CHARACTERISATION DRIVEN PROCESSING OF INDIAN SUB-MARGINAL GRADE OF IRON ORE FOR VALUE ADDITION

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IN
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by

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CERTIFICATE

This is to certify that the Thesis entitled ñ**Characterisation driven processing of Indian Sub-marginal grade of Iron ore for value addition**ò being submitted by Nirlipta Priyadarshini Nayak for the award of Doctor of Philosophy in Engineering to the National Institute of Technology, Rourkela, Odisha, India is a record of bonafide research work carried out by her under our supervision and guidance. The Thesis has fulfilled all the necessary requirements for the award of Ph.D degree at National Institute of Technology, Rourkela as per regulation. It has satisfied the standard pertaining to the required Degree. The results incorporated in the Thesis have not been submitted to any other University or Institution for the award of any Degree or Diploma.

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CONTENTS

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- Nayak, N. P and Pal, B. K (2011) ñFeasibility of Beneficiation of Low Grade Iron Ore Finesò, ACE, 2011, *International Conference on Advances in Environmental Chemistry*, 16-18, November, Aizawl.

Abstract

Iron ore resource has its own typical mineral characteristics which require definite beneficiation process to produce quality raw material. India is endowed with large reserves of high grade hematite ore. However, steady consumption of these iron ores is now a concern forcing to develop beneficiation strategies to utilize low grade iron ores. Characterization has become an integral part of mineral processing and beneficiation depends on the nature of the gangue present and its association with the ore. Different characterization aspects like mineralogy, textural relationship, liberation size, chemical analysis and grain size analysis were studied to develop the beneficiation scheme. As reflected in the National Steel Policy, the life of high grade lumpy ore as on April 2010 will be ten more years. In order to ensure longer period of ore availability, it is important to use low grade Banded Hematite Quartzite (BHQ) & Banded Hematite Jasper (BHJ) iron ores after beneficiation. Looking at the present scenario, Indian Bureau of Mines (IBM) has slashed the threshold value of Fe in hematite to 45% from 55 % (t). According to National mineral policy projections, exploitation of the low grade iron ore horizons is necessary to achieve zero waste mining. BHJ assaying up to 40% Fe (T) had upgraded above 60% Fe (T) to use effectively. Technically it is possible to enhance the quality of low grade as well as BHQ/ BHJ iron ores to an acceptable grade using various techniques like Flotation, Enhanced gravity separation, WHIMS etc. In India, iron ores are generally washed to remove the high alumina containing clayey matter. Conventionally, after washing, the lumps are directly fed to blast furnace and the fines are used after agglomerating them into sinter. However, the slimes are being rejected in the tailing ponds. These slimes in most cases contain substantial iron values in the range of 54ï 58% Fe. Therefore, it is imperative to recover iron values from these slimes because of high demand on the good grade iron ores day-by-day.

Key words: *Iron ore, Beneficiation, Communition, WHIMS, Flotation, Hematite*

LIST OF TABLES

LIST OF FIGURES

CHAPTER- I

INTRODUCTION

INTRODUCTION

1.1 PROLOGUES

Iron is the second most abundant metallic element in the Earthĝs crust and by mass the most common element on Earth. It is the fourth most common element in the Earth's crust accounting for around 5 % of it. The principal minerals of iron are the oxides (hematite and magnetite). Hematite and magnetite are the two important iron ores from which iron is extracted. Of these, hematite is considered to be superior owing to its high grade. Iron & steel is the crux for industrial development in a country. The vitality of the iron & steel industry largely influences the economic status of a country. Iron ore being the essential raw-material for Iron & Steel Industry, its mining arguably is the cynosure of all mining activities undertaken by any country. However, being a non-renewable natural resource the reserve of good quality ore is ever dwindling. In order to meet the present and future requirement it is indeed essential to utilize marginal to sub-marginal grade iron ore. Indian iron ore is relatively rich in Fe as well as contains higher proportion of silica, alumina and phosphorous compared to the other major deposits of the world. World steel demand grew by 3.6% in the year 2013[150] owing to the huge requirement of iron ore by China, the major iron ore producing countries have increased their production by adopting the steps to utilize the lean grade iron ores, fines and slime. Iron and steel industry in India grew exponentially during the last decade. India is slated to become the second largest steel producers in the world by 2015. Steel production in the country has increased at a compound annual growth rate (CGAR) of 6.9% over the year 2008-2012[148].On the basis of the growth witnessed, National Steel Policy, 2008 revised the estimated domestic steel projection as 190 Mts by the year 2020.

India is endowed with large iron ore reserve of around 26 billion tonnes. Current mining practice adopts a cut off grade of 58% Fe content. As a result of which lot of low grade in-situ deposits are locked in operating mines. Besides these in-situ deposits huge stockpiles of low grade ore has been created in all operating mines in course of removal of overburden and selective mining during mine development. This low grade ore can't be utilised due to low industrial value and marketability. According to industry, the high quality iron ore will be exhausted much before the full operational life of the plants in place today or those being planned to set up.

Indian iron ore is generally friable in nature that results in generation of significant quantity of fines (around 35%) during mining and processing in the country [106]. The ratio of lumps to fines produced in the country is 2:3. These fines however can't be used for iron making (blast furnace/ direct reduced iron (DRI) units. These fines could be put to use in the domestic iron & steel industry after suitable beneficiation followed by agglomeration. However, the popularity of these routes is yet to gear up/ pick up the momentum in Indian iron and steel industry. In order to produce 1 ton of lump ore, about 1.5 ton fines are generated of which only 0.5 ton are utilized. The rest is either dumped as stocks at the mine or permanently lost due to lack of proper beneficiation facilities. It is estimated that around 20 MT fines are lost every year [53]. Upon crushing and sizing, the high alumina bearing laterite and friable ores have greater propensity to break down into finer sizes as compared to hard ores which leads to concentration of alumina in ore fines; the slime being richest in alumina.

High alumina of the low grade iron ore and in sinters through iron ore fines and coke ash leads to increase in slag viscosity and in turn makes the blast furnace operation difficult. High alumina is undesirable but unavoidable to a certain extent, especially in the Indian context where alumina rich iron ores are to be exploited. The reduction degradation behavior of the sinter can be improved considerably by lowering its alumina content. In view of using the sinter to share the load in blast furnace, there exists a need for lowering the alumina in sinters.

The selection of the right process route for beneficiation of an ore is strongly dependent on their mineralogical characteristics that need careful investigation. Iron ores in general are associated with gangue such as silica, alumina and other oxides. The valuable iron bearing constituents need to be separated out from the gangue to render them economically usable. This is achieved by taking advantages of differences in physical properties such as size and shape, color, specific gravity, magnetic susceptibility, electrical conductivity, and surface properties between the mineral constituents and the gangue. The treatment to which the ores are subjected to achieve such separation is known as beneficiation. Depending upon the nature of the iron ore it can be subjected to various unit operations such as sizing, washing, gravity separation, magnetic separation, flotation, etc. as reflected in the characterization data.

1.2 SCOPE OF PRESNT INVESTIGATION

The present study is both basic and applied in nature. The wheels of progress, in the rapid mobilization of the primary earth resources, cannot be reversed or stopped even slowing down though possible, will have a wide repression in mineral industry and the economy of many developing countries like India. It is for this reason that many consider the rigid rules and regulations of environmental protection as hindrance to progress.

Mineralogical characterization both qualitative and quantitative of iron ore is a very important and basic aspect that has to get due attention before any attempt for its processing and has become even more important these days because of the increasing demand of the ore. Mineral processing technology is evolved to separate and recover ore minerals from gangue in a commercially viable method and is mainly based on the process of mineral liberation and the process of mineral separation. Therefore, it is important to first get a clear understanding about ore- and gangue minerals and their behavior.

The blast furnace route of iron making is predominant in India. It has been established over the years that the productivity of blast furnace increases and energy consumption decreases by using superior quality of raw materials. One percent increase in iron content improves the productivity by 2% and reduces the coke consumption by 1%.Indian hematite though rich in Fe, but the alumina: silica ratio (1.5 to 3.0) for lumpy ore is detrimental to blast furnace as well as sinter plant productivity and should be less than 1.5 and preferably below 1. In the blast furnace, 1% increase in alumina content increase coke rate by 2.2%, a decrease in productivity by 4% and an increase in flux consumption by 30kg/ t of hot metal production [145].

The scope of this research includes physical, mineralogical and geo- chemical characterization. The investigation is also designed to find out the possible ways of beneficiation for their optimal utilization. With these objectives, the work plan under this Research programme has been structured into two parts: characterization and beneficiation. Before discussing the economical utilization of different lean grade ores, their characteristics and origin are briefly discussed.

1.3 OBJECTIVES OF PRESENT RESEARCH

The primary objectives of the proposed research is to

- Study of regional geology of Iron ore deposits of Singhbhum-Orissa Iron ore belt for understanding the overall geological environment of the deposition.
- To understand the nature of three sub-marginal grade ores of different types through detailed characterization.

- A quantitative and definitive assessment of the extent of silica and alumina reduction possible with state-of-the-art beneficiation technology
- Development of process flow sheet to enrich them to Ó64% Fe with low alumina and silica content
- Correlation between characterisation and beneficiation data for ultimate utilization of iron ores and slimes

1.4 INDIAN IRON ORE - GREAT FUTURE WITH MANY PROBLEMS

The huge and high quality iron ore resources of India are often left out of the equation when global iron ore deposits are surveyed. This might have been correct in the past, when India's domestic demands were small and when itôs steel industry was very much closed off from the world. However, in the present situation with Indian steel companies becoming global leaders and with Indian iron ore exports to China surpassing 100 Mt, it is no longer so.

According to the Indian Bureau of Mines (IBM), iron ore resources in the country amount to a total of 26 billion tons, of which 15 billion hematite and 11 billion tons magnetite. The quality of the Indian resources is excellent, with high Fe content and high share lumpy ore. Almost 60 % of the hematite resources have Fe grades above 62 % and 45 % lumpy ore, 33 % fines and 12 % classified as lump with fines and the balance not classified. These are huge figures which are most probably underestimates for several reasons:

- Detailed exploration has been scanty and shallow and almost no modern exploration work has been done.
- Over the past 25 years resources have further grown in spite of quickly rising production levels.
- The cut-off grade used by the IBM is 45 %[147] which is high by all standards in global prospective (earlier 55%).

It is clear that India's iron ore resources are of a superior quality and far better located compared to many of the deposits which are at present considered for exploitation. It is indicative of the new climate in Indian mining sector that the hurdles that have to be overcome to reach a production of 500 Mt are now discussed and conventional wisdom contested. To reach this level followings issues should be addressed.

- Increased systematic exploration activities using modern methods to reach deeper and cover larger areas should be started.
- A major potential source of iron ore units for the steel industry in India is fines. At present lump ore accounts for most of the blast furnace feed. With increasing steel production, a surplus of fines has been available for exports to China. If the fines fraction could be utilised, as it is around the world for sinter or pellet production and similar electric arc furnace (EAF) feed, additional volumes of iron ores, which today are either not mined or stored in slime dams and waste heaps would be available for both the domestic steel industry and for exports.
- Domestic iron ore prices must reflect the international market situation.

1.5 THE PROSPECTS

The implementation of large scale beneficiation of lean grade iron ore will result in

- Substantial increase in iron ore reserve base.
- Augmentation of available limited resources.
- Increasing the life of tailing pond & decreasing area requirement for waste disposal.
- Decrease in mining threshold value of Fe & subsequently improving mine economics as well as increasing reserve base.

CHAPTER II

GEOLOGICAL FRAMEWORK

GEOLOGICAL FRAMEWORK

The Precambrian greenstone belts and similar supracrustals are the main repositories of banded iron formation hosted iron ore deposits world over [26]. Origin of these iron ores are considered as the product of supergene enrichment processes [63, 79, 81] or hydrothermal mineralization processes [16, 98].

Archean supracrustal belts containing banded iron formations in the Jharkhand-Orissa region, India are commonly referred to as Iron Ore Group [118]. These belts skirt an Archean basement block along its east, south and west. The basement block contains early Archaean volcano-sedimentary assemblages (OMG) as rafts within banded granitoids (OMTG) and granites (SBG-A) [119].

The Singhbhum-Orissa craton (Fig.2.1) forms a triangular crustal block between latitudes 21°0' and 23°15' N and longitudes 84°40' and 86°45' E of a surface area ~40,000 sq. km. The lithological-cum-chronostratigraphic succession of this craton, which is widely referred to in geological literature, has been revised more than a decade ago [110] (Table 2.1). Subsequently, a number of new radiometric ages on the different litho-units of this craton have been generated [41, 42, 75, 77, 119, 120, 121]. The chronostratigraphy of the whole Singhbhum-Orissa craton [6] or part of it was attempted to revise.

Orissa-iron-ore-craton [110, 111] or Singhbhum Orissa craton [76] consists of Iron Ore Group, which were deposited over Older Metamorphic Group. They occur in three basins along eastern, western and southern perimeters of Singhbhum granite batholithic complex, defined as Singhbhum-Keonjhar or Jamda-Koira Basin, Gorumahisani- Badampahar Basin and Daitari-Palalahara Basin respectively [3,76]. The western Singhbhum-Keonjhar or Jamda-Koira Basin extends over a strike length of 60-70 km in NNE-SSW direction from Chakradharpur to Malangtoli [140]. The iron formations and associated rocks are found in horseshoe shaped, gently plunging, and sharply bent synclinorium, known as ñBonai Horseshoe Synclinoriumò (Fig.2. 1). The early works envisaged a stratigraphic unity within the belt and the metamorphosed supracrustal sequence came to be known as the Iron Ore Group, the mafic volcanic rocks as the Dalma lava, thought to be younger than that Iron Ore Group [35].

(i) JAMDA- KOIRA VALLEY

The type area of Iron Ore Group lies in Noamundi-Jamda-Koira valley in the southern part of this NNE-SSW trending basin.

(ii)GORUMAHISANI-BADAMPAHAR IRON ORE BASIN

The BIF in this section is distinctly intruded by epidiorites, Newer dolerites and ultramafic dykes of younger age, whereas in adjacent Sukinda Valley and Tomka-Daitari range, the iron-formations are intruded by chromiferous ultramafic rocks and dolerite dykes [22].

These altered volcanic tuffs are termed as óshalesô but the presence of ubiquitous volcanic material has made is much complicated [68].

(ii) DAITARI-PALA-LAHARA IRON ORE BASIN

It is considered as underlying the IOG of west Singhbhum Keonjhar basin [12, 54]. On this basis, it can be interpreted that the Daitari Iron Formation as well as Gorumahisani-Badampahar formation are older than west Singhbhum- Keonjhar IOG sequences; however this interpretation is quite controversial [109].

These formations form a prominent synform whose axial region is occupied by the Sukinda valley, where chrome bearing ultramafics of ophiolitic affinity occupies the core [14].

2.1 LITHOSTRATIGRAPHY OF SINGHBHUM-ORISSA CRATON

Singhbhum craton is also called as Singhbhum-Odisha craton in eastern India.

The rock-suite constitutes the Singhbhum craton-:

- Singhbhum granite (I, II, III) with enclaves of (i) Older Metamorphic Group (ii) Older Metamorphic Tonalite Gneiss.
- Iron Ore Group (IOG) dominantly Banded Iron formation (BIF) at the margin of Singhbhum granite.
- Volcanics/ Green stone belts

Generalized chrono-stratigraphic succession according to their ages and position is given in Table 2.1.

Older Metamorphic Group

Older Metamorphic Group (OMG) is the oldest known rocks of the Singhbhum craton, [111]. The OMTG rocks are the oldest rocks that occur south of Singhbhum Shear zone which have been named by [32] as the ñOlder metamorphicsò.

Older Metamorphic Tonalite Gneiss (OMTG)

The OMG rocks are synkinematically intruded by Tonalitic Gneiss grading into Trondhjemite and designated as Older Metamorphic Tonalite Gneiss

Singhbhum Granite

The formation of OMG & OMTG was successively followed by emplacement of Singhbhum granite that intruded in 2 phases (SBG-I & SBG-II), deposition and folding of Iron Ore group supracrustals and emplacement of Singhbhum granite phase-III. This granite complex is a part of the earliest continental segment to cratonise and together with the archean supracrustals have been designated the archean cratonic core region by [65].

Iron Ore Group

The Iron Ore Group constitutes the major supracrustal unit in the SOIOC and referred to as ñArchean Supracrustals [65]ò. The study area of Jilling-Langalata deposits lies in the type area of this basin - the ñNoamundi-Jamda-Koiraò valley (Fig.2.1a); which extends to a strike length of 100 km in NNE-SSW direction with widths varying from 20 to 30 km.

The banded Iron formation forms a major component of the greenstone belts and similar supracrustal world over [97]. In all the three basins the supracrustal sequence stars with sandstone-conglomerate at the base followed by ferruginous shales, tuffs, lavas and Banded Iron Formation (BIF) [85, 23]. According to [35, 117] all the iron formations of Jharkhand and Orissa belong to one group. The BIFs belong to different age groups, a view supported by [13, 14, 2]. A two-tier system was suggested by [12] while [4, 5, 6] conceived of a three-tier system.

The **BIF-1** is narrow, BMQ-type, thin banded and and exhibits at least 6 periods of deformation but with no big ore deposits so far known (Fig.2.1b).

BIF-2 forms Tomka- Daitari basin (Fig.2.1b) dies out at Harichandanpur

BIF-3, the Horse-shoe basin is the youngest with Dhanjori sandstone and younger volcanic at its base. It has the best grade and huge sized ore bodies each of more than one km in length at times.

Singhbhum Group

Rock succession lying to the north of the Singhbhum Shear Zone extends in a series of E-W folds for over 200 km.[116, 117] have named the succession lying to the north of the shear zone as Singhbhum Group.

Dhanjori Group

Another group of supracrustals, overlying the Singhbhum Granite and IOG rocks is the Dhanjori Group [116,117,111]. The succession is unconformably deposited over the Singhbhum Granites and Iron Ore Group.

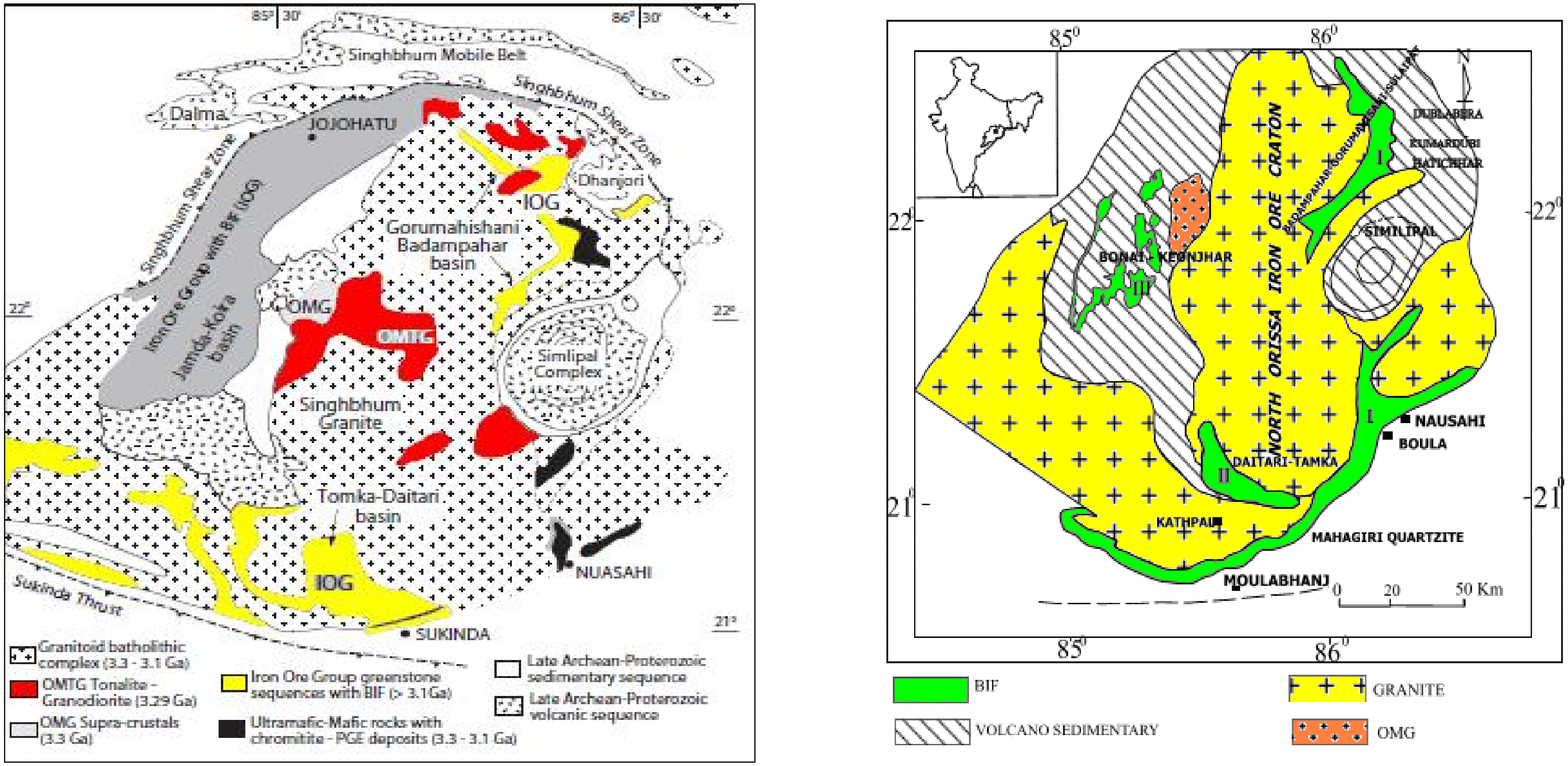


Fig.2.1 (a) Generalised Geological Map Showing BIF-I, BIF-II and BIF-III Surrounding the NOIOC (b)Geology of the Singhbhum craton (modified by Mondal et al. 2006a after Saha, 1994; Sengupta et al. 1997).

TABLE ï 2.1: GENERALISED CHRONOSTRATIGRAPHIC SUCCESSION OF THE SINGHBHUM - ORISSA CRATON (After Saha et al., 1988)

Newer Dolerite dykes and sills		c.1600-950 Ma
Mayurbhanj Granite		c.2100 Ma
Gabbro - anorthosite ï ultramafics		
Kolhan Group		c.2100-2200 Ma
~~Unconformity ~~~~~~~~~~~~~~~~~~~~~~~~~~~		
Jagannathpur lava Malangtoli Lava	Dhanjori - Simlipal lava(c.2300Ma) Quartzite conglomerate	Dhanjori Group
Pellitic & arenaceous Metasediment with mafic Sills (c. 2300- 2400Ma)		Singhbhum Group
~~Unconformity~~~~~~~~~~~~~~~~~~~~~~~~~~~~		
Singhbhum Granite (Phase II)		C. 31.1 Ga
Mafic lava, tuff, acidic volcanics, Tuffaceous shales, BHJ and BHQ with Iron Ores, ferrugenous chert, local dolomite, Quartzite and Sandstone		Iron Ore Group
--		
Singhbhum Granite (Phase I & II) c.3.3 Ga		Nilgiri Granite Bonai Granite
--		
Folding and metamorphism of OMG and OMTG		c.3.4 ï 3.5 Ga
Older metamorphic tonalite gneiss (OMTG)		c.3.775Ga
Older metamorphic group (OMG):		
PeliticSchist, Quartzite, Para-amphibolite, Ortho-amphibolite		C.4000 Ma

Kolhan Group

The Kolhan basin intervenes between the IOG of the Noamundi basin and the Singhbhum Granite [34]. It begins with thin plane- and cross-bedded red and purple sandstones consisting of ferric oxide-rich quartz arenite with beds/lenses of conglomerates deposited in shallow, ephemeral braided streams. [83].

Newer Dolerites

The Newer Dolerites occur in two distinct orientations (NE/SW and NW/SE) in the Singhbhum. Granitoid Complex (SBGC). These dikes are mostly tholeiites and quartz-normative dolerites associated with subordinate norites. The SBGC is transected by several dikes of mafic to acidic compositions, collectively known as the Newer Dolerites [34, 111].

2.2 THRUST AREA

Barsua & Jilling-Langalata the iron ore deposits of Odisha, India are the focus of the present work.

(i) The Jilling-Langalata area is part of the Iron Ore Group of the Precambrian Singhbhum-North Orissa Craton, Eastern India falls in the north east quadrant of Survey of India topographical sheet No. 73 G/5 and is located between Latitudes 21ę 56´ 15ě N and 21ę 59´ 00ě N and Longitudes 82ę 25´ 10ě E and 85ę 26´ 10ě E (Fig. 2.2). The study area, mining lease of M/s Essel Mines, is surrounded by leaseholds of M/s H.C. Pandya in East, towards north, west by M/s OMC Limited and M/s Rungta Mines (P) Limited in the south. According to [9], the area is segmented as the North Orissa Sector I. The detail survey of literature also reveals that the sector consists of several major lithologic groups of sedimentary and igneous origin ranging in age from Archean to the younger proterozoic. The major lithological units of the area comprises of mainly the older metamorphic Banded Iron Formation (BIF).

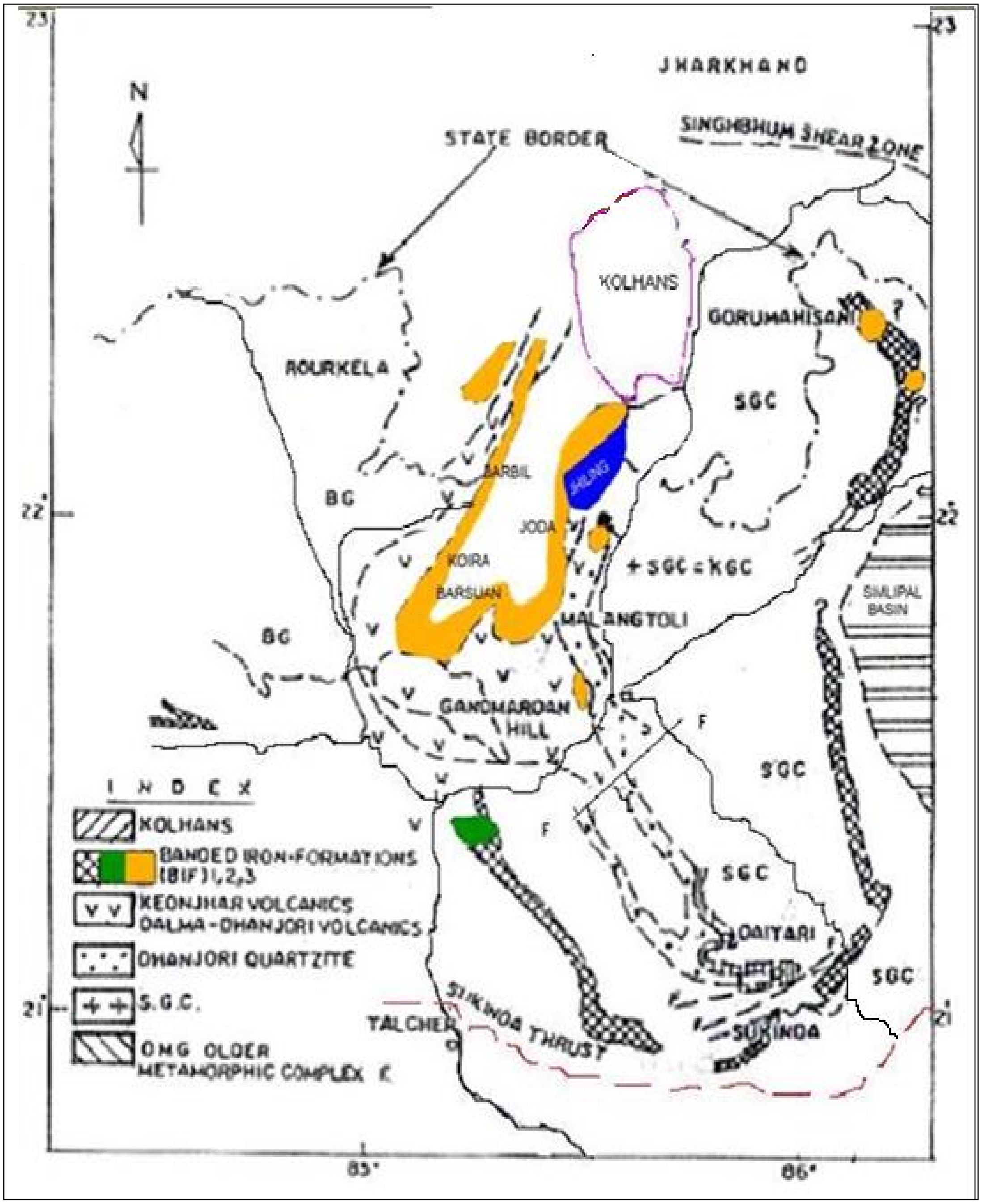


Fig. 2.2: Geological map showing BIF and iron ore occurrences along the horse-shoe shaped synclinorium in the Singhbhum-N Orissa Craton, eastern India.

(i) Jilling Langalota iron ore deposit comprises six (6) ore bodies.There are three main ore bodies of economic significance out of six. These are ï Langalota ore body, Gangaigora ore body and Appahatu ore body. The Langalota ore body further divided into two sections, i.e. Langalota and Jajang. Besides these above three ore bodies, there are three minor ore bodies namely ï Jilling (almost exhausted), Rakhaburu and Khuntpani. Exploration has been done all the ore bodies except the Rakhaburu. The ore bodies are bedded and lensoidal with variable dimension. The ore bodies have thickness ranging from 2.20 to 66.7 m occuring in a maximum depth of 76.90 m in Jhiling area and data generated suggests that the total reserves of Jilling-Langalata deposits is 67.1 million tones.

(ii) In Barsua area, the ore body extends over Barsua-Taldih-Kalta. The ore is generally harder at the top and softer at depths. The irregularly lateritised harder ore forms the crest of the ore body following profile of the hills, as thin mantle of about 10-20 m at Barsua. The average thickness of the ore bodies is in the range of 40 m.

(iii) Jilling ore body is oval in shape covering an area of 79,739 sq. m with its longer axis having a length of 520 m. which is parallel to north-south strike of the regional lithounits. The total reserves of Jilling-Langalata deposits are 67.1 million tonnes as per the ACC report, 1997 which is confirmed from geological mapping, followed by drilling (1525.50 m), sampling and chemical analysis in an area of 866700 m^2. Basing upon detailed investigations, reserves and quality of iron ore up to a depth of 499m were estimated and given in Table 2.2 & 2.3 for BIM deposits. The iron ore is occasionally inter-bedded with thin bands of shale which has been named as parting shale (Fig. 2.4e).

BHJ along with different types of iron ores are well exposed in the Jilling-Langalata and Barsua region. The principal iron oxide minerals include hematite; martite and hydroxides such as goethite and limonite are predominantly observed in most of the sections of different types of iron ores. Due to high resistance, BHJ generally seen to represent most ridges.

Table 2.2: Annual iron ore reserves in Jilling- Langalata iron ore mines

AREA	YEAR	RESERVE (Mts)	GRADE	ROM (Mts)	PRODUCTION (Mts)
456100m^2	2006-07	77.37	58->65%Fe	41,97,451	22,48,588
	2007-08	67.11	58->65%Fe	41,92,378	39,98,499
	2008-09	58.98	58->65%Fe	50,90,370	45,99,848
	2009-10	58.29	58->65%Fe	42,24,984	42,24,984
	2010-11	58.03	45->65%Fe	34,31,188	29,80,406
	2011-12	57.86	45->65%Fe	17,4355	17,4355
	2012-13	57.69	45->65%Fe	23,06,742	23,08,198

BHJ grades into Banded hematite quartzite/ chert in the south. Such gradation is also present within the main ore body occurring as roughed irregular masses. BHJ outcrops are seen on both the sides of Jilling as well as Langalata hill occurring as discontinuous bodies. In Dalco nala section, massive iron ore overlies BHJ. BHJ in the deposit is unevenly banded and the thickness of individual bands varies from a few mm to 5 cm.

In Langalata hill, laminated iron ore exposures are seen towards west. The ore shows north-south trend exhibiting variable dips. The friable and biscuity iron ore could be seen in subsurface. In general, friable ore alternate with laminated iron ore.

(ii) The combine leasehold (ML-130) of Barsua-Taldih-Kalta is situated in the classic iron bearing formations of Orissa. The regional geological set up constitutes part of the Precambrian meta- sedimentary sequence known as Iron Ore Series.

The lease area extends 18kms North-South on the top of the hill ranges in a narrow strip. Its Eastern and Western boundaries lay on the hill slope. The Barsua Iron ore mine along with Kalta, Kiriburu occupies the western limb of Bonai synclinorium The area is located between Latitudes 21^0 59ôòN and 21^0 50ô50ò N nad Longitudes 85^0 14ô07ò E and 85^0 08ô11òE.

The geological reserves in BIM were estimated to be 212.647 Mt out of which mineable reserves were 139.75Mt (01.01.1973). Since, then mining has depleted the reserves to 82.90 Mt as on 01.04.2004. Further depletion due to mining since then the reserve has reduced to 65.03 Mt as on 01.04.2013.

Table 2.3: Annual iron ore reserves in Barsua Iron Mine, SAIL

AREA	YEAR	RESERVE (Mts)	GRADE	ROM (Mts)	PRODUCTION (Mts)
9764300m^2	2006-07	79.23	57->65%Fe	16,01,609	15,27,262
	2007-08	77.63	57->65%Fe	21,25,469	20,13,613
	2008-09	75.51	57->65%Fe	17,98,409	20,58,963
	2009-10	73.72	57->65%Fe	21,05,005	18,90,993
	2010-11	71.62	45->65%Fe	23,47,022	20,24,983
	2011-12	69.28	45->65%Fe	19,79,803	18,00,673
	2012-13	67.31 as on 1-04-12	45->65%Fe	22,81,296	21,56,301
	2013-14	65.03 as on 1-04-13			

2.3 LITHOLOGICAL SUCCESSION IN JILLING-LANGALATA AREA

Upper Shale Formation

The upper shale resembles lower shale in all its physical aspects and is distinguishable only when it is actually seen to be overlying the iron ore body (Fig. 2.4d).

Iron Ore

Exposures of iron ore bodies are observed on the top of Jilling (almost exhausted) in the lease. Though stratigraphically iron ore overlies BHJ but at many places it directly overlies shale. The iron ore bodies are interbedded with thin bands of shale similar in nature to the bottom or top shale and are extensively lateralized. The shale (top) overlies the iron ore and is similar in physical characteristics to the bottom shale. It is often silicified and hard. The iron ore is occasionally inter-bedded with thin bands of shale which has been named as parting shale (Fig. 2.3b)

Banded Hematite Jasper (BHJ)

The Banded Hematite Jasper (BHJ) formation overlies the shale bottom. Thickness of BHJ varies between 2 m to 30 m. The thickness of individual band, however, varies between few millimeters and 10 cm and do not extend more than 5 meter before they pinch and merge with other band. The outcrop consists of alternating layers of hematite and quartz/ jasper

Parting Shale or Middle Shale

Parting shale / middle shale, occuring as thin partings within the iron ore similar to the shale both top and bottom (Fig. 2.3e) and is not restricted to any particular sratigraphic horizon. It is found in the bottom of the active quarry-6 as bottom shale and feruginious shale in between the main Iron ore body as patches.

Laterite

It is found mostly in the surface of the lease area is reddish brown to brown in colour. It is of hard to friable in nature. Some portion consists of lumpy Iron ore. The Fe content varies from high grade to medium grade and below portion of the active quarry consists of blue dust & siliceous blue dust. Laterites blanketing the iron ore deposit and occur in 5 to 15 m. thickness. Goethite (hydrated iron oxide) is the major mineral found in laterites.

2.4 LITHOLOGICAL SUCCESSION IN BARSUA AREA

The litho sequence in Barsua- Kalta may be described as follows

Epidiorites

Upper Shale

The Upper Shale forms the central shale and clay band in entire Barsua and part of Taldih ñAò block after which it gradually swings east and passes along the eastern margin of the ore body in Kalta block

Banded Hematite Jasper/ Quartzite (BHJ/ BHQ)

The BHJ constitutes the hanging wall of the Iron ore deposits, overlooking the western valley. The BHJ grades into Banded hematite cherts and Quartzite (BHQ) in the south. Such gradation is also present within the main ore body occurring as rugged irregular masses in form of tongues and horses indicating the original unaltered rock.

Massive Iron ore (mostly in Barsua)

Massive ore mostly occur as isolated patches in contact with BHJ and sometimes grades to friable and blue dust (Fig. 2.4c).

2.5 CLASSIFICATION OF THE IRON ORES OF STUDY AREA

Based on mineralogy and texture, several ore types can be distinguished at the megascopic scale.

2.5.1 Massive Ore

As the name suggests, they are devoid of bands and laminations (Fig. 2.4d). These ores are steel grey in color and are relatively high grade. They are massive, compact and dense with packed hematite minerals.

2.5.2 Hard laminated Ore

The ore is generally dark grey to iron black in colour, massive in nature devoid of any banding/ lamination. The ore is dense and have a high specific gravity, sometimes finely laminated. Very often the ore is highly broken and jointed (Fig. 2.4f) and sometimes lateralized.

2.5.3 Blue Dust

Megascopically siliceous blue dust looks mono-mineralic, but detailed microscopic examination reveals the presence of an admixture of very fine to coarser fragments of hematite and goethite. It mainly occurs as pockets along with other ore type (Fig. 2.3d).

2.5.4 Goethitic-Lateritic ore and Canga Ore

Laterites are soil types rich in iron and aluminium, formed in hot and wet tropical areas. Nearly all laterites are rusty-red because of iron oxides. Lateritic ore is dull earthy in color with limonitic red, yellow and dull white patches. However, in a fresh surface, it appears darker. Canga forms a valuable ore, which may run as high as 68% iron. Canga ores (Fig. 2.4a) are the erosion products of earlier formed laminated and massive ores.

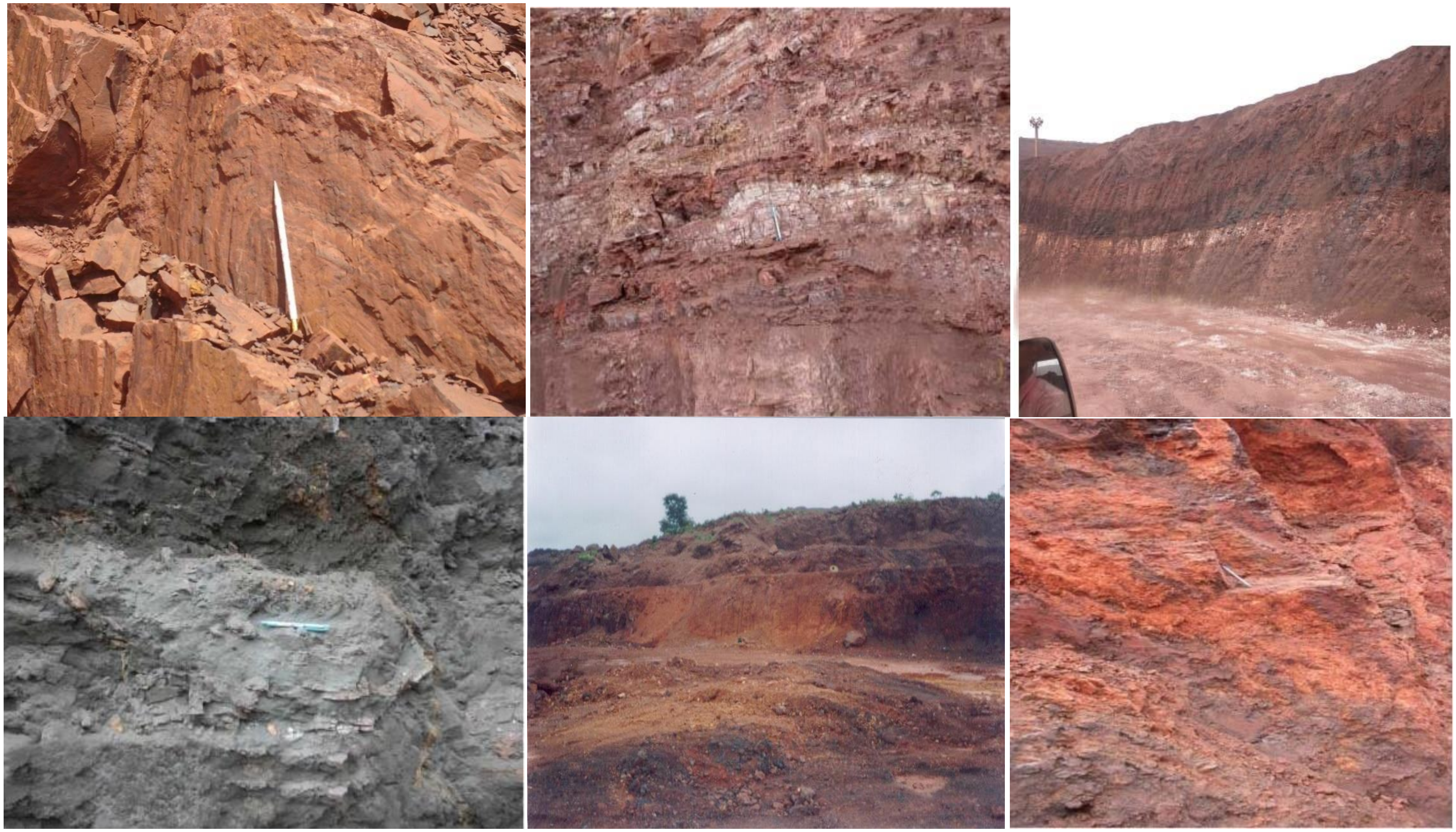


Fig 2.3 Field Photographs showing (a) Tightly Folded Banded Hematite Jasper (b) Shale band (ferruginous & white shale) (c) Alternative band between blue dust and white shale (d) Highly siliceous blue dust (e) parting shale besides soft laminated ore (f) Ochre red Lateritic ore.

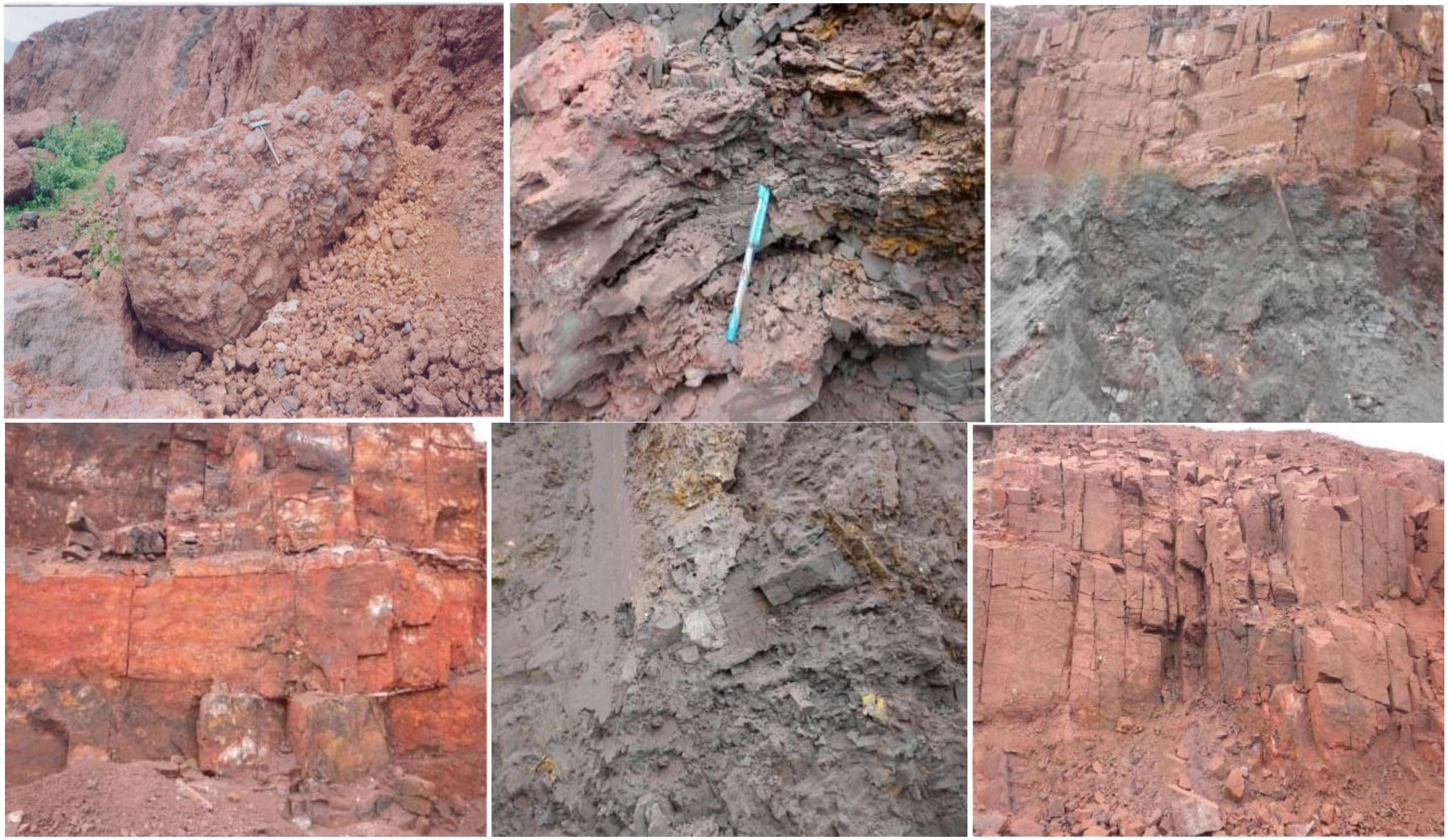


Fig. 2.4: Field Photographs showing (a) Canga ore as top cappings (b) Biscuity ore along joint pattern (c) Litho contact between hard massive ore &Blue dust (d) Hard massive ore (e) Soft Laminated Ore retaining the banding (f) Highly jointed (2 sets) hard massive ore.

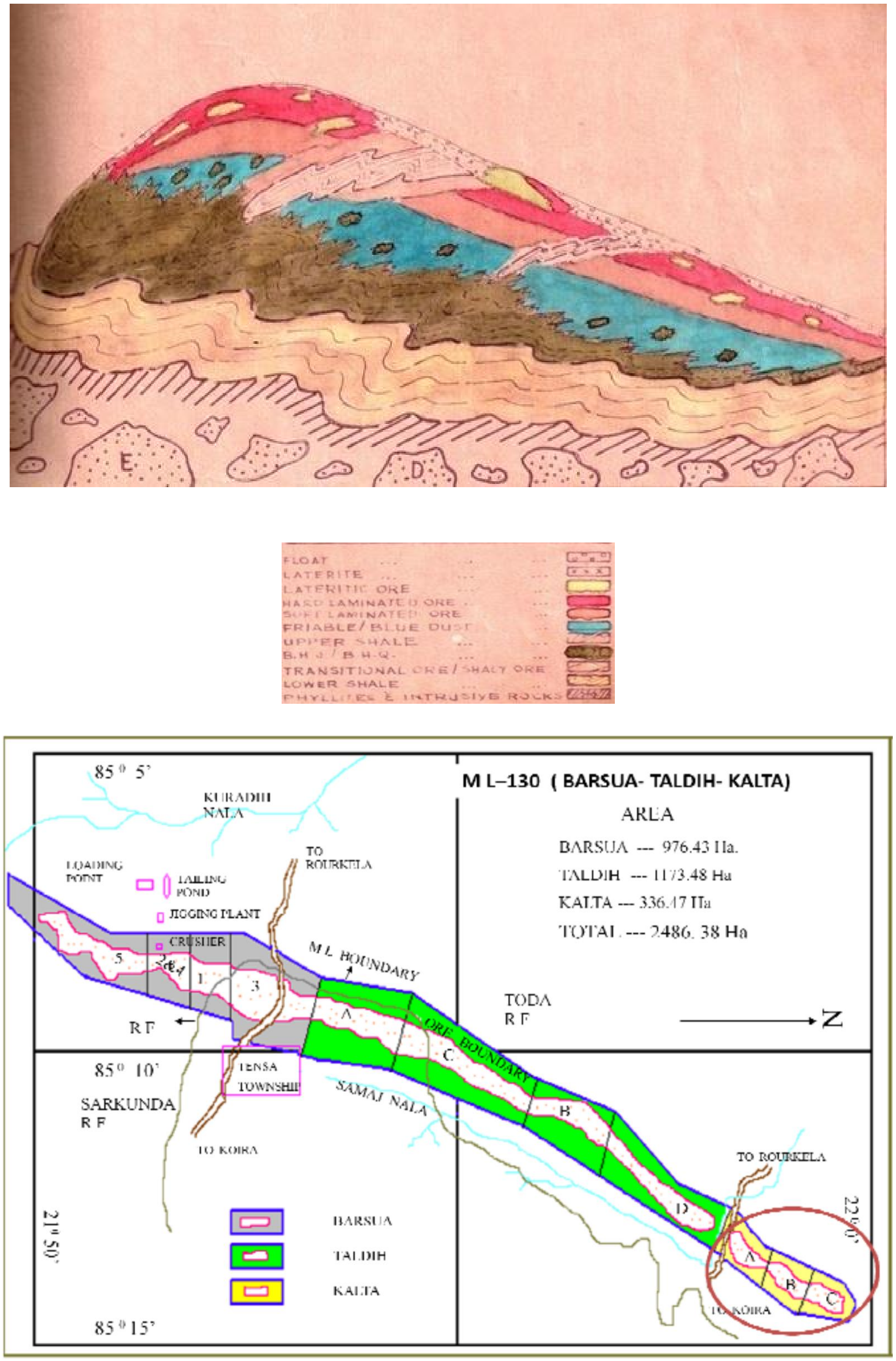


Fig. 2.5: Section showing different lithological units (a) across Barsua Iron ore mines (b) Lenticular shape iron ore deposit of SAIL Barsua- Taldih-Kalta(Source: Survey department, Barsua iron ore mine)

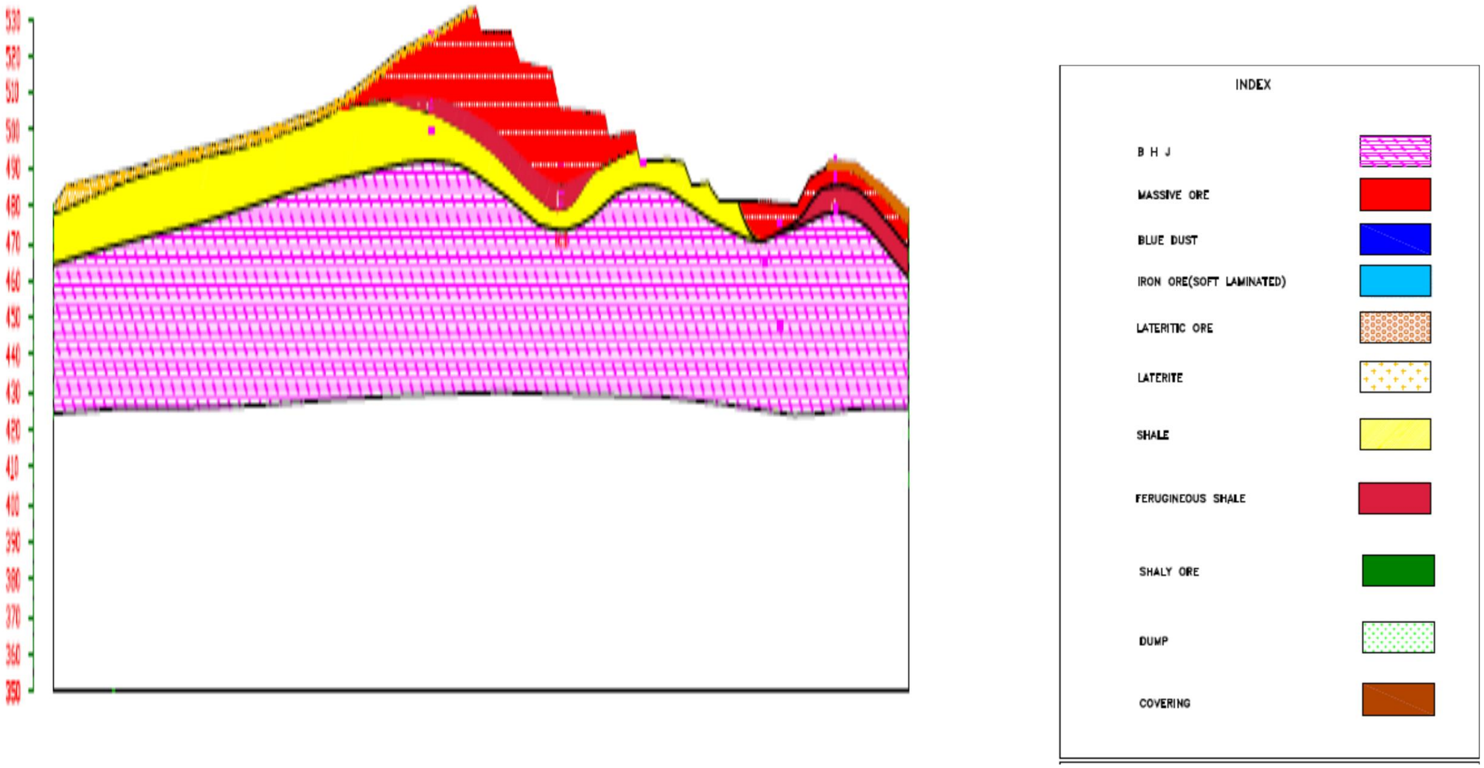


Fig 2.6 Section showing different lithological units across Jhiling- Langalata iron ore mine.

CHAPTER- III

IRON ORE RESOURCES- INDIAN PERSPECTIVE

IRON ORE RESOURCES- INDIAN PERSPECTIVE

Iron & steel is the driving force behind industrial development in a country (Indian Minerals Year Book, 2011). The vitality of the iron & steel industry largely influences its economic status. The mining of iron ore, an essential raw material for Iron & Steel Industry is of prime importance among all mining activities undertaken by any country. Iron ore is the basic raw material for iron and steel industry. India is bestowed with good quality iron ore which can meet the growing demand of domestic iron and steel industry and can also sustain considerable foreign trade. With the total resources of over 28.52 billion tones of hematite (Fe_2O_3) and magnetite ($Fe3O_4$), India is the fourth largest producer of iron ore in the world. United States Geological Survey (USGS) has estimated that the world resources are estimated to exceed 230 billion tons of iron contained within greater than 800 billion tons of crude ore [142]. The global iron ore market earlier was mostly in developed countries including Japan. However, with industrialization in Asian countries, especially in China and to some extent in Republic of Korea, Brazil and India, too the situation has changed giving rise to more consumption in these countries.

3.1 RESOURCES

Magnetite is another principal iron ore that also occurs in the form of oxide, either in igneous or metamorphosed banded magnetite-silica formation, possibly of sedimentary origin. Hematite and Magnetite are the important iron ores in India. About 59% of hematite ore deposits are found in the eastern India and about 92% of magnetite ore deposits occur in southern India, especially in the state of Karnataka. Eastern Indian deposits belong to the Precambrian Iron Ore Group and the ore is within Banded Iron Formations occurring as massive, laminated, friable and also in powdery/blue dust form.

As per UNFC system, the total resources of hematite as on 1.04.2010 are estimated at 17,882 million tonnes of which 8,093 million tonnes (45%) are under reserves category and the balance 9,789 million tonnes (55%) are under remaining resources category [53]. By grades, lumps constitute about 56% followed by fines (21%), lumps with fines (13%) and the remaining 10% are black iron ore, not-known and other grades The remaining are low grade, unclassified resources of lumps and fines or high, medium, low or unclassified grades of lumps and fines mixed etc (Fig. 3.1a). Major resources of hematite are located in Odisha-5,930 million tonnes (33%), Jharkhand-4,597 million tonnes (26%), Chhattisgarh- 3,292 million tonnes (18%), Karnataka-2,159 million tonnes (12%), and Goa-927 million tonnes (5%). (Fig.3.1a). the balance 6% resources are spread in Maharashtra, Andhra Pradesh and Madhya Pradesh. The cut-off grade for estimating the hematite resources has been taken as 45% Fe. At this cut-off grade, the iron ore resources will increase substantially. With the modern technology (like EGS, flotation, magnetic separation) it is possible to utilize iron ore of 45% Fe and above.

The total resources of magnetite estimated at 10,644 million tonnes of which reserves constitute mere 22 million tonnes while 10,622 million tones are placed under remaining resources. Classification on the basis of grade shows 21% resources of metallurgical grade while 79% resources belong to unclassified, not-known and other grades (Indian Mineral Year Book, 2011). Indiaôs 92% magnetite resources are located mainly in 4 states namely Karnataka (7,802MT, 73%), Andhra Pradesh (1464MT, 14%), Rajasthan and Tamil Nadu (527MT,5%).Assam, Bihar, Jharkhand, Kerala, Maharashtra, Meghalaya, Nagaland and Goa together account for the remaining 8% resources (Fig.3.1b). The balance 10,396 million tones constitute remaining resources [52]. Of the total resources, 1,728 million tonnes i.e. only 16% resources are of metallurgical grade while 80% resources are of unclassified grade.

3.2 IRON ORE DEPOSITS OF INDIA

The entire country is divided into five zones with respect to iron ore occurrences [146] as indicated below (Fig. 3.3).

Zone-A Orissa and Jharkhand

Zone-B Chhattisgarh and Maharashtra

Zone-C Karnataka

Zone-D Goa and Redi, and

Zone-E Kudremukh, Bababudan and Kudachadri of Karnataka.

Zone-wise description of the deposits is given below:

ZONE – A

Orissa

The iron ore deposits in Orissa are found in the districts of Keonjhar, Sundargarh, Mayurbhanj, Koraput, Sambalpur and Dhenkanal. Of these, deposits of Keonjhar and Sundargarh districts are worth mentioning. The important deposits containing large reserves of high grade (55% to 69% Fe) are in Thakurani, Joda, Banspani, Joruri, Malangtoli, Khandadhar, Kalmang, Barsua, Bolani, and Kalta. Malangtoli is the largest deposit containing high reserves with Fe content varying from (55% to 63% Fe). Orissa contributes about 50 million tonnes of iron ore production per annum.

Jharkhand

In Jharkhand state, hematite deposits occur in a number of prominent hills in Singhbhum District (east and west Singhbhum). The significant deposits of this district are located in

Noamundi, Gua, Barajamda, Kiriburu, Meghahatuburu, Manoharpur and Chiria. The annual production from Jharkhand is around 21 million tonnes in 2014.

ZONE - B

This zone comprises of Bailadila, Dalli, Rajahara, Rowghat, Mahamaya etc. Two important iron ore bearing areas i.e. Bailadilla range and Rowghat are located in Bastar Tribal region of Chhattisgarh state. Six deposits have been identified with total geological reserves of about 711 million tonnes. Dalli ï Rajahara containing high grade of iron ore.

ZONE – C

Significant deposits are located in Bellary-Hospet sector and those are Donimalai, Ramandurg, Kumaraswami, Thimmappan gudi, Ettinahatti and Belegal**.**

ZONE – D

Huge quantity of friable/blue dust variety of iron ore deposits is concentrated in a small area of about 3700 sq. km in Goa. The production from Goa region is about 24 million tonnes at present.

ZONE – E

This zone contains mainly magnetite ore deposits at Kudremukh, Bababudan and Kuda chadari.

3.3 IRON ORE PRODUCTION

The production of iron ore consisting of lumps, fines and concentrates at 136.02 million tonnes in 2012-13 decreased by 19% as compared to that in the previous year., mainly on account of suspension of mining operation in Karnataka due to Hon'ble Supreme Court order [52]. On the contrary, in the year 2010-11, the total production was 208 million tonnes, showing a decline of about 5% as compared to preceding year. There were 270 reporting mines in 2012-13 as against 313 mines in the previous year.

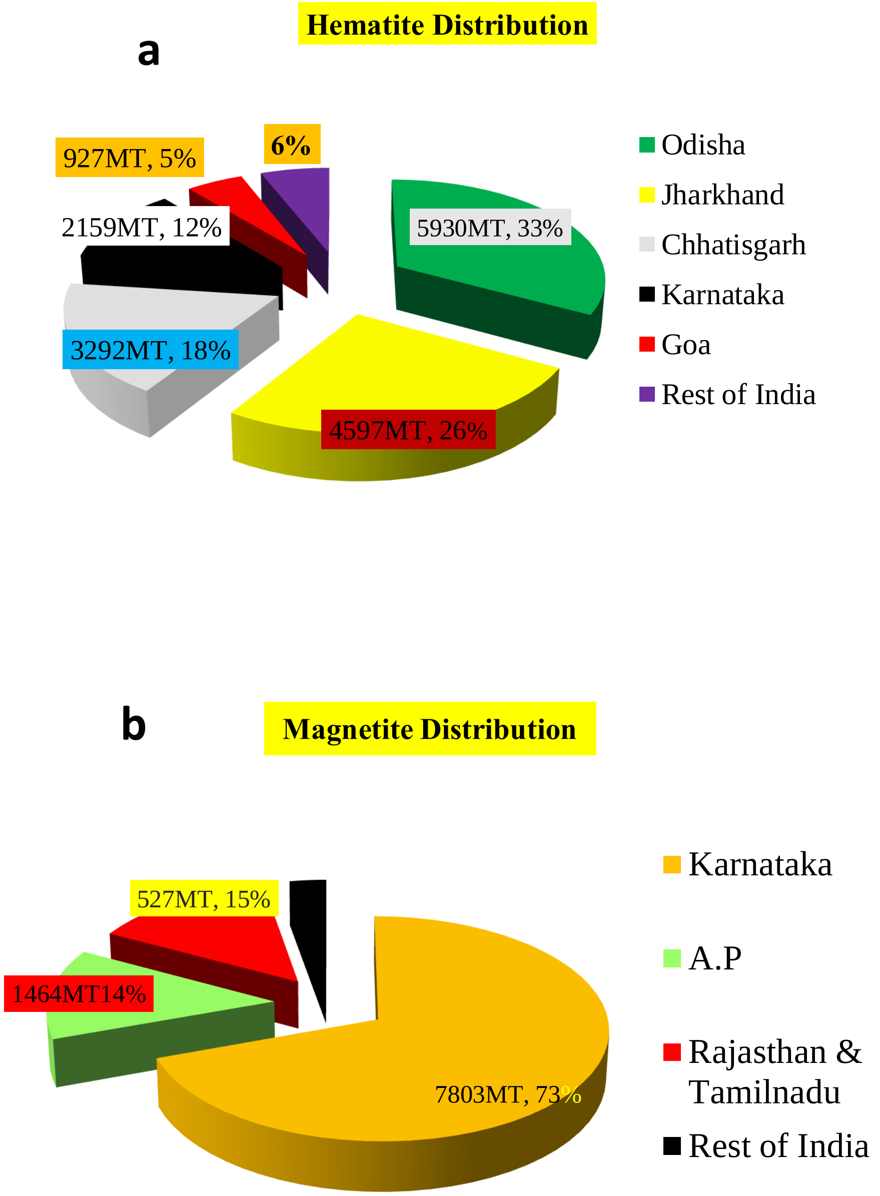


Fig.3.1 Graphical representation of (a) Distribution of Hematite ore in India (b) Distribution of Magnetite (Indian Mineral Year Book, 2011)

Fig 3.2(a) Total resources of Iron ore in India (Iron & Steel vision, 2020, IBM)

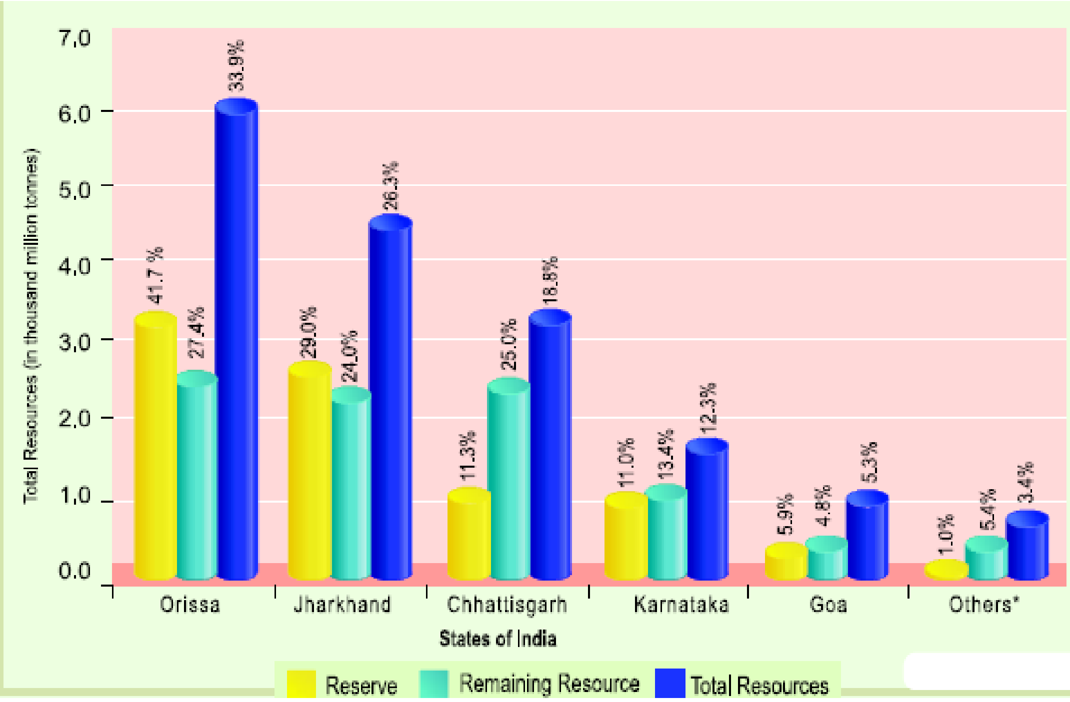


Fig.3.2 (b) State wise reserves & total remaining resources of Hematite.

The production trend of iron ore in public sector and private sector mines since 2007-2011 is given in Fig. 3.5a. Production has decreased from 218.6Mt to 208.1Mt in 2010-11 over the previous year. This decrease is more in private sector mines than in public sector. In 2010-11, the share of public and private sector production was 28% against 27% in the preceding year. The remaining 72% production in 2010-11 was from private sector. About 60% of production comes in the form of fines (including concentrates) during the course of mining operations itself. Further, 10-12% lumps become fines while handling, loading/unloading and while converting them into calibrated lump ore (CLO) for sponge/pig iron plants/exports. On an average 2.5 tonnes of run-of-mines (ROM) are required to get one tonne of CLO [146]. Another demarcation of iron ore production is between Captive and Non-captive mines.

Orissa is a leading producer state with the highest production, followed by Karnataka, Goa, Chhattisgarh and Jharkhand (Fig. 3.2b). It is also to be noted that out of the total production Captive mines are owned by SAILôs steel plants and the Tata Steel besides some other small companies. Out of the total ore production in the country, the non-captive mines produce is 78%, while the share of captive mines is only 22%. Of 208million tonnes in 2010-11, the iron ore lumps constituted 82.2 million tonnes or about 39.5% and fine product is 125.1million tonnes or about 60.2%.

The Working Group for 12th Plan, Planning Commission of India has estimated that the production of iron ore would be about 374 million tons by 2016-17 at 8% growth rate. The apparent consumption is estimated at 218 million tons by 2016-17 at 8% growth rate.

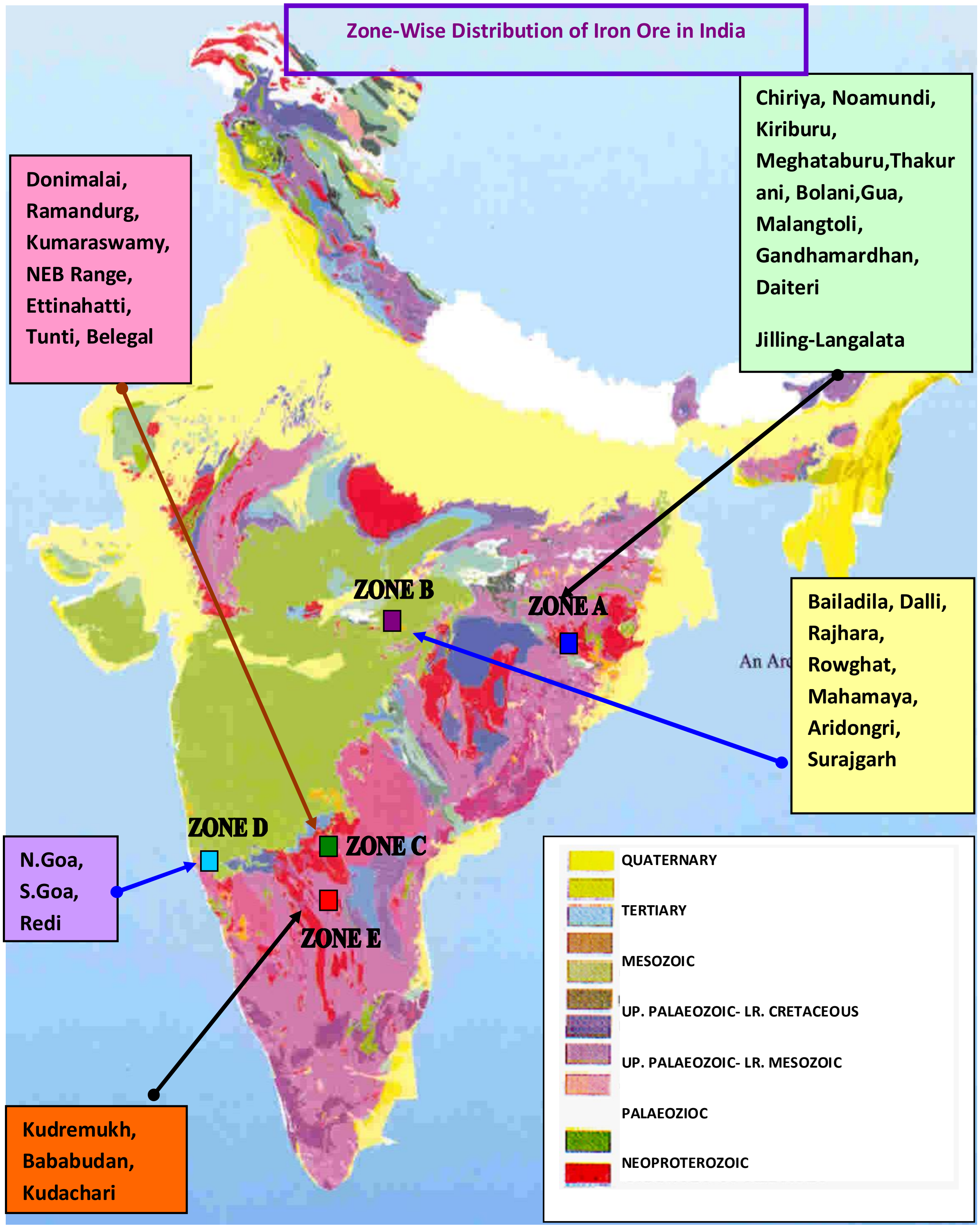


Fig. 3.3 Zone-Wise distribution of iron ore in India

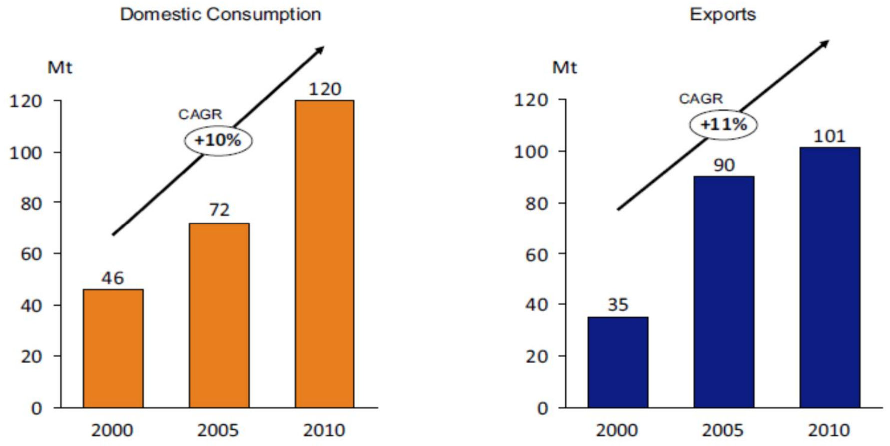
Grade wise analysis of the current yearӧs output reveals that out of total output of 208 million tonnes, iron ore lumps constituted 82.2 million tonnes or about 39.5%, fines 125.1 million tonnes or about 60.2% and concentrates 0.7 million tonnes or about 0.3% of the total output of iron ore lumps. About 23.8 million tonnes or 29.1% was of grade 65% Fe and above, about 30 million tonnes or 36.5% of grade 62% to below 65% Fe, 11.5 million tonnes or 14% was of grade 60% to below 62% Fe and the rest 16.9 million tonnes or about 20.5% of the production was of grade below 60% Fe.

In the case of iron ore fines, 17.2 million tonnes or 13.8% of the production was of grade 65% Fe and above, 53.9 million tonnes or 43.1% of grade 62% to below 65% Fe and balance 53.9 million tonnes or about 43.1% of grade below 62% Fe. Run off mine iron ore, range in size from less than 8 mm to 0.15 mm is designated as fines, whereas, the ore below 0.15 mm are known as slime and slimes are generated in the washing plant. About 70-75% of the total production of iron ore is fines which are generated either at the time of mining or become fines during subsequent handling or conversion of lumps into Calibrated Lump Ore (CLO) [144].

3.4 CONSUMPTION PATTERN

The level of per capita consumption of steel is treated as an important index of the level of socio-economic development and living standards of the people in any country. It is a product of a large and technologically complex industry having strong forward and backward linkages in terms of material flows and income generation. All major industrial economies are characterized by the existence of a strong steel industry and the growth of many of these economies has been largely shaped by the strength of their steel industries in their initial stages of development. Steel industry was in the vanguard in the liberalization of the industrial Sector and has made rapid strides since then the industry has moved up in the value chain and exports have raised consequent to a greater integration with the global economy.

In 2010-11 about 104.05 million tonnes of iron ore was consumed in various industries like iron and steel, sponge iron, ferro-alloys, alloy steel, coal washery and cement. The Iron & steel including sponge was the major consumer of iron ore and accounted for over 98% of its consumption.



Source: Metalytics.

Fig.3.4 Domestic consumption & export of Indian Iron ore.

Iron ore demand is linked with the production of crude steel. The steel plants of SAIL in the public sector and Tata Steel in private sector besides some small plants have their own mines for captive consumption. Another public sector steel plant is Visakhapatnam Steel Plant (VSP) which meets its total requirement of iron ore from NMDC mines located in Bailadila sector of Chhattisgarh state. The domestic consumption of iron ore is shown in Fig. 3.6a.

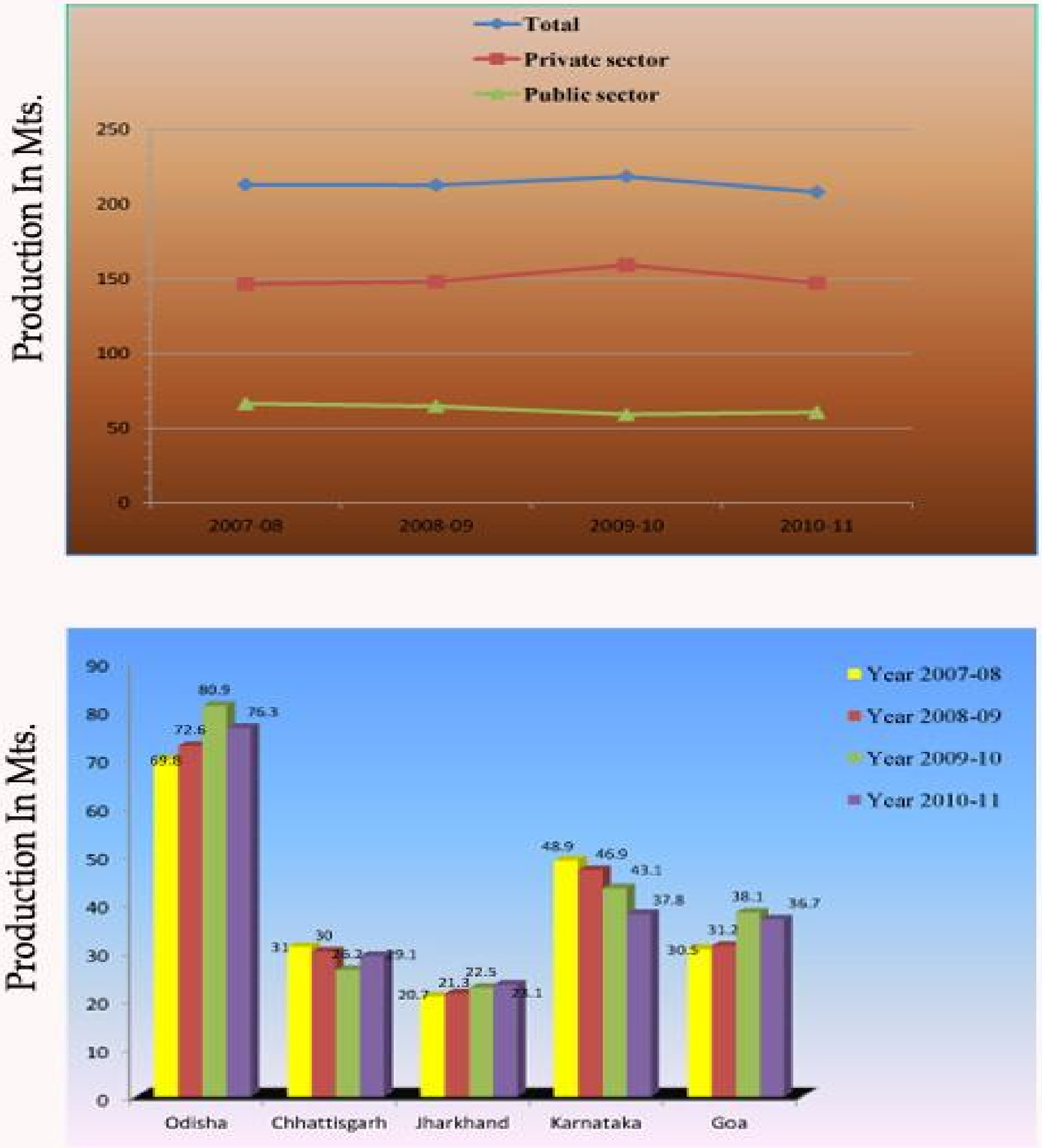


Fig.3.5: Graphical representation of (a) Sector-wise production of iron ore in India (b) State-wise production of iron ore in India (Indian Mineral Year Book, 2011.

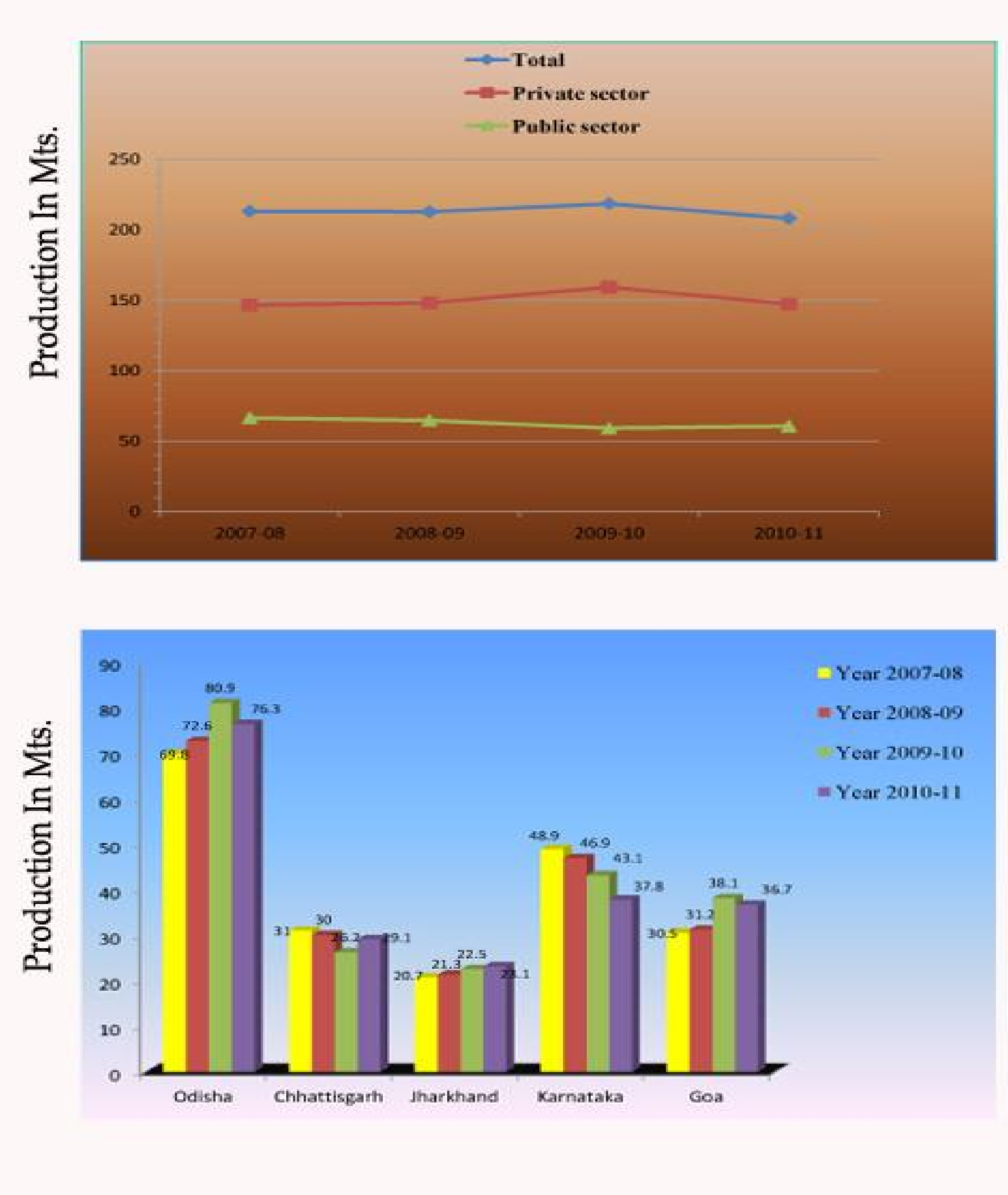


Fig.3.5: Graphical representation of (a) Sector-wise production of iron ore in India (b) State-wise production of iron ore in India (Indian Mineral Year Book, 2011.

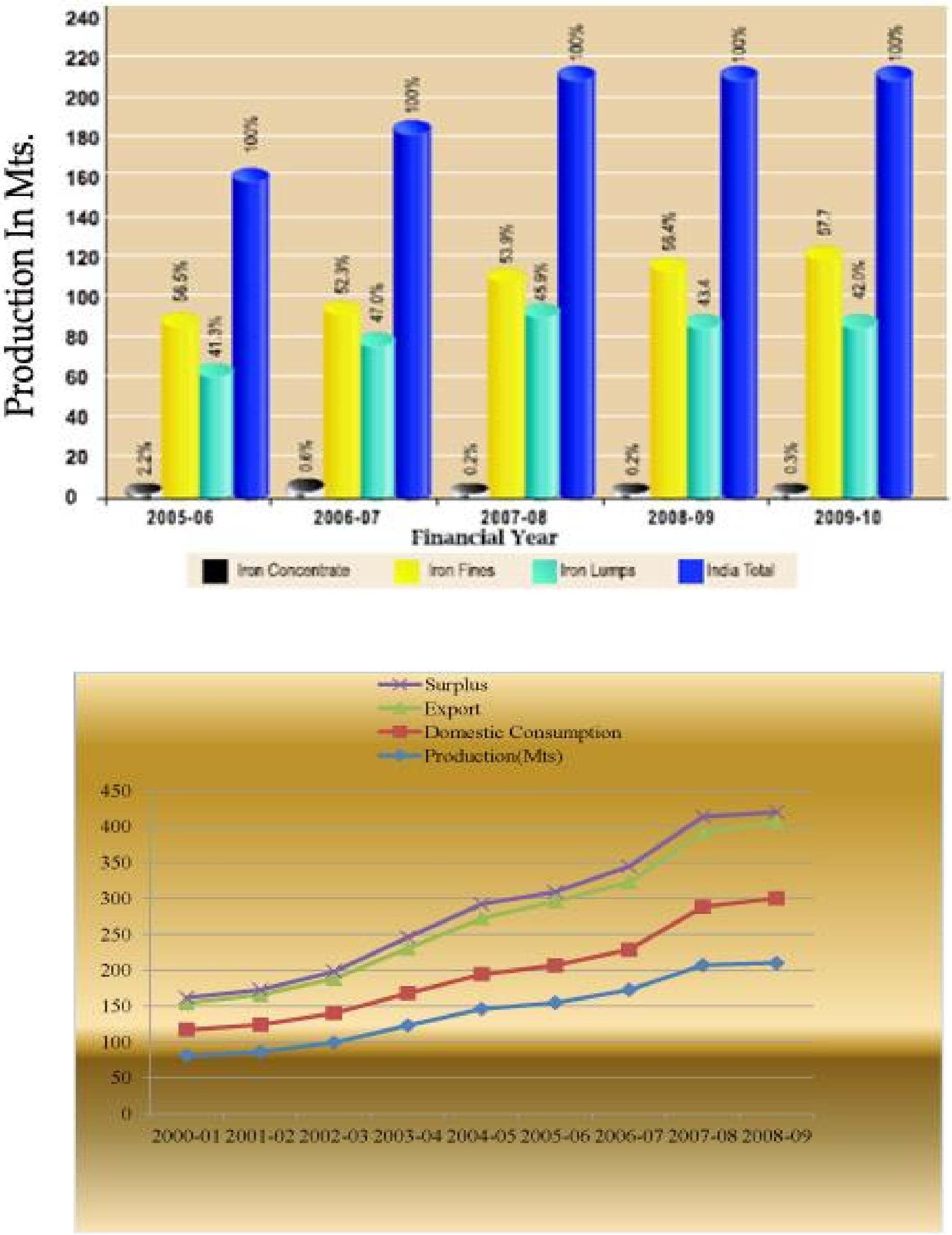


Fig. 3.6a Graphical representation of (a) Production, Consumption and Export of iron ores in India (b) Production of iron ore lumps, fines, concentrate in India (Iron & Steel vision, 2020).

3.5 FOREIGN TRADE

3.5.1 EXPORT:

Exports of iron ore decreased to 46.88 million tonnes in 2010-11 from 101.53 million tonnes in the previous year. In terms of value too, the iron ore exports rose to 21,416 crore in 2010-11 from 28,366 crore in 2009-10. The exports in 2010-11 in terms of volume comprised iron ore fines (92%), iron ore lumps (7%), and iron ore concentrates & iron ore pellets (1%). Exports were mainly to China (91%) and Japan and United Arab Emirates (3% each). If we consider last three financial years, 2008-09, 2009-10 and 2010-11, when the exports demand for iron ore increased from China, still there was a fall in export from 101.53 million tonnes to 46.88 million tonnes which in turn has increased the import of iron ore.

3.5.2 IMPORT:

Imports of iron ore were 1,867 thousand tonnes in 2010-11 as compared to 897 thousand tonnes in the previous year. The imports in 2010-11 comprised of iron ore pellets (60%), fines and non-agglomerated concentrates, etc. The iron was imported from Bahrain, Mali, Brazil and Ukraine. Import of iron ore was 69 thousand tonnes, 897 thousand tonnes, 1,867 thousand tonnes in the year 2008-09, 2009-10, 2010-11 respectively [52, 53]. The imports mainly comprise of iron ore pellets, fines, non-agglomerated concentrates and it was from countries like Bahrain, Brazil, Russia & Ukraine. The export of iron ore in the last nine years is given in Fig. 3.6a. Iron ore production grew gradually and export also increased but the percentage remained almost the same.

3.6 WORLD PERSPECTIVE

The developments in the Chinese steel industry have set the pace of iron ore mining globally. World production of iron ore exceeded 1 billion tonne for the first time in 2002 and 1520 million tonnes in 2005. Production has increased in all major iron ore producing countries. World marine trade of iron ore exceeded 600 million tonnes in 2005 and the same is likely to grow to 650 MT by 2007. Three largest companies viz. CVRD, Rio Tinto and BHP Billiton together control about 30% of the global production. Four companies viz. CVRD, Rio-Tinto, BHP Billiton and Mitsui account for 70% of marine iron ore trade. The world iron ore reserves and reserve base as estimated by U. S. Geological Survey (USGS) [144] are shown in Table 3.1.

Table 3.1: World iron ore reserves and reserve base as estimated by U. S. Geological Survey (USGS Mineral Commodity Summaries, 2013).

	Mine Production		Reserves	
	2011	**2012**	**Crude Ore**	**Iron content**
United States	55	53	6,900	2,100
Australia	488	525	35,000	17,000
Brazil	373	375	29,000	16,000
Canada	34	40	6,300	2,300
China	1,330	1,300	23,000	7,200
India	240	245	7,000	4,500
Iran	28	28	2,500	1,400
Kazakhstan	25	25	2,500	900
Mauritania	12	12	1,100	700
Mexico	15	13	700	400
Russia	100	100	25,000	14,000
South Africa	60	61	1,000	650
Sweden	25	25	3,500	2,200
Ukraine	81	81	6,500	2,300
Venezuela	17	20	4,000	2,400
Other countries	59	61	12000	6,000
World Total(rounded)	2,940	3,000	170,000	80,000

(Qty.: In Mts)

The World Steel Association estimated global crude steel production to be 1548 million tonnes in 2012, 1.2% up on the annual 2011 and the highest total ever. The amount of iron ore produced globally in 2011 was 1.92 billion tons, representing a 4.7 per cent increase from 2010[148]. World crude steel production reached 1,548 mega tonnes (Mt) for the year 2012, up by 1.2% compared to 2011. This is a record for global crude steel production.

3.7 STEELMAKING

Worldôs 80% steel making is through the blast furnace method and hence the role of iron ore as a raw material and its quality becomes very critical to obtain the best quality steel. High Fe content, low alumina and phosphorous contents in iron ore reduce this proportion. Hence, the quality of raw material plays an important role in steelmaking process. Although India is having vast reserves of iron ore, lack of consistency with respect to Al_2O_3/SiO_2 ratio makes these ores unsuitable to use directly in the metallurgical industries without prior beneficiation. It has also been established that the adverse effects of high alumina to silica ratio (ideally it should be < 1) is detrimental to blast furnace as well as sinter plant productivity [107]. Indian iron ores are being beneficiated by washing, scrubbing, hydrocycloning, gravity separation and magnetic separation. During sizing and washing operations the enrichment with respect to iron content is marginal and gangue reduction with particular reference to favorable Al_2O_3/SiO_2 is minimized. Concentration of alumina is the lowest in pure hard ore and blue dust and vice versa in lateritic ores. Indian iron ores consist of higher proportions of impurities in the form of alumina (Al_2O_3) and phosphorus (P). Their presence adversely affects the performance of blast furnaces and hence it is always preferred to maintain their level as low as possible [70]. The higher content of P increases surface cracking during steel making process at higher temperatures and also increases level of inclusions, which adversely affect the mechanical properties of finished steel [138, 141].

Small amounts of aluminum (Al) are present in many ores including iron ore, sand and some limestone. Aluminium is very hard to reduce. However, it does increase the viscosity of the slag [86, 87]. The thicker slag will slow the descent of the charge, prolonging the process and adding cost. Generally, iron oxide deposits must be low in aluminium (<1.5%) to be considered as a viable ore.

Hence, it is important to restrict the alumina and phosphorus inputs in the furnace through raw materials [139]. All the ore types contain silica as gangue in the form of quartz, clay in the form of kaolinite and alumina in the form of gibbsite.

Sulfur (S) is a frequent contaminant in coal. The typical balance of P and S comes from raw materials such as coke (65%), iron ore/sinter (25%) and fluxes/others (10%). The effect of even small amount of sulphur is immediate and serious. The degree of hot shortness (brittleness, usually of steel or wrought iron, when the metal is hot, due to high sulfur content) is directly related to the amount of sulphur present. Higher levels of alkalis lower the mechanical strength of coke and sinter in blast furnace. They create adverse impact on the descending charge due to re-condensation, cause imbalances in furnace stability and increase the RDI of sinter, resulting in higher generation of fines and lower productivity. Use of limestone with low alkalis (0.05%), use of imported coal from Australia with low alkalis (0.12ï 0.16%), use of dunite and pyroxenite sinter with low alkalis (0.05ï 0.1%), use of washed coal and low coke rate are some of the important measures taken for alkali control during steelmaking [139]. Another unwanted contaminant within raw iron ore is Silica. The problem here relates to the fact that Silica requires extremely high temperatures in order for it to be burned off. Therefore, the more silica that exists in the raw material, the more energy is used in producing the ore oxide. Silicon input in the blast furnace burden comes in the form of SiO_2 from coke ash (70%) and sinter and iron ores (30%). The desired level of silicon in the steel is 0.6%. Reduction of silicon from a concentration of 1.1 to 0.6% results in a reduction in coke rate by 14 kg per tonne of hot metal and increases the productivity by 2.5% or 0.035 tonnes m^{-3} per day in iron making through the blast furnace route.

3.8 INDUSTRY OUTLOOK –"IRON ORE"

Iron ore market had seen a paradigm shift since 2000 with emergence of Chinese industrial demand. In the first decade of the 21st millennium, China emerged as the largest producer of steel and consequently became the largest consumer of iron ore. Steel production dropped marginally in 2008 and about 8.1% last year on account of global slowdown. The demand, however, picked up this year once again due to China and it is estimated China alone needs more than 650 million tons of imported iron ore this year to feed its ever growing steel industry. Some of the vital and crucial challenges faced by the industry are mineral conservation, detailed geological studies of the deposits, availability of the land for waste disposal, poor quality (high contents of Al_2O_3 and P) of ores, poor infrastructure, and complicated and lengthy processes for statutory clearances. The following factors play key roles in mineral conservation strategies in India:

(a) Indian iron ore is relatively rich in Fe and contains significant amounts of silica, alumina and phosphorous compared to the other major deposits of the world.

(b) Huge quantity of slime generation during ore processing and their disposal. In order to produce 1 ton of lump ore, about 1.5 ton fines are generated of which only 0.5 ton are utilized. It is estimated that around 20 MT fines are lost every year.

(c) Difficulties in beneficiation of BHJ/BHQ due to due to non-availability of suitable technology.

(d) Safe disposal of mining waste/overburden in particular

(e) Environmental problems due to land degradation, pollution & deforestation.

CHAPTER- IV

LITERATURE REVIEW

REVIEW OF LITERATURE

The Precambrian greenstone belts and similar supracrustals are the main repositories of banded iron formation hosted iron ore deposits world over [26]. Origin of these iron ores is considered as the product of supergene enrichment processes [63, 78, 80] or hydrothermal mineralization processes [16, 98].

BIF has been reported from different part of the world. According to some researchers [48] the source of iron strongly doubtful, both continental and hydrothermal model have been put forward as likely for the source of iron and silica. Recently mid-oceanic ridge or hot spot style tectonic setting are also considered as a source of iron [48, 80]. The several giant and world-class ore systems were formed during intra-plate tectono-thermal and rifting events [92]. Iron was scavenged from the oceanic crust and re-deposited on the ocean floor by hydrothermal fluids, i.e., high temperature hydrothermal alteration of early Archean oceanic crust played an important role in the deposition of BIFs [94].

The Precambrian greenstone belts contain variety of geological information in different tectonic settings [30]. One of the important issues pertinent to the mantle evolution through time is to characterize the Archaean peridotites either of mantle origin or of crystallization product within the crustal greenstone sequence [78].

The famous iron ore bearing state Odisha comprises of three distinct iron ore bearing provinces encircling the North Odisha Iron Ore Craton (NOIOC) [18, 19, 20].

In 1903, eminent geologist, P. N. Bose discovered iron ore deposits in Gorumahisani hills in Mayurbhanj state and brought it to the notice of J.N. Tata in 1904. It was this foresight that led to the setting up of Tata Iron and Steel Company Tata Steel in the year 1911 which was the 5th largest steel industry in the world and 12th at present[145].

The Newer Dolerites occur in two distinct orientations (NE/SW and NW/SE) in the Singhbhum Granitoid Complex (SBGC). These dikes are mostly tholeiites and quartz-normative dolerites associated with subordinate norites [8].

The rich iron ore deposits of Mayurbhanj were investigated [33, 34, 35] and presented a divergent concept of older metamorphic. Results of the investigation presented in a memoir on the ñMineral deposits of Eastern Singhbhum and surrounding areasMost of the sandstone and conglomerates recognised [127] as the base of iron ore series were overlie at the top of that series and dolerite sills stated by him were actually lava flows. The stratigraphic and structural work in Singhbhum [115], found that iron ore series of South Singhbhum-Keonjhar-Bonai region is a low NE plunging synclinorium, overturned towards SE, the eastern limb of which remain normal. They opine that lavas underlie lower shales or BHJ.

The economic aspects were focussed [14, 36, 60] and ore geology of south Singhbhum and Keonjhar. There were evidences [69] that iron was initially deposited as magnetite dust in jasper bands which then remobilised and iron migrated towards pre-existing iron rich bands and precipitated in the form of hematite. Stromatolite in dolomite supports this in addition to suggesting limestone fence [112]. This has not found to develop in BIF-1 and marginally so in BIF-2.

Most of these Banded Iron Formation horizons belong to the oxide facies banded iron-formations as defined by Jones, where as the silicate facies banded iron-formations are locally developed [21]. Jones opined the chemical-sedimentary origin [68] of these Banded Iron Formations.

Due to the monomineralic composition of the ore, the genesis of these high-grade hematite ores remains controversial. Different depositional models have been proposed for the genesis of high-grade iron ores which include deep seated hydrothermal [134], syngenetic and diagenetic [60] varieties. Supergene enrichment followed by metamorphism is the most widely cited explanation for the genesis of high-grade hematite ores in Hamersley province [47, 79, 80, 81]. The Banded Iron Formation (BIF) and the associated litho types of the study area belong to youngest Iron Ore Group (BIF-III) of IOSG [4, 18]. The iron mineral in the basin is predominately oxide facies [56].

Although India is bestowed with large reserves of iron ore, a large amount of iron ores having high amount of impurities in the form of Al_2O_3 and SiO_2, make some of these ores unsuitable for direct use in the blast furnace [24, 53]. With the fast depletion of high grade iron ore and to cope with the increased industrial demand, the low grade iron ore in general, is being the focus of interest now. Beneficiating the low grade iron ore to remove the gangue minerals and enhancing its grade is a prospective proposition today.

Since the goal of every mineral processing operation/ technique is to effectively separate the valuable material from the gangue with minimum metal loss in tailings, the need to develop and employ a sustainable, effective and relatively economical method of separation is imperative. The concentration of the valuable minerals from the gangue involves exploitation of the differences in the mineral properties of the ore after effective comminution [84].

In order to increase the efficiency of blast furnace, some of the issues relating to Iron ores include chemical composition of Iron ore with low Fe content and high Al: Si ratio, low temperature softening and melting behavior of Iron ores, etc. Normally Iron ores with Fe content above 65% are desirable to achieve better productivity either in blast furnace or direct reduction. The other impurities level (such as Na, K, S and P) should be as low as possible [73]. Another problem is the utilization of huge amounts of iron ore fines and slimes which are not only a loss of the very important iron ore resource, but also pose severe long term environmental problems. The issue of the utilization of iron ore slimes, however, is fairly complex owing to the extremely small size of the individual mineral particles and has not met with great success until now. However, many of the other issues related to mineralogical characterization, physical liberation and mineral dissemination are common to the above stated problems. Enrichment of low grade iron ores always involves comminution in order to achieve mineral liberation and there by produce significant amount of ultra-fines which are difficult to concentrate.

The main difficulty in processing and utilization of lean grade iron ores originates from their compositional characteristics, soft nature of some of the ores and high alumina content as well. The composition of the Indian iron ores is typified by high iron content with relatively higher amount of alumina (as high as 10% to 15%). Alumina and Silica content should be within the permissible limit for better fluidity of slag which in turn reduces the coke consumption [67, 141].

The most common gangue mineral found in Iron ore is silica. It may be in the form of quartz/jasper. Silica is undesirable because silicon does not bond with carbon during the smelting process and can remain in the iron after it is refined. Modern steelmaking techniques generally use lime and other fluxes to help removal of the silica from the molten iron ore, and form slag on the surface of the molten metal.

Indian iron ores contain relatively high iron but cost effective reduction of alumina within the specified limits [124] has been a challenging task. Reduction of 1% alumina in iron ore improves blast furnace performance by 3%, reduction in reduction-degradation index (RDI) by 6 points leading to an improvement in productivity by 0.1 tonne per m^3 per day, lowers the coke rate by 14 kg per tonne of hot metal and increases sinter productivity by 10ï 15%, i.e. 800ï 1000 tonnes per day [106].

Alumina in general is associated with iron ores as clay/gibbsite. This is usually removed by washing the iron ore, and by fluxing the same. Generally, iron oxide deposits must be relatively low in alumina (<1.5%) in order to be considered as an ore. It would demand a higher temperature and more sintering time for attainment of satisfactory sinter strength at high alumina [11]. The sulfur problem is not much in case of Precambrian iron ores, as found in the study area, as it is generally associated with Tertiary iron ores [28].

Reduction of alumina [29] in the slime using classification followed by separation in a hydrocyclone was investigated. It was found that it is possible to obtain a product containing 64% Fe, 1.4% Silica and 3.5% Alumina from a feed assaying 57% Fe, 4% Silica and 8.3% Alumina. Several researchers have worked on alumina reduction focusing on flocculation techniques that met with variable degrees of success [43, 46, 66].

Gravity and magnetic separation processes have their own limitation in finer size ranges. Studies were conducted [55] on highly selective reagents to achieve satisfactory separation of hematite and goethite from alumina containing minerals (gibbsite or kaolinite) in the ore and slimes. They found, among all the reagents that starch exhibits the highest selectivity towards the hematite surface with a difference in interaction energy of 63 kcal/mol between hematite and gibbsite surfaces and polyvinyl pyrrolidone (PVP) to be more selective dispersant for kaolinite compared to conventional sodium silicate and sodium hexa metaphosphate.

Phosphorous is a deleterious contaminant because it makes steel brittle, even at a concentration of as little as 0.6% [141], where as the desired levels of phosphorous in hot metal vary from 0.08 to 0.14%. It cannot be easily removed by fluxing or smelting, and so iron ores must generally be low in phosphorus (0.08%) [138,141].

Sulfur is unwanted because it results in a decreased hot strength of iron and steel. Sulfur also increases SO_2 gas in the flue emissions from a smelter and interferes with the smelting process [88]. Today iron ore with 0.03% sulfur or higher is avoided.

India has vast deposits (1209 MT) of superior quality hematite ore, categorized as direct shipping ore, which just needs crushing and sizing to be used as metallurgical feed, such deposits are depleting at faster rate. Apart from such ores, India also has vast deposits of other low-grade iron ore, including banded iron formations like Banded Hematite Quartzite (BHQ), Banded Hematite Jasper (BHJ) etc. Such ores invariably have low iron content, even less than the cut-off grade of 45%. So, currently they are not being exploited in India. Apart from their low iron content, another problem with banded iron formations is intricate mixing of ore and gangue mineral grains, which results in optimum liberation occurring at sizes below 100ï 150 microns [9].

According to National Mineral policy projections, exploitation of low grade iron ore horizons like BHJ is necessary to achieve the zero waste concepts. BHJ assaying up to 40% Fe (T) has to be upgraded above 60%Fe (T) to use effectively during blending and direct sale. BHJ of Bonai region is considered as mother rock has its considerable reserves in India. At present large quantity of BHJ is being rejected at the mine site due to its high silica content. In order to beneficiate BHJ size reduction is needed [44] up to 50µm which reflects very intricate relationship between hematite and quartz and intergrowth patterns developed among ore minerals and gangue minerals. Gravity and magnetic separation equipment, namely, Floatex, gravity slime table [129] and wet high intensity magnetic separator (WHIMS) can be used for BHJ beneficiation. Their results indicate that it is possible to upgrade the sample by both gravity and magnetic separation techniques. However, the WHIMS results indicate that jasper grains report to the concentrate at higher gauss intensities. They studied the applicability of gravity spirals for beneficiating BHJ in the liberation size range of -0.150 mm. The test results indicate that it is possible to obtain a final concentrate assaying 65.75 per cent Fe and 4.75 per cent SiO_2 with a yield of 25.9 per cent and an iron recovery of 41.31 per cent.

Characterization of BHJ of Singhbhum craton for their beneficiation was studied [37, 40] and result show that it is not possible to get >60% Fe at coarser size (>1 mm size) as the silica minerals are finely locked with iron minerals. But, on grinding to liberation size of 100 micron (needs high energy for breaking in conventional grinding) and treating in fines beneficiation circuit, (preferably flotation, as the particles are non-sticky and easily settles and responds to surface response) it is possible to enrich iron content to >65%Fe.

Iron ore is being beneficiated all round the world to meet the quality requirement of Iron and Steel industries. However, each source of Iron ore has its own peculiar mineralogical characteristics and requires the specific beneficiation and metallurgical treatment to get the best product out of it. The choice of the beneficiation treatment depends on the nature of the gangue present and its association with the ore structure. Several techniques such as washing, jigging, magnetic separation, advanced gravity separation and flotation are being employed to enhance the quality of the Iron ore. Washing, jigging and classification are being carried out for the beneficiation of Iron ores in India.

The ever increasing need to utilize the slimes is being reflected in the shift in Steel production from basic blast furnaces to electric arc furnace technology. In the USA, around 40% of Steel is produced in electric arc furnaces by using Iron ore pellets. However the use of pellet in Indian Steel plants is very limited [73]. Lot of low grade Iron ore fines are generated during preparation of lumps, calibrated ores and sinter-fines. In addition to these fines, 10-15% of ore mined is generated as slimes and are discarded as tailings [89]. These fines and tailings are potential sources to produce pellet grade concentrate after suitable beneficiation [113].

During washing and sizing of the ore, slimes with less than 0.21 mm size are generated and discarded into the tailing pond [101].

Beneficiation and utilization of these slimes still remains as a challenging task. This low grade ore cannot be utilized due to low industrial value [102] and marketability a large amount of slime containing 48-62% Fe is also being generated yearly in the beneficiation plants spread all over the country.

The beneficiation of iron ore slime [98] produced from washing plants and tailing ponds of Kiriburu mines using wet high intensity magnetic separators followed by classification in hydrocyclone was studied. It was shown that a concentrate assaying 63% Fe and 3.3% alumina could be produced with an overall iron recovery of 56%. Pradip compared the efficiencies of different unit operations including Wet high intensity magnetic separation (WHIMS) and multi-gravity separator (MGS) and found that it was possible to produce concentrates, at least on a laboratory scale; assaying less than 2% alumina at an overall yield of around 50% from slimes feed analyzing 7-8% alumina. Another noteworthy observation was that the separation achieved in MGS is remarkably close to the theoretical yield predicted based on the sink-float tests. Multi-gravity separation is a useful technique for treating iron ore slime and it is particularly effective for reducing alumina. However, it is still not very successful commercially due to its low capacity.

The reverse flotation study of iron ore slimes [104] by using hydrocyclone followed by flotation was studied. The result shows that the desliming of the slime sample gave a product with a yield of 67.3% contains 60.6% Fe under best condition. It is shown that deslimed product on reverse froth flotation gave yield 46.9% containing 64.5% Fe which can be directly used as pellet feed.

Separation behavior of slime samples [73] collected from Barbil, Goa, Bailadila and Hospet region was investigated. The throughput of hydrocyclone during the experiments was 240 to 780 kg/hr. Classification in hydrocyclone followed by spiral concentration for iron ore slime collected from washing plants [129] and tailing ponds of Kiriburu mines was investigated. The results show that it is possible to raise the iron content up to 64.17% at a yield of 37.3% with a decrease in the alumina content to 1.17%.

The beneficiation prospect of Lateritic ore from Nuamundi was studied [100] and found that the sample contains huge quantity of goethite which is partially weathered, interlocked with hematite and gangue minerals like gibbsite, kaolinite and quartz at different proportions. Mineralogical studies revealed that the concentrate product quality depends on presence of the goethite in the product. Basing up on mineralogical studies, they designed two flow sheets for beneficiation of Lateritic ore. One comprises of classification followed my gravity separation and second one with similar approach but the gravity concentration replaced by magnetic separation. They found that the second flow sheet is more effective.

Iron ores across the globe are being beneficiated by several techniques such as the shaking table, jig [91] and spirals, selective dispersion flocculation methods [96]. Separation processes based upon the surface-chemical differences between iron and alumina containing minerals, for example froth flotation and selective dispersion/flocculation are promising [59]. Gravity concentration using Wilfley Table is a powerful technique for the recovery of fine iron minerals. Many theoretical and experimental investigations of Wilfley table have been reported [39, 71, 72, 126]. Tabling efficiency is quite high when the specific gravity difference between the valuable and gangue minerals is high. In addition, magnetic separation [136] may be preferred, depending on the ore characteristics [61,131, 132, 133]. Floc-magnetic separation process is also reported for the processing of fines [10, 127]. Magnetic separation and flotation are the most widely accepted technologies for upgrading iron ore particles, but these processes result in iron concentrate with high amount of very fine and/ or interlocked silica particles [148]. It was found that flotation [135] is incapable to treat mixed-phase (middling) and weakly hydrophobic particles. To overcome this problem and to achieve a higher iron ore recovery, several new attempts and technologies are being developed with an added aim of achieving economical and environmental benefits through use of the jigging method [49, 38]. Upgrading of iron ore by jigging has been an emerging trend [82]. Flotation is also used for the beneficiation of finely grained ores [99]. The success rate of these conventional methods in fine particle size range is very limited as it depends upon the liberation particle size which in turn causes loss of fine iron ores into tailings.

Flotation is one of the most important methods applied for the separation of mineral fines whose success critically depend on the degree of liberation of various phases present in the ore. Most of the countries producing iron ore use this technique as an effective beneficiation process to upgrade the iron values [74]. Direct anionic flotation or reverse cationic flotation routes are generally employed using fatty acids or amines as the respective collectors [99,143]. Usually cationic collectors are employed for ores bearing silicates and quartz, whereas anionic collectors are used for the beneficiation of iron and phosphorus bearing minerals.

The problems associated with surface-based separation processes such as froth flotation may be overcome by using several enhanced gravity separators recently developed in the mineral processing industry [64]. Notable examples of the units include the Falcon Concentrator, Kelsey Jig, Knelson Concentrator and Mozley Multi- Gravity Separator [137]. All of these units are water-based devices which use centrifugal forces to improve the separation of fine particles based on differences in density.

Surface property-based separation processes such as froth flotation and agglomeration are very selective in rejecting well-liberated mineral matters [114]. However, efficiency of these processes gets reduced if the feed contains disproportionate amount of composite particles. Surface based separation processes are very intricate**,** need close attention and careful operation where as the conventional gravity-based separation techniques like spiral concentrator, water only cyclone or dense media cyclone have all been found to be inefficient for treating ultra fine particles in terms of selectivity and recovery [64].

Conventional gravity methods have limitations in processing very fine material and in removal of aluminous impurities. Falcon concentrator, one of the enhanced gravity separators (EGS), can generate high óGô force up to 300 which can effectively separate very fine iron particles from the aluminous clayey particles. Over the last decade, EGS have found wide acceptance to mineral industries for concentration of fines and ultra-fine minerals in particular to precious metals such as Au, Ag, Pt [128].

The new genre of enhanced gravity separators overcome the problems associated with the surface-based separation processes as well as conventional gravity processes. A Falcon concentrator is a spinning fluidized bed concentrator, which is a combination of sluice and continuous centrifuge [114]. It enables the treatment of particles in the size range of 15-20µm.

The major advantage of enhanced gravity separation is its ability to reject composite particles more efficiently than flotation [143]. Among the enhanced gravity separators, the KCJ is very promising due to its higher production capacities and utilization of less plant area. The KCJ is successfully demonstrated for the concentration of tin, mineral sand, gold, platinum ores and iron ore slime. The Kelsey jig is an appropriate substitute to the conventional jig with some basic similarities [123]. The parameters of conventional jig are entirely utilized along with additional features to vary the apparent gravitational field. The ability to increase the apparent gravitational field enhances the chances of recovery of fine particles by improving their settling characteristics.

The low grade iron ore sample from Gua region was studied [104] and found that the ore is mostly hematitic in nature and considerable amount of goethite/limonitic material is also present in it. The major impurities were quartz and clay and iron bearing phases are poorly liberated above 300 εm and the liberation improves below 300 εm. More than 80% liberation is achieved below 106 εm. Based on the liberation data, ROM was crushed followed by grinding and deslimed. The underflow was subjected to various beneficiation techniques such as tabling, enhanced gravity separator (EGS), wet high intensity magnetic separation (WHIMS) and flotation. All these above methods were able to produce pellet grade concentrate with iron content of 64.5%, however, a marginal higher yield was observed for WHIMS (81%).

The iron ore slime from Goa region was studied. It predominantly consists of goethite with subordinate hematite. The major gangues were reported in the form of ferruginous clay and quartz [25]. Since most of Indian plant tails are aluminous, selectivity of flotation is rendered difficult. Hence, the processing of iron ore slimes by magnetic separation seems attractive. The slime was crushed, scrubbed in log washer followed by classification in screw classifier. The classifier O/ F was subjected to hydrocyclone followed my magnetic separation in Longi VPWHIMS. The result shows that the deslimed -0.1 + 0.01 mm fraction could yield marketable concentrates assaying > 62% Fe with 25-30 wt% yield, increasing production by 5-6%, reducing the load on tail pond by 25%. Longi WHIMS was found to be a viable alternative for traditional WHIMS.

Mineralogical characterization both qualitative and quantitative of iron ore is a very important and basic aspect that has to get due attention before any attempt for its processing and has become almost inevitable these days because of the increasing demand of the ore. Mineral processing technology is evolved to separate and recover ore minerals from gangue in a commercially viable method and is mainly based on the process of mineral liberation and the process of mineral separation. Therefore, it is important to first get a clear understanding about ore- and gangue minerals.

Indian iron ores are soft in nature accounting for around 58% Fe. The ratio between alumina and silica is more than one which is attributed to the association of iron bearing minerals with finely disseminated gangues may be in the form of silica/alumina. Presence of clay mineral like kaolinite, gibbsite contributes alumina [15].

The blast furnace route of iron making is predominant in India. It has been established over the years that the productivity of blast furnace increases and energy consumption decreases by using superior quality of raw materials. 1% increase in iron content improves the productivity by 2% and reduces the coke consumption by 1%.

Indian hematite though rich in Fe, but the alumina: silica ratio (1.5 to 3.0) for lumpy ore is detrimental to blast furnace as well as sinter plant productivity and should be less than 1.5 and preferably below 1. In the blast furnace, 1% increase in alumina content increase coke rate by 2.2%, a decrease in productivity by 4% and an increase in flux consumption by 30kg/t of hot metal production.

It has now been established both in laboratory and plant trials that alumina has an adverse effect on sinter properties like Reduction Degradation Index (RDI). According to one estimate, a decrease in alumina content in the sinter from 3.1 to 2.5% will improve RDI by at least 6%, lower blast furnace coke rate by 14 kg/ t of hot metal and increase its productivity by about 30% under Indian operating conditions. Under these circumstances RDI is even more important.

4.1 SET BACKS

I) Banded iron-formations were created when solutions of iron oxides and silica precipitated in alternating layers. The iron oxides form hematite and/or magnetite; the silica forms chert. Iron and silica were supplied by volcanic activity common during the Precambrian period. The deposits accumulated to form distinctive gray (iron oxides) and red bands, hence the name "banded iron." Banded iron deposits constitute the largest source of iron ore now being mined in the United States and the world. A key question in the enigma of BIFs concerns the genesis of the characteristic alternating iron-rich and silica-rich bands. Itôs very hard to believe that such periodicity can be attributed solely to variations in iron and/or silica influx.

II) The deep-marine depositional environment construed for most BIF deposits. What could be the mechanism of transporting iron in itsô soluble form and subsequently precipitating it, on a regional scale, out of solution?

4.2SCOPE OF THE REASEARCH

The rapid mobilization of the primary earth resources, non- renewable resources in particular cannot be reversed or stopped, even slowing down will have a wide repression in mineral trade, industry and in the economy of a developing country like India.

The present statistics of total reserves are not encouraging. Therefore, the total remaining resources should be converted into reserves by accelerated exploration activities to minimize the demand supply gap as well as to achieve necessitated desired growth. This activity requires certain gestation period for its reality. Only harnessing the high grade ore, our countryôs reserves will deplete in less than 40 years. So in the coming years, a good utilization plan has to be synthesized for the available iron ore.

The overall situation suggests that for Indian steel industry, in this backdrop, the readily available sub-grade resources falling in between threshold value and saleable grade should be utilized. These constitute the potential sources for producing usable grade iron concentrate after beneficiation which needs to be exploited on priority. This processing will not only utilize existing discard material for recovery of valuable but also conserve limited high-grade lumpy hematite reserves in the country. The only way to utilize all types of iron ore within the country and add value to our valuable non-renewable resource is by bringing in new mining, beneficiation & agglomeration technologies. In the present research, much care has been taken in co-relating the characterization data with processing data in order to formulate the most suitable beneficiation route in terms of grade and recovery.

CHAPTER V

MATERIALS & METHODS

MATERIALS AND METHODS

5.1 MATERIAL DETAILS

The study of the different iron ore samples collected from the two localities i.e. Jhiling & Barsua are the main focus of this research project. Different samples collected from outcrops, sections, mine faces and drill cores of the Barsua & Jilling-Langalata iron ore deposits were characterized in respect of their physical, mineralogical and chemical properties and aspects of possible up gradation have been attempted. The different samples include banded hematite jasper, siliceous blue dust, goethite-lateritic ore and iron ore slime.

5.2 METHODOLOGY

- Thorough literature and patent search of various methods and practices of iron ore beneficiation including comminution, classification, gravity and magnetic separation, froth flotation, dewatering and agglomeration
- Collection of data on geology and mineralogy of iron ores from Jilling-Langalata and Barsua- Kalta deposits of eastern India.
- Processing and interpretation of chemical data.
- Major and trace minerals using X-ray Fluorescence Spectrometry (XRF)
- Mineralogical characteristics have been established for the lump ore and the slime. Detailed ore microscopy, image analyzer, Scanning Electron Microscopy- Energy Dispersive Spectroscopy (SEM-EDS) and X-ray Diffractometry (XRD) have been used in the characterization of different types of iron ores and slimes and accordingly the processing parameters designed accordingly.

5.2.1 MINERALOGICAL ANALYSIS

Mineralogy of the various samples has been established by synthesizing the integrated results brought out by the following instrumental methods:

5.2.1.1Optical microscopy

Mineral identification is the most important aspect that is needed to be carried out prior to beneficiation. The basic instrument for mineral identification is an optical microscope. The polished surface types of ore samples were prepared using araldite in a mould to study under reflected light microscope. The samples were polished by conventional polishing techniques, cleaned ultrasonically and examined under Orthoplan Microscope (Leitz make). The mineralogy, texture, microstructure and inclusions etc. in respect of ore samples were studied by this method [45].

5.2.1.2Electron microscopy

Unlike optical microscopy where light is the source for image formation. In electron microscope, the image formation is due to the scattering of electron beam scans over the sample. In general, this study i) brings out the size, shape and micro morphology of minerals and iii) their textural patterns.

For Scanning electron microscope (SEM) study, the sample was degreased and dried then cleaned ultrasonically with acetone. After cleaning the sample was blown by using a compressed gas. Samples were compressed into small disks for mounting. Carbon tapes by an ion sputtered JFC-1100 was used for this purpose. The powder sample was sprinkled lightly with a spatula, pressed lightly to seat and then studied under a Japanese make electron microscope (JEOL JSM-6480LV). For this, the working height was kept at 15mm with working voltage ranging between 10 kV to 20 kV. For EDS, polished samples were taken and examined at 15 mm working height. The working voltages for study was kept at 25 kV with beam current 100 nA. By this technique, Energy dispersive spectra (EDS) spectra of individual sample showing the semi-quantitative abundance of major and minor elements was brought out.

5.2.1.3 X-ray diffraction

X-ray diffraction technique (XRD) was extensively used for identification of various mineral phases especially the clay minerals and gibbsite for assessing the abundance of each phase in an ore sample. The XRD was carried out using PANalytical X-ray Diffractometer, MODEL D500 having automatic receiving slit, divergence slit, and graphite mono-chrometor assembly. Cu, KŬ radiation operating at 40 kv and 20 nA was used for this purpose. A diffraction pattern recording the angle 2ɗ against the intensity was obtained over a range between 10ę to 70ę corresponding to d- values between 20 A and 1.34A. The scanning rate was 2ę per minute with recorder full scale set in to 2 X 10^3 counts. Each mineral phase exhibits a characteristic reflection peak corresponding to its d-values. These of D values were matched from the [57] and various minerals were identified. Further the variations in the peak intensities of different mineral phases in the ore sample indicate their relative abundance.

5.2.1.4 Zeta Potential

In flotation, the response of many minerals is often dramatically affected by p^H .Adsorption of collectors and modifying reagents in the flotation of oxide and silicate minerals is controlled by the electrical double layer at the mineral-water interface. In systems where the collector is physically adsorbed, flotation with anionic or cationic collectors depends on the mineral surface being charged oppositely. Adjusting the pH of the system can enhance or prevent the flotation of a mineral. Thus, the Iso electric point (IEP) of the mineral is the most important property of a mineral in such systems but raising the pH sufficiently above the IEP can repel chemisorbing collectors from the mineral surface. Zeta potentials can be used to delineate this interfacial phenomenon.

5.2.2 CHEMICAL ANALYSIS

The objective of chemical analysis was to determine the chemical composition of the different ore types by different established techniques and distinguish the characteristics of one from the other by chemical means. The major, minor and trace constituents in different samples were taken up by wet chemical methods and using different instrumental techniques such as XRF.

5.2.2.1 X-ray Fluorescence

Major and minor constituents of various slag samples were analysed by XRF spectrometry on Phillips (PW-1400) X-ray spectrometer with Scandium and Rhodium targets using pentaerythritol (Al, Si), Thallium Acid Pathalate (Na, Mg), Germanium (P) and Lithium Fluoride (for heavier elements) as analyzing crystals in vacuum medium. International and in-house standards of appropriate compositions were used for calibration. Both major and minor elements were determined by pressed powered pellet technique. The specific gravity of iron ore samples was measured using picnometer by the standard method.

5.3 BENEFICIATION UNIT OPERATIONS

5.3.1 Crusher and grinder

Crushing is the first mechanical stage in process of comminution in which the main objective is breakage of the material to the required size for effective liberation of valuable minerals from the gangue. Grinding is the last stage in the process of comminution; in this stage the particles are reduced in size by a combination of impact and abrasion. For this study, size reduction was done in a jaw crusher with opening size of 50/25 mm followed by roll crusher with opening size of 10/6mm. The crushed material was charged to batch type ball mill. The operating conditions were (i) weight of the crushed material = 2kg, (ii) weight of the ball charged = 5kg, (iii) duration of grinding = 20 minutes, (iv) rotation of cylinder = 20 rpm.

5.3.2 Hydrocyclone

Hydrocyclones are continuously operating classifying devices that utilize centrifugal forces to accelerate the settling rate of heavier particles. It is one of the most important devices used in the mineral industry. Hydrocyclone operates under variable pressures [146]. It consists of a conically shaped vessel, open at its apex, or underflow, joined to a cylindrical section, which has a tangential feed inlet. The top of the cylindrical section is closed with a plate through which passes an axially mounted overflow pipe. The pipe is extended into the body of the cyclone by a short, removable section known as the vortex finder. The feed is introduced under pressure through the tangential entry which imparts a swirling motion to the pulp.

The centrifugal force developed accelerates the settling rate of the particles thereby separating particles according to size, shape, and specific gravity. Faster settling particles move to the wall of the cyclone, where the velocity is lowest, and migrate to the apex opening. Due to the action of the drag force, the slower-settling particles move towards the zone of low pressure along the axis and are carried upward through the vortex-finder to the overflow. The hydrocyclone used for this investigation was of Richard Mozley.

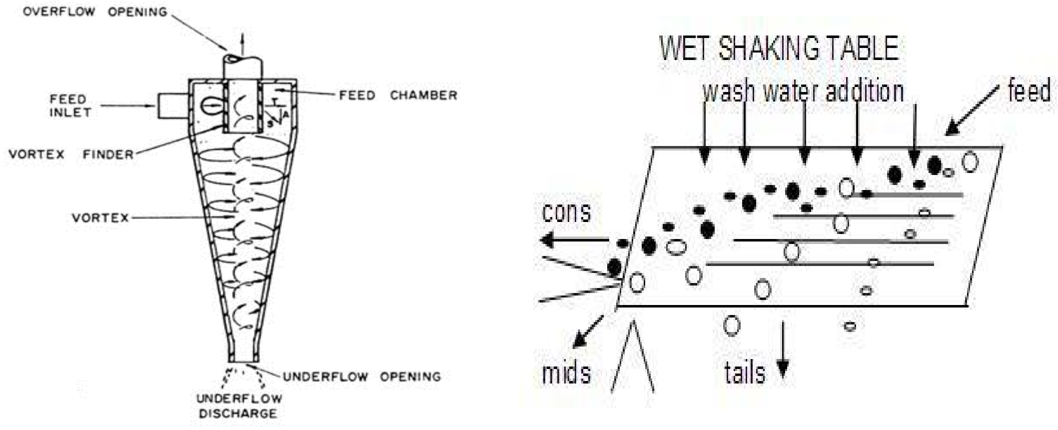


Fig. 5.1.1 Schematic diagram showing different zones and the flow pattern of (a) hydrocyclone (b) wilfley table.

5.3.3 Wilfley Table

Shaking table utilizes flowing film concentration. The flowing film effectively separates coarse light particles from small dense particles. The equipment used for this study was of Carpco, USA make. The unit was driven by a 440 V, 3 phase motor.

5.3.4 Jigging

Jigging is one of the oldest methods of gravity concentration. In the jig the separation of minerals of different specific gravity is accomplished in a bed which is rendered fluid by a pulsating current of water so as to produce stratification. The aim is to dilate the bed of material being treated and to control the dilation so that the heavier, smaller particles penetrate the interstices of the bed and the larger high specific gravity particles fall under a condition probably similar to hindered settling.

5.3.5 Wet High Intensity Magnetic Separator

The magnetic separation was conducted in Wet High intensity Magnetic Separator (JONES-P40, Germany). The variables include: slurry density, feed rate, flow rate of wash-water, field intensity. The field intensity is adjusted depending upon the susceptibility of the minerals to be treated. The ground material in the slurry with about 10 - 15 % solids is fed through a funnel. The magnetic particles are retained in the matrix and the non-magnetic particles are discharged and collected separately. Additional wash-water is added to wash the magnetic particles. The operation is continued till the non-magnetic particles are completely separated. At the end of the operation, the magnetic particles are collected separately. The parameters for the separation are fineness of the material, feed rate, quantity of wash water and field intensity.

5.3.6 Falcon Concentrator

The material is stratified according to specific gravity and then passed over a concentrate bed fluidized from behind by pressure water. The fluidized bed is required to retain coarse particles. Initially the design considered non-continuous operation, but with the years the design was improved and this centrifugal concentrator can work in continuous or not. There are several types of equipments to each need. The equipment functions and rising cycle are automated with variable frequency drive device.

Generally, the higher the field or the stronger separation gravity forces between different particles of different density, the more fast and efficient is the separation. Within limits, an enhanced gravity concentrator can treat more material and recover finer particles if it is spun faster. Falcon concentrator is to produce centrifugal fields of 100g. The equipment can change this value if the unit is equipped with a variable speed motor. Concentrating surface area is the single most important determinant for enhanced gravity concentrator. The bowl has a high depth to diameter ratio when compared to other designs which means that for a given bowl diameter, Falcon has a higher unit capacity. It is not necessary to spin the concentrating surface to apply the enhanced gravity fields, it is also necessary to accelerate the slurry. If the valuable particles must travel through a thicker flowing film, they will need more time to reach the zone where they will be concentrated in the fluidized bed. The smaller the flow of fluidizing water required, the less likely this water will transport fine particles away from the retention zone. The holes through which the fluidization water is injected in the Falcon concentrator are perpendicular to the axis of rotation. This consideration significantly reduces the tendency for holes plugged with solids from the slurry being processed. The retention zone is deep enough to allow the fluidization water holes to be larger and more widely spaced. Beneficiation study was undertaken on iron ore sample using a Falcon concentrator, Model SB-40, Falcon Inc, Canada.

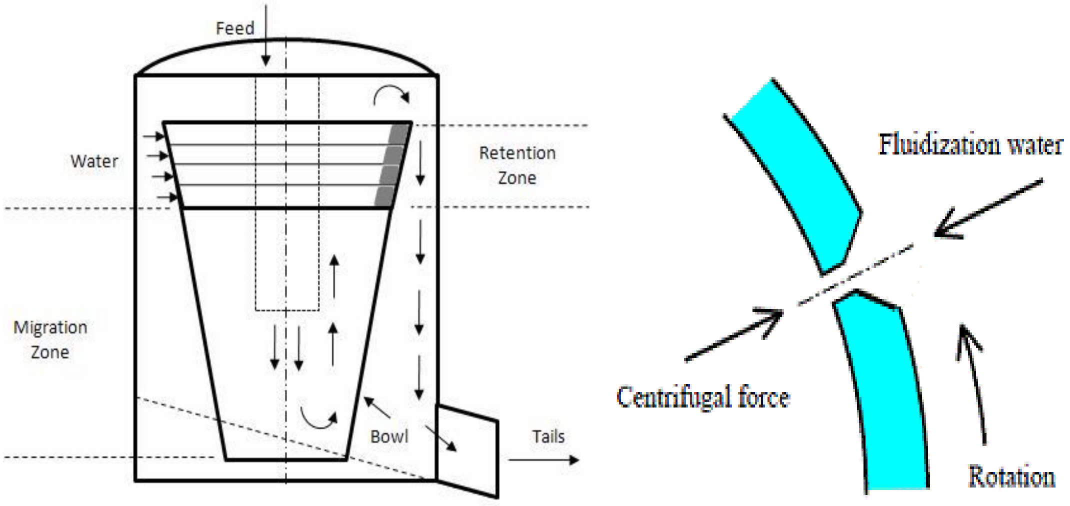


Fig. 5.1.2 (a) Schematic & Various zones of Falcon Centrifugal Concentrator (b) Fluidization Water Injection in Falcon concentrator.

5.3.7 Kelsey Jig

The new genre of enhanced gravity separators overcome the problems associated with the surface-based separation processes as well as conventional gravity processes. The Kelsey Centrifugal Jig (KCJ) works on the separation principles of a conventional jig employing a centrifugal force field. A much higher G-force (80-100 G) is obtained enabling the treatment of particles between 5 and 500 εm. It is apparent for very fine minerals, as the enhanced field significantly reduces the effect of forces that hinder finer particle separation. A schematic of the KCJ is shown in Fig. 5.1.3.The separation efficiency of the KCJ depends upon several factors which include (i) spin frequency (ii) pulsation frequency (iii) nature of ragging material(usually selected on the basis of density that is intermediate of that between the valuables and gangues to be separated) (iv) the ragging bed thickness (v) the feed flow rate (vi) hutch water (required to maintain uniform bed fluidization in conjunction with the pulse frequency but wash fine heavies to tails if excessive) addition as well as (vii) the screen opening. The interaction among these factors is very complex in nature which renders the process extremely difficult to describe from a theoretical or modeling standpoint.

The KCJ is fed down a fixed central pipe and the feed slurry is distributed at the bottom of the bowl, which flows upwards over the surface of a bed of ragging material supported by a cylindrical screen. The screen is spun coaxially with the rotor and pressurized water is introduced into a series of hutches behind the screen [125]. Water is pulsated through the ragging bed, which helps in stratifying the feed as well as dilating the ragging bed. Particles with specific gravity greater than or equal to that of the bed of the ragging material pass through the ragging bed. The principles of differential acceleration hindered settling, and interstitial trickling hold [137]. The differential acceleration rates are substantially enhanced by the higher apparent gravitational forces arising out of the rotation. The denser particles pass through the internal screen to concentrate hutches and then through spigots to a concentrate launder. The lighter particles are swept away by the rising flow and are discharged over a ragging retention ring into the tailing launder as shown in Figure. 5.1.3. A laboratory Kelsey Jig (Model No.J200 supplied by Roche Mining) was used in the study. The influences of spin frequency, pulsation frequency were investigated.

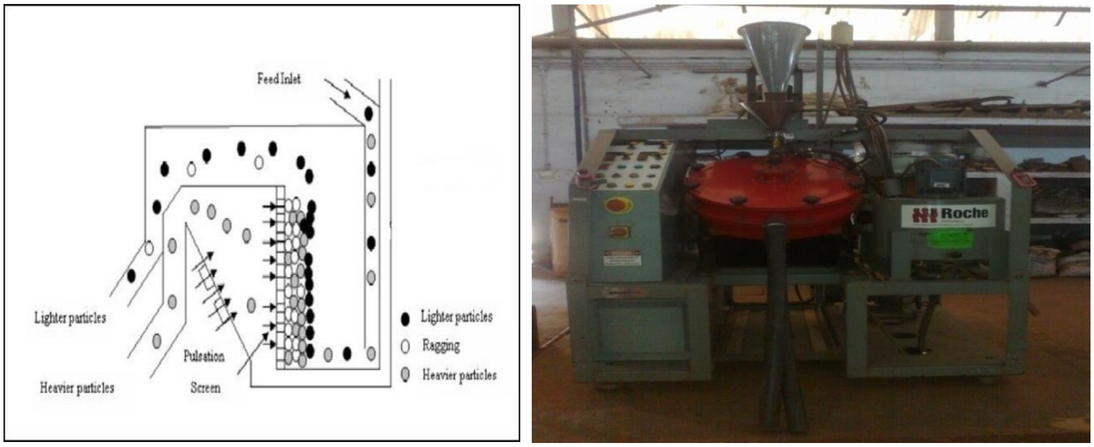


Fig. 5.1.3(a) Schematic of Kelsey Centrifugal Jig (IMPC, 2012) (b) Kelsey Centrifugal Jig set up at National Metallurgical Laboratory, Jamshedpur

5.3.8 Flotation cell

All flotation tests were performed in a 2.0 litre Denver D-12 Sub-aeration flotation cell. Time dependent concentrates were collected till the differences in cumulative weight of the concentrates became nominal. Most of the tests were carried out for 3 to 4 minutes. MIBC is used as frother; sodium oleate is used as collector and sodium silicate as depressant. pH of the pulp was measured by ORION 720-A pH80 meter.

CHAPTER VI

CHARACTERISATION OF IRON ORE

CHARACTERIZATION OF IRON ORES

Mineralogical characterization of iron ore is a very important and basic aspect that has to get due attention before any attempt for its processing and has become almost inevitable these days because of the increasing demand of the ore. Mineral processing technology is evolved to separate and recover ore minerals from gangue in a commercially viable method and is mainly based on the process of mineral liberation and the process of mineral separation.

Therefore, it is important to first get a clear understanding about ore- and gangue minerals. From mineral processing point of view, it is important to identify the ore and gangue minerals (mineralogical study), and their textural relationships (grain size, grain boundary relationship, intergrowths etc.). Geometric information obtained from the textural analysis greatly influences the liberation of gangue minerals from the valuable minerals in the optimum size range during comminution [27]. An effective liberation of gangue minerals and ore minerals influences the optimum separation efficiency.

Ore characterization study can provide critical information that will either assist in the development of a new processing flow sheet or the optimization of an existing one. Ore characterization relates to physical, chemical and mineralogical properties of raw materials to their behavior during their processing such as comminution, physical beneficiation as well as their hydrometallurgical processing. Practical processes for the efficient recovery of metals and minerals from ores are a fundamental requirement for the health of any industry.

The principal objective of the beneficiation is to separate and recover ore minerals from gangue in a commercially viable method and mainly based upon the process of mineral liberation and the process of mineral separation. It has been commonly asserted that the second step is impracticable if the first has not been successfully accomplished [90]. Even though the ore is mined with the highest efficiency of the technology, the excavated ore gets partly contaminated by the surrounding host rock (overburden) and the geological material closely associated with the ore during mining. Both the materials are undesirable and hence form gangue. The knowledge of occurrence of such detrimental elements is helpful to delineate the plan in advance for their removal [108].The mineralogical studies would also reveal the differences in the physical properties, which are relevant to their separation by physical means. The presence of a large number of fissures, voids, crack and joints assist in the grinding process while massive and hard ores are difficult to grind [146].

The description of multiphase particles has always been of special interest to the mineral processing engineers**.** Mineral identification is the most important aspect that is needed to be carried out prior to beneficiation. Optical image analysis is a very convenient tool for obtaining comprehensive information about fine iron ore size fractions and in generating quantified data with respect to mineral distribution [93, 31].

7.1 CHARACTERIZATION OF ORES

Five samples were collected from the study area namely Banded Hematite Jasper, Siliceous blue dust, goethite-lateritic ore and iron ore slime and soft laminated ore. Soft laminated ore assay for more than 63% Fe doesnφt need any beneficiation before agglomeration process. The characterization of the remaining four samples is outlined here.

A number of polish sections of iron ore samples of the area were studied for micro-morphological characteristics under the microscope. The entire mineral assemblages can be divided in to two groups i.e. iron minerals and gangue minerals. Ore microscopic study reveals that the common iron minerals of the study area are hematite, martite, and magnetite. Goethite and specularite appear as the second phase minerals that have been transformed from early minerals. The gangue predominantly comprises of silicate minerals in the form of quartz/ jasper, clay minerals as kaolinite and discrete phase as gibbsite.

6.1.1 CHARACTERIZATION OF BANDED HEMATITE JASPER

BHJ is unevenly banded with alternating layers of hematite and jasper, and the thickness of individual bands varies from a few mm to about 2 cm while average thickness is observed to be 1 to 2 mm. The bands also vary in color from gray or white to red, brown or black.

Crosscutting of iron and jasper bands during different stages of sedimentation and diagenesis attests multiple generation of formation of minerals. In larger grains it is observed that continuous transformation and alteration processes are going on. Bands are generally parallel, while the concentration of iron ore minerals in an ñiron-rich bandò is more or less uniform; in a silica-rich bandò it is highly erratic. There is wide range in thickness of banding of hematite and chert/jasper. One of the factors of thickening of bands is diagenetic intergrowth with band capturing of thin lamminae (Fig.6.3f). The ore shows complex interlocking between hematite and jasper. The ore shows complex interlocking between hematite and jasper (Fig. 6.3a). Secondary quartz veins of various dimensions have been observed with in Banded Hematite Jasper (Fig. 6.1b). These quartz veins show cross cut relationships with Banded Hematite Jasper.

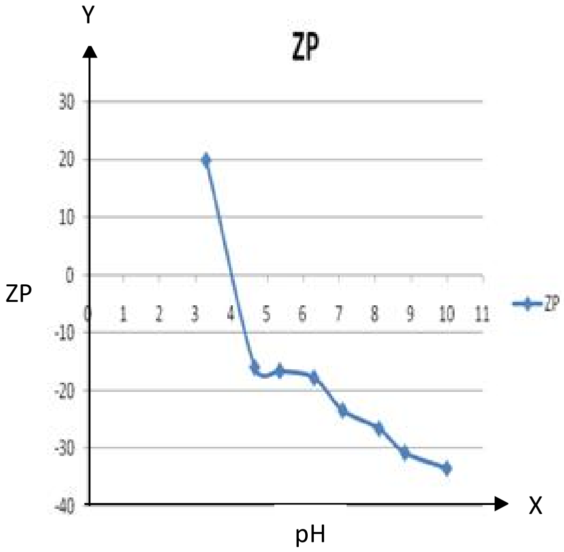
Pinch and swell structures are sporadically observed in the bands (Fig.6.3a), which may be formed due to differential compaction of interlaminated heterogeneous sediments or differential compaction and dehydration of gelatinous material [101] Hematite phase in this ore is of secondary origin & is a product of oxidation of original magnetite called as martite. Martite, hematite and Quartz are in well crystalline form. Hematite appears to be a martitized. The martite, which is pseudomorphs magnetite, in most cases, retains the shape of original magnetite (Fig.6.3e). Disseminated secondary quartz also occurs in many samples. At places there are enriched zones of hematite. In BHJ, transformation of one mineral to another happens under the influence of heat, temperature, pressure. Crystallization proceeds almost homogeneously and a large number of small crystals are formed by recrystallisation. Recrystallisation of Hematite might have produced due to hydrothermal fluids [63] but here magnetite gets converted to hematite due to oxidation. Hematite appears to be a martitized product of magnetite. At places there are enriched zones of hematite.

Salt and pepper texture (Fig.6.3c) is a very common feature in BHJ formed due to Small disseminated volcanoclasts and quartz within the hematite base and vice versa. XRD patterns indicate various discrete mineral phases as shown in Fig. 6.2a. SEM pattern hematite grains stalked upon one another in BHJ (Fig.6.4a). EDS analysis shows a high percentage of Si and complex interlocking of hematite and jasper which made it very difficult for beneficiation.

BHJ containing 35.29 % Fe, 49.12 % silica and 1.96% alumina with LOI of 1.01% had been taken for characterization study with a view to beneficiation. The liberation analysis (Table 6.1) says that in BHJ samples, clay content is negligible but silica content is very high. Hematite and quartz are medium to very fine grained. About 80% of hematite grains carry extremely fine grained inclusions of quartz. The interlocking of quartz with iron oxides is of very complex nature. From size analysis study it was found that the sample is very hard and coarser fraction comprises of around 80% indicating higher concentration of gangues in coarser fractions. Liberation analysis shows that about 48% interlocking still exists in -150+100 εm size. The complexity of interlocking between iron oxides and quartz wherein quartz ranging in size range of 5-10εm are intimately associate with the ground mass of hematite and vice versa creates difficulty in liberation. Some of the iron oxide grains that are free from interlocking also carry fine inclusions of quartz. In BHJ samples, clay content is negligible but silica content is very high. Hematite and quartz are medium to very fine grained. About 80% of hematite grains carry extremely fine grained inclusions of quartz.

The size analysis result of BHJ is listed in Table. 6.2. From the size analysis study it can be confirmed that the ore is of poor grade in nature. The Fe assay is almost uniform in all size ranges. In coarser size Fe accounts for around 30% where as with decreasing size it increases but the increase is not much significant.

From the Zeta Potential study (Fig.6.1), the IsoEletric Point/ Zero Charge Point of BHJ is found to be at at pH 4.0 which in turn indicates that the ideal pHcondition for flotation is in the range of 6-10.



IEP=4.0

Fig.6.1 Zeta potential vs pH of BHJ

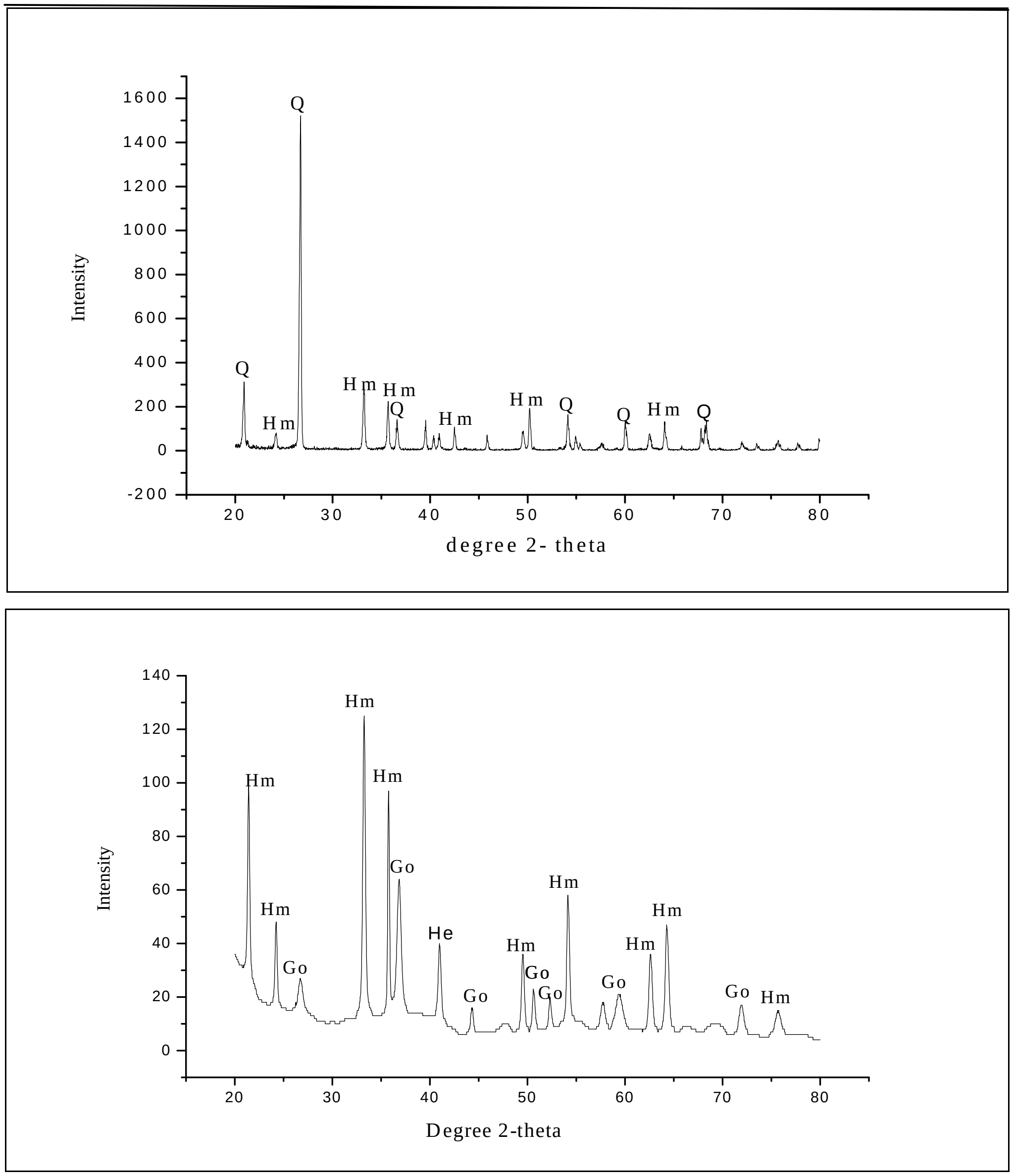


Fig. 7.2: XRD pattern of (a) banded hematite jasper (b) siliceous blue dust with identified phases. (Hm-Hematite,Go-Goethite & Q-Quartz

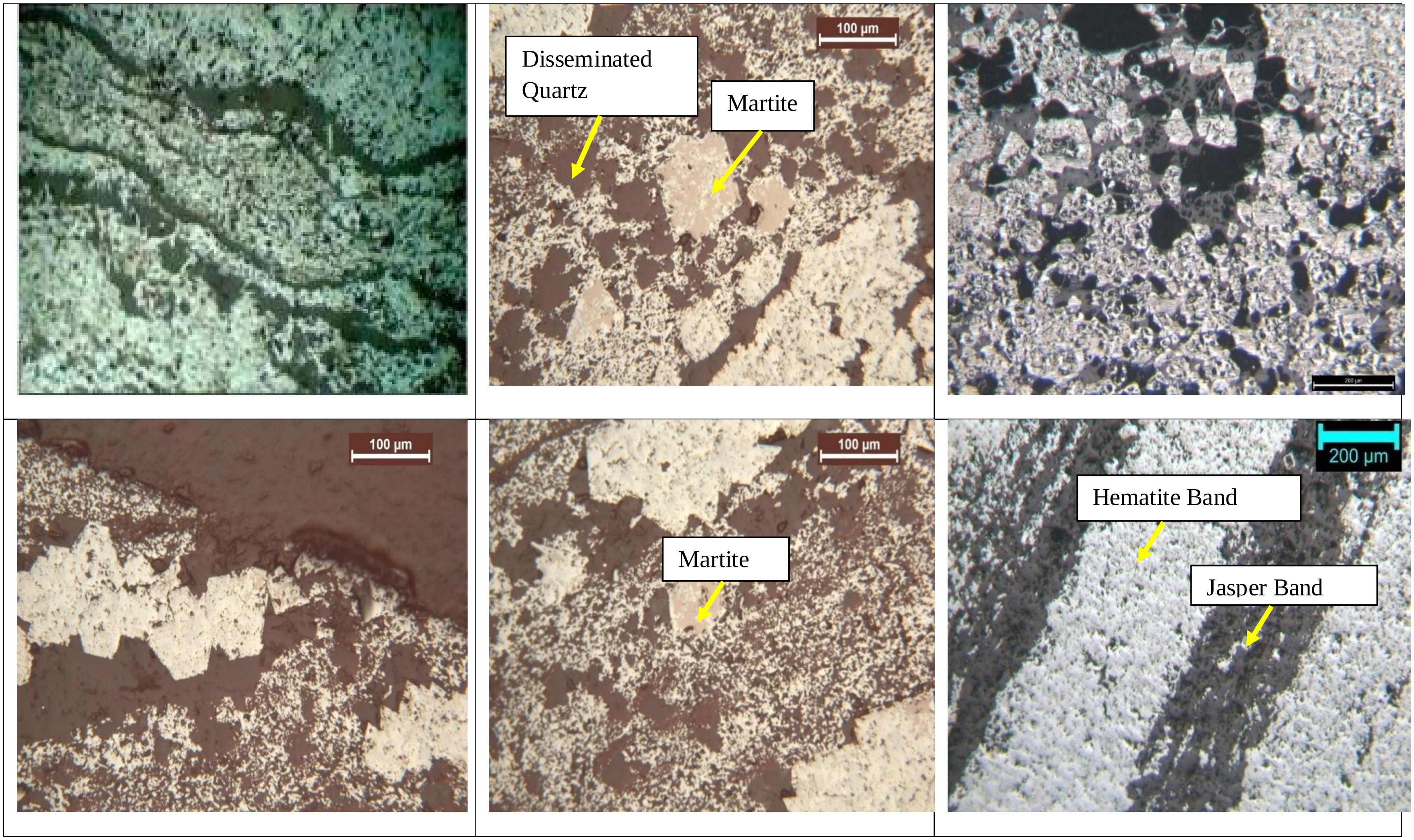


Fig. 6.3: Photomicrographs of Banded Hematite Jasper under reflected light microscope (a) Stylolitic intergrowth of hematite and chert bands of equal amplitude in opposite direction forms pinch and swell (b) disseminated quartz grains. skeletal nature of euhedral martite after magnetite (known as kenomartite) (c) Salt and pepper structure in BHJ (d) Some bands of magnetite are absolutely transformed to hematite (e) Octahedral martite (f) Macro-band of hematite & jasper in BHJ.

6.1.1.1 Distinguished features

The state of art characterization study shows the presence of hematite and quartz as major phases. Ratio of iron ore minerals to gangue minerals concludes size reduction is needed for further beneficiation. Textural study revealed the complex relationship of hematite and quartz due to its mineral association and intergrowth patterns developed among ore minerals and gangue minerals. The exact cut-off size to liberate quartz grains is difficult to determine due to its significant variation of grain sizes. Such a low grade ore with such complex interlocking pattern may not render the beneficiation process economically viable. The ore requires multiple stages of crushing & grinding followed by classification, gravity and magnetic separation and/or froth flotation may be required to produce a sufficiently high grade concentrate. It may also be noted that attaining liberation may be an extremely difficult job requiring comminution down to about a few microns.

Table 6.1: Liberation data of banded hematite jasper, Goethite- lateritic ore, iron ore slime and low grade iron ore fines showing abundance of various phases converted to wt %.

Mineral phases/ Size in micron	**-1000+600**	**-600+500**	**-500+300**	**-300+200**	**-200+150**	**-150+100**
Banded Hematite Jasper						
Free goethite	0	0	0	0	0	0
Percentage of iron liberated	37.85	39.75	40.05	41.40	43.56	48.0
Percentage of interlocking (iron+ gangue)	43.45	40.06	36.59	24.22	17.44	13
Percentage of gangue liberated	17.69	20.18	23.35	34.38	39	39
Goethite- Lateritic Ore						
	-3200+595	**-300+250**	**-250+150**	**- 150+100**	**--**	**--**
Free goethite	16.59	19.98	23.45	26.28	--	--
Free gangue (kaolinite+gibbsite)	12.56	15.94	22.73	25.73	--	--
Free hematite	25.74	29.94	35.93	39.30	--	--
Interlocked (iron + gangue)	45.12	35.14	17.89	8.69	--	--
Percentage of iron mineral liberated	58.46	67.62	81.57	90.16	--	--
Iron ore Slime						
	-500+ 297	**-297+211**	**-211+150**	**-150+100**	**-100+75**	**-75+65**
Free goethite	11.5	11.6	9.3	11.0	12.4	16.7
Free hematite	4.1	5.1	11.6	26.2	35.6	46.0
Interlocked (iron + goethite)	57.1	57.0	52.3	39.3	33.5	23.3
Free Quartz	4.3	3.4	4.2	2.1	4.7	4.0
Percentage of iron mineral liberated	76.9	77.1	77.3	78.6	86.2	90.1
Siliceous blue dust/ Iron ore fines						
	-350+300	**-300+250**	**-250+150**	**-150+100**	**-100+75**	
Free goethite	1.86	2.5	2.72	3.5	**--**	**--**
Free gangue (kaolinite+gibbsite)	5.90	8.24	9.43	10.5	**--**	--
Free hematite	72.89	74.80	77.08	80.81	**--**	--
Interlocked (iron + gangue)	15.29	12.15	8.87	4.69	**--**	--
Percentage of iron mineral liberated	78.38	84.93	86.13	87.78	**--**	--
					--	--

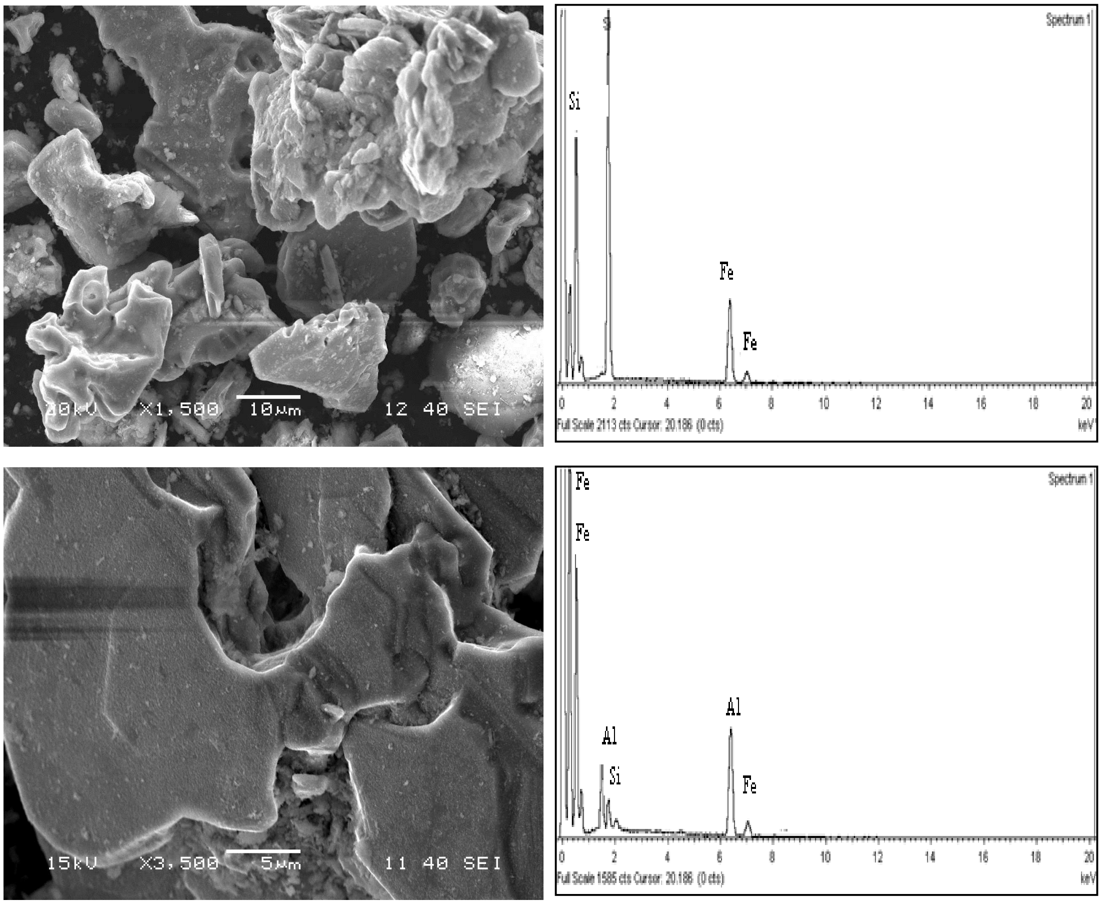


Fig. 6.4 SEM photomicrographs with energy dispersive spectroscopy of iron ore samples, (i) hematite grains stalked upon one another in BHJ (ii) siliceous blue dust sample showing microplaty hematite.

6.1.2 CHARACTERISATION OF SILICEOUS BLUE DUST/ LOW GRADE IRON ORE FINES

Blue dust is a natural occurrence of iron-ore in very fine form and is of high grade. Sometimes it is exposed near the surface and is subjected to weathering. In the surface zone it becomes partially weathered and of low grade. A low grade iron ore fine sample has been taken for characterization and possible beneficiation.

Megascopically siliceous blue dust looks mono-mineralic, but detailed microscopic examination reveals the presence of an admixture of very fine to coarser fragments of hematite and goethite (Fig. 6.5). Hematite and goethite are the iron phases. Quartz and kaolinite are the associated gangue minerals. Hematite, usually occurring as elongated anhedral grains, is the main constituent of low grade iron ore fines. In general, goethite in blue dust is rare but due to near surface weathering it is commonly found and thereby making the ore low grade. Sieving results indicate the presence of ore pieces even larger than 3 mm in size. The coarse grains in different sieve fractions are almost weathered and have a spongy structure. Total removal of interstitial silica has lead to the development of this type of iron ore, which is flaky, extremely friable and fine-grained in nature. Some grains are quite hard and tough. This is because they could have escaped the intense chemical weathering that has leached out the matrix material (mainly the gangue minerals). Therefore, less leached and hard pieces contain least impurities. At places, the cavities of the spongy-structured fragments are filled by secondary clay (Fig. 6.5d).

Goethite being the most common secondary mineral formed in the process of remobilization known as goethitisation along the crack and cleavage planes (Fig. 6.5a). Long slender specular hematite (Specularite) is developed both from magnetite and hematite (Fig.6.5 b & f) in the pressure and/ or shear zone which are also termed as micro platy hematite. Sometimes it is found that specularite co-exists with magnetite.

X-ray diffraction study was carried out with a view to identify mineral phases in the low grade iron ore fine sample. In the diffractogram, shown in Fig. 6.2b it can be seen that hematite and goethite are the major iron bearing phases. SEM of a coarse grain of blue dust shows that it consists of microplaty hematite (Fig. 6.4b). Micro-platy hematite is interlinked like a network of minerals with pores in between. In coarse grains these pores are generally filled with quartz and clay. Secondary microplaty hematite occurs in many different environments but importantly, where unmodified by metamorphism, it is the defining minor component of the high-grade BIF-hosted iron ores of the world that are dominated by martite

Size analysis data of the siliceous blue dust sample is shown in Table 6.3. From these data it is seen that the sample is fine in nature and the size distribution is almost uniform in all fractions. Substantial amounts of the fines are below 150 μm in size range.

The specific gravity of the low grade fines was measured using picnometer by the standard method and found to be 3.19. Low grade blue dust/ Low grade iron ore fine samples contain 50.24% total Fe, 12.86% silica and 4.03% alumina with an LOI of 6.42%. The chemical analysis over various size ranges which is elaborated in Table 6.3., indicate that Fe is predominantly concentrated in the finer size fraction. It can be noted that -100 μm fraction contains about 56.4 % Fe with 6.9% SiO_2 and 5% Al_2O_3.

The low grade iron ore fine sample is powdery in nature consisting of fine flakes of hematite and other impurities; mainly shale/clay and silica. Optical microscopic studies revealed that the size of the impurities which may be inherited from the parent rock or secondary in nature remains around and below 150 μm. The result of the liberation study is presented in Table 6.1. From size analysis study it is found that the Fe distribution is almost uniform over the entire size range. The liberation pattern is intermediate in the upper range with around 15% of interlocking which keeping on decreasing with decrease in size and around 88% of Fe is liberated in -150μm. so a size reduction down to 150μm is required to separate the valuables from gangues.

6.1.2.1 Heavy Liquid Separation

Characterization of LIF was also performed using sink-float studies in heavy liquid to assess the quality of the iron ore samples. Pure bromoform (specific gravity= 2.89) was used to quantify the heavy (sp.gr. >2.81) and light (sp.gr. < 2.81) content of the sample. Heaviesô content in the sample generally increased with decreasing particle size.

Table.6.2: Sink-Float study results of LIF

Size (in microns)	Sink wt%	Fe Assay %
+500	91.8	60.09
+300	91.5	62.89
+200	82.6	63.23
+150	64.8	63.60

6.1.2.2 Distinguished features

Though the alumina and silica content together is close to 16% in the bulk LIF sample, this content is low in the fines. The coarser lumps can be separated by simple screening. The coarser lumps contributing about 80-90% of the alumina and silica require proper beneficiation.

The mode of occurrence of alumina in the coarse lumps (>150 μm size) is interstitial / intra-granular and it is bounded by colloidal hydrated oxides of iron. Therefore, in the lumps it will not be possible to lower the alumina level by simple washing.

Therefore, in the lumps it will not be possible to lower the alumina level by simple washing. At around 300 μm adequate liberation is achieved. Also, the grade of is moderate (52% Fe). Therefore, comminution followed by gravity separation may not be adequate to prepare an acceptable concentrate grade from this type of ores.

Table 6.3: Size distribution and size-wise chemical analyses of BHJ and LIF (Siliceous BD)

Banded Hematite Jasper			Low grade iron ore fines/ Siliceous blue dust		
Particle size εm	Wt. %	Fe %	Particle size εm	Wt. %	Fe %
-6.3+3mm	15.7	28.3	-3+1mm	8.2	43.5
-3+1mm	15.5	31.0	-1000+853	5.2	46
-1000+853	10.10	32.7	-853+600	9.5	47
+600	10.5	35.6	+500	5.5	51.1
+500	6.8	34.9	+300	6.8	52.1
+300	6.829	35.7	+200	5.7	53.7
+200	6.73	34.4	+150	6.9	52.1
+150	6.874	36.5	+100	10.9	54.4
+100	5.92	38.1	+75	10.1	56.4
-100+75	5.15	41.8	-75+66	3.6	46.1
-75+66	3.57	31.1	Composite	100	50.24
Composite	100	34.5			

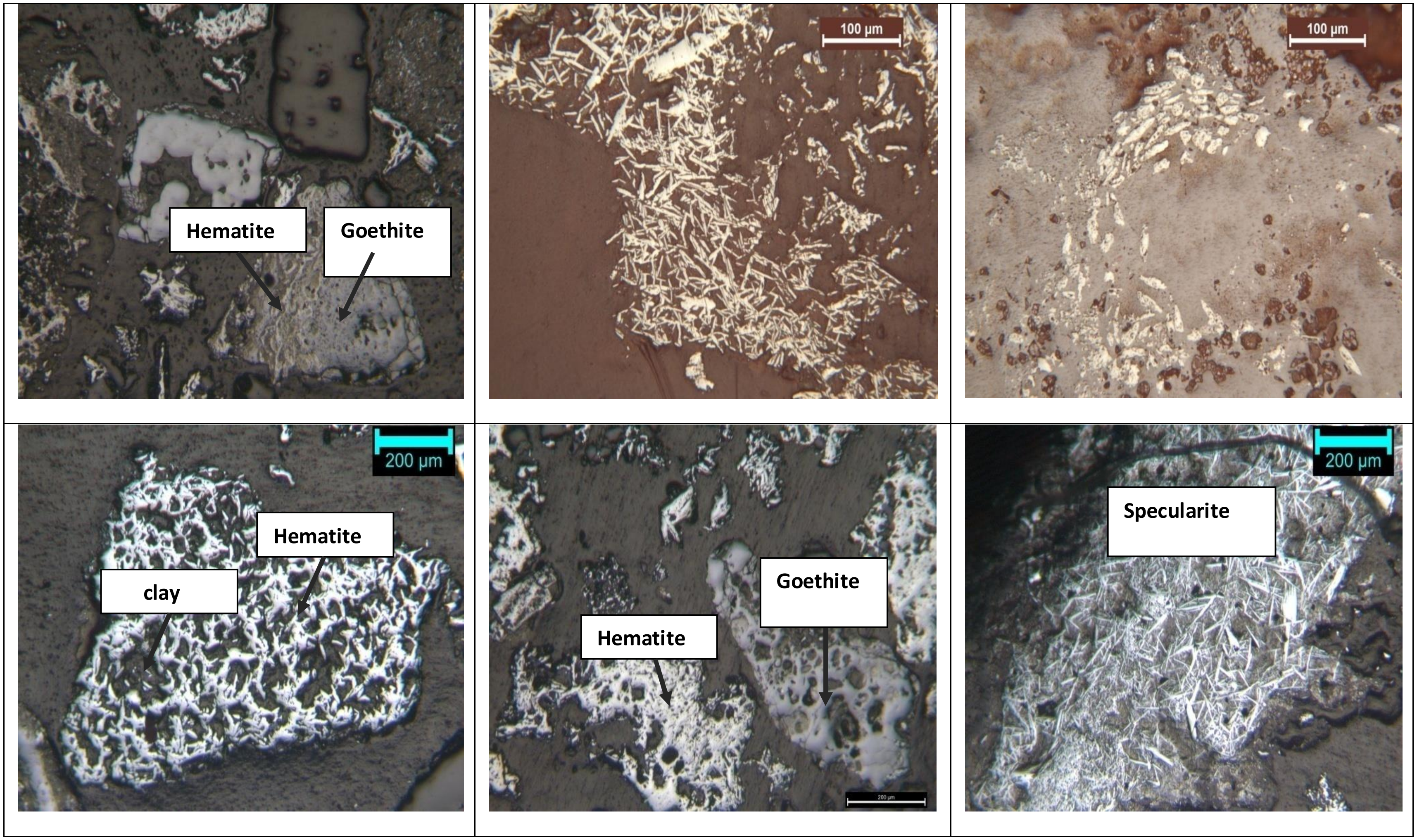


Fig. 6.5: Photomicrographs of LIF showing(a) alteration of hemetite into goethite(b) microplaty Hematite, (c)hemetite disseminated in goethite(d)clay within hematite(e)large grain of hematite with clay(f) Specularite with kaolinite precipitated in void spaces/cavities

6.1.3 CHARACTERISATION OF GOETHITIC- LATERITIC ORE

Lateritic ore is earthy in luster and limonitic red in color, yellow with white patches. Goethite-Lateritic ore mainly contains goethite, hematite (as subordinate mineral), kaolinite, gibbsite and quartz. Goethite which is common in lateritic profile/ surfaces of iron ore deposits is abundant in all the samples. Ore microscopic studies reveal presence of colloform and cavity filling texture. There are extensive vein filling by goethite precipitation.

From mineralogical study, it is evident that the ore has two distinct types of valuable minerals i.e. i) crystalline hematite with disseminated inclusions (Fig.6.8e) and microcrystalline hematite particles with microcrystalline goethite (Fig.6.8d). Vitreous goethite, being hard and crystalline is abundant in the sample (Fig.6.8e). Most of the lateritic samples show high degree of porosity. These pores are the most favorable sites for clay deposition (Fig. 6.8h), which is mainly responsible for the high alumina content in this ore rendering it difficult for use in iron making without rigorous beneficiation. These cavities are also partly filled by gibbsite and kaolinite (Fig.6.8b). Spongy hematite and martite partly or wholly transformed to goethite and later concreted by goethite precipitation along the wall of the tubular pores. This ore also exhibits multiple joint and fracture surfaces along which the clay and goethite precipitation takes place (Fig.6.8c). Goethite replaces hematite indifferent degrees (Fig.6.8c& f). Kaolinite occurs in intimate association with goethite but free quartz grains are uncommon indicating that silica is available in the form of kaolinite. Majority of the kaolinite grains are embedded with iron hydroxide minerals i.e. goethite. Gibbsite is the predominant alumina contributing mineral and occurs intimately intermixed with goethite. Gibbsite & clay minerals are present as microcrystalline to cryptocrystalline aggregates. Colloform texture of weathered goethite is observed in Fig.6.8b. Free quartz is rarely observed.

Goethite changes to limonitic clay due to dissolution and re-precipitation. Goethite occurs as massive mass occasionally with secondary hematite. Goethite and clay at places occur as oolitic or pisolitic grains cemented together (Fig.6.8 a). Small highly altered relicts of martite ore fragments are common within goethite. Goethite partially dehydrates to hematite. The clay bearing laterite contains clusters of gibbsite grains in the voids and fine kaolinite needles in the nodules and pisoids.

XRD pattern reveals that lateritic ores mainly comprise of hematite, goethite and clay minerals (Fig. 6.7). SEM observation of goethite-lateritic ore shows that goethite is the common mineral (Fig. 6.6). It is formed under oxidizing conditions as a weathering product of iron bearing-minerals. The alumino-silicates are intricately associated with goethite and are very difficult to remove from the ore.

SEM observation of goethite-lateritic ore shows that goethite is the common mineral (Fig. 6.6). It is formed under oxidizing conditions as a weathering product of iron bearing-minerals [62]. The alumino-silicates are intricately associated with goethite and are very difficult to remove from the ore**.**

A number of images were processed and the conclusion drawn was most of the iron bearing minerals are fully or partially weathered (Fig.6.6A) resulting in substitution of most of the iron oxides with Al in mineral grains (Fig.6.6B). At point b (Fig.6.6B), it is free of silica which can be substantiated from EDX. At the same time it is porous and rich in alumina. This substitution can normally happen in goethite grains which are resulted due to the weathering of iron oxide particles.

A very low grade Goethite-lateritic ore collected from Barsua iron ore deposits of Eastern India. The sample contains 38.19% Fe, 9.48%SiO_2, 19.97 Al_2O_3. Goethite- In the present work attempts have been made to understand and characterize the lateritic iron ore to ascertain the feasibility of their beneficiation for value addition.

The weight percentage distribution of goethite-lateritic ore sample in respect of various size fractions is shown in Table.6.4. From size measurement it is evident that the ore is coarse in nature at the same time, the finer fraction (<150) accounts for 13% indicating significant amount of slime generation during washing. The coarser fraction requires suitable grinding for proper liberation. The Fe assay is almost uniform over the entire size range.

Liberation analysis of goethite-lateritic ore shows (Table 6.1) that in coarser fractions percentage of interlocking is very high which decreases with decreasing particle size. Low free hematite content and higher gangue contents indicate very low grade of this type of iron ore. Complex interlocking nature of the particles shows that the liberation can be achieved below 150 μm size. Achieving high purity concentrate in beneficiation of this ore is likely to be quite difficult due to the complexity of interlocking. Proper comminution is required to break the interlocking and attain good liberation in this case.

Table. 6.4: Size distribution and size-wise chemical analyses of Goethite-Lateritic ore & Iron ore slime

Goethite-lateritic ore			Iron ore slime		
ParticleSize, ε m	Wt %	Fe Assay	Particle Size, ε m	Wt %	Fe Assay
2000	40.24	42.32	+1mm	19.89	56.08
1000	10.60	41.64	-1+500	6.59	52.04
853	5.87	39.07	-500+250	5.26	54.15
600	8.72	38.24	-250+200	4.72	54.52
500	4.08	38.43	-200+150	7.53	57.35
300	5.74	37.64	-150+100	4.52	58.36
200	2.23	37.35	-100+75	8.53	59.73
150	6.40	37.39	-75+66	3.13	60.76
100	1.68	37.72	-66+50	4.11	61.82
75	2.07	37.20	-50+37	3.09	62.80
66	0.62	35.45	-37+25	4.54	54.23
<66	11.75	33.70	<25	32.92	50.83
Composite	100	38.19	Composite	100	

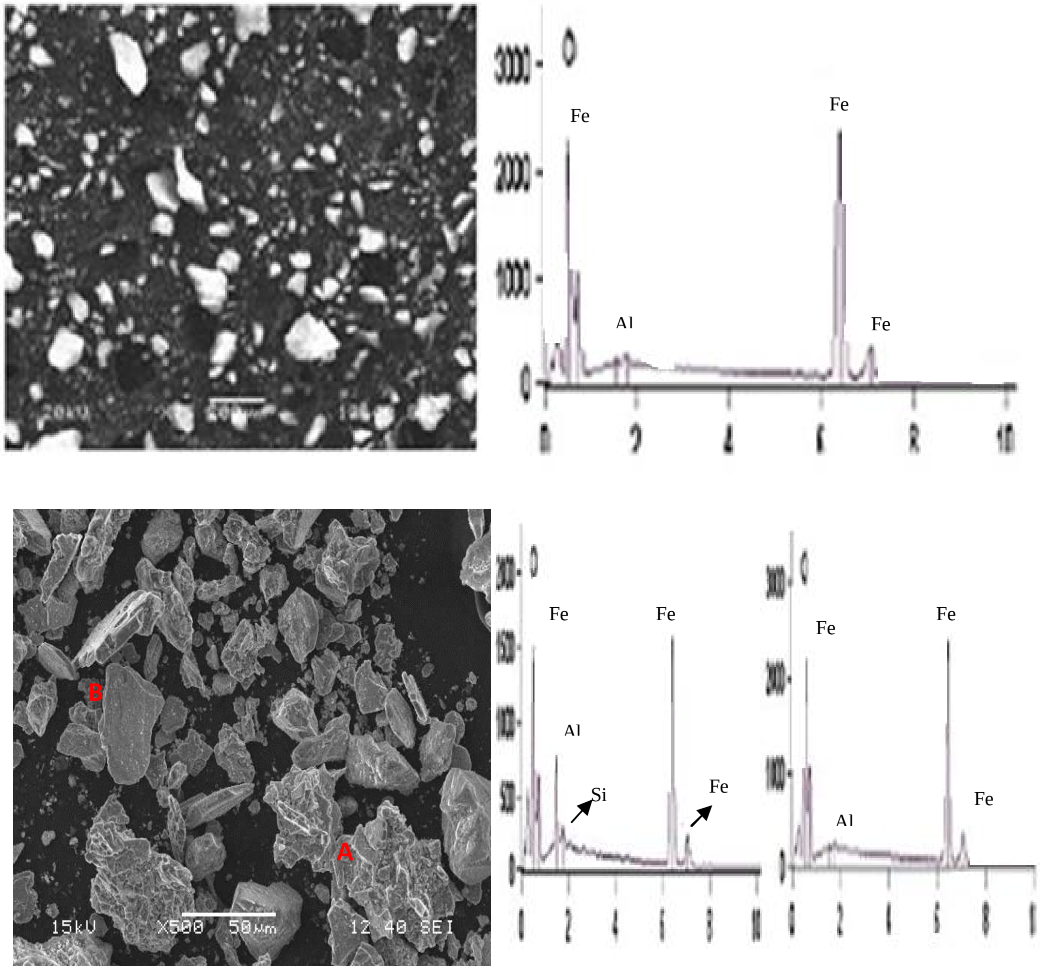


Fig. 6.6 SEM photomicrographs of goethite-lateritic ore

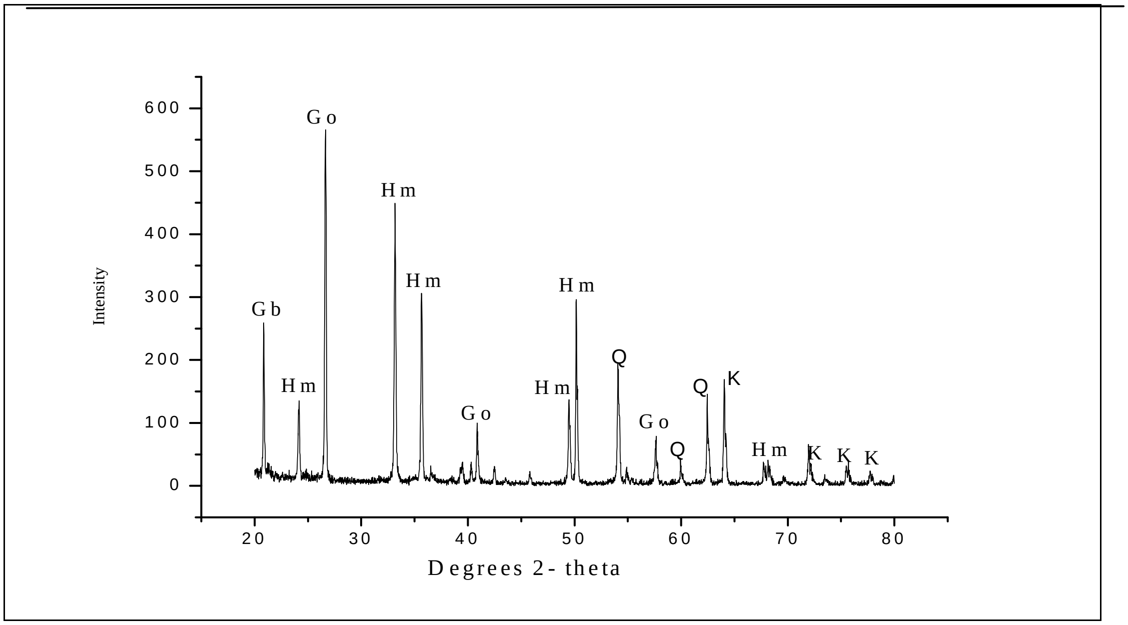


Fig. 6.7: XRD patterns of Goethitic-Lateritic ore (a) ore fraction shows presence of hematite and goethite.

6.1.3.1 Distinguished features

In case of lateritic iron ores, the iron bearing grains are highly weathered due to surface weathering of the bulk ore in the deposit. The iron occurs mainly in hydroxy form as goethite interlocked with kaolinite and gibbsite. The liberation analysis illustrates that the impurities are concentrated at finer size fraction, which contains ferruginous clayee material such as kaolinite etc. These ores must be upgraded by thorough and proper processing after adequate comminution to attain liberation. The concentration criterion [146] for these ores is found to be less than 2.5. Therefore, simple gravity separation will not be much effective. These ores may be upgraded by using advanced gravity separation techniques in the first stage. Further purification may be achieved using wet high intensity magnetic separation. If this stage also fails to achieve the required grade, froth flotation to remove the gangue may be tried at the final concentration stage.

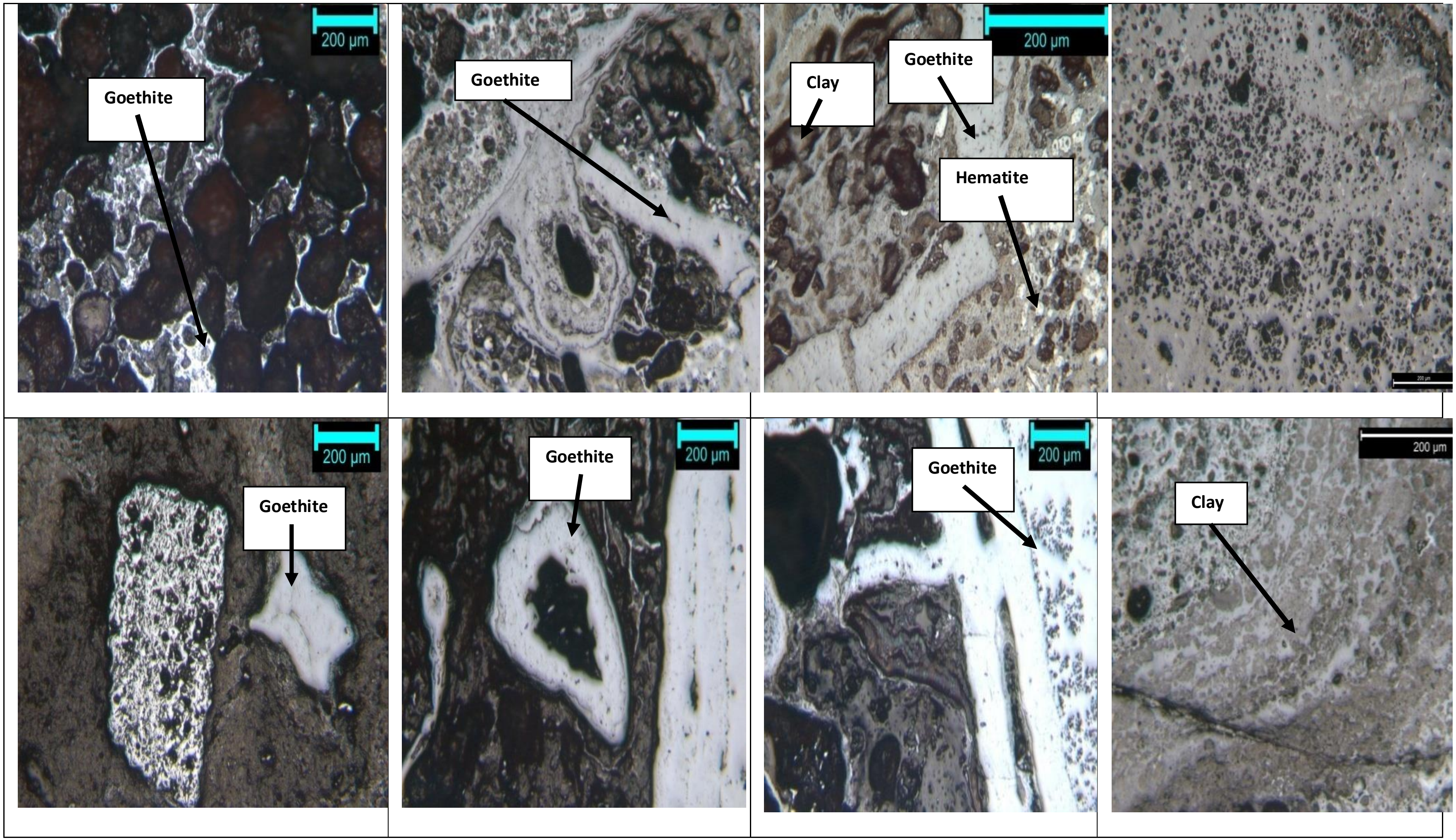


Fig.6.8: Photomicrographs of Goethite- Laterite iron ore (a) Gibbsitic clay (reddish black) bounded by goethite (grayish white), characteristic of Lateritic ore (b) colloform goethite with clay (c) joint and fracture surface along which goethite and clay precipitation takes place (d) microcrystalline hematite with microcrystalline goethite (e) vitreous goethite (f) cavity filling by goethite precipitation (g) Vein filling by goethite precipitation (h) Highly porous goethite & cavities are filled up by clay

6.1.4 CHARACTERISATION OF IRON ORE SLIME

During washing and sizing of the ore, slimes with less than 0.21 mm size are generated and discarded into the tailing pond. It is estimated that around 10 million tonnes of slimes are being generated every year during the processing of hematite ore and lost as tailings containing around 48-62% of Fe. Iron ore slime is typified by the presence of high percentage of alumina. In India, beneficiation and utilization of slime is yet to be practiced on an industrial scale. Considering the present magnitude of the iron ore slimes generation annually, the quantities of slimes accumulated over the years, the fact that these slimes are available in already ground form and assaying reasonably high % Fe, it is obvious that if properly beneficiated, these slimes can be considered a national resource. Beneficiation and utilization of slime is gearing up but not practised on an industrial scale in India.

Sieving of iron ore slime sample was carried out using the Vibratory Laboratory Sieve Shaker. For the separation of 200 micron particles micro-precision sieves were used. It is seen from the size measurement that the slime is extremely fine in nature. Substantial amount of the slime is below 50µm. The size analysis result of iron ore slime is shown in table 6.4.

The presence of hematite, goethite, magnetite, kaolinite, and quartz is also supported by X-ray diffraction data. XRD analysis of the clay material shows that it is mainly composed of kaolinite. Some of the ore fragments have undergone weathering, producing ochreous goethite, and kaolinite. Therefore, this can be termed as lateritic ore. It is generally soft and friable and leads to slime generation during handling.

Microscopic studies reveal that the slime sample consists of relict magnetite, martite, hematite, goethite and quartz as also inferred from XRD. Hematite/martite/magnetite occurs in two different modes: a) as independent coarse grains (Fig. 6.9c) and as intergrowths/

inclusions within goethite (fig. 6.9d). Rim like structure is also developed in goethite where the outer rim is of ochreous goethite and it is interlocked with clay. The inner rim is vitreous goethite which is hard and crystalline in nature (Fig.6.9a). Occurrence of clay is more at places where the ore has become porous due to weathering and altered. Some of the samples are martitized with relict magnetite (Fig.6.9c) grains present in the ore samples indicating oxygen from infiltration water was incorporated into the magnetite lattice during the martite formation. Hematite is recrystallised from magnetite through martite. Martites preserve the skeletal remains of magnetite with internal voids, which is known as Kenomartite (Fig.6.9e).

SEM and EDS of liberated iron particles containing low silica and alumina is shown in Fig. 6.10c. Most of the clays (kaolinite and gibbsite) are ferruginous and occur as limonitic kaolinite. Kaolinite in iron ore slime mainly contributes towards the high Al_2O_3. The iron particles (Fig. 6.10a) are not porous and are relatively compact having smooth surfaces containing very low percentages of impurities. Microscopic studies reveal that the bands consist of relict magnetite, martite, hematite, goethite and quartz as also observed using XRD.

Aluminum is common in weathering environment results in Al substitution in most of the iron oxides. This substitution can also occur in hematite. Hematite is essentially composed of Fe and O, but it may contain variable quantities of impurities viz., Al, Si in the range of about 2-5%.

Liberation analysis shows that in coarser fractions, interlocking between hematite and clay is significant. Predictably, the percentage of clay-hematite interlocking decreases with decreasing particle size. Liberation analysis (Table.6.1) shows that in coarser fractions hematite is highly interlocked with clay.

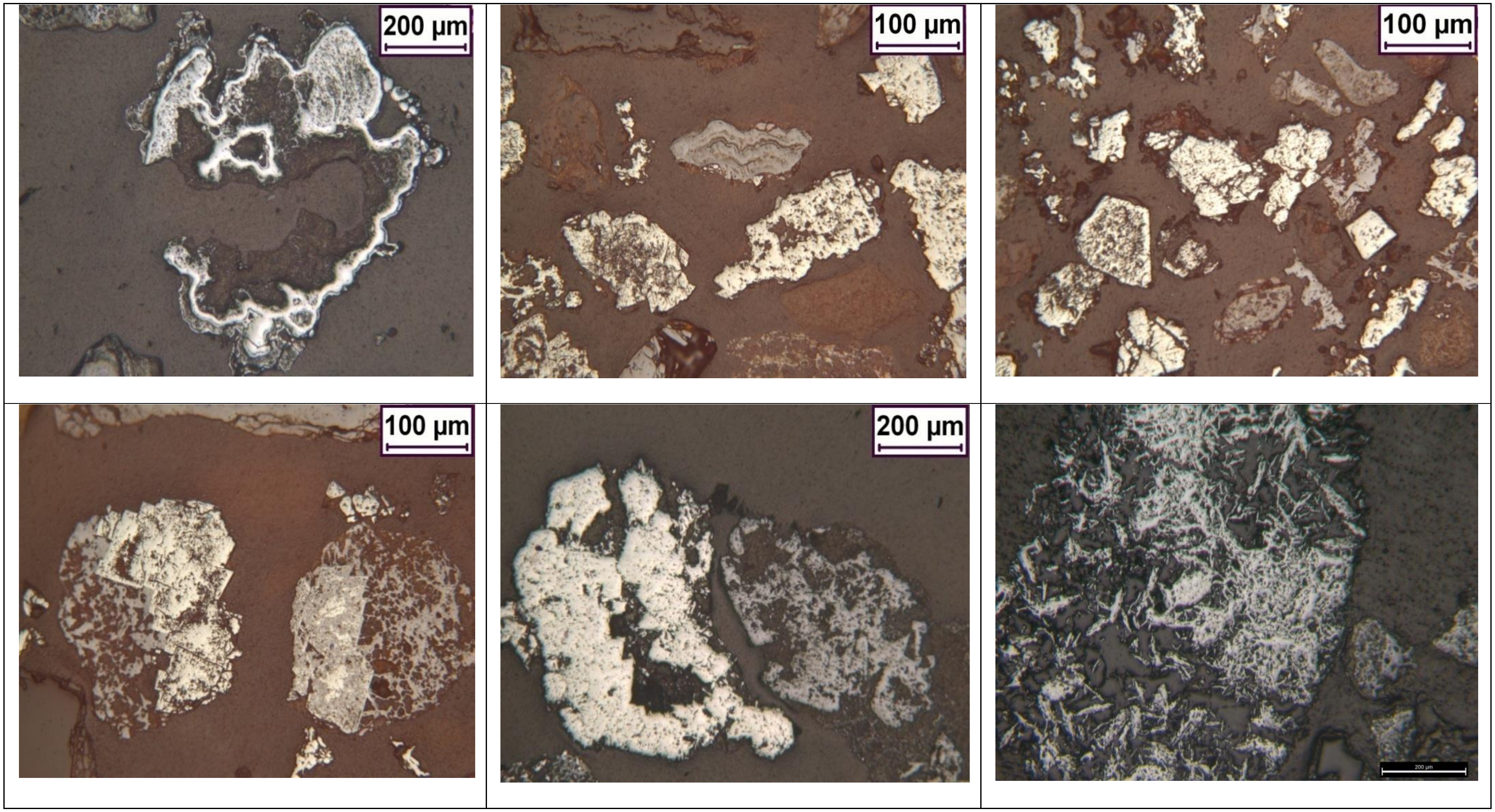


Figure.6.9: Photomicrographs of iron ore Slime under Microscope (a) colloform structure of vitreous goethite with fracture filling(b) Rhythmic precipitation of goethite with porous martite (c) Recrysatllised hematite grains in magnetite base (d) Interlocking of goethite & clay, martite & clay (e) skeletal nature of euhedral martite after magnetite (known as kenomartite) (f) Specularite as secondary iron ore mineral.

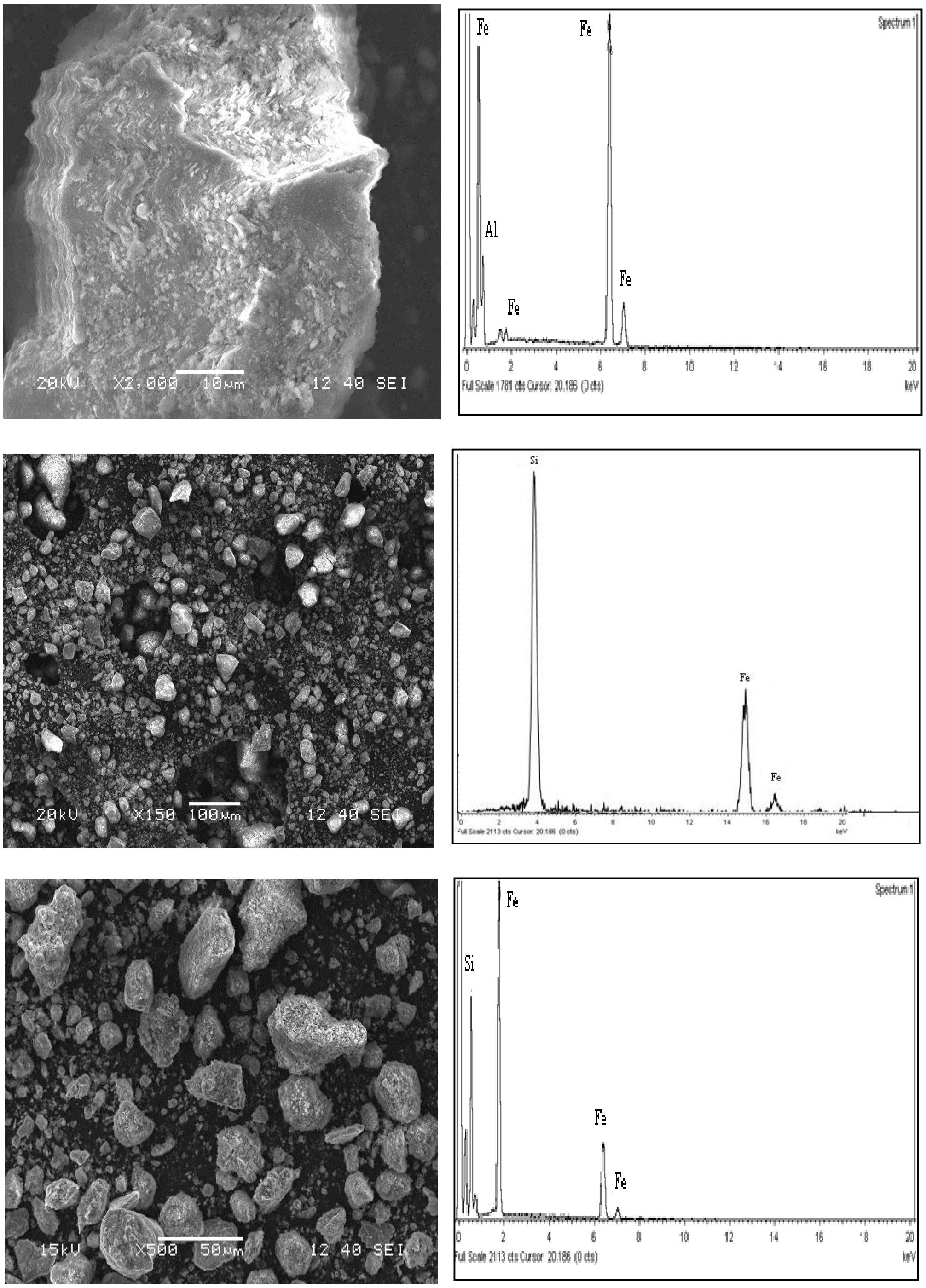


Fig. 6.10: SEM Photomicrographs with EDS of iron bearing particles of slime.

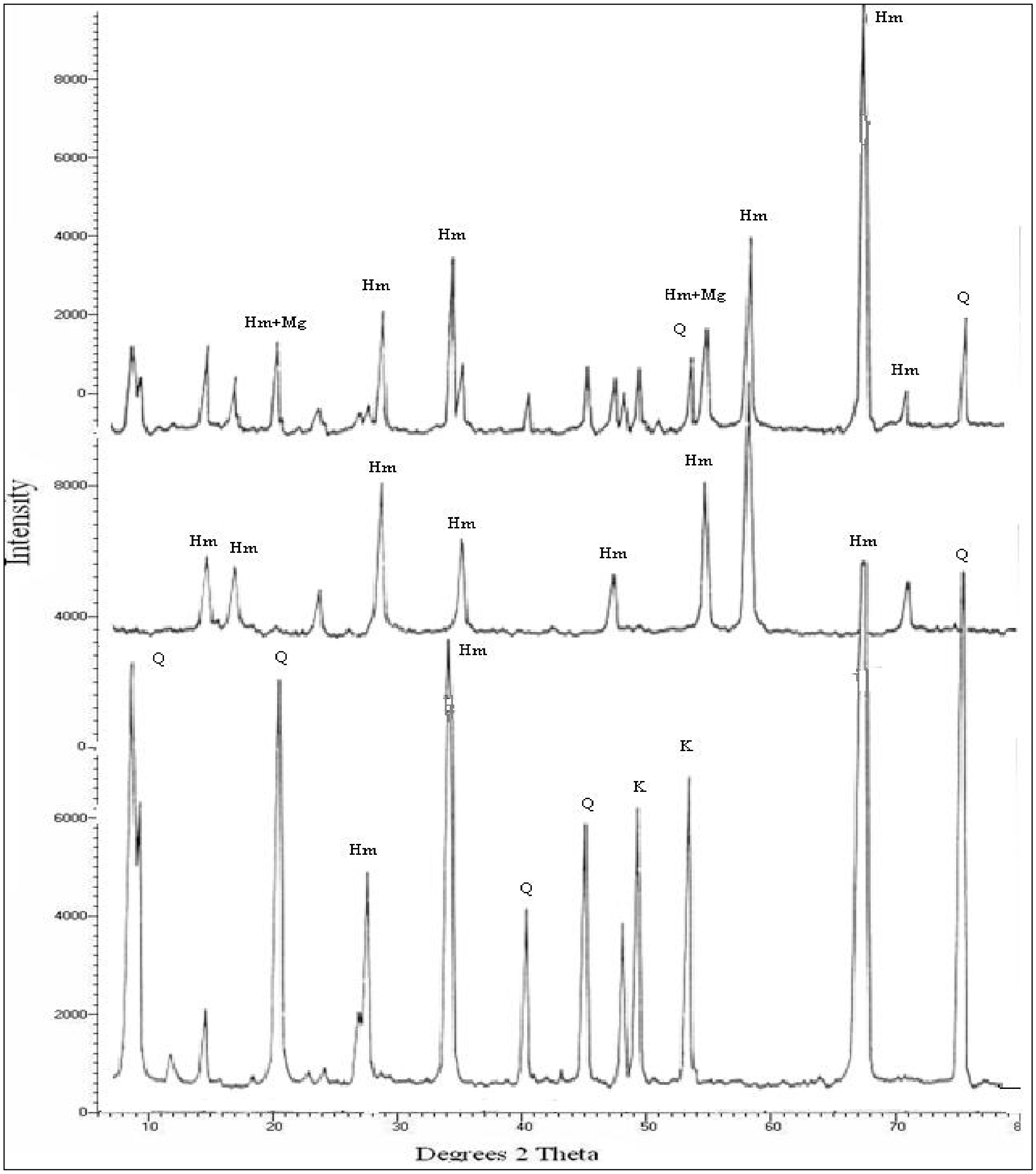


Fig.6.11XRD pattern of iron ore slime of Barsua iron ore with different phases (a) Quartz, goethite and hematite, (b) Hematite and (c) Hematite and magnetite (Qt-quartz, Mt-magnetite, Hm-hematite, Go-goethitie).

6.1.4.1 Distinguished features

Mineralogy, physical and chemical characteristics suggest that the iron ore samples from Indian deposits contain porous and friable oxides and hydroxides of iron with kaolinite and quartz.

In Indian iron ore samples hematite mainly occurs as specularite with inter-granular micro-pore spaces. Goethite is abundant and occurs as secondary colloform texture in cavities along the weaker bedding planes. Such inter-granular pore spaces and voids along the weaker bedding plane are very fragile making the hematite and goethite friable during mining and processing. These friable particles break down and account for the iron content of the slime. Most of the bulk ore samples contain numerous cavities. These cavities are mainly filled with clay in the form of kaolinite and gibbsite. Kaolinite and gibbsite are very friable and easily crumble into ultrafine sizes during mining and processing operation leading to greater concentration of alumina in the slime.

Optical microscopic studies revealed that in Barsua iron ore slime hematite is the most abundant phase and the other iron-bearing phase is goethite having white and light grey features respectively and the goethite occurs in very low quantity. Quartz and clay are the main gangue phases, and they can be easily distinguished from all iron bearing minerals. Iron is interlocked with clay. Most of the quartz occurs as free liberated grains. The gangues are highly liberated where as for iron it is vice versa. It indicates beneficiation will be effective at lower size range. Iron principally present in two phases i.e. oxy-hydroxyl and oxide phase. The principal oxide minerals are hematite; martite and hydroxides such as goethite and limonite are predominantly observed.

CHAPTER VII

BENEFICIATION

BENEFICIATION OF IRON ORES

Iron ore is being beneficiated all round the world to meet the quality requirement of Iron and Steel industries. However, each source of iron ore has its own peculiar mineralogical characteristics and requires the specific beneficiation and metallurgical treatment to get the best product out of it. The choice of the beneficiation treatment depends on the nature of the gangue present and its association with the ore structure. Mineral beneficiation is characterized by a constant adaptation to changing raw materials and market conditions. It is the link between the mined raw material and a marketable product. As a lot of high grade reserves are exploited, a steady deterioration of raw material quality can be observed. At the same time, the customers´ requirements for product purity and consistent quality increase. Several techniques such as washing, jigging, magnetic separation, advanced gravity separation and flotation are being employed to enhance the quality of the Iron ore. Washing, jigging and classification are being carried out for the beneficiation of Iron ores in India.

Indian Iron ore is typified by high alumina and silica in comparison to rest of the world. Along with Hematite, goethite is the other predominant iron phase which causes hurdles in beneficiation.

7.1 BANDED HEMATITE JASPER (BHJ)

The gangue and ore minerals contained in Banded Hematite Jasper vary significantly in their physical properties i.e. magnetic and gravity properties. Therefore gravity and magnetic separation techniques are the potential low cost techniques that can be applied to pre-concentrate or beneficiate such ores. The fine size of the ore and gangue minerals and their poor liberation is however one of the constraint that limits its beneficiation at coarser stage.

The feed size-wise chemical analysis shows 35% Fe (T) with 49% Silica. Textural characterization study revealed the complex relationship of hematite and quartz due to its mineral association and intergrowth patterns developed among ore minerals and gangue minerals. The presence of ultrafine grains of quartz and hematite within the ore and gangue mineral bodies indicates that the BHJ sample is very difficult to beneficiate even at very fine grind size. Proper comminution is required to break the interlocking. Good quality liberation is observed at a particle size < 50 εm. Such a low grade ore with such complex interlocking pattern may not render the beneficiation process economically viable. Achieving high purity concentrate through beneficiation of this ore is likely to be extremely difficult. An elaborate and complicated flow sheet with multiple stages of comminution, classification, gravity and magnetic separation and froth flotation may be required to produce a sufficiently high grade concentrate.

7.1.1 BENEFICIATION OF BANDED HEMATITE JASPER (BHJ)

From the detailed characterization studies, it has been observed that in BHJ, the clay content is low but silica content is very high. Consequently, the grade of the ore is very low (35% Fe). Also, the quartz is very finely disseminated rendering it extremely difficult to attain liberation. Concentration of iron is almost uniform over the entire size range.

In order to improve the grade and obtain a concentrate with permissible gangue content a four-stage concentration is developed. To study the beneficiation prospects of coarse particles, a first stage of gravity separation in Wilfley Table was carried out. It may be seen that about 45.40% solids is recovered in the concentrate product. The experimental conditions, 3ę deck slope and 1.68 cc per cm/ sec. water flow rate are kept constant in all tabling experiments. The results obtained are reported in Table 7.1.1. It is observed that the quality of the ores improved significantly by tabling. In the BHJ, the concentrate grade improved to 49% iron by processing the feed ground to <1mm.

Table 7.1.1Wilfley table test results with 3ę deck slope and 1.68 cc. per cm/sec water flow

Product	Fe (%)	SiO_2 (%)	Al_2O_3 (%)	Yield (%)
Conc.	49.0	27.8	3.8	45.40
Middling	27.0	34.6	8.5	43.24
Tailing	22.0	36.9	9.3	11.36
Feed	35.29	49.12	4.3	100

It is observed that the quality of the ores improved significantly by tabling but the impurity content is beyond permissible limit (alumina: silica < 1.5% and preferably < 1%).

7.1.1.1 Effect of concentration criteria

Theoretically, effective gravity separation is possible when the concentration criterion (Wills, 1988) for these ores is greater than 2.5 (Equation 8.2.1).

$$\frac{D_h - D_f}{D_l - D_f} > 2.5 \qquad \text{------------------------ (7.2.1)}$$

where, D_h is the specific gravity of the heavy mineral, D_l is that of the light mineral and D_f is the specific gravity of the fluid medium.

Gravity separation is relatively easy when the quotient is greater than 2.5. As the value of the quotient decreases, the efficiency of separation decreases. Below about 1.25, gravity separation is not practically feasible [146]. The specific gravity of hematite is 5.5 to 6.5 whereas it is 4.1 to 4.3 for goethite. Specific gravity values of kaolinite, gibbsite and quartz are in the range of 2.3 to 2.6. In the case of hematite ore, separation criterion, as shown in Equation (7.2.1), is estimated to be in the range of 2.81 to 3.44. In the present work, low percentage of iron is going to the tailings product during tabling operation of (Table 7.1.1) feed is observed. This is due to a higher concentration criterion above 2.5 and thereby enhances the efficiency of separation.

Further concentration of tabling concentrate is carried out in a falcon concentrator. A number of tests were conducted by varying the water pressure and rpm. The results under optimum operating conditions are given in Table 7.1.2. The best test results obtained under operating conditions of 40 Hz and 15 psi. Fe content was increased to 60.01%% with a yield of 56.08%. The concentrate grade is still not good enough to be accepted commercially.

Liberation analysis of different ground size fractions of the ores suggests that the grain size reduction to less than 150 sizes is necessary to achieve sufficient liberation of iron ore minerals from its gangue (Table 6.1). Therefore, the falcon concentrate i.e. <1mmsized materials are subjected to further comminution to 150μm. In continuation with the earlier work the Falcon Concentrate of BHJ was subjected to Wet High Intensity Magnetic separator in accordance with mineralogical studies showing that in BHJ ore, most of the irons bearing particles are hematite, which are paramagnetic in nature. So Wet High Intensity Magnetic Separator (WHIMS) has been used and Fe can be enriched to 61.03 with 8.26% SiO_2 and 10.27% Al_2O_3.

In a magnetic separator apart from the magnetic force, several competing forces act on a particle. These are, among others, the force of gravity, the inertial force, the hydrodynamic drag and surface and inter particle forces. However, among the competing forces gravity and hydrodynamic drag forces are the major competing forces.

Table 7.1.2 Falcon &WHIMS test results of banded hematite jasper

	Falcon test results of tabling conc. in optimum condition of 40Hz, 15psi				WHIMS test results of Falcon conc. with 10% solids, .5 Amp. Current and 20 lpm Wash water			
Product	Fe (%)	SiO_2 (%)	Al_2O_3 (%)	Yield (%)	Fe (%)	SiO_2 (%)	Al_2O_3 (%)	Yield (%)
Concentrate	60.01	10.08	2.70	56.08	61.03	8.26	2.3	60.19
Tailing	36.31	12.78	22.40	44.91	29.88	37.48	21.57	39.81
Feed	49.0	27.8	3.8	100	60.0	10.08	2.70	100

The force of gravity is expressed as

$$\vec{F}_g = \rho V \vec{g}$$

Where ρ is the density of the particle while g is the acceleration due to gravity.

The hydrodynamic drag is given by

$$\vec{F}_d = 6\mu\eta b\,v_p$$

Where η the dynamic viscosity of the fluid, b is the particle radius and ν_p is the relative viscosity of the particle with respect to the fluid.

WHIMS result (Table 7.1.2) of 150 εm size ground sample shows that due to relatively higher drag force significant amount of Fe is lost into the tailings and the desired grade could not achieved. Fines generated in the grinding process are not recovered in the concentrate. The WHIMS concentrate is further subjected to Flotation for further up gradation.

Table 7.1.3: Flotation test of WHIMS concentrate at a pH of 9.3, with 10% solids, 5 min. conditioning time, 2.0 kg/t collector (sodium oleate), 2.5 kg/t depressant (sodium silicate), 0.3 kg/t frother (MIBC)

Product	Fe (%)	SiO_2 (%)	Al_2O_3 (%)	Yield (%)
Concentrate	63.47	7.2	1.8	68
Tailing	42.08	18.1	11.2	32
Feed	60.01	10.08	2.3	100

In flotation, the response of many minerals is often dramatically affected by p^H .Adsorption of collectors and modifying reagents in the flotation of oxide and silicate minerals is controlled by the electrical double layer at the mineral-water interface.

In systems where the collector is physically adsorbed, flotation with anionic or cationic collectors depends on the mineral surface being charged oppositely. Adjusting the pH of the system can enhance or prevent the flotation of a mineral. Thus, the Iso electric point (IEP) of the mineral is the most important property of a mineral in such systems but raising the pH sufficiently above the IEP can repel chemisorbing collectors from the mineral surface. Zeta potentials can be used to delineate this interfacial phenomenon. From Zeta potential graph (Fig. 6.3) the IEP was found to be 4.0 which in turn indicate that the ideal pH condition for flotation is in the range of 6-10. Flotation is carried out using Denever D-12 flotation cell with MIBC as frother and soidum oleate as collector and sodium silicate as depressant. The test results are presented in Table 7.1.3.

7.1.2 DISCUSSION

BHJ sample is relatively low grade having 35.29% Fe with exorbitantly high silica and alumina. Ratio of iron ore minerals to gangue minerals, their association infers size reduction is needed for further beneficiation. Textural study revealed the complex relationship of hematite and quartz due to its mineral association and intergrowth patterns developed among ore minerals and gangue minerals is the main constraint in beneficiation. Beneficiation studies using four- stage concentration operation, the feed with grade 35.29% Fe can be enriched to 63.47% Fe by WHIMS and flotation respectively but still the silica content is far beyond acceptable limit. The exact cut-off size of liberation of Quartz grains is difficult to ascertain due to its significant variation of grain sizes. Even in -150 εm, liberation percentage is only 48%. The occurrence of free hematite is observed at a particle size < 50 εm. Therefore, beneficiation of this ore is not commercially viable but at the same time if the silica content can be reduced by modern methods then BHJ will be the best alternative for the dwindling high grade ores.

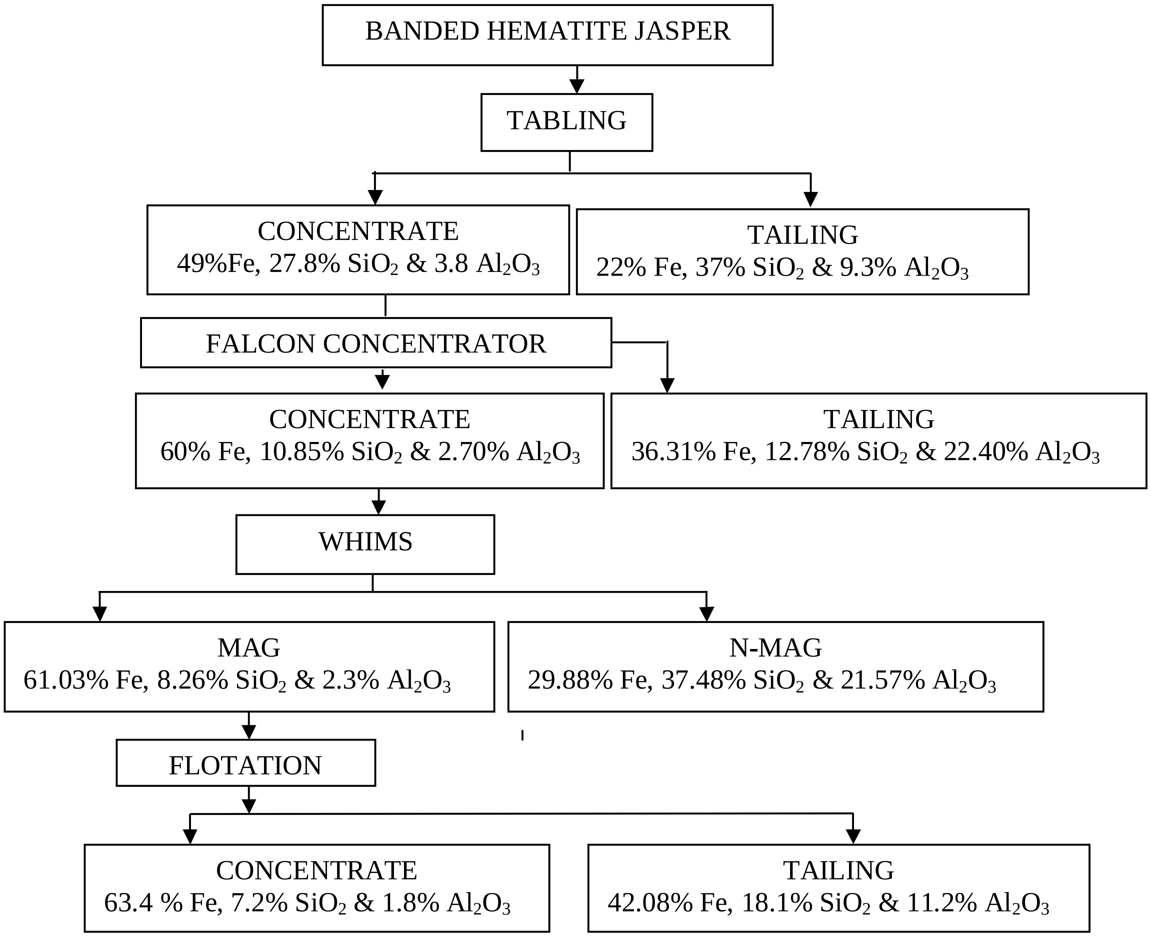


Fig.7.1.1. Processing flow sheet of Banded Hematite Jasper

7.2LOW GRADE IRON ORE FINES (LIF)

Detailed particle characterization of blue dust ore revealed the following characteristic properties of the blue dust that are useful for developing the processing scheme of the sample. From size measurement of the blue dust sample, it is seen that blue dust is fine in nature with substantial amount of ore (31%) below 200 μm (Table 6.3). Chemical analysis reveals that iron is mainly concentrated in the finer size fraction. It was found that Fe content in -150 μm is 56.4%, whereas coarser fraction (+150 μm) has relatively low Fe % (Table 6.3).Chemical analysis of low grade fine sample shows that besides the silica, alumina is also a major impurity. X-ray diffraction study reveals that hematite and goethite are the main iron bearing phases.

7.2.1BENEFICIATION OF LOW GRADE BLUE DUST/FINES

Liberation study shows that iron is mainly interlocked with gangues in the coarser size fraction whereas the finer size fraction is almost liberated (Table 6.1). Quantitative phase analysis indicates that the finer size fractions are devoid of free gangue and rich in free iron bearing minerals. Liberation study of the blue dust sample suggested that grain size reduction lower than 150 μm size would be necessary to achieve sufficient liberation of iron ore minerals from its gangue (clay and quartz). A beneficiation scheme is choosen involving desliming in hydrocyclone followed by magnetic separation. The ROM sample was crushed down to 0.5mm (<48#). The -48# to +100# fraction was subjected to concentration in Kelsey jig and the finer fraction (<100#) was subjected to classification in hydrocyclone and WHIMS for magnetic separation.

The Iron ore fines were first treated in a 2"-hydrocyclone to remove the ultrafines. A number of tests were conducted by varying spigot and vortex finder diameters, pulp density, inlet pressure etc. After each tests both the underflow and overflow fractions were collected and analyzed for grade and yield. Two best results are shown in the Table 7.2.1.

Table 7.2.1 Hydrocyclone test results of iron ore fines

Test-1(5 mm. spigot, 14.3mm. vortex, 0.68MPa feed pressure)				
Product	**Yield (%)**	**Fe (%)**	**SiO_2 (%)**	**Al_2O_3 (%)**
U/F	75	60.28	8.9	3.32
O/F	25	47.83	22.59	18.23
Test-2(5 mm. spigot, 14.3mm. vortex, 0.10MPa feed pressure)				
U/F	80	55.36	10.76	13.88
O/F	20	46.67	27.78	20.12
Feed	100	50.24	12.86	4.03

In the above two hydrocyclone test, cyclone diameter, overflow diameter, inlet diameter, volumetric percentage of solid in the feed, under flow opening diameter, effective cyclone length, specific gravity of solid and liquid were constant. So the cut point, $d_{50,}$ is dependent upon the total volume flow rate. It can be seen from the Table 7.2.1 that with a decrease in inlet pressure yield in the hydrocyclone underflow product decreased as the cut point d_{50} increases although with a better grade. This is due to the fact that a decrease in inlet pressure will cause the cut point to rise. This is because the centrifugal force on the particles will decrease, forcing fewer amounts of fine particles to the cyclone wall and hence reporting to the underflow. On the other hand, an increase in the yield at high inlet pressure is accompanied by an increase in the alumina and silica contents of the underflow. It was observed that the quality of the iron ore fines can be improved to about 60.28% Fe at 75% yield after this stage. The alumina and silica content of this concentrate are not acceptable are not from metallurgical grade point of view. In order to avoid multi- stage operation and conserve energy, a single stage operation involving Kelsey centrifugal jig (KCJ) was tried and the results obtained were quite promising.

Table 7.2.2 WHIMS test with hydrocyclone U/F product of Test 1 with
Wash water: 20 l/pm, Solid: 10%.

0.5 amp				
Product	Fe (%)	SiO_2 (%)	Al_2O_3 (%)	Yield (%)
Magnetic product	66.31	3.4	0.7	74
Non magnetic product	22.30	59.5	4.0	26
0.8 amp				
Magnetic product	63.72	4.4	0.5	76.52
Non magnetic product	24.64	55.2	6.2	23.48
1 amp				
Magnetic product	62.81	4.7	2.4	77.94
Non magnetic product	17.02	65	4.2	22.06
Feed (hydrocyclone (U/F)	60.28	8.9	3.32	100

The Hydrocyclone underflow of Test 1 for iron ore fines was treated in Wet High Intensity Magnetic Separator (WHIMS). A number of tests are conducted with variable current. The results under best conditions are given in Table 7.2.2. It may be seen from Table 7.2.2 that in the iron value can be raised to 66.31% with consequent lowering of alumina and silica values to 0.70% and 3.40%, respectively, with a yield of about 74%. The data indicate that alumina and silica rejection was quite high. The concentrate product (0.5 amp) is pellet grade material.

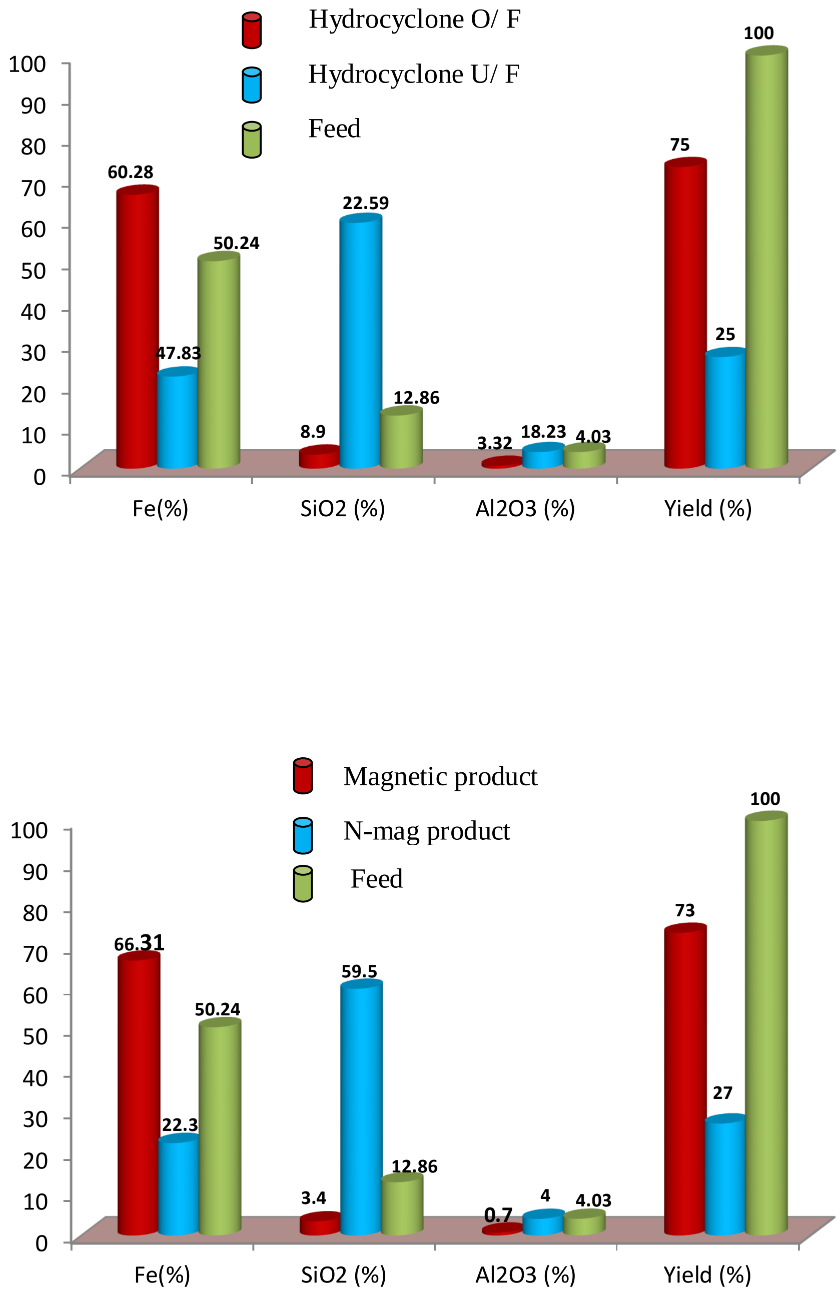


Fig 7.2.1 Graphical representation of a) Desliming of low grade fines in hydrocyclone (b) WHIMS test results of low grade iron ore fine sample (+150 micron) with 10% solids, 0.8 amp. current, and 20 L/pm Wash water,

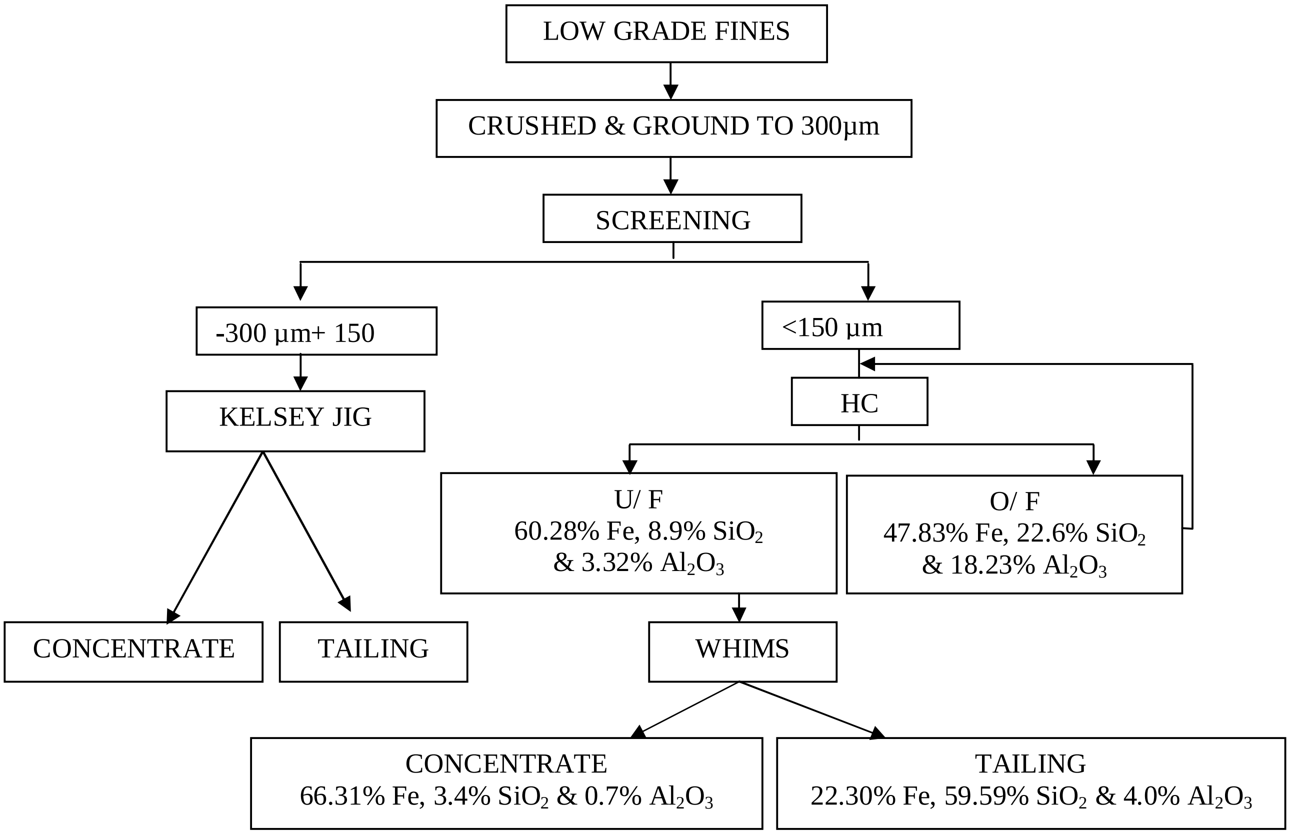


Fig.7. 2. 2. Traditional process flow sheet of the low grade iron ore fines.

7.2.2 EXPERIMENTS IN KELSEY CENTRIFUGAL JIG

The entire ROM was ground below 48 mesh and treated by enhanced gravity separation in a Kelsey Centrifugal Jig (KCJ). In order to study the separation process in KCJ a detailed experimental campaign was undertaken. Considering two factors, namely, Bowl Rotation/ spin frequency (rpm), Bed Pulsation 6 number of experiments was conducted. The factors and their respective levels for the experiments are shown in Table 7.2.2.1 Products from each experiment were analyzed for quantitative information. The experimental campaign was undertaken in a KJS. The details of experiments and results are discussed in the following section.

The influences of spin frequency, pulsation frequency were investigated. The other operating variables were kept constant during the experimental work. A screen with 425 micron opening (internal aperture) was used and magnetite was used as the ragging material. The size of the magnetite was taken as 0.853+0.6 mm. The hutch water flow rate was maintained at 25 L/min under all experimental conditions.

The feed to the KCJ was screened at a size less than the internal screen size to avoid pegging. In the present study, iron ore of size <300 micron were used as feed material. The particle size of the ragging material to be used depends on the pegging factor of the internal screen. Pegging factor is the ratio of internal screen aperture to the bottom size of the ragging material. It is recommended that for smooth operation pegging factor should be close to 0.6. Based on this, the minimum permissible size of the ragging material was estimated at 708 micron. Therefore, the minimum particle size of the ragging material used in this study was 850 micron. The weight of ragging material (300 gms) was kept constant throughout the entire operation.

Feed Rate: 60kg/hr.

Six numbers of tests were performed under varying conditions listed below.

Table.7.2.2.1 Experimental results under different operating conditions

Experimental Condition							
No of Tests	Bowl rotation	Pulsation	Ragging weight	Feed Rate (kg/hr)	Product	Yield%	Fe%
1	600	1000	300	60	Conc.	61.73	59.47
					Tail	38.27	46.20
2	590	1000	300	60	Conc.	46.7	65.90
					Tail	53.3	45.05
3	580	1000	300	60	Conc.	49.05	62.71
					Tail	50.95	46.01
4	580	970	300	60	Conc.	52.42	61.81
					Tail	47.58	45.70
5	590	970	300	60	Conc.	59.62	59.31
					Tail	40.38	47.09
6	550	980	300	60	Conc.	57.15	63.59
					Tail	43.85	42.09

7.2.3 RESULT & DISCUSSION

The Fe% obtained in the above set of experiments is in the range of 59-65% in comparison to 50.24% Fe in the feed. The result thus is quite encouraging. The results clearly indicate that by changing the operating variables, it is possible to get a higher concentrate or cleaner reject**.**

The two operating variables include

(1) Bowl Rotation/spin frequency (rpm)

(2) Bed Pulsation

Spin frequency is the rotational speed of the bowl or in other words it is the centrifugal force acting upon the flow pattern inside the jig. It affects the behavior of ragging bed as well as particle momentum.

The spin frequency has two contradictory effects.

(i) When spin is increased, there is an increase in gravitational force acting upon the ragging bed which in turn becomes more compact and rendering it less porous. As a result very limited quantity of material will penetrate the ragging bed results a decrease in yield but a high grade concentrate. It is inferred from Test-2 & 3, where at a higher frequency there is a drop in yield from 49.05% to 46.70% with an increase in grade from 62.71% to 65.90%.

(ii) With increase in spin frequency, the centrifugal force acting upon the particles increases. It leads to increase in particle momentum which increases the probability of passage of more particles trough the ragging bed. In this condition, there is an increase in yield of concentrate but dilution of grade happened. This can be inferred from Test-1 &2 and Test-1 & 3.In case of Test-1 & 2, with increase in frequency from 590 rpm to 600, there is a sharp rise in yield from 46.7% to 61.73% with Fe percentage decreases from 65.9% to 59.47. More or less similar relation is observed in Test-1 & 3.

By virtue of density, high density particles remain close to the ragging bed and vice-versa, but the particles with intermediate density (goethite) decide the efficiency of separation as they may increase/ decrease the yield there by affecting the concentrate grade.

(2) Pulsation: Pulsating strokes dilates the ragging bed thereby facilitating the movement of particles trough the bed material. In high pulsating condition, particles are prevented from attaining terminal velocity. Thus the differential acceleration between light and heavy particle is maintained. Pulsation stokes are more profound on lighter material. So probability of migration of lighter elements into concentration stream is feeble resulting low yield & high concentrate grade which is reflected in Test-3 & 4.

In high pulsation condition, the time difference between dilation and contraction get reduced, results sluggish movement of particles. As a result less quantity of material will penetrate decreasing the yield. It can be verified comparing Test-5 & 2.

Test No-6 shows the best result with 550 rpm & 980 Bed pulsations i.e. in low rpm and intermediate pulsation condition.

7.2.4 DISCUSSION

Yield and chemical assay of all KCJ products are presented in Table 7.2.2.1 for all the experiments. From this Table, it may be observed that spin frequency affects the porosity of the ragging bed as well as the momentum of the particles. It is established in the present work how the spin frequency needs to be controlled in order to achieve the target mass yield and grade of the products. The pulsation also has been shown to have significant influence on the porosity of the ragging bed as well as the differential acceleration of the particles. A better yield can be achieved through a high pulsation frequency. However, in order to get the best results a moderate level of pulsation is recommended.

Two processing flow sheets are developed for beneficiation of iron ore fines. Beneficiation studies using simple two-stage concentration operation, the feed with grade 50.24% Fe can be enriched to 60.28% Fe and 66.31 % Fe by hydrocyclone and WHIMS respectively. Thus, it may be concluded that a two-stage beneficiation route involving classification in hydrocyclone followed by magnetic separation/ single stage operation involving Kelsey jig is adequate to produce sinter/pellet grade concentrate from this low-grade blue dust/ low grade fines. This ore needs to be deslimed first followed by magnetic separation instead; enhanced gravity separation technique can be adopted to avoid multi- stage beneficiation.

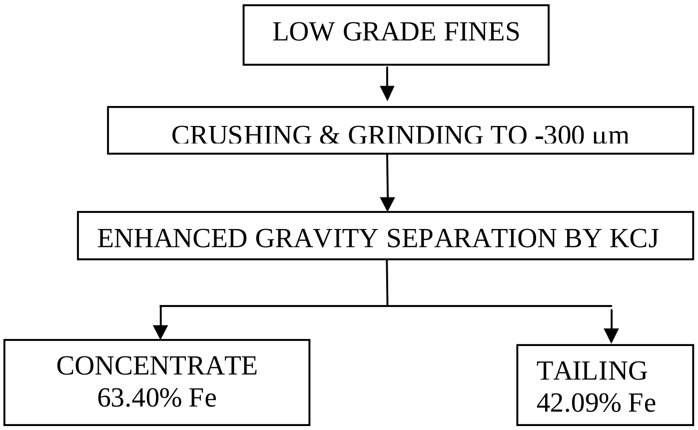


Fig.7.2.2.1 processing flow sheet of the low grade iron ore fines (Single stage operation).

7.3IRON ORE SLIME

During washing and sizing of the ore, slimes with less than 0.21 mm size are generated and discarded into the tailing pond. It is estimated that around 10 million tonnes of slimes are being generated in every year during the processing of hematite ore and lost as tailings containing around 48-62% of Fe. The slimes are ideal for generating the material for pelletization. They can also be used for preparation of sinter feed after microballing. The slimes had considerably low iron content. The density values of the gangue materials (silica and alumino-silicates) are in the range of 2.5-2.8 g/cc while that of hematite is 5.0-5.5 g/cc. Due to sharp density differences, concentration by gravity separation may be adequate to produce a concentrate grade that is acceptable for metal extraction from slime. If not, a further step involving magnetic separation may be required followed by flotation.

7.3.1BENEFICIATION OF IRON ORE SLIME

Detailed characterization of Barsua iron ore slime revealed that most of the alumina and silica is concentrated in the fraction less than 20 μm size. Therefore, it is imperative that a desliming operation to remove the ultrafine fraction would improve the grade. Hence, a beneficiation scheme was chosen involving classification followed by tabling and WHIMS (Fig. 7.3.1). The results of the unit operations are carried out in these slimes discussed in the following section.

7.3.1.1 Classification in hydrocyclone

The iron ore slime from Barsua was first treated in a 2"-hydrocyclone to remove the ultrafines. A number of tests were conducted by varying spigot and vortex finder diameters, pulp density, inlet pressure etc. After each test both the underflow and overflow were collected and analyzed for grade and yield. Two best results are shown in the Table 7.5.1. One of the tests was aimed at obtaining high grade of the underflow with a low yield (Test 1).

Test no. 2 was aimed at obtaining higher yield of the underflow albeit with a lower grade. However, in case of three stages of beneficiation (Fig. 7.3.1.1), hydrocyclone underflow of test 2 (Table 7.3.1.1) was used to obtain a reasonably high yield of the final concentrate.

From the test results (Table 7.3.1.1), it can be seen that most of the free kaolinite and quartz in Indian iron ore slimes are concentrated in the finer size fraction. Therefore, significant removal of impurities takes place during this operation.

Table 7.3.1.1 Hydrocyclone test results of iron ore slime

Test-1(5 mm. spigot, 14.3mm. vortex, 0.68MPa feed pressure)				
Product	Yield (%)	Fe (%)	SiO_2 (%)	Al_2O_3 (%)
U/F	69.56	57.56	5.70	3.89
O/F	30.44	43.56	7.12	10.30
Test-2(5 mm. spigot, 14.3mm. vortex, 0.10MPa feed pressure)				
U/F	79.56	50.33	9.32	7.47
O/F	20.44	36.56	23.79	23.79
Feed	100	54.70	8.32	11.08

7.3.1.2 Concentration of Hydrocyclone underflow using Wet High Intensity Magnetic Separator

The Hydrocyclone underflow of Test 1 for iron ore slime was treated in Wet High Intensity Magnetic Separator (WHIMS). A number of tests are conducted with variable pulp density, current and wash water flow rate. Under best condition of Current: 1Amp, wash water: 20 l/min. and pulp density of 10% solids the results are given in Table 7.3.1.2

7.3.1.3. Gravity separation of slime samples using Wilfley Table

To study the efficacy of Tabling for treating slimes, the Hydrocyclone underflow of Test 2 of Barsua was subjected to concentration in Wilfley Table. The test results are presented in Table 7.3.1.3. It was observed that quality of the slime could be improved significantly. However the concentration grade is about 62.48% indicating concentrate product is not a pellet grade material requiring further enrichment.

Table 7.3.1.2 WHIMS test with hydrocyclone U/F product of Test 1 with
1 amp current, Wash water: 20 L/ m, Solid: 10%.

Product	Fe (%)	SiO_2 (%)	Al_2O_3 (%)	Yield (%)
Magnetic product	66.31	3.4	0.7	74
Non magnetic product	22.30	59.5	4.0	26
Feed	57.56	5.70	3.89	100

Table 7.3.1.3 Wilfley Table test results of Hydrocyclone U/F of Test 2 with 10% solids,
0.25 inch inclination, 280 rpm Speed and 3 L/ m Wash water.

Product	Fe (%)	SiO_2 (%)	Al_2O_3 (%)	Yield (%)
Concentrate	62.48	2.1	1.5	65.53
Tailing	48.34	48.34	2.3	34.47
Feed	50.33	9.32	7.47	100

7.3.1. 4 Concentration of Tabling concentrate using Froth Flotation

The Tabling concentrate was subjected to flotation in a 2.0 litre Denver D-12 Sub-aeration flotation cell with MIBC as frother and soidum oleate as collector and sodium silicate as depressant. The test results are presented in Table 7.3.1.4. Substantial removal of silica and alumina could be obtained in flotation. It may be seen from Table 7.3.1.4 that in Barsua sample iron value is raised to 66.97% from a feed of 62.48% total Fe with consequent lowering of alumina and silica values down to 0.69% and 1.7% respectively.

Table 7.3.1.4 Flotation test of Tabling concentrate at a pH of 5.5 with 10% solids, 3 min. conditioning time, 2.5 kg/t collector (Sodium Oleate), 1.5 kg/t Depressant (Sodium silicate), 0.2 kg/t Frother (MIBC)

Product	Fe (%)	SiO_2 (%)	Al_2O_3 (%)	Yield (%)
Concentrate	66.97	1.7	0.69	68
Tailings	28.87	5.8	3.9	32
Feed (Tabling concentrate)	62.48	2.1	1.5	100

However, small mass of the particles leads to the particles entrainment in concentrate, low probability of collusion with a bubble, difficulty in overcoming the energy barrier between particle and particle and particle and bubble. The fine particles have high surface energy per unit area due to imperfect crystallization, increase cracks dislocation, edges as observed from SEM, which can lead to problem during flotation operation. The high surface areas of the slime particles leads to specific adsorption of reagents, increase hydration, rapid surface reaction, increase solubility, adsorption of large quantity of chemicals, undesirable coating of the valuable particles by ultrafine gangue particles and rigidity of froth [128]. High Fe loses in tailing during flotation of slimes is due to these reasons.

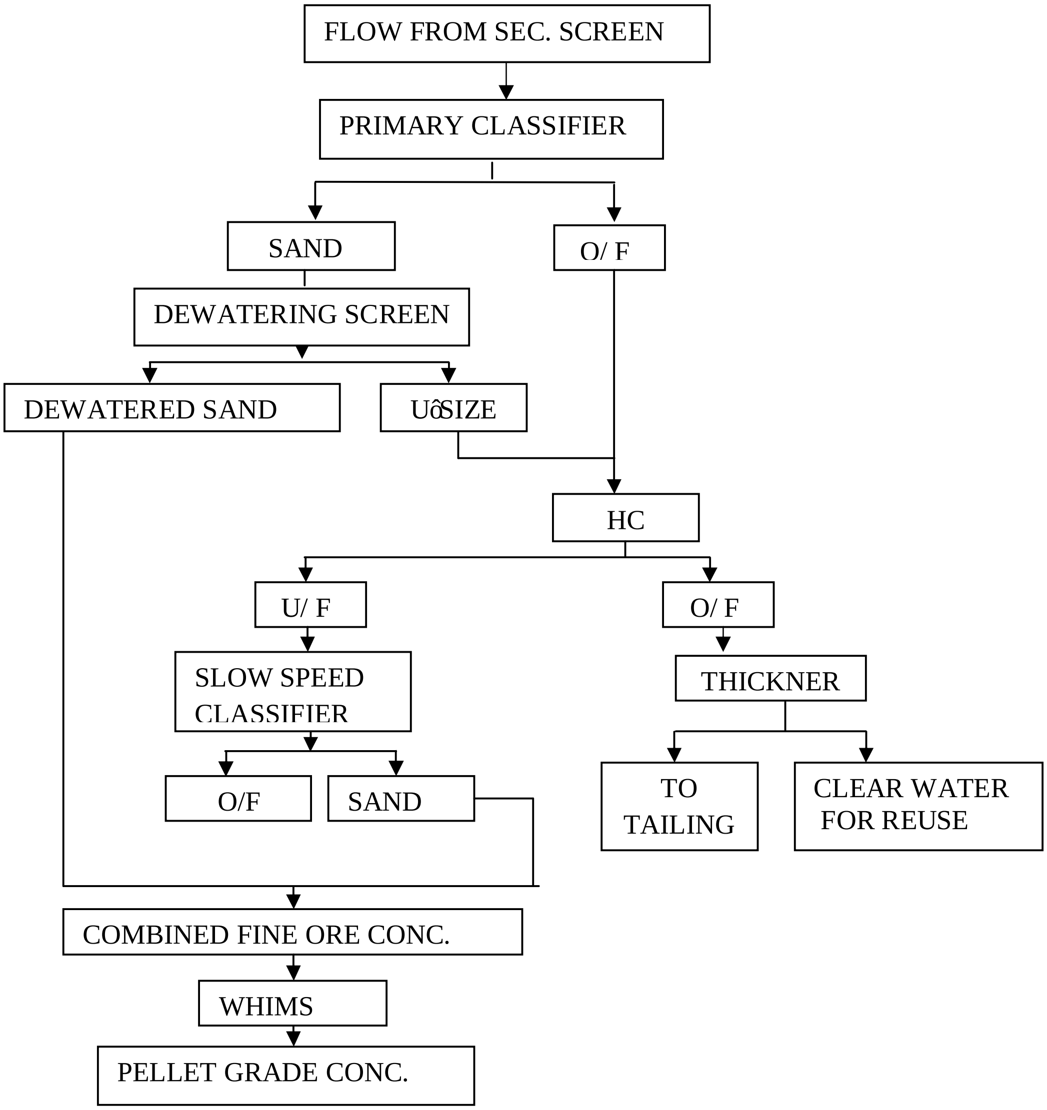


Fig.7.3.1 Traditional processing flow sheet of iron ore slime

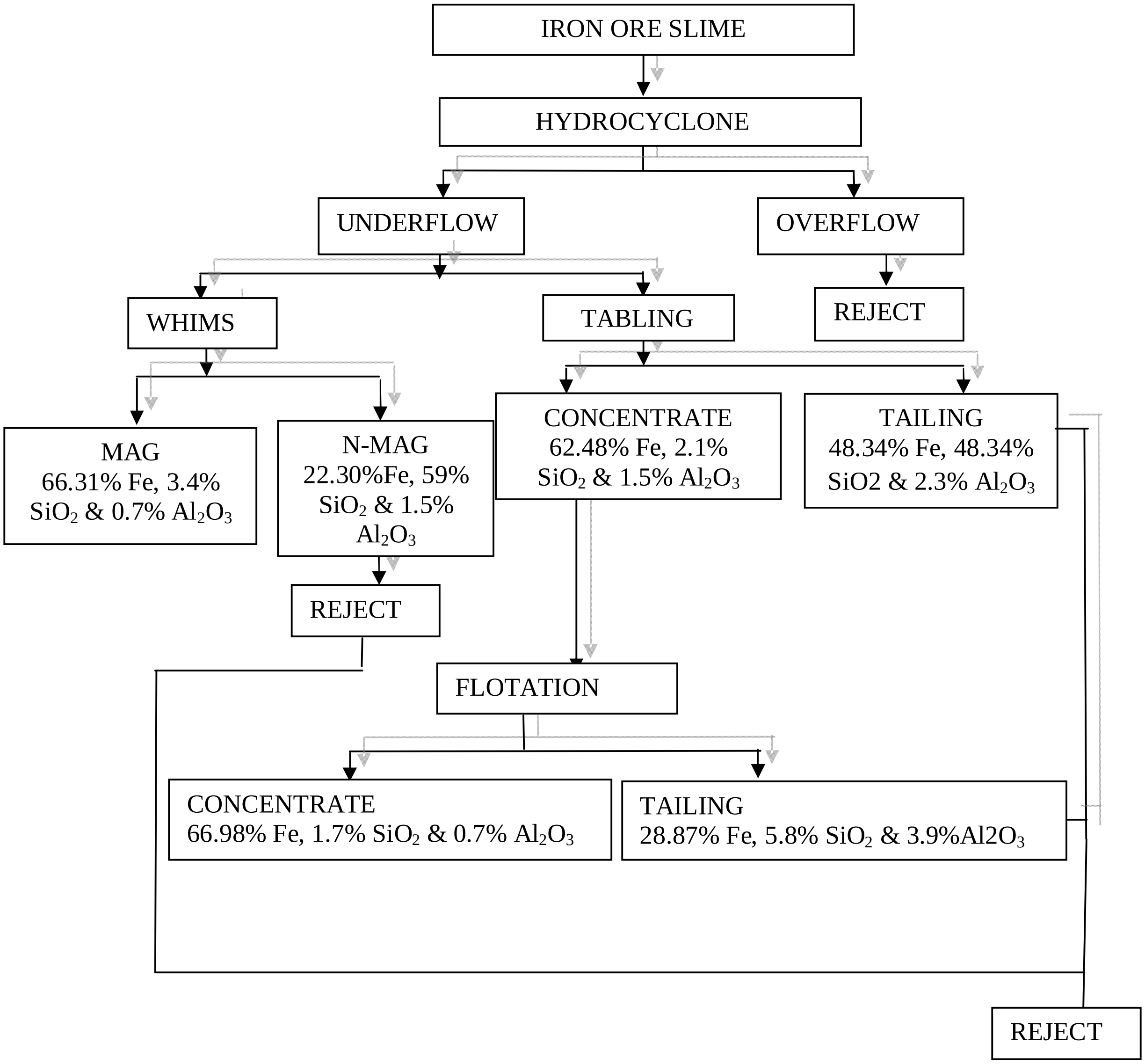


Fig.7.3.1.1 Processing flow sheet of Iron ore slime

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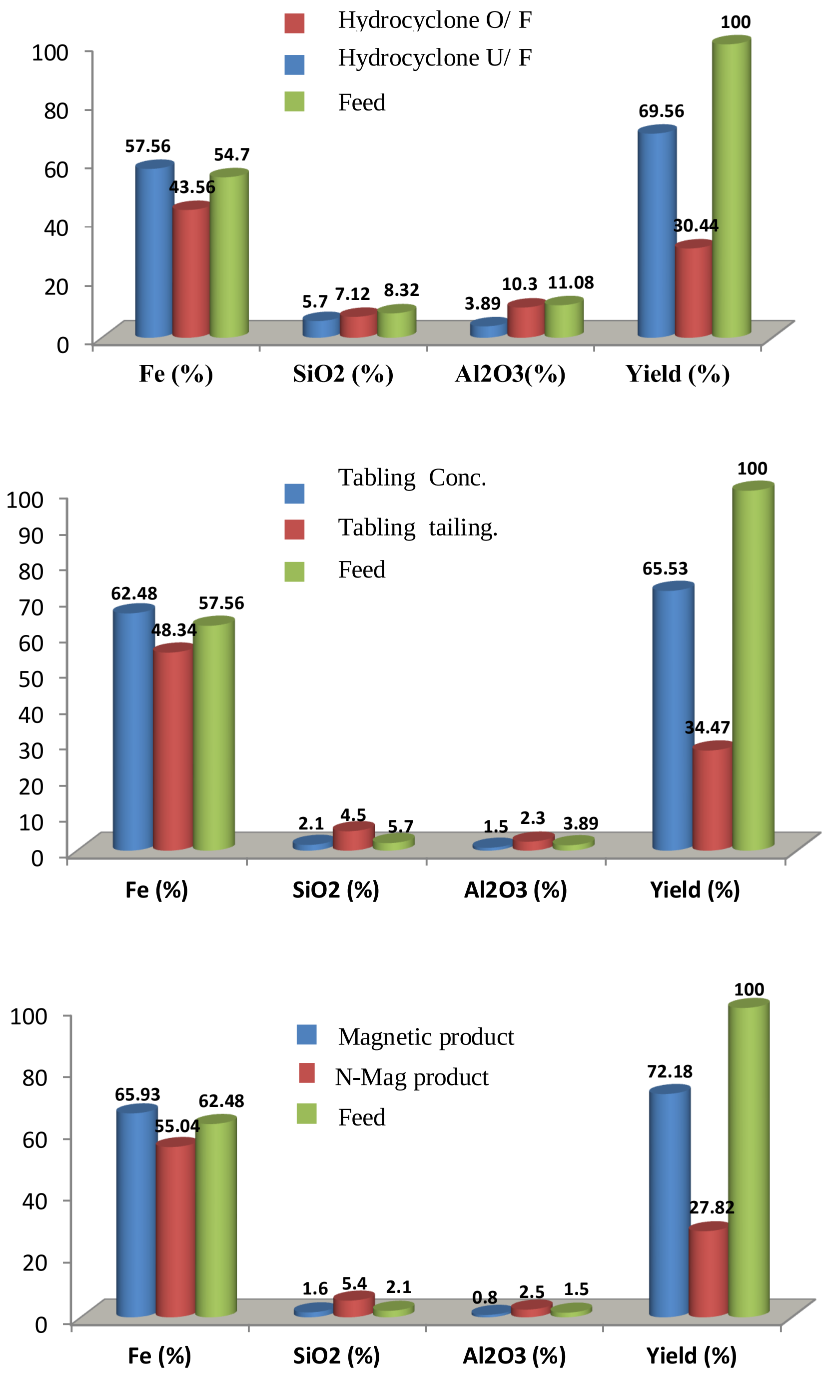

Fig 7.3.2 Graphical representation of a) Desliming of iron ore slime in hydrocyclone (b) Tabling result of hydrocyclone U/ F (c) WHIMS test results of iron ore slime sample (+150 micron) with 10% solids, 1 amp. current, and 20 L/pm Wash water.

7.3.2 DISCUSSION

Characterization studies of slime has been carried out and indicated that the sample from Barsua deposits contains porous and friable oxides and hydroxides of iron with kaolinite and quartz.In iron ore samples hematite mainly occurs as specularite with inter-granular micro-pore spaces. Goethite is abundant exhibiting secondary colloform texture in cavities along the weaker bedding planes. Such voids and inter-granular pore spaces along the weaker bedding plane are very fragile making the hematite and goethite friable during mining and processing. These friable particles break down and account for the iron content of the slime.

A flow sheet involving classification, gravity separation, magnetic separation and flotation is developed with a view to achieve the grade at reasonably high yield. The hydrocyclone underflow product of test 2 (lower grade but higher yield) is treated by gravity separation technique using Wilfley Table to exploit the differences in specific gravity. It is observed that quality of the slime could be improved significantly. However the concentration grade is about 62.48% indicating the requirement of further concentration process. The Tabling results indicate that better grade product can be obtained. The grade improved substantially from 50.3% to 62%. However to make the concentrate grade for pellet making, a fourth stage of processing has been applied. In the fourth stage the physico- chemical surface properties of the particles is used using froth flotation. The flotation results show that iron value in the sample can be raised to 66.97% with lowering of alumina and silica values to 0.69% and 1.7%, respectively. From the above discussion it may be concluded that a relatively simple flow sheets may be quite effective in producing pellet grade concentrate from such low grade iron ore slimes with a reasonable yield.

7.4 GOETHITE- LATERITIC ORE

Lateritic iron ores predominantly consists of iron in hydroxy form as goethite interlocked with kaolinite and gibbsite. Presence of significant amounts of impurities renders the ore low grade. These ores must be upgraded by thorough and complete processing after adequate comminution to attain liberation. The concentration criterion [146] for these ores is less than 2.5, reflecting the inefficiency of simple gravity separation in this case. These ores may be upgraded by advanced gravity separation techniques in the first stage. Further enrichment may be achieved using high intensity magnetic separation. If this stage also fails to achieve the required grade, froth flotation to remove the gangue could be used as the final concentration stage.

7.4.1 BENEFICIATION OF GOETHITE-LATERITIC ORE

Detailed characterization of the iron ore revealed that most of the impurities in the form of alumina and silica are concentrated in the finer size fractions while iron is concentrated in the coarser size fractions. Therefore, it is imperative that removal of ultrafines using a desliming operation would improve the grade. A beneficiation scheme was chosen involving desliming by simple washing, jigging followed by gravity separation. To study the beneficiation prospects of coarse particles a first stage of gravity separation by Jigging is carried out. Finally, further comminution and a second stage of Tabling operation and/or Kelsey jig Separation is employed to generate sinter/pellet grade concentrate. The three stage flow sheet (Fig 7.4.1) was designed for beneficiation of Goethite- lateritic ore. By simple washing the Fe values upgraded substantially, as shown in Table 7.4.1. Desliming improves the Fe % from 40% to 43% while reducing the silica and alumina content from 9.48 % and 19.97 % to 7.87 % and 14.97%, respectively.

The washed lumps, after desliming contains considerable amount of coarse ore pieces (> 3mm). They were crushed to -3000 εm size. The crushing operation generated significant amount of fines less than 853 εm (Table 7.4.2). The -3000 +853 εm size fraction contains 46% total Fe, 4.9% silica and 11.30% alumina. This size fraction was subjected to gravity separation by Jigging. Jigging result, as shown in Table 7.4.3, indicates that only small amount of gangues are rejected. The Fe% increased to 53.10% with a decrease in the alumina and silica content to 6% and 4.20%, respectively, by jigging. It is found that the resulting concentrate is still not acceptable feed material for pelletisation/sintering. Therefore, further concentration was required.

Table 7.4.1: Result of desliming operation

	Wt. (%)	Fe (%)	SiO_2 (%)	Al_2O_3 (%)
Feed	100	40	9.48	19.97
>100µm	75.4	43	7.87	14.97
<100µm	24.6	37.94	13.50	21.30

Table 7.4.2: Analysis of the crusher products

	Yield (%)	**Fe (%)**	**SiO_2 (%)**	**Al_2O_3 (%)**
Feed	100	43	7.87	14.97
-3000+853micron product	65.3	46	4.9	11.30
-853 micron product	34.7	35.32	8.9	19.81

Table 7.4.3: Jigging results of goethitic-lateritic ore

	Yield %	**Fe%**	**SiO_2**	**Al_2O_3 (%)**
Concentrate	79.12	53.10	4.2	6.0
Tailings	20.88	40.04	17.56	7.87
Feed	100	46	4.9	11.30

Liberation analysis of different ground size fraction of the iron ore suggested that grain size reduction to less than 300 μm size was necessary to achieve sufficient liberation of iron ore minerals from its gangue (Table 6.1). Therefore, the Jigging concentrate (-3000+853 µm) was subjected to further comminution.

To investigate the optimum particle size requirement for adequate enrichment, the iron ore was ground separately to three different finenesses, i.e., 300 μm, 200 μm and 150 μm. In order to study the efficacy of gravity concentration, these samples were subjected to concentration in Wilfley Table.

Experimental condition with 3ę deck slope, 1.68 cc. per cm/ sec. water flow rate was kept constant in all tabling experiments. The results obtained from the best tests are given in Table 7.4.4. It was observed that the quality of the ore improved significantly by tabling. Different concentration grade was obtained from the feed ground to different fineness. The concentrate grade improved to 56.29%, 59.57%, 61.01% Fe by processing the three feeds ground to 300 μm, 200 μm and 150 μm, respectively. Processing of 150 μm size ground material shows that the grade of the ore was improved from 53.10 % Fe to 61.01 % Fe (Table 7.4.4). The silica and alumina content of this concentrate were 3.05% and 2.01%, respectively.

Table 7.4.4: Tabling result of goethite-lateritic ore

Product	Feed Size		
	300μm	200μm	150μm
Fe (%)			
Conc.	56.29	59.57	61.01
Middling	45.25	42.60	37.89
Tails	42.22	39.61	31.61
SiO_2 (%)			
Conc.	5.12	4.86	3.05
Middling	5.78	6.68	9.37
Tails	10.16	9.93	10.24
Al_2O_3 (%)			
Conc.	4.65	3.02	2.01
Middling	7.51	5.98	8.11
Tails	8.55	8.48	8.42

7.4.2 DISCUSSION

Theoretically, effective gravity separation is possible when the concentration criterion (Wills, 1988) for these ores is greater than 2.5 (Equation 7.1.1).

$$\frac{D_h - D_f}{D_l - D_f} > 2.5 \qquad \text{-----------------------} (1)$$

where, D_h is the specific gravity of the heavy mineral, D_l is that of the light mineral and D_f is the specific gravity of the fluid medium. When the quotient is greater than 2.5, then gravity separation is relatively easy. As the value of quotient decreases, so the efficiency of separation decreases and below about 1.25 gravity separations are not economically feasible. The specific gravity of hematite is 5.5 to 6.5 whereas it is 4.1 to 4.3 for goethite. Specific gravity of kaolinite, gibbsite and quartz is in the range from 2.3 to 2.6.

In case of hematite ore, separation criterion as shown in Eqn. (1) is estimated to be in the range from 2.81 to 3.44. On the other hand, separation criterion in case of goethite ore is estimated to be in the range from 1.93 to 2.06. Due to high concentration of goethite, the separation efficiency decrease in case of wilfley tabling. As a result, grade dilutes, which also happened in case of jigging. The Tabling concentrate of 150micron is still needs further concentration either by EGS techniques or flotation.

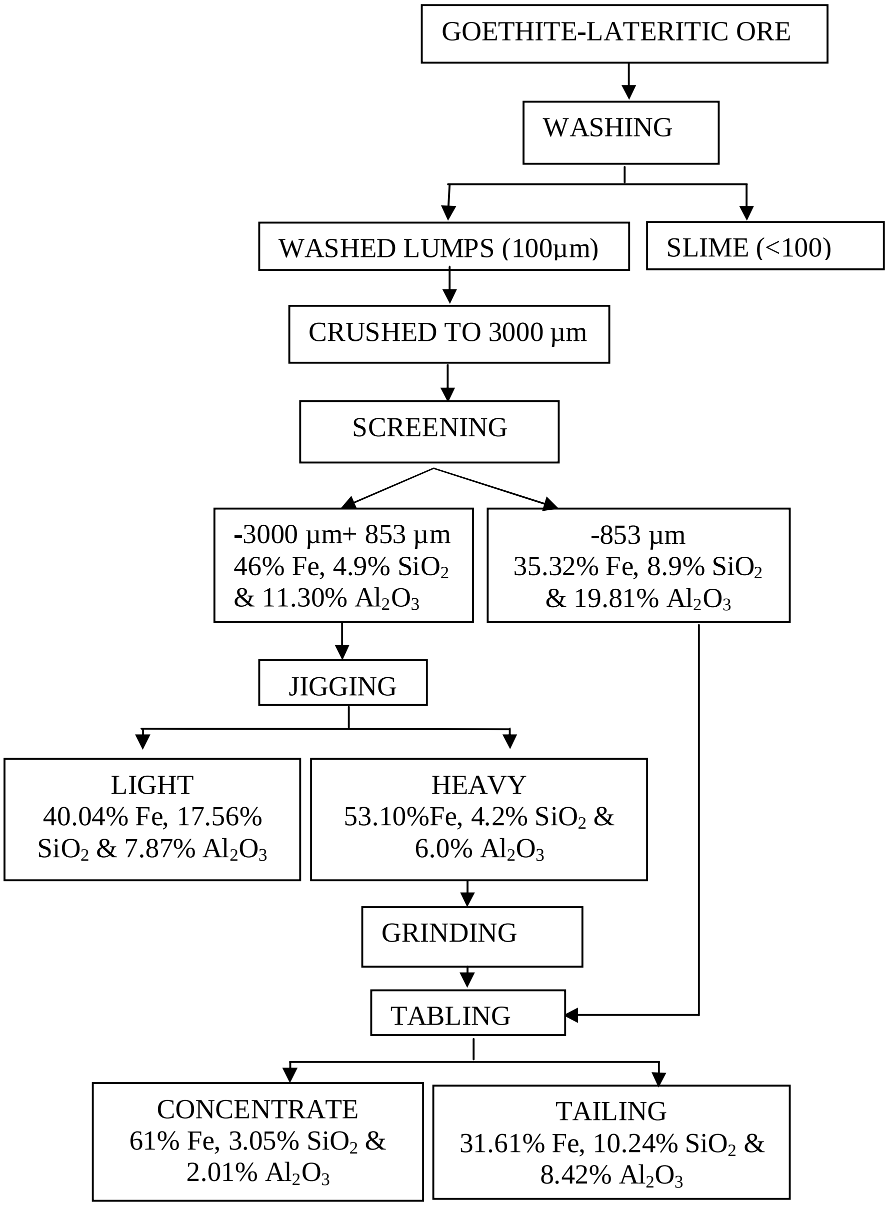

Fig 7.4.1. Processing flow sheet of the Goethite-Lateritic ore

CHAPTER VIII

CONCLUSION

CONCLUSION

The principal object of the present investigation was to provide an economical iron ore beneficiation process for the production of saleable concentrates which are acceptable to the steel mills because they meet the requirements of the mills. The different types of iron ores are characterized in detail with an implication on their beneficiation and utilization.
In view of the known capabilities and the known disadvantages of various prior art beneficiation methods, it is apparent that no single beneficiation process can be found which will lend itself to an economically feasible flow sheet for the production of acceptable saleable concentrates from semi-taconite ore, from low grade concentrates and waste products from previous separations, and other similar services of low grade iron minerals. Accordingly, the present invention is based upon the utilization of the advantageous characteristics of a combination of concentrating procedures. By utilizing several types of processing equipment, it is possible to sort the minerals in the ore so that advantage can be taken of the particular physical and chemical properties of each ore group by using a combination of concentrating procedures.

With high-grade Iron ore rapidly depleting, the necessity of Iron ore beneficiation is becoming a reality. Beneficiation of Iron ore is much more economical than getting rid of gangue at higher end of value chain like in BF or BOF / Electric furnace. It will cost 5 to 10 times more to remove gangue in BF / BOF or Electric arc furnace than in Beneficiation plant.

The pre-concentration of iron values in Banded Hematite Jasper can be achieved through gravity and high intensity magnetic separation. The pre- concentration efficiency of both gravity and magnetic techniques increase with decrease in feed size. The increase in both yield and grade with decreasing feed size suggests a preferential crushing mechanism of ore mineral at the ore-gangue mineral grain boundary which corroborates with the research work done on this subject. In case of Banded hematite jasper, the production cost is more as it requires multiple stages of crushing and grinding. The processing cost of `BHJ is approx Rs. 2500/- per tonne. At the same time the selling price of lump ore is around Rs.4, 600/- per tonne. In the present Research, beneficiation of BHJ was attempted. The pre-concentration of iron values at finer stage of flow-sheet development disables rejection of substantial quantity of silica (7%) mineral thereby increasing the load on grinding mill and processing cost as well. Further, the substantial reduction of silica and alumina content in the coarser size range of BHJ is processed then itôs commercially viable.

Traditional mineral processing techniques become increasingly inefficient as particles sizes are reduced, resulting in unacceptable grades. However, using techniques like jigging, dry high intensity magnetic separator (DHIMS), pre-concentration of iron values at a coarser stage can also be achieved. In case of banded hematite jasper, the enhanced gravity separator (Falcon Concentrator) produced substantial enrichment in the concentrate with 60% Fe.

In case of goethite-lateritic ore, Wilfley Table was found to be promising in reducing loss of fine iron particles and increasing the grade of the concentrate. A beneficiation scheme was framed involving desliming by simple washing followed by gravity separation. Finally, further comminution and a second stage of Tabling operation caused an enrichment of grade to 61% from 40% which needs further processing. Using Multi gravity separator/ KCJ, it can further be upgraded.

Table 8.1 Approximate cost of beneficiation of 1tonne of iron ore

Sl.No	Details	Rs/Ton
1	Electricity charges	60
2	Diesel consumption	48
3	Sub contractor	150
4	Maintenance	50
5	Spare & Wearing parts	100
6	Labour cost	30
7	major sub assembly cost	200
8	Water charges	5
9	Environment	5
10	Other	10
Total B.P Operation cost		658
Total Production cost Rs / Ton		1803(Inclusive of all ancillary works)

In case of low grade iron ore fines, the single stage unit operation is cost effective in comparison to the multi stage unit operations due to low operational as well as capital investment. The average production cost of 1 tonne iron comes around Rs.1, 803/- in conventional wet circuits (gravity separation, WHIMS etc.) and in single stage operation it comes around Rs.1, 560/- per tonne. The saleable price for 1 ton of finished product (0-5mm size, Fe >61%) is around Rs.3, 000/- per tonne. The profit cost analysis of low grade iron ore fines is quite economical.

In iron ore slime sample high percentage of liberated quartz occurs in lower size fraction suggesting that desliming classification would not be useful in this case. To make the concentrate grade for pellet making, a four stage processing was designed for iron ore slimes.

In case of iron ore slime, the feed grade is 54% Fe. Total average cost of finished concentrate is Rs 2, 250/- per tonne. Selling Price of Concentrate is approx Rs.3, 1600/- per tonne (64% Fe). The final concentrate can be used for pellet making. The production cost of pellet is approx ï Rs 4000/- per tonne (including the raw material cost). Selling price of Pellet is approx ï Rs.8, 000/- per tonne. The use of pellets in steel industry saves cost around Rs.1, 800/- per tonne. In case of slime, the concentrate from the wet high intensity magnetic separator can be used for pellet making (66.97% Fe, 1.7 SiO_2, 0.69 Al_2O_3) there by use of costly flotation agents can be avoided by avoiding the flotation in total.

In India, the Public Sector Undertaking (PSU) Mineral major i.e. National Mineral Development Corporation (NMDC) has raised the price of fines up to 3,160/- per tonne. NMDCôs move is an attempt to take advantage of domestic shortð supply scenario mainly after the partial ban in Odisha, India.

As per the present practice, in India, in order to produce one ton of fines (61% Fe), 2.5 ton of ore (46% Fe) will be required. Considering the cost of logistics and conversion to 61% Fe, the price of iron ore dumps have to be very low to make it cost-effective. If the cost of iron ore dumps are more than Rs.100 a tonne, it won't be viable to beneficiate it and use it as feedstock for blast furnaces. For captive miners, due to availability of good plant and machinery, low investment in variables as well, the production cost will remain same even though the cost of iron ore dumps increase beyond Rs.100/-. However, the price rise wonôt go well with private sector steel makers which do not have captive mines. There is a need of government intervention to patronize. Therefore the government should come forward to encourage others in particular, to the economic use of lean grade ore profitably. It will boost the national economy and generate scope of employment too.

ECONOMIC FEASIBILITY OF BENEFICIATION OF IRON ORE FINES

In case of low grade iron ore fines, the single stage unit operation is cost effective in comparison to the multi stage unit operations due to low operational as well as capital investment.

- The average production cost of 1 tonne iron comes around Rs.1, 803/- in conventional wet circuits (gravity separation, WHIMS etc.) and
- In single stage operation it comes around Rs.1, 560/- per tonne.
- The saleable price for 1 tonne of finished product (0-5mm size, Fe >61%) is around Rs.3000/- per tonne. The profit cost analysis of low grade iron ore fines is quite economical.

ECONOMIC FEASIBILITY OF BENEFICIATION OF IRON ORE SLIME

- In case of iron ore slime, the feed grade is 54% Fe.
- Total average cost of finished concentrate is Rs 2, 250/- per tonne.
- Selling Price of Concentrate is approx Rs.3, 160/- per tonne (64% Fe).
- If the concentrate is sold in the market then the profit comes to be Rs 910/- per tonne. The final concentrate can be used for pellet making.
- The production cost of pellet is approx ï Rs 4,200/- per tonne (including the raw material cost).
- Selling price of Pellet is approx ï Rs.6, 000/- per tonne.
- The use of pellets in steel industry saves cost around Rs.1, 800/- per tonne. So it is advisable to make pellets and to be sold in the market rather than selling the concentrates in the market.

SIGNIFICANT FINDINGS:

(i) The beneficiation of BHJ is yet to gather momentum in India. In the present Research, BHJ was upgraded successfully using four- stage concentration operation, the feed with grade 35.29% Fe could be enriched to 63.47% Fe by Tabling, EGS, WHIMS and flotation respectively. Beneficiating lean grade ores will not only augment the existing resource but at the same time it will help to achieve the zero- waste concept.

(ii) In case of low grade fines, the KCJ (Kelsey Centrifugal Jig) was found to be promising. Instead of going for multiple stages of concentration i.e. hydrocyclone followed by WHIMS, the entire ROM can be treated in one single unit operation resulting a better product grade from (50.24% Fe to 65.90%) which will lowers the operational cost and capital investment as well.

(iii) The beneficiation system of iron ore slime (with 65%) Fe has many advantages like

- It will maximize the quantity of saleable products out of existing mines with minimum investment.
- Improving the economics of operation
- Minimising the pollution.
- Conservation of mineral resources.
- Reduction of operation problems in slurry disposal system by reducing the quantity of solids.

REFERENCES

REFERENCES

1. ACC Report, (1997) Jilling Langalota Iron Ore Mines, Unpublished Result, p. 229.

2. Acharya, S. (1986) Textural evolution and mineralparagenesis in Precambrian BIF from sedimentation to metamorphism.Mineral Paragenesis. Theop.Publ Athens, pp. 443-469.

3. Acharya, S., (1993) New facts on the óHorse shoeò iron ore basin of Orissa and Bihar, India. ñIron Ore 2000 and Beyondò - International Seminar, SGAT, pp. 61-63.

4. Acharya, S., (2000) Some observations on parts of the Banded Iron-Formations of Eastern India. Pres.Address, 87th session, Ind. Sc. Cong. Ass., pp. 1-34.

5. Acharya, S., (2004) ñIron ore deposits of Orissa. Supra-or-Infra- to BIFsò, SGAT, Vol.5 (2), pp- 39-41.

6. Acharya,S. (2008) ñGenesis of Banded Iron Formations and associated iron and manganese ore deposits of Orissa-Jharkhand region, India and its role as exploration guideò, Sem. Proc., SGAT, Bhubaneswar, pp. 1-31,.

7. Acharya, S., Ahmed, S. I. S. and Sarangi, S. K., (1968) Carbonate facies of iron- formations, Orissa. Bulletin Geological Society of India, Vol.3, pp.41-44.

8. Akhtar R. Mira, Shabber H. Alvi a & V. Balaram.(2009) Geochemistry,petrogenesis and tectonic significance of the Newer Dolerites from the Singhbhum Orissacraton, eastern Indian shield, International Geology Review, Vol.53(1), 46-60.

9. Anupam. A., Singh.G., Raghav. P.K. and Suresh. N. (2010) Studies on beneficiation of BHQ samples by different methods, XI International Seminar onMineral Processing Technology (MPT-2010), Jamshedpur, pp.572-582

10. Arol, A. I., Aydogan, A., (2004) Recovery enhancement of magnetite fines in magnetic separation. Colloids Surf. A: Physicochem. Eng. Aspects, Vol.232, pp.151ï 154

11. Baijal, A. D. and Kumar, A., (2003) Importance of beneficiation in preparation of raw materials for iron and steel industry. Proceedings of the International Seminar on Mineral Processing Technology MPT-2003, pp.18-25.

12. Banerjee, A. K., (1974) ñOn the stratigraphy and tectonic history of the iron ore bearing and associated rocks of the Singhbhum and adjoining areas of Bihar and Orissaò. Jour. Geol. Soc. India Vol.15, pp.150-157.

13. Banerjee, A. K., (1977) On the Precambrian Banded Iron- Formation and manganese ores of Singhbhum region, Eastern India. Econ. Geo. Vol.72, pp.90ï 98.

14. Banerjee, P.K., (1982) ñStratigraphy, petrology and geochemistry of some Precambrian basic volcanic and associated rocks of Singhbhum district, Jharkhand and Mayurbhanj and Keonjhar district, Orissaò. Mem. Geol. Surv. India. Vol.111, pp.1-54.

15. Banerjee, P. K., Narasimha, M., Rao, S. M., Rai, S. K., China, M., Upadhyay, R. K., Dhar G. S. and Baija, A. D., (2005) ñBeneficiation characteristics of low grade flaky ores, Tata Search, pp.31-38.

16. Barley, M. E., Pickard, A. L., Hagemann, S.G., Folkert, S.L., (1999) Hydrothermal origin for the 2 billion year old Mount Tom Price giant iron ore deposit, Hamersley Province, Western Australia. Miner. Depos., Vol.34, pp.784ï 789.

17. Beukes, N.J. (1983) Geochemistry and sedimentology of a facies transition from microbanded to granular iron formation in the early Proterozoic Transvaal Supergroup, South Africa. Precambrian Res., Vol.47, pp.99-139.

18. Beura, D. (2002) Iron formation, Iron ores and associated rocks around Badampahar region, Mayurbhanj district, Orissa- their structures, stratigraphy and chemistry. Unpubl. Thesis, Utkal Univ., pp 200.

19. Beura, D. and Singh, P. (2005) Geological setting and mineral deposits of Archaean schist belt- A case study around Badampahar belt, north Orissa, India, Int. Sem.KhonKenUni. Thailand, pp.326-329.

20. Beura, D., Singh, P. and Acharya, S. (2007) BIF and iron ore: an academic perspective and commercial vision. Vistas in Geol. Res, Spl. Vol.6, pp.71-73.

21. Bhattacharya, H. N., Chakraborty, I. and Ghosh K. K., (2007) Geochemistry of some banded iron formations of the Archean supracrustals, Jharkhand-Orissa region, India. Journal of Earth Systems Science, Vol.116 (3), pp.245-259.

22. Chakraborty, K. L., Chakraborty, T. L. and Majumder, T., (1980) Staratigraph and structure of the precambriam banded iron formation and chromite-bearing ultramafic rocks of Sukinda Valley, Orissa. Jour. Geol. Soc. India, Vol.21, pp.398-404.

23. Chakraborty, K. L. and Majumder, T., (1986) Geological Aspects of the Banded Iron Formation of Bihar and Orissa. Journal, Geological Society of India, Vol.28, pp.109-133.

24. Chakravarthy, S., Bhatacharya, P., Chatterjee, S. S. and Singh, B. N., (2000) Utilization of Iron ore fines in alternative iron making processes ï An Indian Perspective. International Symposium Processing of Fines, P. 442.

25. Chepong et al.,(2012)Recovery of iron values from iron ore washing plant slimy tailing pond, XXVI International Mineral Processing Congress(IMPC) 2012 proceedings.

26. Clout, J. M. F., (2005) Upgrading processes in BIF-derived iron ore deposits: implication for ore genesis and downstream mineral processing. Applied Earth Science, (Trans IMM, Sec. B), Vol. 112, pp. 89-95.

27. Craig, J.R. and Voughan D.J., (1981). Ore Microscopy and ore petrography, Chapt. 11. A Willey Inter Science Publ., Vol.2, pp.94-299.

28. Das, B., Mohapatra, B. K., Reddy, P. S. R. and Das, S., (1995) Characterisation and Beneficiation of iron ore slimes for Further Processing,ò Powder Handling and Process, Vol7 (1), pp.41-44.

29. Das, B., Prakash, S., Mohapatra, B. K., Bhaumik, S. K., Narasimhan, K. S., (1992) Beneficiation of iron ore slimes using hydrocyclone. Mineral and Metallurgical Processing, Vol.9(2), pp.101ï 103.

30. De Wit and Ashwal, (1995, 1997) Greenstone belts, Oxford monograph on Geology & Geophysics, Vol.35 pp.803.

31. Donskoi, E., Suthers, S. P., Fradd, S.B., Young, J. M., Campbell, J. J., Raynlyn, T. D. and Clout, J. M. F., (2007) Utilization of optical image analysis and automatic texture classification for iron ore particle characterization. Minerals Engineering, Vol.20 (5), pp.461-471.

32. Dunn, J. A., (1929) The geology of north Singhbhum including parts of Ranchi and Manbhum districts. Geol. Surv. India, Mem. No. 54, pp.1-166.

33. Dunn, J. A., (1937) The mineral deposits of eastern Singhbhum and surrounding areas. Mem. Geom. Surv. India, Vol.69, pp.197-206.

34. Dunn, J. A., (1940) The Stratigraphy of south Singhbhum. Mem. GSI v. LXIII (3).

35. Dunn, J. A. and Dey, A.K., (1942) Geology and Petrology of Eastern Singhbhum and surrounding areas. Mem. Geol. Surv. India, Vol.69, 2, pp.281-456.

36. Dutta, A. and Nandy, N.C., (1964) Origin and structure of Noamundi and Joda East Iron ore deposits, Rept., 22nd Session, Int. Geol. Cong., Part-5.

37. Evans, C L, Wightman, E W, Manlapig, E V and Coulter B L, 2011. Application of process mineralogy as a tool in sustainable processing, Minerals Engineering, Vol.24 (12), pp. 1242-1248.

38. Galvin, K.P., Pratten, S.J., Lambert, N., Callen, A.M., Lui, J., (2002).Influence of a jigging action on the gravity separation achieved in a teetered bed separator. Minerals Engineering,Vol. 15 (12), pp.1199ï 1202.

39.Gaudin, A. M., (1987) Principles of Mineral Dressing, Tata McGraw-Hill Publishing Company Limited, Mohan Makhijani at Rekha Printers Pvt. Ltd., New Delhi, 554.

40. Ghosh et al., (2012) Characterization and assessment of low grade iron ores for their beneficiation from Jharkhand-Orissa region, india, IMPC Conference proceedings, pp.01503-01601.

41. Ghosh, G. and Mukhopadhyay, J., (2007) Reappraisal of the structure of the Western Iron Ore Group, Singhbhum craton, eastern India: Implications for the exploration of BIF-hosted iron ore deposits, Gondwana Research, Vol.12, pp.525-532.

42. Goswami, J. N., Mishra, S., Wiedenbeck, M., Ray, S. L. and Saha, A.K., (1995) 3.55 Ga Old zircon from Singhbhum Orissa Iron ore craton, eastern India. Curr. Sci., Vol.69, pp.1008-1011.

43. Gujraj, B., Sharma, J. P., Baldawa, A., Arora, S. C. D., Prasad, N., Biswas, A. K., (1983) Dispersionï flocculation studies on hematite-clay systems. Int. J. Miner. Process. 11, 285ï 302.

44. Gurulaxmi, S.N., Ghosh, T.K. and Mukherjee, A.K., (2010), ñState of Art Characterisation Study of Banded Hematite Jasper for the purpose of Beneficiationò, MPT 2010, XI International Seminar on Mineral Processing Technology.

45. Hagni, R. D., (1978) Ore microscopy applied to beneficiation. Miner. Engg., 30, 1137 - 1147.

46. Hanumantha Rao K., and Narasimhan K. S., (1985) Selective flocculation applied to Barsua iron ore tailing, Int. Jour. Miner. Process. 14, 67-75.

47. Harmsworth, R. A., Kneeshaw, M., Morris, R. C., Robinson, C. J., Shrivastava, P.K., (1990) BIF-derived iron ores of the Hamersley Province. In: Hughes, F.E. (Ed.), Geology of the Mineral Deposits of Australia and Papua New Guinea. Aust. Inst. Min. Metall. Monogr.: Melbourne, Vol.14, pp.617ï 642.

48. Holland H.D., (1973) The oceans: A possible source of iron in iron formations, Economic Geology, 68, 1169-1172.

49. Honaker, R. Q. and Mondal, K., (1999) Dynamic Modelling of Fine Coal Separation in a Hindered Bed Classifier, Coal Preparation, Vol.21, pp.211-232.

50. http://en.wikipedia.org/wiki/Goethite, 2008

51. http://www.fedmin.com/html/noteiron.pdf, 2008

52. Indian Minerals Yearbook (2011): Indian Bureau of Mines, Nagpur, pp.47

53. Indian Mineral Year Book, 2010, Indian Bureau of Mines, Nagpur, pp.47.

54. Iyengar, S. V. P. and Alwar, M. A., (1965) The Dhanjori Eugeosynclinal and its bearing on the staratigraphy of the Singhbhum, Keonjhar and Mayurbhanj districts. In D.N. Wadia commemorative volume. Mining Met. Institute India, 138-162.

55. Jain,V., Rai, B., V. Umesh. and Pradip, Processing of Alumina Rich Iron Ore Slimes Is the selective dispersion flocculation flotation the solution we are looking for the challenging problem facing the Indian iron and steel industry?, Transactions Indian Institute of Metals accepted for publication, in press, 2013.

56. James, H.L., (1954) Sedimentary facies iron formation. Economic Geology, 49, 253-293.

57. JCPDS data book (1980) Int. Centre of diffraction data, 1601, Pensylvania, U.S.A. .

58. Jones, H. C., (1934) The iron ore deposits of Bihar and Orissa. Geol. Surv. India Memoir, 63, 1098-1109.

59. Karmakar, N. C., Goyal, A, Sethi, R. and Gupta S.,(2011) Treatment of Coal mine effluent using Nonionic, Anionic and Cationic Flocculants- proc. of International conference on Technological challenges and Management Issues for sustainability of Mining Industries; 4-6 August, NIT- Rourkela, India, pp. 77-86

60. King, H. F., (1989) The rocks speak, Australasian Institute of Mining and Metallurgy, Monograph, Melbourne, Aus IMM. 15, 1-36.

61. Karmazin ,V. V., Bikbov, M. A. and Bikbov, A. A., (2002) The Energy Saving Technology of Beneficiation of Iron Ore. Magnetic and Electrical Separation,11,4, 211-224.

62. Klein,C., Hurlbut Jr, C. S., (1985) Manual of Mineralogy, 20 th ed., John Wiley and Sons, New York

64. Lascelles, D.F., (2007) Genesis of the Koolyanobbing iron ore deposits, Yilgarn Province, WA, Australia. Applied Earth Science: IMM Transactions section B, Vol. 116, 2, 86-93(8).

65. Luttrell, G.H., Yoon, R.-H., Knoll F.S., Kow, W.S. and Mankosa, M.J., 1995. ñFine Coal Cleaning Using the Multi-Gravity Separator,òProceedings, High Efficiency Coal Preparation: An International Symposium, SME, Littleton, Colorado, pp. 109-117.

66. Mahadevan T.M., (2002) Geology of Bihar and Jharkhand, In (Ed.) Geol. Soc. India, p.564.

67. Mahiuddin, S., Bandopadhyay, S., Baruah, J. N., (1989) A study on the beneficiation of Indian iron ore fines and slime using chemical additives. I. J. M. P, Vol.11, pp.285ï 302.

68. Majumdar, A. K., (2005) Kelsey Jig: A new technique for caol beneficiation, Trans of Mining, Geological & Metallurgical Institute of India.

69. Majumdar, T., (1985) Environment and petrogenisis of the Precambrian banded iron formation of the iron ore group eastern India. Geol. Sur. Fin. Bull., Vol. 331, pp.201-213.

70. Majumdar, T. and Chakraborty, K. L., (1979) Petrography and petrology of the Precambrian banded iron formation of Orissa, India and reformation of the bands. Sed. Geol. Vol.22, pp.243-265.

71. Majumder, T, Venkatesh, A. S, Kumar V., Upadhyay, R.K., (2005) Mineralogical Characterization of Iron Ores from Eastern India with Special Emphasis on Beneficiation of Iron Ore Fines. Iron ore 2005 Intl. conference, Fremantle, WA, Australia, 19-21, Sept, 2005. Trans Aus IMM special publication series no 8/2005, pp.227-231.

72. Mansar, R. J., Barley, R. W., Wills, B. A., (1991) The shaking Table concentrator-The influence of operating conditions and table parameters on mineral separation ï The development of a mathematical model for normal operating conditions,ò Mineral Engineering, Vol.4, 3-4, pp.369-381.

73. Mills, C., (1978) The Theory of gravity separation. Gravity separation Technology, Short Course, University of Nevada, Preprint.

74. Misra, B.K. et al., 2007, In: International Seminar on Iron ore Beneficiation & Pelletization, Ministry of Steel, New Delhi.

75. Mishra, D.P. and Das, S.K. (2013),òApplication of polymeric flocculant for enhancing settling of the pond ash particles and water drainage from hydraulically stowed pond ashò, International Journal of Mining Science and Technology, Elsevier, Vol. 23, Issue 1, pp. 21.

76. Misra, K. C., (2000) Understanding Mineral Deposits, Kluwer Academic Pub. p. 839.

77. Misra, S., (2006) Precambrian Chronostratigraphic Growth of Singhbhum Orissa Craton, eastern Indian Shield: An Alternative Model. Journal of Geological Society of India, Vol.67, pp. 356-378.

78. Misra, S. and Johnson, P. T., (2005) Geochronological Constraints on Evolution of Singhbhum Mobile Belt and Associated Basic Volcanics of Eastern Indian Shield. Gondwana Research, Vol.8, 2, 129-42.

79. Mondal, S. K (2009) Chromite and PGE deposits of Mesoarchean Ultramafic-Mafic suites within the greenstone belts of Singhbhum Craton, India,Journal Geological Society of India, Vol.73, pp.36-51.

80. Morris, R. C., (1985) Genesis of iron ore in banded iron formation by supergene and supergene-metamorphic processes, a conceptual model. In: Wolf, K.H. (Ed.), Handbook of Strata-Bound and Stratiform Ore Deposits, 13. Elsevier, Amsterdam, pp.73ï 235.

81. Morris, R. C., Horwitz, R. C., (1983) The origin of the iron-formation- rich Hamersley Group of Western Australia-deposition on a platform. Precambrian Res. Vol.21, pp.273ï 297.

82. Morris, R. C., Thornber, M. R., Ewers, W. E., (1980) Deep-seated iron ores from banded iron formation. Nature, Vol.288, pp.250ï 252.

83. Mukherjee, A. K, Bhattacharjee, D. and Mishra, B. K., (2006) Role of water velocity for efficient jigging of iron ore. Minerals Engineering, Vol. 19, 9, pp.952-959

84. Mukhopadhyay, D., (2001) The Archean Nucleus of Singhbhum: The Present State of Knowledge. Gondwana Research, Vol.4, 3, pp.307-318.

86. Murty, V G K, Rao, S Mohan, Rao, P V T, Lonial, S K, Chatterjee, Amit, 1995. Role of beneficiation in exploiting the raw material bas at Tata steel, Tata search, pp.24-31.

87. Murthy, V. N. and Acharya, S., (1975) Lithostratigraphy of the Precambrian rocks around Koira, Sundargarh Dt. Orissa, Geological Society of India Journal., Vol.16, pp.55-68.

88. Nayak B., Mohanty S., Rath R.K., Singh R. and Bhattacharyya K.K., (2010) 1st Int. Symp. on Process Mineralogy (Process Mineralogyô10), Nov. 10ï 12, Cape Town, South Africa.

89. Nayak, N. P and Pal, B. K., (2010) ñCharacterization of Solid Wastes generated from Bhilai Steel Plantôô Journal of mines, Metals & Fuels, Vol.(58), no.12, pp.31-37.

90. Nayak, N. P., Das. A and Pal, B. K., (2012) ñFeasibility of Beneficiation of Banded Hematite Jasper of Eastern Indiaò, International Journal of Engineering resource & Technologyò, Vol. 1, Issue 9.

91. Nayak, .N. P., A. Das and B. K. Pal., (2013) ñCharacterization Driven Processing of Indian Iron Ore Slime,ò International Journal of Research in Chemistry and Environment,Vol.3, pp.120-127.

92. Nayak, N. P and Pal, B. K (2013) ñseparation behaviour of iron ore fines in Kelsey centrifugal jigò, Journal of Minerals & Material characterisation & Engineering, Vol.1, Issue 3, pp. 85-89.

93. Olubambi, P. A. and Potgieter, J. H., (2005) Effectiveness of Gravity Concentration For The Beneficiation Of Itakpe (Nigeria) Iron Ore Achieved Through Jigging Operation. Journal of Minerals & Materials Characterization and Engineering, v. 41, pp.21-30.

94. Pirajno, F., Bagas, L., (2008) A review of Australia's Proterozoic mineral systems and genetic models. Precambrian Research, Vol. 166, pp.54-80.

95. Pirard, E., Lebichot, S., Krier, W., (2007) Particle texture analysis using polarized light imaging and grey level intercepts. International Journal of Mineral Processing, Vol. 84, pp. 299-309.

96. Polat, A & Frei, R., (2005) ñThe origin of early Archean banded iron formations and of continental crust, Issue, southern West Greenlandò, Precamb. Res., Vol. 138, pp. 151ï 175.

97. Powell, C. M. A., Oliver, N. H., Li, Z. X., Martin, D. M. B., Ronaszeki, J., (1999) Synorogenic hydrothermal origin for giant Hamersley iron oxide ore bodies. Geology Vol. 27, pp.175ï 178.

98. Pradip(1993), Scientific Design of a Selective Flocculation Process, Minerals & Metallurgical Processing, Vol.10(2), pp. 62-65.

99. Pradip, (1994) Beneficiation of alumina rich Indian iron ore slimes, Metals, Materials & Processes, Vol.6 (3), pp. 170-194.

100. Prasad, N., Ponomarev, M. A., Mukherjee, S. K., Sengupta, P. K., Roy, P. K., Gupta, S. K., (1988) Introduction of new technologies for beneficiation of Indian hematite ores, reduction

of losses and increase in their quality. In XVI International Mineral Processing Congress, Forssberg. pp. 369ï 1380.

101. Quast, K.B., (2000) A Review of hematite flotation using 12- Carbon chain collectors. Mineral Engineering, Vol. 13, pp. 1361-1376.

102 .Raghukumar et al., (2012) Beneficiation of Indian High Alumina Iron Ore Fines ï a Case Study, International Journal of Mining Engineering and Mineral Processing , Vol. 1, pp.94-100.

103. Rai, K. L., Sarkar S. N. and Paul, P.R., (1980) Primary depositional and diagenetic features in BIF and associated iron ore deposits of Noamundi, Sinnghbhum district, India. Mineral Deposita (Berl), Vol.15, pp.189-200.

104. Rakshit, K. N., (1997) Recovery of iron values from slimes and dewatering of the concentrate. Proceedings of the National Seminar on Processing of Fines, NML Jamshedpur, India, pp.77-83.

105. Rao, D. S., T. V. Vijaya Kumar, S. Subba Rao, S. Prabhakar and G. Bhaskar Raju., (2009) mineralogy and geochemistry of a low grade iron ore sample from Bellary-hospet sector, india and their implications on beneficiation, Journal of Minerals & Materials Characterization & Engineering, Vol. 8, No.2, pp 115-132.

106. Rath R., Mohanty S., Mohanta M., Singh R. and Bhattacharyya, K., (2010): Proceedings XXV Int. Mineral Processing Congress (IMPC-2010), Sept. 6ï 10, Brisbane, Australia, 1165.

107. Roy S. and Das, A., (2008) Characterization and Processing of low grade iron ore from Jilling area of India, Mineral Processing and Extractive Metallurgy Review, Vol.29, pp.213-231.

108. Roy, S., Das A. and Mohanty, M. K., (2007) Feasibility of Producing Pellet Grade Concentrate by Beneficiation of Iron Ore Slimes in India, Separation Science & Technology, Vol.42, pp.3271-3287.

109. Roy, S., Das A. and Venkatesh. A. S., (2006) Characterisation of Iron Ore Slimes from different deposits : A Comparative Study, Presented and published in the proceedings of National Conference on Frontier Areas in Geological & Technological Aspects of Fossil Fuel & Mineral Resourcesò, Dhanbad, 2-4 November, 2006, pp.171-179.

110. Roy, S., Das A. and Venkatesh. A. S., (2008) A comparative mineralogical and geochemical characterisation of iron ores from two Indian Precambrian deposits and Krivoy rog deposit, Ukraine: implications for the upgrading of lean grade ore. Applied Earth Science: IMM Transactions section B, Vol.117, 3, pp.125-147(23).

111. Saha, A.K., (1972) Petrogenetic and Structural evolution of the Singhbhum granitic complex, eastern India: Internat. Geol. Cong. 24 Montreal 1972. Proc., sec. 2. Pp.147-155.

112. Saha, A. K., (1988) Some aspects of the crustal growth of the Singhbhum- Orissa iron ore craton, eastern India. Ind. Jour. Geol, Vol. 60 (4), pp.270-278.

113. Saha, A. K., (1994) Crustal Evolution of Singhbhum North Orissa, Eastern India. Memoir, Geol. Soc. India, 341.

114. Sakamoto, T., (1950) The origin of the Precambrian banded iron ores. American Journal Science Vol.248, pp.449-474.

115. Saralya, D. L., Pelletisation- Need of the hour, Iron & Steel Review, pp 100-102.

116. Sarkar et al., (2007) Advanced gravity separators- a review of state of the art technology, Advanced Gravity Separation, POG (AGS-Souvenir), pp. 57-59.

117. Sarkar, S. N. and Saha, A. K., (1962) A revision of the Precambrian stratigraphy and tectonics of Singhbhum and adjacent regions; Quart. J. Geol. Min. Met. Soc. India, Vol.34, pp.97ï 167

118. Sarkar, S. N. and Saha, A. K., (1963) On the occurrence of two intersecting Precambrian orogenic belts inSinghbhum and adjacent areas, India. Geol. Mag., Vol.100, pp. 69-92.

119. Sarkar, S. N. and Saha, A. K., (1977) The present status of the Precambrian staratigraphy, tectonics and geochronology of the Singhbhum- Keonjahaar-majurbhanj region, Eastern India. Indian, Jour. Eart. Sci., pp.37-66.

120. Satpathy, B. & Beura, D., (2013) Establishment of Lithostratigraphy of Some Banded Iron Formations of Iron Ore Super group of Odisha, India, International Journal of Engineering and Innovative Technology (IJEIT) Volume 2, Issue 7, pp 146-150.

121. Sengupta, S., Corfu, E., McNutt, R.H. and Paul, D.K., (1996) Mesoarchaean crustal history of the eastern Indian craton: Sm-Nd and U-Pb isotopic evidence, Precamb. Res., Vol.77, pp. 17-22.

122.Sengupta, S., Paul, D.K., de Laeter, J.R., McNaughton, N.J., Bandyopadhyaya, P.K. and de Smeth, J.B. (1991) Mid-Archaean evolution of the eastern Indian craton: geochemical and isotopic evidence from the Bonai pluton. Precamb. Res., Vol.49, pp .23-37.

123. Sharma, M., Basu, A. R. and Ray, S. L., (1994) Sm-Nd isotopic and geochemical study of the Archean tonalite-amphibolite association from the eastern Indian craton. Contrib. Mineral. Petrol., Vol. 117, pp. 45-55.

124. Shivamohan, R. and Forssberg, E., (1985) Principles of Tabling. International Journal of Mineral Processing, Vol.15, pp.281-295.

125.Singh, R. K. & Das, A., (2012) ñStudy of Separation Features of Fine Coal Cleaning in Kelsey Centrifugal Jig,ò 26th International Mineral Processing Congress, New Delhi, September 2012, pp. 5047-5056.

126. Singh, R., Mehrotra, S.P., (2007) Beneficiation of iron ores for iron & steelmaking,, Steel Tech Vol.1 pp.17.

127. Sinha, S., Bhattacharyya, R., Banerjee, R., (2007) Surface iron ore mining in eastern India and local level sustainability, Resources policy Elsevier, Science Direct, Vol 32 (Issue 1-2), pp. 57-68.

128. Sivamohan, R., (1990) The problem of recovering very fine particles in mineral processing- a review. Inter. Jour. Min. Process, Vol.28, pp.247-288.

129. Song, S., Lu, S., Lopez-Valdivieso, A., (2002) Magnetic separation of hematite and limonite fines as hydrophobic flocs from iron ores. Miner Eng., Vol.15, pp.415ï 422.

130. Spencer, E., and Percival, F. G., (1952) Structure and Origin of Banded Hematite Jasper Singhbhu , India. Economic Geology. Vol.47, pp. 365-383.

131. Sreedhar et al., (2009) Evaluation of gravity spirals for beneficiation of Banded Hematite Jasper iron ore of India, AusIMM, Iron Ore 2009.

132. Srivastava, M. P., Pan, S. K., Prasad, N. and Mishra, B. K., (2001) Characterization and processing of iron ore fines of Kiriburu deposit of India. International Journal of Mineral Processing, Vol.61 (2), pp.93-107.

133. Svoboda. J., (1994) The effect of magnetic field strength on the efficiency of magnetic separation. Miner. Eng. Vol.7, pp.747-757.

134. Svoboda, J., Fujita, T., (2003) Recent developments in magnetic methods of material separation. Miner. Eng. Vol.16, pp.785-793.

135. Svoboda, J. and Ross, V. E., (1989) Particle capture in the matrix of a magnetic separator. Int. J. Miner. Process. Vol.27, pp.75-94.

136. Taylor, D., Dalstra, H. J., Harding, A. E., Broadbent, G. C. and Barley, M. E., (2001) Genesis of high grade hematite orebodies of the Hamersley Province, Western Australia. Economic geology, Vol. 96, pp.837-873.

137. Trivedi, S. and Samanta, A., (2002) Development of User Friendly Software for Fluidized Bed Indian Chemical Engineering Congress (CHEMCON 2002), December, Hyderabad, India.

138. Tucker, P., (1995) Modelling wet high intensity magnetic separation: A case study. Mineral. Eng. Vol.7, pp.1281-1300.

139. Tucker, P., (1994) ñModeling the Kelsey Centrifugal Jig,ò Mineral Engineering, Vol. 8, No. 3, 1995, pp. 333-336.

140. Upadhyay, R.K. (2008) Iron Ore Resources: Their Conservation,Value addition and Impact on Iron and Steel Industry: Tata Search, Vol.1, pp.197-205.

141.Upadhyay, R.K. et al.,(2009) Relevance of geological aspects and ore mineralogy for selecting beneficiation methods for processing of eastern Indian iron ores. Jour. Min. Proc. Extr.Metl. (Trans. Inst. Min. Metall. C), Vol.118, pp.49-59.

142.Upadhyay, R. K., Asokan, S and Venkatesh, A. S., (2011) Mode of Occurrence of Phosphorus in Iron Ores of Eastern Limb, Bonai Synclinorium, Eastern India, Journal geological society of indiaVol.77,pp.549-556.

143. Upadhyay, R. K., Venkatesh, A. S., (2006) Current strategies and future challenges on exploration, beneficiation and value addition of iron ore resources with special emphasis on iron ores from eastern India. Applied Earth Science (Trans.IMM, Sec. B), Vol.115, pp.187-195.

144. USGS, 2013; Mineral Commodity Summaries, January 2006, Posted on : January 26, 1:21 PM, http://minerals.usgs.gov/minerals/pubs/mcs/2013/mcs2013.pdf.

145. Iron & Steel- Vision 2020.

146. Wills B. A. and T. Napier-Munn, ñMineral Processing Technology,ò Elsevier Science & Technology Books, 2006.

147. www.c-tempo.org

148. www.ibef.org

149. www.fedmin.com, 2008

150. www.worldsteel.com.org.

151.www.nmdc.co.in/presentations%20by%20others/Ug%20Mining_NMDC%202008_Asian%20Mining%20Congress.ppt

152. www.steel.nic.in.

153. Yang et al., (2003) Iron ore beneficiation with packed column jig, Journal of Minerals & Materials Characterization & Engineering, Vol. 2, pp43-51

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M.Tech(Mining Engg.)-NIT, Rourkela, Odisha CGPA: 9.13/ 10 2006-2008

M.Sc(Geology) -Utkal University, Odisha 80% 2001-2003

PROJECTS:

- M.Tech project-ñCHARACTERIZATION AND UTILIZATION OF SOLID WASTES GENERATED FROM BHILAI STEEL PLANTò

Dissertation The purpose of the project is to characterize various types of solid wastes generated from Bhilai steel plant in order to recover metal values from waste to justify the zero- waste concept.

- Did a project titled ñ**Effect of Trace element concentration on auto-oxidative tendencies of clean coal”** (Septô06-Julyô07) sponsored by MHRD, Govt of India.

- Associated with **Usha Martin** group to establish a Beneficiation Plant (Iron Ore) and a captive Sinter Plant.

Ph.D

The Research work is entirely focussed on the enrichment of lean grade iron ores of Horse- shoe synclinorium i.e. Singhbhum-North Orissa Craton

- **Noteworthy up gradation of Banded Hematite Jasper from 35% Fe to 64% Fe with 78% yield has completed so far.**
- **Successive up gradation of low grade fines in Kelsey jig from 54% Fe to 65% Fe (Single stage operation).**

LIST OF PUBLICATIONS:

- Nayak, N. P (2013) ñMineralogical constraints in beneficiation of Low grade Iron ores of Barsua, Eastern Indiaò accepted in International Journal of Engineering and innovative Technology.

- Nayak, N. P., Das.A and Pal, B. K (2013)EGS: A new era in beneficiation of Lateritic ore communicated in International Journal of Mining and Mineral Engineering

- Nayak, N. P., Das.A and Pal, B. K (2013) Beneficiation of Banded Hematite Jasper using Falcon Concentrator: An alternative to Iron ore Resources, *Research Open Journal of Mineral and Mining Engineering Vol. 1, No. 6, October 2013, PP: 08 – 14*

- Nayak, N. P., Das.A and Pal, B. K (2013) ñCharacterization Driven Processing of Indian Iron Ore Slime, *International Journal of Research in Chemistry and Environment, Vol.3, Issue 2, pp.120-127.*

- Nayak, N. P and Pal, B. K (2013) ñseparation behaviour of iron ore fines in Kelsey centrifugal jigò, *Journal of Minerals & Material characterisation & Engineering, Vol.1, Issue 3, pp.85-89.*

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- Nayak, N. P., Das.A and Pal, B. K (2013) ñCharacterization and processing of low grad iron ore fines from jhilling area of india communicated in *International Journal of Engineering Science and Advanced Technology*

- Nayak, N. P and Pal, B. K (2013) ñPelletisation in Indian context:-Need of the hourò, *Journal of Mine, Metal & Fuels", Volume61*

- Nayak, N. P., Das. A & Pal, B. K (2012) ñFeasibility of Beneficiation of Banded Hematite Jasper of Eastern Indiaò, published in *International Journal of Engineering resource & Technology", Vol.1, Issue 9, pp.01-11.*

- Nayak, N. P and Pal, B. K (2011) ñFeasibility of Beneficiation of Low Grade Iron Ore Finesò, ACE, 2011, *International Conference on Advances in Environmental Chemistry*, 16-18, November, Aizawl.

- Nayak, N. P and Pal, B. K (2011) ñEcofriendliness vis-a-vis Utilisation of low grade Iron oreò *Technological Challenges & Management Issues for sustainability of Mining Industries (TMSMI*), 4th-6th August, 2011, NIT, Rourkela.

- Nayak, N. P and Pal, B. K (2010) ñCharacterization of Solid Wastes generated from Bhilai Steel Plantò, *Journal of mines, Metals & Fuels,* vol. (58), no.12, pp.31-37 (2010).

- Nayak, N. P and Pal, B. K (2009) ñIsotopic effect using for exploration of Coal, Ore, Oil and Gas Depositsò, *Proc. Of International Conference on Energy and Environment*, 19-21 March

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