Chapter 7
GENETIC INTERPRETATION
AND DISCUSSION
INTRODUCTION


The V-Ti-Fe deposits associated with gabbro-anorthosite complexes in India have been studied by several workers. However, some of the better studied deposits include those of Dublabera-Katwar Pahar, Singhbhum district, Bihar (Dunn and Dey, 1937; Dasgupta, 1968 & 1969); south of Gorumahisami Pahar (Kumardubhi, Betijharan, Amdabera), Mayurbhanj district of Orissa (Roy, 1955); Nausahi (Boula range), Keonjar district, Orissa (Mukherjee, 1958; Chakraborty 1959a & b; Chakraborty et al. 1988) and Sattora in the Bankura district of West Bengal (Bose and Roy, 1966).

In Karnataka, the V-Ti-Fe deposits have been described from

GENETIC MODELS FOR V-Ti-Fe ORES

The subject of origin of the V-Ti-Fe ores has remained a controversy and a variety of interpretations have been put forth to account for the accumulation of these ores. The genetic models proposed for the concordant V-Ti magnetite layers in the Bushveld complex and other gabbroic intrusions can be grouped into i) earlier genetic models and ii) later genetic models (Reynolds, 1985b).

The earlier genetic models (as proposed by Molengraft, 1904; Singewald, 1912; Du Toit, 1918; Osborne, 1928; Wager, 1928; Hall, 1932; Dunn and Dey, 1937; Bateman, 1951; Lister, 1966; Coertze, 1966; Philpotts, 1967; Kolkar, 1982 and Reynolds, 1983a) acknowledged the existence of genetic relation between concordant layered Fe-Ti oxide ores and their host rocks and either invoked separation and accumulation of Fe-Ti crystals to form layers or postulated the existence of Fe-Ti oxide liquids from which the ores crystallized.

Nearly all later genetic models invoke mechanisms whereby episodic increase in oxygen fugacity trigger the crystallization
of enough quantities of Ti-magnetite required for the development of ore-rich layers. The formulation of these models by Molyneux, 1970a; Hill and Roeder, 1974; Irvine, 1975 & 1977; Reynolds, 1980, 1981; Kleem et al, 1982 was preceded by experimental studies of synthetic Fe-bearing systems (e.g., Muan and Osborn, 1956; Osborn, 1959; Roeder and Osborn, 1966) which indicated that oxygen fugacity is an important factor in the crystallization of magnetite and Fe-bearing phases. These studies indicate that the Fe$_2$O$_3$/FeO ratios of magmas are, to a larger extent, dependant on oxygen fugacity and that magnetite precipitation would be enhanced by an increase in the amount of Fe$^{3+}$ in the melt.

**REVIEW OF THE PREVIOUS VIEWS ON THE GENESIS OF CHANNAGIRI, DEVARANARSIPUR AND MULEMANE DEPOSITS**

Regarding the genesis of V-Ti-Fe deposits of Masanikere, Ramíengar et al. (1978) opine that Fe-Ti-V-Cu mineralization in gabbro-anorthosite complex is a result of magmatic differentiation of an iron-rich basic magma and the titanomagnetite deposits are formed by differentiation-crystallization-segregation, thus forming the liquid magmatic type of schneiderhoIn.

Vasudev and Srinivasan (1979) are of the opinion that V-Ti-Fe deposits of Karnataka are deformed and conformable layered type and are gradational to gabbro-anorthosite layers as has been noticed in Bushveld igneous complex. The ore bodies are co-folded with the host rocks indicating their probable syngenetic origin.
Further, they concluded that these deposits can be compared more favourably with concentric complexes of Jackson and Thayer (1972).

Govindaiah et al. (1989) opine that the genesis of V-Ti magnetite layers/bands is intimately related to fractional crystallization of iron-rich basic magma, probably involving several influxes resulting in the concentration of substantial amounts of Fe, Ti and V in the late-stage residual magma. Further, they conclude that the V-Ti magnetite layers are considered to have developed largely by in situ bottom crystallization and subsequent textural evolution of Ti-magnetite layers is believed to have taken place due to variations in oxygen fugacity during subsolidus cooling which resulted in the development of a wide range of ulvospinel, pleonaste and ilmenite microintergrowths.

Naganna et al. (1976) are of the opinion that the iron-titanium oxide ores of Devaranarsipur occur as lenses and stringers interstitial to silicate minerals which is suggestive of the iron-titanium oxide ores to have crystallized from interstitial residual liquids. They conclude that the iron-titanium oxide ores have been formed by extreme iron-titanium enrichment in the residual liquid whereby either final freezing might have occurred to yield a basic igneous rock with interstitial oxides or the residual liquid might have been filter pressed out of the crystal mesh and injected.

Vasudev and Srinivasan (1979) opine that the V-Ti-Fe ore
body of Mulemane is of a transgressive type and has formed by magmatic injection.

GRADATIONAL RELATIONSHIP OF THE V-Ti-Fe ORE BODIES WITH THE HOST ROCKS

Field observations show the close association of V-Ti-Fe bands of Channagiri area with the gabbro-anorthosite suite of rocks showing intrusive relationship with quartz-chlorite ± carbonate schists of Chitradurga group of Dharwar Supergroup. The gabbro-anorthosite members are spatially associated with ultramafics. A gradational passage from gabbro and magnetite gabbro to V-Ti-Fe bands/layers is noticed. This gradational relationship is an evidence of accumulative origin indicating that V-Ti-Fe ores are the cumulate phases of gabbro.

V-Ti-Fe ore bodies at Devaranarsipur occur as disconnected bands which are conformable with the general trend of the associated pyroxenite/serpentinite. The main magnetite body of Mulemane area occurs associated with peridotite/serpentinite. Several small lenses of V-Ti-Fe ores occur within gabbro in the vicinity of the main ore body.

CONSISTENT ASSOCIATION OF MAGNETITE AND ILMENITE

All the ore bodies studied have essentially an association of magnetite and ilmenite with minor proportions of spinel, hübgbomite, chlorite and sulphides. Ore microscopic study has shown that magnetite, titanomagnetite and ilmenite commonly exhibit gently curved to straight grain boundaries which
indicates that equilibrium was not totally attained during subsolidus annealing. Attainment of equilibrium would have resulted in the formation of straight-sided polyhedra (Smith, 1948; 1964 quoted by Reynolds, 1985).

**OCCURRENCE OF A WIDE RANGE OF INTERGROWTHS**

A wide range of ilmenite, ulvöspinel, spinel and hogbomite intergrowths are noticed in the V-Ti-Fe ores. These microtextures of the oxide minerals reflect extensive subsolidus recrystallization during slow cooling from magmatic temperatures.

**WIDESPREAD OCCURRENCE OF HOGBOMITE**

Widespread occurrence of this mineral in all the V-Ti-Fe deposits studied suggests that it is a part of the magmatic phenomenon that has given rise to these deposits. The randomly oriented coarse crystals of hogbomite which occur commonly occupying the interstices of ore grains, bear no evidence of derivation from spinel and constitute early crystallized pyrogenic phase. The thin scales/rods and small blebs/drops of hogbomite occurring in magnetite possibly represent exsolved phase, the exsolution of hogbomite component having taken place in response to falling temperature of crystallization (Devaraju et al. 1981). The slender scales and shreds rimming the spinel grains bear evidence of formation at the expense of spinel — the early formed spinel crystals reacted with the magma partially along the grain boundaries, giving rise to hogbomite rims. Hogbomite occurring along the grain boundaries of magnetite/titanomagnetite appears to have formed by the
replacement of the latter minerals. Considerable variation is observed in the chemistry of hogbomite of different areas in the content of Mg, Fe, and Ti and some tend to be of zincian type. This is probably the result of variation in the composition of magma and the conditions of crystallization.

**OCCURRENCE OF CHLORITES OF DIFFERENT COMPOSITION**

Chlorite is an ubiquitous mineral forming scaly aggregates located interstitially between the ore minerals of all the V-Ti-Fe ore bodies studied except in Mulemane. It shows evidence of being a late stage magmatic mineral. There is no indication of its formation by hydrothermal alteration. The bulk of the Fe and Ti from the magmatic liquids was extracted in the early stages of crystallization as magnetite and ilmenite and there was late stage accumulation of alumina, magnesia and silica in the proportion required for chlorite formation. The separation of alumina and magnesia, however, appears to have taken place in at least two different stages of crystallization; in the early stages as spinel and hogbomite and in the late stage at low temperature when silica accumulated, as chlorite. The absence of free silica in the ore bodies suggests that silica accumulated in the last stages was just enough for chlorite formation. Chlorites of different areas are classified as repidolite, corundophilite, sheridanite and amesite.

**OCCURRENCE OF DIASPOR AND KAOLINITE**

Diaspore occurs as scales and elongated crystals occupying the tight joints, fissures, cavities and other weak planes in the
V-Ti-Fe ores of Mulemane, Magyatahalli and Devaranarsipur areas. In both Magyatahalli and Devaranarsipur areas, diasporite occurs associated with chlorite and in Mulemane ores with kaolinite. The separation of alumina in the late stage at low temperatures appears to have taken place in two different stages of crystallization; in the early stages along with magnesia and silica as chlorite and in the late stage excess alumina formed diasporite. However, in Mulemane area the accumulated alumina and silica which were not extracted in the formation of chlorite, formed kaolinite. Subsequently, the excess alumina available might have resulted in the formation of diasporite.

SIGNIFICANT VARIATION IN THE MAJOR AND TRACE ELEMENT GEOCHEMISTRY AMONGST DIFFERENT V-Ti-Fe DEPOSITS

There are significant differences in the content of major and trace elements of the V-Ti-Fe ores. Also, within the deposits of Channagiri area, the range of variation in Cr, V, Mg, Si, and Cu is greater between the different ore bodies. Cr is significantly high in the Magyatahalli ores, whereas V and Cu are more in Masanikere ores. Fe$^{2+}$ and Fe$^{3+}$ vary significantly between the deposits. These various differences may suggest that there were slight but consistent differences in magma composition and crystallization conditions for the different deposits.

ABSENCE OF SEPARATE VANADIUM MINERALS

Ore microscopic study does not reveal the presence of separate V minerals; it is present in the structure of other ore minerals. The positive correlation between V and Fe/Ti ratio...
indicates the presence of V in the Fe-Ti oxides. In terms of the vanadium content of the ores, the deposits can be placed in the following order: Masanikere > Devaranarsipur > Mulemane > Magyatahalli > Ubrani > Tavarekere.

COMPOSITION OF MAGNETITE AND ILMENITE

Magnetite exhibits a greater range of composition than the ilmenite and can be classified as magnetite proper, titanomagnetite, chromiferous magnetite, chromiferous titanomagnetite and maghemite. Such a variation in the chemistry of magnetite of different deposits and also within the same deposit, is probably the result of variation in the composition of injections of magma and the different conditions of crystallization (Mathison, 1975).

Ilmenite of different deposits varies very little in composition and has very low Fe$_2$O$_3$ content. The present compositions of co-existing ilmenite and titanomagnetite cannot be explained by subsolidus cooling parallel to buffer curves. Ilmenite seems to have lost iron, possibly in part, due to reaction with either the silicates, a silicate liquid or a fluid phase during cooling from magmatic temperatures. This explains the anomalously low hematite contents (Table-10) of the ilmenite (Thy, 1982).

PARTITIONING OF MINOR AND TRACE ELEMENTS BETWEEN MAGNETITE AND ILMENITE

The different elements analysed show a distinct preference for either magnetite or ilmenite. The elements Al, Cr, V and Ni
are all preferentially concentrated in magnetite, whereas Mg and Mn show a preference to ilmenite. The data do not suggest that Zn, Co and Cu are preferred by either magnetite or ilmenite. These preferences are similar to those observed for the Fe-Ti oxides in the Skaergaard intrusion (Vincent and Phillips, 1954).

It is confirmed by mineral chemical study that there are no separate vanadium minerals as reported by earlier workers (Naganna et al. 1976 in the ores of Devaranarsipur) and most of the V is present in the structure of magnetite/titanomagnetite and hagbomite.

THE HIGH CHROMIUM CONTENT OF MAGYATAHALLI DEPOSIT

The high content of Cr₂O₃ in the chlorite-rich magnetite ores of Magyatahalli is due to the fact that chromium in these ores is present in the structure of magnetite/titanomagnetite suggesting existence of solid solution between chromite and magnetite/titanomagnetite. A solid solution between magnetite and chromite, however, is relatively complicated and rare because of their different crystal structure. The Magyatahalli magnetite is thus an exception like the Narankavaara intrusion of the Koillismaa layered igneous complex of Finland, where an apparent solid solution between magnetite and chromite has been recorded (Alapetl, 1982). Spinelis intermediate between chromite and titanomagnetite have also been reported in the volcanic rocks by Gunn et al. (1970) and Thompson (1973). Generally in layered mafic intrusions, spinels are either Ti-rich and Cr-poor, or Cr-rich and Ti-poor, as seen in the case of Bushveld complex. Where both
are present, they usually occur at widely separated stratigraphic horizons. In case of titanomagnetites of Magyatahalli area, however, rather unusually no such separation is recorded between Cr-rich magnetite and Cr-rich titanomagnetite. Hill and Roeder (1974) studied the crystallization of a basaltic melt under varying conditions of temperature and oxygen fugacity. In the temperature range of 1050° to 1200°C and at oxygen fugacity in the range of 10^-0.07 to 10^-4, they obtained a continuous series of spinels from chromite to titanomagnetite, the Cr-rich members forming at high temperature and low oxygen fugacity. The major reason for the discontinuity in composition between chromite and magnetite in layered intrusions is the reaction at low oxygen fugacity between chromite, pyroxene and liquid. If the reaction is not allowed to take place, for example by rapid cooling, intermediate spinel compositions can crystallize such as found in Snake River plain basalts (Thompson, 1973). Similar conditions might have favoured the formation of chromium-rich magnetite of Magyatahalli area.

GENESIS OF V-Ti-Fe DEPOSITS OF THE PRESENT STUDY

Based on the foregoing discussion of the various aspects of field characters, textures, mineralogy, mineral chemistry and geochemistry of the V-Ti-Fe deposits under investigation, it is concluded that the most common titanium-rich magnetite bodies of Channagiri area have formed at a late stage and the rare chromium-rich magnetite bodies have separated in the early stage of crystallization of an iron-rich basic magma which was initially enriched in Ti and V. The chlorite-rich chromiferous
magnetite of Magyatahalli area might initially have formed as pyroxene-magnetite rock and subsequently under shearing and low grade metamorphism the assemblage changed over to a chlorite-rich magnetite. The original pyroxene of the pyroxene magnetite rock seems to have been totally chloritised and the alumina required was possibly derived from the feldspars of the associated gabbro/anorthosite. This chlorite has a relatively high Fe and Cr contents than the chlorite of all other ore bodies. There is evidence to show that the chlorite of these ores has diffused into the magnetite grains along weak planes sometimes simulating exsolution lamellae along definite crystallographic directions.

The V-Ti-Fe magnetite bodies of Devaranarsipur area seem to have formed by filter pressing of a residual liquid enriched in V, Ti and Fe and injection into the associated pyroxenite/serpentinite. The main magnetite body of Mulemane area is a result of late magmatic accumulation of Fe-Ti oxide minerals and their injection into the associated serpentinite.

The copper content in the magma which was initially low was progressively built up during fractionation and eventually resulted in a later sulphide phase which is supported by the fact that copper mineralization is associated with the V-Ti-magnetite of the different deposits studied.

CRYSTALLIZATION CONDITIONS

It is generally accepted that when the Buddington and Lindsley (1964) geothermometer and oxygen barometer is applied to
equilibrium crystallized titanomagnetite and ilmenite pairs from plutonic complexes, only the subsolidus cooling history is recorded (Thy, 1982). Fe-Ti oxide minerals undergo extensive recrystallization and change in composition as the temperature or oxygen fugacity is lowered or changed. If equilibrium is maintained during cooling in the Fe-Ti oxide system, then the subsolidus conditions can be inferred from the co-existing phases.

With the low hematite content of the ilmenites of all the V-Ti-Fe deposits studied, precise temperature and oxygen fugacities are not determinable. In order to allow a better estimate of the crystallization conditions, the original composition of the primary phases has to be deduced. Accepting the Buddington and Lindsley hypothesis that the secondary coarse grained ilmenite originated from a primary titanomagnetite solid solution by oxidation-exsolution, the original composition can be obtained by combining the present modal proportions expressed as weight percent of titanomagnetite and secondary ilmenite. This recalculation assumes that ilmenite does not change composition during cooling (Thy, 1982). But in the present study, modal proportions of titanomagnetite and ilmenite have not been obtained and it is not attempted to estimate the crystallization conditions by recalculating the original composition of the primary phases. However, as the present compositions of titanomagnetite and ilmenite of all the deposits studied are closely comparable to those of the Fongen-Hullinglen basic complex, Norway (Thy, 1982), the results obtained for the complex
may as well be extended to the present study. The results obtained for the said complex lie below 800°C and an oxygen fugacity of $10^{-17}$ bar between the FMQ (fayalite - magnetite - quartz) and MW (magnetite - wustite) buffer curves, or on the MW buffer. It may be suggested that ilmenite reequilibrated with titanomagnetite to the present composition in response to cooling along a path oblique to both ulvospinel and ilmenite isopleths in $T - fO_2 - X$ space (Thy, 1982).

**DEUTERIC READJUSTMENTS AND AUTOMETAMORPHISM**

The V-Ti-Fe bodies bear evidence of autometamorphism related to deuteroc or late stage readjustments. These include widespread martitization of magnetite and transformation of magnetite to hematite and goethite.

The shearing movement associated with the low grade metamorphism appears to have affected the border zones of some of the magnetite bodies, contributed to some extent and modified locally the metamorphic changes. However, the effects of autometamorphism and subsequent low grade metamorphism appear to have produced overlapping changes which are not distinguishable. The interstitially occurring chlorite is largely or completely a deuteric phase and has remained stable during subsequent low grade metamorphism.

**SECONDARY ALTERATION**

Upliftment, uncovering and extensive weathering have affected all the rock types including V-Ti-Fe ores. The process has particularly affected the exposed and the near surface
portions of the ore bodies. The secondary alterations seem to have magnified the deuteric alterations and as a result the portions affected by secondary alterations are characterised by greater proportions of martite, hematite, goethite and oxidation of iron.