CHAPTER V

Petrographic features of V-Ti Magnetite Ores

5. Introduction

This chapter deals with the information on various ore texture (both primary and secondary) and their genetic significance, which is provided by the photomicrographs of polished surfaces of ore-samples collected from the study area. Petrographic features of V-Ti Magnetite ore of both oxides and sulphides associated with the ultramafic-mafic rock / layers of Devarnarsipur area which are designated as “Devarnarsipur ultramafic-mafic complex” in the present thesis is discussed in detail.

The prime pre-requisite for understanding the iron-titanium oxide mineral modification is based on primarily oxidation and ex-solution, with a well established optical characteristic database. This chapter provides information on the present investigation about the microscopic description of oxide assemblage and associated sulphide assemblage. The microscopic descriptions include the optical properties like colour, shape, pleochroism, isotropism versus an-isotropism, various ore textures and their interpretations. 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 based on the various textural features observed in V-Ti-magnetite ores and the associated sulphides of the Devarnarsipur area.

5.1 Macroscopic Textural Features of the Ores

V-Ti magnetite ores of Devaranarasipur ultramafic-mafic complex are of medium grained and made up predominantly of Ti magnetite crystals (6-3 mm) with subordinate granular ilmenite (2-3 mm) and minor pleonaste.
The more massive portion of the ore consists almost entirely of closely-packed polygonal Ti-magnetite crystals that meet in well-defined triple junctions, with an interfacial angle of 120° (Fig.5.1 and Fig.5.2). Variable amounts of smaller granular and elongated ilmenite crystals are located along the grain boundaries between neighboring Ti-magnetite crystals.

The Ti-magnetite ores and their associated silicate layers have traditionally been regarded as cumulus rocks that formed via processes of magmatic sedimentation (Wager and Brown, 1968; Molyneux, 1964, 1970b, 1974; Willemse, 1969; Von Gruenewaldt, 1985) and many of their textural features are consistent with this theory. The silicate-poor Ti-magnetite layers commonly contain less than 5% volume of silicate and can be classified as adcumulus rocks following the nomenclature of Wager et al. (1960). The more silicate-rich varieties exhibit textural variations that range from typical orthocumulate through to mesocumulate and heterocumulate rock types. This terminology is retained in a descriptive sense, as defined by Irvine (1982), and is not used in a genetic sense.

The validity of the “cumulus” theory is at present being seriously challenged (inter alia Campbell, 1977, 1978; Mc Birney and Noyes, 1979; Irvine, 1980a, b, 1982). The available evidence points towards the insitu bottom-crystallization of individual layers rather than the accumulation of crystals by various settling mechanisms.

Regardless of the mechanisms involved, a stage will be reached during the development of individual layers during which the primocrysts will form a framework of touching crystals and will be surrounded by an intergranular liquid. The conversion of this assemblage of crystals and liquid into an essentially monomineralic layer, has been accounted for by a process of diffusion-controlled adcumulus growth, during which the primocrysts are enlarged and the intergranular liquid is displaced (Hess, 1939, 1960; Wager et al., 1960). The
resultant grain boundaries would, therefore, be expected to show impingement textures, caused by the mutual interference of the enlarging crystals but this mechanism cannot be invoked in the present case as the Ti-magnetite ores are characterized by the presence of equilibrium grain-boundary relationships with interfacial angles of $120^\circ$ (Fig.5.1 and Fig.5.2).

Reynolds (1979a) noted that the grain-boundary relationships in the titaniferous iron ores can be compared with the textures that are developed in dense, polycrystalline aggregates formed by sintering. This process is widely used in the metallurgical and ceramic industries and involves the heating of powders at temperatures below their melting points. This results in the solid-state densification and subsequent coarsening of the grain size, of sintered aggregate via grain-boundary migration under the driving force of surface free energy (Coble and Burke, 1963; Thummler and Thomma, 1962; Voll 1960; Weedon 1965, and Vernon 1970) have also suggested that sintering processes might be important in the development of similar grain-boundary relationships in cumulus rocks.

A process similar to that sintering could be invoked in the Devarnarsipur V-Ti-magnetite layers at the elevated temperatures existing immediately after the formation of the Ti-magnetite layers. The process is initiated by the formation of grain boundaries between Ti-magnetite crystals at points of mutual contact (neck growth). These grain boundaries then increase in size under the driving force of surface free energy and the separate crystals begin to lose their identity (grain growth). This leads to densification within the Ti-magnetite layer and the expulsion of intergranular liquid through inter-connected pore spaces and along grain boundaries (densification). The result is an essentially monomineralic Ti-magnetite rock in which the grain curvature, thus allowing for the development of small numbers of large crystals at the expense of large numbers of smaller ones. The final product is represented by a dense/coarse-grained polygonal aggregate of Ti-magnetite showing equilibrium grain-boundary relationships (Fig.5.1 and Fig.5.2).
Freezing of the entrapped intergranular liquid before it is completely expelled results in the crystallization of various phases in the inter-granular areas (Fig. 5.3). The sizes and morphologies of the primocryst Ti-magnetite octahedra are commonly preserved in areas where the intergranular liquid crystallized before any noticeable grain growth occurred (Fig. 5.4). These features are commonly preserved in typical heteradcumulate textures developed in small poikilitic silicate clots and silicate-rich layers that are present in the more massive and coarsely-crystalline ores.

The presence of primocryst ilmenite, plagioclase and intergranular phases appears to have impeded grain-boundary migration, with the result that their presence led to a marked decrease in the grain size of the Ti-magnetite in the immediate vicinity (Fig. 5.3).

5.2 Minerogetic Features of the V-Ti- Magnetite ores

Naganna et al., (1976) described some of the mineralogical and textural aspects of the V-Ti magnetite ores of the Devaranarasipur area and this reference should be read in conjunction with what follows. In the present study, emphasis is given on the investigation observations and on aspects not covered in detail by earlier workers. Interpretation of microstructures is according to the modern ex-solution theory based on the work of Brett (1964), Yund and McCallister (1970) and Champness and Lorimer (1976).

The polished surface of V-Ti-magnetite ore samples of the Devaranarasipur area represented by both Oxide assemblages consists of ilmenite, ulvospinel, pleonaste, magnetite, hematite (martite), and maghemite and the Sulphide assemblage which are represented by pyrite and chalcopyrite.
5.2.1 Oxide Assemblage

5.2.1.1 Ti magnetite

Ti magnetite is the most predominant and abundant oxide mineral in V-Ti-magnetite ore bodies (magnetite ranges from 70 to 80%, modally) and magnetite gabbro (magnetite ranges from 25 to 45%, modally). It exhibits white colour with brownish tint at places. It is non-pleochroic and isotropic in character. It occurs as coarse to fine idiomorphic (Fig.5.1) to hypidiomorphic (Fig.5.2) and xenomorphic crystals (Fig.5.3). The ulvospinel, pleonaste and ilmenite minerals occur as ex-solution bodies in the form of lamellae. Magnetite contains idiomorphic to xenomorphic grains of chalcopyrite. It is characterized 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 is a common feature noticed in almost all ore samples of V-Ti magnetite. A few grains of magnetite are not affected by martitization (Fig.5.1). Some grains are completely martitized (Fig.5.4), and others are partially martitized (Fig.5.5). 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.5.5). Magnetite is also oxidized to maghemite, but the transformation of magnetite to maghemite is much less regular 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 (Fig.5.3) Magnetite grains are deformed which is indicated by fracturing, brecciation and pressure fringes (Fig.5.6).
5.2.1.2 Ulvospinel

Typical ulvospinel cloth textures (Fig. 5.7) is noticed in Ti magnetite. In this cloth texture, networks of micrometer-sized ulvospinel lamellae are aligned parallel to (100) planes of the Ti magnetite. In some cases the fine network of ulvospinel is partially oxidized to ilmenite. The mineral is closely associated with pleonaste in magnetite.

In this cloth texture, networks of micrometer-sized ulvospinel lamellae are aligned parallel to (100) planes of the Ti magnetite. These ulvospinel lamellae are considered to have formed via the ex-solution under conditions of relatively low oxygen fugacity as proposed for similar ores elsewhere (Verhoogen, 1962; Buddington and Lindsley, 1964; Haggerty, 1976). These intergrowths exhibit a wide variation in size and degree of development, with some intergrowths clearly being visible under medium-power magnification.Others are much finer and can be resolved at the highest magnification. The cloth-type ulvospinel is usually developed right up to the grain boundaries of the Ti magnetite hosts. These intergrowths often exhibit signs of coarsening and lamellar breakdown which is usually associated with the development of micrometer-sized ilmenite.

Presence of ulvospinel is also seen in some Ti magnetite grains as much broader and longer lamellae that form distinct rectangular box works or frames around sparsely-distributed transparent pleonaste lamellae. In this type, the ulvospinel is again aligned parallel to (100) planes of the Ti magnetite and in some cases, smaller irregular ulvospinel grains are noticed around the borders of the transparent pleonaste lamellae. According to Yund and McCallister (1970) and Champness and Lorime (1976), this type of ulvospinel probably represents the earliest exsolved ulvospinel that nucleated heterogeneously at energetically-favorable dislocation sites caused by the growth of the transparent spinel. This interpretation is supported by the much finer scale and less robust development of the usual ulvospinel cloth textures in the immediate vicinity of the boxworks, suggesting an earlier phase of
The coarse ulvospinel lamellae probably contained some magnetite in solid solution on formation, which would have exsolved subsequently as finer sub-microscopic lamellae on cooling as proposed by Reynolds (1986).

### 5.2.1.3 Pleonaste

Pleonaste is commonly appearing in inter-grown in both granular and lamellae forms with the Ti-magnetite. It is generally more abundant in Ti-magnetite in ore-rich layers than in the silicate-rich layers. Equant to subhedr al grains are commonly noticed along the Ti-magnetite grain boundaries (Fig.5.5) and in the spinelliferous ilmenite rims it developed around the granular ilmenite crystals (Fig.5.8). These grains nucleated heterogeneously at grain-boundary imperfections at elevated temperatures which allowed for large-scale ionic migration. Rounded to subhedral pleonaste grains are sparingly present towards the central portions of certain Ti magnetite crystals (Fig.5.9). The origin of these pleonaste granules is not certain, but they probably represent phases nucleated heterogeneously at dislocations within the Ti-magnetite at approximately the same time as the from the marginal areas of the Ti-magnetite crystals presumably reflects the lower AI and Mg contents of these areas caused by the preferential external granule ex-solution of pleonaste.

Pleonaste platelets or lamellae are also commonly developed in certain Ti-magnetite crystals where they are exsolved parallel to (100) (Fig.5.9). These lamellae usually decrease markedly in size towards the margins of the Ti-magnetite grains and the areas between the individual pleonaste lamellae also commonly show the development of a further set of much finer lamellae. These spinel lamellae are typically absent from the immediate vicinity of the larger pleonaste granules and the spinelliferous rims. This indicates the concentration gradients within the Ti-magnetite, due to the earlier migration of suitable Al and Mg components from the neighboring areas into the earlier-formed spinel granules.
The common occurrence of small pleonaste granules along the interface between ilmenite and Ti-magnetite have been described and are a very characteristic feature of many ilmenite-bearing Ti-magnetite crystals. The ex-solution of pleonaste from Ti-magnetite is extremely common (Haggerty, 1976; Reynolds, 1978b), but no direct experimental work has been carried out. Turnock and Eugster (1962) showed that an extensive miscibility gap exists between magnetite and hercynine (FeAl₂O₄) below 860°C, but the relationships become complicated by the presence of ulvospinel and pleonaste solid solutions in the magnetite. A miscibility gap also exists between pleonaste and ulvospinel (Muan et al., 1972) and the textural evidence confirms the presence of an extensive miscibility gap between pleonaste and “Titaniferous magnetite”. The exsolution of pleonaste usually commences at an earlier stage (and thus at a higher temperature) than that of ulvospinel (Haggerty, 1976). The common association of pleonaste granules with ilmenite oxidation/exsolution lamellae has also been cited as evidence supporting the view that the pleonaste exsolution is in cases dependent on the oxidation of the host titaniferous magnetite (Wright and Lovering, 1965; Haggerty, 1976). An alternative explanation might be that structural dislocations then represent energetically-favorable sites for the heterogeneous nucleation and growth of pleonaste exsolution bodies from the saturated or super-saturated magnetite-ulvospinel-pleonaste solid solution.

5.2.1.4 Ilmenite

Ilmenite is pinkish brown in colour Fig.5.16. Ilmenite occurs either as coarse discrete grains or as various types of intergrowths within the Ti-magnetite crystals. Ilmenite is detailed in the form they occurred as follows, coarse granular ilmenite, fine inter-granular ilmenite and lamellar ilmenite.
5.2.1.4.1 Coarse Granular Ilmenite

The relative proportion of ilmenite grains tends to increase with an increase in the proportions of silicates present and this larger ilmenite often represent the dominant oxide phase in many of the associated gabbroic rocks. According to Molyneux (1970b) and Reynolds (1985b), this feature appears to be a common feature of titaniferous iron ores.

Coarse, granular ilmenite (10-15 volume per cent) is commonly seen in the ore-rich layers. They are usually smaller than the co-existing Ti- magnetite and are somewhat elongated (Fig.5.1 & Fig.5.2).

Ti magnetite and the ilmenite exhibit gently curved grain boundaries (Fig.5.4) but, in detail, appear highly irregular and serrated due to the presence of pleonaste-bearing ilmenite rims (Fig.5.8). These tiny pleonaste grains are located along the ilmenite/Ti-magnetite interfaces. These rims are commonly reported to occur in ores of this nature (Duchesne, 1970, 1972; Reynolds, 1985b) and are caused by the continued solid-state growth of the ilmenite crystals during sub-solidus cooling as a result of external granule exsolution. The presence of externally exsolved pleonaste along the Ti magnetite interfaces, however, interferes with the grain-boundary migration of the growing ilmenite. The grain boundaries cannot easily migrate around the pleonaste grains and Coble and Burke (1963) have shown that the energy required for a boundary to migrate past an inclusion has to be provided by a decrease in the surface area elsewhere in the boundary. This is not usually possible and the spinel grains remain along the magnetite-ilmenite interfaces where varying complexities of grain-boundary configurations arise, due to the pinning of one component of the interfaces while the continued growth of the next segment occurs. In rare cases where the ilmenite grain boundaries have succeeded in migration past pleonaste granules parallel to the outer margins of their ilmenite hosts.
In the central parts of the coarse granular ilmenite a narrow, sparsely-distributed lamellae of magnetite are developed parallel to (001) of their hosts (Fig.5.10). Micrometer-sized pleonaste granules are also often noticed along with the Ti-magnetite and sometimes form parts of individual lamellae. Magnetite is only very sparingly soluble in ilmenite, even at elevated temperatures, and it is doubtful whether these intergrowths represent true exsolved phases (Buddington and Lindsley, 1964) ilmenite does, however, usually contain some Fe₂O₃ in solid solution. They thus represent reduction/exsolution lamellae as suggested by Buddington et.al. (1963) and Lindsley & Spencer (1982) and are indicative of very low oxygen fugacities during sub-solidus cooling.

The coarse granular ilmenite often shows the development of sparsely-distributed twin lamellae (Fig.5.11). Presence of twin lamellae is usually ascribed to the effects of some form of applied stress which causes shearing along planes parallel to (001) and less commonly (101) (Chakaravathy, 1961; Ramdohr, 1969; Smith and Steele, 1976). In the present study, these twinned grains are noticed in weathered ores which are generally highly fractured due to volume changes caused by oxidation and hydration. It is thus possible that this twinning may in part be related to this fracturing. Hiemstra and Liebenberg (1964), however, report the presence of twinned ilmenite grains in fresh ore from borehole cores, which suggest that other factors might be involved. In some cases these might represent annealing twins that have developed during the sintering of the ores.

Based on the size, distribution, and nature of these coarse, granular ilmenite crystals, it is suggested that they represent primocryst phases that co-precipitated together with the Ti-magnetite, as proposed for similar ores by Reynolds (1986). Their original morphologies have been modified considering by grain-boundary adjustment during sintering and adcumulus growth, as well as by their continued solid-state growth via the addition of externally-exsolved ilmenite. The areas of the lamellae are developed might be indicative of
the approximate of the original primocryst crystals by virtue of their apparent compositional difference.

5.2.1.4.2. Fine Inter-granular ilmenite

A number of very much smaller isolated single crystals or stringers of ilmenite are noticed along the grain boundaries between the very much larger polygonal Ti-magnetite grains. These fine granular ilmenite also exhibit spinelliferous outer rims (Fig.5.12). Distribution of these ilmenite grains, morphologies and sizes are consistent with their having formed via external granule ex-solution or contemporaneous oxidation/ex-solution from the neighboring Ti magnetite. Titaniferous magnetite can contain 0.5% by mass of excess oxygen at 1300°C (Taylor, 1964) and 0.3% at 1200°C (Webster and Bright, 1961) which correspond to approximately 15% and 8% ilmenite, respectively. Anderson (1968) evaluated these data with reference to the La Blache Lake titaniferous magnetite deposit and concluded that a maximum of approximately 10% of ilmenite could ex-solved sense stricto from igneous titaniferous magnetite and that this would take place at temperatures above 800°C. Any additional ilmenite would only form via the contemporaneous oxidation/exsolution of the magnetite-ulvospinel solid solutions. Lindsley (1976a, b) however, reiterated that the spinel field is not sufficiently wide even at 1300°C to account for many natural ilmenite-magnetite intergrowths by a simple process of exsolution. A certain proportion of this intergranular ilmenite and part of the overgrowths on the larger primocryst ilmenite may thus represent true exsolved ilmenite according to Anderson’s (1968) data. Once this amount of exsolved ilmenite exceeds several per cent by mass, however, any additional ilmenite would have to originate via the contemporaneous oxidation/exsolution mechanism. This external granule exsolution and/or oxidation/exsolution would occur during the initial stages of sub-solidus
cooling where the high ionic mobilities at these elevated temperatures would favor this process with heterogeneous nucleation occurring at grain-boundary imperfections.

5.2.1.4.3. Lamellar Ilmenite

This type of ilmenite is not commonly developed in the Ti-magnetite crystals of ores of Devaranarasipur area. It is normally considered to be a product of contemporaneous oxidation/exsolution of the magnetite-ulvospinel solid solution (Buddington and Lindsley, 1964; Lindsley, 1976b; Haggerty, 1976). Their relative paucity is thus a further indication of the presence of overall low oxygen fugacities during sub-solidus cooling as demonstrated by the widespread ex-solution of ulvospinel.

They appear to have nucleated heterogeneously at grain-boundary imperfections and at dislocations along fractures from where they have grown inwards into their hosts parallel to (111). They are occasionally connected to small intergranular ilmenite grains with which they are in optical continuity (Fig. 5.13). Broad ilmenite lamellae are sparingly seen in the Ti-magnetite. They are rarely to the extent where they form distinct trellis networks and also show relatively wide size range, even within single Ti-magnetite crystals (Fig. 5.14). Numbers of small equant-to-rounded pleonaste granules as commonly developed along the interfaces between the lamellae and their Ti-magnetite hosts. It is suggested that the bulk of these lamellae developed via contemporaneous oxidation/exsolution under conditions of slightly increased oxygen fugacity, and the relative abundance of the lamellae probably reflects the degree of oxidation that occurred. Their relatively large size is indicative of high ionic mobilities at their time of formation which, in turn, suggests that this occurred at elevated temperatures above the magnetite-ulvospinel solvus, i.e. this represents supersolvus ilmenite as suggested by Buddington and Lindsley (1964), and Duchesne (1970).
Fine and more abundant ilmenite lamellae are developed in the Ti-magnetite. They are commonly only a micrometer or less in width and rarely attain 20 m in length. They form extensive trellis networks parallel to (111) of the magnetite (Fig. 5.15) and take the place of the usual ulvospinel cloth texture. They are also sometimes slightly spinelliferous due to the development of small numbers of micrometer-sized pleonaste grains along their lengths. They are also considered to be developed by contemporaneous oxidation/ex-solution, but their very much smaller size suggests that this occurs at lower temperatures below the magnetite-ulvospinel solvus, as suggested by Reynolds (1986).

5.2.1.5 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 oxidized 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. 5.17). Though maghemite is meta-stable form of Fe₂O₃ with the structure of magnetite, the impurities like vanadium and titanium appear to favor the formation of maghemite from magnetite and to make maghemite more stable.

5.2.1.6 Hematite and Martite

Both Hematite and martite are greyish white in colour. They are non-pleochroic and anisotropic in shades of greenish grey and light brownish tints. Deep red internal reflections are distinctly noticed.
Hematite and martite exhibit similar optical properties, excepting the fact that the martite is secondary mineral after magnetite. Hence are grouped together for the purpose of description. Martite as xenomorphic grains gives the spongy appearance at places in some samples. They exhibit a relatively higher reflectivity than magnetite, ilmenite and even goethite Fig.5.5.

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 (Fig.5.6). In most of the samples the alteration of the magnetite to hematite is almost complete (Fig.5.4). 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.5.6). The presence of relics of magnetite grains in martite gives the impression of graphic texture. Martite replaces magnetite mainly along the octahedral planes producing triangular network and also grain boundaries (Fig.5.5).

5.2.1.7 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 oxy-hydration (Fig.5.18). Goethite is the hydrated product of magnetite. It replaces magnetite, ilmenite and hematite along the grain boundaries forming colloform bands (Fig.5.20).
5.2.2 Sulphide Assemblage

In Devaranarasipur area, minor amount of sulphide are, closely associated with oxide assemblage they are observed in the V-Ti-magnetite ore bodies. Sulphides are represented by chalcopyrite and pyrite. Chalcopyrite occurs as subhedral inclusions in the Ti magnetite grains and also in the coarse granular ilmenite. It exhibits sharp contacts with Ti magnetite grains, suggesting any replacement relationship. This mode of occurrence of chalcopyrite indicates its development along with the host Ti magnetite grains probably due to liquid immiscibility.

5.3 Weathering of V-Ti Magnetite Ores

V-Ti-magnetite ores show different degrees of oxidation and hydration that are related to near surface weathering processes. Ti-magnetite has been subjected to partial which starts from grain boundaries and other permeable features. Martite, is replacing Ti-magnetite, in the form of thin lamellae which grow parallel to (111) planes of Ti-magnetite (Fig.5.19). The lamellae of martite gradually become thicker and thicker and finally coalesce until the Ti-magnetite grain is completely martitized (Fig.5.4). Volume change occurred due to martitization so that the martite between the earlier-formed martite lamellae is commonly porous (Fig.5.19). Reduction in volume also took place as a result of which irregular fractures are developed (Fig.5.6). Due to progressive oxidation, Ti-magnetite which consists of ulvospinel intergrowths oxidizes through the development of maghemite as an intermediate phase. This also starts along the permeable features, but migrates into the Ti-magnetite in irregular form (Fig.5.7), which subsequently inverts to martite with progressive oxidation.

The maghemite may show some hydration to from goethite, but it more commonly inverts directly to hematite which is subsequently hydrated to goethite. The volume changes caused by the oxidation and hydration of the oxides and silicates, leads to the extensive
fracturing of the ores and the precipitation of vein-lets of delicately banded botryoidal and concretinary goethite (Fig.5.18).

The maghemitization process involves the conversion of a stoichiometric spinel into a cation-deficient, defect spinel, but the exact nature of the mechanism is highly controversial. Lindsley (1976a), Basta (1959), Colombo et al. (1965) and Davis et al. (1968) have stated that, since the magnetite crystals structure of a nearly close-packed array of large oxygen anions, any cation deficiency must result from the diffusion of Fe-cations out of the crystal, rather than by the diffusion of extra oxygen anions into it. This is accomplished by oxidation of Fe$^{2+}$ at the surface which upsets the charge balance within the crystal. It is thus necessary to remove 2Fe$^{3+}$ ions form every three oxygen’s at the surface. As a result, Fe ions for diffuse through the oxygen framework to the surface of the crystal where they may be either removed in solution or be deposited in the form of maghemite or hematite on the surface of the grain concerned.

The diffuse nature of the Ti-magnetite/maghemite boundaries reflects the progressive increase in the number of vacancies caused by the removal of irons ions. The outer rims of hematite can arise either via the epitaxial nucleation and growth of hematite, or by the inversion of maghemite to hematite. Relics of un-oxidized Ti-magnetite commonly survive in the cores of crystals in partially oxidized ores. This Ti-magnetite grades into maghemite with increasing oxidation and may be replaced by hematite around the grain boundaries and along fractures (Fig.5.17). This situation is commonly reversed in the more highly weathered ores where zones of magnetite are developed on such grains have been converted to maghemite, hematite and/or goethite. This reversal in oxidation sequence is problematical and may arise in situations where the oxidation of Fe$^{2+}$ to Fe$^{3+}$ at the exposed surfaces cannot keep pace with the rate at which Fe$^{2+}$ ions migrate to these sites. As a result, the earlier-formed
maghemite is replaced by magnetite. This is supported by the generally poor preservation of fine-scale microstructures in these areas of “secondary magnetite”.

5.4 Micro Structural Evolution

The V-Ti-magnetite layers probably contained less than 50 per cent of inter-granular liquid at their time of formation. Their conversion to dense, essentially monomineralic rocks, would have thus necessitated the removal of the bulk of this liquid via various post-depositional processes. The conversion of these Ti-magnetite concentrations into essentially monomineralic ores and the subsequent development of their characteristic microstructures, are envisaged to have occurred in different stages as suggested for similar V-Ti-magnetite ore-rich layers of Bushveld Igneous complex (Reynolds, 1986) as follows:

A homogenous high-temperature member of the magnetite-ulvospinel solid-solution series was precipitated in sufficient quantities to form an ore-rich layer. Minor ilmenite and silicate minerals might also have co-precipitated.

Neck-growth processes were initiated at mutual contacts between Ti-magnetite crystals during, or shortly after, crystallization. Continued diffusion-controlled growth of the Ti-magnetite crystals was also initiated and continued until diffusion between the inter-granular fluid and the overlying magma chamber was restricted by the increasing thickness of the overlying crystal pile.

Grain-boundary migration commenced under the driving force of surface free energy once the neck-growth stage had been completed. This resulted in the densification of the ore-rich grains developed by nucleation at grain-boundary imperfections (external granule exsolution). These processes probably remained operative until the temperature had fallen to approximately 800°C, below which ionic mobility become too low to allow for such large-scale solid-state diffusion.
The ex-solution of transparent spinel was initiated during subsequent cooling and resulted in the development of external pleonaste granules along grain boundaries where they impeded further grain-boundary migration. The overall polygonal mineral grain boundaries reached their final stage of development and the bulk of the inter-granular liquid was expelled. Crystallization of any entrapped inter-granular liquid also occurred. The large ilmenite developed during this a stage by contemporaneous oxidation/ex-solution under conditions of slightly increased oxygen fugacity. Nucleation of ilmenite occurred heterogeneously at grain boundaries and the lamellae grew inwards into their hosts’ parallel to (111). The oxygen fugacities were low enough in most of the ores at this stage for the stable existence of magnetite-ulvospinel solid solutions. They also favored the reduction of coexisting ilmenite-hematite solid solutions resulting in the reduction/ex-solution of thin magnetite plates in some of the ilmenite crystals. Grain-boundary imperfections along the interfaces between ilmenite lamellae and their Ti-magnetite formed energetically-favorable sites for the heterogeneous nucleation and growth of transparent spinel granules, thus forming spinelliferous ilmenite lamellae. Ex-solution of lamellar pleonaste occurred towards the end of this stage.

Cooling below the magnetite-ulvospinel solvus (<500°C) resulted in the initiation of ulvospinel ex-solution via heterogeneous in the initiation at dislocations formed around transparent pleonaste lamellae. This was followed at slightly lower temperatures by the development of typical ulvospinel cloth textures in cases where cooling occurred under conditions of low oxygen fugacity. The presence of higher oxygen fugacity led to the oxidation/ex-solution of abundant fine ilmenite lamellae parallel to (111) of the Ti-magnetite, in place of the ulvospinel lamellae. These processes continued with the progressive decrease in temperature of about 200°C due to extremely low ionic mobility at such temperatures.
Many of the late-stage alteration phenomena developed during this stage. The occurrence of locally increased oxygen fugacity’s in local intergranular areas resulted in the development of narrow oxidized rims along fractures at Ti-magnetite/plagioclase grain boundaries, probably as a result of the action of late-stage fluids. Some degree of oxidation of the ore may also have occurred, resulting in the formation of maghemite.

The extensive oxidation and hydration of the ores occurred during near surface weathering processes.

5.5 Paragenesis

A paragenetic scheme has been worked out as shown in fig5.21, based on the observed textures described above for V-Ti Magnetite Ores of Devarnarsipur area.

Ti-magnetite and granular ilmenite have crystallized simultaneously filling the interstices of the silicate minerals and are in close association with each other forming a massive ore. Ilmenite forming granular, lamellar and emulsion intergrowths with magnetite are formed later by un-mixing during decreasing temperature conditions. Goethite is a secondary mineral transformed from Ti-magnetite and hematite. Maghemite is formed at different stages of oxidation of magnetite without affecting the ilmenite.

The V-Ti-magnetite layers containing intergranular liquid at their time of formation. Their conversion to dense, essentially monomineralic rocks, would have thus necessitated the removal of the bulk of this liquid via various post-depositional processes. The conversion of these Ti-magnetite concentrations into essentially monomineralic ores, The V-Ti-magnetite layers probably contained less than 50 per cent of intergranular liquid at their time of formation, the subsequent development of their characteristic microstructures, are envisaged to have occurred in different stages as suggested for similar V-Ti-magnetite ore-rich layers of Bushveld Igneous complex (Reynolds, 1986).
A homogenous high-temperature member of the magnetite-ulvospinel solid-solution series was precipitated in sufficient quantities to form an ore-rich layer. Minor ilmenite and silicate minerals might also have co-precipitated. Neck-growth processes were initiated at mutual contacts between Ti-magnetite crystals during, or shortly after, crystallization. Continued diffusion-controlled growth of the Ti-magnetite crystals was also initiated and continued until diffusion between the intergranular fluid and the overlying magma chamber was restricted by the increasing thickness of the overlying crystal pile.

Grain-boundary migration commenced under the driving force of surface free energy once the neck-growth stage had been completed. This resulted in the densification of the ore-rich layer by pore-space reduction involving the expulsion of part of the intergranular liquid and the development of polygonal grain boundaries (sintering). Cooling of the solidified aggregate also commenced during this stage and resulted in the external granule exsolution of ilmenite, either by direct exsolution (Anderson, 1968) or by contemporaneous oxidation exsolution (Buddington and Lindsley, 1964).

The exsolution of transparent spinel was initiated during subsequent cooling and resulted in the development of external pleonaste granules along grain boundaries where they impeded further grain-boundary migration. The overall polygonal mineral grain boundaries reached their final stage of development and the bulk of the intergranular liquid was expelled. Crystallization of any entrapped intergranular liquid also occurred. The large ilmenite developed during this stage by contemporaneous oxidation/exsolution under conditions of slightly increased oxygen fugacity. Nucleation of ilmenite occurred heterogeneously at grain boundaries and the lamellae grew inwards into their hosts parallel to (111). The oxygen fugacities were low enough in most of the ores at this stage for the stable existence of magnetite-ulvospinel solid solutions. They also favored the reduction of coexisting ilmenite-hematite solid solutions resulting in the reduction/exsolution of thin magnetite plates in some
of the ilmenite crystals. Grain-boundary imperfections along the interfaces between ilmenite lamellae and their Ti-magnetite formed energetically-favorable sites for the heterogeneous nucleation and growth of transparent spinel granules, thus forming spinelliferous ilmenite lamellae. Exsolution of lamellar pleonaste occurred towards the end of this stage.

Cooling below the magnetite-ulvospinel solvs (<500°C) resulted in the initiation of ulvospinel exsolution via heterogeneous in the initiation at dislocations formed around transparent pleonaste lamellae. This was followed at slightly lower temperatures by the development of typical ulvospinel cloth textures in cases where cooling occurred under conditions of low oxygen fugacity. The presence of higher oxygen fugacity led to the oxidation/exsolution of abundant fine ilmenite lamellae parallel to (111) of the Ti-magnetite, in place of the ulvospinel lamellae. These processes continued with the progressive decrease in temperature of about 200°C due to extremely low ionic motilities at such temperatures.

Many of the late-stage alteration phenomena developed during this stage. The occurrence of locally increased oxygen fugacity’s in local intergranular areas resulted in the development of narrow oxidized rims along factsures at Ti-magnetite/plagioclase grain boundaries, probably as a result of the action of late-stage fluids. Some degree of oxidation of the ore may also have occurred, resulting in the formation of maghemite.

The extensive oxidation and hydration of the ores occurred during near surface weathering processes.
Ore Minerals

Primary

- Ti-Magnetite
- Ilmenite (Coarse granular)
- Chalcopyrite
- Pyrite

Exsolved Phases

- Ulvospinel
- Pleonaste
- Ilmenite (Lamellae/external granules)

Secondary

- Ti-maghemite
- Martite (Hematite)
- Goethite

Fig5.21 Paragenetic diagram for the Ore-minerals of Devarnarsipur area
Fig: 5.1, Photomicrograph of Idiomorphic grains of magnetite (white) and ilmenite unaffected by martitization well defined boundaries of ore minerals with the interfacial angles of $120^\circ$ at triple junction

Fig: 5.2, Medium-grained polygonal ore exhibiting well-defined granoblastic boundaries with the interfacial angles of $120^\circ$. Note the ilmenite presence and also externally ex-solved euhedral pleonaste (black) along the Ti-poor magnetite crystals
Fig: 5.3, Medium-grained ore exhibiting several volume percent inter granular silicates (black). Note the smaller size and curved nature of grain boundary of the Ti-magnetite crystal in the vicinity of silicates indicating that equilibrium has not been attained.

Fig: 5.4, Polygonal nature of magnetite and ilmenite 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 occurs as idiomorphic crystal which are not affected by martitization showing . Plane polarised reflected light
Fig: 5.5, Idiomorphic grains showing partial affected by martitization. Note the Plane polarized reflected light grain boundary containing abundant pleonaste inclusions in the form of small, Equant granules (black) developed between ilmenite and Ti magnetite.

Fig: 5.6, Magnetite grains (white) undergoing martitization show fracturing and brecciation due to deformation Plane polarised reflected light.
Fig: 5.7, Ti-magnetite crystals consist of typical ulvospinel cloth textures. Note the presence of lamellae of pleonaste (black) aligned parallel to (100) planes of the Ti magnetite. Incident light, 50X.

Fig: 5.8, Spineliferous grain boundary containing abundant pleonate inclusions in the form of small, equant granules (black) developed between ilmenite and Ti magnetite (white). Note the irregular and serrated ilmenite-Ti magnetite interfaces.
Fig: 5.9, Sub-rounded to subhedral pleonaste granules noticed in the central portions of Ti-magnetite crystals. A further set of tiny pleonaste lamellae (black) are developed parallel to (100) planes of Ti magnetite. Note the absence of these lamellae little away from the large granule, Incident light.

Fig: 5.10, Ilmenite grain contains a number of closely spaced lamellae of Ti magnetite (now oxidized to martite) that are developed parallel to (0001) in the central portions. Incident light, Oil immersion, 125 X.
Fig: 5.11, The coarse granular ilmenite showing the development of sparsely-distributed stress twinning lamellae Incident light, slightly uncrossed polars (nicols), Oil immersion, 125X.

Fig: 5.12, Fine inter-granular ilmenite (pinkish colour) grains noticed along the grain boundaries between the very much larger polygonal Ti-magnetite grains. They also exhibit spinelliferous outer rims.
Fig: 5.13, Fine inter-granular ilmenite grains have nucleated heterogeneously at grain boundary imperfections and dislocations along fractures from where they have grown inwards into their hosts parallel to (111). Note the ilmenite grains which are in optical continuity.

Fig: 5.14, Broad ilmenite lamellae are sparingly seen in the Ti-magnetite. They are rarely to the extent where they form distinct trellis networks and also show relatively wide size range, even within single Ti-magnetite crystals. Incident light, Oil immersion, 125 X.
Fig. 5.15. Trellis net work of fine ilmenite lamellae (grey) aligned parallel to (111) planes of Ti-magnetite incident light, oil immersion 125X.

Fig. 5.16. Pinkish brown in colour Ilmenite grain showing perfect octahedral shape which is unaffected by martizitation.
Fig: 5.17. Extensively weathered ore in which the Ti-magnetite has been completely converted to maghemite, resulting in fracturing (black).

Fig: 5.18. Martite hydrated to goethite which exhibits banded botryoidal and concretionary structure. Incident light, 20X.
Fig. 5.19. Martite (white) replaces Ti-magnetite along its (111) planes in the form of thin lamellae. Note the spinelliferous ilmenite granule, unaffected by martitization.

Fig. 5.20. Polygonal granular ilmenite showing ex-solution discs and blebs of hematite. Note that goethite replaces martitized magnetite and also ilmenite forming colloform bands. Plane polarized reflected light.