CHAPTER VI

SUMMARY
AND
CONCLUSIONS
The area under investigation is located around the village Masanikere lying between lat. $13^{\circ}49'$ to $13^{\circ}54'$ and long. $75^{\circ}54'$ to $76^{\circ}5'$. It forms the southeastern portion of Shimoga greenstone belt of the Karnataka craton.

The rock types recognised in the area are granitic gneisses, schists, quartzites, ultramafics, gabbro-anorthosite suite of rocks with V-Ti-magnetite ore bands. Besides, there are a number of dolerite dykes and quartz veins noticed in the area. V-Ti-Fe-Cu ore mineralization is found within gabbro-anorthosite members, particularly confined to magnetite-gabbro, indicating a distinct lithologic control for the ore mineralization in the area. Brief description of each one of the important rock types and ore minerals is given in the following pages.

6.1 GRANITIC GNEISSES

Larger part of the study area is occupied by the granitic gneisses of the Peninsular Gneissic Complex which form the basement for the quartz-chlorite-calcite schists and quartzites of Chitradurga Group. Extensive outcrops of these rocks are seen in the form of island like domal masses and also as prominent isolated outcrops. They exhibit well developed gneissic foliation. They are grey coloured and
medium grained. Mineralogically, they are composed predominantly of quartz, plagioclase (An$_{25}$ to An$_{45}$), K-felspar and biotite with accessories like magnetite, sphene and apatite. Biotite is the only mafic mineral found in these rocks. Plagioclase is generally more abundant than K-felspar. K-felspar is represented by microcline.

6.2 SCHISTS

Schists are the typical low grade metamorphic rocks with well developed schistosity noticed in the area. Prominent exposures occur as patches, parallel and discontinuous bands and are surrounded by granitic gneisses. They show unconformable relationship with the basement granitic gneisses. Based on the mineral assemblages, two varieties of schists are recognised, viz. (1) quartz-chlorite-calcite schist and (2) quartz-chlorite schist. Both these varieties exhibit well developed schistose texture. Mineralogically, they are composed essentially of quartz, chlorite and calcite in the quartz-chlorite-calcite schist and quartz and chlorite with minor amounts of calcite in the quartz-chlorite schist. They are intruded by ultramafics, gabbro-anorthosite suite of rocks and V-Ti-magnetite ore bands and also dolerite dykes.

6.3 QUARTZITES

Quartzites are exposed as discontinuous bands of variable length and width at many places interspersed with
the schists of the area. Five quartzite bands have been recognised in the area, of which three bands are interspersed with schists and the other two bands are exposed in the basement granitic gneiss complex. They are bluish grey in colour, fine grained and hard in nature. They are essentially made up of quartz with minor amount of muscovite and magnetite.

6.4 ULTRAMAFICS

Ultramafics occur as patches, lensoid bodies and parallel bands intruding into the schists of the area. They are closely associated with gabbro-anorthosite suite of rocks. Bore hole data indicates that they occur as parallel bands alternating with the gabbro-anorthosite layers. These rocks are highly deformed and recrystallised. They are represented by serpentinites and ultramafic schists, viz. (1) tremolite-actinolite shist and (2) talc-chlorite schist. Among these varieties, serpentinites are more abundantly exposed in the area. Field relations of ultramafics indicates that they are intrusives into the quartz-chlorite-calcite schist of the study area.

Chemical study of ultramafics reveals that both major and trace elements have little variation in their distribution among serpentinites, tremolite-actinolite schist. Silica content is somewhat higher in talc-chlorite schist. Serpentinites and tremolite-actinolite schist are olivine normative and talc-chlorite schist is quartz
normative, indicating an addition of quartz during migmatitization. Ultramafic s exhibit high Mg/Mg+Fe++ ratios, high MgO content and low TiO₂ and Al₂O₃ contents which indicates that they have been formed by a high degree of partial melting of mantle peridotite. They are mainly peridotitic in nature as revealed by MgO-CaO-Al₂O₃ diagram. TiO₂ /Al₂O₃ and TiO₂/CaO ratios for the ultramaics of the study area are clearly nonchondritic indicating nonkomatiitic nature of these rocks. Ultramaics have high Ni and Cr values. Ni and Cr versus MgO correlation of these rocks is consistent with the early separation of olivine and chromite from the magma that resulted in low concentrations of these elements in the late differentiates.

6.5 GABBRO-ANORTHOSITE SUITE OF ROCKS

There are a number of gabbro-anorthosite bodies of variable dimensions from less than 1 sq.km. to 2.5 sq. kms. carrying bands and lenses of V-Ti-magnetite and disseminations of sulphides. Gabbro-anorthosite rocks occur as patches and lensoid bodies showing gradational relationship with V-Ti-magnetite ore bodies. They are medium grained. They are closely associated with ultramaics in the study area. These rocks exhibit varied fabrics essentially due to recrystallization of plagioclase caused by deformation and metamorphism. Considering the extent of recrystallization in these rocks three types have been recognised. They are: (1) tectonically least deformed varieties, (2) partly recrystallized varieties and (3) fine
grained fully recrystallized varieties. These rocks preserve igneous characters to a great extent. A well defined relict cumulus texture wherein hornblende fills the interstices of plagioclase crystals is preserved. Least deformed varieties contain plagioclase megacrysts which exhibit polygonal xenomorphic fabric. Megacryst of plagioclase are broken down into fine grains in partly recrystallized varieties. Polyhedral granular texture with near equant finer grains of plagioclase and crude orientation is seen in thoroughly recrystallized varieties. Mineralogically, these rocks are composed of plagioclase, chloritized hornblende, magnetite, uralitized pyroxene, calcite, pyrite and chalcopyrite in various proportions. Based on the modal plagioclase content, the gabbro-anorthosite suite of rocks are classified according to definitions given by Windley (1973), as magnetite-gabbro, gabbro, anorthositic-gabbro, gabbroic anorthosite and anorthosite.

Magnetite-gabbro is medium grained with greyish black in colour. It exhibit excellent cumulus texture. It is composed essentially of saussuritized plagioclase, ilmenite rich magnetite, chloritized hornblende with minor amounts of calcite, chalcopyrite and pyrite. The ilmenite rich magnetite get seggregated to give rise to ore bands/layers.

Gabbro occurs as patches and lensoid bodies. It is
leucocratic, hard and medium grained. It exhibits a well defined relict cumulus texture, wherein chloritized hornblende fills the interstices of plagioclase crystals.

Gabbro on further depletion of chloritized hornblende grades on to anorthositic gabbro, gabbroic anorthosite and anorthosite.

Anorthite content of plagioclase in these rocks ranges from $\text{An}_{40}$ to $\text{An}_{70}$ which is within the range of An content of layered anorthositic rocks. The spread in anorthite content values may be the result of amphibolite-grade retrogression as evidenced by the appearance of hornblende and zoisite-clinozoisite in the Masanikere gabbro-anorthosite suite of rocks. A similar spread in anorthite content in the anorthosite suite of rocks of the Nuggihalli schist belt was observed with the anorthite values ranging from $\text{An}_{51}$ to $\text{An}_{95}$ with an average of $\text{An}_{75}$ (Nijagunappa and Naganna, 1983). Anorthite content of Masanikere anorthositic rocks are slightly lower than the anorthositic rocks of Nuggihalli. Abundance of carlsbad and combined carlsbad-albite laws exhibited by plagioclase of the anorthositic rocks of the study area are considered to be characteristic of igneous nature. The twinned plagioclase crystals are fractured and the twin lamellae are displaced after fracturing. Plagioclase, in all cases, is saussuritized and composed of granular fine grained alteration material which consists of zoisite and epidote and minor amounts of clinozoisite. Rarely it is possible to
identify the original pyroxene because of intensive uralitization noticed in the gabbro-anorthosite suite of rocks.

The gabbro-anorthosite suite of rocks have been analysed for major and trace elements. They show little variation in silica and an appreciable variation in $Al_2O_3$ and $CaO$ contents which increase from gabbroic rocks to anorthositic rocks. $Fe_2O_3$ and $TiO_2$ show an increasing trend from anorthosite to gabbro and to magnetite-gabbros. Sulphur up to 0.45% is noticed in magnetite-gabbro which reflects the presence of sulphides.

AFM diagram for the ultramafics and gabbro-anorthosite suite of rocks reveals an alkali-poor predominantly tholeiitic trend with a moderate high degree of iron enrichment.

Major elemental variations with the index of fractionation (100 FeO/(FeO+MgO) reveals that $SiO_2$ is fairly uniform throughout and $Al_2O_3$, $CaO$, $Na_2O$ and $TiO_2$ all increase fairly with fractionation.

Following Barton et al. (1979) an attempt is made to know the composition of parental magma which is indicated to be 6.4% of $Al_2O_3$ and 9.87 % of $MgO$, which do not tally with any known magma type. This is not surprising if the trend of magnetite-gabbros is also considered which reflects yet another magnetite fractionation (MFT) trend. If one
assumes that isochemical crystallization occurred throughout and that the pyroxene fractionation immediately followed that of olivine, the MFT can still upset the estimated parental magma composition. Further, the pyroxene fractionation is not accounted for by Barton et al. (1979), whereas pyroxene appears to have been a significant cumulus component in the Masanikere gabbro-anorthosite suite of rocks. Hence, it is felt that major element model as used by Barton et al. (1979) have no general applicability to the rocks of Masanikere area.

Trace element data for the gabbro-anorthosite suite of rocks and ultramafics indicates that the compatible elements such as Cr and Ni are strongly enriched in ultramafic rocks, while Sr is enriched in the gabbro-anorthosite suite of rocks. The incompatible elements such as Zr in all these rocks do not exceed 30 ppm. These features confirm the dominantly cumulus nature of the Masanikere complex with cumulus olivine and pyroxene controlling the chemistry of the ultramafics and the cumulus plagioclase felspar dominating the chemistry of gabbro-anorthosite suite of rocks.

In the total FeO-MgO diagram, the average trend of anorthositic rocks from the study area correspond to the Archaean anorthositic rocks of other well known areas of the world. Therefore, it is concluded that the anorthositic rocks of the study area are Archaean.
Origin of gabbro-anorthosite suite of rocks is often debated on two opposing views, viz. (a) metasedimentary and (b) magmatic. Plot of Niggli al-alk versus C and Niggli 'mg' against Ni and Cr confirm the igneous crystallization of the gabbro-anorthosite suite of rocks. MgO-CaO-Al_2O_3 triangular diagram and CaO/Al_2O_3 ratios are suggestive of tholeiitic nature of the parent magma for the gabbro-anorthosite suite of rocks of the study area.

6.6 V-Ti-Magnetite and Sulphide Ores

V-Ti-magnetite deposits in the Masanikere area distributed over an area of about 83 sq.kms. in the southeastern part of the Shimoga schist belt, which is one of the several greenstone belts of the Karnataka craton. Several V-Ti-magnetite ore bodies occur as discontinuous outcrops and also as parallel bands showing gradational contact with the gabbro-anorthosite suite of rocks. These ore bodies are confined to the predominant ridges and hilly regions spreading float ore pebbles all along their flanks and plains around the ore bodies of the area. V-Ti-magnetite bodies of varying dimensions occur in the area. The major bodies have 3 to 50 m. of surface width and length of 0.5 to 1 km. The surface exposures are traversed by twosets of joints and the resultant blocks are rectangular. The ore samples are massive, hard, compact and medium to fine grained. They are steel grey to greyish black in colours. At some places, the weathered ores exhibit brown colouration. Exploratory drilling carried out
Masanikere indicates that these ore deposits consist of closely spaced parallel bands of magnetite and magnetite-bearing gabbro-anorthosite layers alternating with the ultramafic rocks. The V-Ti-magnetite ore bodies are gradational to the gabbro-anorthosite layers which is similar to the relationship observed in the Bushveld Igneous Complex (Willemse, 1969; Tankard, et al., 1980) and in the Nuggihalli ultramafic-gabbro complex (Nijagunappa and Naganna, 1983). The width of the V-Ti-magnetite layers varies from 0.3 to 8 m. A gradational passage from anorthosite, gabbro and magnetite-gabbro to V-Ti-magnetite bands/layers is a strong evidence of accumulative origin indicating that V-Ti-magnetites are the cumulate phases of gabbros. All the ore bodies of the study area are described under four groups, viz. (a) Masanikere deposit, (b) Taverekere deposit (c) Magynthahally deposit and (d) Ubrani deposit.

Ore microscopic studies of V-Ti-magnetite ores and magnetite-gabbro of the study area reveals the presence of both oxide and sulphide assemblages indicating two phases of ore mineralization. The oxide phase predominates over the sulphide phase in the area. The oxide assemblage is represented by hoegbomite, magnetite, ulvöspinel, pleonaste, ilmenite, rutile, hematite (martite), maghemite and goethite. The sulphide assemblage is represented by pyrite, chalcopyrite-I and chalcopyrite-II as dominant phases followed by cubanite, pyrrhotite, sphalerite and
Occurrence of hoegbomite is reported for the first time from the V-Ti-magnetite ore bodies of the area and second time from India. It occurs in two generations. The prismatic crystals of hoegbomite which occurs in close contact with magnetite crystals is regarded as primary igneous constituents of the ores and the small droplets/scales/needles of hoegbomite are considered to represent exsolved phase in the magnetite crystals.

Magnetite is the most predominant primary oxide mineral which constitute the bulk of the V-Ti-magnetite ore bodies and essential constituent of magnetite gabbros. It is characterised by the development of microintergrowths of lamellae of ulvospinel along (100) planes, two generations of pleonaste along (100) planes, lamellar, granular, emulsion and graphic intergrowths of ilmenite.

Occurrence of both ulvospinel and pleonaste has been reported for the first time from the Masanikere area. Ulvospinel which occurs as fine hair like network of lamellae oriented in (100) planes of magnetite is believed to be formed by exsolution process which has taken place at lower temperature. Pleonaste which occurs in two generations in the (100) planes of magnetite is also formed by exsolution process.

The crystallographic orientation of fine lamellae of
Ilmenite aligned parallel to (111) planes of magnetite producing well developed equilateral triangles is a prominent feature noticed in the ores. Absence of any replacement relationship indicates an unmixing origin for the lamellar ilmenite. Granular intergrowth of ilmenite with magnetite suggests simultaneous formation of ilmenite with magnetite in the ores of the area. The major types of ilmenite bearing intergrowths that have developed in the ores of the area are (1) broad ilmenite lamellae and external granules that are developed due to increased oxygen fugacity at a highest subsolidus temperatures (2) the fine ilmenite lamellae that are developed at lower temperature than the larger broad lamellae and fine internal granules that are developed under conditions of high oxygen fugacity during subsolidus cooling above the magnetite-ulvöspinel solvus (Buddington and Lindsley, 1964; Reynolds, 1985) and (3) oxidation of earlier formed ulvöspinel to second generation ilmenite which is termed protoilmenite (Willemse, 1969) which caused a patchy optical anisotropy in Ti-magnetite grains.

Ilmenite exhibiting emulsion intergrowth with magnetite is thought to be the result of exsolution (Ramdohr, 1969).

Martitization of magnetite at different stages is the prominent secondary textural feature noticed in the V-Ti-magnetite ores, though rims of goethite is found around magnetite, ilmenite and hematite. The primary fabric in magnetite is disrupted due to intensive oxidation process.
and pseudomorphs of hematite after magnetite are formed due to oxidation and the product of oxidation is colloquially referred to as martite. Intensity of martitization decreased as we go deep as indicated by the core samples of the area. Martite replaces magnetite along the octohedral planes producing triangular network and also along grain boundaries.

Maghemite is the secondary oxidised product of magnetite. The transformation of magnetite to maghemite has taken place along the cracks instead of cleavage planes.

Goethite is the hydrated product of magnetite. It replaces magnetite, ilmenite and hematite along the grain boundaries forming colloform bands.

Sulphides are found as disseminations throughout the V-Ti-magnetite ores and magnetite-gabbro samples as revealed in the core samples of the area. Sulphides are not noticed in the surface outcrops of these lithological units. However, sulphide mineralization is indicated by the presence of copper carbonates such as malachite and azurite stains and encrustations on the surface outcrops of V-Ti-magnetite ores. Among the sulphides, pyrite is the most abundant mineral. It occurs as euhedral crystals exhibiting fracturing and marginal granulation. It is replaced by magnetite and chalcopyrite-II.

Chalcopyrite occurs in two generations. Chalcopyrite-I
which occurs as hypidiomorphic grains and droplets was held in liquid immiscibility in magnetite and formed along with magnetites. Chalcopyrite-II which occurs as hypidiomorphic to allotriomorphic grains is more abundant than chalcopyrite-I. It replaces pyrite and magnetite mainly along grain boundaries. It fills the fractures in pyrite and magnetite indicating the initial stage of replacement.

Sphalerite starlets in chalcopyrite II are interpreted as exsolution products indicating relatively a high temperature. Lamellae of pyrrhotite in chalcopyrite-II have also been formed by exsolution at high temperature.

The lamellae of cubanite in chalcopyrite indicates their formation by exsolution. Covellite replaces chalcopyrite to chalcopyrite-II along grain boundaries forming colloform bands/rims.

Bulk chemical analyses are carried on the V-Ti-magnetite ore samples collected from all the four deposits for both surface and bore hole samples. They have been chemically analysed both for major and trace elements. The important geochemical characters noticed are: (i) both TiO$_2$ content and Fe$_2$O$_3$ (total iron) in these ores increase progressively as we go upwards on to the surface, (ii) V$_2$O$_5$ content exhibits an antipathetic relationship to TiO$_2$ in these ores, (iii) SiO$_2$, Al$_2$O$_3$, MgO, Na$_2$O, K$_2$O and MnO contents do not show any consistent variations in their distribution in these ores.

178
Absence of any discrete vanadium mineral as indicated by optical studies, a strong positive correlation between $V_2O_5$ and total iron and a negative correlation obtained for $V_2O_5$ and TiO$_2$ contents of the V-Ti-magnetite ores suggest that vanadium may be replacing iron in the structure of magnetite rather than in ilmenite.

A significant positive correlation between V and Fe/Ti ratio indicate an increase of vanadium with Fe/Ti ratio suggesting the relative amount of magnetite and ilmenite in these ores and partition of minor elements between magnetite and ilmenite. The high Fe/Ti ratio (6.58 to 10.95) in these deposits is due to a relatively low TiO$_2$ content suggesting a late-stage crystallization during magmatic differentiation (Lister, 1966).

Field relations, petrological, mineralogical and geochemical characteristics of V-Ti-magnetite ore bodies as well as those of their host gabbro-anorthosite suite of rocks indicate that the genesis of V-Ti-magnetite layers/bands is intimately related to fractional crystallization processes that were responsible for the formation of their host rocks. The distribution and geologic relationships of these ores clearly indicate that they are the integral components of the layered sequence of gabbro-anorthosite and ultramafics of the study area.

The chemical data and elemental variations indicate that these ores and gabbro-anorthosite suite of rocks are
the result of fractional crystallization of iron-rich tholeiitic magma. Their cumulus textures indicate the enrichment of Fe and Ti in the residual liquids which might have migrated downwards through the early formed mesh of silicates.

The development of monomineralic layers in stratiform basic intrusions has been a subject of considerable debate. The general consensus until recently is that monomineralic rocks are formed by 'magmatic sedimentation processes' that resulted in the accumulation of precipitated crystals in layers on the floor of the magma chamber (Wager and Brown, 1968). These layers may have formed by a simple process of gravitative crystal settling (Wager et al., 1960; Irvine, 1979). In contrast, it has recently been recognised that layering in igneous complexes is in many cases not the result of crystal settling processes, but due to the dominant mechanism known as insitu bottom crystallization (Campbell, 1977, 1978; McBirney and Nyes, 1979; Irvine, 1982). Campbell et al. (1978) have experimentally shown that the plagioclase will float in relatively dense iron-enriched basaltic liquids of the type expected to be present during the later stages of fractional crystallization.

In the present investigation, as the plagioclase is the main constituent of gabbro-anorthosite rocks and magnetite-gabbros, it is difficult to reconcile any mechanism involving the gravitational accumulation of
plagioclase crystals with these facts. The large scale insitu bottom crystallization of plagioclase might have resulted in a marked increase in the total Fe content and a concomitant increase in density of the residual liquids which might have accumulated to form stagnant layers on the floor of the magma chamber, from which large quantities of V-Ti-magnetites might have crystallized. The bulk of V-Ti-magnetite is formed by insitu bottom crystallization. The nucleation and growth of magnetite within the layers and gravitative settling of these crystals might have augmented the growth of the layers (Reynolds, 1985). Therefore, it can be concluded that though the V-Ti-magnetite layers are considered to have developed largely by insitu bottom crystallization, but the possibility of gravitational settling of magnetite crystals is not entirely discounted.

Copper in the Masanikere area is concentrated in the V-Ti-magnetite ore and magnetite-gabbros and ranges from 1035 to 4760 ppm in these rocks. Copper content increases from surface outcrops to depth is noticed in the area. Geochemically, Cu$^{2+}$ is closer to Fe$^{2+}$ among major elements and Cu:Fe ratio increases with fractionation (Taylor, 1965). Copper content is initially low in the magma as indicated by the chalcopyrite-I which was held in liquid immiscibility and formed along with the magnetites. Cu:Fe ratio has increased with fractionation and copper content has increased which is indicated by abundant quantity of the chalcopyrite-II and formation of cubanite and pyrrhotite.
later by exsolution process.

Field relations indicate that V-Ti-magnetite deposits with gabbro-anorthosite suite of rocks and ultramafic s of the study area are intruded into the quartz-chlorite-calcite schist of Chitradurga Group of Dharwar Supergroup. The layered nature of V-Ti-magnetite ores, their cumulus textures and close association with ultramafic-mafic suite of rocks and tectonic setting suggest that the Masanikere complex is not of alpine type, but a part of stratified igneous complexes.