CHAPTER IV

MINERALOGY AND TEXTURES OF V–Ti–MAGNETITE AND SULPHIDE ORES
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V-Ti-MAGNETITE AND SULPHIDE ORES

4.1 INTRODUCTION

It is now well established that earth's magnetic field passes through periodic and episodic cycles of polarity reversals. However, the highlights of research during the early part of the last decade indicates the possibility that still exists that some rocks would show or perhaps undergo a self-reversal magnetic process that would result in a direction that is contrary to the direction of the ambient geomagnetic field. The rocks carry a magnetic signature because of the presence of iron-titanium oxides which, in magnetic measurements, reflect the state of the magnetic field at the time of the rocks were formed. Oxidation and exsolution are the major and most important modifying mineralogical parameters by which any subsequent magnetic measurements will be modified. At valency levels the detection limits are pronounced in magnetic measurements but it is beyond the resolution of the ore microscopist. However, the heterogeneity and complexity of a major portion of iron-titanium oxides in all eruptive, hypabyssal and plutonic rocks is decidedly on the sides of the ore-petrologist.

The problems of magnetic self-reversals are less
prominent now, but continues and will remain a significant unanswered mineral-geophysical question unless a renewed and imaginative frontal attack is made.

Since a well characterised optical database is an essential and prime pre-requisite in understanding the iron-titanium oxide mineral modification, based primarily on oxidation and exsolution, an attempt is made in the present investigation to give a detailed microscopic descriptions of oxide assemblage and the associated sulphide assemblage accompanied by photomicrographic coverage. The microscopic descriptions include the optical properties like colour, shape, pleochroism, isotropism versus anisotropism, mode of occurrence, micro-chemical tests, optical constants like reflectivity in green light, Vicker's microindentation hardness of different ore minerals, various ore textures and their interpretations. Based on the various textural features observed in V-Ti-magnetite ores and the associated sulphides of the study area, paragenesis of individual ore minerals is discussed and a probable paragenetic diagram has been drawn in order to know the order in which different ore minerals are formed. The paragenetic diagram is presented in Table 6.

4.2 MINERAGRAPHY

A detailed ore microscopic study of polished V-Ti-magnetite ores and magnetite-gabbro of the Masanikere area reveals the presence of both oxide and sulphide assemblages.
The oxide assemblage predominates over the sulphide assemblage.

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 covellite.

4.2.1 Oxide assemblage

4.2.1.1 Hoegbomite:

A detailed optical investigation both in transmitted light and reflected light of V-Ti-magnetite ore and magnetite-gabbro has revealed the presence of hoegbomite. The mineral occurs as (i) coarse elongated prismatic/subhedral crystals (Fig. 4.1), measuring upto 0.4 mm. x 0.15 mm, (ii) as small droplets (0.038 mm. x 0.025 mm)/patches (0.095 mm. x 0.025 mm) and scales/needles/rods (0.29 x 0.03 mm) oriented in one or two directions within the magnetite crystals (Fig. 4.2). The mineral is observed in all the four V-Ti-magnetite ore deposits, viz. Masanikere deposit, Taverekere deposit, Magyathahally deposit and Ubrani deposit of the study area.

In transmitted light, the mineral is honey brown in colour. It exhibits strong pleochroism in yellowish brown
and E=dark brown colour. It shows one set of well developed longitudinal cleavages, strong absorption parallel to elongated portion of the mineral, distinct anisotropism in shades of brown and bluish green colours, polysynthetic twinning and uniaxial negative characters.

In reflected light, hoegbomite exhibits greyish white colour with moderate reflectivity. Reflection pleochroism is weak in air, but it is distinct on twin boundaries in oil and anisotropism is moderate in air and it is masked by strong yellowish brown internal reflections. Fracturing and granulation of prismatic crystals of hoegbomite due to deformation is a common feature noticed in the ores.

4.2.1.2 Magnetite

Magnetite is the most predominant and abundant oxide mineral which constitute the bulk of the V-Ti-magnetite ore bodies (magnetite ranges from 70 to 80%, modally) and magnetite-gabbro (modally, magnetite ranges from 25 to 45%). It is greyish white in colour with brownish tint at places. The mean reflectivity of the mineral in green light is 20.31% and Vicker's microindentation hardness ranges from 425 Kg/sq.mm. to 690 Kg/sq.mm. The mineral is non-pleochroic and isotropic in character. It occurs as coarse to fine idiomorphic (Fig. 4.3) to hypidiomorphic (Fig. 4.4) and xenomorphic crystals (Fig. 4.5) showing martitization at all stages. The mineral contains exsolution bodies in the form of lamellae of ulvöspinel, pleonaste, ilmenite and
droplets/scales/rods of hoegbomite, and idiomorphic to xenomorphic grains of chalcopyrite-1. It is characterised by the development of lamellar-crystallographic, granular and emulsion intergrowth of ilmenite. Optical study does not disclose any separate vanadium bearing mineral indicating that vanadium may occur preferentially in the structure of magnetite.

Martitization of magnetite is gradual and a common feature noticed in almost all ore samples. A few grains of magnetite are not affected by martitization (Fig. 4.3). Some grains are completely martitized (Fig. 4.6), and others are partially martitized (Fig.4.5). The pseudomorphs of hematite after magnetite are formed and the end product of oxidation is colloquially known as martite. The primary fabric in magnetite is disrupted due to the intensive oxidation process. Magnetite is replaced by martite mainly along octahedral planes and grain boundaries (Fig. 4.5). Magnetite is also oxidised to maghemite, but the transformation of magnetite to magnetite is much less regular (Fig. 4.7) than in martite. Magnetite is altered to goethite mainly along the grain boundaries. Sometimes replacement by goethite proceeds into the grains leaving relict magnetite. The mineral shows pitted appearance having lot of silicate inclusions and high degree of corrosion, indicating magmatic origin of magnetite. Magnetite grains are deformed which is indicated by fracturing, brecciation (Fig. 4.8) and pressure fringes.
Etch test indicates that magnetite is positive to HCl as the mineral turned brown and it is negative to HNO₃ and KOH.

4.2.1.3 Ulvöspinel

The mineral occurs in the form of finer hair like network of lamellae aligned parallel to (100) planes of magnetite giving rise to cloth microtexture (Fig. 4.9). In some cases the fine network of ulvöspinel is partially oxidised to ilmenite (Fig. 4.10). The mineral is closely associated with pleonaste in magnetite.

4.2.1.4 Pleonaste

Pleonaste is grey in colour with low reflectivity and isotropic. Two generations of mutually perpendicular pleonaste lamellae are noticed in magnetite host (Fig. 4.11). The first generation consists of a coarse network of mutually perpendicular lamellae aligned parallel to (100) planes of magnetite and the second generation consists of smaller pleonaste lamellae that are aligned parallel to first generation. However, pleonaste is not observed within ilmenite or along the magnetite-magnetite grain boundaries.

4.2.1.5 Ilmenite

Ilmenite is pinkish brown in colour and distinctly pleochroic under oil in shades of pinkish brown and brown. It is anisotropic in shades of grey and greyish brown in oil. The mean reflectivity of ilmenite in green light is 18.74% and the Vicker's microindentation hardness is found
to be 578 Kg/sq.mm. Etch test on ilmenite indicates that it is negative to all standard reagents except HF. The mineral occurs in four forms closely associated with magnetite as (a) lamellar-crystallographic intergrowth with magnetite in which well defined both coarse lamellae (Fig. 4.13) and fine lamellae (Fig. 4.14) of ilmenite are aligned parallel to the octahedral planes and cubic parting planes of magnetite and also occur in two sets of lamellae of uniform thickness oriented at right angles (Fig. 4.15), and two sets of ilmenite lamellae of varying thickness aligned parallel to (111) and (110) planes of magnetite host (Fig. 4.16) (b) as granular aggregates with polygonal grain boundaries showing smooth and gently curving contacts without any tongues or protuberances into magnetite (Fig.4.17), (c) as fine droplets/blebs/worm like grains in magnetite giving rise to emulsion intergrowth (Fig. 4.18) and (d) unoriented grains found graphically intergrown with magnetite.

The polygonal granular ilmenite contains exsolution discs and blebs of hematite that are restricted to central or inner parts of ilmenite (Fig. 4.19). Frequently thin elongated lamellae of hematite oriented in the (0001) planes of ilmenite are also noticed (Fig. 4.20). The size of these exsolution bodies varies greatly and perhaps related to the size of the ilmenite grains.

Larger grains of ilmenite exhibit polysynthetic twinning (Fig. 4.21). Bending and displacement of coarse
lamellae of ilmenite after fracturing due to deformation is a common feature noticed in the V-Ti-magnetite ores of the study area. Neither ilmenite replaces other minerals nor it is being replaced. The sharp and bold grain boundaries of ilmenite against magnetite grains indicate that no replacement relationship exists between the two minerals indicating that these intergrowths are of primary crystallization.

4.2.1.6 Rutile

Rutile is a secondary alteration product after ilmenite. It is observed only in some ore samples.

4.2.1.7 Maghemite

Maghemite is bluish grey with a distinct bluish tint against magnetite. Its reflectivity is higher than magnetite but is relatively lower than hematite. It is non-pleochroic and optically isotropic without any internal reflections. Maghemite is the secondary oxidised product of magnetite. The transformation of magnetite to maghemite has taken place mainly along the cracks that are developed due to reduction in volume from the magnetite to maghemite (Fig. 4.7). Though maghemite is metastable form of Fe₂O₃ with the structure of magnetite. The impurities like vanadium and titanium appear to favour the formation of maghemite from magnetite and to make maghemite more stable.
Hematite and martite are grouped together for the purpose of description because they exhibit similar optical properties, excepting the fact that the martite is secondary mineral after magnetite. Both hematite and martite are greyish white in colour with a bluish tint. But martite gives a distinct bluish tint particularly under oil. They are non-pleochroic and anisotropic in shades of greenish grey and light brownish tints. Deep red internal reflections are distinctly noticed. Martite as xenomorphic grains give the spongy appearance at places in some samples. They exhibit a relatively higher reflectivity than magnetite, ilmenite and even goethite.

The phenomenon of martitization in magnetite is noticed at almost all stages particularly in surface ore samples of V-Ti-magnetite and magnetite-gabbro. However, the intensity of martitization of magnetite decreases as we go deep which is evidently seen in the core samples of the area. It is regular in some samples and irregular in other samples. In most of the samples the alteration of the magnetite to hematite is almost complete (Fig. 4.7). The pseudomorphs of hematite after magnetite are described as martite and it is always diagnostic. In some samples, martitization is partial, where martite is found to retain the shape of the magnetite grains (Fig. 4.7). The presence of relics of magnetite grains in martite gives the impression of graphic
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texture. Martite replaces magnetite mainly along the octahedral planes producing triangular network and also grain boundaries (Fig. 4.22).

5.4.1.9 Goethite

Goethite is greyish in colour with moderate reflectivity. It is non-pleochroic and feebly anisotropic in shades of greenish blue and greenish grey. The combined effects of both oxidation and hydration processes on magnetite are referred to as oxyhydration. Goethite is the hydrated product of magnetite. It replaces magnetite, ilmenite and hematite along the grain boundaries forming colloform bands (Fig. 4.19).

4.2.2 Sulphide assemblage

Iron, copper and zinc sulphides closely associated with oxide assemblage are observed in the V-Ti-magnetite ore bodies, magnetite-gabbros and also anorthosites of the study area. Iron sulphide is represented by pyrite, copper sulphides are represented by chalcopyrite, cubanite, pyrrhotite, covellite and zinc sulphide is represented by sphalerite only. Sulphide mineral phase is less dominant compared to oxide mineral phase. The sulphide mineral phase is very well noticed only in the core samples of V-Ti- magnetite ore bodies, magnetite-gabbro and anorthosite rocks of the area. Pyrite and chalcopyrite show replacement relationship with oxide assemblage. The sulphides occur as disseminations and stringers in the host magnetite ore bands.
and gabbro-anorthosite suite. The sulphide mineral grains show deformation as indicated by the fracturing, brecciation and pressure fringes etc. Remobilisation due to deformation is limited to flattening of the sulphide grains along the schistosity of the host rocks and chalcopyrite filling the fractures in pyrite and also in magnetite.

4.2.2.1 Pyrite

Pyrite is the most predominant primary sulphide mineral followed by chalcopyrite, cubanite, pyrrhotite and covellite, in order of abundance among the sulphide assemblage of the area. The mineral is yellowish white in colour, non-pleochroic and isotropic in character. It occurs as idiomorphic to hypidiomorphic grains. The coarser idiomorphic grains of pyrite exhibit rectangular or square outlines (Fig. 4.23). Idiomorphism is more pronounced in almost all grains giving rise to panadiomorphic texture. Pyrite occurs as inclusions in chalcopyrite-II. Etch test on pyrite indicates that it is positive to HNO₃, which stains the mineral and is negative to HCl, KOH, FeCl₂, KCN etc. Pyrite shows cataclasis as indicated by fracturing and brecciation of the grains. The fractures in pyrite are filled up by xenomorphic grains of chalcopyrite-II and secondary covellite, initiating the replacement along the fractures (Fig. 4.24). Pyrite exhibits replacement relationship with magnetite and chalcopyrite-II along the
4.2.2.2 Chalcopyrite

Chalcopyrite is next to pyrite in order of abundance amongst the sulphide assemblage. It is golden yellow, non-pleochoric and feebly anisotropic in shades of greenish yellow and yellow. Chalcopyrite of two generations are noticed and distinguished as chalcopyrite-I and chalcopyrite-II. The mean reflectivity of chalcopyrite in general in green light is 42.63% and the Vicker's microindentation hardness ranges from 180 to 218 Kg/sq.mm. It is positive with HNO₃: as it stains the mineral brown and negative to HCl, KCN and KOH.

Chalcopyrite of first generation-chalcopyrite-I occurs as idiomorphic to hypidiomorphic grains and also as minute droplets within the magnetite crystals (Fig.4.26), indicating that chalcopyrite-I might have been formed simultaneously with magnetite, due to liquid immiscibility. Chalcopyrite-I do not show any replacement relationship with magnetite crystals as the margins of the two minerals are sharp at their contacts.

Chalcopyrite of second generation-chalcopyrite-II occurs relatively in large quantities as medium to coarse hypidiomorphic grains replacing pyrite. It occurs as thin veins along with secondary covellite in the fractures of pyrite (Fig. 4.24), and less abundantly in the fractures of magnetite (Fig. 4.25). Chalcopyrite-II encloses pyrite
grains in some samples. Exsolution starlets of sphalerite are observed in chalcopyrite-II in some specimens. Secondary covellite is seen replacing chalcopyrite II as concentric colloform bands (Fig. 4.29). Large lamellae of cubanite (Fig. 4.2) occur within chalcopyrite-II indicating its formation as a result of exsolution. Chalcopyrite II contains exsolution lamellae of pyrrhotite (Fig. 4.29).

4.2.2.3 Sphalerite

Sphalerite is light grey with a delicate bluish tinge. It exhibits very low reflectivity and isotropism. It occurs in the form of dust like linear and star shaped inclusions in chalcopyrite-II indicating a relatively high temperature.

4.2.2.4 Pyrrhotite

Pyrrhotite is cream with a faint pinkish brown tint. The mineral exhibits a distinct reflection pleochroism in shades of E=brownish cream and O=pinkish brown. It shows moderate reflectivity and anisotropism in shades of greyish yellow and greyish brown. Etch test on the mineral indicates that it is positive to HNO₃ as mineral stains brown and negative to HCL, KCN etc. It occurs as exsolution bodies in the form of thin lamellae/rods/needles in one or two directions within chalcopyrite-II (Fig. 4.29). It also occurs as stringers in chalcopyrite-II.
4.2.2.5 Cubanite

Cubanite is creamy yellow with pale brownish tint. It is more yellow and less pinkish against pyrrhotite and pinkish grey against chalcopyrite. It exhibits weak reflection pleochroism in \( \text{O} = \) creamy yellow and \( \text{E} = \) brownish yellow and strong anisotropism in shades of greyish blue and reddish brown. Reflectivity on the mineral in green light is 41.3\%. Etch test on the mineral indicates that it is positive to \( \text{HNO}_3^- \) as the mineral stains light brown and negative to \( \text{HCl}, \text{KCN}, \text{KOH} \) etc. The mineral occurs as lamellae in chalcopyrite-II (Fig. 4.30), indicating its formation as a result of exsolution.

4.2.2.6 Covellite

Covellite is blue with violet tint. It exhibits very strong reflection pleochroism in shades of \( \text{O} = \) blue with violet tint and \( \text{E} = \) bluish white. It is distinctly anisotropic in shades of orange and reddish brown. It exhibits four positions of extinction at 45° revolution. Etch test on the mineral indicates that it is positive to \( \text{KCN} \) and negative to \( \text{HNO}_3 \), \( \text{KOH} \) etc. It occurs as xenomorphic grains replacing chalcopyrite-II along the grain margins producing colloform bands (Fig. 4.28). Ramdohr (1969) feel that covellite is the decomposition product of chalcopyrite. In the present case, covellite is secondary after chalcopyrite-II as it occurs as xenomorphic grains and patches partially rimming chalcopyrite showing replacement
4.3 ORE TEXTURES AND THEIR INTERPRETATIONS

4.3.1 Introduction

V-Ti-magnetite ores and the associated sulphides of the study area exhibit a variety of ore textures. Different ore textures of these ores are identified based on the degree of crystallisation, the shape and size and mainly the mutual relationship existing between the various ore minerals of both oxide and sulphide assemblage. These textures are described and interpreted to know the paragenesis of individual ore minerals.

Many of the ore minerals are capable of forming solid solutions and these solid solutions under certain conditions of cooling are found to unmix with each other giving rise to distinct exsolution or unmixing textures. Solid solutions in oxide and sulphide opaque minerals of the study area are recognised based on these distinctive exsolution textures.

Different ore textures exhibited by both oxide and sulphide assemblages (Table 7) of the study area are described under the headings namely, panadiomorphic texture, cataclastic texture, mutual boundaries texture, exsolution intergrowth textures, such as magnetite-hoegbomite intergrowth, magnetite-ulvöspinel intergrowth, magnetite-pleonaste intergrowth, magnetite-ilmenite intergrowth like
4.3.2 Panadimorphic texture

Panadimorphic texture is well exhibited by pyrite grains which occur as idiomorphic crystals (Fig. 4.23). Idiomorphism of pyrite crystals is observed even in hand specimen of V-Ti-magnetite ore and magnetite-gabbro. Panadimorphic texture is suggestive of free crystallisation of pyrite crystals.

4.3.3 Cataclastic texture

Both magnetite and pyrite exhibit cataclastic textures in the form of fracturing, marginal granulation, brecciation and pressure fringes of magnetite and pyrite crystals. The fractures developed in magnetite crystals to a lesser extent are healed up by xenomorphic grains of chalcopyrite-II in narrow veins (Fig. 4.25). Idiomorphic as well as hypidiomorphic pyrite crystals exhibit extensive fracturing, brecciation and granulation. The fractures in the deformed pyrite crystals are filled up by later formed xenomorphic
grains of chalcopyrite-II in narrow veins (Fig. 4.24).

4.3.4 Mutual boundaries' texture

This texture is observed between magnetite and chalcopyrite-I. Minute idiomorphic and hypidiomorphic grains of chalcopyrite-I (Fig. 4.26) are found in the magnetite crystals. The boundaries of both the minerals are sharp and smooth without showing any projections of one mineral into the other indicating mutual boundaries texture. This type of texture is suggestive of simultaneous crystallisation of minerals (Edwards, 1965). The absence of replacement relationship between magnetite and chalcopyrite-I indicate that chalcopyrite-I might have been held in liquid immiscibility and formed simultaneously with magnetite.

4.3.5 Exsolution intergrowth textures

4.3.5.1 Magnetite-Hoegbomite

Following the discovery of hoegbomite by Gavelin (1916), it has been reported to occur in various rock types. The occurrence of hoegbomite in V-Ti-magnetite ores and magnetite-gabbros of the study area is perhaps the fourth example of its kind, the first three having been reported from Bergen, Norway (Kolderup, 1928, quoted by Mckie, 1963), Liganga, Tanzania (Zakrezewski, 1977) and from Madangere, Karnataka (Devaraju et al., 1981). The close association of hoegbomite with aluminium spinel is a common
feature for many hoegbomite occurrences in metamorphic as well as igneous rocks (Mckie, 1963; Wilson, 1977; Zakrezewski, 1977). Hoegbomite generally occurs as rims around the spinel and this type of hoegbomite is of secondary metamorphic origin. Hoegbomite which occurs as prismatic crystals is regarded to be of primary igneous constituent of the ores (Gavelin, 1916; Zakrezewski, 1977; Devaraju et al.,1981).

In the present investigation, hoegbomite which occurs as coarse prismatic/subhedral crystals (Fig. 4.1) found in close contact with magnetite in the spinel-free portions, without showing any replacement relationship with magnetite is regarded as the primary igneous constituent of the ores and later got enclosed in the later formed magnetite crystals.

Hoegbomite also shows exsolution intergrowth relationship with magnetite. The mineral occurs as small droplets/patches/rods within magnetite crystals. The rods are oriented in one or two directions (Fig. 4.2) in magnetite. The mutual relationship of these rods of hoegbomite with magnetite crystals indicate that they represent the exsolved phase formed during decreasing conditions of temperature of magmatic crystallization.

4.3.5.2 Magnetite-Ulvöspinel intergrowth

Since Mogensen's first recognition of ulvöspinel as a natural mineral in 1946 and the appearance of Ramdohr's
paper (1953) dealing with results of some detailed microscopic investigation on titaniferous magnetites containing ulvöspinel (essentially Fe₄ TiO₄) as an exsolved phase drawing attention to the importance of this mineral both from petrological and ore-dressing stand points, ore microscopists have been on the look out for ulvöspinel and it is no exaggeration to say that ulvöspinel now ranks as a common mineral, though almost entirely restricted to exsolution bodies in magnetite.

Ulvöspinel and its significance has been reported from V-Ti-magnetite and gabbros. It has been described by Roy (1955a); Vincent (1960); Varadarajan and Pande (1965); Duchesne (1970); Neybergh et al. (1980); Reynolds (1985); Chakruborty et al. (1988). In all these occurrences the mineral is found to occur in the form of thin hair like lamellae oriented in (100) planes of Ti-magnetite producing cloth microtexture.

Buddington and Lindsley (1964) and Haggerty (1976) opine that magnetite-ulvöspinel microintergrowth in the Ti-magnetite results from the cooling of original magnetite-ulvöspinel solid solution under conditions of low oxygen fugacity.

Deer et al. (1962) suggest that magnetite has continuous relationship with ulvöspinel (Fe₂TiO₄) and hence any amount of Ti can enter magnetite structure and is present there in solid solution as ulvöspinel molecules.
Naganna and Phene (1969) recorded high percentage of TiO$_2$ in the V-Ti-magnetite ores of Nuggihalli greenstone belt and concluded that Ti entered into the magnetite structure and is held there partly as ilmenite and partly as ulvöspinel molecules exsolving ilmenite along (111) planes and ulvöspinel along (100) planes into the magnetite host at low temperature.

In the earlier account of V-Ti-magnetite ores of Masanikere area by Ramiengar et al. (1978) the presence of ulvöspinel has been doubted but not confirmed.

In the present investigation, magnetite is characterised by the development much finer hair like network of ulvöspinel oriented in (100) planes of magnetite host giving rise to cloth microtexture (Fig. 4.9). In some cases, the fine network of ulvöspinel is partially oxidised to ilmenite (Fig. 4.10). Therefore, the author feels that ulvöspinel in magnetite is formed by exsolution process which has taken place at lower temperature than the formation of the ilmenite by oxidation, as the network of ulvöspinel retains its density right up to the margins of magnetite grains (Fig. 4.9). The chemical data of V-Ti-magnetite ores indicate that they have high percentage of TiO$_2$ (8.32 to 13.33%). Elaborating on the ideas proposed by Naganna and Phene (1969) it can be suggested that Ti might have been entered into magnetite structure and is held there partly as ilmenite and partly as ulvöspinel molecules.
exsolving in magnetite host as ilmenite oriented along (111) planes and ulvöspinel along (100) planes.

4.3.5.3 Magnetite-Pleonaste intergrowth

Cloth microtexture is noticed between magnetite and pleonaste in the study area (Fig. 4.11). Two generations of pleonaste of which first generation consisting of a coarse network of mutually perpendicular lamellae in (100) planes of magnetite and second generation consisting of smaller pleonaste lamellae that are aligned parallel to the first generation are noticed. A numerous mutually perpendicular pleonaste lamellae aligned parallel to (100) planes in magnetite are also noticed within the magnetite-ulvöspinel intergrowth (Fig. 4.9). Lamellae of pleonaste intersecting at angles other than right angles exsolved parallel to (100) in the magnetite are also noticed in the ores (Fig. 4.12). However, pleonaste is not observed in ilmenite or along the magnetite-ilmenite boundaries.

- Pleonaste exsolved from the magnetite-ulvöspinel solid solutions at temperature above the magnetite-ulvöspinel solvus is indicated by textural observations (eg. Haggerty, 1976) and also by homogenization experiments (Price, 1981). The pleonaste exsolution may pre-or post-date the oxidation exsolution event of ilmenite.

In the present case, the absence of pleonaste lamellae in magnetite-ilmenite intergrowth indicates its formation
prior to the formation of ilmenite lamellae within magnetite as exsolved phase.

4.3.5.4 Magnetite-Ilmenite intergrowth

Intergrowths of ilmenite with magnetite are noticed in four forms, viz. lamellar-crystallographic intergrowth, granular intergrowth, graphic intergrowth and emulsion intergrowth as follows:

Lamellar-crystallographic intergrowth: Lamellar intergrowth of ilmenite with magnetite is the most common type of intergrowth noticed in the V-Ti-magnetite ores of the study area. The crystallographic orientation of fine lamellae of ilmenite are aligned parallel to (111) planes of magnetite (Fig. 4.14). The fine lamellar intergrowth of ilmenite with magnetite forms Widmanstätten texture or trellis intergrowth as described by Buddington and Balsley (1961). The width of fine lamellae of ilmenite varies from 0.01 to 0.03 mm. Both coarse and fine lamellae of ilmenite give rise to well developed equilateral triangles (Figs. 4.13 and 4.14). The equilateral triangles are formed by ilmenite lamellae on (111), exposed on an octahedral plane of the host magnetite. A similar pattern has been reported from iron-titanium oxide minerals in norites of Bengal, India (Bose and Roy, 1966). The ilmenite lamellae also occur in two sets oriented almost at right angles producing rectangles (Fig. 4.15). Two sets of ilmenite lamellae of varying thickness aligned parallel to (111) and (100) planes
of magnetite host are also noticed (Fig. 4.16)

Granular intergrowth: Granular intergrowth is noticed between magnetite and ilmenite (Fig. 4.17). Granular aggregates of both ilmenite and magnetite with polyhedral grain boundaries exhibit mutual grain boundaries texture, indicating the absence of replacement relationship. Ilmenite grains have bold outlines against magnetite and there is no tongues or projections of one mineral into the other.

Intergrowths of magnetite with ilmenite and with ulvospinel are known in nature. However, intergrowths with ilmenite are certainly more readily observed and probably more common. This fact has provided the fundamental basis for assuming the existence of magnetite-ilmenite solid solutions at high temperatures. The existence of magnetite-ilmenite solid solutions has also been proved experimentally. Ramdohr (1926), Kamiyama (1929), Wilson (1953) and Roy (1954) have reported successful homogenization of magnetite-ilmenite intergrowths by heating samples.

The theory of 'unmixing' and the formation of separate minerals in a two component system during the decreasing temperature condition is a well established fact. The lamellar intergrowth (widmestatten texture) exhibited by magnetite and ilmenite is probably resulted by the process of unmixing during the cooling of the residual ore-rich
liquid. Roy (1955a), Schwartz (1931), Chakroborthy (1959a) and Naganna (1964) feel that lamellar intergrowth in two minerals is due to unmixing and exsolution, particularly when lamellae are confined to certain weak planes without any enlargement.

In the present investigation, both coarse and fine lamellae oriented in (111) planes and also (100) planes of magnetite making constant angles among themselves. The consistency of textural relation and absence of any replacement relation between magnetite and ilmenite unequivocally suggest an unmixing origin for ilmenite intergrowth in magnetite.

Granular intergrowth of ilmenite with magnetite is noticed in the ores of the study area. Magnetite show smooth regularly gently curving contacts without any projections of one mineral into the other, which can be called mutual boundary texture, suggestive of contemporaneous formation common in sulphide minerals (Edwards, 1965). Alternatively, in oxides, if cooling of solid solution of magnetite-ilmenite is slow, the ilmenite lamellae tend to diffuse to the margins of magnetite crystals forming granular intergrowth of ilmenite and magnetite (Edwards, op.cit.). Granular aggregates of ilmenite and magnetite is a product of exsolution from high temperature solid solution which originally separated from magma as a single phase of crystallization. Exsolution from solid solution is considered to have commenced with the

Buddington and Lindsley (1964) from their study of phase relations in the Fe$_3$O$_4$-Fe$_2$TiO$_4$ system and experiments relating to the solubility of Fe TiO$_3$ in Fe$_3$O$_4$, demonstrated that observed textural features in titanomagnetites can be ascribed to two processes and described under two broad headings, such as, 1) exsolution above the magnetite-ulvöspinel solvus and (2) exsolution below the magnetite-ulvöspinel solvus.

Any high temperature magnetite-ulvöspinel solid solution is stable only under low oxygen fugacity conditions and will exsolve on slow cooling below the magnetite-ulvöspinel solvus (Buddington and Lindsley, 1964; Haggerty, 1976). Increased oxygen fugacity results in oxidation of the Fe$_2$TiO$_4$ component of rhombohedral ilmenite + cubic magnetite (Ramdohr, 1953). This ilmenite is virtually insoluble in its magnetite host and is consequently exsolved (Buddington and Lindsley, 1964; Duchesne, 1970 and Haggerty, 1976). Formation of the wide variety of ilmenite and ulvöspinel microintergrowths within the Ti magnetite of the study area and their relative development is interpreted according to this model.

The major types of ilmenite bearing intergrowths that are developed in the V-Ti-magnetite ores of the study area are (1) broad ilmenite lamellae and external granules
(Fig. 4.31) (ii) fine ilmenite lamellae and internal granules (Fig. 4.32) and (iii) oxidation of pre-existing ulvöspinel intergrowths (Fig. 4.10), and they are described as follows:

(i) Broad ilmenite lamellae and external granules: Increased oxygen fugacity at highest subsolidus temperature has led to the development of ilmenite external granules and large broad lamellae. These bodies nucleate heterogeneously at grain boundary dislocations and develop externally and/or grow into their magnetite hosts parallel to (111) planes (Fig. 4.31). The number of lamellae that develop and their spacing is largely a function of oxygen fugacity, temperature and composition. The lamellae of ilmenite are irregularly spaced.

(ii) Fine ilmenite lamellae and internal granules: Fine lamellae of ilmenite forming trellis networks oriented parallel to (111) planes of their magnetite hosts are noticed in the V-Ti-magnetite ores of the study area. The fine lamellae of ilmenite are developed over the entire width of their host magnetite crystals (Fig. 4.32). In some cases, the lamellae are confined to the immediate vicinity of the grain boundaries.

Reynolds (1985) opine that fine ilmenite lamellae might have developed at lower temperatures than the larger broad ilmenite lamellae reflecting lower ionic mobilities under these conditions.
Small internal ilmenite granules are developed under conditions of high oxygen fugacity in their magnetite hosts. These granules of ilmenite are present in areas between more widely spaced ilmenite lamellae (Fig. 4.32). These microtextures point to higher oxygen fugacity during subsolidus cooling above the magnetite-ulvøspinell solvus (Buddington and Lindsley, 1964).

(iii) Oxidation of earlier formed ulvøspinell: The exsolved ulvøspinell is very susceptible to oxidation to form ilmenite and magnetite. Increased oxygen fugacity at lower temperatures below the magnetite-ulvøspinell solvus results in the oxidation of earlier formed ulvøspinell exsolution bodies to ilmenite+magnetite, as described by Ramdohr (1953). This ilmenite is oriented such that (0001) of the ilmenite is parallel to (111) of the host magnetite (Ramdohr, 1953). This second generation ilmenite (Vincent, 1960) has been termed protoilmenite by Willemse (1963b) in order to distinguish it from other forms of ilmenite.

In the present investigation, in majority of the samples investigated, the exsolved ulvøspinell is oxidised to protoilmenite which causes a patchy optical anisotropy in magnetite grains (Fig. 4.10).

Emulsion intergrowth: Microscopic inclusions of rounded to subrounded, worm like and also euhedral grains of ilmenite are seen in magnetite giving rise to emulsion intergrowth (Fig. 4.18). Minute ilmenite grains which are
often spotty are seen distributed throughout magnetite. These ilmenite grains are not guided by any crystallographic directions. As opined by Ramdohr (1969), emulsion intergrowths have various genetic interpretations; they may be entrapped droplets in liquid magmatic formation, undigested replacement relics etc. However, he opines that the most important and typical examples of emulsion intergrowth results from exsolution.

**Graphic intergrowth:** This texture is seen between magnetite and ilmenite. Unoriented ilmenite grains are found graphically intergrown with magnetite in a few specimens. The intergrowth is not guided by any crystallographic directions, and the texture has no continuity throughout the grains. There is a much controversy regarding the origin of this texture. Edwards (1954) observed this type of intergrowth in several sulphide minerals and thought that this texture is formed due to simultaneous crystallisation. In the present case, there is no replacement relationship between these minerals which suggest that magnetite and ilmenite are formed by simultaneous crystallization.

4.3.5.5 Chalcopyrite-II - Sphalerite

Ramdohr (1969) opines that starlets and other inclusions of sphalerite in chalcopyrite are the exsolution products which indicate relatively a high temperature.

In the present case, sphalerite occurs as linear and
starshaped inclusions in chalcopyrite-II host. The sphalerite stars are interpreted as exsolution products indicating a relatively a high temperature.

4.3.5.6 Chalcopyrite-II - Cubanite

Broad lamellae of cubanite are seen in chalcopyrite-II (Fig. 4.30), showing smooth and regularly gently curving contacts indicating absence of any replacement relationship. This relationship between chalcopyrite-II and cubanite indicates that cubanite lamellae might have been formed as a result of exsolution.

4.3.5.7 Chalcopyrite-II - Pyrrhotite

Pyrrhotite lamellae in chalcopyrite are the decomposition products of cubanite indicating high temperature of formation (Ramdohr, 1969), and pyrrhotite stringers in chalcopyrite are exsolution products. Chalcopyrite and pyrrhotite are capable of solid solution at temperatures above 600 °C. and solution of pyrrhotite in chalcopyrite occurs at about these temperatures.

In the present case, the sharp and smooth boundaries of lamellae/rods/stringers of pyrrhotite in chalcopyrite-II, absence of enlargement of pyrrhotite lamellae at the point of their intersection, disconnected units rather than a network as in replacement cleavages clearly indicate their formation by exsolution at high temperature.
4.3.6 Secondary texture

Martitization of magnetite at different stages is the most prominent secondary textural feature noticed in the V-Ti magnetite ores, though rims of goethite is found around magnetite (Fig. 4.19), hematite and ilmenite (Fig. 4.19). 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 end product is colloquially referred to as 'martite' and the oxidation process is known as martitization.

Maghemitization of magnetite is another secondary textural feature less commonly noticed in V-Ti-magnetite ores of the area.

4.3.7 Replacement textures

Replacement/metamatism has been defined as the disolving of one mineral or group of minerals, and the simultaneous deposition of another mineral or group of minerals in its place. Solution and deposition process concurrently without the intervening development of appreciable open spaces and the substitution commonly involves no change in volume. Various replacement textures are developed as a result of either partial or complete replacement of one mineral by another mineral. They may be related to grain boundaries, cleavage planes, fractures, rims, cores of the minerals. Replacement textures exhibit
an interconnecting link between oxides, and sulphides of the area. Both supergene and hypogene replacements are noticed in the ores. Following are the ore minerals which exhibit well illustrated replacement relationship between them:

**Magnetite-Martite**: Martite which is the pseudomorph of hematite after magnetite is found to replace magnetite mainly along the octahedral planes and grain boundaries (Fig. 4.5). Intensity of martitization varies from grain to grain and martite is found to retain the shape of magnetite at places. Some of the magnetite grains are partly replaced and some of them are completely replaced. Intensity of martitization decreases at deeper levels of the ore bodies, as indicated by the core samples of the area. The exsolved ilmenite is not affected by martitization.

**Goethite-(Magnetite-Ilmenite-Hematite)**: Goethite is a secondary oxide mineral derived by oxidation-hydration of magnetite and it is found to replace magnetite, ilmenite, hematite. The replacement of these minerals is mainly along the margins producing colloform bands which is very clear under oil (Figs.4.19).

**Magnetite-pyrite**: Pyrite is seen replacing magnetite mainly along the grain margins (Fig. 4.33). The grain boundaries of the two minerals are corroded and irregular with advancing replacement indicated by tongues of pyrite in magnetite. The residual inclusions of magnetite are also noticed in pyrite grains.
Magnetite-Chalcopyrite-II: Fractures in the deformed crystals are filled up by chalcopyrite-II (Fig. 4.25), showing initial stages of replacement of magnetite along fractures. The grain boundaries also show replacements which is indicated by irregular contacts between them and tongues of chalcopyrite-II in magnetite crystals.

Chalcopyrite-II-Pyrite: Replacement relationship is well illustrated between chalcopyrite-II and pyrite. Chalcopyrite-II is found to replace pyrite mainly along grain boundaries (Fig. 4.35), which is indicated by protruberances of chalcopyrite-II to pyrite crystals and also along the fractures of deformed pyrite crystals. The early formed pyrite has been shuttered by small movements contemporaneous with mineralization and it is invaded by the younger chalcopyrite-II along the network of fractures in narrow veins (Fig. 4.24) giving rise to vein replacement.

Chalcopyrite-II-Covellite: Supergene replacement of chalcopyrite-II by secondary covellite which grows as a narrow rim around the chalcopyrite-II giving rise to rim replacement (Fig. 4.28), which is indicated by irregular extension of covellite into chalcopyrite-II.
TABLE 6. PARAGENETIC DIAGRAM FOR ORE MINERALS OF MASANIKERE AREA
<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Ore textures</th>
<th>Oxide assemblage</th>
<th>Sulphide assemblage</th>
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<td>1</td>
<td>Panadimorphic texture</td>
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<td>Pyrite</td>
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<td>2</td>
<td>Cataclastic texture</td>
<td>Magnetite</td>
<td>Pyrite</td>
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<tr>
<td>3</td>
<td>Mutual boundaries' texture</td>
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<td>4</td>
<td>Exsolution intergrowth textures</td>
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<tr>
<td>a.</td>
<td>Lamellar intergrowth</td>
<td>Magnetite-ilmenite</td>
<td>Chalcopyrite-II-cubanite</td>
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<td>b. Granular intergrowth</td>
<td>Magnetite-ilmenite</td>
<td>Chalcopyrite-II-pyrrhotite</td>
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<td></td>
<td>c. Graphic intergrowth</td>
<td>Magnetite-ilmenite</td>
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<td></td>
<td>d. Emulsion intergrowth</td>
<td>Magnetite-ilmenite</td>
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<td>e.</td>
<td>Magnetite-ulvospinel</td>
<td>Chalcopyrite-II-sphalerite</td>
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<td>f.</td>
<td>Magnetite-pleonaste</td>
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<td>5</td>
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<td>Mardtitization of magnetite</td>
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<td>Maghemization of magnetite</td>
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<td>6</td>
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<td>Magnetite-martite</td>
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<td>Goethite-(Magnetite, ilmenite,</td>
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<td>Magnetite</td>
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chalcopyrite-II
Fig. 4.1 Elongated subhedral crystals of hoegbomite (reddish brown) in close contact with magnetite (black)
Plane polarised reflected light, oil immersion 32X

Fig. 4.2 Exsolution needles/rods/patches of hoegbomite (reddish brown) in one or two directions within magnetite crystals (black)
Plane polarised reflected light, oil immersion 32X

Fig. 4.3 Idiomorphic grains of magnetite (greyish white) unaffected by martitization
Plane polarised reflected light, oil immersion 32X
Fig. 4.1 Elongated subhedral crystals of hoegbomite (reddish brown) in close contact with magnetite (black)
Plane polarised reflected light, oil immersion 32X

Fig. 4.2 Exsolution needles/rods/patches of hoegbomite (reddish brown) in one or two directions within magnetite crystals (black)
Plane polarised reflected light, oil immersion 32X

Fig. 4.3 Idiomorphic grains of magnetite (greyish white) unaffected by martitization
Plane polarised reflected light, oil immersion 32X
Fig. 4.4 Hypidiomorphic grains of magnetite affected by martitization
Plane polarised reflected light, oil immersion 32X

Fig. 4.5 Xenomorphic grains of magnetite (greyish white) showing martitization. Magnetite is replaced by martite (white) mainly along actohedral planes and grain boundaries.
Plane polarised reflected light, oil immersion 32X

Fig. 4.6 Polygonal nature of magnetite (white) and ilmenite (grey) showing smoothly curved grain boundaries and well defined triple junctions, which meet at an angle of 120°. Note that magnetite grains (white) are completely martitized and ilmenite grains are not affected by martitization.
Plane polarised reflected light, oil immersion 32X
Fig. 4.7 Magnetite (grey) is oxidised to maghemite (white). The planes along which oxidation has taken place is not well defined and the characteristic fabric is seen along the cracks instead of cleavages. Note that the pleonaste lamellae (grey) aligned parallel to (100) planes of magnetite. Plane polarised reflected light, oil immersion 32X

Fig. 4.8 Magnetite grains (grey) undergoing martitisation show fracturing and brecciation due to deformation. Plane polarised reflected light, oil immersion 32X

Fig. 4.9 Finer hair like network of lamellae of ulvöspinel aligned parallel to (100) planes of magnetite (greyish white) giving rise to cloth microtexture (box texture) and advancing martitization along the right margins. Note the mutually perpendicular lamellae (coarse) of pleonaste (black). Plane polarised reflected light, oil immersion 32X
Fig. 4.10 Magnetite (greyish white) – ulvospinel intergrowth
Note the fine hair like lamellae of ulvospinel are oxidised to ilmenite (protoilmenite).
Plane polarised reflected light, oil immersion 32X

Fig. 4.11 Coarse and fine network of mutually perpendicular lamellae of pleonaste (two sets) aligned parallel to (100) planes of magnetite (greyish white), indicating two generations.
Plane polarised reflected light, oil immersion 32X

Fig. 4.12 Lamellae of pleonaste (black) intersecting at angles other than right angles exsolved parallel to (100) in the magnetite (greyish white).
Plane polarised reflected light, oil immersion 32X
Fig. 4.13 Lamellar-crystallographic intergrowth in which coarse lamellae of ilmenite (grey) aligned parallel to (100) and (111) planes of magnetite host (greyish white) producing well defined equilateral triangles.

Plane polarised reflected light, oil immersion 32X

Fig. 4.14 Lamellar-crystallographic intergrowth in which fine lamellae of ilmenite (grey) are aligned parallel to (100) and (111) planes of magnetite host (greyish white) producing well defined trellis intergrowth or Widmanstatten texture.

Plane polarised reflected light, oil immersion 32X

Fig. 4.15 Two sets of mutually perpendicular ilmenite lamellae (grey) of nearly uniform thickness with irregular spacing aligned parallel to (100) planes of magnetite host (greyish white) producing rectangles.

Plane polarised reflected light, oil immersion 32X
Fig. 4.16 Two sets of ilmenite lamellae of ilmenite (grey) of varying thickness aligned parallel to (100) and also (111) planes of magnetite host (greyish white). Plane polarised reflected light, oil immersion 32X

Fig. 4.17 Granular intergrowth between magnetite (white) and ilmenite (grey). Plane polarised reflected light, oil immersion 32X

Fig. 4.18 Emulsion intergrowth between magnetite (greyish white) and ilmenite (grey). Plane polarised reflected light, oil immersion 32X
Fig. 4.19 Polygonal granular ilmenite (grey) showing exsolution discs and blebs of hematite (white). Note that goethite (greyish white) replaces martitized magnetite (white) and also ilmenite (grey) forming colloform bands. Plane polarised reflected light, oil immersion 32X

Fig. 4.20 Thin elongated hematite lamellae (white) oriented in (0001) planes of ilmenite (grey) Plane polarised reflected light, oil immersion 32X

Fig. 4.21 Polysynthetic twinning in ilmenite (grey). Partially uncrossed polars, oil immersion 32X
Fig. 4.22 Martite (white) replacing magnetite (greyish white) mainly along octahedral planes producing triangular network and also along the grain boundaries.
Plane polarised reflected light, oil immersion 32X

Fig. 4.23 Idiomorphic crystals of pyrite (white) showing panodiomorphic texture.
Plane polarised reflected light, oil immersion 32X

Fig. 4.24 Fractures in deformed pyrite crystals (white) are filled up by later formed xenomorphic chalcopyrite-II (grey) in narrow veins.
Plain polarised reflected light, oil immersion 32X
Fig. 4.25 The fractures in deformed magnetite crystals (grey) are healed by chalcopyrite-II (white) in narrow veins.
Plane polarised reflected light, oil immersion 32X

Fig. 4.26 Idiomorphic and hypidiomorphic grains and droplets (white) of chalcopyrite-I in magnetite (grey) exhibiting mutual boundaries' texture.
Plane polarised reflected light, oil immersion 32X

Fig. 4.27 Hypidiomorphic grain of chalcopyrite-II (white)
Plane polarised reflected light, oil immersion 32X
Fig. 4.28 Covellite (blue) replacing chalcopyrite-II (yellow) along the grain boundaries as concentric coloform bands/rims
Plane polarised reflected light, oil immersion 32X

Fig. 4.29 Exsolution lamellae of pyrrhotite (grey) in chalcopoyrite-II (greyish white)
Plane polarised reflected light, oil immersion 32X

Fig. 4.30 Exsolved cubanite (white) lamellae in chalcopyrite (greyish white)
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Fig. 4.31 External granular ilmenite (grey) and broad lamellae of ilmenite (grey) in the (111) planes and (100) planes of magnetite host (greyish white). Plane polarised reflected light, oil immersion 32X.

Fig. 4.32 Fine ilmenite lamellae (grey) and internal granules of ilmenite (grey) in partially martitized magnetite (greyish white). Plane polarised reflected light, oil immersion 32X.

Fig. 4.33 Pyrite (yellowish white) is replacing magnetite (greyish brown) along the grain boundaries. Plane polarised reflected light, oil immersion 32X.
Fig. 4.34 Chalcopyrite-II (yellow) is replacing magnetite (greyish brown) along grain margins. Plane polarised reflected light, oil immersion 32X

Fig. 4.36 Chalcopyrite-II (yellow) is replacing pyrite (yellowish white) along the grain boundaries. Plane polarised reflected light, oil immersion 32X