CHAPTER IV
CHAPTER - IV

ORE PETROGRAPHY, MINERAL CHEMISTRY AND P-T CONDITIONS OF METAMORPHISM

4.1 INTRODUCTION

In this chapter, the ore petrography including the optical properties of various ore minerals, textures and their interpretation, chemistry of some important silicates [olivine, serpentine, chrome serpentine, chrome chlorite (kammererite) plagioclase, hornblende] and ore minerals (both fresh and altered chromite, Ti magnetite and ilmenite), P-T conditions of re-equilibration estimated based on olivine-spinel thermometry, Ti magnetite-ilmenite geothermometry and P-T conditions of metamorphism based on metamorphic mineral assemblages in ultramafic rocks and plagioclase-hornblende geothermometry are presented.

4.2 ORE PETROGRAPHY OF CHROMITE ORES AND ULTRAMAFIC ROCKS

4.2.1 Ore minerals

The various ore minerals identified based on their optical properties like colour, pleochroism, isotrophism/anisotrophism under reflected light microscope (ore microscope) in the chromitites and ultramafic rocks of the study area are chromite, ilmenite, ferritchromit and magnetite.

4.2.1.1 Chromite: Both thin sections and polished surfaces of rocks and ores are observed. Chromite grains exhibit black to coffee brown colours in thin sections. Chromite in polished specimen exhibits grey to greyish white colour and occurs as euhedral grains with triangular, hexagonal and square outlines. In some cases, the
chromite grains exhibit subrounded to rounded outlines. The chromite grains also exhibit skeletal to dendritic patterns.

The grain size of chromite depends on the amount of matrix of ores and associated ultramafic rocks. Serpentine is the main material. If the amount of this material is more the grain size of chromite is small. The size of chromite grain varies from 0.1 mm to 0.9 mm. The chromite grains are seen in aggregates, cemented together by serpentine material.

4.2.1.2 Ilmenite: Slender lamellae of ilmenite are observed on chromite grains. Ilmenite shows pleochroism from pinkish brown-to-brown colour. It is strongly anisotrophic. It shows intergrowth relationship with the chromite grain.

4.2.1.3 Ferritchromit and magnetite: The reflecting rims/zones in the chromite grains of the study area reveal the alteration of chromite to ferritchromit and magnetite. The strong reflectivities of the rims at the margins of chromite to magnetite EPMA studies of chromite and its altered phases have confirmed the presence of ferritchromit and magnetite.

4.3 TEXTURES OF CHROMITE ORES AND THEIR INTERPRETATION

The various textures have been identified and are classified into primary and secondary (deformed) textures and described as follows:

4.3.1 Primary textures

The chromite ores show typical primary textures like cumulus, chain, occluded silicate clot and intergrowth textures.

4.3.1.1 Cumulus texture: In thin sections, chromite bearing dunite exhibits relic cumulus texture (Fig. 4.1) in which olivine often shows marginal alteration to blades
of antigorite. Chromite in polished ore exhibits grey to grayish white colour. Chromite ore exhibits cumulus texture in which euhedral grains with triangular and square outline, with very little or not interstitial serpentine/talc forming a granular mosaic. The grains size of chromite differs when the amount of matrix (serpentine/talc) differs. If the matrix material is more the grain size of chromite is small. The size of chromite grains varies from 0.30 to 1.90 mm, indicating that size grading took place during gravity settling process.

4.3.1.2 Chain texture: Chromite grains occur as chains around the olivine grains (Fig. 4.2). Both these minerals are packed together, wherein the olivine grains are larger than the associated chromite crystals. The chromite crystals are packed between the olivine grains. Both olivine and chromite crystals are thought to be primary precipitate minerals. The chromite bearing dunite layers also show the euhedral, even grained, closely packed chains of chromite grains, which represent the mineral phase that crystallized early and settled to the floor of the magma chamber. Partly serpentinised olivine represent the intercumulus material, which is moulded around these settled chromite crystals, commonly poikilitically and is thought to have crystallize in the pore-spaces surrounding these crystals.

4.3.1.3 Occluded silicate texture: The chromite ores exhibits occluded silicate structure in which partly serpentinized olivines are surrounded by chains of euhedral chromite grains and olivine altered to chrome - chlorite (kammerarite) (Fig. 4.3). These occluded silicates reveal that they have inclusion - free cores surrounded by border zones which poikilitically enclose numerous fine-grained (0.6 mm) chromite grains.
4.3.1.4 Clot texture: In the chromite ores, the clots are usually spheroidal and ellipsoidal in outline and they vary in size from 0.2 mm to 2 cm measured along their major axes. Mineralogically, the clots are composed of fine-grained chromite and silicates represented by antigorite and magnesite, which occur in massive and coarse-grained chromite. The amount of silicates increases towards the center of the clot. The size of the coarse-grained chromite ranges from 1.30 to 3.00 mm in diameter and that of clot-forming chromite (fine-grained chromite) varies from 0.20 to 0.30 mm. The coarse-grained chromite is subhedral to euhedral in outline with slightly rounded outlines at places, whereas the clot forming chromite is mostly euhedral and associated silicates are anhedral in shape. The borders of the coarse-grained chromite are corroded at the contacts of the clots indicating their replacement by the silicates and fine-grained chromite. In thin sections, the host-forming chromite crystals have translucent cores, whereas clot-forming chromite are devoid of such cores (Fig. 4.4). Zoned clots are also observed in the chromites, which consist of sparsely developed concentric banding form by periodic fluctuations in the relative proportions of the chromite and silicates represented by antigorite and magnesite. The fine-grained chromites are not crushed due to the presence of intervening silicates in the clots (Fig. 4.5).

4.3.1.5 Intergrowth texture: Ilmenite exhibits intergrowth and occurs as slender lamellae in chromite grains. The ilmenite lamellae are mostly confined to deformed chromite grains (Fig. 4.6).
4.3.2 Secondary (deformed) textures

The layered ultramafic rocks along with chromite layers show various deformation features. Cumulus chromite, with little serpentine material, has been subjected to deformation resulting in the formation of a number of fractures with later filled up by carbonate material during late stage intense hydrothermal activity. Pale violet kammererite (chrome-chlorite) (Fig. 4.7) is formed after chromite.

Pull-apart (matching wall) texture is developed in chromite grains suggesting movements of fragments of chromite grains away from the planes of fracturing. Pull-apart texture is well developed in coarse-grained chromite, normal to the axis of stretching and the gaps are later filled up by secondary mineral after olivine. The deformed chromite grains are replaced by serpentinised olivine, along the grain boundaries (Fig. 3.22, see in Chapter III).

4.3.3 Chromite alteration

Chromite shows zonation in which parent chromite core is mantled by ferritchromit, which in turn is rimmed by magnetite. Three combinations of phases are observed during chromite alteration. They are represented by i) chromite – ferritchromit – magnetite (Fig. 4.7), ii) chromite – ferritchromit and iii) chromite – magnetite (Fig. 4.8). The parent chromite core is encircled either by two rims represented by ferritchromit and magnetite are by only a single rim of magnetite. There is a variation both in reflectivity and thickness of these altered phases. The reflectivity of parent chromite core is weak, whereas the reflectivity of ferritchromit is intermediate between that of magnetite and the parent chromite. The reflectivity of magnetite is strong at the margins of altered single grain.
4.4 MINERAL CHEMISTRY OF OLIVINE AND CHROMITE

Chemical analysis of olivine, both fresh and altered chromite grains were carried out using Electron Probe Micro Analyser (EPMA) CAMECA SX50 in the Department of Studies in Geology, Manasagangotri, University of Mysore, Mysore. The analytical conditions were 15 kV and 20 nA of beam current and the beam size is 2-5 microns. Calibrations were done using both natural mineral and synthetic oxide standards. The accuracy of analytical results was 0.01 wt% for all elements. The oxide wt. % was calculated by stoichiometry. The total iron in chromite is expressed in terms of FeO. Fe$^{2+}$ and Fe$^{3+}$ were calculated stoichiometrically by applying the formula:

$$\text{Fe}^{3+} = \frac{2}{3} \left( \text{Fe}^t + \text{Mg} + \text{Mn} - [2\text{Ti} + \frac{1}{2}(\text{Cr} + \text{Al})] \right)$$


Mineral chemistry data (EPMA) of olivine and unaltered chromites are presented in Table 4.1.

Olivine: It can be seen from table 4.1, that $X_{\text{Mg}}$ value of olivine in chromite-bearing dunite, indicate that it is forsterite-rich ($\text{Fo}_{94-95}$).

Chromite: The chemistry of unaltered chromites when plotted on $100\text{Cr}/\text{Cr}+\text{Al}$ and $100\text{Fe}^{3+}/(\text{Cr}+\text{Al}+\text{Fe}^{3+})$ vs. $100\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$ diagrams (Fig. 4.21a a & b), they typically fall in the fields of the stratiform complexes and on the Sinduvalli field of Sargur schist complex (after Srikantappa et. al., 1980).

The EPMA data of the zoned chromites are presented in Table 4.2. There is decrease in Cr, Al and Mg and increase in total Fe from parent chromite (core) to ferritchromit (rim) as seen from the concentration curves of Cr, Fe, Mg and Al vs. points of microprobe analysis (Fig. 4.22a) and to magnetite (rim) (Fig. 4.22b). It is suggested
that this variation is due to increase in the reflectivity from core to ferritchromit and magnetite phases indicating an increase in total iron. These elemental variations indicate that magnetite rim is characterized by extreme iron enrichment and marked depletion of Cr, Al and Mg whereas ferritchromit represents intermediate chemical composition between parent chromite core and the magnetite outer rim.

4.5 P-T CONDITIONS OF METAMORPHISM

In the present study, P-T conditions of metamorphism of ultramafic rocks were estimated based on the metamorphic mineral assemblages in the ultramafic rocks. In the ultramafic rocks, presence of antigorite with forsteritic olivine with talc is recorded. This association indicate the development of antigorite by the reaction; talc + forsterite → antigorite which corresponds to temperatures of around 450º C to 530º C in the P-T diagram (Fig. 4.23) showing equilibria in the system MgO-SiO₂-H₂O (after Turner, 1982).

4.5.1 Olivine–spinel geothermometry

It is well known that olivine and spinel co-exist in a number of geological environments including alpine peridotites, layered intrusions, meteorites, metamorphic assemblages and basaltic flows. Metamorphic reactions in the ultramafic rocks may take place in the presence of olivine. The equilibrium distribution of Fe²⁺ and Mg between these minerals can be expressed as follows:

\[
\frac{1}{2}\text{Fe}_2\text{SiO}_4 + \text{Mg (Cr}_\alpha \text{Al}_\beta \text{Fe}^{3+}_\gamma \text{)}_2 \text{O}_4 = \frac{1}{2} \text{Mg}_2\text{SiO}_4 + \text{Fe (Cr}_\alpha \text{Al}_\beta \text{Fe}^{3+}_\gamma \text{)}_2 \text{O}_4.
\]

Where \(\alpha\), \(\beta\) and \(\gamma\) are the atomic fractions of the respective trivalent cations. This exchange is sensitive to temperature, especially for Cr-rich spinels, and Irvine (1965) has described how it may be used as a geothermometer.
In the present study, temperatures were calculated based on the composition of olivine-chromite using the following equation of Roeder et al., (1979):

\[
t(°K) = \frac{\alpha \cdot 3480 + \beta \cdot 1018 - \gamma \cdot 1720 + 2400}{\alpha \cdot 2.23 + \beta \cdot 2.56 - \gamma \cdot 3.08 - 1.47 + 1.987 \ln K_D}
\]

Where \( \alpha = Cr/Cr+Al+Fe^{3+} \), \( \beta = Al/Cr+Al+Fe^{3+} \) and \( \gamma = Fe^{3+}/Cr+Al+Fe^{3+} \), \( K_D = (X_{Mg}/X_{Fe^{2+}}) \text{ olivine} \cdot (X_{Fe^{2+}}/X_{Mg}) \text{ spinel} \).

This equation has been employed to estimate the temperatures using the chemical composition of relatively unaltered chromites and olivine (Table 4.1). \( \alpha \), \( \beta \) and \( \gamma \) values for unaltered chromites and the distribution co-efficient (\( K_D \)), for the distribution of \( Fe^{2+} \) and \( Mg \) between co-existing olivine and chromite were calculated and are presented in Table 4.1. The estimated temperatures for the olivine-chromite pair of the study area range from 450° C to 490° C following equation of Roeder et al., (1979). Pressures, calculated based on the temperatures obtained from olivine-spinel thermometry, using the P-T diagram (Fig. 4.23) after Turner (1982), range from 2 to 3 K bars.

Therefore, based on the chemistry of olivine and chromite, it is suggested that the chromite-bearing ultramafic rocks have responded to lower amphibolite-grade metamorphism around 500° C and at pressures at 2 to 3 K bars. These temperatures suggest that Mg and \( Fe^{2+} \) have re-equilibrated at subsolidus temperatures in these layered ultramafic intrusions.
4.6 DISCUSSION AND CONCLUSIONS

The chromite bearing ultramafic rocks with marginal gabbroic rocks and chromite ores occurring with in the Peninsular gneisses in the study area exhibit both the primary and secondary textures. The various textural features and their petrogenetic significance, chemistry and mechanism of chromite alteration is discussed as follows:

Euhedral crystals of chromite with large smooth faces with sharp edges and cumulus textures, layering in chromitites, and other primary igneous textures represented by clot, zoned clot, occluded silicate and intergrowth textures are interpreted to represent magmatic features developed as a result of gravity settling process. These features are much similar to stratiform chromitites of Stillwater complex (Jackson, 1963) and for chromite deposits of Sukinda valley, Orissa (Chakraborty and Chakraborty, 1984) and from the Nuggihalli stratiform chromites (Vinayaka et. al., 1999). The chains of chromite intergrowths in the poikilitic partly serpentinised olivine, are formed by simultaneous crystallization of chromite and olivine (now serpentinized) in situ.

Presence of lamellar intergrowth of ilmenite in chromite, is interpreted to be product of oxidation - exsolution of ilmenite from Ti-rich spinel solid solution (Spencer and Lindsley, 1981; Haggerty, 1991). These exsolved ilmenite lamellae in chromite are recrystallised to coarser ilmenite inclusions and rounded segregated grains suggesting a prograde metamorphic alteration, which took place during lower amphibolite grade metamorphism.

The Cr/Fe ratios of chromite range from 1.92 to 2.35, which is typical of stratiform complexes. The chemistry of chromite of the study area is similar to the chromite deposits of Bushveld Igneous Complex, Stillwater complex and Nuggihalli schist belt.
According O’Hanley et. al., (1989) antigorite is a high temperature mineral formed around 460° C in prograde metamorphic regime. According to Voloshina and Petrov (1995), antigorite – talc – tremolite - carbonate assemblage becomes major rock forming minerals in the epidote - amphibolite and amphibolite facies rocks. Reaction between chrome-spinel and host silicate minerals in slowly cooled rocks is well documented (Roeder, 1994). In particular, inter diffusion of Mg and Fe and between chrome-spinel and olivine was calibrated as a geothermometer (e.g., Roeder et. al., 1979; Sack and Ghiorsso, 1991). The range of temperature estimated based on the chemical composition of olivine - chromite pair of the Sindhuvalli chromite deposits in the adjacent Sargur schist complex (Srikantappa et. al., 1980) ranges from 486° C to 750° C indicating that recrystallization has proceeded during regional metamorphic temperatures of upper amphibolite grade and the lower temperature range obtained from the olivine-spinel data may reflect the effect of late stage environment, highly charged with fluid phase. According to Varadarajan and Verma (1982) the ultrabasics of the Sinduvalli-Talur-Doddakanya and the Nuggihalli schist belt, have recrystallized and equilibrated at 700° C and interpreted them to be older than the associated Sargur supracrustal rocks.

Based on these metamorphic mineral assemblages like antigorite with forsteritic olivine and talc, it is concluded that the ultramafic rocks have been subjected to lower amphibolite grade metamorphism. This is in agreement with the temperatures obtained based on the olivine-chromite geothermometer, which gives temperature estimates ranging from 460° C to 500° C at pressures at 2 to 3 K bars. It is suggested that the chromite - bearing ultramafic rocks have experienced lower amphibolite -
grade metamorphism around 500°C and the Mg and Fe\textsuperscript{2+} have been re-equilibrated at subsolidus temperatures in these layered ultramafic rocks.

The EPMA data of the altered phase of olivine such as serpentine and altered phases formed during chromite alteration (Cr-serpentine and chrome-chlorite) of the study area is presented in Table 4.3. From this Table, it can be seen that in serpentine \( \text{SiO}_2 \) varies from 42.82 to 44.32, \( \text{Al}_2\text{O}_3 \) varies from 2.5 to 3.4, \( \text{FeO}^\text{t} \) ranges from 5.54 to 6.23, \( \text{MgO} \) from 35.46 to 36.42 (wt.%) and other elements such as \( \text{TiO}_2 \), \( \text{CaO} \), \( \text{Na}_2\text{O} \), \( \text{K}_2\text{O} \), \( \text{Cr}_2\text{O}_3 \) and \( \text{NiO} \) (wt.%) are present in small proportions and show marginal variation.

EPMA data of Cr-serpentine indicates that \( \text{SiO}_2 \) ranges from 38.89 to 40.84, \( \text{Al}_2\text{O}_3 \) varies from 3.82 to 3.99, \( \text{FeO}^\text{t} \) ranges from 5.79 to 5.84, \( \text{MgO} \) from 38.54 to 39.38 (wt.%) and other elements such as \( \text{TiO}_2 \), \( \text{CaO} \), \( \text{Na}_2\text{O} \), \( \text{K}_2\text{O} \), \( \text{Cr}_2\text{O}_3 \) and \( \text{NiO} \) (wt.%) are present in small proportions and show marginal variation.

EPMA data of chrome-chlorite (Kammerarite) indicates that \( \text{SiO}_2 \) varies from 31.54 to 32.21, \( \text{Al}_2\text{O}_3 \) varies from 14.21 to 15.04, \( \text{FeO}^\text{t} \) ranges from 3.98 to 4.05, \( \text{MgO} \) from 32.98 to 33.23 (wt.%) and other elements such as \( \text{TiO}_2 \) varies from \( \text{CaO} \), \( \text{Na}_2\text{O} \), \( \text{K}_2\text{O} \), \( \text{Cr}_2\text{O}_3 \) and \( \text{NiO} \) (wt.%) are present in small proportions and show marginal variation.

Chromite alteration has been interpreted in different ways. The strongly reflecting rims or zones in chromites of Sukinda area Sachinath Mitra (1972), Boula-Nausahi igneous complex (Mohanti and Sahoo, 1996) and in the Nuggihalli schist belt (Govindaiah et. al., 2002) are interpreted to be formed due to serpentinization. Bliss and MacLean (1975) suggest that alteration of chrome-spinel to ferritchromit represents a product of prograde metamorphic reaction between chrome-spinel core
and surrounding magnetite rims. However, Roeder, (1994) has shown that it could also occur as a result of metamorphic reaction of chrome spinel with the chlorite of host rocks. Burkhard (1993) consider that the decrease in Cr content accompanied by a decrease in Mg and Al content and relative increase in Fe content in the chrome-spinels from ophiolites of the central Alps, is a typical metamorphic alteration pattern for Cr-rich spinels. Devaraju et. al., (2004) opine that the olivine in the chromite-bearing ultramafic rocks of the southeastern boundary of Shimoga schist belt has altered to chlorite through serpentine and antigorite and Al required for chlorite formation was provided to a large extent by deuteric liquids enriched in alumina and chromite with 14 % Al₂O₃. They are also of the opinion that outer zones of chromite grains were involved in autometamorphic and low-grade metamorphic reactions.

In the study area, three combinations of phases are observed during chromite alteration. They are represented by 1) chromite-ferritchromit-magnetite, 2) chromite-ferritchromit and 3) chromite-magnetite. It is suggested that alteration of chromite occurred in two stages. Formation of ferritchromit represents the first stage and formation of magnetite the last stage of alteration. Chemistry of the altered phases of chromite of the study area indicates that there is decrease in Cr, Al and Mg and increase in total Fe from parent chromite (core) to ferritchromit (inner rim) and to magnetite (outer rim). This zonation is a replacement process in which Fe is substituted for Mg, Al and to lesser extent Cr. This replacement has taken place during serpentinization in the lower amphibolite grade metamorphism as suggested for similar chromite ores elsewhere (Roeder, 1994). The chromium released from chromite during alteration, entered in to antigorite and chrome-chlorite, Cr-serpentine,
during prograde metamorphism. Another prograde metamorphic alteration of chromite is recrystallization of exsolved ilmenite lamellae in to coarser ilmenite inclusions and rounded segregated grains, which took place during lower amphibolite grade metamorphism.

4.7 ORE PETROGRAPHY OF V-Ti MAGNETITE ORES

The ore petrographic description including mineralogical and textural aspects have been described earlier by Govindaiah, et. al., 1983, Pathan and Govindaiah, 1986 and Govindaiah et. al., 1989. They reported various primary textures like cumulus texture, exsolution intergrowth textures (magnetite-hogbomite, magnetite-ulvospinel magnetite-pleanoste, magnetite-ilmenite intergrowths, among oxide phases and chalcopyrite-sphalerite-cubnite-pyrrotite intergrowths among sulphide phases).

No attempts have been made to investigate the effects of metamorphism of primary microstructures of these ores, their mineral chemistry and temperature fO₂ conditions of equilibrium. Therefore in the present study the descriptions pertaining to the various stages of modifications of original textural/microstructural features of the V-Ti magnetite ores, during regional amphibole metamorphism mineral chemistry, P-T estimates of equilibrium of these ores are described here.

Ore petrographic studies of gabbroic rocks and V-Ti magnetite layers revealed the presence of Fe-Ti oxides represented by Ti magnetite and ilmenite. The V-Ti magnetite ore bodies are essentially made up of Ti magnetite with model composition varying between 60-70 % and 10-20 % granular ilmenite and up to 10 % pleonaste. The magnetite-gabbro contains up to 25-volume percentage of Ti magnetite and ilmenite. Both these minerals are euhedral in outline producing a polygonal texture.
The Ti magnetite crystals are always larger than the associated euhedral ilmenite crystals. The Ti magnetite grains show gently curved / straight boundaries, which meet, indistinct triple functions having interfacial angles of 120°. Small polyhedral ilmenite crystals are located interstitial between the larger Ti magnetite crystals. The interstitial silicate phases are represented by chlorite and plagioclase, which occupy small tricuspate areas of triple junction points between Ti magnetite crystals or are present as thin films along the grain boundaries. The grain size of Ti magnetite is evidently smaller at places where these intercumulus silicates are present in large quantity or where the silicate surrounds the Ti magnetite crystals. The boundaries are strongly curved in the immediate vicinity of silicate mineral inclusions and the normal polygonal texture is not observed.

The ores of the southeastern part of the Shimoga greenstone belt exhibit various types of microstructures illustrating their behavior during progressive regional metamorphism. Based on the stages of modifications of the original textural microstructural features of these ores during regional amphibolite grade metamorphism, they are classified into four categories for the purpose of description, since there is a gradation noticed among these types.

4.7.1 Ores showing relic microstructures

Primary nature of V-Ti magnetite ores is illustrated by the slightly modified relic microstructures in which the ore grains show development of trellis network of fine ilmenite aligned parallel to (111) planes (Fig. 4.9). The ore grains also contain a set of larger and more widely spaced, ilmenite lamellae. These microintegrowth closely
resemble those of the Ti magnetite from the unmetamorphosed ore of the layered igneous complexes, indicating their primary nature.

Ti magnetite contain short and stumpy laths of pleonaste that are coalesced to form larger more irregularly shaped grains and granules along the margins of the ilmenite lamellae (Fig. 4.9). The pleonaste morphologies indicate that slight modification has taken place.

4.7.2 Ores showing partially modified microstructures

The V-Ti magnetite ores contain abundant granular ilmenite in the form of polygonal crystals (3 mm in size) that are located interstitially between larger Ti magnetite crystals. This granular ilmenite constitutes 15-20 volume percent of the ore. The ilmenite crystals exhibit spineliferous outer rings with a number of small equant pleonaste granules that are located along ilmenite-Ti magnetite interfaces. The pleonaste granules of varying sizes are partially or completely enclosed by ilmenite. Spineliferous ilmenite-Ti magnetite interfaces are highly irregular and serrated in outline (Fig. 4.10).

A number of rounded to sub-rounded and lensoid grains of pleonaste are noticed in partially martitized Ti magnetite grains (Fig. 4.11). This is in direct contrast to the rod-like shape of similar bodies in Ti magnetite from unmetamorphosed ores (Fig. 4.12). The origin of these pleonaste granules is not certain, but they probably represent phases nucleated heterogeneously at dislocation with in the Ti magnetite at approximately the same time as the external granules were developing, as proposed for similar ores by Reynolds (1986).
The Ti magnetite crystals are characterized by the development of robust ilmenite lamellae aligned parallel to (111) in the form of trellis networks (Fig. 4.13). These lamellae are much thicker (15-40 m) in relation to their length (0.05-0.15 mm) than normal (Fig. 4.9). These lamellae exhibit abrupt termination and do not taper gently towards their margins or at mutual intersections, as in the usual case. Some of the lamellae have coalesced to form larger, more irregular grains. A number of smaller rounded to sub rounded pleonaste and ilmenite granules (Figs. 4.13 and 4.14) are noticed in the Ti magnetite grains. These granules are irregularly distributed throughout their Ti magnetite hosts.

4.7.3 Ores showing extensively modified microstructures

Complex vermiform intergrowths of small elongated and rounded ilmenite grains instead of the usual lamellae of ilmenite, are noticed within the Ti magnetite crystals (Figs. 4.15 and 4.16). The ilmenite grains exhibit variation in grain size from 10-40 mm with in the short intervals. In some cases, relic ilmenites are noticed, but they also exhibit minor modification. These intergrowths are aligned parallel to (111) their magnetite hosts. There are three sets of lamellae of ilmenite corresponding to the three fold axis of the symmetry, suggesting their development through the break down spheroidization of the original ilmenite lamellae, as suggested for similar ores elsewhere (Reynolds, 1986). Ti magnetite crystals contain irregular to semi circular bodies of ilmenite and pleonaste indicating an advanced stage of the spheroidization processes (Fig. 4.17). In martitized Ti magnetite ground mass well rounded bodies of ilmenite and sub rounded bodies of pleonaste indicating the final stages of the spheroidization processes (Fig. 4.18).
4.7.4 Recrystallised ores

Anhedral, elongated ilmenite granules are present as stringers along grain boundaries, between neighboring Ti magnetite crystals. These ilmenite granules might have developed as a result of external granule exsolution of ilmenite from Ti magnetite at elevated temperatures during regional metamorphism, which reactivated contemporaneous oxidation-exsolution processes. They are connected to the relic spineliferous ilmenite lamellae that are developed in the adjacent Ti magnetite crystals (Fig. 4.19). Coalescence of number of these ilmenite granules and their continued growth during metamorphic annealing resulted in a relatively coarse grain size and development of well-defined polygonal granoblastic texture in which small granular ilmenite is located between larger and more abundant Ti magnetite crystals. Euhedral to subhedral pleonaste crystals are also located interstitially to the ilmenite and Ti magnetite (Fig. 4.20).

The granular ilmenite consists of a number of thin (1-4 mm wide) closely spaced lamellae of Ti magnetite that are developed parallel to (0001) the central portions (Fig. 4.10). Small granules of pleonaste as well as micrometer sized platelets forming the parts of individual lamellae of magnetite are also noticed.

4.8 CHEMISTRY OF Ti MAGNETITE – ILMENITE

Microprobe analysis of Ti magnetite and ilmenite from gabbro-anorthosite suite of rocks and V-Ti magnetite ores, were carried out using Electron Probe Micro Analyser (EPMA) CAMECA SX50 in the Department of Studies in Geology, Manasagangotri, University of Mysore, Mysore. The analytical conditions were 15 kV and 20 nA of beam current and the beam size is 2-5 microns. Calibrations were done using both
natural mineral and synthetic oxide standards. The accuracy of analytical results was 0.01 wt. % for all elements. The oxide wt % was calculated by stoichiometry.

4.8.1 Ti magnetite

The chemical compositions of Ti magnetite grains from areas that are free from Ti-bearing intergrowths are given in Table 4.4. The ore shows variation in TiO$_2$ content from 3.80-9.01 wt. %. The lower values of TiO$_2$ in Ti magnetite may be due to extensive expulsion of Ti-bearing components by oxidation-exsolution of ilmenite during subsolidus cooling and regional metamorphism. This depletion is also reflected by low values of Al$_2$O$_3$ (0.37 to 1.42 wt. %) and of MgO (0.01 to 0.42 wt. %) due to extensive exsolution of pleonaste. It is also suggested that part of original MgO content of Ti magnetite might have been partitioned into coexisting ilmenite during re-equilibration, both during subsolidus primary cooling and subsequent metamorphism.

FeO$^t$ content in Ti magnetite varies from 85.13 to 90.34 wt. %. It contains 0.16 to 0.72 wt. % of SiO$_2$, and 0.02 to 0.40 wt. % of CaO. Cr$_2$O$_3$ content varies from 0.01 to 0.08 wt. %, thus indicating partial substitution of Cr for Fe$^{+3}$ in Ti magnetite. V$_2$O$_5$ content varies from 1.15 to 1.19 wt. %, which remains in Ti magnetite due to substitution of V$^{3+}$ for Fe$^{3+}$ in the spinel structure.

4.8.2 Ilmenite

EPMA data of ilmenite representing types of intergrown ilmenite and the adjacent granular ilmenite in Ti magnetite of magnetite-gabbro and V-Ti magnetite ore have obtained and presented in the Table 4.4. It is seen from the Table-4.4, that there is only minor compositional variation between different types of intergrown ilmenite and the adjacent granular ilmenite in Ti magnetite, suggesting that extensive re-equilibration
might have taken place at relatively low subsolidus temperatures. The liquidus composition of the ilmenite crystals are not known as their minor element chemistry (Mg and Mn) gets modified by re-equilibration during slow subsolidus cooling. MnO content in the ilmenites of the study area vary from 1.10 to 2.18 wt. % while MgO varies from 0.03 to 0.34 wt. %. The variation in both Mn and Mg is not entirely systematic but the overall trend does appear to be real and may reflect control of primary fractional crystallization. The Mn and Mg content of ilmenite (MnO = 1.10 to 2.18 wt. % and MgO = 0.03 to 0.34 wt. %) are significantly higher than those of the coexisting Ti magnetite (MnO = 0.02 to 0.03 and MgO = 0.03 to 0.42 wt. %), suggesting the preferential partitioning of Mn and Mg into ilmenite relative to Ti magnetite. This preferential partitioning of Mn and Mg into rhombohedral phases relative to cubic phases during crystallization and subsequent subsolidus re-equilibration is a well-established feature (Vincent and Phillips, 1954; Neumann, 1974; Himmelberg and Ford, 1977; Reynolds, 1980 and 1986). It may be seen that small amount of SiO₂ (0.02 to 0.05 wt. %), Al₂O₃ (0.02 to 0.03 wt %), CaO (0.01 to 0.05 wt.% ) are present among the major element. Fairly large concentration of V₂O₅ (2.53 to 2.75 wt %) is present and these values are higher than the values of V₂O₅ found in Ti magnetite (1.15 to 1.19 wt. %). It may be observed that Cr₂O₃ is a rarely present in Ti magnetite (0.01 to 0.08) and ilmenite (0.01 to 0.04).

All the Al₂O₃ and Cr₂O₃ contents are constantly lower than those of co-existing Ti magnetite, It may be presumed that both Al₂O₃ and Cr₂O₃ are preferentially partitioned into co-existing Ti magnetite during crystallization and subsolidus re-equilibration.
4.8.3 Ti magnetite-Ilmenite Geothermometry

The values of mole fractions of Usp (ulvospinel) and Ilm (ilmenite) for three V-Ti magnetite ore samples (Mk-45, Tk-46 and Mh-47) are obtained according to the method of Stormer (1983) from the composition of co-existing Ti magnetite-ilmenite. The values of mole fractions of Usp (ulvospinel) and Ilm (ilmenite) have been presented (Table 4.4) and utilized to obtain the temperatures of equilibrium and fO$_2$ conditions from the T-fO$_2$ graph of Buddington and Lindsley (1964).

The temperature of equilibration for the V-Ti magnetite ores of the study area as observed in the graph of Buddington and Lindsley (1964) range from 580º C to 650º C with fO$_2$ ranging from Log$_{10} = -20.50$ to Log$_{10} = -18.20$ (Table 4.4). This data is plotted on Temperature vs. fO$_2$ diagram (Fig. 4.24) along with the data of Ti magnetite-ilmenite pairs of Skaergaard Buddington and Lindsley (1964), Dublabera of Singhbum district, Bihar (Dasgupta, 1969), basic intrusion of Mayurbhnuj, Orissa (Das and Mukherjee, 1987) and Joida area (Govindaiah et. al., 1997), for comparison and also plotted on modified T-fO$_2$ diagram (Fig. 4.25) of Spencer and Lindsley (1981), along with the data of compositions of co-existing ilmenite and Ti magnetite pair of Bushveld complex (Reynolds, 1985) and Durgagudda-Upper Kanari layered complex (Govindaiah et. al., 1997). In these diagrams, the data of the study area defines a path very close to that of QFM buffer curve.
4.9 P-T CONDITIONS OF METAMORPHISM

As described earlier, in the ultramafic rocks, presence of the antigorite in association with the forsterite olivine and talc indicate the reaction talc + forsterite → antigorite for the development of antigorite. This reaction corresponds to temperatures of around 475º C to 550º C with pressures of 2 K bars in the Mg/(Mg+Si) vs. Tº C diagram (Fig. 4.23) of Turner (1982).

The amphibolite grade of metamorphism has been supplemented by quantification of P-T conditions of metamorphism using the mineral chemistry data of plagioclase-hornblende of gabbroic rocks. Though some of the hornblende grains exhibit clineopyroxene cores, the assemblage is essentially made up of yellow to grass green hornblende + plagioclase. EPMA data of the co-existing hornblende and plagioclase from gabbroic rocks is given in Table 4.5.

The temperatures of metamorphism were calculated based on the chemistry of plagioclase and hornblende using the model of Blundy and Holland (1994), which gives metamorphic temperatures of 540º C to 610º C at pressures of 3 K bars. In summary it is concluded that ultramafic-mafic rocks of the study area have been subjected to amphibolite grade metamorphism (temperature ranging from 475º C to 610º C) at pressure 2 to 3 K bars.

4.10 EFFECTS OF METAMORPHISM ON V-Ti MAGNETITE ORES

As described earlier the ultramafic-mafic complex has been intruded into the Dharwar super group of rocks, this complex has been subjected to the lower amphibolites facies metamorphism (T-475º C to 610º C at 2 to 3 K bars pressure). Estimates of temperatures of and fO2 based on chemical composition of co-existing Ti magnetite-
ilmenite pairs range between 580 to 650º C with fO$_2$ ranging from Log$_{10}$ = -20.50 to Log$_{10}$ = -18.20. According to the magnetite-ilmenite geothermometers of Buddington and Lindsley (1964). Nevertheless, these low temperatures indicate that extensive sub-solidus re-equilibration remained effective down to during regional amphibolite – facies metamorphism and the fO$_2$ was effectively buffered by the oxide assemblages during sub-solidus cooling and that the resulting T-fO$_2$ path is closed to that of the QFM buffer.

The lower temperatures are close to or slightly above the consolute point of the magnetite-ulvospinel solvus, which has been placed at 490º C by Price (1981) and approximately 90º C higher by Lindsley (1981).

The elevated temperatures associated with this regional metamorphism modified the original textural and microstructural relationships.

The morphological modifications of pleonaste body to lensoidal or rounded bodies in the Ti magnetite grains of the study area indicate the earlier stages of a spheroidization process in which the high surface free energies of original plate-likes exsolution bodies are reduced by assuming spherical shapes (Brett, 1964; Vernon, 1976). This process does not operate during the development of primary microstructures in Ti magnetite crystals, due to a concomitant decrease in ionic mobility with falling temperatures (Reynolds, 1985a). The existence of elevated temperatures over a prolonged period of time during regional metamorphism would have provided the driving force for the spheroidization process (Reynolds, 1985a).

Magnetite is sparingly soluble in ilmenite and the presence of oriented magnetite lamellae in ilmenite is generally ascribed to the reduction of an ilmenite-hematite solid
solution under conditions of low oxygen fugacity (Buddington and Lindsley, 1964; Haggerty, 1976). These conditions may have existed during primary subsolidus cooling, but it is probable that these conditions developed during regional metamorphism when the fO$_2$ of the system would have been buffered by the presence of large amounts of magnetite as suggested by Reynolds (1986).

The development of exsolution and oxidation/exsolution lamellae of ilmenite and pleonaste in Ti magnetite occurs with falling temperatures. The resultant decrease in ionic mobility at lower temperatures prevents any large-scale rearrangements and spheroidization during normal cooling processes and the lamellar morphologies are retained. Increased temperature during metamorphism, however, can cause reactivation of the exsolution processes due to an increase in ionic mobility. According to Buddington and Lindsley (1964) and Haggerty (1976) ilmenite is virtually insoluble in magnetite, so that any increase in temperature would favour the breakdown and spheroidization ilmenite lamellae, the degree of modification being a function of the temperature and duration this metamorphic event. The oxygen fugacity during metamorphism would have buffered by the large amount of Ti magnetite in the ores. Microscopic examination indicates that the prevailing fO$_2$ was high enough to allow for stability of the magnetite-ilmenite assemblage rather than the magnetite-ulvospinel assemblage, which would have been stable only at lower fO$_2$. In the present study, the successive stages in the breakdown and spheroidization of the original ilmenite lamellae, which gave rise to almost spheroidal bodies are shown in Figs. 4.10 to 4.17. The final stages of the process, which involved the breakdown of Ti magnetite
hosts and their recrystallization to form polycrystalline aggregates, are shown in Fig. 4.20.

The discrete pleonaste grains cannot represent co-precipitated phases, as extensive miscibility exists between the various spinel end-members at elevated temperatures. In particular solid solution exists between magnetite and hercynite (FeAl$_2$O$_4$) above 860º C (Turnock and Eugster, 1962). Miscibility between Fe-rich pleonaste and magnetite at low temperatures is, however, restricted and ex-solution will occur during subsequent slow cooling (Reynolds, 1986). The original ore would have consisted of Ti magnetite crystals. These crystals consist of ex-solved pleonaste rods aligned parallel to (111) planes and also externally ex-solved pleonaste granules along the Ti magnetite grain boundaries. Coarsening of original ex-solved bodies and extensive external granule ex-solution of pleonaste from the grain boundaries of Ti magnetite crystals, might have taken place due to reactivation of ex-solution processes in response to increased temperatures during regional metamorphism. The coalescence of a number of small externally ex-solved granules of pleonaste resulted in the formation of discrete large grains during metamorphic annealing.

In a similar manner to that of pleonaste, abundant coarse granular ilmenite and stringers of ilmenite along grain boundaries are also developed as a result of external granule ex-solution of ilmenite from Ti magnetite during metamorphism. Elevated temperatures also might have allowed for the reactivation of annealing processes that resulted in the gradual recrystallization of the ore.

This process is dominated by solid-state grain boundary migration (Coble and Burke, 1963; Thummler and Thomma, 1967; Reynolds, 1985b, 1986) and might have
promoted the coalescence of numbers of small grains to form larger crystals, which are located at triple junction points. The approach towards equilibrium conditions during annealing resulted in the development of well-defined granoblastic polygonal textures in which larger Ti magnetite crystals are the dominant phases with minor amounts of smaller ilmenite grains and silicates. The reactivated contemporaneous oxidation-exsolution processes effectively perged the Ti magnetite of its Ti-bearing components resulting in a paucity of ilmenite intergrowths and low residual TiO$_2$ contents as suggested for similar ores (Reynolds, 1986)