0 from core to rim.

Plagioclase :

Plagioclase (SM96/3) contains 0.23-0.24 X_{An}, 0.75 - 0.76 X_{Ab} and 0.008 - 0.009 X_{Or}. No zoning is detected in plagioclase megacrysts not in contact with garnet.

Albite partitioning is distinct in the two feldspars in contact (SM96/3). In the plagioclase X_{Ab} varies from 0.75 to 0.76 while in K-feldspar in contact has 0.10 to 0.15 X_{Ab}. and has been useful in thermometry.

Orthopyroxene :

Mineral composition of orthopyroxene is given in Table-IVE. Compositionally both the orthopyroxenes are hypersthene (Deer et al., 1974). The X_{Mg} (= Mg/(Mg + Fe^{2+} + Ca)), orthopyroxenes varies from 0.714 to 0.718. Slight compositional zoning from core to rim of orthopyroxene is recorded. X_{Ca} (= Ca\ Ca + Mg + Fe^{2+}) of orthopyroxenes are generally negligible.

Spinel :

Representative microprobe analysis of the spinels from the pelitic granulites are given in Table-IVF. Most of the spinel in pelitic granulite is hercynite variety with FeO-35.9 - 36.5 wt%, Fe2O3 1.9-3.18 wt%, Al2O3- 55.7 -56.6 wt%, MgO- 2.3-2.6 wt%, MnO 0.12-0.17 wt%, SiO2 0-0.094 wt% and ZnO 0.4-0.63 wt%. In the pelitic granulites affected by Erinpura granitic activity FeO ranges from 16.7-18.9 wt%, Fe2O3 4.89-6.95 wt%, Al2O3 60.3-61.7 wt%, MgO 14.8-15.8 wt%, Cr2O3 0.4-0.45% while the Titaniferous magnetite in the same rock contains FeO 42.119-46.29 wt%, Fe2O3 29.39-39.89 wt%, TiO2 13.75-18.62 wt%, Cr2O3 0.10-0.32 wt%.

Ilmenite :

Mineral composition of ilmenite from pelitic granulites is given in Table-IVF. Ilmenite (SH/D) is predominantly $FeTiO_3$ (93.185 mole%) with very limited amount of $MgTiO_3$ (0.059 mole%) and $MnTiO_3$ (0.008 mole%). On stoichiometric consideration ilmenites are free of Fe_2O_3. TiO2- 47.75 wt%, SiO2- 2.2 wt%, FeO- 43 wt% and Al2O3- 4 wt%.

Sapphirine :

Mineral composition of sapphirine is given in Table -IVG. It is rich in Al 4.194 - 4.186, Mg 1.654 - 1.587, Si 0.748 - 0.776, Fe 0.547 - 0.569 mole % from core to rim. This suggests continuous increase in Si, Fe and Ti from core to rim and decrease in Al, Mg, Mn and K in sapphirine. These trends, particularly Si increase from core to rim suggests that it has been formed by reaction between spinel and silica (Keith & Schairer, 1952).

IV.3 Mineral Reactions

Important textural relations of the constituent phases in pelitic granulites include

(i) inclusions of sillimanite, cordierite, biotite, plagioclase, quartz and zircon in garnet;

(ii) inclusion of aluminosilicate and biotite in k-feldspar,

(iii) development of quartz-cordierite symplektite. These inclusion in garnet and k-feldspar, may represent relicts of an earlier stage of mineral formation.

(iv) inclusion of spinel, sapphirine and staurolite within the garnet porphyroblast,

(v) inclusion of staurolite within spinel associated with the development of sapphirine

(vi) inclusion of spinel within orthopyroxene.

(vii) presence of chloritoid within fractures in the garnet

(viii) Low anorthite in plagioclase in contact of garnet in comparison to that in plagioclase porphyroblast away from garnet indicate participation of plagioclase in garnet forming reaction.

(ix) symplectites due to breakdown of osumilite and garnet.

All these observations suggest,

Chloritoid $\longrightarrow$ Fe-cordierite + hercynite + vapour (1)

Chloritoid $\longrightarrow$ almandine + staurolite + hercynite + vapour (2)

Staurolite + almandine $\longrightarrow$ Fe-cordierite + hercynite + vapour (3)

Fe-cordierite $\longrightarrow$ mullite/ sillimanite +liquid (4)

(Halferdahl, L.B., 1961, J. Petrol., v.2, p.49)

Spinel + quartz $\longrightarrow$ sapphirine (5)

Spinel + quartz $\longrightarrow$ orthopyroxene (6)

Biotite + aluminosilicate + quartz + plagioclase $\longrightarrow$ garnet + K-feldspar + vapour/melt (7)

Bands/lenses of quartz and feldspar in pelitic granulites may indeed represent melt fraction as indicated in reaction (7)

Sillimanite needles as well as fibrolitic variety of sillimanite form (S_e) which warps against the garnet porphyroblast and delicate intergrowth of biotite and quartz and myrmekite develops in the rock are possible result of reversal of (7)

Garnet + K-feldspar + V biotite + sillimanite + quartz (8)

Alternatively, reaction (8) could have resulted from melt-solid interaction on cooling (Paterson and Newton, 1989).

Sporadic presence of staurolite in the pelitic granulite other than as an included variety shows that conditions of metamorphism shifted from staurolite-spinel (hercynite) - almandine field to sillimanite - spinel - sapphirine -almandine field.

Simultaneous growth of biotite and cordierite observed in some samples (6D3) may be explained by hydration reactions of the type :

6 Gt + 4 Kfs + 4 H_2O ⟶ 3 Qz + 3 Cord + 4 Bi 9

(in Qz saturated domains)

and

9 Gt + 5Kfs + 3 Sill + 5 H_2O ⟶ 6 Cord + 5 Bi 10

(in Qz poor domains)

Gt-Bio and Gt-Cord thermometry in this sample gives 750°C (c) - 650°C (r) and 840°C (c) - 810°C (r) respectively.

In some of the samples the textural relations involving cordierite suggest that it does not represent a cogenetic prograde mineral with garnet, but rather indicate cordierite production relatively late in the metamorphic history of the rocks. It may coincide with sillimanite-biotite formation from garnet according to reaction ..11

1Gt + 1 Kfs + 1 H_2O ⟶ 1 Sill + 1 Bi + 2 Qz 11

Such cordierite formation may have resulted from decompression. This conclusion is further supported by spinel + cordierite features which are possibly the consequence of the reaction :

5 Qz + 2 Sp ⟶ 1 Cord 12

Spinel inclusions in cordierite have been interpreted as the minerals of the reaction 11. However the spinel inclusions in garnet which frequently occur together with sllimanite probably represent a prograde feature and may be related to breakdown of staurolite, once present, by the reaction (in Qz-deficient rocks) :

10 stau + 3 Gt = 11 Sp + 31 Sill + 5 H_2O 13

Relictic (metastable ?) staurolite is imperceptibly present within spinel. In very magnesian metapelites, quartz + spinel gests converted into sapphirine prior to cordierite formation. The supposed quartz + spinel assemblage may have formed from a prograde reaction :

1 Bi + 3 Sill ⟶ 3 Sp + 1 Kfs + 3 Qz + 1 H_2O 14

TABLE -IV A

Representative Microprobe Analysis of Garnet in Pelitic Granulites.

Sample No.	SH/D	SH/D	SH12	SH12	SH12	SH12
Anal. No.	R	C				
SiO_2	37.261	37.084	37.862	37.799	37.742	38.131
Al_2O_3	19.867	19.588	20.324	19.913	20.292	20.116
FeO	36.709	37.097	34.979	34.252	35.863	35.032
MnO	1.299	1.392	1.256	0.997	1.492	1.198
MgO	3.226	3.304	4.929	4.855	4.547	4.905
CaO	0.890	0.805	0.833	0.928	0.866	0.906
Total	99.252	99.27	100.183	98.744	100.459	100.288

24 Oxygen basis

Si^{IV}	6.075	6.063	6.049	6.108	6.038	6.084
T site	6.075	6.063	6.049	6.108	6.038	6.084
Al^{VI}	3.817	3.775	3.827	3.792	3.826	3.783
O site	3.817	3.775	3.827	3.792	3.826	3.783
Fe^{+2}	5.005	5.072	4.674	4.629	4.798	4.674
Mn^{+2}	0.179	0.193	0.170	0.136	0.156	0.162
Mg	0.784	0.805	1.174	1.170	1.084	1.167
Ca	0.155	0.141	0.143	0.161	0.148	0.155
A site	6.124	6.212	6.160	6.095	6.186	6.158

X_{Al}	0.817	0.817	0.76	0.76	0.76	0.76
X_{Py}	0.128	0.130	0.19	0.19	0.18	0.19
X_{Sp}	0.03	0.03	0.03	0.02	0.03	0.03
X_{Gr}	0.025	0.23	0.02	0.03	0.03	0.02

TABLE -IV A (Contd.)

Representative Microprobe Analysis of Garnet in Pelitic Granulites.

Sample No.	1D3	1D3	SM96/3	SM96/3	SM96/3	SM96/3	SM96/3
Anal. No.	C	R					
SiO_2	37.688	37.814	38.574	38.746	38.456	38.328	37.609
Al_2O_3	20.134	20.327	20.329	20.324	19.854	20.146	19.776
FeO	36.845	37.584	32.181	32.022	32.748	34.707	35.599
MnO	1.593	1.534	1.732	1.550	1.607	1.692	1.870
MgO	3.131	2.059	6.257	5.689	5.494	5.537	5.066
CaO	0.889	1.110	0.836	0.947	1.113	0.968	0.966
Total	100.280	100.428	99.909	99.278	99.272	101.378	100.886

24 Oxygen basis

Si^{IV}	6.081	6.109	6.103	6.158	6.147	6.051	6.013
T site	6.081	6.109	6.103	6.158	6.147	6.051	6.013
Al^{VI}	3.829	3.870	3.791	3.807	3.740	3.748	3.726
O site	3.829	3.870	3.791	3.807	3.740	3.748	3.726
Fe^{+2}	4.971	5.078	4.258	4.256	4.378	4.582	4.760
Mn^{+2}	0.218	0.210	0.232	0.209	0.218	0.226	0.253
Mg	0.753	0.496	1.476	1.348	1.309	1.303	1.207
Ca	0.154	0.192	0.142	0.161	0.191	0.164	0.165
A site	6.096	5.976	6.108	5.974	6.095	6.275	6.386

X_{Al}	0.82	0.82	0.70	0.71	0.72	0.73	0.75
X_{Py}	0.12	0.08	0.24	0.23	0.21	0.21	0.19
X_{Sp}	0.04	0.03	0.04	0.03	0.04	0.04	0.03
X_{Gr}	0.02	0.03	0.02	0.03	0.03	0.02	0.03

TABLE -IV A (Contd.)

Representative Microprobe Analysis of Garnet in Pelitic Granulites.

Sample No.	6D3	6D3	SM97/1	SM97/1
Anal. No.	R	C		
SiO_2	37.527	37.674	40.644	40.436
Al_2O_3	20.233	20.307	21.099	21.215
FeO	37.686	36.480	22.281	22.503
MnO	1.319	1.266	1.234	1.233
MgO	2.824	3.537	13.712	13.855
CaO	0	0.990	1.151	1.154
Total	99.589	100. 254	100.121	100.396
Si^{IV}	6.099	6.062	6. 099	6.060
T site	6.099	6.062	6.099	6.060
Al^{VI}	3.876	3.851	3.731	3.747
O site	3.876	3.851	3.731	3.747
Fe^{+2}	5.122	4.909	2.796	2.821
Mn^{+2}	0.182	0.173	0.157	0.157
Mg	0.684	0.848	3.067	3.096
Ca	0	0.171	0.185	0.185
A site	5.988	6.100	6.205	6.258
X_{Al}	0.86	0.80	0.45	0.45
X_{Py}	0.11	0.14	0.49	0.49
X_{Sp}	0.03	0.03	0.03	0.03
X_{Gr}	-	0.03	0.03	0.03

TABLE-IV B

Representative Microprobe Analysis of Cordierite in Pelitic Granulites

Sample No. / Anal. No.	SH/D	SH/D	SH12	SH12	1D3	1D3	6D3	6D3
SiO_2	49.630	48.868	49.024	49.529	48.795	48.717	43.113	47.962
Al_2O_3	31.458	30.680	31.419	31.101	31.123	30.501	29.857	30.529
FeO	11.498	11.182	11.049	10.847	11.749	11.790	9.558	12.560
MgO	7.267	7.096	7.385	7.651	6.698	7.189	4.083	6.429
MnO	0.211	0.186	0.083	0.169	0.112	0.062	0.120	0.129
CaO	0.002	0.021	0.002	0.009	0.010	0.009	0.518	0
K2O	0.009	0.004	0.008	0	0.008	0.008	0	0.020
Na_2O	0.072	0.232	0.029	0	0.006	0.020	0	0.126
TiO_2	0.025	0.027	0.011	0	0.006	0.020	0	0
Total	100.174	98.296	99.010	99.307	98.661	98.297	87.249	97.754

18 oxygen basis

Si	5.087	5.104	5.072	5.104	5.086	5.097	5.048	5.072
Al^{+3}	3.800	3.776	3.831	3.777	3.823	3.761	4.120	3.805
Fe^{+2}	0.986	0.977	0.956	0.935	1.024	1.032	0.936	1.111
Mg	1.110	1.105	1.139	1.175	1.041	1.121	0.713	1.013
Mn	0.018	0.016	0.007	0.015	0.010	0.005	0.012	0.012
Ca	0	0.002	0	0.001	0.001	0.001	0.065	0
K	0.001	0.001	0.001	0	0.001	0.001	0	0.003
Na	0.014	0.047	0.006	0	0.033	0	0	0.026
Ti^{+4}	0.002	0.002	0.001	0	0	0.002	0	0
X_{Fe}	0.470	0.469	0.456	0.443	0.495	0.479	0.567	0.523
X_{Mg}	0.529	0.530	0.543	0.556	0.504	0.520	0.432	0.476

TABLE -IV C

Representative Microprobe Analysis of Biotite in Pelitic Granulites

Sample No. Anal. No.	SH/D	SH/D	SH/D	SH/D	SH12	SH12	SH12	SH12
SiO_2	35.646	35.337	35.964	36.097	37.653	37.785	38.396	37.999
TiO_2	3.836	3.700	4.145	4.326	6.560	6.564	6.419	6.683
Al_2O_3	16.655	15.452	16.898	16.400	13.415	14.134	14.356	13.738
Cr_2O_3	-	-	-	-	-	-	-	-
FeO	21.764	21.995	21.244	21.739	14.174	13.160	11.752	11.713
MnO	0	0.004	0.061	0.037	0	0.045	0.045	0.050
MgO	9.532	9.028	8.818	9.558	14.920	15.319	17.050	16.327
CaO	0.027	0	0.026	0	0.043	0.027	0.035	0.041
K_2O	9.681	9.932	9.585	9.622	9.654	10.077	9.984	9.945
Na_2O	0	0	0	0.150	0.031	0	0.287	0.015
H_2O	3.913	3.890	3.929	3.916	4.046	4.060	4.089	4.088
Total	101.054	99.338	100.670	101.845	100.496	101.171	102.413	100.599

20 oxygen basis

Si^{IV}	5.404	5.485	5.451	5.423	5.551	5.514	5.493	5.539
Al^{IV}	2.596	2.515	2.549	2.577	2.331	2.431	2.420	2.360
Ti^{IV}	0	0	0	0	0.118	0.056	0.087	0.100
T site	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al^{VI}	0.380	0.311	0.470	0.327	0	0	0	0
Ti^{VI}	0.437	0.432	0.472	0.489	0.610	0.665	0.603	0.632
Fe^{+2}	2.759	2.855	2.693	2.731	1.748	1.606	1.406	1.428
Mn^{+2}	0	0.001	0.008	0.005	0	0.006	0.005	0.006
Mg	2.154	2.089	1.993	2.141	3.279	3.332	3.636	3.548
O site	5.730	5.687	5.636	5.692	5.637	5.609	5.651	5.615
Ca	0.004	0	0.004	0	0.007	0.004	0.005	0.006
Na	0	0	0	0.044	0.009	0	0.080	0.004
K	1.872	1.967	1.853	1.844	1.816	1.876	1.822	1.849
A site	1.877	1.967	1.858	1.888	1.831	1.880	1.907	1.860
OH	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000
X_{Fe}	0.561	0.577	0.574	0.560	0.347	0.325	0.278	0.286

TABLE -IV C (Contd.)

Representative Microprobe Analysis of Biotite in Pelitic Granulites

Sample No.	1D3	1D3	1D3	1D3	SM96/3	SM96/3	SM96/3	SM96/3
Anal. No.	R	C	R	C	R	C		
SiO_2	35.768	35.866	34.896	35.219	31.587	33.259	33.648	38.862
TiO_2	4.485	4.078	4.345	4.310	0.049	0.199	0.104	0.074
Al_2O_3	16.463	16.742	16.214	16.471	20.172	20.069	19.099	20.640
FeO	20.356	20.273	22.461	22.096	20.176	18.711	21.238	20.669
MnO	0.049	0	0.024	0.061	0.094	0.074	0.139	0.061
MgO	9.872	9.608	8.062	7.649	13.812	12.284	11.492	11.335
CaO	0.018	0.051	0.014	0.010	0.534	0.246	0.181	0.186
K_2O	9.896	9.685	9.683	9.752	4.066	5.889	2.120	2.397
Na_2O	0.248	0.116	0	0.101	0.171	0	0.116	0.049
H_2O	3.928	3.940	3.887	3.896	4.033	4.046	4.090	4.109
Total	101.083	100.359	99.856	99.565	94.694	94.777	92.227	93.382

Number of ions on the basis of 20 oxygen

Si^{IV}	5.399	5.439	5.406	5.445	4.971	5.214	5.369	5.308
Al^{IV}	2.601	2.561	2.594	2.555	3.029	2.786	2.631	2.692
Ti^{IV}	0	0	0	0	0	0	0	0
T site	8.000	8.000	8.000	8.000	8.000	8.000	8 .000	8.000
Al^{VI}	0.328	0.431	0.367	0.446	0.713	0.922	0.960	1.122
Ti^{VI}	0.509	0.465	0.506	0.501	0.006	0.023	0.012	0.009
Fe^{+2}	2.570	2.571	2 .910	2.857	2.656	2.453	2.834	2.710
Mn^{+2}	0.006	0	0.003	0.008	0.013	0.010	0.019	0.008
Mg	2.222	2.172	1.862	1.763	3.241	2.871	2.733	2.649
O site	5.635	5.638	5.648	5.575	6.628	6.279	6.559	6.498
Ca	0 .003	0.008	0.002	0.002	0.090	0.041	0.031	0.031
Na	0.073	0.034	0	0.030	0.052	0	0.036	0.015
K	1.906	1.874	1.914	1.923	0.816	1.178	0.432	0.479
A site	1.981	1.916	1.916	1.955	0.959	1.219	0.498	0.526
OH	4.000	4.000	4 .000	4.000	4.000	4.000	4.000	4.000

X_{Fe}	0.536	0.542	0.609	0.618	0.450	0.461	0.509	0.505

TABLE -IV C (Contd.)

Representative Microprobe Analysis of Biotite in Pelitic Granulites

Sample No.	6D3	6D3	SM97/1	SM97/1
Anal. No.				
SiO_2	35.402	35.846	38.413	38.859
TiO_2	4.136	4.255	0	4.314
Al_2O_3	16.755	17.296	15.726	15.316
FeO	21.895	21.458	9.371	9.079
MnO	0.053	0.016	0.071	0.033
MgO	8.045	8.310	19.589	20.400
CaO	0.015	0	0	0
K_2O	9.652	9.894	9.789	9.831
Na_2O	0	0.218	0	0.072
H_2O	3.908	3.913	4.158	4.154
Total	99.861	100.846	97.117	102.058

20 oxygen basis

Si^{IV}	5.440	5.391	5.711	5.492
Al^{IV}	2.560	2.609	2.289	2.508
Ti^{IV}	0	0	0	0
T site	8.000	8.000	8.000	8.000
Al^{VI}	0.475	0.488	0.467	0.044
Ti^{VI}	0.478	0.486	0	0.459
Fe^{+2}	2.814	2.726	1.165	1.073
Mn^{+2}	0.007	0.002	0.009	0.004
Mg	1.843	1.882	4.342	4.298
O site	5.616	5.584	5.983	5.877
Ca	0.002	0	0	0
Na	0	0.064	0	0.020
K	1.892	1.917	1.857	1.773
A site	1.895	1.982	1.857	1.792
OH	4.000	4.000	4.000	4.000

X_{Fe}	0.604	0.519	0.211	0.199

TABLE -IV D

Representative microprobe analysis of Feldspar from Pelitic-Granulites.

Sample No.	6D3	6D3	SM96/3	SM96/3	SM96/3	SM96/3
Anal. No.	C	R				
SiO_2	64.923	64.591	62.452	61.421	65.153	65.537
Al_2O_3	17.452	17.114	23.047	22.599	16.979	17.471
FeO	0	0	0	0	0	0
MgO	0	0	0	0	0	0
MnO	0	0	0	0	0	0
CaO	0.016	0.006	5.441	5.481	0.072	0.081
K_2O	15.417	15.305	0.159	0.181	15.599	14.775
Na_2O	1.150	0.974	9.743	9.938	1.134	1.727
TiO_2	0	0	0	0	0	0
Total	98.958	98.99	99.842	99.62	98.937	99.591

Oxygen basis

Si	3.026	3.037	2.760	2.754	3.040	3.028
Al	0 959	0.948	1.200	1.194	0.934	0.951
Fe^{+2}	0	0	0	0	0	0
Mg	0	0	0	0	0	0
Mn	0	0	0	0	0	0
Ca	0 001	0	0.258	0.263	0.004	0.004
K	0.917	0.918	0.009	0.010	0.929	0.871
Na	0.104	0.089	0.835	0.864	0.103	0.155
Ti	0	0	0	0	0	0
Total	5.005	4.992	5.062	5.086	5.009	5.009

X_{An}	0.10	0	23.4	23.13	0.3	0.4
X_{Ab}	10.2	8.8	75.7	76.0	10.0	15.0
X_{Or}	89.7	91.2	0.88	0.88	89.6	84.6

TABLE - IV E

Representative Microprobe Analysis of Pyroxenes from Pelitic Granulites

Sample No.	SM97/1	SM97/1
Anal.No.		
SiO_2	47.857	47.560
TiO_2	0.065	0.136
Al_2O_3	8.227	8.646
Cr_2O_3	0	0
Fe_2O_3	8.146	8.544
FeO	10.928	10.444
MnO	0.363	0.256
MgO	25.696	25.932
CaO	0.053	0.049
Na_2O	0.015	0
K_2O	0.015	0
Total	101.414	101.567

Number of ions on the basis of 6 oxygens

Si	1.715	1.699
Al^{IV}	0.285	0.301
T site	2.000	2.000
Al^{VI}	0.064	0.064
Ti	0.002	0.004
Cr	0	0
Fe^{+3}	0.220	0.230
Fe^{+2}	0.327	0.312
Mn^{+2}	0.011	0.008
Mg	1.372	1.381
Ca	0.002	0.002
Na	0.001	0
K	0.001	0
M1,M2	2.000	2.000

X_{Fe}	0.285	0.282
X_{Mg}	0.715	0.718
X_{En}	0.714	0.717
X_{Fs}	0.285	0.282
X_{Wo}	0.001	0.001

TABLE- IV F

Representative Microprobe Analysis of Spinels and ilmenite from the Pelitic Granulites

Sample No. Anal. No.	SH/D	SH/D	1D3	1D3	SM97/1	SM97/1	SM97/1	SM97/1	SM97/1
SiO_2	0	2.237	0.094	0	0	0	0.033	0	0
TiO_2	0.168	47.756	0.061	0.039	0.011	0	0	13.750	18.623
Al_2O	56.6	104.029	55.719	56.622	60.328	60.726	61.747	0	0.132
Cr_2O_3	0.275	0	0.171	0.104	0.405	0.458	0.323	0.099	0 102
Fe_2O_3	1 944	0	3.183	2.514	6.310	6.952	4.899	39.890	29.397
FeO	35.928	43.170	36.320	36.472	16.733	18.072	18.975	42.119	46.299
MnO	0.129	0.374	0.179	0.166	0.178	0.145	0.070	0.092	0
MgO	2.630	1.553	2.349	2.214	15.851	15.660	14.865	0.284	0.314
CaO	0	0	0	0	0	0	0	0	0
NiO	0	0	0	0	0	0	0	0	0
ZnO	0.509	0	0.477	0.637	0.442	0	0.454	0.004	0
Total	98.193	99.119	98.553	98.768	100.258	102.012	101.366	96.238	94.867

Number of ions on the basis of 4 oxygen

Si	0	0.082	0.003	0	0	0	0.001	0	0
Ti	0.004	1.320	0.001	0.001	0	0	0	0.407	0.556
Al	1.944	0.175	1.918	1.941	1.867	1.855	1.896	0	0.006
Cr	0.006	0	0.004	0.002	0.008	0.009	0.007	0.003	0.003
Fe^{+3}	0.043	0	0.070	0.055	0.125	0.136	0.096	1.182	0.878
Fe^{+2}	0.875	1.327	0.887	0.887	0.367	0.392	0.413	1.387	1.538
Mn	0.003	0.012	0.004	0.004	0.004	0.003	0.002	0.003	0
Mg	0.114	0.085	0.102	0.096	0.620	0.605	0.577	0.017	0.019
Ca	0	0	0	0	0	0	0	0	0
Ni	0	0	0	0	0	0	0	0	0
Zn	0.011	0	0.010	0.014	0.009	0	0.009	0	0
total	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000

1 Hercynite (SH/D)
2 Ilmenite (SH/D)
3 & 4 Hercynite (1D3)
5 - 7 Greenish black spinel (SM97/1)
8 & 9 Titaniferous magnetite (SM97/1)

TABLE-IV G

Representative Microprobe Analysis of Sapphirine in Pelitic Granulites (Mg-rich)

Sample No.	SM97/1	SM97/1
Anal. No.		
SiO_2	12.603	12.066
Al_2O_3	57.697	57.360
FeO	11.062	10.557
MgO	17.301	17.894
MnO	0.132	0.157
CaO	0.015	0
K_2O	0.004	0.010
Na_2O	0	0
TiO_2	0.045	0.022
Total	98.859	98.066

10 oxygen basis

Si	0.762	0.732
Al^{+3}	4.110	4.103
Fe^{+2}	0.559	0.536
Mg	1.559	1.619
Mn	0.007	0.008
Ca	0.001	0
K	0	0.001
Na	0	0
Ti^{+4}	0.002	0.001