CHAPTER - V

CALC GRANULITES

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Calc-silicate granulites occur as a large distorted S-shaped lensoidal band flanked by pelitic granulites on northern side of the charnockitic rocks (Fig.2.1, Chapter-II). These comprise two main varieties, both occurring in close association. One is greenish variety and the other is coarse grained greyish variety. In the outcrops and hand specimen alternate greenish grey and whitish bands with smoky patches are visible. The lighter (whitish) bands are mostly calcite, plagioclase while the smoky white patches are of scapolite. Sometimes sphene is seen as honey yellow minute elongated grains. Garnet is noticed in the calc-granulites associated with pelitic granulites in the western part particularly Divani Hills. These garnets are seen as small circular spots (1-3 mm diameter) pinkish or dull brown in colour. Pock marks after the removal of garnets are sometimes visible on highly weathered surface in appropriate sections. Garnet is rarely observed in calc-granulites in the eastern part of the study area. The darker greenish grey bands are of diopside. In the eastern part (Dhanpura, Ghoda area) the dark grey calc-granulite bands are studded with fine minute white needles of tremolite **(Plate-V.1A)**. Such calc-granulite areas are devoid of calcite. Calc-granulite bands, marked by rib and furrow structures on the weathered surface, are conformable to the regional gneissic foliation. Often the calc-granulite bands are seen to show lot of contortions, ptygmatic folds and irregular folds, which are not congruent to / conformable with the regional style of deformation or the style of folding in the associated pelitic granulites. As such the author considers these folds in calc-granulites to be the result of differential expansion of the various calc-silicate minerals during metamorphism.

V.1 Petrography

On the basis of mineral assemblage, calc granulites can be classified into two types, occurring in closely spaced domains. One is fine grained dark greenish variety while the other is a coarse grained greyish white variety. Under the microscope, both the varieties are composed of granoblastic aggregates **(Plate-V.1B)** of clinopyroxene (diopside-hedenbergite) + scapolite (meionite) + tremolite + plagioclase + garnet + wollastonite + Sphene (titanite) + apatite + calcite and quartz. The greenish variety predominates in diopside while the greyish variety contains more scapolite as seen in the table (after Desai et al, 1978) below :

Plate-V.1A Dark grey calc-granulite bands are studded with fine minute white needles of tremolite

Plate-V.1B Granoblastic texture of calc granulites (XPL, 40X)

	Greenish Variety		Grey variety	
Diopside	40.70	86.60	39.26	53.20
Plagioclase	54.28	-	29.10	03.90
Scapolite	-	07.02	-	22.50
Hypersthene	-	-	-	22.50
Sphene	-	-	01.24	-
Calcite	-	06.37	07.30	00.80
Quartz	-	-	23.10	-
Opaques	02.03	-	-	-
Total	100.03	99.99	100.00	99.8

Clinopyroxene :

Clinopyroxene occurs in both the assemblages. It is green, non-pleochroic and shows inclined extinction (Z∧C, 35° to 37°). Some of the dark green coloured grains show extinction upto 43°. It is biaxial negative. The grains are subhedral and form porphyroblasts with well developed prismatic cleavage. It is patchily altered to uralite and calcite. Clinopyroxene porphyroblasts form equilibrated grain boundary with titanite. Often clinopyroxene contains inclusions of calcite and plagioclase **(Plate-V.2A)**. Coronal garnet develops around clinopyroxene and separates it from plagioclase and scapolite **(Plate-V.3A, B)**. Coalescence of such coronal garnets give the appearance of porphyroblastic garnet. Granules of iron-ore sometimes develop in the alteration. The clinopyroxene is diopside.

Scapolite :

Scapolite is colourless and occurs in idiomorphic grains with some tendency to rounded grains. Cleavage is not well developed except in basal sections where two cleavages intersecting almost at 90° can be seen. The birefringence is moderate, being generally in the second order. It is uniaxial negative. It is meionite ($\omega = 1.585$). The scapolite crystals have inclusions of apatite, zircon, and needle like bodies of brown rutile oriented parallel to the optic axes of the mineral. Scapolite grains show triple point junction and mutual boundary with smaller plagioclase grains.

In addition to the homogeneous scapolite crystals, grains with a symplectitic structure resembling myrmekite are comparatively common. This structure is mainly represented by a worm like intergrowth of quartz and scapolite **(Plate-V.4A & B)**. Further, intergrowths of scapolite with plagioclase and calcite are found, or of plagioclase and calcite only. Homogeneous meionite crystals may either form the core of the symplectite grains or adjoin them or they may occur separated from such grains.

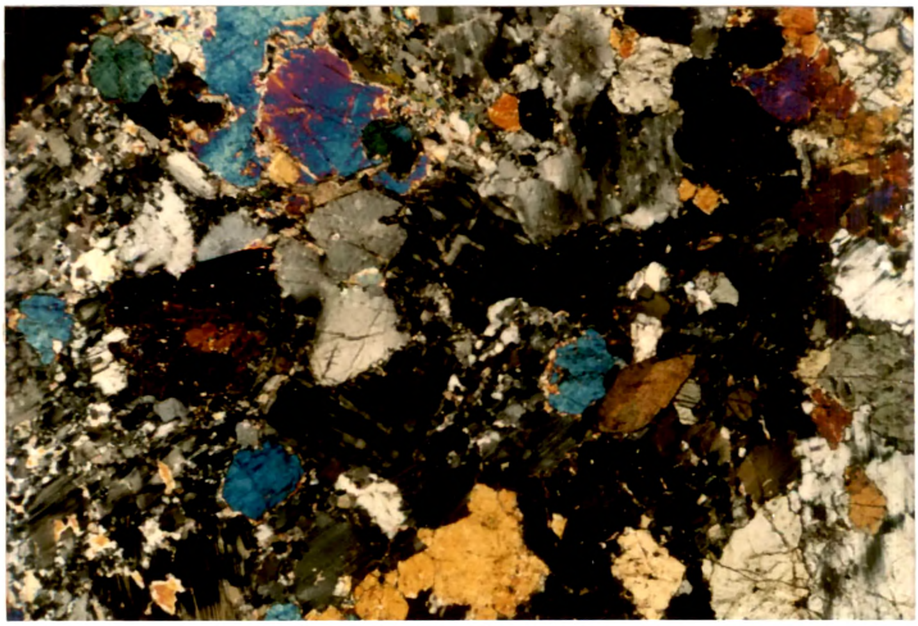


Plate-V.2A Clinopyroxene with inclusions of calcite and plagioclase (PXPL, 40X)

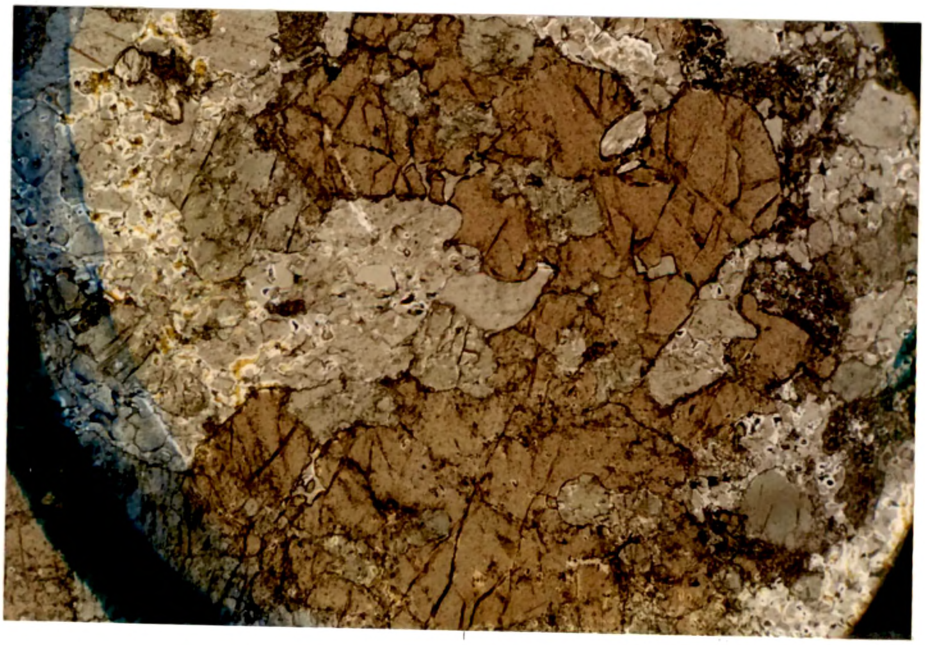


Plate-V.3A Coronal garnet develops around clinopyroxene and separates it from plagioclase and scapolite. (PPL, 40X)

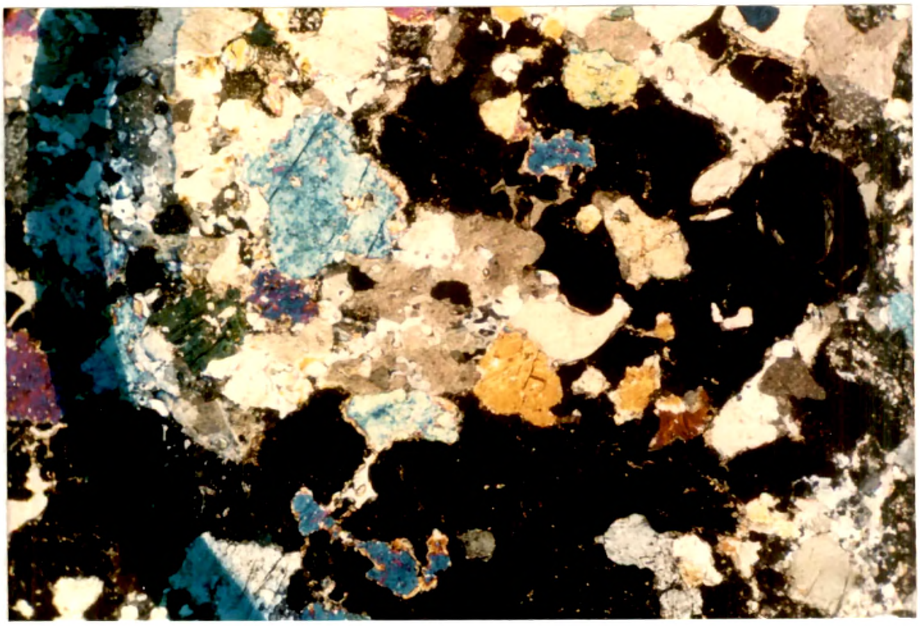


Plate-V.3B Coronal garnet develops around clinopyroxene and separates it from plagioclase and scapolite. (XPL, 40X)

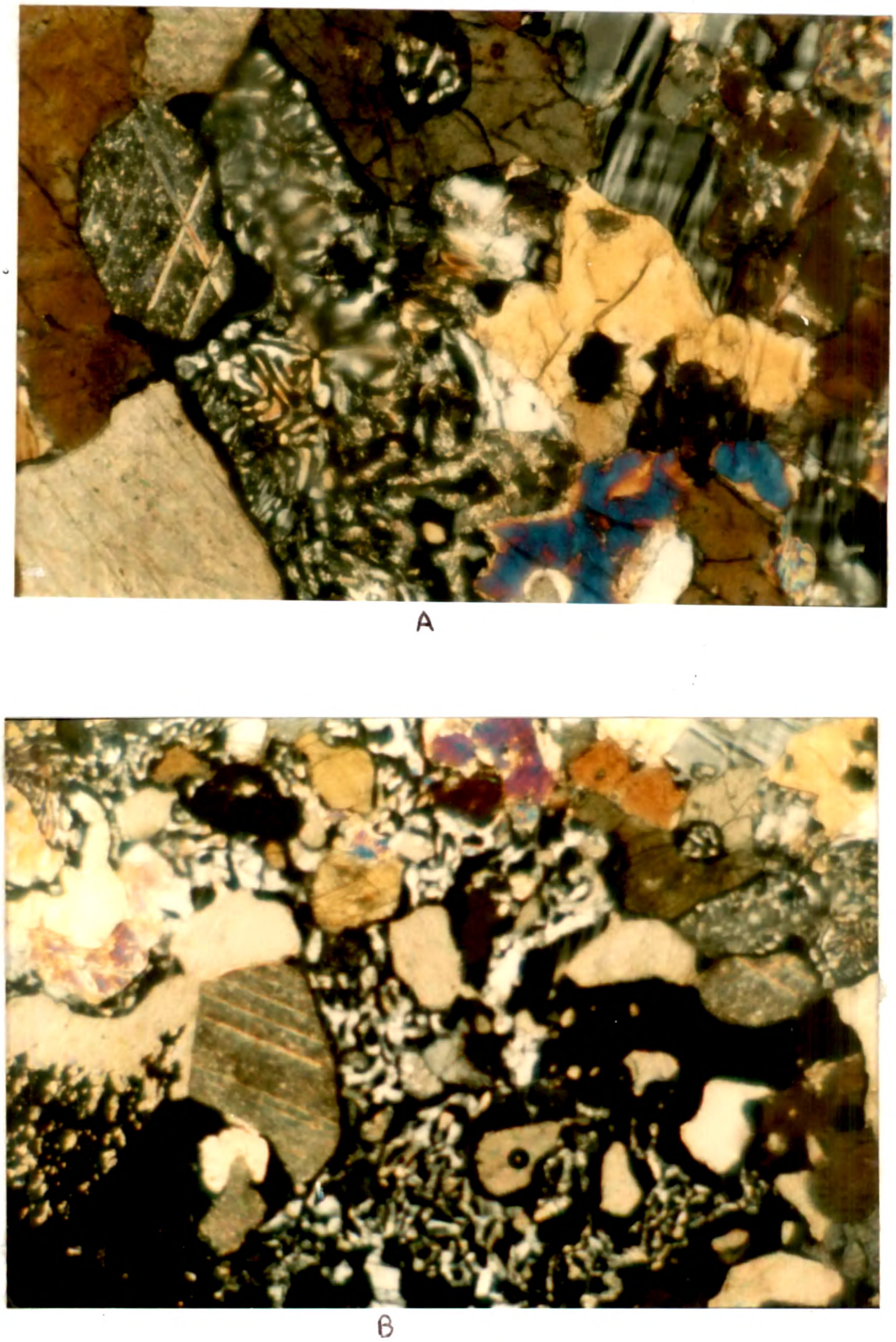


Plate-V.4A & B Symplectitic structure resembling myrmekite structure represented by a worm like intergrowth of quartz and scapolite. (XPL, 40X).

The scapolite worms and the homogeneous part of the crystal extinguish simultaneously. The quartz worms, on the other hand, have a tendency to cross the boundary of the symplectite and to expand into small separate quartz grains outside the intergrown crystal. These quartz grains extinguish simultaneously with a part of the symplectitic quartz worms only. Thus the quartz component does not always belong to a single crystal. On the other hand, however, the presence of quartz immediately outside the intergrown crystal does not seem to be necessary condition for the formation of symplectite. Aggregate of scapolite grains embay porphyroblastic plagioclase **(Plate-V.5A)**. Scapolite is always seen to develop at the cost of plagioclase as is evident from tongues of scapolite protruding into plagioclase from grain boundaries **(Plate- V.5A)**. Small calcite grains are included in scapolite. Calcite veinlets are found to replace scapolite along the grain boundaries. Sphene (titanite) shows mutual boundary relation with scapolite. Garnet develops around scapolite separating it from calcite, quartz and clinopyroxene.

Garnet :

Garnet, is pale honey or mauvish in colour, in calc granulites as a coronal phase, appears around clinopyroxene, scapolite, calcite, quartz and plagioclase separating one of the above mentioned phase from others. Quartz is present in both the assemblages and never shows mutual contact with scapolite in garnet present locales. With increase in the Ca content, the colour becomes darker brownish.

Coalescence of coronary garnets finally looks like porphyroblast with inclusions of clinopyroxene, scapolite etc. **(Plate-V.6A, B)**.

In one sample from the eastern part,wollastonite and grossularite occur together. Garnet occurs as anhedral grain replacing diopside. Together with wollastonite, grossularite, corresponds to the very last and wholly exceptional phase of metamorphism.

Calcite :

It occurs in several modes, either as included phase within clinopyroxene or as small grains in all the assemblages. They are surrounded by small scapolite grains but occurs as small veinlets and grows over scapolite.

Plagioclase :

It shows high refractive index, first order grey interference colour, lamellar twinning and is biaxial negative. Plagioclase occurs in two modes (1) It occurs as small included grains within clinopyroxene **(Plate-V.2A)**. (2) Porphyroblasts of plagioclase are the most common variety. Aggregate of scapolite grains embay plagioclase **(Plate-V.5A)**.

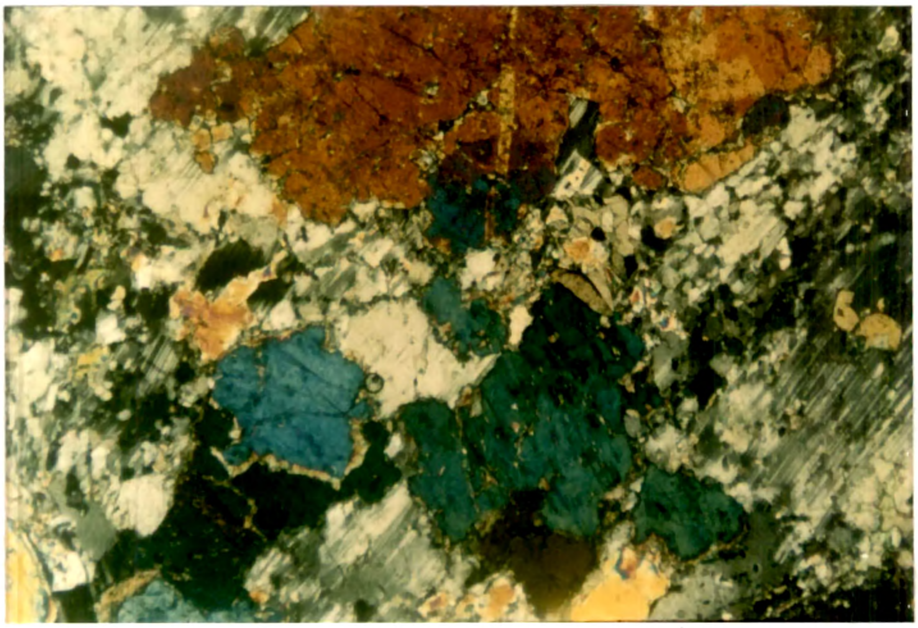


Plate-V.5A Aggregate of scapolite grains embay porphyroblastic plagioclase (XPL, 40X).

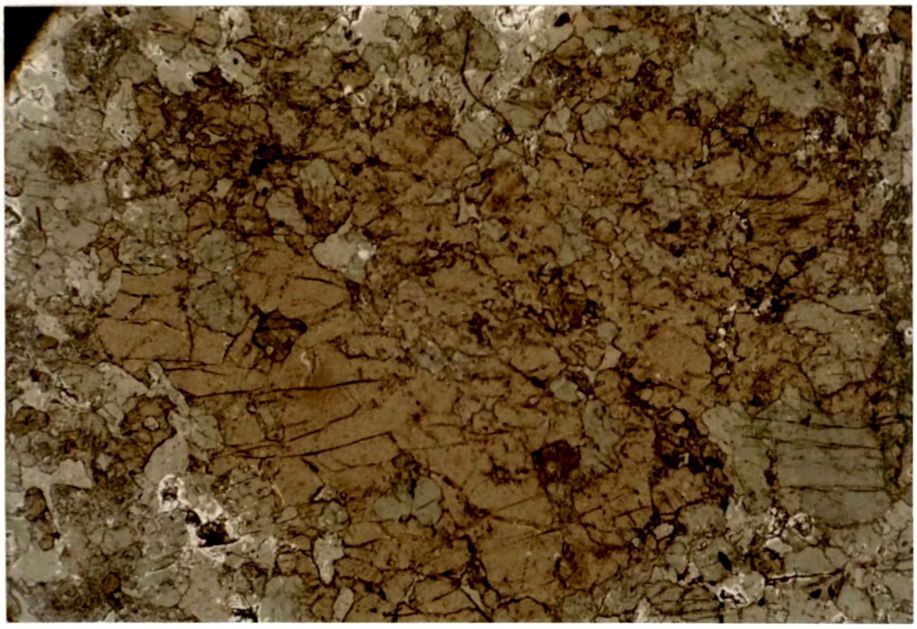


Plate-V.6A Coalescence of coronary garnets finally looks like porphyroblast with inclusions of clinopyroxene, scapolite etc. (PPL, 40X),

Plate-V.6B in XPL.

K-feldspar :

Small patches of K-feldspar are more common in garnet bearing calcgranulite as interstitial minute patches. Vague cross hatched twinning and grey interference colours are characteristic.

Quartz :

Subhedral to anhedral quartz grains of different sizes are present. It does not have common boundary with either scapolite in garnet - present locales. Some quartz show shadowy extinction and contains minute dusty inclusions, perhaps of rutile.

Titanite :

Titanite is a common mineral in both the assemblages. It occurs as an included phase within clinopyroxene as well as plagioclase porphyroblasts. Often it occurs within scapolite and plagioclase as honey yellow - brownish elongated grains - often approaching diamond shape in thin sections and pleochroic.

Tremolite :

Fine acicular tremolite is seen within garnet free dark greenish grey calc granulite in the eastern part near Dhanpura area in essentially diopside rich variety.

Hypersthene

It is distinctly pleochroic in shades of X = pink, Y = bright yellow and Z = bluish green indicating an aluminous hypersthene.

Wollastonite :

Fine acicular / laths of wollastonite are seen in calc granulites. These are radiating in habit and are colourless to pale greenish grey. In hand specimen, it has silky lustre. In thin section it is seen to occur as granoblastic aggregates, together with green diopside and large sphene crystals.

Opaques :

These are mostly magnetite. Large grains of sulphide possibly pyrrhotite are the main accessories and are most often associated with the pyroxene.

V.2 Mineral Chemistry

Chemical composition of the minerals were determined by a Jeol Microbeam EPMA operated at 15 KV accelerating voltage and 2 um beam diameter. Natural mineral standards were used and some representative PAP corrected analysed are given in Tables-V A to V F.

Clinopyroxene :

Representative clinopyroxene analyses are presented in Table-V A. Clinopyroxene in both the assemblages are solid solution of diopside - hedenbergite and fall in the salite field (Deer et al, 1974). Clinopyroxene is of the composition $X_{Ca} = Ca / (Ca + Fe^{2+} + Mg) = 0.575\text{-}0.577$ in garnet free calc-granulite and 0.513-0.520 in garnet bearing calc-granulite; $X_{Mg} = Mg/(Fe^{2+}+Mg) = 0.652$ to 0.677 in garnet free and 0.719 to 0.736 in garnet bearing calc-granulite. A coreward decrease in X_{Mg} is observed in this clinopyroxene. Al is both tetrahedrally and octahedrally coordinated with Al^{iv} varying between 0.304 - 0.31 per formula unit (p.f.u.) and 0.033 -0.039 p.f.u. in garnet free and and garnet bearing assemblages while Al^{vi} varies from 0.05 - 0.31 p.f.u. in garnet free assemblage. Al^{vi} is absent in garnet bearing calc-granulites.

Plagioclase :

Representative chemical analyses of plagioclase are given in Table-VB. The X_{An} (=0.95) content in plagioclase core shows a rimward increase to 0.97 There is proportionate decrease in X_{Ab} from 0.042 to 0.023. X_{Or} is 0.002 in the core and is absent towards the rim.

Scapolite :

Representative analyses of scapolite are given in Table-VC. Total oxide weight percent ranges from 90.865 to 92.542 suggesting that total $(CO_3^{-2} + Cl^{-1} + S)$ to be around 7.458 to 9.13 %. Meionite (Eq_{An}) percentage in scapolite is calculated as 100(Al -3)/3 on 25 oxygen basis. Following the calculation scheme, Eq_{An} component in scapolite varies between 56.76 to 63.93 (Core and rim compositions).

Titanite :

Analysis of sphene (titanite) is given in Table-VD. Ti is partly replaced by Al and Fe^{3+} in octahedral site.

Garnet :

Representative analyses of garnet are given in Table-V E. Garnets in both the varieties are solid solutions of andradite and almandine. Total percentage of pyrope, and spessartine components in these garnets varies between 1 mole% to 2 mole% . Grossular and almandine mole% of these garnets ranges between 72 to 73 and 26 mole % respectively. Grossular component in garnet is very insignificant ranging between 0.07-0.19 mole % while compositionally it is andradite.

X_{Gr} (the grossular i.e. Ca component) in garnet is seen to decrease from rim towards core while pyrope and spessartine components are seen to increase towards core.

Wollastonite :

Microprobe analysis of wollastonite is given in Table-VF. It contains slight Fe (0.45% and Al 0.11).

V.3 Mineral Reactions

Textural relationships of the phases in both the associations suggest early stabilization of the assemblage clinopyroxene- plagioclase - calcite - quartz - scapolite -titanite.

Textural features such as aggregate of scapolite grains embaying large porphyroblast of plagioclase and calcite and scapolite replacing plagioclase along the grain boundary suggest the formation of scapolite by the following reaction

Plagioclase + Calcite ——> scapolite (i)

(Anorthite) (meionite)

$3CaAl_2Si_2O_8 + CaCO_3 \longrightarrow Ca_4Al_6Si_6O_{24}CO_3$

The other textural relationship indicate the reaction :

Calcite + anorthite + quartz ——> grossular + CO_2 (ii)

Slight compositional variation within garnet suggests participation of clinopyroxene (hedenbergite component) in reactions (ii) and (iii)

Hedenbergite + calcite + anorthite + quartz ——> $garnet_{ss} + CO_2$ (iii)

Formation of coronal garnet over scapolite, calcite, anorthite and clinopyroxene as well as the variation in composition of the garnets from rim to core suggests the reaction :

Hedenbergite + calcite + scapolite + quartz ——> $garnet_{ss} + CO_2$ (iv)

and

Anorthite + calcite + quartz + hedenbergite ——> $garnet_{ss} + CO_2$ (v)

V.4 Discussion

Petrographic studies reveal that an early assemblage of clinopyroxene - quartz - calcite - titanite - plagioclase was stabilized in these calc granulites. Scapolite appeared later at the expense of plagioclase. Subsequent mineral reactions stabilized coronal garnet.

According to Desai et al.(1978) meionite originated exclusively from the primary bulk of the rocks. The mineral assemblage quartz - calcite - meionite - diopside indicates calc-magnesian sediments as their precursors and represents conditions corresponding to pyroxene granulite sub-facies.

The probable mineral reactions are :

1) Anorthite + calcite = scapolite [quartz, grossular, vapour]
2) Anorthite + calcite + quartz = grossular + vapour [scapolite]
3) Scapolite + quartz + calcite = grossular + vapour [anorthite]
4) Scapolite + quartz = grossular + anorthite + vapour [Calcite]

Formation of scapolite from calcite and plagioclase denotes increase in temperature and this reaction, occurred during the prograde metamorphism. Both the deduced garnet - forming reactions can occur in response to either increase in T or increase in X_{H2O} or both

The origin of scapolite from plagioclase as suggested by the textural relationships between the two could be due to the metasomatic processes involving such fugitive constituents as CO2, Cl. SO3 etc. released during the regional metamorphism. According to Deer et al, (1967), the primary scapolite develops at the expense of plagioclase in those rocks in which the ratio Ca: (Ca+Al+Na+K) is 0.39 (as in the present case). Thus, in addition to the temperature required for the diopside formation, development of scapolite was not only dependent on the presence of high P_{CO2}, but also on the deficiency of (Al+Na+K) with respect to Ca. Under such conditions Ca-rich scapolite and not plagioclase is the stable aluminosilicate. The fugitives necessary for scapolitisation of plagioclase might have been liberated from "within" during metamorphism itself, the CO2 having been freed during reactions between carbonate rocks while SO3 and Cl were possibly contributed by the granitic melt formed from the metamorphism of pelitic rocks.

Formation of coronal garnet in rocks of diverse bulk composition is not energetically plausible during prograde metamorphism, which would normally lead to porphyroblastic garnets. Thus, while scapolite appeared during prograde metamorphism and formed porphyroblastic phases, coronal garnet formed at the expense of scapolite, plagioclase and calcite during retrogression either due to falling P or increase in X_{H2O}.

It may be noted that the hedenbergite-involving reactions produce garnets with grossular : almandine ratio 5:1. The studied garnet compositions are not that almandine-rich. Therefore, it is envisaged that these reactions were accompanied partially by the solid-solid reaction,

Hedenbergite + anorthite = grossular + almandine + quartz. (vi)

Scapolite bearing mineral assemblage similar to study area was also reported by Harley and Buick (1992) from the Rauer Group in East Antarctica. They noted that the reactions

Calcite + anorthite + quartz = grossular + CO_2

and

Scapolite + calcite + quartz = grossular + CO_2

occur in wollastonite-absent domains. Similar reactions were also inferred by Schenk (1984) and Frisch (1988). Harley and Buick (1992), Harley et al (1994) and Fitzsimons and Harley (1994) critically evaluated the role of clinopyroxene in the formation of grandite-almandine garnets in calc silicate rocks. The reactions

Scapolite + hedenbergite + calcite + quartz = garnet + CO_2

and

Scapolite + calcite + hedenbergite = garnet + CO_2

both produce grossular-rich garnet (84-89 mole%) according to the stoichiometry of the reactions (Harley and Buick, 1992).

Hence, to produce more almandine-rich garnet the operation of another reaction viz.

Hedenbergite + plagioclase = grossular + almandine + quartz

is necessary. As the garnet in the present study is having 26 mole % almandine, this reaction also must have taken place concomitantly.

Andradite is suggested to have been derived from originally impure calcareous sediments by the following reaction :

$3CaCO3 + Fe2O3 + SiO2 \longrightarrow Ca3Fe2Si3O12 + 3CO2$ ....

Introduction of FeO leads to formation of hedenbergite and insufficient silica leads to development of magnetite (spinel) :

$4CaCO3 + 2Fe2O3 + 2FeO + 5SiO2 \longrightarrow Ca3Fe2Si3O12 + CaFeSi2O6 + Fe3O4 + 4CO2$ ......

Artificial synthesis of andradite from its powdered component oxides requires 20 kilobar pressure and 900°C.

Coexisting calcite (white recrystallised marble) along with wollastonite suggests that the parent sediments had insufficient quartz for transformation of all CaCO3 to wollastonite by the following reaction :

$CaCO_3 + SiO_2 \longleftrightarrow CaSiO_3 + CO_2$

(Harker, R.I. & Tuttle, O.F., 1956) for **Fig. 5.1** PCO2-T curve for this reaction.

Early work by Bowen et al (1933) on the system CaO-FeO-SiO2 showed that hedenbergite is not stable at liquidus temperature but undergoes an inversion at 965°C to an iron-rich wollastonite solid solution (as is seen in the composition of wollastonite from the study area). Investigation of the CaMgSi2O6-CaFeSi2O6 system after Turnoc, A.C., 1962 **(Fig. 5.2)** has shown that it has a binary character only for compositions having between 0 and approximately 60 mol.% of the hedenbergite component. In the iron-rich part of the system a wollastonite solid solution crystallizes at liquidus temperatures and subsequently inverts to an iron-rich member of the diopside-hedenbergite series at subsolidus temperatures.

Development of wollastonite may have depleted all silica which facilitated spinel formation along with hedenbergite.

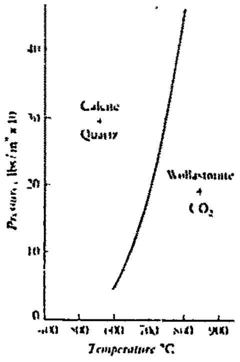
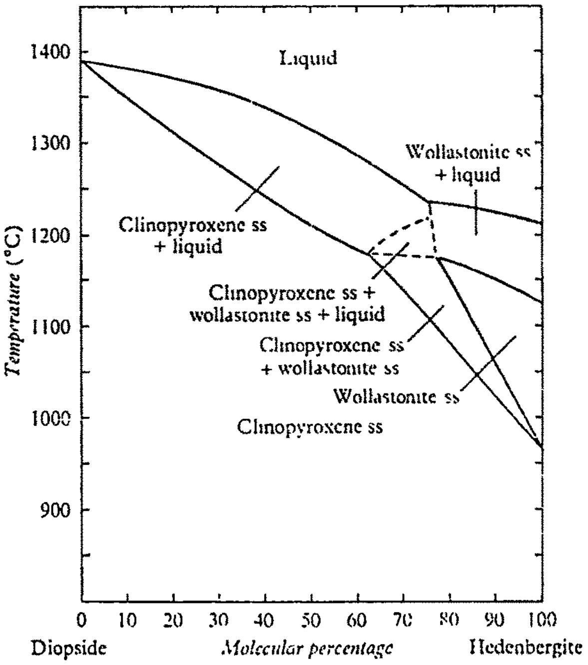


Fig. 5.1A PCO_2-T Curve for Wollastonite (Harker & Tuttle, 1966)



Phase diagram of the join diopside-hedenbergite

Fig. 5.1B $CaMgSi_2O_6$-$CaFeSi_2O^6$ System (Turnock, 1962)

TABLE -V B

Representative microprobe analysis of Feldspar im Calc - Granulites.

Sample No.	2D3	2D3
Anal. No.	C	R
SiO_2	43.638	43.427
Al_2O_3	33.053	33.313
FeO	0	0
MgO	0	0
MnO	0	0
CaO	21.884	21.616
K_2O	0.026	0.005
Na_2O	0.531	0.286
TiO_2	0	0
Total	99.133	98.647

4 Oxygen basis

Si	2.057	2.053
Al^{VI}	1.837	1.856
Fe^{+2}	0	0
Mg	0	0
Mn	0	0
Ca	1.105	1.095
K	0.002	0
Na	0.049	0.026
Ti	0	0
Total	5.049	5.032

X_{An}	95.6	97.7
X_{Ab}	4.2	2.3
X_{Or}	0.20	nil

Table - V C

Representative Microprobe Analysis of Scapolite from Calc Granulites

Sample No.	2D3	2D3
Anal.No.		
SiO_2	45.041	43.208
Al_2O_3	25.236	25.896
FeO	0.059	0.073
MgO	0.007	0
MnO	0.029	0
CaO	18.410	18.727
K_2O	0.128	0.151
Na_2O	3.632	2.810
TiO_2	0	0
Total	92.543	90.864

Number of ions on the basis of

[illegible] 25 oxygens

Si	7.692	7.520	7.122	6.963
Al	5.079	5.312	4.703	4.918
Fe^{+2}	0.008	0.011	0.008	0.010
Mg	0.002	0	0.002	-
Mn	0.004	0	0.004	-
Ca	3.368	3.492	3.119	3.233
K	0.028	0.034	0.026	0.031
Na	1.203	0.948	1.113	0.878
Ti	0	0	-	-

Cation/(24 oxygen)

Si	6.8367	6.6839
Al	4.5151	4.7216
Fe	0.0075	0.0094
Mg	0.0015	-
Mn	0.0038	-
Ca	2.9943	3.1040
K	0.0247	0.0299
Na	1.0619	0.8428
Ti	-	-

Table - V D

Representative Microprobe Analysis of Sphene (Titanite) in Calc-Granulites.

Sample No.	2D3	2D3
Anal.No.		
SiO_2	29.216	29.614
Al_2O_3	1.575	1.644
FeO	1.050	1.004
MgO	0.138	0
MnO	0	0.038
CaO	27.429	26.797
K_2O	0.007	0
Na_2O	0	0
TiO_2	38.795	38.629
Total	98.209	97.726

Oxygen basis

Si	0.974	0.988
Al	0.062	0.065
Fe^{+2}	0.029	0.028
Mg	0.007	0
Mn	0	0.001
Ca	0.979	0.958
K	0	0
Na	0	0
Ti	0.972	0.958
Total	3.023	3.010

Cation/(20.0 Oxygen)

Si	3.8942	3.9532
Al	0.2474	0.2587
Fe	0.1171	0.1121
Mg	0.0274	-
Mn	-	0.0043
Ca	3.9175	3.8329
K	0.0012	-
Na	-	-
Ti	3.8890	3.8781

TABLE -VE

Representative microprobe analysis of Garnet in Calc-Granulites.

Sample No.	2D3	2D3
Anal.No.	C	R
SiO_2	38.492	36.924
Al_2O_3	10.064	10.289
FeO	15.587	15.711
MnO	0.157	0.087
MgO	0.439	0.316
CaO	33.250	34.437
Total	97.989	97.764

24 Oxygen basis

Si^{IV}	6.405	6.214
T site	6.405	6.214
Al^{VI}	1.974	2.041
O site	1.974	2.041
Fe^{+2}	2.169	2.211
Mn^{+2}	0.022	0.012
Mg	0.109	0.079
Ca	5.928	6.209
A site	8.228	8.512
Total	16.507	16.766

X_{Al}	0.26	0.26
X_{Py}	0.003	0.001
X_{Sp}	0.01	0.009
X_{An}	0.72	0.73

X_{Al}, X_{Py}, X_{Sp}, X_{An} are almandine, pyrope, spessartine and andradite respectively.

X_i = i/ i, i = Fe, Mg, Mn, Ca.

X_{An}	53.78
X_{Gr}	19 00

TABLE -V F

Representative microprobe analysis of Wollastonite in Calc - Granulites.

Sample No. Anal. No.	180:1/1	180:1/2
SiO_2	50.446	49.768
Al_2O_3	0.113	0.017
FeO	0.451	0.407
MnO	0.115	0.072
MgO	0.150	0.122
CaO	46.674	47.401
K_2O	0.022	0.018
Na_2O	0.088	0.210
TiO_2	0.039	0.070
Total	98.098	98.084

18 Oxygen basis

Si	5.976	5.923
Ti	0.003	0.006
Al^{+3}	0.016	0.002
Fe^{+2}	0.045	0.041
Mn	0.012	0.007
Mg	0.026	0.022
Ca	5.924	6.044
Na	0.019	0.048
K	0.003	0.003
Total	12	12