CHAPTER III

BANDED IRON FORMATIONS

3.1 Introduction

Banded Iron Formation (BIF) is both a rock and an ore and hence it is important academically as well as economically. While it is being mined at present as an iron ore in some countries including India, it serves as a huge potential reserves for future in many countries. BIFs hold the key for many unsolved problems of Precambrian geology, including origin of life. And hence it constitutes the subject for many branches of science particularly petrology, mineralogy, palaeontology and economic geology. In Precambrian geology, BIFs are significant as they are exclusively confined to that period (with some minor exception).

It appears that there is a definite pattern of distribution of BIFs with reference to space and time and it is very much certain with reference to the latter. BIF is a common and major lithotype in most of the shield areas or Precambrian terrains like Lake Superior Region of USA and Canada, Krivoy Rog and Kursk region of USSR (including European part), Western Australia, parts of South America, South Africa and our Indian Peninsula. Thus it is seen, in almost all the continents, BIFs occur. This worldwide distribution of the rock during a definite period reflects a
major event on a global scale in the history of the earth's evolution. Even with reference to plate tectonics, BIFs help in understanding the evolution of the earth's crust. On this subject, Goodwin (1973) has concluded," The world distribution pattern of Precambrian sedimentary iron formations in general and those of early Proterozoic age in particular indicate their deposition according to some global plate boundary pattern which is generally subparallel to that of modern oceanic ridges at accreting plate boundaries. The origin and pattern of the iron-formations may be related to some type of plate motion that affected proterozoic crust. If so, the apparent subparallelism in the distribution of early proterozoic iron-formations and modern plate boundaries supports Hurley's contention of the stability of 'Pre-drift' continental nuclei. This would impose some broad restrictions on the degree of precretaceous dispersion, disorientation and reassemblage of Precambrian crustal nuclei".

Since such a similar event of major BIF deposition did not take place subsequently (with some minor exception), particularly in recent geologic past, there is difficulty in understanding these ancient rocks.

Another problem is that they have been modified much, subsequent to their formation. In the background of this multiple importance and problems on one hand and several constraints and limitations on the other, BIFs have been
taken up as a major topic for research throughout the globe. Particularly important are the American workers confining on Lake Superior Region and Russian workers on the Krivoy Rog and Krusk Region. However, much work remains to be done on other BIFs, like those of Indian Peninsula.

3.2 Indian occurrence

In Indian Peninsula, all the Precambrian terrains have prominent BIF ranges, very important is that in many places, BIFs have close genetic relationship with high-grade hematite-goethite deposits. These places are as follows. In Bihar and Orissa, BIFs along with high-grade ores and associated with shales, phyllite, lava flows and tuffs are found in the Singbhum-Keonjhar-Bonai belt. BIFs here, form prominent ridges raising between 800-1000 mtrs. altitudes. In Madhya Pradesh, BIFs occur at many places but those at Bailadila, are well exposed along with hematite ores. In Karnataka, which is the type area for Dharwars, large reserves of high-grade hematite ores occur along with BIFs at places like Sandur-Hospet-Bellary area, Kemmangundi, Kalhatgiri etc.

Apart from the above said BIFs which are believed to have given rise to high-grade ores, there are very extensive outcrops of BIFs occurring as prominent hill ranges but without high-grade ores in almost all the states of Indian
Peninsula. One such important region or tract in Indian Peninsula is the Western Ghats lying in the states of Maharashtra, Goa, Karnataka, Tamil Nadu and Kerala. Here BIFs occur in different geological environments. But very diagnostic are those (lying southward mostly in the state of Tamil Nadu and partly in South Karnataka) which are highly metamorphosed to granulitic facies and the others which are very extensive and less metamorphosed. Some of the prominent latter group in Karnataka are as follows (district wise): Bijapur (Amingarh), Chikmagalur (Bababudan, Kudremukh, Gangamula), Chitradurga (Vajra, Lakkihalli), North Kanara (Anmod, Supa), Shimoga (Kodachadri, Shankargudda), Tumkur (Chikanayakanahalli). Bababudan schist belt situated in between Western Ghats and maidan region constitutes one of the best terrains especially for the study of BIFs.

3.3 Development of literature on BIFs

We can trace back the efforts of systematic studies on BIFs way back in 1911 by Van Hise and Leith on Lake Superior Region. At the almost same period even in India also there was an attempt to understand them i.e., in Karnataka, Sampath Iyengar (1912), studied on Kudremukh-Gangamula deposits. Subsequently, throughout the globe (particularly on Lake Superior Region and Russain province) BIFs have been studied. Some of the prominent works are listed in Appendix I (in chronological order).
A glimpse of the work in the Appendix I shows that the literature on BIFs has been accumulating steadily since the beginning of the century and that the prominents are American and Russian workers studying on the deposits of their respective countries. We can consider that in the history of development of literature on BIFs, the year 1973 is a landmark since it was during this year that the deliberations of the two important International Symposia (one held at Kiev and another at Minnesota) published.

Kiev and Duluth Symposia: The Kiev symposium was the first of this kind to be held on an international level to discuss on various problems of Precambrian iron and manganese deposits. The general outcome of the symposium was to make further detailed studies, particularly on the relation between chert-iron-manganese on one hand and volcanogenic formations on the other. It was very much felt that the first task is to undertake the systematisation of classification of these rocks at different countries and a need to have a unified system of nomenclature and detailed studies including aspects of metamorphism and secondary enrichment.

The symposium stressed the importance of understanding the conditions of depositions, role of the associated volcanics and the post-depositional changes like
metamorphism and secondary enrichments. The need for absolute age dating of BIFs and their position in the Precambrian stratigraphic sequence was also stressed.

The 1972 Duluth symposium was primarily designed for a global assessment of the nature and distribution of Precambrian iron-formations. Other aspects are to review the status of specialised investigation and to consider the ultimate question of origin and significance. The contributions are exclusively on manganese free iron-formations and project the extreme world distribution and possible methods in approaching the various problems on the study of BIFs. This has definitely helped for researchers as guidelines, for concentrating on specific problems and hence the post-1973 period has seen some very significant contributions. These include even works outside Lake Superior Region and Russian province like those in Australia, South Africa and India.

Very important contributions of the post-1973 period are the two comprehensive volumes of Elsevier publications (Mel’nik 1982, and Trendall and Morris 1983). Many recent workers, also guided by 1970 and 1972 deliberations, have confined to specific problems with latest techniques and approaches like estimation of REE and other nuclear geochemical studies. Some of these works are listed in Appendix II.
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3.4 Problems and Scope

Before proceeding to examine the various problems confronting BIFs, if we look at the nomenclature of BIFs, there is a lot of confusion about the terms, their definition and their applicability. Several terms are in vogue in different countries. This has been reviewed by workers like James (1954, 1966), Dimroth (1975), Kimberley (1978), Mel’nik (1982), Trendall (1983), etc. Trendall (1983) preferred to retain the term 'Iron-formation' as a general lithological and stratigraphic term for iron rich sedimentary rock in original sense of James (1954, not 1966). He modified the latter’s definition of iron formation as any sedimentary rock whose principal chemical characteristic is an anomalous high content of iron. The classification of iron-formations proposed by earlier workers were also essentially underwent reviews and modifications by several researchers like James (1954), Gross (1965), Dimroth (1975), Kimberley (1978), Beukes (1980), Mel’nik (1982) and Trendall (1983).

The classical 'facies' concept of James (1954) is not applicable in all the areas as has been observed by workers like Mel’nik, Trendall and others. All transitions are observed between oxide, carbonates and silicate rocks (Beukes 1973; Bayley and James, 1973; French, 1975; Klein, 1973 and 1974; Appel, 1974; Floran and Papike, 1975; Klein
and Fink, 1976; Klein and Bricker, 1977). With his own experience, Trendall (1983) felt to abandon the term 'facies' and recommended the usage of terms like oxide iron-formation, carbonate iron-formation etc. as mere descriptive terms. He, like some others, (Klein, 1981; Gole, 1981 etc.) did not favour much, the classification of iron-formations by Gross (1965).

The various other problems of BIFs are their exclusive confinement to Precambrian times, banded/laminated character, source and mode of transportation and deposition, role of volcanism or organisms, paleo-environmental conditions, type and nature of primary mineral and their subsequent modifications etc. While many of these problems exist, BIFs have been recognised at least as of two major types viz., those of Archaean (>2500 m.y.) and Proterozoic (1800 to 2500 m.y.). Even in these two, more similarities are recorded as significant than their differences, probably because of the general conditions during Precambrian times. Gole and Klein (1981) have shown that contrasts between the two largely reflect differences in the tectonic setting of Proterozoic and Archaean terrain. Other major observation regarding the two by them was the stratigraphic sequence in which iron-formation occurs is of highly variable and indicate that they are formed in many depositional environments. Despite these differences in associated lithology and sedimentary
textures, Precambrian iron-formations are similar in bulk composition and mineral assemblages implying that the chemical conditions of iron formation depositions were similar throughout much of the Precambrian period. So the minor differences between the two identical major types on one hand and those individual ones within specific type have to be explored and worked out carefully in order to elucidate main problems particularly the origin aspects.

In the light of the above observations, Bababudans appear to be one of the ideal terrains with very extensive BIFs preserving to some extent a few possible primary features like textures and organisms and also showing vivid post-depositional effects mainly through diagenesis, deformation, metamorphism, hydrothermal activity and secondary enrichment.

3.5 BABABUDAN BIFs

3.5.1 Introduction

In the Bababudan region, there are not only different types of BIFs but also they show varying post-depositional effects. The present study confines mainly to BIFs of Bababudan hill ranges commencing from west of Rudragiri to Hebbegiri (Map 3.1). The main aspects of study of BIFs, therefore, are to classify and describe them in detail and then to account for their origin. A brief description of
MAP No. 3.1 ENLARGED MAP OF 2:1 SHOWING DISTRIBUTION OF BIFs OF BABABUDAN REGION
MAP No.3.2 SCHEMATIC MAP SHOWING BROAD ZONATION IN BIFs DEPOSITION
associated rocks in Chapter II will help to understand the geological setting of BIFs in the schist belt. Since BIFs constitute a major and prominent lithotypes here (Figs.A, 3.2 and 3.3), it is shown that BIFs can also help partly in understanding the geological setting of the area as detailed in 3.5.2. BIFs have clearly preserved in them the post-depositional effects/changes in terms of structure, texture, mineral assemblages and geochemistry etc., as are outlined in the following text.

3.5.2 Stratigraphy and Geological setting of BIFs

As mentioned in Chapter II (Table 2.1), BIFs are grouped under Mulaingiri Formation (classification by Chadwick et al., 1985). BIFs constitute a minor group of rocks when compared to the extensive igneous and other clastic sedimentary rocks. While the volcanics occur with various forms and manifestations right from the oldest to youngest formations, clastic rocks particularly quartzite and phyllites occur as definite beds. Infact, based on this quartzite/conglomerates Chadwick et al., (op.cit) classified the Bababudan Group into several formations. BIFs are the only major representatives of non-clastic group. A significant factor is the absence of rocks like limestone (with minor exception) and manganiferrous formations. Inspite of the smallness of the BIFs, they appear very prominent and also help understand the structure of the
Bababudans. The Mulaingiri Formation represents the end of the major sedimentary cycle followed by extensive volcanism (Jagar Formation) and also the beginning of a new cycle of sedimentary sequence (Mundre Formation) as detailed by Chadwick et al. (1985).

A glimpse of the occurrence of various rocks in different formations (Table 2.1) shows that most of the rocks except ultramafics are represented in the Mulaingiri Formation. These common rocks in addition to the important BIFs are quartzite, phyllites, shales and metavolcanics. Therefore, a study in detail of the rocks of this formation particularly BIFs help to reveal the nature of sedimentary process (both clastic and non-clastic) and also repeated cycles of volcanic activity. These aspects are discussed while summarising at the end.

3.5.3 General distribution and field characters of BIFs

BIFs form the most striking and very prominent lithogroups, which often define the hill ranges (Fig. 3.1, 3.2, 3.3 and 3.4) of the Bababudan schist belt. The proper Bababudan schist belt i.e., Bababudan hill ranges which has been taken for the present study comprises, mostly of Mulaingiri Formation, which is well defined by the BIFs commencing from west of Rudragiri through proper Rudragiri (Rudragiri range/block), Mulaingiri, Bababudangiri (Attigundi range/block), and passing through Mahal,
Kalhatgiri (Mahal range/block), Kemmangundi and further Hebbegiri (Kemmangundi-Hebbegiri range/block) and ultimately culminating in the back waters of Bhadra river and further westwards near Balehonnur. Therefore, the BIFs can be studied under these four main blocks, namely, Rudragiri, Attigundi, Mahal and Kemmangundi-Hebbegiri. A detailed description of the nature of outcrops along with other associated rock is given separately. As far as the distribution of different types (facies) and number of beds of BIFs are concerned there is slightly confusion owing to intermixing, severe deformation and weathering. Some earlier workers attempted to recognise the typical banded magnetite quartzite as oxide type and the other with occasional occurrence of amphiboles etc., as ironstone (Viswanatha and Ramakrishnan, 1981). There is also much difference of opinion as to the actual number of beds of BIFS. In the present study, the main contribution is the recognition of two entirely different types of BIFs namely, the oxide types and the mixed oxide types. This aspect is described in detail under classification and petrography.

In the proper Mulaingiri Formation, before the onset of deposition of the main BIFs, there was initial stages of deposition as indicated by thin discontinuous BIFs. As far as the number of beds of BIFs is concerned, there are two prominent beds (the first older bed with an average thickness of 150 mtrs. and second younger one with 60 mtrs.) at least from west of Rudragiri to Hebbegiri (refer Map 3.1) and in
the remaining part (i.e. western portion), the BIFs occur as single bed (Map 2.1) pinching and culminating near Balehonnur and further south due to severe structural tightening. The frequency of occurrence of a number of BIF outcrops with different disposition in the area particularly between Attigundi and Mahal block indicate the existence of other younger at least 3 to 4 minor beds. The thickness of these beds varies from few mtrs. to more than 70 mtrs. and individual bed often shows pinching, swelling and other disturbed structural features.

Exposures of BIFs are seen all along the escarpment slopes of the hill ranges (Figs. 3.1, 3.2 and A). Good outcrops are seen exposed in following areas: in escarpment sections of Mulaingiri i.e., the ghat road to Seethalayan temple, Kavikalgundi and proper hill ranges of Rudragiri, Bababudangiri in southern portion, Kalhatgiri-Kemmangundi (eastern and north eastern portion) and Hebbegiri (in northern portion). These BIFs are often associated with meta basalts, phyllites/shale, quartzite and/or schist. BIFs are well exposed along these associated rocks are seen at many places. In one of the typical areas like Bababudangiri hill, the following is the sequence of rocks:

Laterite
Shale/phyllite (II cycle)
Quartz vein, meta-dolerite
Thin beds of BIFs
Metabasalts
Main BIFs with minor intercalation of phyllite/amphibolite.

Phyllite (I cycle) with quartzite
Ferruginous quartzite with thin beds of BIFs with amosite asbestos beds.

Generally BIFs exhibit perfect banding with well defined layers of dark grey and grey iron and white to brown quartz (Figs. 3.5, 3.6). A variety with impersistent faint banding is also noticed at few places. The thickness of individual layers varies from a fraction of a mm. to 3 cm. giving rise to thin and thickly banded types. The rock is fairly constant in lithology. In the oxide type the variations are generally in the nature and thickness of ferruginous and siliceous matter. The bands are regular and generally parallel, but different types of macro-, micro-folds, (Fig. 3.8) joints, faults and intraformational folding, crumpling and fractures are also common at places.

The colour and texture of the silica bands also vary considerably. They may be white, grey or in various shades of red or brown. Some of the laminae are composed wholly or predominantly of ferruginous or siliceous matter, but more often the layers are formed of intimately intermingled iron minerals and quartz. Vioinsts of quartz sometimes cut across the general direction of banding (Fig. 3.5). Quartz in these veins is of different texture and contain coarsely
crystalline hematite (Specularite).

To describe the nature of outcrops and geological setting, the proper Bababudan hill ranges are divided into 4 blocks viz., i) Rudragiri block, ii) Attigundi block, iii) Mahal block and iv) Kemmangundi-Hebbegiri block.

3.5.3.1 Nature of outcrops of BIFs in different blocks/ranges

Rudragiri Block

The hill ranges of Rudragiri block extend for nearly 6.5 km. starting from Somavahinihalli ie west of Rudragiri to the Seethalayan temple in the east (ie near Mulaingiri in the southern part of the hill range). The rock types exposed in this block besides the typical BIFs, are metabasalts, ferruginous quartzite, schists and phyllites. The sequence of rocks exposed in the Rudragiri block is as follows:

- Intrusives (quartz vein, dolerite)
- Phyllite (II Cycle)
- Main BIFs separated by metabasalts
- Ferruginous quartzite with thin beds of BIFs
- Phyllites (I cycle), chlorite schist
- Ferruginous quartzite
- Metabasalts, hornblende schists.

Because of severe folding in the form of isoclinal and
superimposing folds, certain members are repeated.

BIFs show NW and WNW strike direction in general, in both the western and eastern side ends but in the middle it is more or less E-W with mostly northwardly dips varying from 30° to 50°. Horizontal beds are also observed at the hill top. Folds of megascopic scale are found to be mainly of two kinds, one is isoclinal with limbs drawn out thin and with thick hinges. Second one is open with the axial plane along in mainly two directions i.e. WNW and N to NNE.

Outcrops of BIFs are fully exposed throughout the entire length (6.5 km.) of the main ridge clearly on the steep southern slopes. There are two major beds the upper one having thickness of 120 mtrs. and the lower one having a thickness varying from 60 to 100 mtrs. and these two are separated by metabasalts. These beds become wider towards eastern and western extremities. Thin detached outcrops of BIFs are considered to be folded limbs of the same band. Shales or phyllites occupying the synclinal through separates them into different units. Thin bands of silicate minerals are present in fresh samples at greater depths. It is also associated with pyrite and other sulphide minerals in the form of disseminations in quartz bands.

Attigundi Block

The portion from east of Seethalayan temple (near Mulaingiri) to Dathathreya Peetha (i.e. near Bababudangiri
peak) in the southeastern portion of the hill range is considered as Attigundi block. There are two main BIFs beds widely outcropping at the top of the hill and on the steep southern slope. Only upper bed is exposed on the northern slope. In addition to these two major beds, in this area, at least there are two to four younger and older beds. The I, II, III and IV beds have an average thickness of 110, 60, 40 and 15 mtrs. respectively.

These beds are seperated by either metabasalts, phyllite, shale or quartzite. The lower most BIF bed is underlain by ferruginous quartzites having thin layer of silicates, and amphibolites or schists further below. Shales and phyllites occupying the synclinal trough isolate them from the main bed of BIF. The first and second major beds of BIFs are typically exposed in the road cutting near Kavikalgundi (Fig. 3.4). They show E-W trend with dips of 50° - 60° towards north. Macro and micro folds (Fig.3.8), joints etc. are well seen.

Details of three adits at Attigundi block (Map 3.1) are as follows:

<table>
<thead>
<tr>
<th>No</th>
<th>Total length</th>
<th>RL</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adit I</td>
<td>56.55 mtrs.</td>
<td>1516.25 mtrs.</td>
<td>S 4° W</td>
</tr>
<tr>
<td>Adit II</td>
<td>149.30 mtrs.</td>
<td>1628.00 mtrs.</td>
<td>S 6° E</td>
</tr>
<tr>
<td>Adit III</td>
<td>74.83 mtrs.</td>
<td>1562.00 mtrs.</td>
<td>S 3° E</td>
</tr>
</tbody>
</table>
General strike of BIF beds in Attigundi block at the top of the hill range varies from NE-SW to E-W and further swing to NW-SE with mostly northward dips varying from 30° - 45°.

Mahal Block

The hill ranges extending from Dattatreya Peetha (near Bababudangiri peak) to west of Kalhatgiri in the eastern portion of the hill range is considered as belonging to Mahal block. The rock types exposed in this block besides BIFs are metabasalts, chlorite schists, phyllites, shales and quartzites. The sequence of the rocks exposed in Mahal block is as follows:

- Laterite of different types
- Altered trap rocks, talc-chlorite schists, phyllites
- Upper BIFs (main beds)
- Metabasalts /schists
- Lower BIFs
- Ferruginous quartzite with very thin beds of BIFs
- Phyllites/ greenstone (schists) lenses.

BIFs are exposed mostly at the top of the hill ranges and on both the eastern and western slopes. The main BIFs beds are overlain by talc-chlorite schists and/or phyllite (II cycle). At places BIFs are mostly oxidised and lateritized. Metabasalts/schists occur below the main ore
bands. Formation below the lower bands of BIFs is not exposed in the eastern slope due to soil cover, debris and forest. However, a small patch of weathered outcrop indicates ferruginous quartzite with thin bands of BIF and phyllite (I cycle). In the fresh BIF, association of pyrite is common. In this block generally the BIFs and other associated rocks show N-S trend and the beds are dipping towards west (i.e. Jagar valley) to amounts of 10° to 48°.

Kemmangundi-Hebbegiri Block

In Kemmangundi-Hebbegiri range particularly along the northern side of the hill range, there are two main BIF beds widely exposed at the top of the hill and on the steep northern slope with a length of more than 10 kms. and thickness of 40 to 110 mtrs. But only the upper bed is typically exposed on the southern slope. In Kemmangundi area in addition to the first two beds of BIF, there are two to three minor beds of BIFs which are exposed in the eastern slope of the hill range. The rock types exposed in the ranges besides BIFs, are phyllite/schists, quartzite and metabasalts. The main upper BIF bed at places is overlain by phyllite (II cycle) and usually underlain by either metabasalts or schist and at places quartzite. The second and the third main bed are intercalated either with metabasalt/schist and occasionally with band of quartzite or amphibolite.
The glittering magnesio-riebeckite and ferroactinolite minerals occur in the lower BIF bed and this bed is usually associated with schists and phyllites (I cycle).

In Kemmangundi area, due to intensive weathering and oxidation, the BIFs are altered and enriched giving rise to high-grade hematite ore (discussed in the last chapter). Because of weathering, quartz in BIFs is partially leached out. But fairly hard and slightly weathered BIFs occur below the hematite deposits. The former show poor lamination of silica and iron bands.

General strike of BIF beds in Kemmangundi area at the top of the main ridge varies from N-S to NW-SE with westernly dip varying from 10° to 45°. In Trishul and Hebbegiri region, the BIFs beds strike is E-W and further west of Hebbegiri the beds show SW trend with dip towards south (20° - 45°). Near Trishul, the EW trending beds are faulted and shows three sets of joints.

3.5.4 Classification

BIFs of Bababudan area were used to be called earlier as 'Banded magnetite quartzite' (BMQ). These BMQs were studied by earlier workers and there were attempts to classify or to recognise BMQs as belonging to different stratigraphic horizons. Some of these earlier workers (Viswanatha and Ramakrishnan, 1981) attempted to distinguish atleast two units namely, the lower or older amosite bearing
BMQ (iron stone) and upper or younger BMQ with simple and almost pure type having only magnetite (or its alteration products) and quartz. The lower or older BMQs were described as being thin when compared to the very thick main bands (in the present study each band is considered as a bed irrespective of the thickness) of the younger group of BMQs, which constitute the main litho units of Mulaingiri Formation. These older thin beds of BMQ have seams of amosite (sometimes to the extent of workable deposits) and other iron silicates, carbonates, etc., with varying proportions and these differ physically and also slightly chemically, with the younger thick beds of relatively pure BMQ. Therefore, these dissimilarities make one to recognise at least two types of BMQ, i.e. the older impure one and the younger pure one. In the present investigation, following James (1954, 1966), both types are considered as BIFs and also it is attempted to detail this classification, which may reflect the environment of deposition. Hence, James (1954) 'Facies' concept has been tried, but a closer and detailed study shows that it is difficult to propose such a clear cut two separate and distinct environments for the two different types as there is no regular and uniform distribution of the two. Therefore, following Laajoki and Saikkonen (1977), Mel'nik (1982), Trendall (1983) and others it is proposed to delete the term 'Facies' and to designate the two types respectively as 'Mixed Oxide Types' (impure) and 'Oxide Types' (pure).
3.5.4.1 Mixed oxide types of BIFs (Manikyadara type)

Since these are well exposed near Manikyadara (Map 3.1) falls, near Bababudan peak, these are designated as 'Manikyadara Type'. These include, apart from mainly amosite (grunerite) bearing BIFs, other BIFs, which contain many minerals (with varying proportions) in addition to magnetite (and its altered products) and quartz. According to this, most of the younger BIFs which were believed to contain only magnetite and quartz belong to the mixed oxide types. Hence the main criterion for this two fold classification is the 'mineralogy'. These minerals apart from magnetite and quartz which help recognise totally a different type belong to several groups and include mainly varieties of amphiboles and also carbonates, sulphides etc., all of which are detailed under petrography.

3.5.4.2 Oxide types of BIFs (Kemmangundi type)

In Kemmangundi area (Map 3.1) most of the oxide types of BIFs have given rise to high-grade hematite ores. There are also fresh outcrops of unaltered oxide type of BIFs. Therefore, this area is taken as type area and accordingly, oxide types are designated as 'Kemmangundi type'. These types have mainly magnetite and quartz. This simple mineralogy is reflected in the BIFs as typically hard, and banded brownish, fresh litho types. This has been referred by earlier workers (Chadwick et al., 1985) as belonging to
'Oxide facies'.

There is no regional clear cut and well defined demarcation between these two major types of iron-formations, so as to suggest separate stratigraphic units for the two. There is often the gradation and intermixing between the mixed oxide type and oxide type and thus reflecting, the fluctuation in the environment of deposition and this is discussed in detail at the end in the last chapter. This gradation is three dimensional i.e., there is variation in the BIFs lithology vertically (along the depth) laterally (along the dip) and even along the extension (i.e. along strike). This picture can be well demonstrated by considering the first main BIF bed of the Mulaingiri Formation. This along with the second bed constitute the main iron-formations and define the horse-shoe shaped structure of the Bababudan hill ranges. The overall nature of the first older bed is of mixed oxide type but pure oxidic members also occur within it as discontinuous lenses, streaks and pockets as clearly shown in samples of Adit No. II (Map 3.1) and in road cuttings near Kavikalgundi. Older to this main bed at lower levels there are several thin discontinuous gently dipping (well exposed along the escarpment slope Figs. 3.2, and 3.3) BIFs which typically belong to mixed oxide type. The second main and subsequent beds particularly in the region of Attigundi and Kemmangundi area are of mainly oxidic type, although at places there are
the occurrence of minerals other than magnetite and quartz. For example, in adit I, BIFs contain minerals like aegirine, magnesio-riebbeckite and carbonates. These two major types of BIFs and hence the broad zones of environments are shown in Map 3.2.

3.5.5 Petrography of BIFs

The petrographic characters, such as textures and mineral assemblages of the BIFs described in this chapter are based on the microscopic study of a number of thin sections. In general, BIFs of the Bababudan area are dark coloured banded rocks. The banding of different scales is due to the occurrence of dark coloured iron and light coloured silica rich minerals in alternate layers (Figs. 3.5, 3.6 and 3.7). This is typically one of the most characteristic features as in other Precambrian BIFs. There is large variation in thickness of the individual bands and have been classified as macro- meso- and micro-bands (Trendall, 1965). While the macro- and meso- bands are generally 0.1 to >4 cms. thick, the micro-bands are in the scale of one millimetre to fraction of a millimetre. The bands are generally folded (Fig. 3.8), faulted and have several minute joints of different orientations. The bands also show pinch and swell structures(Fig 3.7). Individual bands usually persist over a distance of few cms. but some thicker bands continue for several metres long.

In thin section, BIFs show strong mineralogical
seperation into individual bands (Fig. 3.9) and elongation of the minerals are generally parallel to the banding. Sometimes, separation of silica and iron minerals in the individual bands is not clear cut, because of the presence of some fine grained iron minerals in the silica bands or vice-versa. The average grain size of the silica and iron minerals is 400 to 300 microns respectively. There is considerable variation in grain size of the minerals across the banding. There is totally a lack of recognisable clastic components. The microbands within the meso bands have mineral composition, typical of the individual petrographic types. After a detailed microscopic study, the BIFs of the area have been broadly classified as (1) mixed oxide types (impure) and (2) oxide types (pure). In mixed oxide types, the alternating microbands of quartz-magnetite usually are associated with minerals like grunerite/amosite, ferro-actinolite, magnesio-riebeckite/crocidolite, aegirine, stilpnomelane, chlorite, carbonates like calcite, ferrodolomite, ankerite, siderite and sulphide minerals like pyrite and chalcopyrite. These iron silicate, carbonate and sulphide minerals occur either as thin or thick layers or disseminated grains within the individual quartz/iron bands. In oxide types the micro-and meso-bands consist mainly of quartz and magnetite and sometimes with varying proportion of martite, goethite/lepidocrocite, hematite/specularite, which are generally the altered products of magnetite.

3.5.5.1 Mixed Oxide Types
These types of BIFs are fine to medium grained rocks and essentially consist of dark grey, black or brown coloured magnetite bands in alternation with those of light coloured quartz. They are often associated with minerals like magnesio-riebeckite/crocidolite, grunerite/amosite ferro-actinolite, aegirine, stilpnomelane, chlorite, carbonates, and sulphides. While amphiboles often occur as bands, carbonate and sulphide minerals are disseminated either in the quartz or magnetite bands. Based on the abundance of iron silicate minerals, the BIFs are further subdivided into four different petrographic sub types, they are:

1. Magnesio-riebeckite/crocidolite bearing BIFs
2. Grunerite/amosite bearing BIFs
3. Ferro-actinolite bearing BIFs
4. Aegirine bearing BIFs.

In all these sub types while quartz and magnetite are ubiquitous minerals, carbonates are usually represented by one or the other type.

(1) Magnesio-riebeckite/crocidolite bearing BIFs: In hand specimen these show well banded and folded structures. The bands of quartz and iron vary in thickness. The glittering prismatic, needle or acicular magnesio-riebeckite occurs either as a thin layer in between quartz...
and magnetite or disseminated grains either in the quartz or magnetite bands. When fresh, it is shining with adamantine lustre. Usually carbonate minerals are present with occasional occurrence of sulphides.

In thin section, this type shows typical banded and folded texture and the minerals are varying in size. Along the bedding planes and also within the individual bands of quartz and magnetite, magnesio-riebeckite occurs as thin layer (Fig. 3.10) or disseminated grains (Fig. 3.11). Generally carbonates (Figs. 3.12 & 3.13) and occasionally sulphides occur scattered within the bands but sometimes as independent bands.

Quartz: It is colourless, anhedral and varying in size. Grains of quartz show mosaic texture in the undisturbed bands. In folded bands, quartz shows elongation parallel to bedding and in the elongated strained grains which show undulose extinction and some amount of fine grained needles of riebeckite.

Magnesio-riebeckite/crocidolite: They occur either as thin layers or as disseminated grains within the meso bands of quartz or magnetite. The long magnesio-riebeckite grains tend to grow either parallel or perpendicular (Fig. 3.13) to bedding planes and have poor lateral continuity. Some grains have become iron rich so as to become opaque. Fine grained fibrous riebeckite (crocidolite) are very common in some samples. This crocidolite often occurs in sheared
quartz, lying parallel to the length of sheared quartz grains. Riebeckite occurs as prismatic needle to radiating (Figs. 3.11, 3.12 & 3.13) and also often as fibrous crocidolite (Fig. 3.11). It shows strong pleochroism with \( X = \text{Prussian blue to dark} \), \( Y = \text{Prussian blue to violet blue} \), \( Z = \text{pale yellowish to yellowish green} \). The mineral shows good amphibole cleavages. Birefringence is 0.015 to 0.018 and sign is optically -Ve with \( 2V_x = 55 \) to \( 61^\circ \) and \( X^\perp c = 40^\circ \) to \( 10^\circ \).

Calcite: It occurs as subhedral to anhedral colourless to greyish grains (Fig. 3.13) and shows change in relief and good rhombic cleavages.

Ferrodolomite/ankerite: These occur as relict granules, discontinuous lenses and as disseminate grains in quartz band. They are colourless, show high relief and birefringence.

(2) Grunerite/amosite bearing BIFs: In hand specimen this sub-type shows well banded structures. The bands consist of light coloured silica (quartz), grunerite/amosite and steel grey to black coloured iron minerals. Grunerite is usually confined to silica band. It is colourless in fresh samples while in altered samples it is yellowish brown in colour, which is probably related to the superficial individual magnetite staining and this colour turns greyish white and semi-transparent when treated with warm dilute hydrochloric acid. The mineral occurs as needles and exhibits sheaf like aggregation in rough linear and radial
arrangement. Long fibrous grunerite needles grow either perpendicular or parallel to bedding planes. Amosite mostly occurs as very thin to thick bands (Fig. 3.14). The length of amosite needles is usually perpendicular to bedding planes. It is white to yellowish in colour, the yellow colour is due to staining from magnetite alteration. It shows pearly/silky lustre. The contact between amosite and magnetite bands is very sharp. In this amosite bearing BIFs, quartz occurs in subordinate amounts.

In thin section, the BIFs are usually banded, with occasional folded and faulted structures. Sometimes, the bands are discontinuous. The minerals included apart from magnetite and quartz, are grunerite and/or amosite with subordinate amount of carbonates (Fig. 3.15). Sometimes stilpnomelane, and chlorite occur as accessories. Usually, grunerite, stilpnomelane and carbonates are disseminated in the quartz bands (Figs. 3.15, 3.16), but amosite occurs as individual thin to thick bands alternating with magnetite bands(Fig.3.18).

Quartz: It is anhedral and occurs as bands and also as inclusions within the magnetite layers. It shows undulose extinction.

Grunerite: It occurs as needles and sheaf like aggregates, which show rough linear and fan like arrangement and is either perpendicular or parallel (Figs.
3.16 & 3.17) to general banding. It also occurs as prismatic (Fig. 3.15) showing diagonal orientation. It is colourless to pale yellow in colour with very feeble pleochroism. Prismatic grains show characteristic multiple twinning. It shows variation in birefringence from 0.021 to 0.023 and n-β is 1.679 which is somewhat lower than those normally reported for comparable composition of the mineral (Deer et al., 1963), but almost similar to those obtained by Hietanen (1938) and Klein (1964). Z ^ c ranges from 16 to 20°.

Amosite: This generally occurs as a fibrous aggregates whose length is either diagonal or perpendicular to the banding (Fig. 3.18). It is colourless to pale yellowish in colour. The pale yellow colour may be due to the staining of magnetite. It shows variation in interference colour (Fig. 3.18) and extinction.

Stilpnomelane: It generally occurs as fine needles (Fig. 3.15) and shows pleochroism from X=pale yellow or yellow, Y=Z deep brown to nearly dark, with straight extinction.

Chlorite: It occurs as an anhedral grains showing strong absorption from pale yellowish green to brown or dark green. It also shows anomalous interference colour.

Calcite: It is very prominent, occurs as subhedral to anhedral colourless grains and shows change in relief with good rhombic cleavages.
Ankerite/ferrodolomite: They are fine anhedral to subhedral grains, occurring as very thin streaks or as relic clusters. Etching tests indicate that ankerite is soluble with difficulty in cold dilute HCl.

Magnetite: It occurs as subhedral to anhedral coarse grains as discrete grains which are concentrated into separate layers and lenses and also as disseminated idioblastic crystals in quartz layers.

(3) Ferro-actinolite bearing BIFs: In hand specimens, these rocks are well banded with light coloured quartz and dark coloured magnetite. The bands vary in size. The dark coloured ferro-actinolite is closely associated with the magnetite bands only.

In thin section, the rock shows banded texture. The bands consist of light coloured quartz and dark coloured magnetite. The pale green actinolite grains are confined to pod like open spaces seen in magnetite bands (Figs. 3.19, 3.20 & 3.21). The contact between the magnetite and actinolite occurring in the pods is generally very sharp, but in the disseminated actinolites (Fig. 3.21), the contact is not clear. Actinolite grains usually tend to grow parallel or diagonal to the bedding plane and have poor lateral continuity (Figs. 3.19 & 3.21).

Quartz: It occurs as anhedral grains with undulose extinction.
Ferro-actinolite: It is prismatic and pale green to yellowish green in colour. It shows well developed amphibole cleavages and moderate pleochroism of X=pale yellow, Y=yellowish green and Z=pale green. It has moderate birefringence of 0.016 to 0.019, $2V = 69$ to $78^\circ$, $Z^c c = 12$ to $15^\circ$ and is optically $-Ve$.

Calcite: It is prominent occurring as crystalline aggregates.

(4) Aegirine bearing BIFs: In hand specimen the rock shows alternate bands of quartz and magnetite. In some instances, within the magnetite bands, very thin to thick layers of aegirine (Fig.3.22) occur. The aegirine bearing bands are greenish in colour with radiating habit and usually associated with carbonates and these bands show reaction to acid.

In thin section also, the rock shows typical banded texture and bands vary in thickness. The rocks consist of quartz, magnetite, aegirine, carbonates (calcite, siderite/ankerite) and often with subordinate amount of magnesio-riebeckite. Usually, aegirine occurs as thin layers within the magnetite bands. Carbonates occur either as thin layers or disseminated in aegirine layer and also in the magnetite and quartz bands. Occasionally, magnesio-riebeckite generally occurs as disseminated grains.

Quartz: Quartz is anhedral often sheared and shows
Ferro-actinolite: It is prismatic and pale green to yellowish green in colour. It shows well developed amphibole cleavages and moderate pleochroism of X=pale yellow, Y=yellowish green and Z=pale green. It has moderate birefringence of 0.016 to 0.019, 2V = 69 to 78\(^\circ\), Z\(^c\) = 12 to 15\(^\circ\) and is optically -Ve.

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Quartz: Quartz is anhedral often sheared and shows
undulose extinction.

Aegirine: Aegirine occurs as a radiating to lath shaped grains (Figs. 3.23 & 3.24) generally growing from a common point along the bedding. The grains occur parallel as well as perpendicular to the banding. They are greenish in colour with feeble pleochroism and show one set of cleavages. Under crossed nicols, they show high order of interference colour and undulose extinction. The undulose extinction may be due to radiating habit. Lamellar twinning is conspicuous. $X^c = 4$ to $8^\circ$ and $2Vz = 60$ to $65^\circ$. The grains show inclusions of magnetite and quartz along its cleavage planes.

Calcite: It occurs as a subhedral grains within the aegirine bands (Fig. 3.24) and also as independent thin layers and clusters. It shows change in relief and well developed cleavages.

Siderite/ankerite: They are colourless, occurring as a discontinuous lenses and as disseminated grains in aegirine bands. They show high relief and birefringence.

Magnesio-riebeckite: It occurs as fine fibrous to needle shaped grains as crocidolite. It shows bluish colour with strong pleochroism.

Magnetite: Magnetite is opaque, occurring as a separate discrete band and also as disseminated grains within the
quartz band.

Modal analysis: Modal analysis of the different sub-types of BIFs are given in the Table 3.1. A glance at the table reveals that there is a considerable variation in the proportion of different minerals.

3.5.5.2 Oxide types of BIFs

Two sub-types namely hematite poor and hematite rich BIFs are recognised in the oxide type. The hematite poor sub-type represents the normal banded to laminated magnetite quartzite (sometimes jasper). In contrast to this, are the hematite rich type which is altered and is enriched in iron by the presence of more hematite, goethite at the cost of leached out quartz. This hematite rich ore occurs as pockets and lenses within the hematite poor sub-type and occasionally with the mixed oxide types. Very good deposits of this type occur at several places like Kemmangundi, Kalhatgiri, Attigundi etc.

The absence of any amphiboles or carbonates in oxide types of BIFs is very obvious even in hand specimen. They are tough, hard and show typical banded structures and the bands vary in size from meso to micro. The light coloured quartz/jasper bands alternate with dark coloured iron bands. Usually quartz bands are thicker than iron bands. In weathered samples, leaching of iron and silica is very clear.
Often bands are folded, jointed and faulted with pinch and swell structures (Figs. 3.7 and 3.8) being common.

In thin section, the hematite poor BIFs show typical banded, folded and sometimes brecciated to faulted textures (Figs. 3.9, 3.25 and 3.26). In some, micro-desiccation cracks (Fig. 3.27) are also noticed. The individual bands vary in thickness. Within the meso bands, micro-bandings are noticed. The siliceous band consists usually quartz and sometimes jasper. The iron rich bands consist of magnetite and its altered products. Quartz also occurs in minor amounts in iron rich band and vice-versa.

Quartz: It occurs as anhedral grains constituting bands. It also occurs in subordinate amount in iron rich bands. In parallel bands, quartz shows interlocking mosaic texture. In folded bands quartz shows peculiar elongation either diagonal, or transverse to banding. Some quartz grains contain fine dusty inclusions of iron oxide (magnetite). Both fine and medium grained quartz shows weak to moderate undulose extinction.

Magnetite: It is opaque and clustered together to constitute bands. It is idioblastic and fine to medium grained. It also occurs as an inclusions within the quartz bands.
3.5.6 Ore Microscopic Studies of BIFs

As in thin sections, the polished samples of BIFs also show typical banded, folded, brecciated and deformed texture (Figs. 3.28, 3.29, 3.30 & 3.31). Sometimes, BIFs show diffusion of bands. The bands are constituted chiefly by quartz and iron (in the form of magnetite and its altered minerals). However, other minerals like amphiboles, pyroxene and carbonates also occur in many BIFs (mixed oxide types). All the opaque minerals are identified by ore microscopic characters followed by Vickers microhardness determination (VHN) and etch tests (Table 3.2). Of all the ore minerals present in BIFs, magnetite constitutes the most dominant and widespread mineral followed by martite, goethite/lepidocrocite, hematite/ specularite, pyrite and chalcopyrite in decreasing order of abundance.

Magnetite: The mineral in hand specimen is black, steel grey or brown in colour. It gives black streak and is highly magnetic. Under ore microscope, magnetite is the most essential and abundant iron oxide mineral in fresh and unaltered BIFs. Its form varies from anhedral to subhedral (Figs. 3.32, 3.33 & 3.35). It is generally arranged in a discrete grains which are concentrated into separate bands which in turn alternate with quartz bands. It also occurs as lenses and disseminated (Fig. 3.32) idioblastic crystals in quartz bands. Magnetite with sharp octahedral grain boundaries are not uncommon. Coarse octahedral magnetite grains at times show orientation diagonal or transverse to
banding.

Magnetite shows grey to greyish white colour with brownish tint. It is generally isotropic, but the feeble anisotropism in some is due to its intimate association with martite to which the former readily alters. Magnetite shows moderate reflectivity. It takes good polish and its polishing hardness is less than that of martite. It is positive to HCl and aquaregia and negative to all other reagents. There are many minute inclusions of quartz/silicates in some magnetite grains giving a badly pitted surface on polishing.

Fine grained magnetite grains are completely martitized, whereas the coarse grained ones possess fresh cores. The process of martitization in fine magnetite grains appears to be irregular not following any crystallographic directions. But in coarse grains there is a tendency of martitization commencing initially along crystallographic directions (Fig. 3.33) as can be seen in feebly altering BIFs. The martitized magnetite grains are replaced to a very small extent by goethite along the borders (Fig. 3.35). In some mixed oxide types of BIFs, minerals like magnesio-riebeckite have grown cutting across magnetite porphyroblasts (Fig. 3.34). The mutual relationship that magnetite has with secondary minerals like martite, goethite etc. is clearly that of a relict nature, indicating the former's early formation.
Martite: It replaces magnetite following in the beginning along crystallographic directions (Fig. 3.33), and then later covering the entire grains. This mineral shows greyish white in colour and feeble anisotropism under crossed nicols. It takes good polish and its polishing hardness is greater than that of other ore minerals. It is negative to all reagents. It is usually replaced by goethite either partially or fully (Figs. 3.33, 3.37 & 3.38). Sometimes, clusters of martitized magnetite porphyroblasts are surrounded by secondary hematite (Fig. 3.36).

Goethite: It is one of the essential mineral constituents in the altered varieties, particularly in hematite rich BIFs often replacing along borders of magnetite and martite minerals. It also occurs as irregular forms rimming and engulfing magnetite and martite minerals either fully or partially (Figs. 3.33 & 3.38). It is fine to coarse grained and may form pseudomorphs after magnetite (Fig. 3.37). It also shows good colloform textures (Fig. 3.40 & 3.42) in some sections and in highly altered BIFs, goethite predominates over magnetite/martite. Small octahedra and granules of goethite are pseudomorph after magnetite. It is typically dark bluish grey in colour with slight bireflectance and is perfectly anisotropic under crossed nicols. It shows good brown to reddish brown internal inflections. The colloform texture of the mineral is indicative of their colloidal origin (Edwards, 1965).
Lepidocrocite: It is less common than goethite and present in more altered varieties of BIFs. It occurs as thin veins and often associated with goethite (Figs. 3.40, 3.42 & 3.39) rimming and bordering rhythmically. It shows greyish white colour with strong shades of grey anisotropism (Fig. 3.41). When it occurs along with goethite it is easy to identify as even the feeble colour contrast between the two is sensitive to eye, otherwise it is often mistaken to goethite.

Hematite: This in contrast to martite represents an independent origin often developed in highly altered and enriched BIFs (hematite rich subtypes of oxide type). This secondary nature is evident by its various forms including fine vermicular aggregates to irregular granules and colloform forms (Figs. 3.40 & 3.42). Unlike martitization, the process of hematitization involves the remobilisation of the iron present particularly from magnetite and then crystallization of hematite (discussed in detail in the next chapter). There is a variation in this process and hence in the frequency of occurrence. In partially altered types, hematite is associated with all other iron minerals and in such cases it is difficult to distinguish between hematite and martite by optical properties. There appears to be two generations of hematite, one older than goethite which occurs as veins in the former (Figs. 3.40 & 3.42) and the other younger than goethite which is traversed and cut.
across by hematite (Fig. 3.44). So these various forms of hematite not only help to distinguish it from other iron minerals but also indicate its two generations. Even with respect to martite, hematite is distinguished by its form and mode of occurrence (Fig. 3.36) and absence of widmanstatten texture, which is typically shown by the former (Fig. 3.45). In some intensively altered BIFs, hematite engulfs all the martitized magnetite porphyroblasts (Fig. 3.36).

Specularite: It occurs as deformed tabular clusters (Fig. 3.46) and often with mutual boundary and sharp contact with martite (Fig. 3.47). In these figures (3.46 & 3.47) deformation characters (also in quartz band) are evident. An enlarged figure (3.48) shows platy nature of specularite often with inter connections to martites. The importance and significance of specularite is discussed in the last chapter. When it is fresh, it shows good reflectivity and also anisotropism. It often occurs in cavities and as well developed platy crystals. In highly deformed BIFs specularite laths are arranged hapazardly (Figs. 3.46 & 3.47).

Sulphides: Pyrite is the main sulphide occurring as thin layers in between quartz and magnetite bands (Fig. 3.49) or as stringes or patches, streaks and veins. It also occurs as disseminated euhedral grains either in quartz or magnetite bands (Fig. 3.50). The sulphide minerals, generally, within themselves show replacement textures (Fig.
3.52). Usually pyrite is replaced by chalcopyrite thus indicating that the pyrite has formed earlier. Pyrite in most of the cases show good cubic shaped crystals as well as crystal aggregates. In some cases, it also occurs as fine grains constituting thin layers. It shows yellowish colour. The bireflectance is not distinctly seen in all the polished samples but some orientations show very feeble bireflectance along the boundaries. It is generally isotropic but in some cases it shows weak anisotropism in the shades of blue, reddish brown and greenish yellow. It is usually associated, in addition to quartz and magnetite, with chalcopyrite, calcite, siderite/ankerite and rarely with iron silicates.

Chalcopyrite: It is brass yellow in colour. It occurs as coarse to fine anhedral patches (Fig. 3.51) and also as veins along pyrites. The relict of magnetite in some samples is very common(Fig 3.51). It shows feeble anisotropism but certain grains show distinct shades of greyish blue, greyish yellow interference colours.

3.5.7 Texture of ore minerals

Textural relations are one of the most important evidences which can explain the ore genesis. Varieties of textures are recognised during the study of ore minerals under reflected light microscope. Different textures and structures exhibited by the ore minerals of both the oxide
and mixed oxide types of BIFs are described as follows:

a. Banded texture
b. Replacement texture
c. Relict texture
d. Mutual boundary texture
e. Cataclastic/deformed texture
f. Colloform texture.

a. Banded texture: The most conspicuous characteristic feature of the BIFs, however, is their banded texture, which is well defined by the presence of alternate iron and silica bands (Fig. 3.28). The bands are generally discontinuous over a long distance and may show parting, splitting etc.

It was previously believed that the regular and well defined bands of BIFs represent a primary sedimentary feature, and in order to explain its primary origin various theories have been proposed. Sakamoto (1950) stated that the bands developed in response to climatic periodicity of the depositional environment, while Dunn (1935) proposed (for the Indian BIFs) iron enrichment of pre-existing well-banded ferruginous shale. But recently opinions have changed and some workers have expressed the view that the regular bands may be of secondary origin (Alexandrov, 1973; Beukes, 1973; Majumder, 1976; Eichler, 1976) or may be a diagenetic phenomenon (Dimroth and Chauvel, 1973).
b. Replacement texture: This is very common in BIFs of altering types. Replacement is commonly seen along magnetite grain boundaries and other crystallographic directions, where martite replaces magnetite (Figs. 3.33, 3.35, 3.36, 3.37, 3.38, & 3.51). Replacement relationship is observed between the following minerals.

i) Magnetite replaced by martite  
ii) Magnetite replaced by goethite  
iii) Magnetite replaced by hematite  
iv) Magnetite replaced by pyrite  
v) Martite replaced by goethite  
vi) Hematite replaced by goethite  
vii) Goethite replaced by hematite  
viii) Pyrite replaced by chalcopyrite

The replacement textural relationship clearly suggest that magnetite is the earliest formed mineral.

c. Relic texture: This texture is observed between these minerals: magnetite-martite,-goethite,-hematite,-pyrite, chalcopyrite. The original relict of small magnetite patches is often very clearly seen in martite, goethite and occasionally in hematite and pyrite (Figs. 3.33, 3.37 & 3.51). The development of this type of texture is attributed to the replacement of magnetite by martite, goethite and or other secondary minerals.

d. Mutual boundary texture: This texture sometimes is observed between pyrite and chalcopyrite, which commonly
otherwise show replacement relations. The minerals show smooth, regular and curved contacts without definite projections of one mineral into the other.

e. Cataclastic texture: This texture is well exhibited by magnetite, martite, goethite and specularite minerals. Extensive folding, fracturing and brecciation due to severe deformation can be seen in the iron oxide bands (Fig. 3.44, & 3.45). The later formed minerals have occupied along cracks, fissures and fractures. Due to deformation euhedral iron oxide minerals are converted to platy or elongated crushed shapes (Figs. 3.46 & 3.47).

f. Colloform texture: This is the texture typically exhibited by the secondary iron ores, i.e., the supergene enriched oxide type of BIFs. The chief minerals present are hematite, goethite and lepidocrocite. The colloform textures are vivid and varied (Figs. 3.40, 3.42 & 3.41) and are indicative of activity of colloidal solutions.

3.5.8 Metamorphism

3.5.8.1 Metamorphic minerals

The mineralogy of BIFs also helps in understanding the metamorphism of the Bababudan belt. Though the metamorphic history of Bababudan region is of significance, not much work has been done on this aspects by earlier workers. Viswanatha and Ramakrishnan (1981) working on Bababudan belt have opined that metamorphism of the Bababudan Group
decrease from border to core in syncline, ranging from amphibolite facies to greenschist facies. Further they have reported that magnetite-quartz-grunerite as "the common assemblages".

In the present study the various minerals recorded in the major litho types of the Bababudan schist belt are shown in Table 3.3.

Table 3.3

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Major litho type</th>
<th>Chief metamorphic minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Meta ultramafics</td>
<td>Talc-tremolite-actinolite</td>
</tr>
<tr>
<td>4.</td>
<td>Meta-pelites</td>
<td>Quartz-chlorite-sericite-garnet</td>
</tr>
<tr>
<td>5.</td>
<td>Meta-psammite</td>
<td>Quartz-sericite-fuchsite-biotite</td>
</tr>
</tbody>
</table>

The presence of iron-magnesium silicate minerals particularly the amphiboles in the mixed oxide type of BIFs (Manikyadara types) helps very much in understanding the metamorphism of the region. As described previously there is a variety of such minerals in the Bababudan region but there is no regularity in the distribution of such silicate minerals. The importance and significance of such silicate minerals particularly in understanding metamorphism, in
general, has been very effectively explored in other areas by many workers like James (1955); Klein (1973, 1974, 1978, 1983); French (1968); Floran and Papike (1975); Haase (1979a, 1979b, 1982a); Gole and Klein (1981b); Mel'nik (1982); Miyano (1978b, 1987) etc. Detailed metamorphic aspects of the Bababudan region has not been taken up so far partly due to non-availability of fresh core samples drawn from different parts of the region. However, based on the study of the good samples taken out from surface, adits and also some selected core samples, an attempt is made to reconstruct the metamorphic history of at least a part of Bababudan region (belonging to Mulaingiri Formation).

3.5.8.2 Epidote-amphibolite facies

The three minerals namely magnesio-riebeckite, grunerite and ferro-actinolite mentioned in the Table 3.3, which constitute the basis for the recognition of three petrographic types out of the total four, also helps in understanding of the metamorphism. All these three minerals are believed to be of metamorphic in origin and the possible reactions that have given rise to these minerals are also discussed. One important aspect is the co-existence of minerals of lower grade (magnesio-riebeckite, stilpnomelane/chlorite etc.) with those of higher grades (grunerite ferro-actinolite etc.). The same kind of association is also noticed in other major litho types like, amphibolites, metabasalts etc, where albite, chlorite, actinolite and
epidote (of green schist facies) co-exists with typical common hornblende and oligoclase (of amphibolite facies). In view of this, following Eskola (1920, 1939), Miyashiro (1973) and Veblen and Ribbe (1982) it is proposed that based on the mineralogical assemblages both in BIFs and the associated dominant metavolcanic rocks, the overall grade of metamorphism of Bababudan hill ranges (belonging to Mulaingiri Formation) can be assigned to the "Epidote-amphibolite facies", which represent a transition in the grades of metamorphism between greenschist and amphibolite facies as originally conceived by Eskola (1939). Since most of the major litho types of Bababudan schist belt or region exhibit the mineralogy as detailed in Table 3.3, it follows that "epidote-amphibolite facies" is applicable to even the larger horizon.

3.5.8.3 Origin of minerals

An attempt is made here to account for the origin of some of the important minerals through examining some of the possible metamorphic reactions.

Magnesio-riebeckite: It occurs in a very wide range of P-T conditions like grunerite as given in the figure (Fig. 3.53). Its sporadic and minor occurrence in BIFs of many areas like Brockman iron formation (Western Australia) and Bababudan region made it difficult for detailed study. While Ernst (1968) accounted (for riebeckite) authigenic and/or very low grade metamorphic origin, Lesher (1978)
suggested only authigenic origin.

Stilpnomelane: Stilpnomalane has been quoted by Klein (1983) to be as probably the most common Fe-silicate in most very low grade metamorphic iron formations (Klein and Gole, 1981; Miyano and Miyano, 1982). In the absence of minerals like greenalite, it has been suggested that no inference can be made about its relation to possible precursor materials.

Grunerite/Amosite: These are the predominant minerals with well developed form and habit in most of the mixed oxide BIFs as detailed under petrography. The probable types of reactions that might give rise to grunerite are given as follows (Klein, 1973).

\[ 7\text{Ca} (\text{Fe,Mg})(\text{CO}_3)_2 + 8\text{SiO}_2 + \text{H}_2\text{O} \rightarrow (\text{Fe,Mg})_7 \text{Si}_8\text{O}_{22}(\text{OH})_2 + \text{Ferro-dolomite Quartz Grunerite} \]

\[ 7\text{CaCO}_3 + 7 \text{CO}_2 \rightarrow \text{Calcite} \]  

\[ 8(\text{Fe,Mg})\text{CO}_3 + 8\text{SiO}_2 + \text{H}_2\text{O} \rightarrow (\text{Fe,Mg})_7 \text{Si}_8\text{O}_{22}(\text{OH})_2 + 7\text{CO}_2 \rightarrow \text{Grunerite} \]  

\[ 7\text{Fe}_3\text{Si}_4\text{O}_{10}(\text{OH})_2 \rightarrow 3\text{Fe}_7 \text{Si}_8\text{O}_{22}(\text{OH})_2 + 4\text{SiO}_2 + 4\text{H}_2\text{O} \rightarrow \text{Minnesotaite Grunerite} \]  

For the formation of the bulk of the grunerite of the Bababudan region, the above 1 and 2 reactions are favoured. The textural relationship of minerals (refer petrography Fig.3.15) suggest that carbonates and quartz are directly involved in the grunerite formation without the much intermediate formation of minnesotaite (which later could have given rise to grunerite). This inference is also
have given rise to grunerite). This inference is also supported by reaction 4, where Ferro-actinolite is formed at the cost of carbonates probably at higher grades of metamorphism (Fig. 3.53). There are typical textures where the entire band in mixed oxide types of BIFs is made up of amosite or grunerite with some relicts of carbonates (Fig. 3.15). This may be a case of transformation of earlier carbonates (Precursor) and quartz as per reactions 1 and 2. Several others also favoured these types of reactions in other areas (French, 1968; Klein, 1973, 1978; Floran and Papike, 1978; and Gole, 1981). Laajoki and Devaraju (1989) observed no relics of minnesotaite in the BIFs of Chiknayakanahalli, but after Melnik (1982) they felt that grunerite has formed probably from minnesotaite.

Ferro-actinolite: The occurrence of grunerite with calcium clino-amphiboles particularly the ferro-actinolite in BIFs of the region is of much significance, particularly as it confirms higher grades of metamorphism than greenschist facies (Fig. 3.53). Such co-existences are the result of the following types of reaction (Klein, 1973).

\[
5\text{Ca(Fe,Mg)}(\text{CO}_3)_2+8\text{SiO}_2+\text{H}_2\text{O} \rightarrow \text{Ca}_2(\text{Fe,Mg})_5\text{Si}_8\text{O}_{22}(\text{OH})_2+3\text{CaCO}_3+
\]

Ferro-dolomite Quartz Actinolite calcite

\[7\text{CO}_2\] (4)
### Table 3.1: Modal Analyses.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>48.61</td>
<td>27.43</td>
<td>52.40</td>
<td>46.60</td>
<td>58.70</td>
</tr>
<tr>
<td>Magnetite</td>
<td>45.90</td>
<td>49.36</td>
<td>40.90</td>
<td>42.00</td>
<td>41.30</td>
</tr>
<tr>
<td>Mg-Riebeckite/crocidolite</td>
<td>4.56</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Grunerite/mamsite</td>
<td>-</td>
<td>0.43</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ferro-Actinolite</td>
<td>-</td>
<td>0.33</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aegirine</td>
<td>-</td>
<td>0.33</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Stilpnomelane</td>
<td>-</td>
<td>0.43</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Calcite</td>
<td>0.63</td>
<td>1.83</td>
<td>1.00</td>
<td>2.15</td>
<td>-</td>
</tr>
<tr>
<td>Ferrodolomite/ankerite</td>
<td>0.30</td>
<td>0.27</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Siderite</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.05</td>
</tr>
</tbody>
</table>

1. Riebeckite bearing BIFs. 4. Aegirine bearing BIFs. 2. Grunerite – do – 5. Pure Oxide type BIFs. 3. Actinolite – do –

### Table 3.2: Ore-microscopic data of iron ore minerals with VHN and Etch test.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Form and habit</th>
<th>Colour</th>
<th>Birefringence</th>
<th>Anisotropy</th>
<th>VHN 65p</th>
<th>HCl</th>
<th>HCl+SnCl₂</th>
<th>SnCl₂</th>
<th>Etch tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetite.</td>
<td>subhedral to</td>
<td>grey with</td>
<td>absent</td>
<td>isotropic</td>
<td>720-830</td>
<td>darkens tarnishes</td>
<td>negative</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>anhedral</td>
<td>pale brown tint</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hematite</td>
<td>mostly</td>
<td>greyishwhite</td>
<td>very weak</td>
<td>strong; shades of grey and blue</td>
<td>850-900</td>
<td>---</td>
<td>negative</td>
<td>negative</td>
<td></td>
</tr>
<tr>
<td>(includes specularite, martite)</td>
<td>anhedral</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goethite.</td>
<td>as secondary</td>
<td>grey</td>
<td>absent</td>
<td>distinct with good internal reflection</td>
<td>500-530</td>
<td>negative</td>
<td>stains</td>
<td>brown</td>
<td></td>
</tr>
<tr>
<td></td>
<td>mineral typical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td></td>
<td>colloform tex/</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lepidocrocite.</td>
<td>as veins</td>
<td>greyish white;</td>
<td>feeble</td>
<td>distinct shades of grey</td>
<td>300-350</td>
<td>negative</td>
<td>negative</td>
<td>etches</td>
<td></td>
</tr>
<tr>
<td></td>
<td>associates</td>
<td>more whiter than goethite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>with goethite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 3.53 Evaluation of the stability field of grunerite from a combination of published pressure-temperature estimates for various metamorphosed iron-formations and thermodynamic calculations (from Miyano and Klein, 1983b). Curve a" represents the apparent upper stability limit for grunerite, whereas curve c" is the adjusted upper stability limit for minnesotaite. (after Klein, 1983)
3.1 View of Bababudan hill ranges, covering Rudragiri, Mulaingiri, Bababudangiri from left to right.

3.2 Steep westerly dipping BIFs exposure.
3.3 'Kalhatgiri falls' along the BIFs.

3.4 Dipping and folding BIFs constituting the entire hill ranges (near Kavikalgundi).
3.5 Alternate bands of jasper (brown) and magnetite (black) in typical oxide types.

3.6 Alternate banding still conspicuous even after quartz (white) removal during weathering in typical oxide types.
3.7 Pinch and swell structure in BIFs.

3.8 Typical folds in BIFs.
3.9 Typical banding as seen in the microscope. Cross polarised light x 25.

3.10 Magnesio-riebeckite layer in BIFs. Cross polarised light x 63.
3.11 Disseminated needles of mg-riebeckite showing high order interference colour. Cross polarised light x 63

3.12 Mg-riebeckite associated with carbonates. Crossed nicols x 25.
3.13 Mg-riebeckite occurring parallel and perpendicular to bedding carbonates are also associated. Cross-polarised light x 63.

3.14 Amosite (white) alternating magnetite in BIFs of mixed oxide type (Field sample).
3.15 Grunerite, stilpnomelane and carbonates. Cr polarised light x 63.

3.16 Grunerite parallel to banding and across as radiating. Plane polarised light x 25.
3.17 Grunerite radiation resulting fan shaped texture
Cross polarised light x 63.

3.18 Amosite fibrous showing variation in interference colour. Cross polarised light x 25.

3.20 Ferro-actinolite needles showing different orientation Cross polarised light x 63.
3.21 Disseminated ferroactinolite in magnetite band
Cross polarised light x 25.

3.22 Aegirine in BIFs. (Field sample).
3.23 Radiating aegirine growth across quartz band, carbonate is also associated. Cross polarised light x 25.

3.24 Typical clusters of aegirine needles surrounded by carbonates. Cross polarised light x 63.
3.25 Deformed magnetite bands of oxide type BIFs. Cross polarised light x 25.

3.27 Microdessication cracks filled by secondary quartz.
Cross polarised light x 25.

MICRO PHOTOGRAPHS OF BIFS UNDER REFLECTED LIGHT

3.28 Alternate bands of quartz (brown) and magnetite (white). Plane polarised light x 100.
3.29 Folded and distorted layers of magnetite. Plane polarised light x 50.

3.30 Brecciated magnetite band. Plane polarised light x 50
3.31 Microbands of deformed martite. Plane polarised light x 50.

3.32 Subhedral to anhedral unaltered magnetite grains. Plane polarised light x 100.
3.33 Martitization along crystallographic direction. Plane polarised light x 200.

3.34 Riebeckite cutting across magnetite porphyroblasts. Plane polarised light x 100.


3.40 Goethite, lepidocrocite viens in the matrix containing secondary hematite and martite. Plane polarised light x 100
3.41 Lepidocrocite and goethite with martite inclusions. Cross polarised light x 200.

3.42 Goethite, lepidocrocite vein in hematite matrix. Plane polarised light x 100.
3.43 Mixture of hematite, goethite, martite and specularite in enriched ores. Plane polarised light x 200.

3.45 Intensive secondary hematite with martite (showing Widmanstratian texture) and other inclusions. Cross polarised light x 200.

3.46 Deformed specularite with martite. Plane polarised light x 100.
3.47 Enlarged growth of specularite showing platy character. Plane polarised light x 200.
Porphyroblasts of pyrite and also veins of pyrite parallel to banding. Plane polarised light x 100.

Porphyroblasts of pyrite with magnetite inclusions. Plane polarised light x 100.
Magnetite inclusion in chalcopyrite. Plane polarised light x 200.

Chalcopyrite grown along pyrite boundary. Plane polarised light x 200.