The chemistry of various mineral fractions separated from different litho-units is discussed in this chapter. The petrography of the pelitic schists, gneisses and associated rocks revealed mineralogical associations which are characteristic of certain specific metamorphic zones. Some of the index minerals like garnet, biotite, feldspar etc. have been analysed in order to decipher their chemical composition in relation to composition of the host rocks. The principal objective of such studies is to precisely identify the minerals species-wise and to decipher the changes in their elemental composition as a function of metamorphic grade exhibited by the rocks. Such a study is also important in establishing the chemical controls of host rock composition on the mineral phases occurring in them. This has to be deciphered in conjunction with the equilibrated/non-equilibrated metamorphic conditions depicted by the whole rock. The species-wise identification of the separated mineral fractions has been ascertained by X-ray diffraction studies and the determination of their structural formulae based on their chemical composition.
FELDSPARS :

The separation of purer feldspar fractions from the rocks has been a difficult task. As is evident from the petrographic investigations, most of the feldspar constituting the rocks of the study area are perthitic and anti-perthitic in nature. It could not be feasible, therefore, to separate purest fractions of K-feldspars and plagioclases. Most often these fractions also contained a few grains of quartz, some of which could be separated under the binocular microscope. However, mixed feldspar-quartz fractions could only be used for their X-ray and chemical analyses.

Chemical analysis :

The separated and purified fractions of feldspars (95% purity) were chemically analysed for their Na₂O, CaO and K₂O contents.

The feldspar end-members Or, Ab and An were calculated from the chemical data and have been expressed in percentage (Table-2).

X-ray studies :

Five feldspar fractions separated from the augen gneiss in the study area were subjected to X-ray diffraction investigations following the method discussed earlier in
Chapter I. Obliquity/triclinicity (\(\alpha\)) of the feldspars was measured from the diffractograms. The importance of such investigations for deciphering the structural state of feldspars and for computing their compositions have been stressed by Goldsmith and Laves (1954), Mackenzie (1954), Dietrich (1962), Orville (1967), Wright and Stewart (1968), Scotford (1969), Barth (1969), Fujiyoshi (1984), Santosh (1986a) and others. These authors realised that in monoclinic feldspars, there is only one peak (131) which in triclinic feldspar resolves into (131) and (\(\overline{1}31\)) reflections and the separation of these reflections corresponding to \(2\theta\) (131) and \(2\theta\) (\(\overline{1}31\)) forms the basis for calculation of triclinicity (\(\alpha\)) of the feldspars.

During the present studies, the measurement of the X-ray patterns were done following the procedure outlined by Wright and Stewart (1968) and Wright (1968). The reflections \(201\), 002, 113, 060 and 204 were carefully indexed and measured following the procedure given by Wright (1968) for the "three peak method". However, the "three peak method" of Wright (op. cit.) was used to determine the structural state and composition of the feldspars by using \(2\theta\) (060) and \(2\theta\) (204) and \(2\theta\) (201) data respectively. By plotting these data on the diagram of Wright (1968), the structural state of feldspars was determined directly in terms of the closest plotted feldspars of known structural state. It was observed that three feldspar samples fit well within the field of Orthoclase series with structural state approximately close to Benson (Wright, 1968).
The composition of feldspar has also been determined using the equations:

(i) \( \text{Or} \% = 1930.77 - 87.69 \times 2 \theta_{201} \) for Orthoclase series

and

(ii) \( \text{Or} \% = 2031.77 - 92.19 \times 2 \theta_{201} \) for Maximum microcline - Low albite series

(Wright, op.cit.)

The calculated data for the feldspars using these equations substantiate the plot of three feldspar samples in the field of Orthoclase series (Fig. 16, after Wright, 1968). Further, it is evident that the results have a positive relationship with the chemical data.

As pointed out earlier, on the basis of optical determinations, the feldspars in the rocks are mostly perthitic in nature. The perthitic character of these feldspar fractions, as discussed earlier, is supported by the presence of (002) and (111) reflections of albite in the X-ray diffractograms. Presence of (113) reflections in all the feldspars reveal that both potassic and sodic phases are coexisting (Hutchison, 1974, p. 195). The preponderance of sodic component in these perthitic feldspars is very well substantiated by the X-ray data, chemical composition and petrographic observations.
Triclinicity: It is evident that the symmetry of the feldspars can be ascertained by the separation of 131 and 131 reflections which gradually increases with the degree of obliquity of feldspars usually denoted as (triclinicity). It is calculated by using the relationship 
\[ \Delta = 12.5 \left( d_{131} - d_{131} \right) \] (Goldsmith and Laves, 1954). The triclinicity calculated for TW-18 sample is of the order of 0.755 i.e. intermediate microcline type. In case of the other analysed samples, the reflections 131 and 131 are not observed in the X-ray diffractogram. The plots of KT-20 and KT-28 fall out of the limits of the diagram (Fig. 16) which is also true when the calculated Or percentage (Wright, 1968) and the chemical compositions of these feldspars are considered. However, this may be caused by the overlap/interference by some reflections which could not be precisely determined during the present work.

HORNBLLENDE:

Three hornblende fractions H₁, H₂ and H₃ were separated from the amphibolites with sample numbers KT-7, TW-7 and TW-19 respectively.

Chemical analysis:

The separated hornblende fractions have been chemically analysed and their chemical composition as well as structural
formulae, calculated on the basis of $2+ (0)$, are presented in Table-4. The structural formulae for the calcium-rich amphiboles have been expressed as follows:

$$X_{2-3} Y_{7/2} Z_8 O_{22} (OH, F, Cl)_2$$

Where

- $X$ = Ca, Na and K.
- $Y$ = Mn, Mg, Fe$^{+2}$, Fe$^{+3}$, Al$^{VI}$ and Ti.
- $Z$ = Si and Al$^{IV}$

(Deer et al., 1983)

Ernst (1968) defined the range of calcic amphiboles by the general formula:

$$(Na, K)_{0-1} (Na, Ca, Mn, Mg, Fe^{+2})_2 (Mg, Fe^{+2}, Fe^{+3}, Mn, Ti, Al)_5 (Si, Al, Fe^{+3})_8 O_{22} (0, OH, F)_2.$$  

The range of various ions of the studied amphiboles also falls within the framework of the formula proposed by Ernst (op.cit.) thereby confirming the calcic nature of the amphiboles in the studied area. The basic difference in chemical composition of these hornblendes is shown in the Table-4 and this difference is due to host rock compositional variations.
The amphiboles which are hornblendic in nature show Si values varying between 6.66 and 6.88, in the analysed fractions. The Si content in actinolite and tremolite is greater than 7.2, which distinguishes the analysed amphiboles from actinolite-tremolite (Miyashiro, 1968, p. 818).

In a plot of $\text{Al}^{IV}$ versus $\text{Mg}$ (Fig. 17) after Shido and Miyashiro (1959), it is found that all the analysed amphiboles fall in the middle hornblendic field. Low grade amphiboles (actinolite) has $\text{Al}^{IV}$ content of about 0.53 (Compton, 1958) and in metamorphic aluminous hornblende, it is about 0.48 (Holdaway, 1965, p.964). The amphiboles studied during the present investigations have $\text{Al}^{IV}$ content of the order of 1.10 to 1.32, which characterises their hornblendic nature. This is further supported by their optical data.

Plotting these data, in diagrams (Figs. 18, 19, 20, 21 and 22) after Colville et al. (1966), it is observed that calcic amphiboles are the members of a complicated solid solution series and this is reflected in their variable chemical compositions:

$$(\text{Na, K})_{0-1} (\text{Na, Ca, Mg, Mn, Fe}^{2+})_2 (\text{Mg, Fe}^{2+}, \text{Fe}^{3+}, \text{Mn, Ti, Al})_5 (\text{Si, Al, Fe}^{3+})_8 \text{O}_{22} (\text{OH, O, F})_2$$

(Ernst, 1968)

In almost all the plots, it is found that the studied amphiboles exhibit a linear relationship. Compositionally, the
amphiboles show a seriate variation viz., $H_1$ is plotting on the ferropargasite side and $H_3$ on pargasite side (Fig. 20). This is further evidenced by the plots (Figs. 18, 19, 20, 21 and 22) after Colville et al., 1966. It is evident that common hornblends carry abundant pargasite + magnesiohastingsite, ferropargasite + hastingsite, edenite and tremolite end-members and only minor amounts of the ferro-edenite, ferrotremolite, tschermakite and ferrotschermakite end-members. In a plot (Fig. 23) of $\text{Al}^4$ versus $(\text{Na} + \text{K})$ after Liou et al., 1974 for the analysed hornblends, it is observed that $H_2$ plots in the magmatic amphibole field. $H_3$ though very close, lies outside the field and $H_4$ falls nowhere near the field. It can be explained by the enrichment of these hornblends in $(\text{Na} + \text{K})$ content during metamorphism.

Leake (1965) plotted Si versus Ti data of calciferous and sub-calciferous amphiboles occurring in both metamorphic and igneous rocks and observed that igneous amphiboles usually contain more titanium than the metamorphic ones. He pointed out that igneous and metamorphic amphiboles show a steady increase in the maximum possible amount of titanium with decreasing Si content. These observations suggest that temperature is an important controlling factor in determining the amount of titanium substitution in amphibole structure. Evidently, therefore, the amphibole with higher content of titanium should occur in the rocks of higher metamorphic grade. The amphiboles studied during the present investigations
point to this relationship. The increase in titanium content of the hornblende places the rocks in the higher metamorphic grade and shows variation in colour from green to olive green. Deer (1938, p. 74) observed that with the increase in titanium content the hornblende becomes more brown.

In the plot (Fig. 24) of TiO$_2$ versus (Na$_2$O + K$_2$O), the analysed hornblendes occupy fields of amphibolite to granulite facies. Hornblende with low titanium content falls in the amphibolite facies while those with higher Ti content lie in the granulite facies, as also indicated by Engel and Engel (1962, p. 1499). They observed a rise in the (Na$_2$O + K$_2$O) content of hornblende with increasing grade of metamorphism in the amphibolites of Adirondack Mountain. It indicates more of alkali (Na + K) substitution in the hornblende structure.

The CaO and Na$_2$O data for the analysed hornblendes with respect to host rocks have been plotted in Fig. 25, for the study area. Engel and Engel (op. cit.) depicted a rise in the Na/(Na + Ca) ratio with the increasing grade of metamorphism. On the contrary Leake (1965, p. 306) stated that the Na/(Na + Ca) ratio should decrease with the increasing metamorphic grade, since it is an accepted view that the anorthite content of plagioclase tends to increase with increase of metamorphic grade. The data obtained during the present work support the contention of Engel and Engel (1962). The Na/(Na + Ca) ratio in low grade hornblende is 0.1570 and in that of higher grade it is 0.3214.
Fe$^{3+}$/Fe$^{2+}$ ratio in hornblende can also be utilized for assigning the grade of metamorphism. Engel and Engel (op. cit.) and Miyashiro (1968), have shown that the Fe$^{3+}$/Fe$^{2+}$ ratios decrease with increasing metamorphic grade. In the present case Fe$^{3+}$/Fe$^{2+}$ ratio ranges between 0.088 to 0.183 and this points to a higher grade of metamorphism.

MgO content is responsible for the brown colour observed in hornblendes of high metamorphic grade. In the present case a decrease from 12.10% (weight percent) of MgO from lower metamorphic grade to 9.03% (weight percent) in that of higher grade is noticed and is well-correlated with the MgO content of host rock. The distribution pattern of various elements in minerals is controlled chiefly by metamorphic grade, host rock composition and paragenesis.

Octahedral Al and Si in metamorphic hornblende is one of the most important correlative parameters testifying to the variation in mineralogical composition as a function of metamorphic grade. Al successively replaces larger amount of Si in the tetrahedral position and that the excess of Al is thought to be accommodated in the (Mg, Fe)$_5$ position. The increase in the Al$^{IV}$ is commensurate with decrease in Si content. The analysed hornblendes exhibit such features. The low grade
metamorphic hornblende has $\text{Al}^{IV}$ value of 1.10 whereas in that of high grade it is 1.32. The value of Si decreases from 6.88 to 6.66 in low to high metamorphic grade hornblends.

Engel and Engel (1962) have used the Al/Si ratio of hornblende for determining the grade of metamorphism. The value of Al/Si ratio rises from 0.2616 to 0.2883 in hornblendes from low-to-high grade of metamorphism.

**X-ray studies:**

The $H_1$, $H_2$ and $H_3$ mineral fractions were also subjected to the X-ray diffraction study and the data have been presented in Table 5. The X-ray data support the preceding observations based on the petrographic and chemical determinations. A perusal of the table reveals that the hornblendes from the amphibolites have the following compositions:

- **KT-7:** $(\text{Al}, \text{Fe}^{+3})_{2.01} (\text{Ca}, \text{Fe}^{+2}, \text{Mn}, \text{Mg})_{5.59} \text{Si}_{6.74} 0_{24}$.  
- **TW-7:** $(\text{Al}, \text{Fe}^{+3})_{2.23} (\text{Ca}, \text{Fe}^{+2}, \text{Mn}, \text{Mg})_{5.45} \text{Si}_{6.66} 0_{24}$.  
- **KT-19:** $(\text{Al}, \text{Fe}^{+3})_{1.95} (\text{Ca}, \text{Fe}^{+2}, \text{Mn}, \text{Mg})_{5.80} \text{Si}_{6.88} 0_{24}$.  

The molecular percentage of the end-members have been calculated for the hornblendes from their chemical analysis and are given in Table-5.
On the basis of preceding discussion it can be said that the hornblendes exhibit a definite relationship between grade of metamorphism and major element distribution pattern which may be a reflection of the variable metamorphic environment in which the hornblendes crystallised.

BIOTITE:

Five biotite samples were separated from augen gneisses and were chemically analysed. Since some of the rock samples were very poor in their biotite content, a large number of samples of these rocks were used to separate biotite fractions. The biotite fractions were also subjected to X-ray studies so as to identify the mineral species-wise. The data so gathered help to decipher the nature of metamorphic changes, in this index mineral, in relation to the host rock composition.

Chemical analysis:

The chemical data for biotites and calculations on the basis of 24 (0, OH), their structural formulae, charge balance, and various ratios are posted in Tables-6, 7 and 8.

These data help in appreciating the subtle variations in the chemical composition of the analysed biotites. A perusal of the analysed data reveals that the biotite are rich in alumina. In a plot (Fig.26) of octahedral $R^+$ and tetrahedral $R^+$ after
Chinner (1960), it is noticed that two of the five analysed samples fall in between the end-members, eastonite micas $K_2(Mg, Fe)_5Al_3Si_{20}O_{20}(OH)_4$ and lepidomelanes $KFe^{+2}_{1.66}(Fe^{+3}, Al)Al_{1.33}Si_{2.67}O_{10}(OH)_2$. Such alumina-rich biotites have earlier been reported from the pelitic schists that coexist with andalusite in a low pressure regional metamorphic terrain in the Panamint Mountains, California (Labotka, 1981) and from low- and medium-grade regional, low pressure, metamorphic terrain of the Fichtelgebirge area, NE-Bavaria (Mielke et al., 1979).

The analysed biotites have been plotted in Fig.27 which brings out the relationship between octahedrally coordinated Mg, Fe$^{+2}$ Mn and (Al+Fe$^{+3}$+Ti). The field of phlogopite, Mg- and Fe-biotite, siderophyllite and lepidomelane as defined by Foster (1960) are shown for comparison. All the biotites except $B_4$ fall between Mg- and Fe-fields and show an increase in Mg content from $B_2$ to $B_5$. $B_4$ lies outside Foster's (1960) field, away from Mg apex, and is comparable to low-Mg biotites reported by Santosh (1986b). Sodium content in all these biotites ranges from 0.03 to 0.17. In order to arrive at a better correlation between biotites and host rocks, a triangular diagram (Fig.28), $(FeO + MnO) - (Fe_{2.3}O_3 + TiO_2) - MgO$, has been plotted after Heinrich (1946) in which the biotites plot between gneisses and schists and diorites. $B_4$ lies towards the granite field, thereby indicating that the biotites of the study area may be of metamorphic origin.
Investigations of biotites have been shown to depend, primarily on their paragenesis and hence this mica has been considered to be a good indicator of genetic environment and metamorphic conditions. In order to ascertain the variation in composition related to the paragenesis of the studied biotites, the data have been plotted in the $\text{Al}_2\text{O}_3 - \text{Fe}^t\text{O} \ (\text{Fe}_2\text{O}_3 \times 0.9 + \text{FeO}) - \text{MgO}$ triangular diagram (Fig. 29), after Albuquerque (1973). It is observed that except $\text{B}_1$, all the biotites fall in the field of biotites unaccompanied by other Fe-Mg minerals. $\text{B}_1$ lies close to the field where biotites coexist with muscovite. In another triangular diagram ($\text{FeO} + \text{MnO}) - \text{MnO} - (\text{Fe}_2\text{O}_3 + \text{TiO}_2$), showing the fields marked by Heinrich (1946) and Gokhle (1969), it is observed that except for $\text{B}_1$ all the biotites fall in the metamorphic zone (Fig. 30). On the basis of preceding discussions, it can be said that $\text{B}_1$ biotite has not been a stable phase and has altered to muscovite. This has been supported by the plot of biotites in the diagram (Fig. 28).

In a plot of $\text{MgO}/(\text{MgO} + \text{FeO})$ ratio determined in biotites and their analysed host rocks, it is found that all the points fall below the 1:1 line (Fig. 27).

The $\text{TiO}_2$ content of biotites ranges between 0.66 and 1.69. An increase in $\text{TiO}_2$ content with metamorphic grade has been shown by various workers viz., Engel and Engel (1960), Oki (1961), Janardhanan (1965), Guidotti (1970), Gupta (1970),
etc. On the contrary, Butler (1967) showed that there is no specific rise in TiO$_2$ content of biotite with increasing grade of metamorphism. On plotting the data for analysed biotites no specific relationship is noticed in the TiO$_2$ content of the mineral and the host rocks. An insignificant variation in TiO$_2$ content of biotites may be related to the host rock composition. Plot of TiO$_2$ (weight percent) in biotite versus those in host rocks (Fig. 32) shows that one sample (B2) plots on the 1:1 line and rest of the samples B1, B3, B4 and B5 fall between 1:2 and 1:4 lines of (R$_{TiO_2}$/$B_{TiO_2}$) distribution. A similar situation has been observed for the biotites of Kishtwar, J & K State, India (Sandhu, 1982).

The changes in biotite composition with respect to the variation in rock oxidation ratio have been reported by Chinner (1960). Similar relationship has been established by Hounslow and Moore (1967) in the garnet staurolite schists. In order to portray this relationship, the MgO x 100/(MgO + FeO) ratio in the analysed biotites have been plotted against rock oxidation ratio (Fig. 35). A considerable compositional change in biotite is noticed in the ratio MgO x 100/(MgO + FeO) which does not show any specific relationship with the increase in rock oxidation ratio.

In the diagram (Fig. 33) where MgO and FeO content of biotites and those in their respective host rocks are plotted, it is found that in case of FeO, host rock is the controlling
factor. Metamorphic processes could also be the other factor. The MgO content in biotite varies between 6.34 and 12.78\% and FeO from 20.00 to 22.56\% while in the rock, it ranges from 0.16 to 0.74 and 1.91 to 3.67 respectively.

The parameters like, the correlation of rock oxidation ratio with molar total iron magnesium ratio \((2Fe_2O_3 \times 100/(2Fe_2O_3 + FeO))\) in biotite (Fig. 36c), molar ratio of iron \((Fe \times 100/(Fe + Mg + Mn + Ca))\) in garnet (Fig. 36b) and biotite oxidation ratio \((Mg/Mg + Fe^0)\) (Fig. 36a) are presented in Fig. 36. In all the three plots, it is observed that the values of ratio increases with the increase in rock oxidation ratio.

The compositional variation observed in the studied biotites reflect the physico-chemical conditions under which these minerals were crystallised as well as the role of host rock composition in causing the diversity.

**X-ray studies**

The data obtained from the X-ray studies together with other optical and physical properties are presented in Table-9. It is evident from the data that the strongest reflection observed is at 10.03 Å and is noticed in all the analysed biotites. The second strong intensity is noticed at 3.35 Å. Every reflection below 10.03 Å is an indication of the analysed
mineral being biotite. This fact is further corroborated by the absence of 7.1 Å reflection which is characteristic of vermiculite.

GARNET:

In order to understand the variation in the chemical composition of garnet with respect to metamorphism, three separated garnet fractions from the rocks were purified and chemically analysed. The rock from which the garnets have been extracted is staurolite-garnet-mica schist. The host rock control on the chemical composition of garnets, in relation to metamorphism, has been examined during the present study.

Chemical analysis:

The garnets have been chemically analysed and the data, various ratios of oxides, and number of cations calculated on the basis of \(2^+\) (O) have been posted in Table-10. The molecular percentage of end-members and structural formulae (Deer et al., 1983), have been presented in Table-10A. The excess of Si (more than 6.00) in the samples may be related to extremely small quartz inclusions in garnet, which are not separable even on fine crushing and hand-picking under the binocular microscope.
The garnets from the study area are rich in almandine molecule ranging from 51.91 to 69.87%, while andradite, spessartine, grossularite and pyrope molecules range from 4.58 to 5.60, 1.49 to 2.48, 2.71 to 9.94 and 16.62 to 36.52 respectively.

\[
\begin{align*}
G_1 &= \text{Alm}_{51.91} \text{And}_{5.09} \text{Sp}_{1.96} \text{Gr}_{4.52} \text{Py}_{36.52} \\
G_2 &= \text{Alm}_{66.38} \text{And}_{4.58} \text{Sp}_{2.48} \text{Gr}_{9.94} \text{Py}_{16.62} \\
G_3 &= \text{Alm}_{69.87} \text{And}_{5.60} \text{Sp}_{1.49} \text{Gr}_{2.71} \text{Py}_{20.33}
\end{align*}
\]

In a triangular variation diagram CaO (FeO + Fe₂O₃ + MnO + MgO) - Al₂O₃ (Fig.40), the composition of garnet from the study area is plotted and the affinity of garnets towards pyralspite is noticed.

A number of investigations have been carried out on the composition of garnet by various workers and varying results have been obtained. Goldschmidt (1920) was the pioneer researcher in relating the composition of garnet with its grade of metamorphism and he showed that Fe²⁺ and Mg contents of garnet increase while Mn and Ca decrease with the increasing grade of metamorphism. These observations were supported by Barth (1936), Miyashiro (1953), Kretz (1959), Lambert (1959), Engel and Engel (1960), Sturt (1962), Atherton (1965a, 1965b, 1968), Nandi (1967), Hietanen (1969), Okrusch (1971), Cygan & Lasaga (1982), Franceschelli et al. (1982), Dempster (1985) and
Within an individual zone the variations in MnO, FeO, MgO, CaO are between 0.65 and 0.98%, 22.44 and 30.08%, 1.75 and 9.11% and between 2.81 and 5.18% respectively. These oxides have been plotted in a variation diagram (Fig.37) which shows smooth increase in FeO, decrease in CaO and MgO and no significant variation in MnO content. A general plot of (FeO + MgO)% and (CaO + MnO)% after Nandi (1967) does not show any specific trend and the analysed garnets from garnet-staurolite zone fall in the kyanite as well as in sillimanite zones (Fig.39).

Variation in MnO-content: Miyashiro (1953, 1961) has related the MnO content of garnet with the type of metamorphism. Based on mineral assemblages and MnO content, he observed Almandinous and Non-almandinous types of metamorphism. The garnets rich in Mn content and in association with andalusite are formed at low pressure whereas the one with poor Mn-content and occurring within sillimanite is characteristic of high pressure or 'Barrovian' type of metamorphism. The latter condition is observed in the area, where garnet occurs with sillimanite. Engel and Engel (1960) proposed a decrease in Mn-content of garnet with increasing grade of metamorphism. Lambert (1959) suggested the decrease in CaO content of garnet with the increasing grade of metamorphism. Sturt (1962) observed a general inverse correlation between (MnO + CaO) content of garnet and overall grade of metamorphism. Atherton (1965b) and many other workers criticised the consideration of
keeping Mn-content as pressure indicator. Nevertheless, it can still be considered as a supporting evidence for petrographic and field criteria. Harte and Henley (1966) marked the decrease in Mn and increase in Fe\(^{+2}\) towards the margins of individual garnet grains and suggested the reason for this as conditions of metamorphic grade. Hollister (1966) proposed that the compositional zoning in metamorphic garnet resulted from the partitioning of manganese between garnet and its matrix. According to Chinner (1960), the MnO content varies between 1.06 and 11.50\% in pelitic gneisses of sillimanite zone in Glenclove. In Grenville (Hounslow and Moore, 1967), it varies between 0.13 and 10.90\% in pelitic schists of staurolite-kyanite zone. The MnO content of garnets in the study area varies between 0.65 and 0.98\% in the garnet-staurolite zone. Atherton (1968) suggested that zoning and progressive change in garnet composition were due to change in distribution coefficients of the divalent cations with increase in grade. Edmunds and Atherton (1971, p.152) have shown that during growth of regional garnet, FeO and MnO show a complementary variation with depletion of MnO, while during thermal growth, there is a tendency for them to increase together.

In a plot (Fig. 38) of MnO\% of rock versus MnO\% of garnet, it is observed that the MnO-content of garnet decreases with the increase in MnO-content of the host rock. Plot of MnO \times 100/MnO + FeO versus oxidation ratio of the rock does not show any significant relationship (Fig.41).
Variation in Mg-content: An increase in the MgO content is noticed from 1.75 to 9.11% in the garnets of the study area which is similar to the observations of Atherton (1965b). The garnets of the study area when plotted in a diagram MgO x 100/(MgO + FeO) of the rock versus MgO x 100/(MgO + FeO) of garnet (Fig.42) show a paucity of MgO in the mineral with respect to that in the host rock. In a plot of MgO x 100/(MgO + FeO) versus MnO, of the garnets, the present data show a decrease in the ratio with the increase in MnO content (Fig.43a). In another plot (Fig.43b), it shows an increase in MgO content with the rise in MnO x 100/(MnO + CaO) ratio. Plot of CaO % versus MgO x 100/(MgO + FeO) ratio is represented in Fig.43c in which the former decreases with respect to the rise in the ratio. It is evident from Fig.36 that the molar ratio of iron increases with the rise in rock oxidation ratio (Fig.36).

X-ray studies:

The purified garnet fractions were subjected to X-ray diffraction studies. The X-ray data are presented in Table-11. The cell parameters (a°) calculated from the data vary between 11.57 Å and 11.59 Å indicating thereby that these garnets are rich in almandine, pyrope with small amounts of grossularite, andradite and spessartine molecules. These data are in conformity with the structural formulae of garnets calculated from their chemical composition.
TABLE - 2

CHEMICAL ANALYSIS DATA FOR FELDSPARS

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<td>Or</td>
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### Table 8

**X-Ray Diffraction Data for Feldspars**

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**Number of Cations on the Basis of 24 (0)**

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## TABLE - 5

X-RAY DIFFRACTION DATA FOR HORNBLENDES

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END-MEMBERS OF HORNBLENDES

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**OXIDE PERCENTAGE OF BIOTITES AND OTHER PARAMETERS**

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**NUMBER OF CATIONS ON THE BASIS OF 24 (0)**

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### Table 7

**Structural Formulae of Biotites**

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<td>(K$<em>{0.68}$ Na$</em>{0.17}$ Ca$<em>{0.11}$) (Mg$</em>{1.94}$ Fe$^{3+}<em>{0.14}$ Fe$^{2+}</em>{2.66}$ Mn$<em>{0.03}$ Ti$</em>{0.07}$ Al$^{	ext{VI}}<em>{1.19}$) (Si$</em>{16.60}$ Al$^{	ext{IV}}<em>{1.38}$ P$</em>{0.02}$) 0 21.26 OH$_{2.74}$</td>
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<td>(K$<em>{0.61}$ Na$</em>{0.14}$ Ca$<em>{0.11}$) (Mg$</em>{2.15}$ Fe$^{3+}<em>{0.14}$ Fe$^{2+}</em>{2.64}$ Mn$<em>{0.03}$ Ti$</em>{0.11}$ Al$^{	ext{VI}}<em>{0.96}$) (Si$</em>{16.67}$ Al$^{	ext{IV}}<em>{1.30}$ P$</em>{0.03}$) 0 21.06 OH$_{2.92}$</td>
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</tr>
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<td>(K$<em>{0.65}$ Na$</em>{0.03}$ Ca$<em>{0.14}$) (Mg$</em>{2.81}$ Fe$^{3+}<em>{0.18}$ Fe$^{2+}</em>{2.47}$ Mn$<em>{0.03}$ Ti$</em>{0.17}$ Al$^{	ext{VI}}<em>{0.56}$) (Si$</em>{16.23}$ Al$^{	ext{IV}}<em>{1.75}$ P$</em>{0.02}$) 0 20.90 OH$_{3.10}$</td>
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$FeO = (Fe^{+2} + Fe^{+3})$
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**Number of Cations on the Basis of 24 (O)**

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<td>Al₃.91 And₇.09 Sp₁.96 Gr₄.52 Py₃6.52</td>
<td>( \text{Fe}^{+2} <em>{2.90} \text{Mn}</em>{0.11} \text{Mg}<em>{2.09} \text{Ca}</em>{0.56} \text{Na}<em>{0.12} \text{K}</em>{0.04} \text{Si}<em>{6.64} \text{O}</em>{24} )</td>
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<td>K-11</td>
<td>Al₆₆.₃₈ And₄₄.₅₈ Sp₂₄.₄₈ Gr₉₉.₄₄ Py₁₆.₆₂</td>
<td>( \text{Fe}^{+2} <em>{3.74} \text{Mn}</em>{0.13} \text{Mg}<em>{0.40} \text{Ca}</em>{0.86} \text{Na}<em>{0.12} \text{K}</em>{0.04} \text{Si}<em>{6.66} \text{O}</em>{24} )</td>
</tr>
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<td>K-17</td>
<td>Al₆₉.₈₇ And₅₅.₆₀ Sp₁₄.₉₁ Gr₂₇.₇₁ Py₂ₐ.₃₃</td>
<td>( \text{Fe}^{+2} <em>{4.00} \text{Mn}</em>{0.09} \text{Mg}<em>{1.₅₆} \text{Ca}</em>{0.₄₈} \text{Na}<em>{0.₀₉} \text{K}</em>{0.₁₂} \text{Si}<em>{6.₃₄} \text{O}</em>{24} )</td>
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**TABLE - 11**

X-RAY DIFFRACTION DATA FOR GARNETS

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<td>G₂</td>
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<td>2.586</td>
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**LATTICE PARAMETERS**

- KT-5/G₁: \( a(\text{Å}) = 11.59 \pm 0.01 \)
- K-11/G₂: \( a(\text{Å}) = 11.57 \pm 0.02 \)
- K-17/G₃: \( a(\text{Å}) = 11.58 \pm 0.02 \)
Fig. 16 Corresponding values of $2\theta_204$, and $2\theta_201$ for alkali-feldspars using CuKα₁ radiation (after Wright, 1968). The three major series—maximum microcline—low albite, orthoclase; and high sanidine—high albite—are shown in solid lines. Dashed lines are for specific alkali-feldspars which have been well studied. In order of increasing structural state they are (lowest) 1, Spencer U; 2, Spencer B, 3, low albite 111; 4 SH 1070; 5, Benson, 6 S62-34, 7, Puye, and 8, S63-30 (highest). (From Wright, 1968.)
Fig. 17 The plot of $\text{Al}^{IV}$ vs $\text{Mg}$ for hornblendes of the study area.

Fig. 18 Distribution of natural amphiboles in the composition range: tremolite - ferrotremolite - (pargasite - magnesiohastingsite) - (ferropargasite + hastingsite) (Colville et al., 1966).
Fig. 19 Distribution of natural amphiboles in the composition range: edenite-ferroedenite-(pargasite-magnesiohastingsite)-(ferropargasite-hastingsite) (Colville et al., 1966).

Fig. 20 Distribution of natural amphiboles in the composition range: tremolite-ferrotremolite-pargasite-ferropargasite (Colville et al., 1966).
Fig. 21 Distribution of natural amphiboles in the composition range: pargasite-
magnesiohastingsite-hastingsite (Colville et al., 1966)

Fig. 22 Distribution of natural amphiboles in the composition range: tschermakite-
ferrotschermakite-(pargasite+magnesiohastingsite)-(ferropargasite-
hastingsite) (Colville et al., 1966)
Fig. 23 $\text{Al}^{IV}$ vs (Na+K) diagram for analysed hornblends (Liou et al. 1974).
Fig. 24 The plot of TiO$_2$ wt% vs Na$_2$O$\cdot$K$_2$O wt% for the hornblends of the investigated area.

Fig. 25 The plot of CaO in hornblende vs CaO in rock and Na$_2$O in hornblende vs Na$_2$O in rock.
Fig. 26 Biotites of the study area plotted after the manner of Yoder (1959). 

QR. = Biotite field of Chinner, 
Fig. 27 (Al\textsuperscript{VI}, Fe\textsuperscript{3+}, Ti) — Mg — (Fe\textsuperscript{2+}, Mn) diagram for the biotites of the study area. Dashed lines indicate the field of natural biotites (Foster 1960).

Fig. 28 Plot of MgO—(Fe\textsubscript{2}O\textsubscript{3}+TiO\textsubscript{2})—(FeO+MnO) for biotites from the study area. Zones drawn by Heinrich (1946). Line separating biotites of magmatic rocks from those of metamorphic-metasomatic rocks (Gokhle, 1968).
Fig. 29 MgO – FeO – Al₂O₃ plot for the biotite of the study area

Dashed lines indicate the limits of igneous and metamorphic rocks. (after Heinrich, 1946)

Fig. 30 Comparison of the composition of biotite from the study area. Dashed lines indicate the limits of igneous and metamorphic rocks. (after Heinrich, 1946)
Fig. 31 Plot of MgO/(MgO + FeO) for biotites and corresponding host rocks of the study area.

Fig. 32 Plot of TiO$_2$ wt% for biotites and corresponding host rocks of the study area (R: Rock, B: Biotite).
Fig. 33 Plot of FeO & MgO wt% for biotites and corresponding host rocks of the study area (R1-R5 = Rocks; B1-B5 = Biotites)
Fig. 34  Plot of wt% for biotite and corresponding host rocks of the study area (Symbols as in Fig. 29)

Fig. 35  Correlation of molecular \( \frac{\text{MgO} \times 100}{\text{MgO} + \text{FeO}} \) of biotites of the study area with rock oxidation ratio (after Chinner, 1960)
Fig. 3.6 Correlation of rock oxidation ratio with (a) molar, total iron magnesium ratio in biotite, (b) molar ratio of iron in garnet, (c) biotite oxidation ratio (Fe²⁺: Fe²⁺ + Fe³⁺).
Fig. 37 Plot of oxide% of the garnets of the study area

Fig. 38 Plot of MnO% garnets vs MnO% rocks
Fig. 39 Nature of variation of (FeO*MgO) with (CaO*MnO) in garnets with different grades of metamorphism. (Boundary of Zones after Nandi, 1967)
Fig. 40 Chemical composition of garnets from the study area

Fig. 41 Plot of MnO of garnets vs oxidation ratio of the respective rocks

Fig. 42 Plot of MgO of garnets vs that of respective rocks
Fig. 43 Variation of MnO% and CaO% in garnets with MnO and CaO content of garnets