IRON AND MANGANESE ORE DEPOSITS: MINERALOGY, GEOCHEMISTRY, AND ECONOMIC GEOLOGY

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Summary

Iron and manganese are two essential ingredients for the production of steel, and despite the predicted rise of humanity into the "silicon age," there is at present no satisfactory substitute for steel in modern industrialized society. The supply of the necessary resource of iron and manganese by mining ore deposits will therefore remain an important fundament to industrial development in the twenty-first century. The majority of ore deposits of both iron and manganese are of sedimentary origin. At present, high-grade iron ore deposits formed by hydrothermal and supergene enrichment of Proterozoic banded iron formations constitute the most important source for iron ores, with only some magmatic and skarn-type iron ore deposits being mined. Economically important manganese ore deposits are all of sedimentary origin, comprising Proterozoic manganese formations, black shale-hosted carbonate deposits, and shallow marine oolitic deposits. Assuming a constant rate of consumption, the reserve base of iron and manganese ores in known deposits will last at least for another 160 years for iron and 275 years for manganese. These limits will almost certainly have to be extended, as new deposits are discovered and mining of deposits of lower grade becomes feasible.

1. Introduction

Iron, in the form of cast iron and steel, is arguably the backbone of all industrial development, and indispensable to modern civilization. The earliest iron tool was manufactured from meteoritic native iron—a small sickle as old as 6000 years that was found in the Khufu pyramid in Egypt. The technique of smelting iron was developed approximately 2700 BC, but the so-called "Iron Age" only developed at about 1400 to 1500 BC, when Hittite smiths in eastern Anatolia discovered how to toughen cast iron by repeating a process of hammering and quenching it. This technique spread after the fall of the Hittite empire at about 1200 BC.

Cast iron is brittle and has to be transformed into steel to give it greater strength, hardness and flexibility. This is achieved by minimizing the amount of carbon to less than 1 wt.% and by distributing this small amount of carbon homogeneously. It took until AD 1730 before the first modern raw steel was produced, but the process used was labor-intensive and only capable of yielding small amounts of steel at great cost. This problem was solved by the introduction of minor amounts of manganese, a metal discovered only in 1774. Manganese became the metal that allowed humankind to move into the modern steel age. It is added into steel for its deoxidizing and desulfurizing properties. Every tonne of raw steel produced today contains between 4 kg and 7 kg of manganese metal, a relatively small amount, but it accounts for almost 90% of all manganese ore mined. Only small amounts of manganese are consumed by other industries, most notably in the production of dry-cell batteries.

Although recycled scrap metal has risen to become a significant resource to the steel industry, it is the exploitation of natural mineral deposits that remains the predominant supplier of iron and manganese ore. The global manufacture of 780 million tons of raw steel in 1999, for example, required the mining of 992 million tonnes of iron ore and approximately 18 million tonnes of manganese ore. This production is from a nonrenewable reserve base. The size of this reserve base is certainly finite, but estimates of its true size have to be revised continuously. With almost 5 wt.%, iron is the fourth most abundant element (after oxygen, silicon, and aluminum) in Earth's crust, and about 50 times more abundant than manganese. It is not surprising that the global iron ore reserve base (estimated at about 160 billion tons iron metal) is about 32 times greater than similar estimates for manganese ore (5 billion tonnes of manganese metal).

Iron and manganese ores are hosted by deposits of various size, grade, and origin. However, more than 95% of all deposits exploited today are of sedimentary origin and originated as chemical precipitates from ancient ocean water. The process of accumulating these sedimentary deposits is controlled by the physicochemical properties inherent in iron and manganese. The two chemical elements are very similar and generally intimately associated in nature. Both are red-ox sensitive elements with weakly oxidized ionic species (Fe^{2+}, Mn^{2+}) which are fairly soluble in water in surface environments under oxygen-deficient (dysaerobic or anaerobic) conditions, and both are oxidized to poorly soluble Fe^{3+} and Mn^{4+} in aerobic environments. Fractionation of iron and manganese, a prerequisite for the origin of ore deposits of either or both elements, is usually attributed to the fact that the solubility of manganese in water is generally higher than that of iron. As a consequence, precipitates of both elements are usually spatially

separated along gradients of pH or Eh in the ocean water column. Another important fractionation mechanism is the fixation of iron as poorly soluble sulfide in sediments under anaerobic conditions, a process that does not effectively affect the concentration of manganese.

Economically important manganese and iron ore deposits were not created evenly through Earth's history. The formation of sedimentary and residual deposits of iron and manganese, in particular, is determined by complex interactions in the ocean–atmosphere–lithosphere–biosphere system. Most prominent is the example of banded iron and manganese formations formed in the Late Archean and Early Paleoproterozoic. Their formation reflects the stepwise oxygenation of the atmosphere–ocean system by early microbial life that populated the shallow oceans and terrestrial environments and produced oxygen by photosynthesis. First iron and then manganese were oxidized and precipitated when anoxic iron- and manganese-rich deep ocean water mixed with oxygen-bearing shallow ocean water on shelf platforms that rimmed the first large cratons. Oxygenation of the deep ocean water in the Late Paleoproterozoic (2.0 to 1.8 Ga) meant the demise of manganese and iron formations. They reappeared only during the Neoproterozoic, in the aftermath of global glaciation.

Deltaic and shallow marine deposits that sourced metals from terrestrial weathering processes and continental runoff replaced iron and manganese formations. Important examples include oolitic ironstones, shallow marine oolitic manganese ores, and black shale-hosted manganese ores. These deposit types predominate the geological record since the Late Paleoproterozoic. Their distribution depends on the supply of iron- or manganese-rich meteoric water through fluvial systems into shallow marine environments. Such supply was available especially during times of warm global climate and high sea level stand, conditions under which efficient chemical (lateritic) weathering prevailed on the continents, and shallow seas covered large parts of the continents. The formation of residual deposits of iron and manganese requires similar preconditions. Humid and warm tropical climates lead to the development of deep lateritic weathering profiles. Two periods of Earth's history appear to have been particularly suitable for the origin of such residual deposits, namely the Late Paleoproterozoic (2.2 to 2.0 Ga) and the Late Mesozoic (Cretaceous and Tertiary).
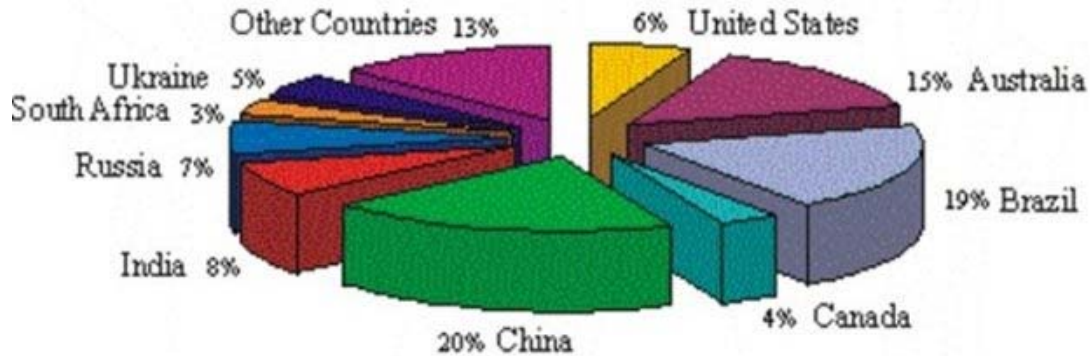
2. Iron Ore Deposits

Iron ore deposits are known to occur in sedimentary, hydrothermal, and magmatic environments, but production today is almost entirely from three types of deposit: deposits related to Precambrian banded iron formations provide about 90% of all iron ore mined, and the remainder is derived from metasomatic skarn and magmatic magnetite deposits. Very large but low-grade resources are hosted by oolitic ironstones and residual laterites (Table 1).

Deposit type	Maximum deposit size (Mt ore)	Grade (wt % Fe)	Orebody shape	Remarks	Examples
Supergene/ hypogene enriched BIF					
Transvaal-Hamersley-type	> 1,000	56–69	sheet, lens	Predominant importance	Sishen (S-Africa), Serra do Carajas (Brazil), Mt. Tom Price (WA)
Algoma-type	< 100	50–67	sheet , lens, shoot	Rare type	Buhwa (Zimbabwe)
Rapitan-type	< 1,000	50–58	sheet, lens	Rare type	Urucum (Brazil)
Metamorphosed BIF					
Taconite	> 10,000	15–40	stratiform bed	Low grade resource	Mesabi Range (USA)
Itabirite	> 1,000	35–50	stratiform bed	Not mined	Brazil, Australia
Ironstone					
Oolitic ironstone	500	25–45	stratiform bed	Not mined	Minette (Europe), Cinton (USA)
Reworked laterite	>1,000	50–59	Channel deposit	Significant exploration potential	Robe River (Australia)
Magmatic deposits					
In mafic and ultramafic rocks	> 1,000	30–60	plug, layer, irregular bodies	not mined	Bushveld magnetite layers and plugs; Taberg (Sweden)
In alkaline complexes	2,500	60–65	massive tabular, plug, dyke, flow	Regional significance	Kiruna, Gällivara, Grängesberg (Sweden)
Skarn deposits					
Magnetite skarn	1,000	40–60	irregular mass, vein, plug	Regional significance	Magnitaya Gora (Russia)
Siderite skarn	< 100	20–60	irregular mass	Regional significance	Marquesado (Spain)

Table 1. Major characteristics of important types of iron ore deposits

World Mine Production (1999)

Other Countries 13%
6% United States
Ukraine 5%
15% Australia
South Africa 3%
Russia 7%
19% Brazil
India 8%
4% Canada
20% China

Reserve Base (1999)

Other Countries 15%
9% United States
16% Australia
Ukraine 18%
7% Brazil
Sweden 3%
2% Canada
South Africa 1%
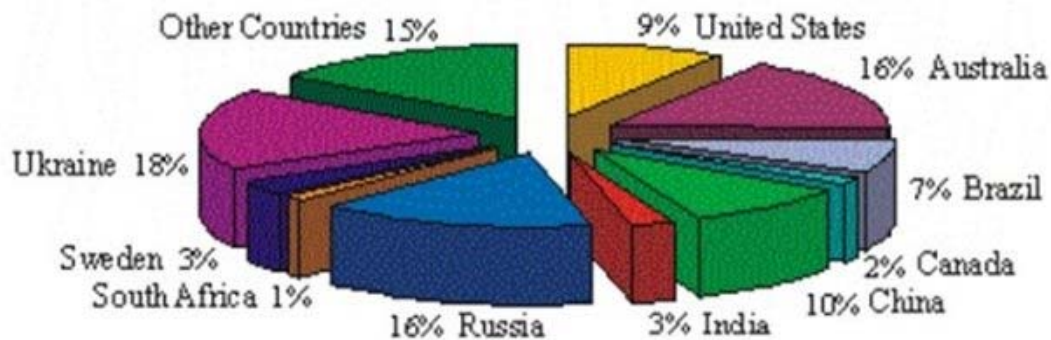10% China
16% Russia
3% India

Figure 1. Production and resources of iron ore

2.1. Banded Iron Formations

Banded iron formations (or BIF) are finely bedded chemical sedimentary rocks composed of interlaminated quartz (chert) and iron-bearing minerals with an iron content of about 30 wt.%. Four principal types of BIF are distinguished, all of which are restricted to well -defined time intervals in the Precambrian (Figure 2). BIF are notably absent from the Phanerozoic geological record.

• Algoma-type BIF is widespread in the Archean greenstone belts, prior to 2.75 Ga. Many examples are known from all Archean cratonic nuclei. Algoma-type BIF are relatively restricted and always in close association with mafic volcanic rocks.

- Hamersley-Transvaal-type BIF is very large and laterally extensive iron-formations that are essentially restricted between 2.0 Ga and 2.75 Ga. They represent the by far largest BIF deposits known and covered as finely laminated mud below wave base of the extensive shelf platforms that developed around the first large stable cratons. Hamersley-Transvaal-type BIF has no apparent link to penecontemporaneous volcanism. Type examples are found in the Hamersley Group (Australia) and in the Transvaal Supergroup of South Africa. Most economically important BIF-hosted ore deposits are restricted to this type of BIF.

- Granular iron formations are closely related to the previous type, but are slightly younger (1.8 to 2.1 Ga), of much smaller lateral extent, and were deposited above wave base. They show much coarser banding than the Hamersley-Transvaal type and are typically composed of closely packed granules and oolites of iron oxides or chert. Type examples are found in the Lake Superior region (North America).

- Rapitan-type iron formations are Neoproterozoic (0.8 to 0.6 Ga) iron formations that are characterized by their distinct association with glaciomarine sediments. They are thought to have been deposited in the immediate aftermath of a so-called "Snowball Earth" state. Examples include the Rapitan group (Canada), the Yudnamutara subgroup (Australia), the Chuos formation (Namibia), and the Jacadigo group (Brazil).
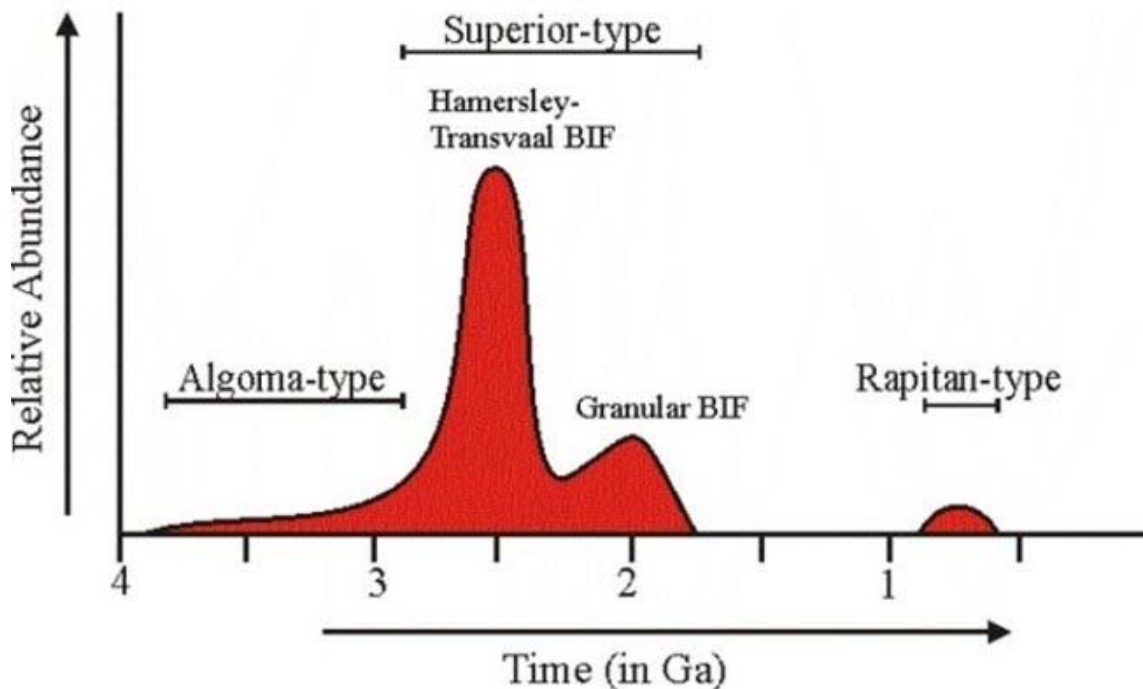

Figure 2. Time/volume distribution of BIF through time

The origin of BIFs in general remains enigmatic. Algoma-, Hamersley-Transvaal, and Superior-type BIF may have been deposited in a stratified ocean system with surface water that was enriched in oxygen by early forms of photosynthetic microbial life, and a deep-water mass that was anoxic and enriched in dissolved iron and manganese by

volcanic exhalations and hydrothermal alteration processes along midoceanic ridges. Iron precipitation took place along a transition zone between these two water masses. Oversaturation with respect to silica, because of the absence of silica-secreting microbes, may have caused almost continuous precipitation of chert, interrupted only by the deposition of iron minerals because of seasonal or other effects in the shallow surface water layer. A few authors oppose this model, and favor a continental source for iron, and precipitation in response to evaporation of continental runoff in restricted basins.

Following the deposition of granular BIF (ca. 1.8 Ga) the oceans probably became completely mixed and depleted in iron, as indicated by the absence of iron formations in Midproterozoic times. BIFs resurface only in the Neoproterozoic as Rapitan-type iron formations.

Banded iron formations contain different iron-bearing minerals, usually in intimate association with quartz. Oxide, carbonate, silicate, and sulfide facies BIF are distinguished. Rapitan-type iron formations are marked by a specifically simple mineralogy, being composed essentially of hematite intercalated with chert. Precambrian iron formations are surprisingly similar with respect to their average major element composition. Iron concentrations range between 23 and 34 wt.% Fe, and $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ ratios between 0.05 and 0.58. SiO_2 is the second major constituent, in concentrations between 43 and 55 wt.%. Minor constituents are usually CaO and MgO, rarely Al_2O_3. Average concentrations of Mn, Na_2O, K_2O, and P are 0.1 to 0.5 wt.%.

An immense amount of iron is contained in BIF, but it is usually of too low grade to be of any economic significance. Iron formations (see section 2.2.) are mined only as iron ore, if coarse-grained metamorphogenic magnetite abounds, a mineral that can easily be concentrated by magnetic separation (so-called "taconites," mined in the Superior Region of the northeastern United States), or if metamorphosed and later strongly weathered to a saprolite, which is composed of rather coarse-grained iron oxides and quartz that can be separated by gravitation (so-called "itabirites" in Brazil).

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Biographical Sketches

Jens Gutzmer, mineralogist and economic geologist, is Associate Professor in the Department of Geology at the Rand Afrikaans University, Johannesburg, South Africa. He obtained his Diploma in Mineralogy at the Technical University Clausthal, Germany in 1993 and his Ph.D. at the Rand Afrikaans University, South Africa, in 1996. Following a Postdoc appointment at RAU he was in 1999 and 2000 employed as a scientific assistant at the WWU Münster, Germany, before being appointed into his present position. His research interests center around the reconstruction of interactive evolutionary processes between lithosphere, atmosphere, hydrosphere, and biosphere in the Proterozoic, and the consequences of these processes on the origin of sedimentary and sediment-hosted deposits of manganese, iron, and base metals.

Nicolas Johannes Beukes, sedimentologist and economic geologist, is Professor of Geology and chair of the Department of Geology at Rand Afrikaans University, Johannesburg, South Africa. He obtained his M.Sc. in Geology at the University of the Orange Free State, Bloemfontein, South Africa, in 1969. He joined RAU as a lecturer in 1970, after working for one year for the Geological Survey of South Africa, Pretoria. He earned his Ph.D. at RAU in 1978. From 1985 to 1988 he was honorary fellow of the Center for the Study of Evolution and the Origin of Life at the University of California, Los Angeles, followed by a visiting professorship at the University of New Mexico, Albuquerque in 1987; in 1993–1994 he spent time at the California Institute of Technology as a visiting associate in Geology, and in 1999 he was recipient of the Gleddin visiting senior fellowship of the University of Western Australia, Perth. His research focuses on Early Precambrian sedimentology and sequence stratigraphy, the early evolution of System Earth, and the origin of Proterozoic sediment-hosted mineral deposits.