

2.0 General Geology, Mineralogy, Ore Genesis, Impurities and Classification

2.1 GENERAL GEOLOGY

Iron ore occurs in different geological formations in India, ^(1,2,3) but the most important deposits belong to the pre-Cambrian age. However, the later formations especially Gondwanas and the Deccan Traps contain ores which are comparatively of little importance in the present day, though they were once used in

the indigenous furnaces. But when high grade ores will deplete and technological advancement will take place, the same may again be used by future generation. The geological setting of Indian iron ore formations together with the nature of ores and the regions in which the important deposits occur is shown in Table 2.1. ⁽¹⁾

TABLE 2.1: GEOLOGICAL SETTING OF INDIAN IRON ORE FORMATIONS

Formation	Nature of ore	Occurrence
Quaternary	Laterite	Many States-derived from many formations including Deccan Traps
Tertiary Miocene & Eocene	Ironstones	South India-Travancore, Malabar, etc. Assam- N E districts. U.P.- Kumaon
Jurassic Rajmahal Trap (intertrappean beds)	Ironstones	West Bengal, Bihar-Rajmahal, Birbhum
Gondwana Barakar Mahadeva Ironstone shales Triassic	Ironstones & siderite Siderite Ironstone & siderite Haematite and goethite	West Bengal-Birbhum Bihar-Auranga coalfield West Bengal-Raniganj Coalfield, Kashmir
Cuddapah Bijawar Gwalior	Haematite & ferruginous quartzite	Madhya Pradesh- Gwalior, Indore, etc. Andhra Pradesh-Cuddapah
Pre-Cambrian Basic & ultrabasic rock Granodiorite Granite Banded Iron Formation	Titaniferous & vanadiferous magnetites Apatite-magnetite rocks Magnetites(residual) Haematite(Massive shaly, powdery, etc.	Bihar-S.E.Singhbhum Orissa-Mayurbhanj Singhbhum Assam-Jaintia Hills, Kudremukh Orissa-Sundergarh, Keonjhar, Mayurbhanj; Karnataka-Shimoga, Bellary-Hospet, Dharwar, etc. Bihar-Singhbhum(West) Maharashtra-Ratnagiri, Chandrapur, Madhya Pradesh-Bastar (Bailadila), Durg, Jabalpur
Banded Iron Formation (metamorphosed)	Magnetite-quartzite	Tamil Nadu-Salem, Tiruchirappalli, A.P.-Guntur, Karnataka-Shimoga, Chikmagalure, etc Himachal Pradesh- Mandi

2.1.1 Description of Formations

2.1.1.1 Pre-Cambrian

The most important iron ore deposits of India are those associated with the banded haematite jasper/quartzite of the Dharwarian formations of South India and their equivalents of the Iron Ore Series found in Northern India. The ores are derived from the enrichment of banded ferruginous rocks by the removal of silica. The orebody generally forms the tops of the ridges and hillocks which are often of great magnitude. Most of them contain high grade ores near the surface, with an iron content of over 60 percent and are associated with even larger quantities of low grade ores. Where metamorphosed regionally or by igneous intrusives, these banded haematite jaspers have been converted into banded-quartzite-magnetite rocks which also attain considerable importance in certain areas in Tamil Nadu and in Southern Karnataka. These ores are of low grade, as they occur, containing only about 35 to 40 percent iron, but are amicable to concentration after crushing to a suitable size. At some places in Singhbhum and Mayurbhanj districts, titaniferous magnetite bodies are associated with basic and ultrabasic intrusives. These deposits are considered to be of ortho-magmatic origin. The copper belt of Singhbhum contains apatite-magnetite ores associated with granodiorite.⁽¹⁾

2.1.1.2 Cuddapah

The Bijawars of Central India and the Pulivendla quartzites of Cuddapah district in Andhra Pradesh contain workable deposits of rather small size. They seem to be locally enriched portions of ferruginous formations.⁽¹⁾

2.1.1.3 Vindhya

No useful deposits are known in these formations though some sandstones are to some extent ferruginous. Occasional pockets and concretions of limonite are associated.

2.1.1.4 Gondwanas

The Barakar formations in rare instances contain concretionary masses of limonite. In the Auranga Coalfield in Bihar, clay-ironstones are found in these formations. Some of these

deposits appear to have been derived from the original carbonate ore by oxidation and hydration. The ironstone shale stage, particularly of Raniganj Coalfield, contains considerable amount of clay. Ironstone derived from siderite is irregularly distributed as thin lenses in the formation. At some places, iron ore lenses and concretions are reported to form 5 to 7 percent volume of strata. In the succeeding Raniganj-Kamthi group, there is much disseminated iron to produce the prevailing red tints in the sandstones, but nowhere sufficient concentration of the material to constitute workable ore is found.⁽¹⁾

2.1.1.5 Jurassic

The inter-trappean beds of Rajmahal Hills contain thin beds and concretions of ironstone which were formerly worked for smelting in small indigenous furnaces.⁽¹⁾

2.1.1.6 Deccan Traps

The tropical weathering of Deccan Traps at and near the surface has given rise to massive beds of laterite which at many places is fairly rich in iron, perhaps averaging 25 to 30 percent of the metal. The laterites also contain deposits of titaniferous bauxite. They are likely to assume importance in future when attention is focussed on lower grade ores. It is known that the Late Sir Cyril Fox conducted some experiments to smelt laterite to obtain pig iron. Laterite also occurs over gneissic rocks in Malabar and Travancore and over the Rajmahal Traps in Bihar. The limonitic material from laterite, often forming rich concretions, has been won and smelted by the indigenous artisans for many centuries. At present, however, they are of little value as ores, because the rich haematite ores of the pre-Cambrian formations are available in abundance.⁽¹⁾

2.1.1.7 Tertiary

The Nahan series of Siwaliks in Uttar Pradesh and Assam Himalayas, the Tipam series of Upper Assam and the Rajahmundry, Cuddalore and Varkala sandstones of Tamil Nadu and Kerala all contain fairly rich concretions of ironstone which were formerly used as ore in the respective regions. They are of the Miocene to Pliocene age.⁽¹⁾

2.2 MINERALOGY

Iron ore is regarded as naturally occurring mineral that is used for extraction of metallic iron under existing economical and technological conditions. The term also includes material that may similarly be used as a result of changes in available supplies, technologic improvement and economic conditions. Accordingly, an iron-bearing mineral which is not an ore today may turn into ore in future due to improved economical and technological factors leading to available supplies, etc.⁽³⁾ The composition, physical structure, and amenability are the properties essential for the concentration of the iron ore. Iron, an abundant element, occurs in variable amounts in many minerals. However, few of them contain appreciable amount of iron from which iron can be

economically obtained at the current time or in future.⁽³⁾

Iron forms a large variety of mineral oxides, hydrated oxides, carbonates, sulphides, silicates, etc. Amongst many iron-bearing minerals, most commonly met with in iron ores are haematite and magnetite (both oxides) followed by goethite or limonite (hydrated oxides). These iron-bearing minerals form the principal constituents of iron ores along with silica, alumina, lime and magnesia minerals present in large quantities. In addition, iron ore contains other elements either as constituents of the iron-bearing minerals themselves or as separate entities.

A list of common iron-bearing minerals along with their chemical composition, iron content, specific gravity, hardness and colour is given in Table 2.2.

TABLE 2.2: LIST OF COMMON IRON MINERALS⁽³⁾

Mineral	Composition	Iron content (percentage)	Specific gravity	Hardness	Colour
NATIVE IRON OXIDES	Fe	100	7.3-7.87	—	Steel grey to red
Haematite (alpha) & Martite	α -Fe ₂ O ₃ (Haematite pseudomorphous after magnetite)	69.9	4.9-5.3	6.5	Steel grey to red
Turgite	2Fe ₂ O ₃ ·H ₂ O	66.1±	4.2-4.7	6.5	Brown to red
Goethite (Limonite)	HFeO ₂	62 ±	3.3-4.3	5.5	Brown to yellow
Lepidocrocite	FeO(OH)	62 ±	3.3-4.3	5	Brown, reddish brown
Ilmenite	FeTiO ₃	29.4	4.72	5-6	Black, brown-black
Meghemite (gamma)	γ-Fe ₂ O ₃	69.9	4.88	5	Brown
Magnetite	Fe ₃ O ₄	72.4	5.17	5.5-6.5	Black, blue or brown-black
CARBONATES					
Siderite	FeCO ₃	48.2	3.96	3.5-4	Ash-grey to brown
Dolomite Ankerite Kutnahorite	CaMg(CO ₃) ₂ CaFe(CO ₃) ₂ CaMn(CO ₃) ₂ }	26	2.8-3.1	3.5-4	White, grey, brown
SULPHIDES					
Pyrite	FeS ₂	46.5	5.01	6-6.5	Brass-yellow
Marcasite	FeS ₂	46.5	4.8	6-6.5	Light brass yellow
Pyrrhotite	Fe _(1-x) S	61-63	4.5-4.6	3.5-4.5	Bronze yellow
SILICATES					
Chamosite	(Mg, Fe, Al) ₆ (Si, Al) ₄ O ₁₄ (OH) ₈	33-42	3-3.5	--	Green to light yellow

Continued...

TABLE 2.2 (Concl.)

Mineral	Composition	Iron content (percentage)	Specific gravity	Hardness	Colour
Glauconite	$K(Fe,Mg,Al)_2(Si_4O_{10})(OH)_2$	Varies	2.5-2.8	--	Dark green, black earthy
Greenalite	$(OH)_{12}Fe^{+9}Fe^{+3}Si_8O_{22} \cdot 2H_2O$	Varies	3	--	Olive-green light greenish
Minnesotite	$Fe_3(OH)_2SiO_4O_{10}$	Varies	3-3.2	--	Pale green, yellow green
Stilpnomelane	$(OH)_4(K,Na,(Ca)_{0.1}(Fe,Mg,Al)_{7-8}Si_8O_{23-24} \cdot 24H_2O$	Varies	2.7-3	--	Dark greenish
Grunerite	$Fe_7Si_8O_{22}(OH)_2$	Varies	3.2-3.5	--	Light green-brown
Cummingtonite series	$(Fe,Mg)_7Si_8O_{22}(OH)_2$				
Anthophyllite	$(Mg,Fe)_7Si_8O_{22}(OH)_2$	Varies	2.9-3.4	--	White, grey-brown
Hypersthene	$(Fe,Mg)SiO_3$	Varies	3.4-3.5	5-6	Dark green-brown

2.2.1 Principal Ore Minerals

2.2.1.1 Haematite

Haematite is the most abundant iron ore mineral and is the main constituent of the iron ore industry. It occurs in a variety of geological conditions throughout the world. It is the red oxide crystallizing in hexagonal system. The fine-grained haematite is deep red, bluish red, or brownish red and may be soft and earthy ocherous, compact or highly porous to friable, or granular, or may form dense hard lumps. Considerable siliceous or argillaceous impurities are common. Fine-grained red haematite may occur in smooth reformed masses (Kidney ores) in botryoidal or stalactitic shapes, or may be columnar, fibrous, radiating, or platy, etc. The coarse crystalline haematite is steel grey with bright metallic to dull grey lustre and occasionally, coarse crystals have a deep bluish to purplish iridescent surface. The coarse-grained haematite is known as specularite or specular haematite and may form blocky or platy crystals with a strong micaceous parting. The cherry red streak is difficult to observe on this variety. The composition of haematite is Fe_2O_3 . Ideally, haematite contains 69.94 percent

iron and 30.06 percent oxygen. The specific gravity varies from 4.9 to 5.3 (when it is pure, i.e. 69.9 percent Fe_2O_3) but the ores met in practice generally have less specific gravity. The hardness varies from 5.5 to 6.5 for hard ore and is much less for softer earthy varieties. Haematite is feebly magnetic, but a variety termed maghemite is found in many orebodies in small quantities having magnetic properties closely akin to those of magnetite.

The iron content of the ore and physical characteristics vary from place to place in different types of ores. Some idea about the change in iron percentages and in bulk densities/tonnage factors of different types of ores mined in some important regions of India is given in Table 2.3.^(2,3)

2.2.1.2 Martite

The name martite is now commonly used for haematite that is pseudomorphous after magnetite and rarely after pyrite. It is usually iron-black with a sub-metallic lustre ranging from red to brownish red. Martite may occur in large powdery masses, and these may sometimes be metamorphosed to micaceous haematite, though a micaceous haematite is not necessarily derived from martite powder.

1 A mineral that has an⁶ uncharacteristic crystalline form as a result of assuming the shape of another mineral that it has replaced.

TABLE 2.3 : CHANGE IN THE CHARACTERISTIC OF IMPORTANT HAEMATITE DEPOSITS IN INDIA ⁽²⁾

Sl.No.	Type of ore	Iron content	Bulk density/tonnage factor
1. Singhbhum-Keonjhar-Bonai Deposits			
	a) Massive ore	65 to 69.9%	4.5 to 5
	b) Laminated ore	55 to 65%	3.5 to 4.8
	c) Blue dust	65%	3.3 to 3.4
	d) Lateritic ore	52%	2.3
2. Goan Deposits			
	a) Massive bedded ore	59 to 62%	3 to 3.4
	b) Platy ore	58 to 62%	3 to 3.2
	c) Brecciated ore	56 to 62%	2.8 to 3.2
	d) Mixed ore	45 to 59%	2.5 to 3.0
	e) Biscuity ore	59 to 65	2.9 to 3.1
	f) Concretionary ore	57 to 62%	3.1 to 3.4
	g) Lateritic	40 to 50%	2.3 to 3.3
	h) Blue dust or powdery ore	58 to 66%	2.8 to 3.0
3. Bellary-Hospet Deposits			
	a) Lumpy ore (Massive & Laminated)	67 to 69%	3 to 3.5
	b) Blue dust	Average 65%	3.8
4. Bailadila Deposits			
	a) Massive ore & Massive & Laminated	67 to 68.26%	4.69 to 5.11
	b) Laminated ore	63.47%	3.4 to 4.19
	c) Lateritic ore	47.46%	3.46 to 3.65

Martite, which may be feebly magnetic due to residual magnetite inclusions, occurs in many different environments, particularly in strongly oxidized zones overlying magnetite occurrences. The chemical composition of martite is Fe_2O_3 , as that of haematite.

2.2.1.3 Magnetite

It is the most common species in the magnetite series of spinel mineral group and is the second most important iron-bearing mineral of economic importance. It is black magnetic oxide of iron crystallizing in the isometric system and has hardness of 5.5 to 6.5. Its specific gravity is 5.17 and magnetic attractability 40.18 compared to 100 for pure iron. It occurs as fine or coarse-grained masses or in octahedral or less commonly dodecahedral crystals. It occurs as veins and stringers in igneous rocks and as lenses in crystalline schists. Large deposits are

considered to be the results of magnetic segregation and its low grade deposits occur as disseminations in metamorphic and igneous rocks. It also occurs as a replacement product in sedimentary or metamorphic rocks. It is found as placer deposits as "black sand" in beach deposits and as banded layers in metamorphic and igneous rocks.^(2,3)

2.2.1.4 Goethite and Limonite

These minerals are hydrated oxide of iron, forming a part of a complex group in which proportion of the various radicals can undergo considerable variations. Their colour is brown to ochreous yellow but may be black or dark brown to reddish brown and they are often called "brown iron ores". Their specific gravity varies from 3.3 to 4.3 and hardness is 5.5. They may contain 10 to 14.5 percent combined water and are converted into haematite or magnetite on

calcination. These are secondary minerals, being the product of alteration. They occur as thick cappings formed by weathering and hydration of the underlying orebody. When silica is leached out, iron content improves by 10 to 15 percent. These minerals form flakes and needles generally of small dimensions occurring as intergrowths with the original constituents.⁽²⁾

2.2.1.5 Siderite

Siderite, also called "spathic ore", is a carbonate of iron. Its colour is ash grey to brown with yellow and red stains resulting from oxidation and hydration.

Its specific gravity is 3.8 and hardness varies from 3.5 to 4. It crystallises under rhombohedral division of the hexagonal system. It occurs as sedimentary or replacement deposits.⁽²⁾

2.2.1.6 Pyrite

It is a sulphide of iron with golden yellow colour having metallic lustre. It crystallises in cubic system. Its specific gravity is 5.1 and hardness varies from 6 to 6.5. It may be used as an iron ore after the sulphur has been removed by calcination. However, it is not much favoured as an iron ore at present.⁽²⁾

2.2.1.7 Iron Silicates

Greenalite, chamosite, taconite, etc. are iron silicates of varying composition. Lately, taconites have been regarded as iron ore of economic importance. Taconite is a hard, fine-grained, sedimentary rock containing 25 to 30 percent iron as silicate. The principal gangue mineral is silica in which iron minerals are disseminated.⁽²⁾

2.3 ORE GENESIS

As would be expected in case of multi-origin deposits, iron ores are deposited under various geological conditions. They occur in basins of sedimentation, with eroded, deep-seated intrusive and where deep tropical weathering prevails. The various processes and geological factors involved in the origin and genesis of iron ore deposits are described below^(4,5):

2.3.1 Igneous-Magmatic Segregations

The igneous deposits are due to the segregations of iron ore from cooling of basic or acidic magma or from volcanic emanations. The

products of crystallisation form a magma segregate into lenses or stratified sheets. The ore minerals are magnetite or titaniferous magnetite. They are associated with acidic igneous rocks, such as granodiorites and also with anorthosite, norite, pyroxenites, etc. Examples of these are found in Scandinavia, Lapland, South Africa (The Bushveld igneous complex), USA (Adirondack mountains), Iron Mountains in Wyoming. In India, the titaniferous deposits in south-east of Singhbhum (Bihar) are associated with ultrabasic rocks. In the neighbourhood of volcanic vents, crystalline haematite is sometimes formed, and it is believed to be the result of the interactions of gases containing iron chloride with steam^(1,6).

2.3.2 Contact Metasomatic/ Contact Deposits

Magnetite and haematite are sometimes developed at the contact of limestones or with intermediate or basic igneous rocks. They are generally associated with typical contact minerals, such as garnet, pyroxene, epidote, etc. Pyrite and chalcopyrite are sometimes present. Such occurrences are found in Pennsylvania and the Western States of the USA and Japan. Sources of these deposits are now regarded as of metasomatic (replacement) origin^(1,6).

2.3.3 Lode Deposits

These deposits are formed due to the formation of lodes in fracture zones deposited from solution derived from igneous sources. The haematite deposits of Elba (Italy) are found as veins and lenses in limestone. Lode of siderite in Siegsland (Germany) and near Wallendorf (Czechoslovakia) are found in sedimentary rocks not far from igneous masses. The Veldurti deposit in Kurnool (Andhra Pradesh) occupies a fault zone in rocks of Cuddapah age. The lode deposits are, however, not of much importance.

2.3.4 Replacement Deposits

These deposits are formed due to the replacement of the country rock by iron-bearing solution at comparatively low temperatures. Typical examples are the haematites of the Lakes district (England) and Bibao (Spain) which occur as replacements in limestone.

These are generally low in phosphorus. The pyrite deposits of Rio Tinto (Spain) are also considered as replacement deposits.

2.3.5 Sedimentary Iron Ores

These include several large deposits of the world. They belong to one or the other of the following classes: (a) the banded iron ore formation of India, Brazil, Venezuela, South Africa, Lake Superior region, etc., (b) oolitic haematites, such as those of Alabama (USA), and (c) carbonate ores, such as the Minette ores of Lorraine. The sedimentary iron ores generally consist of haematite but they may be associated with varying quantities of hydrous iron silicates, such as greenallite and chamosite, etc. There are also beds of sideritic and limonitic ores, such as those in the ironstone shales of Raniganj Coalfield of West Bengal, India and the black band ironstone of the Coalfields of Scotland. Oolitic beds of haematite are found in Alabama in the USA. Massive carbonate ores occur in some places, the best examples being the Minette ores of Lorraine- Luxembourg and the Cleveland ores of England. Bog iron ores are formed in swamps and lakes in moist climate as ferrous carbonate or ferric hydroxide which may be brought in as bicarbonate of iron solution. In the formation of these ores, bacteria and decaying organic matter may play an important part. Though bog iron ores are found in Sweden and Spain, they are commercially not very important.⁽¹⁾

The most important bodies of iron ore belonging to the banded ferruginous quartzite is haematite-jasper type. The original rock consists of alternating bands of haematite and jasper or chalcedony. In some cases, certain iron silicates seem to be the original iron minerals. The alternating bands are the products of chemical sedimentation helped perhaps to some extent by biochemical processes. The sources of the material may be either products of weathering brought in by ordinary river water draining a land rich in iron or emanations from submarine lava flows. Some scientists are of the opinion that the ordinary processes of weathering should be able to account for these formations while others like Van Hise and Leith have held the view that the iron as well as silica must have

been largely derived from contemporaneous volcanic activity. Such deposits are extensively developed in south Singhbhum, Keonjhar, Bonai, Bastar, etc. in India.

2.3.6 Residual and Superficial Deposits

When rocks containing iron are weathered, iron goes into solution and is later deposited more or less in situ. It may also become concentrated at the surface by being drawn up through capillary pore spaces in the rock. Many deposits capping banded ironstones are really to be considered as residual deposits. The ultrabasics have given rise to lateritic capping as a result of weathering. Typical examples are those of Cuba (Mayari deposits) Philippines and Borneo.

Rocks containing magnetite and ilmenite, when they undergo weathering may yield sands rich in heavy minerals. Such sands may be concentrated later into workable deposits by the action of rivers or sea waves along the coast. Ilmenite deposits of this nature are found along certain parts of the coasts of India, Malaysia, Brazil and also in Pleistocene and Recent formations in Japan and Indonesia.

2.4 IMPURITIES

The impurities in iron ore consist of slag-forming constituents and other minerals like arsenic, titanium, vanadium, copper, lead, zinc, tin, chromium, nickel, phosphorus, sulphur, etc. The acid constituent of slag-forming minerals is mainly silica, while the lime and magnesia and alumina form the basic slag. In removing certain impurities, the composition of the slag has a vital bearing and the above constituents of slag influence their action to the extent of 90 percent. For optimum performance of the blast furnace, these two constituents in the burden must be well balanced in accordance with a limited and well-defined ratio. Acid ores are far more prevalent than basic ores and, therefore, an excess of basicity can always be corrected by addition of acid ores, but an excess of acidity has normally to be corrected by addition of lime at the cost of increased coke consumption. Generally, basicity ratio, i.e. $(CaO+MgO) : (SiO_2)$ of 1.4 is adapted for the blast furnace charge so that satisfactory removal

Flux - A chemical, mineral used to increase the fluidity or reactivity

of sulphur may be achieved but many a times, it has to be varied to suit local conditions. An increase in basicity beyond these limits may result in increased viscosity of the slag with all its attendant difficulties in tapping, etc. whereas under certain conditions, ultra-acid melting using CaO:SiO₂ ratio of 0.6 to 0.8 is also possible. For foundry pig iron or Bessemer pig iron, which is high in silicon, a lower value than 1.4 can be used but for Thomas pig iron low in silicon, a higher value than 1.4 must be used if effective removal of sulphur from the pig iron in the blast furnace is desired. Apart from composition, the quantity of slag formed is also important. Although too much slag formation is deleterious to the efficient functioning of the blast furnace resulting in higher coke consumption, it should not be below a certain minimum required to remove the sulphur present in the blast furnace charge as it cannot absorb more than 3 percent sulphur. Generally, 300 to 400 kg. slag per tonne of pig iron is necessary to obtain satisfactory desulphurization. The detailed description of impurities is given below :

2.4.1 Slag-Forming Constituents

(i) Silica: Silica is the most important slag-forming constituent which occurs in the form of quartz, in iron-bearing aluminosilicates, as chlorites, garnets, amphiboles, pyroxenes, and clay minerals. If the ore has a high silica content, a large amount of slag is formed. A great amount of slag in blast furnace causes high fuel/coke consumption, which is further increased if lime is added in the form of limestone. On an average, an increase of 100 kg. slag per tonne of pig iron raises the coke consumption by 40 kg per tonne of pig iron. Siliceous ores are, therefore, either beneficiated or mixed with lime-rich ores. If they cannot be beneficiated, the amount of slag in the blast furnace can be decreased by using less limestone than normal, that is by working with an acid slag rendering the slag acidic with a basicity under 1.2, which, however, results in high sulphur pig iron.^(2,5)

(ii) Alumina: In iron ore, alumina is generally found in considerably smaller amounts than silica. During beneficiation of ores, some clays that carry most of the alumina are removed in

washing. Ores that contain appreciable alumina as clay tend to be sticky when high in moisture and thus pose certain problems in handling. Alumina is seldom used as a flux in blast furnace practice, but it is present in large number of crude ores as an impurity. As a result, it appears in the slag. It is generally present as a constituent of some silicates. Alumina influences the fluidity of the slag and its proportion has to be carefully controlled as with too low a content, i.e. less than 10 percent, the behavior of the slag is unsatisfactory. About 10 to 15 percent alumina in the slag increases the fluidity of basic blast furnace slags and thus makes it possible to use a higher basicity which facilitates the removal of sulphur. If the alumina content of the ore is high as is the case with most of the Indian ores, the alumina content of the slag goes up to as high as 25 to 30 percent. Such a slag requires high temperature in the blast furnace to get the right fluidity. With the resultant loss in fluidity of the slag, the burden does not descend smoothly and tapping of the slag is difficult. In that case, silica has to be added to increase the slag volume and magnesia in the form of dolomite to increase its fluidity. Therefore, magnesia and limestone can be used advantageously as a flux when operating with aluminous ores. Further, MgO has a fluxing power of approximately 1.4 times that of CaO. With high alumina contents, a slag with a low melting point may be obtained by lowering the basicity from 1.4 to 1.08, but it tends to give a high sulphur iron. However, if a basicity of 1.4 is maintained, a high coke ratio giving a high hearth temperature is necessary and this results in a high silicon iron, which is suitable for foundry purposes. If in these conditions, coke ratio is kept low, to obtain low silicon iron thereby resulting in a low hearth temperature, scaffolds soon begin to form in the furnace, and the pressure rises, so much so that coke rate has to be increased. Thus, when using aluminous ores with normal basicity slag, the rate of production and the quantity of iron produced is very erratic.^(2,5)

(iii) Lime: Lime and magnesia are the dominant constituents of a basic slag. The lime

content in most ores runs well under 10 percent; but larger quantities, around 15 to 20 percent, give ores self-fluxing characteristics. Lime, which is present in iron ores as an oolite, or as a part of complex silicates and aluminosilicates, is a highly desirable slag-forming component upon smelting. Its function is to form a trial slag with the coke ash, ore gangue and other burden impurities, that is, a chemical composition that will effectively control the slag in the pig iron. Except for burdens with highly self-fluxing ore, limestone is usually added to the charge to provide a sufficiency of lime for the smelting process.^(2,5)

(iv) Magnesia : Magnesia, the other dominant constituent of slags, is usually present in iron ore in small amounts only. The greater viscosity of blast furnace slags with more than normal percentages of alumina may often be offset by increasing the magnesia content. This has been effective especially in practices for iron ore to alumina-silica ratio over 1. However, the content of magnesia tends to "deaden" a slag. In such cases, the temperature must be raised above normal level to increase slag fluidity. Dolomite composed principally of calcium magnesium carbonate, is sometimes used in conjunction with limestone in blast furnace burden to improve the efficiency of the process. Limestone, however, is preferred when the amount of sulphur to be removed is large.

Besides the above four slag-forming constituents, there is the fifth one, i.e. manganese oxide. It is a special kind of constituent in iron ore whose major portion is reduced to metal. It is described in detail along with other impurities under para 2.4.2 (iii).

2.4.2 Other Impurities

(i) Phosphorus: Phosphorus is generally present as isolated grains of apatite ($3\text{Ca}(\text{PO}_4)_2$) but can also be found as vivianite ($\text{Fe}(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$) and as inclusions in iron-bearing minerals. It is present in all iron ores. The entire phosphorus content of the blast furnace burden goes into the pig iron. The sintering also does not remove this impurity. It forms solid solution in iron as iron phosphide (Fe_3P), which may be separated out as an

eutectic, brittle under shock. The presence of high phosphorus in the steel reduces its impact on toughness and the steel becomes cold brittle, although a certain amount of phosphorus in steels is desirable as it increases the tensile strength and corrosive resistance. The process of steel making to be adapted depends upon the amount of phosphorus present in the ore. A non-phosphoric ores can be treated in the acid open hearth or acid Bessemer converter, whilst a phosphoric ore must be treated by the basic Bessemer or Thomas Process. Pig iron for the manufacture of high quality steel in acid open hearth furnace or the acid Bessemer converter should contain less than 0.025 percent phosphorus, whereas it may have 0.04 to 0.045 percent phosphorus for the production of ordinary commercial steel. However, the extreme limit of phosphorus content in the pig iron is 0.08 to 0.1 percent with the result that the Bessemer ore should not contain more than 0.0009 percent of phosphorus for each percent of iron in the ore. On the other hand, pig iron for the Thomas Process should have a phosphorus content of 1.7 to 2 percent, which means that the ore should contain 0.02 percent phosphorus for each percent of iron in the ore. Pig iron for the basic open hearth process can have a phosphorus content from 0.03 percent to more than 1.5 percent, although high phosphorus content is a drawback as more lime is required for its elimination, thereby increasing the slag volume and fuel consumption.^(2,5)

(ii) Sulphur : It is a very undesirable impurity frequently found in iron ores. It is present in the form of pyrites or pyrrhotite, occasionally as gypsum and sometimes as barytes. A reduction of 0.1 percent sulphur in the ore will reduce the coke rate by 2 percent and limestone consumption by 6 to 7 percent. Similarly, a reduction of 0.1 percent sulphur in the coke can reduce the coke rate by approximately 1 percent with a proportionate increased blast furnace productivity and a limestone consumption reduced by 1.5 to 2 percent. Only a small percentage of sulphur in a blast furnace burden is removed with the gas and the rest is divided between the slag and the pig iron. For

satisfactory removal of sulphur in the slag, it should be basic and low in iron. It should be in large quantities at a high temperature. High silicon in large pig iron is favourable for removal of sulphur and a high manganese content is also regarded as an advantage. The maximum extent to which sulphur can be absorbed in the basic blast furnace slag is 3 percent and the ratio of the percentage of sulphur in the slag to the percentage of sulphur in the pig iron varies from about 15, for a slag basicity of 1.2 and a silicon content in the pig iron of 0.5 percent to about 170 for a slag basicity of 1.7 and a silicon content of 3 percent. Excess sulphur in the pig iron makes the resulting steel red short, i.e. brittle when reshaped while hot due to formation of films or grains of iron sulphide, but if manganese is present at the same time, the resultant manganese sulphide grains do not affect the strength of steel as iron sulphide does, and therefore, manganese is added to the steel to the extent of 4 to 8 times the amount of sulphur present. Alternatively, desulphurizing pig iron in the ladle with soda ash or magnesium or in rotary drum with solid lime can be resorted to. Good steel only has as much as 0.05 percent sulphur. In steel used for automatic screwstock, sulphur is allowed from 0.07 to 0.15 percent, for the chips of steel formed during working readily break up instead of curling⁽⁵⁾.

(iii) Manganese: Manganese is generally present as one of the numerous manganese oxides, but can also be present as one of the constituents of the alumino-silicates. Certain orebodies contain all kinds of gradations from pure iron ores to pure manganese ores. Manganese in the blast furnace burden goes into the pig iron as well as the slag. Its presence increases the desulphurizing properties of the slag and is, therefore, very helpful in obtaining low sulphur pig iron with high sulphur coke. The percentage of manganese going into the pig iron is 70 to 75 for rich ores and 50 to 60 for poor ores. It is impossible to eliminate the manganese in its entirety from the metal and some of it does ultimately pass into the finished steel. The ores containing high manganese can be used to produce spiegel iron with 10 to 30 percent manganese, however, ores with a very high manganese content equal to eight times the

iron content and with a silica content of less than 8 percent can be used to produce ferro-manganese with 80 percent manganese.⁽⁵⁾

(iv) Arsenic : Arsenic is another undesirable impurity although not so commonly found in iron ores beyond 0.1 percent. It may occur in ores as arseno-pyrite (FeAsS), lollingite (FeAs_2) and scorodite ($\text{FeAsO}_4 \cdot 2\text{H}_2\text{O}$). Most of the arsenic present in the blast furnace burden goes into pig iron and generally remains in the steel during the steel-making processes, but can be eliminated through the oxygen converter. Small quantities of arsenic up to 0.15 to 0.28 percent range can be allowed in ordinary steel and 0.05 to 0.1 percent in steel for temper hardening, as excess of arsenic causes cold brittleness in the steel and impairs its welding properties.⁽⁵⁾

(v) Titanium : Titanium is usually present as ilmenite (FeTiO_3) and sometimes as rutile (TiO_2). Presence of this renders the slag difficult to fuse by producing a mass of particles of nonfusible titanium carbonitrides (TiCN). If the titanium content of the pig iron exceeds 0.5 percent, pig iron is rendered very viscous leading to tapping difficulties. A slag containing over 17 to 18 percent of TiO_2 will not tap easily but will tend to block the slag notch and will form crusts at the bottom of the furnace; but if the average titanic oxide content of the ore does not exceed 1 to 2 percent corresponding to a slag with less than 3 to 6 percent of titanic oxide, no operating difficulties with the blast furnace are experienced. However, for the production of pig iron in the electric furnaces, the titanic oxide can be as high as 3 percent without creating any operational difficulties.⁽⁵⁾

(vi) Vanadium : Many iron ores, especially if they are rich in phosphorus or titanium, such as titano-magnetites also contain some vanadium. In the blast furnace, about 70 to 90 percent of vanadium goes into the pig iron, but it can be oxidized easily in the steel furnaces, passing into the slag if the iron ore is not high in silicon or titanium. In some cases, this vanadium-rich slag can be used to produce ferro-vanadium alloy.⁽⁵⁾

(vii) Copper: Copper usually occurs as chalcopyrites (CuFeS_2) most frequently in the orebodies with a predominance of magnetite.

Any copper in iron ore goes into the pig iron in the blast furnace and then it cannot be removed by oxidation during the steel-making process. A certain amount of copper improves the corrosive resistance of steel but too high content causes hot brittleness. A copper content of above 0.3 to 0.4 percent in ordinary rolled steel begins to cause trouble in rolling or forging at high temperatures forming a copper-rich low-melting alloy on the surface of the steel that penetrates the grain boundaries resulting in minute cracks on the surface which are difficult to remove. This difficulty is overcome if the steel also contains nickel or cobalt equal to at least 0.5 to one time its copper content. In some kind of foundry pig iron and steel castings for special purposes, copper contents of 1 to 2 percent can be allowed and copper up to 4 percent is sometimes added as an alloying element in steel castings to increase fluidity and improve some mechanical properties.^(2,5)

(viii) Lead, Zinc and Tin : Lead is very seldom found in iron ores. It does not pass into the pig iron but owing to its high specific gravity, it accumulates in the well of the furnace and destroys the joints of the lining by gradual penetration. Zinc is found in small quantities in some iron ores. It is volatilized during reduction and escapes with the gas from the blast furnace if the zinc content in the iron does not exceed 0.2 percent; but with ore exceeding this percent, the formation of scaffolds takes place on the furnace walls impairing the operation of the furnace and destroying the refractory lining by penetration into its joints, which may ultimately lead to actual fractures in the shell of the furnace. Tin is generally not present in iron ore, but if it is there, all of it goes into the pig iron in the blast furnace and then it cannot be removed by oxidation during the steel-making process. Ordinarily steel should not contain more than 0.05 percent of tin.^(2,5)

(ix) Chromium and Nickel : Chromium in iron ore is generally found in the form of chromite ($\text{FeO}, \text{Cr}_2\text{O}_3$). About 80 percent of chromium goes in to the pig iron but most of it can be oxidized in the steel-making process when low carbon steels are produced. It is useful in pig iron in small quantities for preparing

alloying cast iron with good physical and mechanical properties, but is undesirable for steel making as it thickens the slag. Steel for welding purposes should not contain more than 0.2 to 0.3 percent chromium. Nickel may be found in lateritic ores up to one percent or more and like tin it goes completely into the pig iron in the blast furnace and cannot be removed by oxidation during steel making. Its presence in certain quantities improves the mechanical properties of certain types of steels whereas in others like transformer sheet steel, nickel is totally unacceptable.

2.5 CLASSIFICATION OF IRON ORES

Iron ores have not been classified so far by any specific complete pattern and many criteria have been used for their classifications in different countries for different purposes. The various criteria that have been used in this connection are beneficiation characteristics, iron content and size range, chemical and mineralogical composition, slag-forming constituents, nature of impurities, origin, structure and texture, and reducibility. In addition, certain commercial classifications have also been adapted in various countries.⁽²⁾

(i) Beneficiation Characteristics : Iron ores have been classified into seven groups depending upon their general characteristics concerning beneficiation techniques and behaviour in the blast furnace. These groups consist of magnetites, haematites (or martites) brown haematites (limonites, oolitic ores), siderites, titano-magnetites, laterites (goethite with a generic connotation) and pyrites.⁽²⁾

(ii) Iron Content and Size Range: The commonest classification is by iron content and size range. In India, haematite ores, both lumpy and fines, containing above 65 percent iron are classified as high grade. The ores containing 62 to 65 percent iron is medium grade and below 62 percent iron-bearing ores are low grade. However, in Canada, ores with plus 58 percent, 40 to 57 percent, and below 40 percent iron content are regarded as high grade, medium grade and low grade, respectively. Ores above 6 to 10 mm are generally referred as lumps and the rest, i.e. minus 6 mm as fines.⁽²⁾

(iii) Mineralogical Composition : Iron ores are frequently referred by the preponderance of the iron-bearing mineral present in the ore, such as haematite ore (containing less than 10 percent FeO), magnetite ores (containing above 10 percent FeO) and so on.⁽²⁾

(iv) Slag Forming Constituents : The ores are also classified as basic or acid ores depending on whether the slag forming constituents are lime and magnesia or silica and alumina.^(2,3)

(v) Nature of Impurities : Iron ores are also classified, according to the nature and quantity of the impurities present like Bessemer (phosphorus less than 0.045 percent), low phosphorus non-Bessemer (phosphorus up to 0.18 percent), high phosphorus non-Bessemer (phosphorus more than 0.18 percent), manganiferous (manganese more than 2 percent), siliceous (silica more than 18 percent), titaniferous, high sulphur, etc.⁽²⁾

(vi) Origin of Deposit : Iron ores may be classified into six groups depending on their origin and modes of occurrences. These groups are: 1) Igneous magmatic segregations, 2) Contact metamorphic deposits, 3) Lode deposits, 4) Replacement deposits, 5) Bedded or sedimentary deposits, and 6) Residual and superficial deposits including laterite (for details see para 2.3.1)

(vii) Structure and Texture : Depending upon the structure and texture, iron ore has been classified as oolitic ores, lateritic ores, banded ores, hard massive ores, soft ores and powdery ores. In oolitic ores, oolites which are spherical nodules, generally less than 0.5 mm but also up to 2 to 3 mm diameter, consisting of layers of concentric or radiating crystals of silicates, carbonates, hydrates of iron oxides, etc. in varying proportions are embedded in a matrix of similar composition but with the constituents distributed at random. Lateritic ores consist of iron hydroxides, alumina hydroxides and other minerals mixed together and distributed around large pores, vugs and channels. Banded ores consist of alternate bands of iron-bearing minerals and quartz, jasper or silicates, etc., which are usually a few mm thick but are sometimes as thick as several centimeters. Hard massive ores are fine-grained and consists of

constituent crystals having intergrown into a homogenous mass, whereas in soft ores, such crystals are knit together rather loosely and the grain size is bigger. Powdery ores are soft ores which are very porous and disintegrate into powder or in small biscuit-like slabs.^(2,5)

(viii) Reducibility : Reducibility is the proportion of iron oxides which will be reduced through direct contact with the gases as compared with that reduced through direct contact with fuel, which should be as small as possible and is an essential quality of an iron ore for use in the blast furnace. Reducibility depends largely on permeability of the gases which in turn depends on porosity and size range. The methods adapted for determining reducibility vary from country to country and, therefore, it is difficult to compare ores. In the Commonwealth of Independent States(CIS), the average reducibility for different types of ores is as follows:

Magnetic haematite difficult to reduce	--- 40 to 45 percent
Solid red haematite	--- 50 to 60 percent
Solid brown haematite	--- 60 to 70 percent
Porous brown haematite	--- 80 to 90 percent

In most countries, a "direct reduction index" (rd) is used to show the relative amount of iron obtained by direct reduction from the iron oxides at the expense of the solid carbon. In CIS, another direct reduction index (Rd) is also used, showing the amount of oxygen eliminated by direct reduction as proportion of the total quantity of oxygen in the oxides contained in the iron ore. The values of "rd" and "Rd" found applicable in the CIS for the production of pig iron and cast iron are given in Table 2.4.^(2,3)

TABLE 2.4 : CLASSIFICATION OF IRON ORE BY DIRECT REDUCTION INDEX

S.No.	Type of ore or agglomerate	rd	Rd
1.	Easily reducible: roasted siderite, rich brown haematite	0.35-0.55	0.3-0.4
2.	Haematite martite ore, standard quality agglomerate	0.45-0.65	0.35-0.45
3.	Solid magnetite agglomerate with a high content solid siderite	0.55-0.75	0.5-0.6
4.	Solid magnetite, crude titano-magnetite, strongly fused agglomerate.	0.7-0.85	0.45-0.55

(ix) Commercial Classification : Iron ores have been classified as direct shipping ores, concentrated or beneficiated ores besides, by-product and co-product ores. Direct shipping ores are those that may be used in the blast furnace as mined and do not require any treatment except crushing and sizing. Concentrated or beneficiated ores, as the name indicates, are ores that have been beneficiated for use in the blast furnace. The various processes used for this include crushing, concentration and agglomeration. By-product and co-product ores are those that are recovered as a by-product from an ore which is being mined for some other valuable constituent as well. Apart from this classification, various large producers have their own grade names for their various products. Iron ore is also graded as BF grade and SMS grade according to the specifications laid down for ores used in blast furnaces and steel melting shops. Indian Standard Classification for iron ores is given in Table 2.5. ^(2,3)

TABLE 2.5: CLASSIFICATION OF LUMPY, SIZED AND CALIBRATED ORES DEPENDING UPON ITS CHEMICAL COMPOSITION

Grade	Contents in Percent				
	Fe	Al ₂ O ₃	S(Max)	P(Max)	Total of other metal: Mn, Mg & Ca(max.)
67/66	67.0-66.0	5	0.10	0.10	0.15
66/64	66.0-64.0	7	0.10	0.10	0.15
65/62	65.0-62.0	8	0.10	0.10	0.15
62/60	62.0-60.0	11	0.10	0.10	0.15
60/58	60.0-58.0	12	0.10	0.10	0.15
58/56	58.0-56.0	13	0.10	0.10	0.15
56/50	56.0-50.0	20	0.10	0.10	0.15

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