

3. STRATIFORM IRON

3.1 Lake Superior-type iron-formation

3.2 Algoma-type iron-formation

3.3 Ironstone

3. STRATIFORM IRON

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INTRODUCTION

About 5% of the Earth's crust is composed of iron, the fourth most abundant element after aluminum, silicon, and oxygen, and the most abundant element in the ferride group (atomic numbers 22-28) – iron, titanium, vanadium, chromium, manganese, cobalt, and nickel. The ferride elements are strongly lithophile and form compounds with oxygen or oxyanions. Nickel and cobalt are strongly chalcophile and combine readily with sulphur and, to a lesser extent, with oxygen. Iron and manganese are both chalcophile and lithophile and commonly occur as oxide and sulphide minerals. Iron is also strongly siderophile, but occurrences of native iron are rarely found. Because of its chemical properties and abundance in the Earth, iron is widely distributed in rocks in silicate minerals and concentrated in oxide, sulphide, and carbonate minerals in most of the mineral deposits that occur in, or are associated with, metalliferous

sediments or igneous rocks. Iron ore deposits are highly diversified and only the principal types of metallogenetic significance in Canada are considered here.

More than 95% of the iron ore resources of the world occur in iron-formation. The term iron-formation has been used for stratigraphic units of layered, bedded, or laminated rocks of all ages that contain 15% or more iron, in which the iron minerals are commonly interbanded with quartz, chert, and/or carbonate. The bedding of iron-formation generally conforms with the primary bedding in the associated sedimentary, volcanic, or metasedimentary rocks (James, 1954; Gross, 1959a, 1965; Brandt et al., 1972).

Iron-formations consist of minerals formed during diagenesis and metamorphism, and many inferences have been made about the nature of the precursor hydrolithic sediments from which they were derived. Some recent metalliferous sediments on the seafloor are similar in composition to various lithofacies of iron-formation that were deposited by chemical and biochemical processes. These consist of complex mixtures of amorphous particles of iron oxide and silica, hydrated iron oxide minerals (goethite), various forms of quartz and silica gel, carbonate, iron sulphide, and a variety of complex clay minerals, including montmorillonite, illite, and smectite muds. Subsidiary amounts of detrital minerals are commonly present in, or interbedded with, metalliferous sediments.

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1996: Stratiform iron; in *Geology of Canadian Mineral Deposit Types*, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, *Geology of Canada*, no. 8, p. 41-54 (also Geological Society of America, *The Geology of North America*, v. P-1).

Iron-formations are a major part of aqueochemically precipitated (hydrolithic) metalliferous sedimentary rocks classified by Gross (1990) as the stratafer group: "...lithological facies formed by chemical, biogenic, and hydrothermal effusive or exhalative processes, commonly composed of banded chert and quartz interbedded with oxide, sulphide, carbonate, and silicate minerals containing ferrous, nonferrous, and/or precious metals". This group includes the common iron-rich oxide, silicate, carbonate, and sulphide lithofacies of iron-formation, and associated lithofacies units interbedded and associated with them, that evidently formed by similar processes and which may contain economically important amounts of manganese, copper, zinc, lead, gold, silver, rare-earth elements, tungsten, nickel, cobalt, niobium, barite, and/or other elements.

The stratafer group of siliceous hydrolithic sediments has special metallogenetic importance, as they are the source rocks for more than 75% of the metals mined in the world (Gross, 1993a). Iron deposits include the common iron-rich oxide, silicate, carbonate, and sulphide lithofacies of iron-formation which are described in the following papers. Other members of the stratafer group include deposits of manganese and a variety of polymetallic sulphide (stratiform massive sulphide) deposits which are described elsewhere in this volume as volcanic-associated massive sulphide base metals (subtype 6.3) and sedimentary exhalative (subtype 6.1). The polymetallic sulphide deposits are massive and bedded lenses that may contain extensive stratiform concentrations of barium, copper, zinc, lead, gold, silver, rare-earth elements, nickel, tin, tungsten, cobalt, niobium, and/or other associated metals. These are interpreted to have formed by similar processes to the iron-formations and constitute sulphide lithofacies.

Following long established precedent, the term ironstone or clay ironstone is retained for bedded goethite-siderite-chamosite-bearing hydrolithic sedimentary rocks, that commonly have oolitic textures, a relatively high content of alumina and phosphorus, and a low content of silica. Iron-formation and ironstone are not only distinct lithologically, but are also interpreted to have different metallogenetic significance. Modern facies of iron-formation that are forming by hydrothermal-effusive or exhalative processes at many sites on the seafloor provide important analogues for understanding and interpretation of ancient iron-formations and the stratafer sediments associated with them. In contrast, the ironstones appear to have been deposited in sedimentary basins dominated by hydrogenous and chemical-biogenic sedimentary processes. The principal lithofacies and depositional environments for major types of iron-formation and ironstones in North America are indicated in Figure 3-1. The typical compositions of the main types of iron-formation and ironstone are given in Table 3-1.

Deposits of the stratafer group, including the common lithofacies of iron-formation distributed throughout the geological record, mark ancient sites of mineral deposition by hydrothermal-effusive and/or epigenetic processes. Iron-formations are prominent metallogenetic marker beds for the diverse spectrum of lithofacies included in the stratafer group, and have been used effectively for guiding mineral exploration (Frietsch, 1982a, b; Gross, 1986, 1991, 1993a).

SEDIMENTARY LITHOFACIES OF THE STRATAFER GROUP

Understanding the distribution and interrelationships of the various lithofacies in the stratafer group is required for the assessment of their mineral resource potential. Development of the facies concept was a major step in understanding the genesis of chemical sediments and their broader metallogenetic significance. Krumbein and Garrels (1952) demonstrated that pH and Eh in solutions were major factors controlling the composition and mineralogy of hydrolithic sediments deposited in different basin environments. James (1954) applied these concepts in the study of iron-formations in the Lake Superior region and defined four distinct primary facies of iron-formation: oxide, silicate, carbonate, and sulphide. The concept of primary sedimentary facies as demonstrated for iron-formations has provided a basis for understanding the origin and distribution of the variety of other lithofacies in the stratafer group.

Recognition and documentation of facies relationships in iron-formations (Krumbein and Garrels, 1952; James, 1954; Goodwin, 1956; Gross, 1965, 1970a, 1973, 1993a) and in other major groups of stratafer sediments, have been inhibited in many cases because of inadequate stratigraphic and structural data, inadequate documentation of

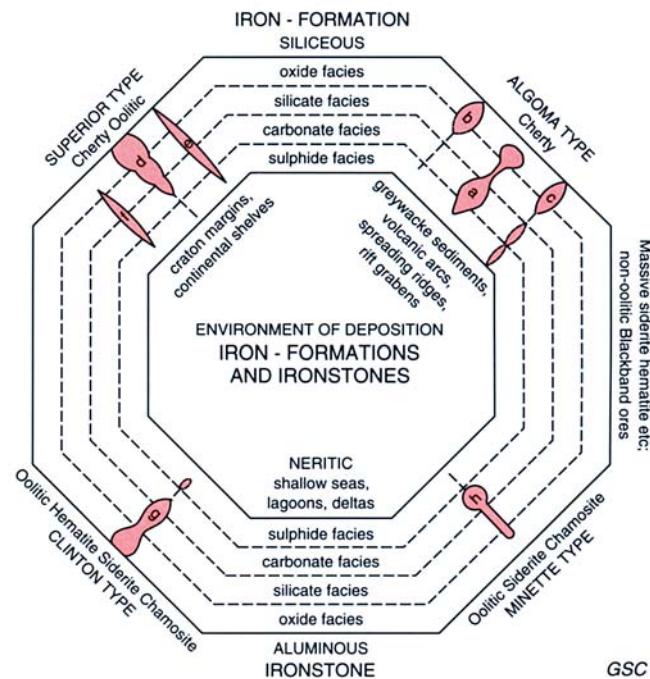


Figure 3-1. Diagram showing major types of chemically precipitated iron-formation and ironstone with their sedimentary facies and depositional environment. Examples are from a) Michipicoten, Ontario; b) Moose Mountain, Ontario; c) Temagami, Ontario; d) Knob Lake, Labrador and Quebec; e) Iron River, Michigan; f) Gunflint and Biwabik iron-formations, Ontario and Minnesota; g) Wabana, Newfoundland; h) Clear Hills, Alberta (after Gross, 1965).

geological events, and a lack of basin analyses. Nevertheless, multiple facies relationships, including the commonly recognized oxide, carbonate, silicate, and sulphide facies of iron-formation, have now been documented in most of the stratafer group. Stratafer lithofacies are now generally accepted as having formed by similar hydrothermal-sedimentary processes, are interbedded in many stratigraphic successions, and occur throughout the geological record from Early Archean to the modern possible protofacies on the seafloor (Gross, 1987, 1988b).

Mineral exploration for deposits of the stratafer group has been oriented mainly to assessing the resource potential for specific metals or particular mineral groups, ferrous, nonferrous, or precious metals. In formulating guidelines for exploration, some have overlooked, ignored, or not recognized the association of lithofacies in the stratafer group of metalliferous sediments as a whole, and the distribution of metals and interelement relationships between them. Considerable confusion exists in current literature because different facies of iron-formation are not

identified or are described under different names, detailed stratigraphic relationships are not reported, primary depositional and diagenetic features are not recognized, and distinctions between isochemical metamorphism and alteration by epigenetic and metasomatic processes are not made.

Discrepancies and inconsistencies in nomenclature and terminology in petrographic descriptions have also contributed to confusion in understanding the relationships of lithofacies and have seriously distracted from our understanding of common genetic processes for the whole assemblage of metalliferous sediments. The development of consistent descriptive nomenclature for local stratigraphic features is of course needed, but it should be placed in the context of established schemes of nomenclature and accepted usage or at least referred to them (cf. Gross, 1965, 1970b, 1990; Brandt et al., 1972).

Studies of genetic processes have tended to be carried out independently on the major lithofacies groups, the iron-formations, the manganese-iron, polymetallic sulphide, and

Table 3-1. Compositions of different types of iron-formation and ironstone (from Gross, 1965).

Type	Iron-formation			Ironstone		
	Algoma	Lake Superior		Rapitan	Clinton	Minette
Location	Temagami	Knob Lake area		Snake River	Wabana	Peace River
Facies	Oxide ¹	Oxide ²	Silicate Carbonate ³	Oxide ⁴	⁵	⁶
Fe (wt.%)	33.52	33.97	30.23	38.93	51.79	30.9
SiO ₂	47.9	48.35	49.41	33.03	11.42	28.0
Al ₂ O ₃	0.9	0.48	0.68	1.08	5.07	5.79
Fe ₂ O ₃	31.7	45.98	16.34	54.71	61.83	29.81
FeO	14.6	2.33	24.19	0.85	11.00	13.0
CaO	1.45	0.1	0.1	3.58	3.32	1.9
MgO	1.8	0.32	2.95	1.66	0.63	1.5
Na ₂ O	0.2	0.33	0.03	0.05	ND	0.3
K ₂ O	0.32	0.01	0.07	0.03	ND	0.5
H ₂ O+	0.47	2.0	5.2	ND		
H ₂ O-	0.1	0.04	0.38	0.48	1.94	13.1
TiO ²	0.05	0.01	0.01	0.19	0.015	0.1
P ₂ O ₅	0.1	0.04	0.08	0.58	1.96	1.5
MnO	0.3	0.25	0.65	0.17	0.17	0.1
CO ₂	ND	0.03	0.22	3.45	2.15	2.8
S	ND	0.013	0.05	0.02	.023	ND
C	ND	0.08	0.15	ND	ND	ND

Notes:

1) Average of 4 analyses for 15 m of section sampled; Algoma-type magnetite-quartz iron-formation, mainly oxide facies, Temagami Lake area, Ontario (analyses, Geological Survey of Canada laboratories).

2) Average of 6 analyses for 100 m of section sampled; Lake Superior-type hematite-magnetite-quartz iron-formation, oxide facies, Knob Lake iron ranges, Quebec and Labrador (analyses, Geological Survey of Canada laboratories).

3) Analyses for 15 m of section sampled; Lake Superior-type silicate-carbonate-chert facies, Knob Lake iron ranges, Quebec and Labrador (analyses, Geological Survey of Canada laboratories).

4) Average of 42 samples collected at random of typical oxide facies, Rapitan-type hematite-quartz iron-formation, Snake River area, Mackenzie Mountains, Yukon Territory (analyses, Geological Survey of Canada laboratories).

5) Analysis of large composite sample; Clinton-type ironstone, Wabana, Newfoundland (courtesy, Wabana Mines).

6) Average of 11 samples, each of 4.5 m of section; Minette-type, oolitic siderite-chamosite-limonite ironstone, Peace River district, Alberta (Mellon, 1962).

7) ND: not determined.

other sedimentary-exhalative facies. Hydrothermal-effusive or volcanogenic processes, proposed initially in Europe and seriously considered about a century ago in the study of iron-formations, were considered independently for the genesis of the other facies in the stratafer group, and have been discussed in voluminous literature. The many distinctive lithofacies of the stratafer group are interbedded in many sedimentary and volcanic successions, have been traced laterally from one group to another, and syngenetic relationships between the facies groups cannot be ignored.

Patterns in the distribution of metalliferous lithofacies in relation to hydrothermal-effusive and volcanic centres that are evident from empirical data, and that are analogous to the patterns for ancient stratafer sediments, have been outlined for sulphide, silicate, carbonate, and oxide facies in recent marine sediments. Descriptive data for these metalliferous sediments from Honnorez et al. (1973); Cronan (1980); Bornhold et al. (1982); Hekinian (1982); Smith and Cronan (1983); Bischoff et al. (1983); Gross (1983b, 1987); Koski et al. (1984); Gross and McLeod (1987); and many others are summarized as follows:

1. Polymetallic "massive" sulphide facies occur within and close to volcanic vents. The thinly banded and layered iron-rich sulphide facies associated with them usually extend to areas distal from the vents.
2. Stacks, mounds, crusts, and gelatinous sediments are developed around vents from which high temperature hydrothermal fluids are discharged. Transitional zoning outward from the vents, from iron and copper-zinc sulphides, to iron and manganese sulphide and oxide facies, evidently follows high-to-low temperature gradients.
3. Sedimentary sulphide facies were deposited close to the higher temperature effusive centres; iron oxide and silicate facies were intermediate, and manganese-iron facies were deposited around cooler hydrothermal vents and in areas distal from active hydrothermal discharge. Overlapping and transitions in facies types are common.
4. Sequential development of different facies of metalliferous sediments during the evolution of a spreading ridge system gave rise to the deposition of iron and manganese oxide facies in the initial and cooler stages of effusive hydrothermal activity along ridge axes, and deposition continued along ridges in the direction of propagation of a ridge system. Facies development extends laterally from polymetallic and iron sulphide facies proximal to vent areas, to silicate facies, and carbonate facies usually in shallow water, to iron and manganese oxide facies distal from hydrothermal centres.
5. Hydrothermal effusive systems are commonly initiated at the intersection of ridge axes and transverse faults and achieve their greatest intensity and maturity in these areas.
6. Metals from hydrothermal effusive sources may be carried in currents and plumes for distances of 100 km or more before they are deposited as iron-dominated metalliferous sediments or manganese nodules.
7. As ridge systems develop, the earlier formed metalliferous deposits are carried on the spreading plate laterally from the axial zone and become covered with clastic sediment, including turbiditic beds, or with lava and

TECTONIC BELTS, FRACTURE SYSTEMS

PLATFORMAL BASINS, CRATON MARGINS - LOW RELIEF

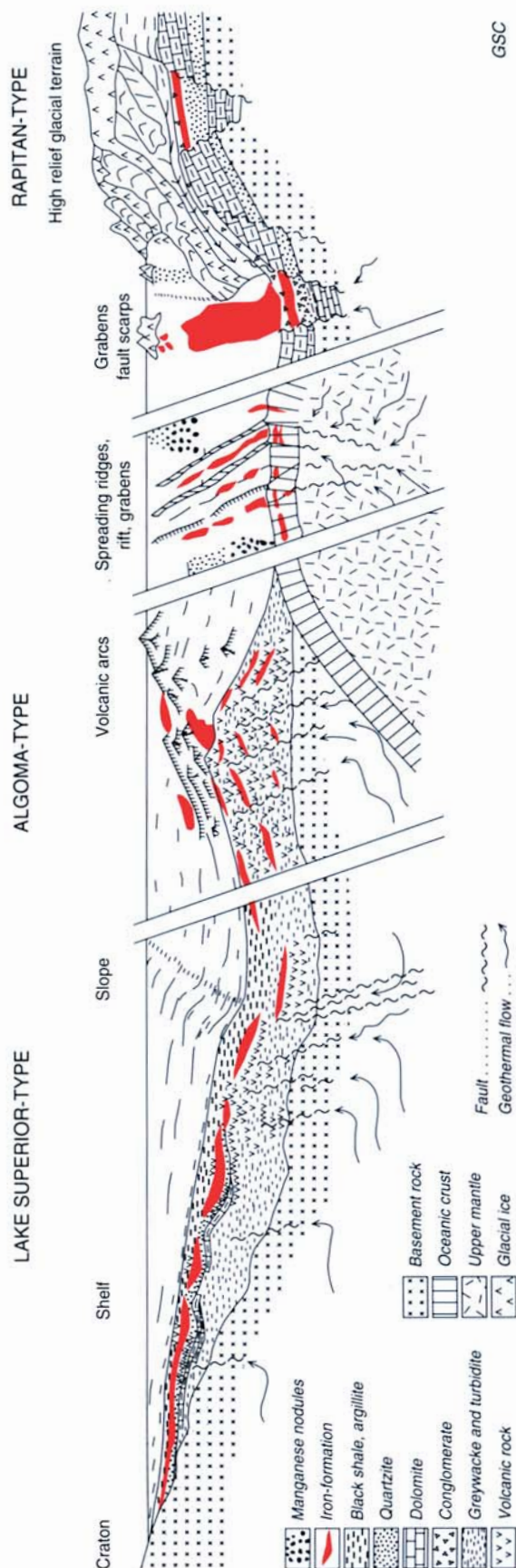


Figure 3-2. Tectonic environments for the deposition of iron-formation.

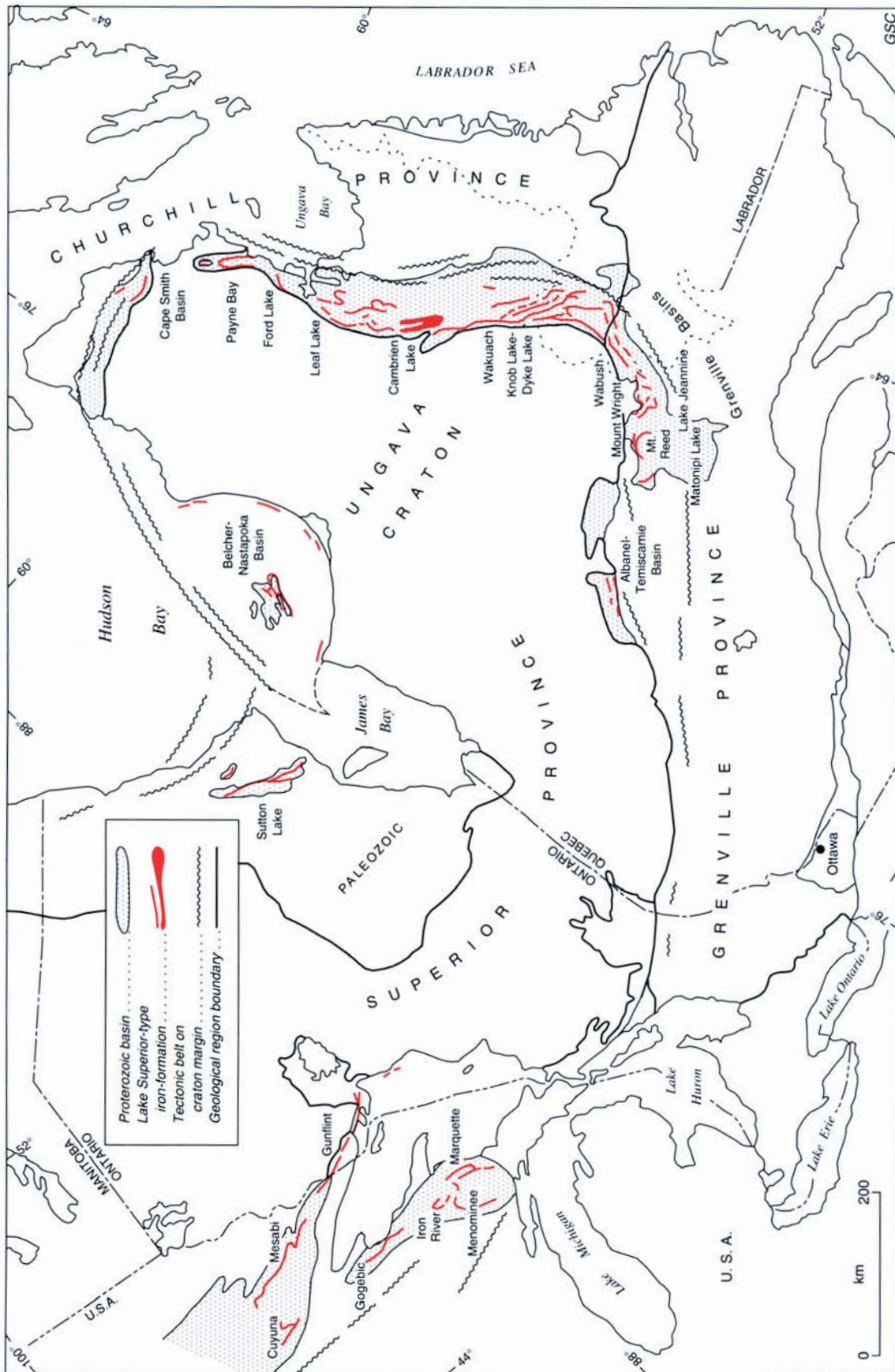


Figure 3-3. Distribution of Lake Superior-type iron-formation in sedimentary-tectonic basins marginal to the Ungava-Superior craton.

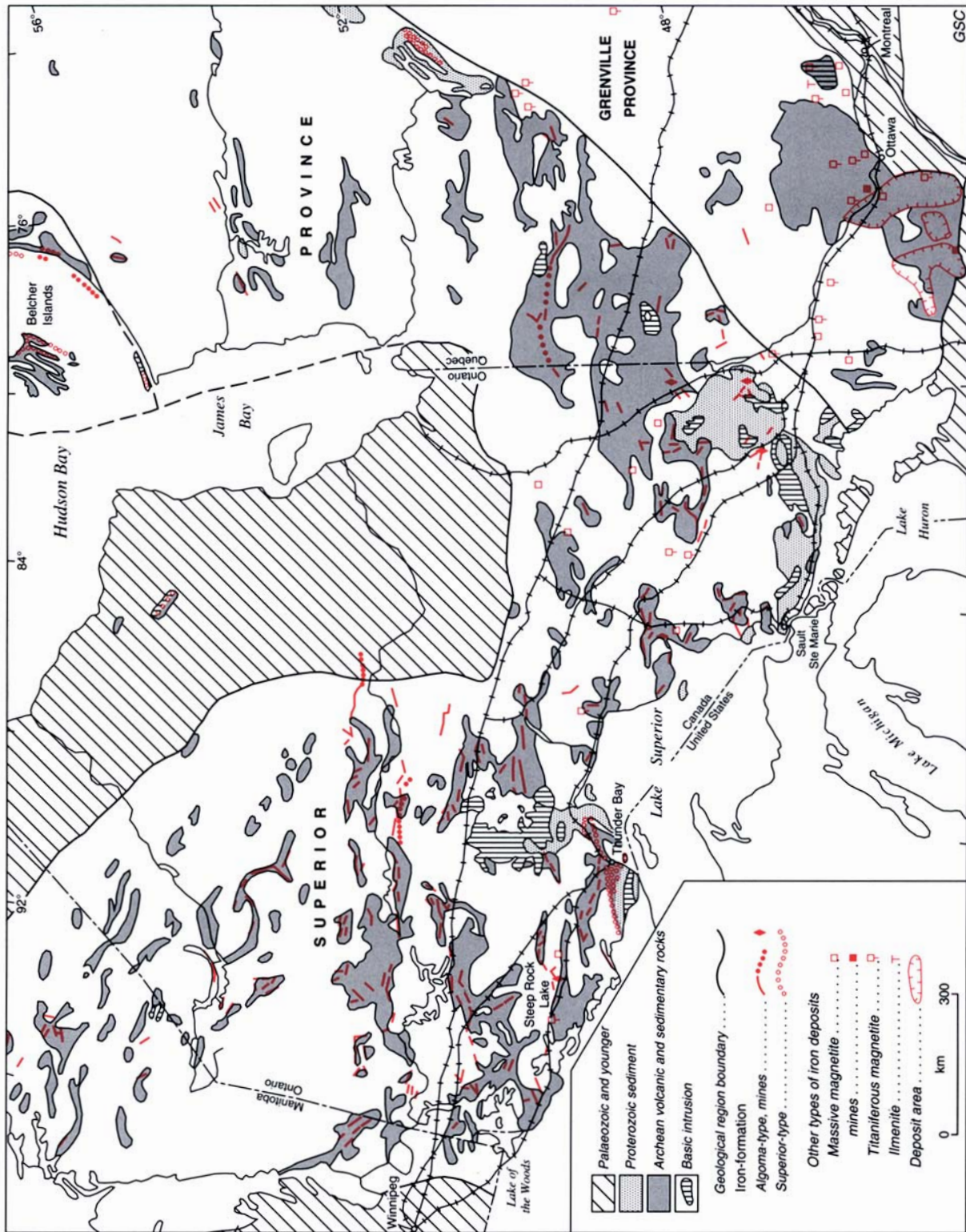


Figure 3-4. Algoma- and Lake Superior-type iron-formations, iron deposits, and mines of the southern Canadian Shield (modified after Lang et al., 1970).

tuff. Deposition of higher temperature polymetallic sulphide minerals takes place in the tectonically active and faster spreading segments in the propagating parts of ridges.

8. Metalliferous sediments, including manganese nodules, accumulate throughout the entire period of ridge development in basins distal from ridge axes where the rate of clastic sedimentation is low.
9. Hydrolithic sediments (e.g., chert) are commonly interspersed with volcanic rocks, clastic sediments, and dolomite, and record hydrothermal-effusive and exhalative processes in the history of an area.

LITHOFACIES OF THE STRATAFER GROUP

Modern concepts for understanding the metallogeny of iron-formations and other members of the stratafer group are based on the recognition of three main factors:

1. their hydrolithic nature and derivation from primary aqueochemically precipitated protofacies;
2. the predominant role of hydrothermal-effusive and volcanogenic processes in their genesis; and
3. the interrelationships and diverse nature of lithofacies formed by hydrothermal-sedimentary processes.

Iron-formation lithofacies

Lithofacies of stratafer sediments that contain more than 15% iron are classified as iron-formation. They are widely distributed throughout the geological record and were deposited in a broad spectrum of depositional environments ranging from continental shelves and platforms, through craton and oceanic plate margins, to tectonic basins and volcanic arcs along subduction zones. The most diverse group of iron-formation lithofacies are proximal to volcanic centres in association with turbidites and volcanic rocks along offshore tectonic-volcanic belts, island arcs, spreading ridges, and rift zones in deep ocean basins (Gross, 1973, 1980, 1983a).

Gross (1959a, 1965) considered the iron-formations and associated hydrolithic sediments to be sensitive indicators of their depositional environments. He recognized two principal types of iron-formation, Lake Superior and Algoma, based on tectonic setting, types of associated rocks, and depositional environment. Both types were considered to have formed by similar hydrothermal-effusive or exhalative processes, but in distinctly different tectonic and depositional environments as depicted in Figure 3-2 (Gross, 1965, 1973, 1983a).

Iron-formations of Lake Superior type have been the principal sources of iron ore throughout the world for more than a century. They formed in shelf and platform basins along the margins of Early to Middle Proterozoic cratons and are preserved on all of the continents. They are associated with normal shelf-type sedimentary rocks, including dolostone, quartz arenite, arkose, black shale, and conglomerate, and with tuff and other volcanic rocks in linear basins along craton margins. The distribution of Lake Superior-type iron-formations around the margins of the Superior-Ungava craton of the Canadian Shield is outlined in Figure 3-3.

Algoma-type iron-formations occur throughout the geological record in marine depositional environments that are distributed along volcanic arcs, spreading ridges, grabens, fault scarps, and fracture zones, and are interbedded with greywacke, turbidites, metalliferous sediments, and volcanic rocks (Gross, 1959a, 1965, 1973, 1983a). Algoma-type iron-formation and other associated stratafer lithofacies are widely distributed and appear to be consistently present in belts of volcanic and sedimentary rocks such as the Archean greenstone belts of the Superior Province (Fig. 3-4).

Rapitan-type iron-formations have distinctive lithological features, being associated with diamictites (tillite), including dropstones, sandstone, conglomerate, and argillites. Examples, such as the Snake River banded chert-hematite facies in the Mackenzie Mountains in northwestern Canada (Gross, 1964a; Yeo, 1978, 1986) and the Jacadigo iron-formation in Brazil (Dorr, 1973), were deposited in grabens and fault scarp basins along the rifted margins of continents or ancient cratons in sequences of Late Proterozoic and Early Paleozoic rocks.

Evidence for hydrothermal-effusive processes in the genesis of iron-formations, especially the stratigraphic association of Algoma-type iron-formation with volcanic episodes, as pointed out by Goodwin (1962, 1973), Gross (1965, 1983a), Ohmoto and Skinner (1983), and Shegelski (1987), has established a basis for linking their metallogenesis with that of other metalliferous facies of the stratafer groups. Modern iron-formation facies on the seafloor are analogous to common lithofacies of the stratafer group in the rock record (Bischoff, 1969; Honnorez et al., 1973; Bischoff et al., 1983; Smith and Cronan, 1983; Boström and Widenfalk, 1984; Koski et al., 1984; Gross and McLeod, 1987; El Shazly, 1990), supporting the early interpretations of their hydrothermal-sedimentary origins (Gross, 1965, 1991). The history of the development of hydrothermal-effusive, volcanogenic, and exhalative concepts for the origin of iron-formation and associated stratafer lithofacies has been reviewed by Gross (1991) and Stanton (1991).

Manganese iron-formation lithofacies

Manganiferous facies interbedded in iron-formations are the principal host rocks throughout the world for large manganese deposits (Gross, 1983b, 1990). The major deposits consist of primary manganiferous lithofacies and "secondary enrichment deposits" hosted in manganese-rich iron-formation. Roy (1981) comprehensively reviewed manganese deposits throughout the world. An excellent overview of genetic concepts for manganese deposits was presented by Varentsov and Grassely (1980a, b, c) for Africa, South America, Hungary, India, South Korea, and the former Soviet Union. Manganese carbonate facies in iron-formation on the Nastapoka Islands in Canada were reported by Bell (1879), and manganese oxide facies in iron-formation at Woodstock, New Brunswick were mined as iron ore from 1848 to 1884 (Gross, 1967; Anderson, 1986). Manganese facies in iron-formation in the Lake Superior iron ranges have been described by James (1954), Lepp (1963, 1968), and Schmidt (1963); in high-grade metamorphic terrain in India by Devaraju and Laajoki (1986); in the Karadzhai deposits in Kazakhstan by Sapozhnikov (1963) and Kalinin (1965); at Jalisco, Mexico by Zantop

(1978); in Minas Gerais, Bahia, and Morro do Urucum in Brazil by Park et al. (1951) and Dorr et al. (1956); in South Africa by De Villiers (1956), Beukes (1973), and Sohnge (1977); in Sweden by Frietsch (1982b); and in the former U.S.S.R. by Varentsov and Grasselly (1980b).

Aside from manganese nodules, manganese deposition related to active hydrothermal fields took place in areas distal from hydrothermal vents, in the outer margins of the sedimentary basins, and manganese was generally transported beyond the main depositional areas for siliceous iron-rich facies (Gross, 1987).

Polymetallic sulphide lithofacies

Polymetallic sulphide (massive sulphide) lithofacies were considered separately in North America until the late 1950s when the common syngenetic relationships between oxide, carbonate, silicate, and sulphide facies in iron-formation were recognized by many exploration geologists. The metallogenic significance of hydrothermal-effusive, exhalative, and volcanogenic processes were emphasized in Canada in the early work of Gross (1959a, 1965, 1973); Stanton (1959); and Goodwin (1962). These concepts were applied successfully in the exploration for massive sulphide deposits (Stanton, 1960; Roscoe, 1965; Hutchinson, 1965; Gilmour, 1965). Hutchinson et al. (1971) pointed out that the distinction between the exhalative iron-formations and the associated sulphide deposits was based on metal content rather than genetic process.

Interbedding of oxide, carbonate, and sulphide facies of iron-formation has been observed throughout the world, for example in the Bathurst area, New Brunswick (McAllister, 1959; Gross, 1967; Van Staal and Williams, 1984); in the Manitouwadge and Michipicoten areas, Ontario (Goodwin, 1962; Franklin et al., 1981); at Broken Hill in New South Wales, Australia (Stanton, 1976); in the Gamsberg base-metal sulphide deposit in Cape Province, South Africa (Rozendaal, 1980); in the Isua iron-formation in Greenland (Appel, 1979); in Sweden (Frietsch, 1980a, b, c, 1982a, b); in Lake Superior-type iron-formations in the Labrador-Quebec fold belt in Canada (Barrett et al., 1988); in the Kuroko and related volcanogenic massive sulphide deposits in Japan (Ohmoto and Skinner, 1983); in the Red Sea metalliferous sediments (Degens and Ross, 1969; El Shazly, 1990); and in many other stratiform sulphide deposits in Canada referred to by Sangster (1972), Franklin et al. (1981), and Franklin and Thorpe (1982).

Gale (1983) discussed the sedimentary and volcanic settings of stratiform Proterozoic exhalative massive sulphide deposits, mainly from the Canadian Shield, and referred to the stratabound nickeliferous sulphide deposits at Outokumpu, Finland and at Thompson, Manitoba, associated with biotite gneiss, quartzite, calc-silicate rock, pelitic schist, greywacke, and banded iron-formation.

The primary nature of many sulphide deposits is obscure because of the extensive recrystallization and remobilization of constituents in sulphide facies in the vent area during their formation, and during metamorphism (see Introduction, deposit Type 6, "Exhalative base metal sulphide"). Element mobility in sulphide facies during diagenesis and metamorphism greatly exceeds that in other lithofacies of the stratafer group and the syngenetic

distribution of elements and primary sedimentary features are not well preserved in many cases, or may be totally destroyed. Depending on the location and configuration of a depositional basin relative to the hydrothermal vents or metal sources, sulphide, oxide, and manganese-iron facies are locally developed as discrete units. Lateral transitions from one facies to another, and the genetic relationships of protofacies, are commonly obscure.

Sedex lithofacies

Sedex deposits (see "Sedimentary exhalative sulphides (Sedex)", subtype 6.1) are another sedimentary-exhalative member of the stratafer group, distinguished by the dominance of zinc and lead, by their predominantly sedimentary depositional environment, and in some cases by the apparent lack of directly associated volcanic rocks. Some Sedex deposits contain significant amounts of copper, antimony, tungsten, tin, gold, silver, and mercury, and relatively minor amounts of iron and manganese in the associated siliceous and carbonate facies (Edwards and Atkinson, 1986). Some Sedex deposits are not clearly distinguished from polymetallic volcanogenic massive sulphide deposits because of similarities in their genesis and in specific lithofacies (see Introduction, "Exhalative base metal sulphide").

The spatial association of iron-formation lithofacies with the Sedex and VMS lithofacies is well established. For example, Schultz (1966) and Edwards and Atkinson (1986) pointed out that oxide facies iron-formation at Tynagh mine, Ireland is the lateral stratigraphic equivalent of the bedded lead-zinc sulphide ore, and they described the association of iron-formation with the sulphide ore beds at Broken Hill, Australia. They considered Howards Pass and Sullivan deposits in Canada; Rammelsberg and Meggen in Germany; Broken Hill, Mount Isa, and McArthur River in Australia; Gamsberg in South Africa; and Tynagh and others in Ireland to be typical sedimentary-exhalative deposits. All are associated with banded chert and carbonate, and some are associated with sulphide and oxide lithofacies of iron-formation.

The tectonic setting and origin of the Jason deposit in the Yukon Territory, described by Winn and Bailes (1987), is considered to be representative of many Sedex deposits that were formed by the expulsion of hydrothermal fluids along a fault zone at the margin of a graben basin. The silicified, carbonatized, and brecciated rocks (stockworks) associated with the main stratiform bedded mineral zone are believed to mark hydrothermal conduits in the area.

The Sedex members of the stratafer group are of special metallogenic interest because some contain economically significant amounts of the minor or trace elements that are consistently present in the common lithofacies of iron-formation. The following examples illustrate the great variety of metalliferous strata of hydrothermal-sedimentary origin that are included in the stratafer group: phosphorus-rich facies of iron-formation in Finland (Laajoki, 1986) and in Sweden (Frietsch, 1974); zinc-bearing iron-formations in the Grenville Province in southern Quebec (Gauthier et al., 1987); highly metamorphosed zinc deposits related to iron-formation such as the Balmat-Edwards-Pierrepoint deposits in New York State, and similar deposits in Sweden (Frietsch, 1982a); stratiform tungsten deposits of San Luis, Argentina

(Brodtkorb and Brodtkorb, 1977); King Island scheelite mine in Tasmania (Burchard, 1977); antimony-tungsten-mercury deposits in the eastern Alps (Höll, 1977); stratiform tin deposits in Bolivia (Schneider and Lehmann, 1977); and stratiform mercury and antimony-tungsten-mercury deposits in Turkey (Sozen, 1977).

Rare-earth elements in iron-formation

Trace amounts of rare-earth elements (REEs) occur in iron-formations in all parts of the world, regardless of their age and facies. Typically the iron-formations are enriched in La and light relative to the heavier REEs and have marked positive Eu anomalies in chondrite-normalized data, except for facies that have a mixed provenance of chemically precipitated and clastic constituents. The REEs, like other minor elements, are not distributed uniformly and their content varies greatly from bed to bed in the cherty iron-formations (Gross, 1993a).

The largest known ore reserves of REEs occur in the Bayan Obo iron-formations in Inner Mongolia, China, where estimates of the iron ore reserves exceed 1000 million tons (907 Mt) containing 30 to 35% Fe, 5.7% REEs, 0.126% Nb, and 2% fluorite (Gross, 1986, 1993b). Oxide and carbonate facies of this highly folded and metamorphosed iron-formation are interbedded with oolitic dolostone in a typical succession of Early to Middle Proterozoic quartz arenite and arkose, dolomite, and black slate-shale that was deposited in a linear basin along the rifted margin of the North China Platform. The distribution of the REEs in the iron-formation and dolomite is interpreted by Gross (1993b) to be syngenetic. For example, although the contents of minor elements range from 10 to 2000 times greater in the Bayan Obo iron-formations than the average contents in most Lake Superior-type iron-formations, the interelement correlation patterns, including those for REEs, are similar to patterns found consistently in similar facies of most other iron-formations (Gross, 1993b). The abnormally high content of REEs and other minor elements in the Bayan Obo iron-formation is attributed to extensive hydrothermal contribution of constituents from the mantle and ideal conditions for rapid precipitation with dolomite and iron-formation and adsorption on the primary iron oxide minerals. Other iron-formations containing abnormally high amounts of REEs have been reported in China (Tu et al., 1985) and these occurrences, along with Bayan Obo, illustrate the metallogenetic importance of REEs in some of the iron-formations.

Gold in iron-formation

The common association of gold with iron-formations and stratafer sediments throughout the world has been recognized for more than a century. Iron-formations are now used widely as marker beds in the exploration for gold in fold-belts of sedimentary-volcanic rocks. Iron-formations and stratafer sediments are good host rocks for gold for the following reasons:

1. they are competent and brittle, providing excellent fracture systems for vein development;
2. their high iron contents in oxide, carbonate, silicate, and sulphide minerals are interpreted to be conducive to the precipitation of gold from hydrothermal solutions; and

3. as hydrolithic sediments they consistently contain minor but significant amounts of syngenetic gold (Gross, 1988a; see subtype 15.3, "Iron-formation-hosted stratiform gold") which may increase to an economically important content in some cases, as in the Homestake mine, South Dakota (Rye and Rye, 1974), in Lupin mine in the Northwest Territories (Kerswill et al., 1983), in the Kolar schist belt of India (Natarajan and Mukherjee, 1986), in many deposits in Canada (Hodgson and MacGeehan, 1982; Hodder and Petruk, 1982; Macdonald, 1990), in Zimbabwe (Saager et al., 1987); and in many other deposits throughout the world.

Element correlation patterns in many iron-formations show that Au distribution is commonly correlated with Sb, Bi, As, S, Zn, and that Au is enriched in mineral assemblages such as the sulphosalts that formed at moderate to lower temperatures in the hydrothermal systems (Gross, 1988a). Hannington and Scott (1988) provided evidence to show that different sulphide mineral equilibria and FeS contents in sphalerite reflect the same physical and chemical conditions which influence gold content. They suggested that petrological indicators of the sulphidation state may be useful guides to gold mineralization in volcanogenic massive sulphide deposits.

TYPES OF IRON ORE DEPOSITS

Iron ore deposits are highly diversified in their characteristics and origin and many different kinds of deposits are recognized. Descriptions of their physical, chemical, and geological features should provide an objective basis for recognizing the different types of ore deposits, primary and secondary genetic processes and genetic models, and an indication of the probable size, grade, and quality of ore that can be extracted from them (Gross, 1965, 1967, 1968).

Gross (1970b) classified iron deposits into five major types; bedded, massive, residual, byproduct, and "other" types. An extension of this classification, which includes six major types of deposits that are defined on the basis of descriptive data and geological features (Gross, 1959a, 1965; Lang et al., 1970), is as follows:

1. iron-formation (see subtype 3.1, "Lake Superior-type iron-formation" and subtype 3.2, "Algoma-type iron-formation"), ironstone (subtype 3.3), and other iron-rich sediments;
2. residual deposits derived from iron-formations by leaching of silica and concentration of iron oxide (see subtype 4.1, "Enriched iron-formation");
3. residual deposits, including chemically and mechanically transported surface deposits, placer sands, bog iron, laterite;
4. deposits in or associated directly with plutonic rocks, including 4a) mafic and ultramafic rocks (see Type 26, "Mafic intrusion-hosted titanium-iron") and 4b) felsic granitoid, and alkaline granitic rocks;
5. skarn, contact metasomatic, vein and structurally-controlled replacement deposits, (see subtype 20.4, "Skarn iron"); and
6. other types of deposits.

About 20 subtypes of these main types are found in Canada. Most of the iron ore resources in Canada occur in siliceous hydrolithic sediments classified as Lake Superior- or Algoma-type iron-formation.

IRON ORE

Iron ore is natural material of suitable grade, composition, and physical quality that can be mined and processed for profit or economic benefit, and similar resources that could be mined under present circumstances if a market and demand for them existed. Iron ore resources include all categories of measured, indicated, and inferred resources, and potential resources that include materials that could provide a source of iron in the future.

Many complex and interrelated factors are considered in the identification and appraisal of iron ore resources. These include the size, location, chemical composition, physical characteristics, amenability of ore to concentration and beneficiation, the quality and composition of other raw materials such as coal and limestone that will be used in smelting the ore, and the kind of smelting and steel-making process being used (blast furnace or direct reduction in rotary kilns; Bessemer, non-Bessemer, open hearth, oxygen smelting, electric-crucible direct reduction, etc.). It is desirable to use natural material that meets the required physical and chemical specifications, or ore that can be easily concentrated and processed to improve its quality and to meet required specifications. Hard lump ore with a low proportion of fine sized particles is still a premium product. It is not available in quantity in North America, and most of the ore now used consists of mineral concentrates that are sintered or pelletized to provide the desired physical and chemical properties and grade required for a particular smelting process.

The most desirable iron ore will have the highest iron and lowest silica and alumina contents possible; low contents of magnesium and calcium carbonate, depending on the amount of fluxing agents needed in a particular furnace burden; less than 2% manganese; and low contents (<0.05%) of phosphorus, sulphur, arsenic, sodium, potassium, titanium, and other ferride elements. A high proportion of the iron ore used throughout the world is processed and marketed as pellets, concentrate, or sinter feed and products.

The compositions of typical high quality iron ore pellets produced in Canada in 1985 and sintered ore blended in special processes are given in Table 3-2. Iron ore containing more than 2% manganese is usually sold separately as manganiferous iron ore and used for blending with iron ore from other sources, or in the production of ferromanganese.

Table 3-2. Typical composition of iron ore pellets and sinter produced in Canada in 1985.

%	Pellets	Sinter
Fe	64.76	47.81
P	0.008	0.016
SiO ₂	4.90	8.31
Mn	0.10	2.24
Al ₂ O ₃	0.31	1.31
Ca	0.51	12.69
Mg	0.38	6.46
S	0.003	0.083
LOI	0.19	0.87
Moisture	1.15	—
LOI = Loss on ignition		

Iron ore containing as much as 1% titanium has been used, but because titanium causes slags to become viscous, it is generally not accepted for blast furnace burden.

ACKNOWLEDGMENTS

This introduction was edited by C.W. Jefferson and R.I. Thorpe. Word processing assistance was provided by C.M. Plant and L.C. O'Neill.

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3.1 LAKE SUPERIOR-TYPE IRON-FORMATION

G.A. Gross

INTRODUCTION

Lake Superior-type iron-formations are chemically precipitated (hydrolithic) banded sedimentary rocks composed of iron oxide, quartz (chert), silicate, carbonate, and sulphide lithofacies that were deposited along Paleoproterozoic craton margins, on marine continental shelves, and in shallow rift basins. They are typically associated with texturally and compositionally mature sedimentary rocks such as quartz arenite, dolostone, black shale, and argillite, with additional tuffaceous strata and other volcanic rocks. Lithofacies that are not highly metamorphosed or altered by weathering processes have been referred to as taconite and the more highly metamorphosed as metataconite, itabirite, or banded iron-formation (BIF). The iron oxide lithofacies selected for iron ore usually contain at least 30% iron and a minimum amount of carbonate and silicate lithofacies that must be separated from the iron oxide minerals in the processing of the crude ore and production of high grade ore concentrates. The highly metamorphosed iron-formations are coarser grained and are generally more amenable to processing and concentration of the iron oxide minerals than the fine grained lithofacies. Iron ore consisting of mineral concentrates is usually processed further by

pelletizing and sintering, and blended with other types of ore to improve the overall grade and structural quality of the furnace burden, the blended mixture of iron ore, coke, coal or carbon fuel, and carbonate rock charged to blast furnaces.

IMPORTANCE, SIZE, AND GRADE OF DEPOSITS

Lake Superior-type iron-formations include the thickest and most extensive stratigraphic units of iron-formation, and provide the largest iron deposits and the source rocks for more than 60% of the iron ore resources of the world. About 35 million long tons (35.6 Mt) of iron ore concentrate have been produced in Canada annually from 82 million long tons (83.3 Mt) of highly metamorphosed hematite and magnetite lithofacies of iron-formation from the Humphrey, Smallwood, and Wabush mines in southwest Labrador, and the Mount Wright mine in northeast Quebec (Fig. 3.1-1). In 1985, the Humphrey and Smallwood mines produced 34 million long tons (34.6 Mt) crude ore containing 38.9% iron, which yielded 15 million long tons (15.2 Mt) of concentrate grading 63.9% iron; and the Mount Wright mine produced 37 million long tons (37.6 Mt) of crude ore containing 39.9% iron, to provide 15 million long tons (15.2 Mt) of concentrate grading 63.9% iron.

Taconite deposits are not mined in Canada, but a major part of the 40 million or more long tons (40.7 Mt) of ore concentrate produced annually from taconite in the United States has come from the Minnetac, Hibbing, Hoyt Lakes

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Plant, Eveleth (Thunderbird), Minorca, and National Steel Pellet Project, Erie, and Reserve mine properties on the Mesabi Range in Minnesota, and the Tilden, Empire, and Republic mines in Michigan. Taconite mines in the Great Lakes Region produced 118 million long tons (119.9 Mt) of crude ore containing 32% iron in 1986, to provide 40 million long tons (40.7 Mt) of concentrate grading 63.9% iron.

Potential resources of magnetite-rich taconite have been outlined in large deposits in the Schefferville area of Quebec and Labrador, and near Lac Albanel in Quebec. Other large taconite deposits occur on the Belcher Islands, in northeastern Quebec, and in the Gunflint iron-formation, northwestern Ontario. Many iron-formation units in Canada are host rocks for more than 1000 Mt of measured iron resources and some have even greater resource potential.

GEOLOGICAL FEATURES

Tectonosedimentary setting

Lake Superior-type iron-formations form a major part of the successions of folded Proterozoic sedimentary and volcanic rocks that were deposited within extensive basins, some interconnected, along the northeastern and southwestern craton margins of the Superior Province of the Canadian Shield (see Introduction; Fig. 3.3). The Labrador-Quebec fold belt, consisting of sequences of sedimentary and volcanic rocks and mafic intrusions deposited in smaller interconnected subbasins, is the largest continuous stratigraphic-tectonic unit that extends along the eastern margin of the Superior-Ungava craton for more than 1200 km (Fig. 3.1-2). The principal iron-formation unit, the Sokoman Formation, forms a continuous stratigraphic unit that thickens and thins from subbasin to subbasin throughout this fold belt.

As the tectonic systems and volcanic arcs developed along the margins of the Superior-Ungava craton, iron-formation units were deposited in the marginal basins in association with thick sequences of shale, argillite, dolostone, stromatolitic dolostone, chert, chert breccia, black carbon-rich shale, quartz arenite, conglomerate, siltstone, redbeds, tuff, and other volcanic rocks. Lateral transitions occur in many basins from stratigraphic sequences of iron-formation and typical mature clastic sediments that were deposited in nearshore environments on the platform, to sequences of greywacke, turbidites, and shale interbedded with iron-formation, tuff, and volcanic rocks deposited near volcanic centres offshore from the craton margins (Fig. 3.1-3). The thickest sections of iron-formation in the Labrador-Quebec and Belcher-Nastapoka fold belts were deposited in basins adjacent to thick accumulations of volcanic rocks, gabbro, and ultramafic intrusions in the volcanic belts offshore.

The Knob Lake Group in the Labrador-Quebec fold belt (Table 3.1-1) typifies a stratigraphic section of Lake Superior-type iron-formation.

Characteristic structural settings for iron-formations in the fold belts along the craton margins include low-dipping homoclines of quartz arenite and iron-formation that lie unconformably on Archean gneisses, granulites, and granitoid cratonic rocks near the original basin shorelines. Outward from the craton to its faulted margins, these homocline structures are succeeded by broad, open folds that are intensely deformed by complex isoclinal folds and faults, imbricate thrust sheets, and nappe structures that

developed by tectonic transport directed toward the craton. Structural deformation of the marginal basins appears to be related to the initial stages of plate subduction that took place along the craton margins.

The southern part of the Labrador-Quebec fold belt is truncated by the Grenville Front along the northern margin of this orogenic belt (Fig. 3.1-2), but iron-formations and associated shelf metasediments extend southwest into the Grenville Province for more than 200 km. Iron-formations and associated rocks within the Grenville orogen are highly metamorphosed and complexly folded, forming numerous isolated structural segments that have been mapped in detail in mines at Lac Jeannine, Fire Lake, and Mount Wright, and at the Smallwood, Humphrey, and Scully mines in the Wabush Lake area. Iron-formations north of the Grenville belt in the central part of the Labrador-Quebec fold belt are not metamorphosed beyond greenschist facies, but metamorphism increases to lower amphibolite facies in a large area west of Ungava Bay (Gross, 1962, 1967, 1968). Iron-formation in the basins marginal to the Superior Province was deposited between 2100 and 1850 Ma ago, with major deposition about 2000 Ma ago (Morey, 1983; Barrett et al., 1988). Because basin development may have migrated along the craton margin, it is unlikely that major episodes for the deposition of iron and silica were contemporaneous in all areas. Folding and metamorphism related to the Grenville orogeny between 1200 Ma and 800 Ma ago played an essential role in the development of the large iron deposits in the southern Labrador-Quebec fold belt (Fig. 3.1-2) (Gross, 1968; Gross and Zajac, 1983).

Typical successions of Proterozoic rocks within the deeper basins along the Quebec-Labrador belt include basal argillite and shale overlain in sequence by dolostone, quartz arenite, black shale, iron-formation, and black shale. Stratigraphic units become thinner or pinch out near the margins of the depositional basins, and only thin members of quartz arenite, iron-formation, and shale are present in some areas (Fig. 3.1-3). Thin units of iron-formation

Table 3.1-1. Stratigraphy of the Knob Lake Group, Schefferville area, Labrador and Quebec.

Menihiek Formation – Carbonaceous slate, shale, quartzite, greywacke, mafic volcanic rocks; minor dolomite and chert.

Purdy Formation – dolomite, developed locally.

Sokoman Iron-formation – oxide, silicate, and carbonate lithofacies, minor sulphide lithofacies, interbedded mafic volcanic rocks, ferruginous slate, slaty iron-formation, black and brown slate, and carbonaceous shale.

Wishart Formation – feldspathic quartz arenite, arkose; minor chert, greywacke, slate, and mafic volcanic rocks.

Fleming Formation – chert breccia, thin-bedded chert, limestone; minor lenses of shale and slate.

Denault Formation – dolomite and minor chert.

Attikamagen Formation – green, red, grey, and black shale, and argillite, interbedded with mafic volcanic rocks.

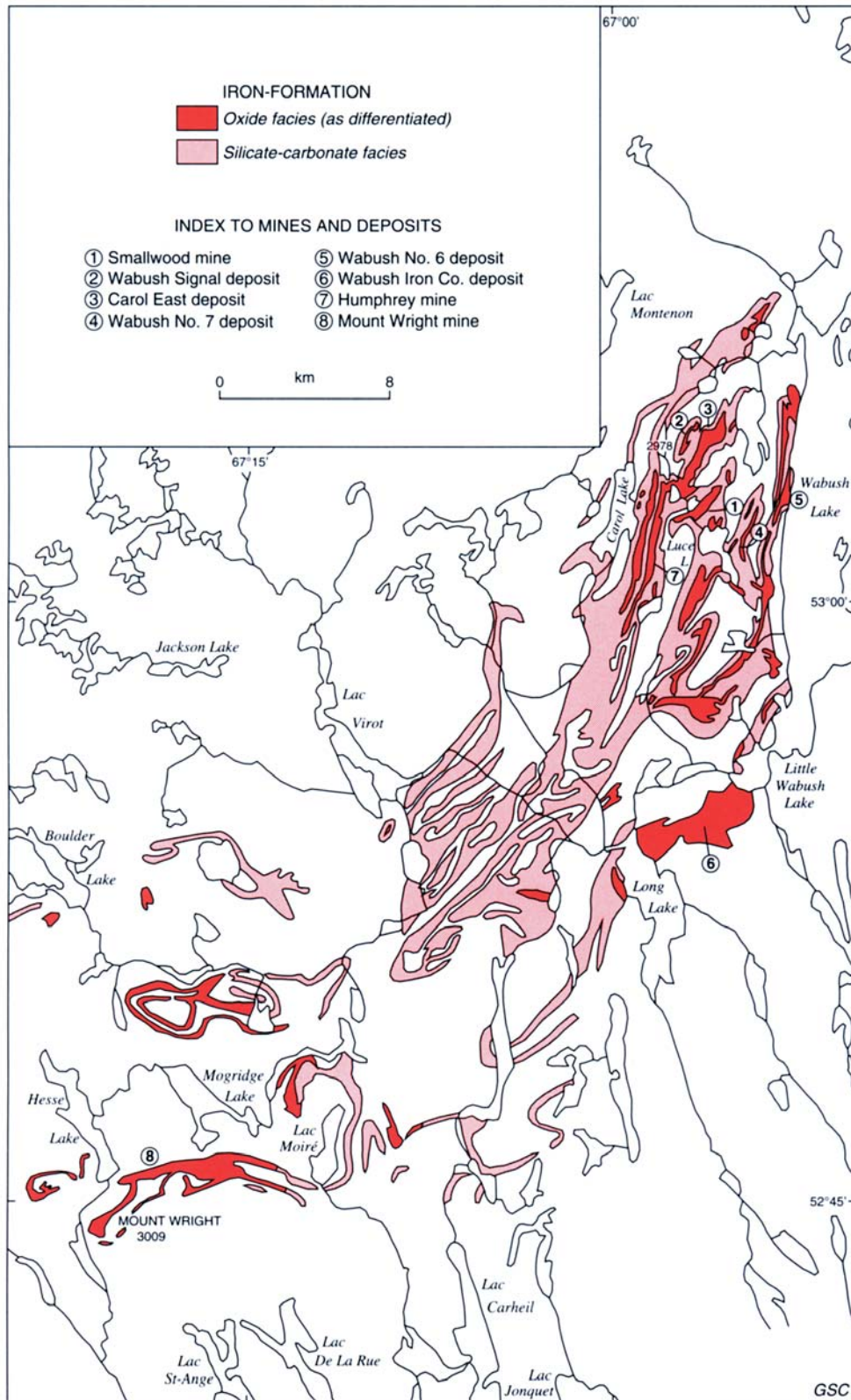


Figure 3.1-1. Iron deposits in highly metamorphosed Lake Superior-type iron-formation in the Wabush Lake and Mount Wright areas, Labrador and Quebec (from Gross, 1968).

STRATIFORM IRON

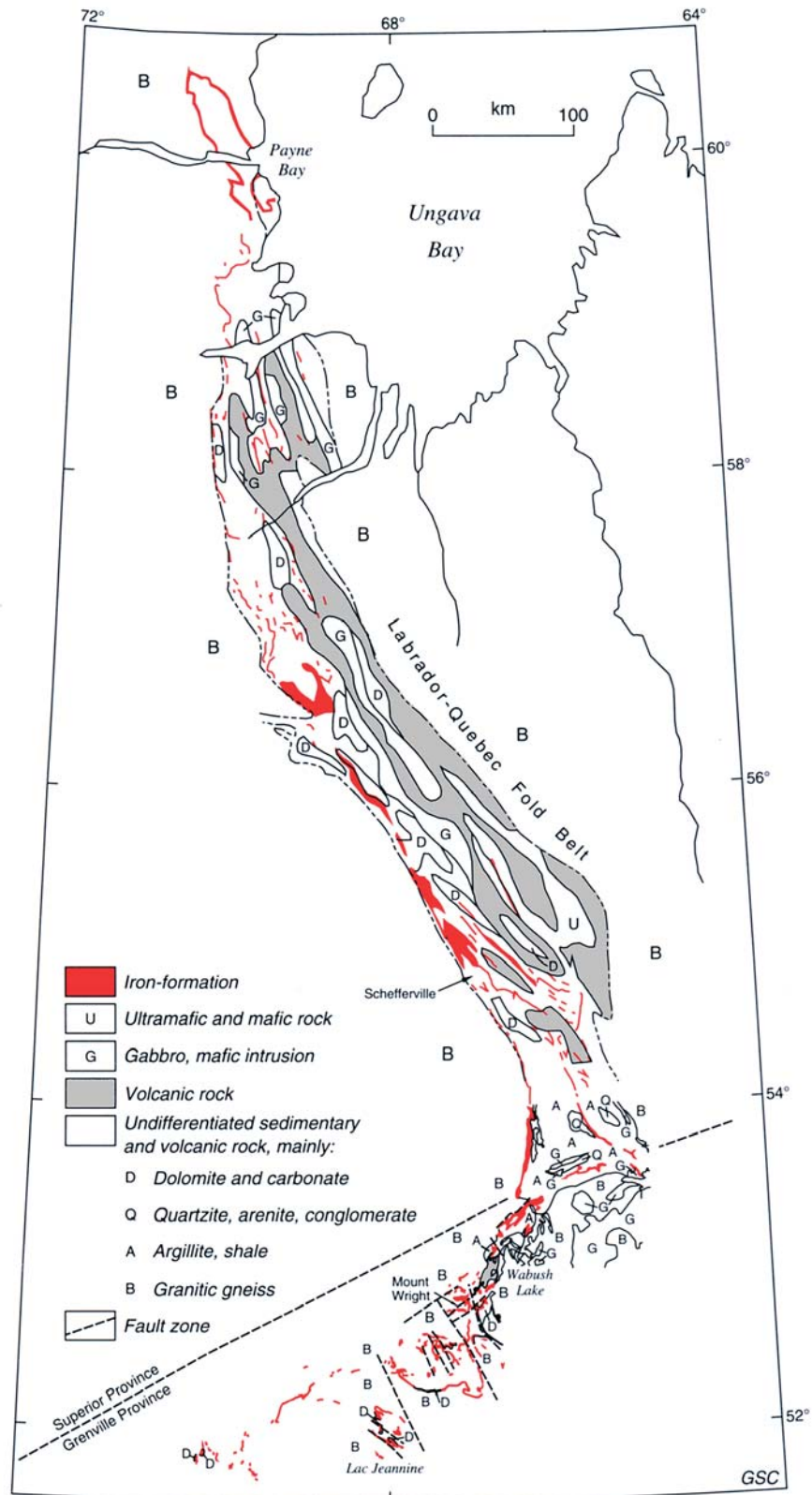


Figure 3.1-2. Iron-formation distribution and tectonic setting of the Labrador-Quebec fold belt (after Gross, 1961, 1968).

unconformably overlie gneissic rocks along the western margin of the Labrador-Quebec fold belt west of Knob Lake (Fig. 3.1-2, 3.1-3).

Lithology

The principal ore zones throughout the Sokoman Formation consist of discrete stratigraphic units of oxide lithofacies of iron-formation (Fig. 3.1-4). Silicate and carbonate lithofacies are consistently developed in the lower parts of the iron-formation and locally in the middle and upper parts, where they interfinger on a microscopic and macroscopic scale (Fig. 3.1-5). Sulphide lithofacies iron-formation occurs near the base of the upper black shale member, and with greywacke and volcanic rocks in some areas that have been mapped in detail. Macroscopic bands commonly range in thickness from 1 to 10 cm, and exceed 1 m in a few places; microscopic bands (<1 mm thick) are rare.

Primary sedimentary features such as granules and oolites in a chert or carbonate matrix, interlayered beds of chert or quartz and iron oxide minerals, crossbedding, intraformational breccia, slump folds, compaction and desiccation structures, and stromatolite-like forms are well preserved and widely distributed in the Sokoman Formation (Gross, 1964, 1968; Zajac, 1974).

Metamorphism was mainly isochemical; lithofacies of metamorphosed iron-formation reflect the distribution of primary sedimentary facies. Element mobility was minimal in oxide lithofacies iron-formation, even under high-rank metamorphism, but was maximized in silicate, carbonate, and sulphide lithofacies.

Form of deposits

Mineable deposits consist of selected oxide lithofacies of iron-formation with cumulative stratigraphic thicknesses ranging from 30 to 300 m and strike lengths of several

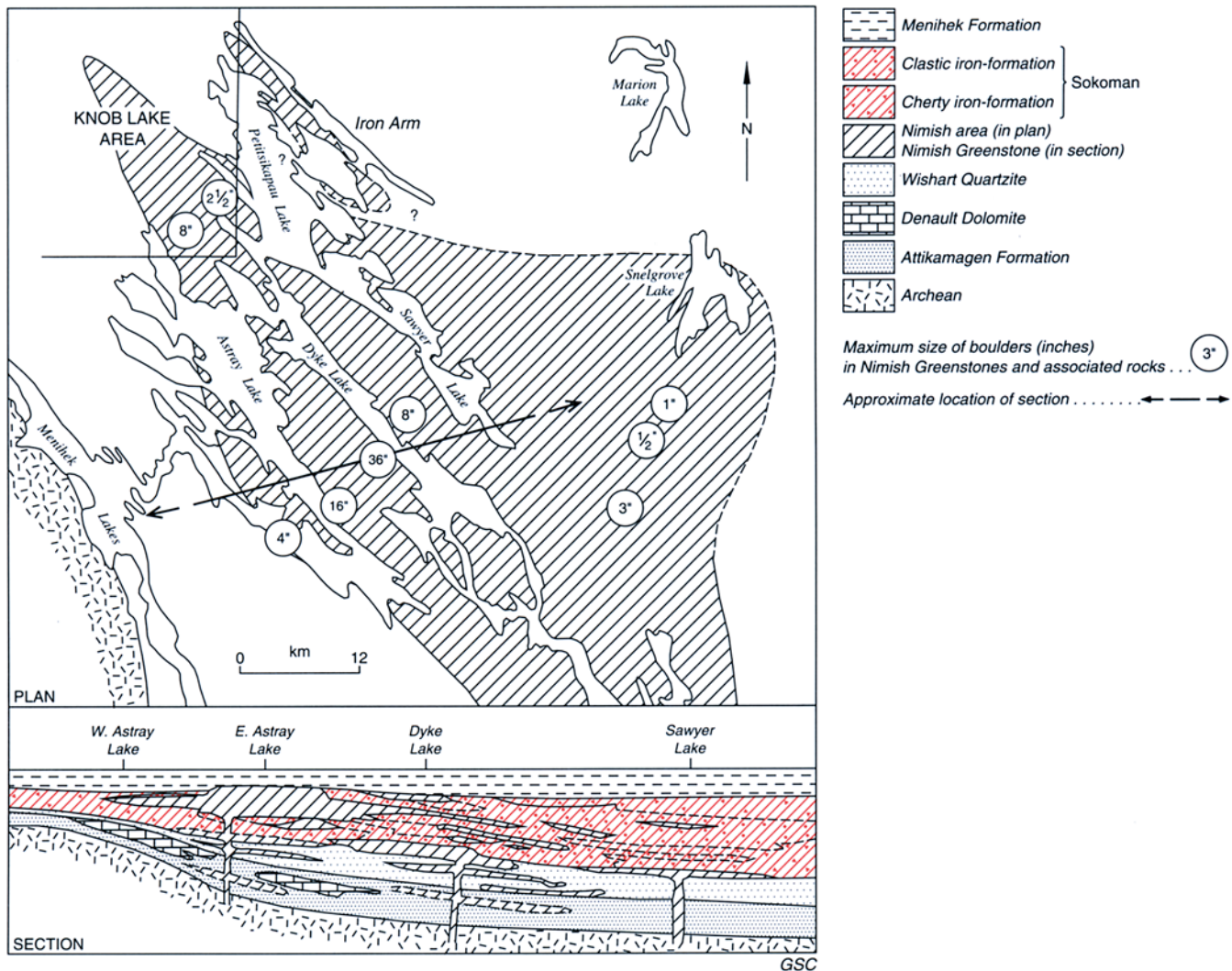


Figure 3.1-3. Distribution of iron-formation and Nimish volcanic rocks in southern part of Knob Lake basin, Quebec-Labrador fold belt (from Zajac, 1974).

kilometres. In the Wabush Lake and Mount Wright areas of Labrador and Quebec, repetition of iron-formations by complex folds and thrust faults has produced extensive thicknesses of ore. Here, too, amphibolite-grade metamorphism has enlarged the grain size of magnetite, hematite, and quartz, greatly improving its amenability to concentration and beneficiation (Fig. 3.1-6). Difficulties commonly are encountered in achieving uniform grade and quality in crude ore mined from deposits in which iron silicate or carbonate lithofacies are infolded and interlayered with oxide lithofacies.

Mineralogy

Taconite ores in iron ranges of the Lake Superior region have not been affected greatly by metamorphism; mineral distribution reflects the composition of the layers and beds formed during their sedimentation and diagenesis. The iron and silica remain distributed as very fine grained and intimately intermixed mineral aggregates of quartz, magnetite, and hematite, typically in discrete beds, layers, granules, and oolites

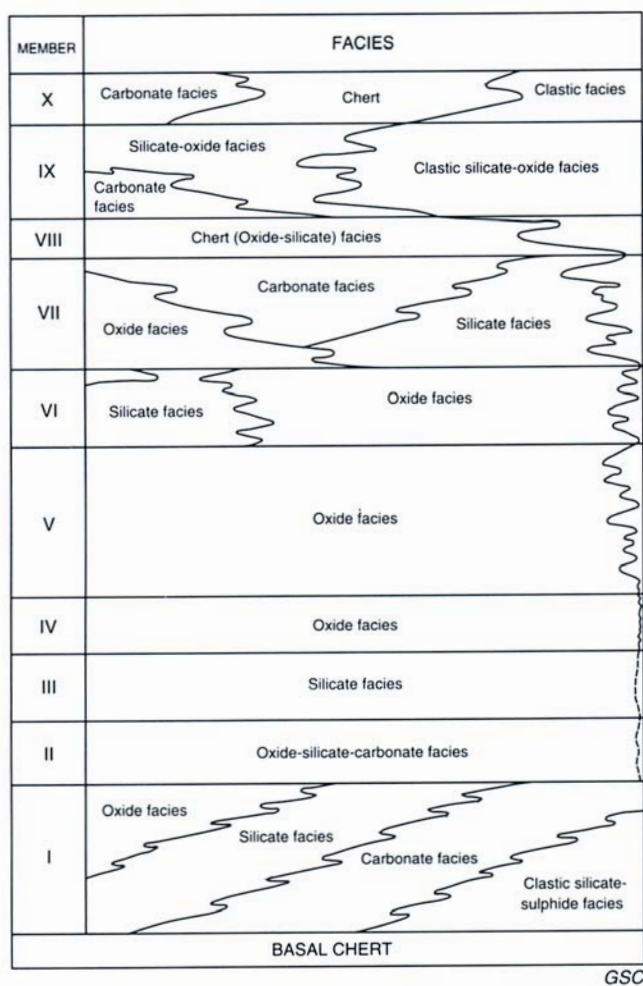


Figure 3.1-4. Subdivisions of the Sokoman Formation (after Zajac, 1974).

of the crude taconite ore. Consequently, mineral assemblages in taconite ore tend to be very complex in comparison with the highly metamorphosed iron oxide lithofacies.

Hematite and magnetite, the principal ore minerals in Lake Superior-type iron-formation, are associated with minor amounts of goethite, and with pyrolusite, manganite, and hollandite in manganiferous oxide lithofacies. Other minerals in the finely laminated crude ore are quartz, in granular and chert form, iron silicates, iron carbonates, and iron sulphides as primary mineral assemblages or their metamorphic derivatives.

Metamorphism

Typical sequential changes in grain size, texture, and mineralogy associated with increasing rank of metamorphism in the oxide lithofacies of iron-formation are illustrated in Figure 3.1-6. As grain size of both quartz and iron oxide

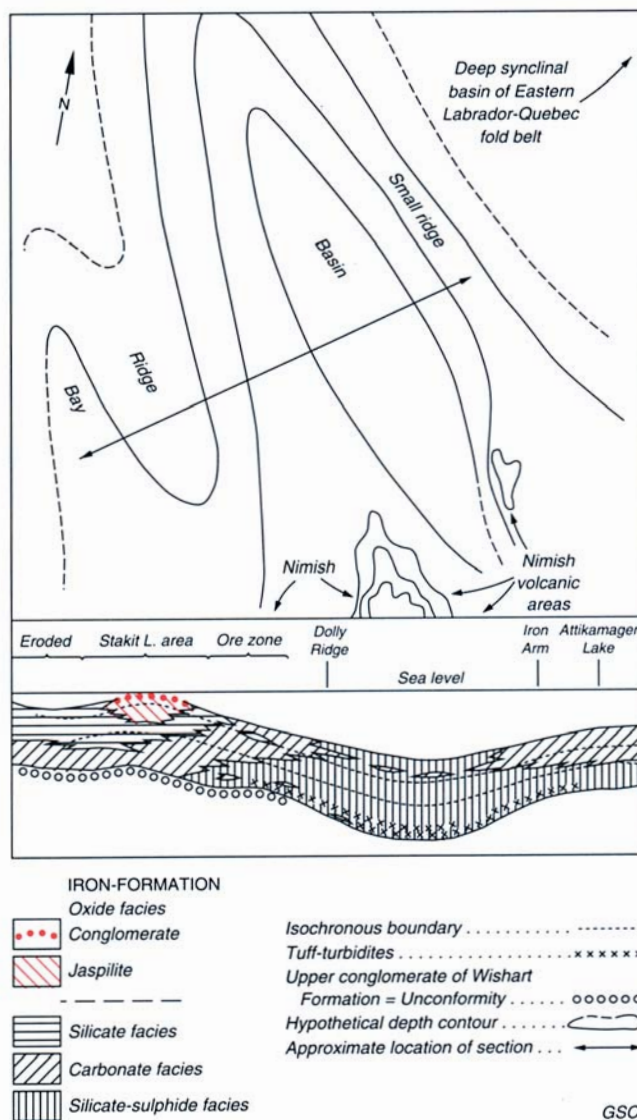


Figure 3.1-5. Interpretation of depositional environment, Member 1 of the Sokoman Formation (after Zajac, 1974).

minerals increases, primary chert is transformed to coarse granular quartz, and discrete grains of iron oxide are distributed in a granular quartz matrix. Iron silicate minerals are recrystallized to form higher rank metamorphic minerals such as minnesotaite, grunerite, cummingtonite, and hypersthene or forsterite. Iron silicate minerals also form under special conditions by the reaction of quartz and iron oxide. As the rank of metamorphism increases, siderite, ankerite, and dolomite break down and magnetite, actinolite, cummingtonite, grunerite, minnesotaite, and various other silicate minerals are formed. Foliation developed during metamorphism is parallel or subparallel to primary bedding. The evidence for mobilization of elements during metamorphism and their transfer to fracture and cleavage zones is minimal in oxide facies iron-formation, but increases significantly in silicate, sulphide, and carbonate lithofacies.

Composition of ore

The typical composition of Lake Superior-type iron-formations mined in Labrador-Newfoundland, Quebec, Minnesota, and Michigan, and of the iron ore concentrate or pellets produced from them, is given in Table 3.1-2.

DEFINITIVE CHARACTERISTICS OF ORE

Ore deposits in Lake Superior-type iron-formation are characterized by the following:

1. Iron content is 30% or greater;
2. Discrete units of oxide lithofacies iron-formation are clearly segregated from silicate, carbonate, or sulphide facies and other barren rock, and are amenable to concentration and beneficiation of the iron to meet required chemical and physical specifications;
3. Iron is uniformly distributed in discrete grains or grain-clusters of hematite, magnetite, and goethite in a cherty or granular quartz matrix;
4. Iron-formations, repeated by folds and faults, provide thick sections for mining; and
5. Metamorphic enlargement of mineral grain size has improved the quality of the crude ore for concentration and processing.

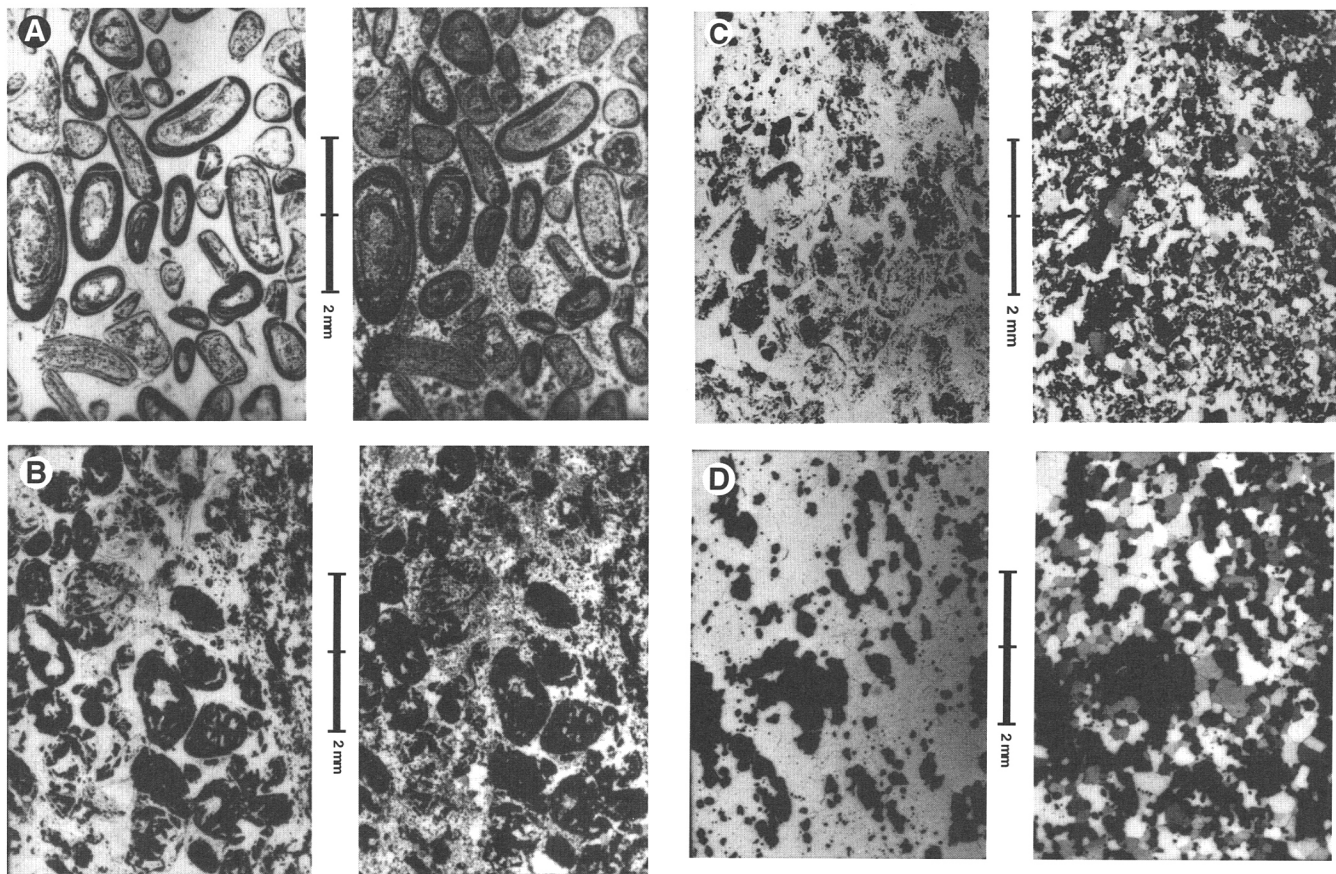


Figure 3.1-6. Textures of Lake Superior-type magnetite-hematite-chert iron-formation, illustrating effect of metamorphism on grain size (Gross, 1968). In each pair of photomicrographs, the left-hand view is in plane light, and the right-hand view is with crossed nicols. **A)** Gunflint Range near Thunder Bay, Ontario; very little metamorphism. GSC 204578X **B)** Near Schefferville, Quebec; greenschist facies. GSC 204578Y **C)** Southwest of Ungava Bay, Quebec; epidote-amphibolite facies. GSC 204538T **D)** Mount Wright area, Quebec; upper epidote-amphibolite facies. GSC 204538R

GENESIS OF LAKE SUPERIOR-TYPE IRON-FORMATION

Two principal genetic models have been considered for the origin of iron-formations and the associated stratafer lithofacies (see Introduction, Type 3; Gross, 1965, 1990, 1991). One model has emphasized volcanogenic and hydrothermal effusive or exhalative processes and the other hydrogenous-sedimentary processes with derivation of the iron, silica, and other constituents by deep weathering of a landmass. Controversy on the origin of the Lake Superior-type of iron-formation is here attributed to inadequate consideration of the diversity in lithofacies, and of other types of iron-formation that have been documented throughout the geological record (Gross, 1965, 1991). The history of genetic concepts is summarized as follows.

Prior to the early part of this century it was generally believed that the iron and silica in iron-formations were derived from deeply weathered rocks and deposited in restricted basins where chemical precipitation predominated over clastic sedimentation. Important contributions to understanding the solution, transportation, and

deposition of iron and silica in thinly laminated beds by inorganic processes or with the assistance of bacteria were made by Harder (1919), Grout (1919), Gruner (1922), Moore and Maynard (1929), Woolnough (1941), Sakamoto (1950), and Spencer and Percival (1952).

Deposition of metalliferous sediments by volcanogenic and hydrothermal effusive or exhalative processes was recognized as early as 1650 and seriously considered in Europe in the nineteenth century. More recently, volcanogenic processes were considered by Van Hise and Leith (1911), Collins et al. (1926), Landergrén (1948), Oftedahl (1958), Zelenov (1958), Gross (1959a, 1965), Goodwin (1962), Eugster and Chou (1973), and many others.

Controversy regarding the origin of iron-formation has continued in recent years, and many theories still fail to account for important features of stratafer sediments. Trendall (1973), Button (1976), and Garrels (1987) for instance, have suggested that some iron-formations were formed as evaporites in restricted, brine-filled basins. The evaporite suggestions do not account for observed facies (sulphide and carbonate as well as oxide) and thickness variations in the basins discussed by these writers.

Table 3.1-2. Typical composition of Lake Superior-type iron-formations, concentrates, and pellets (weight per cent)

1/ Mesabi taconite, Biwabik iron-formation, Minnesota 2/ Hibbing taconite pellets 3/ Sokoman iron-formation, oxide facies, Knob Lake, Quebec and Labrador 4/ Sokoman iron-formation, oxide facies, French mine, Knob Lake Ranges					5/ Wabush Lake area iron-formation, oxide facies, Labrador-Newfoundland 6/ Carol Lake concentrate, Labrador-Newfoundland 7/ Wabush Mines pellets 8/ Mount Wright concentrate, northeast Quebec 9/ Negaunee iron-formation, Empire mine, Michigan 10/ Empire pellets (acidic)					
	1	2	3	4	5	6	7	8	9	10
Fe (total)	28.36	63.61	26.41	33.97	33.46	64.08	63.62	64.15	30.20	63.67
Fe ₂ O ₃	18.70	nd	45.76	45.98	39.93	nd	nd	nd	6.72	nd
FeO	19.71	nd	nd	2.89	2.33	nd	7.11	nd	32.81	nd
P	0.035	0.010	0.020	0.017	0.009	0.008	0.008	0.010	0.017	0.017
SiO ₂	46.40	4.66	49.11	48.35	45.82	4.46	3.06	4.74	33.63	5.43
Mn	0.49	0.07	0.08	0.019	0.25	0.11	1.90	0.02	0.86	0.08
TiO ₂	0.04	nd	nd	0.00	nd	nd	nd	nd	0.11	nd
Al ₂ O ₃	0.90	0.18	0.43	0.48	0.63	0.16	0.30	0.32	0.50	0.42
CaO	1.60	0.21	0.09	0.002	1.62	0.44	0.06	0.02	0.03	0.23
MgO	2.98	0.31	0.65	0.31	0.89	0.29	0.04	0.02	2.22	0.27
Na ₂ O	0.004	0.02	0.15	0.033	0.04	nd	0.024	nd	nd	0.29
K ₂ O	0.13	0.02	0.10	0.01	0.009	nd	0.03	nd	nd	0.047
S	nd	0.001	0.007	0.013	0.006	0.004	0.004	0.007	nd	0.003
CO ₂	6.90	nd	0.50	0.033	3.22	nd	nd	nd	nd	nd
C	0.17	nd	0.136	0.083	0.88	nd	nd	nd	nd	nd
H ₂ O+/-	1.92	3.65	1.04	2.045	0.31	2.77	2.88	3.02	18.32	2.50
LOI	1.72	nd	nd	nd	nd	0.25	nd	nd	18.32	nd

DATA SOURCES

Note: Analyses for natural material. nd = no data

1. Bayley and James, 1973. 2. American Iron Ore Association, 1987, p. 65; Cliffs Mining Company, 1987, p. 18. 3. Gross, 1990. 4. Gross and Zajac, 1983. 5. Gross, 1990. 6. American Iron Ore Association, 1987, p. 70. 7. American Iron Ore Association, 1987 p. 70; Cliffs Mining Company, 1987, p. 19. 8. American Iron Ore Association, 1987, p. 70. 9. Davy, 1983. 10. American Iron Ore Association, 1987, p. 64; Cliffs Mining Company, 1987, p. 18.

MacGregor (1927), Lepp and Goldich (1964), and Cloud (1973) considered that Lake Superior-type iron-formations were the product of atmospheric evolution. In this model, iron was derived from weathered rocks and through an extensive time period became concentrated in seawater as ferrous carbonate. The ferrous iron was then rapidly and widely deposited as ferric iron because of a sudden increase of atmospheric oxygen that was generated by the widespread action of photosynthesizing organisms which evolved in the early Proterozoic. This theory has received wide attention, but faces the following problems:

1. No clear evidence has been established for saturation of ferrous carbonate in Archean seas, nor for the specific role of organisms in the deposition of iron.
2. Some evidence has been presented to show that significant concentrations of oxygen existed in the Archean atmosphere (Dimroth and Kimberly, 1976).
3. According to the "atmospheric change" model, deposition of oxide-facies iron-formation should be restricted to a relatively brief period of geological time. Geochronological data, however, indicate that Lake Superior-type iron-formations were deposited over several hundred million years (Gole and Klein, 1981; James and Trendall, 1982; Gross, 1983a).
4. Other iron-formation and stratafer lithofacies (oxide, carbonate, silicate, and sulphide) are also widely distributed in Archean, Phanerozoic, and Recent marine basins (Gross, 1964, 1967, 1968, 1970, 1983a, 1987).

Lake Superior-type iron-formations throughout the world are directly related to, and form a part of, the tectonic belts developed along the margins of cratons or plates in the early Proterozoic. Deposition of the successions of clastic sediments, iron-formation, stratafer lithofacies, and volcanic rocks in these marginal basins was related to basin architecture and the many factors controlling their depositional environments. Direct evidence of hydrothermal effusive or exhalative processes active during basin development is registered in the composition and trace element content of the iron-formations, and in volcanic centres which have been mapped (Fig. 3.1-3). Evidence of many of the volcanic and effusive centres has been lost through extensive overthrusting and deformation of basin areas related to subduction at the plate margins. Unlike many areas with Algoma-type iron-formation, the spatial relationship of the sedimentary facies developed and volcanic centres is not well preserved.

Many have suggested that iron-oxidizing micro-organisms played a key role in concentrating and precipitating iron. Evidence demonstrating that organisms played an essential part in the deposition and accumulation of large quantities of iron appears to be lacking, but bacteria, morphologically similar to fossils in Lake Superior-type iron-formations, are present in modern iron and manganese sediments (Nealson, 1982). Tunnicliffe and Fontaine (1987) have demonstrated a microbial origin for iron-rich particles associated with abundant inorganic deposition of iron in modern metalliferous sediments.

Borchert (1960) suggested that diagenetic porewater from clastic sediments could transport iron in a ferrous state from anoxic to oxidizing environments where ferric oxides would be precipitated. Holland (1973) and Button et al. (1982) suggested that very low concentrations of ferrous iron in anoxic deep basins were transported landward by upwelling seawater and precipitated with silica as ferric hydroxide in shallow water oxygenated by photosynthesizing organisms.

Gross (1965, 1968, 1983a, 1986) emphasized the extensive evidence for hydrothermal effusive or exhalative processes in the origin of iron-formation, and showed that the distribution and correlation patterns for the major and minor elements are consistent with volcanogenic processes. Analytical data indicate that the bulk composition, correlation, and distribution patterns for the minor and rare-earth elements in more than fifty iron-formation units, that range in age from early Archean to Recent, are similar to those in modern marine deposits of metalliferous sediments which are forming by hydrothermal effusive processes (Gross and McLeod, 1980, 1987; Gross, 1988, 1990, 1991, 1993c). With few exceptions, tuffaceous beds and volcanic rocks are now known to be present in, or closely associated with, iron-formations of all types.

Gross (1965) suggested that hot springs along a volcanic arc could have been an adequate source of iron and silica to form the iron-formations in the 1200 km long Labrador-Quebec fold belt in about 50 000 years. Previous objections to this model had hinged on (1) the apparent lack of evidence in some areas for contemporary volcanism (evidence now available), and (2) failure to recognize other primary stratafer lithofacies (carbonate and sulphide), which are now known to be associated with iron-formations, and are generally accepted as having formed by hydrothermal effusive or exhalative processes.

A convincing body of data thus indicates that iron-formations have formed by volcanogenic or hydrothermal effusive processes, and that the depositional environment, tectonic setting, and the composition of the exhalative hydrothermal fluids were the principal factors that controlled the composition of the lithofacies developed from them. Modern submarine metalliferous sediments, which have formed by hydrothermal effusive processes that are widely distributed on the seafloor, are the final proof and considered as analogous to facies protolithic to iron-formation.

RELATED TYPES OF DEPOSITS

Lake Superior-type iron-formations extend continuously through transitions in their depositional environments from sites where they are associated with mature clastic sediments in typical continental shelf basins to distal offshore sites where they are associated with greywacke, tuff, volcanic, and other members of the stratafer group (such as base-metal-bearing sulphide lithofacies) that are more characteristic of depositional environments for Algoma-type iron-formations, as reported in the Krivoy Rog basin (Alexandrov, 1973; Belevtsev, 1973); Damara Supergroup, South Africa (Beukes, 1973, 1983); Cuyuna Range, Lake

Superior Region (Bayley and James, 1973); and in parts of the Sokoman Formation in the Quebec-Labrador belt (Gross, 1968; Zajac, 1974). Examples of related deposits are provided in the following.

Lake Superior-type iron-formations are the source rocks or protore for the large high grade direct-shipping iron ore deposits formed by secondary enrichment processes that have provided the extensive resources of iron ore now being mined in Australia, Brazil, Venezuela, India, South Africa, present day Russia and Ukraine, and in the Lake Superior and Labrador-Quebec regions in North America in the past.

Manganese facies of iron-formation in the Lake Superior, Labrador-Quebec, and other areas have provided manganese iron ore containing more than 3% manganese. Large, rich manganese deposits are associated with iron-formations in the Transvaal Supergroup in South Africa (Beukes, 1983), and with iron-formation in the Nova Lima Group in Minas Gerais, Brazil (Dorr, 1973).

Manganese-bearing facies of Lake Superior-type iron-formation in North America are relatively uncommon. Small occurrences in Canada include: beds rich in manganese (<1 m thick) in carbonate facies iron-formation that have been traced for several kilometres on Belanger and Flint islands, on the east side of Hudson Bay (Bell, 1879; Chandler, 1988); thin beds of oxide facies containing up to 2% manganese at Mount Reed, Quebec; and manganese-rich facies iron-formation in the Wabush Lake area, Labrador, and at Sutton Lake, Ontario. Manganese iron-formations have been investigated in the Cuyuna Range of Minnesota. Most iron-formations of this type were deposited in relatively shallow basins in platform and continental shelf environments where conditions fluctuated and lithofacies range from predominantly banded manganese- and hematite-rich strata developed under highly oxidizing conditions, to predominantly siderite, chert-siderite, sulphide, and manganese carbonate lithofacies, deposited under reducing conditions.

Highly metamorphosed iron-formation containing 5 to 6% rare-earth elements is part of a Middle Proterozoic sequence of dolostone, potassium-rich black schist, shale, quartz arenite, and arkose that is intruded in places by dykes of alkaline rock in the Bayan Obo mine area in Inner Mongolia. The iron-formation sequence extends for a distance of 20 km, and more than 1500 Mt of iron ore containing 0.10% niobium and 5 to 6% rare-earth elements has been defined in 16 deposits. The rare-earth elements are distributed throughout the iron-formation and in some of the dolostones closely associated with it. Although highly deformed and altered (see Fig. 3.1-6 for typical progression of textural changes in Labrador iron-formations with metamorphism), in many places the iron-formation preserves granular and oolitic textures, microbanding, and other relict sedimentary features; it is typical in scale for Lake Superior-type iron-formation, and is interpreted to have formed in a marginal basin along a major fault zone at the edge of the North China Platform. A syngenetic origin for the niobium, rare-earth elements, and fluorite in the iron-formation and dolostone has been clearly demonstrated (Gross, 1986, 1993b). The highly anomalous niobium, rare-earth elements, and fluorite in the iron-formation and dolostone has been ascribed to hydrothermal metasomatic processes by

Chao et al. (1993), and others have considered its possible affinity to carbonatite deposits. The writer is satisfied that the range of isotope dates mark different stages or periods in metamorphism of the iron-formation.

Sulphide lithofacies in Lake Superior-type iron-formations are less abundant than in Algoma-type, but still common. Sediment-hosted sulphide lithofacies in the northern Labrador-Quebec fold belt form lenses 40 m thick and 400 m long, and have an average content of 2% copper and zinc, and less than 0.2% lead (Barrett et al., 1988). Extensive sulphide lithofacies have been described in the Lake Superior iron ranges by James (1954), and Han (1968), and in many other parts of the world.

Anomalous amounts of lead and zinc occur in many of the carbonate sequences associated with Lake Superior-type iron-formations, and small lead-zinc deposits in the Nastapoka Group were mentioned by Chandler (1988). Likewise, copper deposits hosted by black shale and by redbeds may be genetically related to hydrothermal systems that produced iron-formations in their vent areas.

The origin and distribution of gold in Lake Superior-type iron-formations has not been widely documented. The background content of gold in Sokoman oxide lithofacies at Schefferville, Quebec, deposited in a shallow water shelf environment, is about half (0.02 ppm) the average content in oxide lithofacies of Algoma-type iron-formation (Gross, 1988).

Small amounts of riebeckite, arfvedsonite, crocidolite, and other sodium-rich amphibole and silicate minerals are associated with stilpnomelane in many of the metamorphosed Lake Superior-type iron-formations, and "tiger's eye" quartz is genetically related to these mineral occurrences. In most cases, the sodium-rich silicate minerals appear to have developed where tuffaceous material was intermixed with the iron-formation. Blue asbestos, crocidolite, and riebeckite deposits in iron-formation in South Africa and Australia have been mined for many years (Trendall and Brockley, 1970).

Graphite-iron-sulphide- and kyanite-bearing gneisses and schist associated with highly metamorphosed iron-formation in the northeastern Grenville orogenic belt, noted by Gross (1968), appear to be the metamorphosed equivalents of carbonaceous and aluminous Menihek slate rocks which overlie the Sokoman iron-formation. The Lac Knife graphite deposit located about 35 km south of Fermont in the Mount Wright and Wabush Lake area of Quebec and Labrador, now under development, is a highly metamorphosed carbonaceous sedimentary deposit (Bonneau and Raby, 1990).

EXPLORATION GUIDELINES

Lithofacies of Lake Superior-type iron-formation selected for iron ore have the following characteristics:

1. The composition, texture, and grade of the crude ore must be such that ore concentrates can be produced that meet required chemical and physical specifications in a particular industrial area.
2. Discrete, well defined magnetite and hematite lithofacies of iron-formation are preferred with a minimum of other lithofacies and clastic sediment interbedded in the crude ore.

3. Granular, medium- to coarse-grained textures with well defined, sharp grain boundaries are desirable, to enable liberation and clean separation of mineral grains in the concentration and beneficiation of the crude ore. These features are achieved in highly metamorphosed iron-formation where there is maximum grain enlargement, and magnetite lithofacies are usually preferred over hematite or mixed facies.
4. Mineable thicknesses of ore, usually 30 to 100 m or greater, may vary depending on location and economic factors in the market area. Ore deposits may consist of thick primary stratigraphic units or a succession of ore beds that were repeated by folding and faulting.
5. Uniform granularity and mineral composition, with a minimum of infolding of barren sediment or marginal facies of iron-formation, are advantageous factors for grade control and in processing of the crude ore.
6. Oxide facies iron-formation deposited in highly oxidizing environments normally has a low content of minor elements, especially sodium, potassium, sulphur, and arsenic, which have deleterious effects in the processing of the ore and quality of steel produced from it.
7. The content of minor elements varies significantly in some different iron-formations, depending on the kinds of associated volcanic, sedimentary, intrusive, and other stratafer lithofacies.
8. Most iron-formations are regional-scale stratigraphic units that are relatively easy to define by mapping or with the aid of aeromagnetic and gravity surveys. Detailed stratigraphic information is an essential part of the data base required to define grade, physical and chemical quality, and beneficiation and concentration characteristics of the ore.
9. Basin analysis and sedimentation modelling enable definition of factors that controlled the development, location, and distribution of different iron-formation lithofacies.
10. Metamorphic mineral assemblages reflect the composition and mineralogy of the primary sedimentary facies.

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3.2 ALGOMA-TYPE IRON-FORMATION

G.A. Gross

INTRODUCTION

Algoma-type iron-formations consist primarily of microscopic to macroscopic alternating layers and beds of chert or quartz, and iron-rich minerals, magnetite, hematite, pyrite, pyrrhotite, iron carbonates, and iron silicates (see "Introduction", Type 3). They are composed of a variety of interbedded oxide, carbonate, sulphide, and silicate lithofacies, and include extensive manganese-rich lithofacies; sulphide lithofacies rich in copper, zinc, lead, tin, and gold; oxide and carbonate lithofacies bearing rare-earth elements; tungsten-bearing lithofacies; and various lithofacies of iron-formation that host syngenetic and epigenetic gold deposits (Gross, 1970, 1988a, b, 1990a, 1993a, b). These iron-rich lithofacies form a major part of the large assemblage of siliceous hydrolithic sediments referred to as the stratafer group (Gross, 1986, 1991, 1993a; see "Introduction", Type 3).

Algoma-type iron-formations were deposited with volcanic rocks and greywacke, turbidite, and pelitic sediments in volcanic arc and spreading ridge tectonic settings (Gross, 1965, 1970, 1983a; Lang et al., 1970). They range in age from 3.2 Ga to modern, possibly protolithic facies on the seafloor. Iron ore is recovered from Algoma-type iron-formation, from naturally enriched deposits, and from selected zones of oxide lithofacies which are the principal kind discussed here.

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World class examples include Kudremuk in India, Cerro Bolivar in Venezuela (enriched), Carajas in Brazil (enriched), large highly metamorphosed oxide lithofacies in Sweden, oxide lithofacies in northern China such as Qinan, and numerous deposits in Precambrian terrane in Canada, the Scandinavian Shield, Australia, Africa, India, and the former U.S.S.R.

IMPORTANCE, SIZE, AND GRADE

Metamorphosed magnetite oxide and carbonate lithofacies of Algoma-type iron-formation are the second most important source of iron ore after the taconite and enriched deposits in Lake Superior-type iron-formations. They range in size from about 1000 to 100 Mt or smaller.

In 1986 production from oxide lithofacies at the Adams, Griffith, and Sherman mines in Ontario amounted to more than 8.1 Mt of crude ore grading 19 to 27% iron for the recovery of 2.1 Mt of ore-concentrate and pellets. In 1986, Algoma Ore Division at Wawa, Ontario, produced more than 1.7 Mt of siderite crude ore grading 34.15% iron that provided 1.2 Mt of sinter and agglomerate.

The ore-concentrate, pellets, sinter, and agglomerate produced from these mines provided about 10% of the total iron ore produced in Canada in 1986, and the compositions of the ore products recovered from Algoma-type iron-formation are given in Table 3.2-1.

Iron ore deposits in Precambrian Algoma-type iron-formations usually contain less than 2% manganese, but many Paleozoic iron-formations such as those near Woodstock, New Brunswick, contain 10 to 40% manganese and have Fe/Mn ratios of 40:1 to 1:50 (Gross, 1967).

GEOLOGICAL FEATURES

Algoma-type iron-formations and associated stratafer sediments are interbedded with volcanic rocks of mafic to felsic composition, and with greywacke, turbidites, argillite, and

shale of all ages. They formed both near to and distal from extrusive centres along volcanic belts, deep fault systems, and rift zones and may be present at any stage in a volcanic succession. Algoma-type iron-formations include silicate, oxide, carbonate, and sulphide facies and base metal lithofacies of the stratafer group (Type 3, "Introduction"), and are interbedded in assemblages of black shale, carbonate, turbidite, and siltstone sediments and volcanic rocks, or their metamorphosed equivalents (Stanton, 1959, 1976, 1991; Gross, 1965, 1986, 1991; Gauthier et al., 1987; Beeson, 1990).

Depositional environments for Algoma-type iron-formations are varied and diverse. The proportions of volcanic and clastic sedimentary rocks vary greatly from one fold belt to another and are rarely mutually exclusive. In Ontario, volcanic rocks are predominant in areas around Adams mine in Boston township; Sherman mine near Temagami Lake; Moose Mountain mine and at Bending Lake, and metasediments are most abundant at Griffith mine, Nakina, and at Lake St. Joseph, where deltaic fan sequences have been described (Gross, 1965, 1983a; Lang et al., 1970; Meyn and Palonen, 1980). A series of preliminary maps compiled by Gross (1963) show the extensive distribution of Algoma-type iron-formations in "greenstone belts" of the Superior Structural Province and outline their rock associations and geological settings. Algoma-type iron-formations and associated stratafer sediments are consistently present in the "greenstone belts" of the Canadian Shield and are marker beds for locating other sulphide and stratafer lithofacies, as well as indicating ancient sites of mineral deposition by syngenetic and epigenetic hydrothermal processes (see Fig. 3-4, Introduction).

Oxide, silicate, carbonate, and sulphide lithofacies are commonly interbedded in iron-formations composed of microscopic to macroscopic alternating layers or beds of silica (chert or quartz) and iron-rich minerals. Thin beds of iron-formation are usually interbedded with clastic sediments and volcanic strata at the margins of stratigraphic units. Rocks associated with Algoma-type iron-formations vary greatly in composition, even within local basins, and range from felsic to mafic and ultramafic volcanic rocks, and from greywacke to black shale, argillite, and chert interlayered with pyroclastic and other volcanoclastic beds or their metamorphic equivalents.

Primary sedimentary features, including those related to compaction, contraction, and desiccation of the beds, microscopic banding, bedding, and penecontemporaneous deformation features of the hydroplastic sediment such as slump folds and faults, are abundant, and can be recognized in many cases in highly metamorphosed oxide lithofacies of iron-formation and even in some granulite metamorphic lithofacies (Gross, 1964). Mineral distribution in highly metamorphosed iron-formations closely reflects the composition and distribution of primary sedimentary facies. Metamorphism is mainly isochemical and produces grain enlargement and the segregation of quartz and gangue from the iron oxide and carbonate minerals, thus enhancing the beneficiation qualities of crude ore (Fig. 3.2-1). Element mobility during metamorphism is minimal in oxide lithofacies even under high rank conditions, but increases in silicate and carbonate lithofacies to

a maximum in sulphide lithofacies, in which many of the primary sedimentary features are destroyed during diagenesis and metamorphism.

Most of the iron ore resources in Algoma-type iron-formation consist of specially selected oxide lithofacies composed mainly of magnetite, hematite, and quartz. Oxide facies usually contain variable amounts of magnetite, hematite, siderite or ferruginous ankerite, and dolomite, manganoan siderite, and silicate minerals. Silicate lithofacies are characterized by iron-silicate minerals including grunerite, minnesotaite, hypersthene, reibeckite, and stilpnomelane, associated with chlorite, sericite, amphibole, and garnet. Siderite ore containing pyrite and pyrrhotite beds and lenses has been mined in the Wawa area of Ontario for more than 50 years.

Economic iron ore deposits have been developed mainly where metamorphosed sequences of oxide lithofacies of iron-formation are 30 to 100 m thick and several kilometres in strike length. Thick sequences of ore beds have been developed in many areas where strata have been repeated by isoclinal folding and thrust faulting and economic feasibility for mining them has been greatly enhanced.

Algoma-type iron-formations are most widely distributed and achieve their greatest thicknesses in Archean terrane. They range in age from 3.2 Ga in India, China, Canada, and Greenland, to the large number deposited between 2.5 and 2.9 Ga in the volcanic belts of the Canadian Shield and in Scandinavia, to the smaller and frequently manganiferous facies in Paleozoic rocks, to Mesozoic facies in the Cordillera, and to potentially protolithic facies of iron-formation that are being deposited at the present time near volcanic centres located along island arcs and spreading ridges (Gross, 1973, 1983a, 1988a, b; Gross and McLeod, 1987).

Table 3.2-1. Composition of ore-concentrate, pellets, and sinter produced from Algoma-type iron-formation in Ontario in 1986.

Range in composition (%)		
	pellets and ore-concentrates	sinter and agglomerates
Fe	66.2 - 66.7	48.32
SiO ₂	3.5 - 5.5	8.0
P	0.03 - 0.02	0.018
Mn	0.03 - 0.12	2.36
Al ₂ O ₃	0.29 - 0.4	1.06
CaO	4.7 - 4.9	12.14
MgO	1.7 - 1.8	7.19
S	<0.027	0.09

DEFINITIVE CHARACTERISTICS OF IRON ORE IN ALGOMA-TYPE IRON-FORMATION

Iron ore deposits in Algoma-type iron-formation consist mainly of metamorphosed oxide and carbonate lithofacies that contain 20 to 40% iron. The quality of oxide facies crude ore is greatly enhanced by metamorphism which leads to the development of coarse granular textures and discrete grain enlargement (Gross, 1961). Mining feasibility has been improved greatly where the ore beds have been repeated and thickened by folding and faulting. Carbonate lithofacies containing a minimum of interbedded chert and sulphide minerals provide suitable crude ore for processing and beneficiation, and the production of sinter and agglomerated ore products.

Coarse, granular, magnetite-quartz lithofacies are most easily concentrated and beneficiated to remove gangue quartz, silicate, and alkali-bearing minerals, and significant amounts of minor elements that are commonly present in Algoma-type iron-formations (Landergrén, 1948; Gross, 1965, 1980, 1990b; Frietsch, 1974).

The compositions of Algoma-type iron-formations mined in Canada and the ore concentrate, pellets, and sinter produced from them at five mines are given in Table 3.2-2.

GENESIS OF ALGOMA-TYPE IRON-FORMATION

It is generally accepted that Algoma-type iron-formations are hydrolithic sediments formed by volcanogenic and hydrothermal-effusive (exhalative) processes. Genetic models invoking deep weathering of a landmass and transport of the iron and silica to restricted basins along with the depletion of other major rock forming constituents do not account for the broad range in depositional environments, facies development, composition, and the diversity in content and distribution of minor elements found in Algoma-type iron-formations. The bulk composition, distribution and correlation patterns for major and minor elements in Algoma-type iron-formation are strikingly similar to those in marine siliceous metalliferous sediments that are forming on the modern seafloor in many parts of the

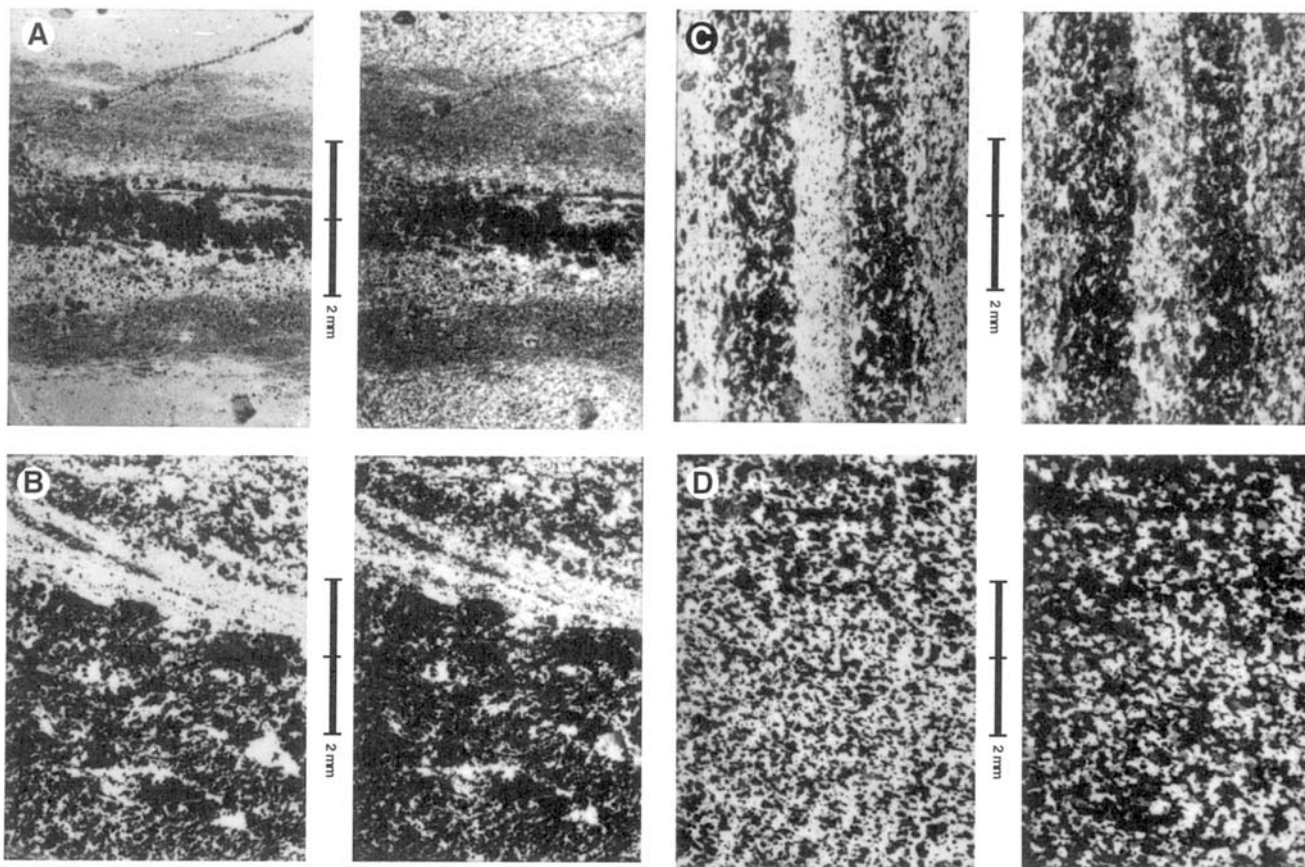


Figure 3.2-1. Textures of Algoma-type magnetite-hematite-chert iron-formation. Photomicrographs with transmitted light on left and polarized light on right. **A)** Lower greenschist metamorphic facies from Temagami Lake, Ontario. GSC 204578T **B)** Greenschist metamorphic facies from Kirkland Lake, Ontario. GSC 204578U **C)** Upper greenschist metamorphic facies from Capreol area, Ontario. GSC 204578S **D)** Associated with garnet-biotite-hornblende schist from Zealand township, Ontario. GSC 204578W (from Gross, 1965).

STRATIFORM IRON

world by hydrothermal-effusive processes, and considered to be protolithic facies of iron-formation and other stratafer sediments (Gross, 1987, 1988a, 1990a, b, 1991, 1993c).

Iron-formations were formed by the deposition of iron and silica in colloidal size particles by chemical and biogenic precipitation processes. Their main constituents evidently came from hydrothermal-effusive sources and were deposited in euxinic to oxidizing basin environments, in association with clastic and pelagic sediment, tuff, volcanic rocks, and a variety of clay minerals. The variety of metal constituents consistently present as minor or trace elements evidently were derived from the hydrothermal plumes and basin water and adsorbed by amorphous iron

and manganese oxides and smectite clay components in the protolithic sediment (Gross, 1993c). Their development and distribution along volcanic belts and deep-seated faults and rift systems was controlled mainly by tectonic rather than by biogenic or atmospheric factors.

Algoma-type iron-formations were deposited relatively close to volcanic centres and include a broad range of lithofacies. Study of available data on recent metalliferous sediments on the seafloor (Gross and McLeod, 1987; Gross, 1987) shows that sulphide facies were deposited close to the higher temperature effusive centres, iron oxide and silicate facies were intermediate, and manganese-iron facies were deposited from cooler hydrothermal vents and in areas

Table 3.2-2. Compositions of Algoma-type iron-formation concentrates, pellets, and sinters.

Average composition %										
	1	2	3	4	5	6	7	8	9	10
Fe total	29.680	60.800	27.900	60.240	31.930	66.750	38.830	63.35	36.60	48.32
Fe ₂ O ₃	28.170	*nd	24.840	nd	31.050	nd	37.420	37.42	nd	nd
FeO	12.810	nd	13.520	nd	13.110	nd	16.260	16.26	nd	nd
P	0.07	0.02	0.05	0.018	0.090	0.020	0.050	0.05	0.017	0.029
SiO ₂	53.640	5.410	55.220	5.270	46.460	3.550	42.150	42.15	9.10	8.00
Mn	0.040	0.060	0.090	0.030	0.080	0.110	0.050	0.05	2.19	2.36
Ti	0.010	nd	0.050	nd	0.070	nd	0.010	0.01	0.042	nd
Al ₂ O ₃	0.440	0.270	1.200	0.400	3.540	0.430	0.590	0.59	1.145	1.06
CaO	2.130	4.950	0.770	4.730	1.270	nd	1.580	1.58	1.065	12.14
MgO	1.620	1.850	1.560	1.700	1.520	nd	1.890	1.89	4.33	7.17
Na ₂ O	0.100	0.052	0.040	0.035	0.450	nd	0.100	0.10	0.055	nd
K ₂ O	0.150	0.062	0.100	0.056	1.450	nd	0.110	0.11	0.05	nd
S	0.170	0.030	0.300	0.027	0.080	nd	0.213	0.213	5.62	0.099
CO ₂	0.480	nd	0.760	nd	0.200	nd	0.270	0.27	nd	nd
C	0.130	nd	0.210	nd	0.050	nd	0.070	0.07	nd	nd
H ₂ O+/-	0.220	0.980	1.270	0.830	0.470	0.680	0.570	1.30	nd	nd
<p>*nd = no data Sources of data: 1. Gross, 1990b; 2. American Iron Ore Association, 1987, p. 69; Cliffs Mining Company, 1987, p. 19; Cliffs Mining Company, 1987, p. 13; 3. Gross, 1990b; 4. American Iron Ore Association, 1987, p. 69; Cliffs Mining Company, 1987, p. 19; 5. Gross, 1990b; 6. Cajka and Cadieux, 1985, p. 13; 7. Gross, 1990b; 8. Boucher, 1979, p. 16; 9. Goodwin et al., 1985; 10. American Iron Ore Association, 1987, p. 68.</p>										
<p>1. Adams mine iron-formation, oxide facies 5. Griffith mine iron-formation, oxide facies 8. Moose Mountain, fluxed pellets 2. Adams mine, fluxed pellets 6. Griffith mine, fluxed pellets 9. Algoma iron-formation, oxide facies 3. Temagami iron-formation, oxide facies 7. Moose Mountain, oxide facies 10. Algoma sinter, super-fluxed 4. Sherman mine, fluxed pellets</p>										

distal from active hydrothermal discharge. Overlapping and lateral transitions of one kind of lithofacies to another appear to be common and are to be expected (Gross, 1988a, 1991, 1993a).

RELATED TYPES OF DEPOSITS

Algoma-type iron-formations are protore for high grade, direct shipping types of residual-enriched iron ore deposits that are mined in many parts of the world. Residual-enriched iron ore was mined in the Old Helen mine in the Michipicoten district, and at Steep Rock Lake near Atikokan, Ontario, that was derived from siderite and sulphide lithofacies of iron-formation. Other enriched iron ore deposits of this type derived mainly from oxide lithofacies include the Cerro Bolivar deposits in Venezuela (Dorr, 1973), the Carajas deposits in Brazil (Hoppe et al., 1987; Gibbs and Worth, 1990), and deposits in Swaziland, southern Africa (Beukes, 1973).

Algoma-type iron-formations and associated stratafer sediments commonly show a prolific development of different facies types within a single stratigraphic sequence of rocks or metallogene. Oxide lithofacies are usually the thickest and most widely distributed units of iron-formation in a region and serve as excellent metallogenetic markers (Frietsch, 1977, 1980a, c, 1982a, b; Gross, 1986, 1988a, 1991, 1993a, c; Gauthier and Brown, 1986; Gauthier et al., 1987).

Transitions from Lake Superior- to Algoma-type iron-formations occur in areas where iron-formations extend from continental shelf to deep water environments along craton margins as reported in the Krivoy Rog iron ranges (Belevtsev, 1973).

Manganese-iron lithofacies

Significant amounts of manganese are associated with Algoma-type iron-formation in several types of deposits (Gross, 1983b, 1990a). Manganese is commonly associated with carbonate lithofacies which range from predominantly siderite (FeCO_3) to rhodochrosite (MnCO_3). Siderite does not contain more than 2% MnO and the distribution of manganese in the dolomite-ankerite-kutnahorite group of minerals is more complex. Dolomite and ankerite may have ratios of $\text{Mg}:(\text{Fe}, \text{Mn})$ less than 1:2.6, and Mn-rich carbonate may have ratios of $\text{Mn}:(\text{Mg}, \text{Fe})$ less than 1.32. Some dolomitic lithofacies of iron-formation contain less than 26% FeO and 23.4% MnO, but the MnO content in most of the Precambrian Algoma-type iron-formations is usually less than 15% (Gross, 1965). Sinter products from the siderite ore in the Wawa area, Ontario, contain 2 to 2.5% manganese which has enhanced their value for blending with other iron ores that have a low content of manganese.

The world-wide distribution of manganese-rich facies in oxide and carbonate facies of iron-formation was studied by Varentsov and Grassley (1980a, b, c), Roy (1981), and Gross (1983b). Important deposits of this type occur in India, Japan, China, Brazil, Africa, and Australia. Typical examples of transitions from cherty manganese to iron oxide lithofacies in Devonian and Tertiary iron-formations are found at the Karadzhai deposit in Kazakhstan (Sapozhnikov, 1963; Kalinin, 1965) and at Jalisco, Mexico (Zantop, 1978), in which Fe/Mn ratios range from 10:1 to

1:1.5 and the manganese content is 40% or less. The manganese-rich jasper-hematite lithofacies at Woodstock, New Brunswick, are less than 30 m thick and the iron content ranges from 11 to 30% and the manganese content from 12 to 25%. The overall iron to manganese ratio is about 1.5 (Gross, 1967, 1983b, 1990a, b).

Sulphide deposits in Algoma-type iron-formation

The common association of sulphide and oxide lithofacies of Algoma-type iron-formation has been overlooked or not mentioned in many cases in the descriptions and documentation of sulphide lithofacies that contain large stratiform "massive" sulphide deposits. The following large deposits illustrate the important association of oxide and sulphide lithofacies: Manitouwadge, Bathurst-Newcastle, Matagami, Sturgeon Lake (Shegelski, 1987), Sherridon, and Michipicoten (Goodwin, 1962) in Canada; Gamsberg, South Africa (Rozenal, 1980); Broken Hill, Australia (Edwards and Atkinson, 1986); Tynagh, Ireland (Schultz, 1966); Cyprus; Kuroko-type deposits, Japan (Ohmoto and Skinner, 1983); deposits in Sweden (Frietsch, 1980a, b, c, 1982a, b); and Atlantis II deep in the Red Sea (El Shazly, 1990).

Gauthier and Brown (1986) described the association and relationship of various zinc-rich stratigraphic zones in pyrrhotite, pyrite, graphite, and magnetite lithofacies of iron-formation in the Maniwaki-Gracefield district of Quebec and concluded that these iron-formations formed by submarine exhalative processes (Gauthier et al., 1987). Occurrences of sphalerite in magnetite iron-formations in Sweden have been described by Frietsch (1982a, b).

Gold in Algoma-type iron-formation

Algoma-type iron-formations are considered to be prime metallogenetic markers in exploration for gold because of their syngenetic gold content, as at Homestake mine in South Dakota, and the Lupin mine, Northwest Territories; remobilization of gold in iron-formations during metamorphism; and the favorable chemical-structural environment provided by iron-formations for deposition of gold in veins, fractures, and shear zones (Hodder and Petruk, 1982; Macdonald, 1990). Gross (1988b) found that the average content of gold in oxide facies, based on random sampling of 40 Algoma-type iron-formations in the Canadian Shield, was about 0.04 ppm.

Minor elements in Algoma-type iron-formation

The average content of most of the minor elements in Algoma-type iron-formations is usually about double that in similar facies of Lake Superior-type iron-formation. This reflects the nature of the hydrothermal systems that produced them, and the prominent types of associated igneous rocks (Gross, 1990b, 1991, 1993a). Algoma-type iron-formations are therefore regarded as good metallogenetic marker beds in prospecting for other metals. For example, the tungsten-bearing iron-formations in Greenland were probably related genetically to a granitic igneous system (Appel, 1986) and are part of a sequence of stratafer lithofacies.

Furthermore, many Algoma-type iron-formations have a significantly high content of rare-earth elements. Lithofacies that are rich in rare-earth elements (analogous to the Bayan Obo deposits in China in Lake Superior-type iron-formations) would be expected where Algoma-type iron-formations are associated with alkaline rocks (Gross, 1993b).

EXPLORATION GUIDELINES

Because of their smaller size, more complex facies development, and the higher content and erratic distribution of minor elements, large iron deposits are not as numerous or as easily defined in Algoma-type iron-formations as in Lake Superior-type. Electromagnetic, magnetic, and electrical conductance and resistivity survey methods are used effectively in tracing and defining the distribution of Algoma-type beds, either in exploring for iron and manganese ore, or for using these stratafer beds as metallogenetic markers. The use of iron-formation geochemistry for understanding the metallogeny of an area and as an exploration guideline is considered to be in its initial stages of development.

Guidelines and recommendations for exploring for iron ore are outlined for Lake Superior-type iron-formations also apply for Algoma-type:

1. The composition, texture, and grade of the crude ore must be such that ore concentrates can be produced that meet required chemical and physical specifications in a particular industrial area.
2. Discrete, well defined magnetite and hematite lithofacies of iron-formation are preferred with a minimum of other lithofacies and clastic sediment interbedded in the crude ore.
3. Granular, medium- to coarse-grained textures with well defined, sharp grain boundaries are desirable, to enable liberation and a clean separation of mineral grains in the concentration and beneficiation of the crude ore. These features are usually achieved in highly metamorphosed iron-formation where there is maximum grain enlargement, and magnetite lithofacies are usually preferred over hematite or mixed facies.
4. Mineable thicknesses of ore, usually 30 to 100 m or greater, may vary depending on location and economic factors in the market area. Ore deposits may consist of thick primary stratigraphic units or a succession of ore beds that have been repeated by folding and faulting.
5. Uniform granularity and mineral composition with a minimum of infolding of barren sediment or marginal facies of iron-formation, are advantageous factors for grade control and in processing of the crude ore.
6. Oxide facies iron-formation normally has a low content of minor elements, especially sodium, potassium, sulphur, and arsenic, which have deleterious effects in the processing of the ore and quality of steel produced from it.
7. The content of minor elements may vary significantly in different iron-formations depending on the kinds of volcanic, igneous, and stratafer rocks associated with them.
8. Iron-formations are usually large regional geological features that are relatively easy to define by mapping or with the aid of aeromagnetic or gravity surveys. Detailed stratigraphic information is an essential part

of the database required for defining grade, physical and chemical quality, and beneficiation and concentration characteristics of the ore.

9. Basin analysis and sedimentation modelling enable definition of factors that controlled the development, location, and distribution of different iron-formation lithofacies.
10. Metamorphic mineral assemblages reflect the composition and mineralogy of primary sedimentary facies.

ACKNOWLEDGMENTS

This paper was critically read by D.F. Sangster, R.I. Thorpe, and C.W. Jefferson. Carol Plant and Lara O'Neill assisted with word processing.

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3.3 IRONSTONE

G.A. Gross

INTRODUCTION

Following established precedent (Gross, 1965), the term ironstone refers to lithofacies of hydrolithic sediments composed of yellow to brown or blood-red iron oxide, clay minerals, and fine grained clastic and fossil detritus that commonly have well developed oolitic and granular textures. Selected lithofacies of ironstone requiring a minimum of processing are used as iron ore and because of their relatively high content of calcium and magnesium provide suitable fluxing components in blast furnace burden. Iron ore should have the highest content of iron and the lowest possible content of slag-forming constituents (alumina and silica), and meet grade and quality specifications of a

particular iron and steel industry. The use of ironstone for iron ore is restricted because of its high content of phosphorus, but it is accepted for use in areas where the phosphorus-rich slag produced from it can be used in the production of fertilizers or for other industrial purposes. The content of deleterious constituents, such as sulphur and arsenic, must be kept low and controlled to very rigid specifications.

Goethite is the principal iron oxide mineral in the brown ironstones, e.g., **Minette-type** Jurassic Lorraine Basin in France and Luxembourg (Bubenicek, 1961, 1971; Teyssen, 1984), in the Midlands of England (Taylor, 1949), and Peace River area of Alberta (Mellon, 1962). Hematite is the most abundant iron oxide in the purple to red **Clinton-type** ironstones, e.g., Lower Ordovician in Wabana mine of Newfoundland, and in Alabama and Appalachian area of United States. Both types have significantly high contents of alumina, phosphorus, calcium, and magnesium.

Descriptive data and interpretation of Ordovician ironstone in Wabana mine, Newfoundland, are used here to illustrate this deposit type and its genesis.

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IMPORTANCE

Ironstone has provided a relatively small amount of iron ore in Canada. About 80 million long tons (81.3 Mt) of Clinton-type ironstone, mainly from underground stopes, were shipped from Wabana mine on Bell Island, Newfoundland, during its operation from 1892 to 1965. Nearly 35 million long tons (35.6 Mt) of this ore were used in Canada and the remainder was shipped to England and Germany. The highest rate of production was achieved in 1960 when 2.8 million long tons (2.84 Mt) of ore were mined.

Large resources of Minette-type ironstone have been explored in the Peace River area of Alberta, and about 350 000 long tons (355 600 t) of ore were produced from the Nictaux-Torbrook ironstone in Nova Scotia between 1825 and 1916.

A significant amount of iron ore has been mined from ironstone deposits in Alabama in the past. The Clinton Formation extends through the Appalachian fold belt for more than 1000 km into New York State (Cotter and Link, 1993). The Minette ironstone deposits in England, France, Luxembourg, and Germany were one of the principal sources of iron ore in western Europe until production was phased out in recent years.

Ironstone has provided a source of ferrous iron in the preparation of fertilizer products for use in tropical areas where iron is oxidized by weathering processes and the soils become depleted in essential ferrous iron compounds.

SIZE AND GRADE OF DEPOSITS

The iron content in Clinton-type ironstone in the Lower, Middle, and Upper ore beds in Wabana mine, Newfoundland, ranged from 45.00 to 59.60%, and the silica content from 6.5 to 20%. The average iron content in ore mined in 1965 was 48% and after treatment in the heavy media plant to remove shale the ore shipped contained 50.18% iron, 12.92% silica, and 1.77% moisture.

The Jurassic Minette-type ironstones of the Lorraine Basin in France and Luxembourg, and in Northhamptonshire in England contain from 25 to 35% iron; silica ranges from 5 to 20%; and the amounts of other constituents vary greatly.

Grade and quality are of special concern in the use of ironstone iron ore. The total thickness of stratigraphic units of ironstone rarely exceeds 10 m but estimates of iron resources in single basins often exceed one billion tonnes.

GEOLOGICAL FEATURES

Ironstone lithofacies range in age from Late Precambrian to Recent. They are associated with black shale, siltstone, sandstone, shale, limestone, and manganese, phosphatic, or pyritic shale, and were deposited in neritic oxygenated and euxinic environments in continental shelf and estuarine basins. Ironstones are included in the stratafer group of hydrolithic sediments (see Type 3 "Introduction").

Stratigraphic and sedimentary features typical of many Clinton-type ironstones are exposed in a sequence of Cambro-Ordovician sedimentary rocks at Wabana mine on

Bell Island, Newfoundland (Table 3.3-1). The ironstone ore zones and enclosing strata dip gently to the north (Fig. 3.3-1) and extend under Conception Bay.

The description of the stratigraphy of the Wabana ironstone within the Lower Ordovician Wabana and Bell Island groups (Table 3.3-2) is based mainly on data from Hayes (1915) and illustrated in Figure 3.3-1. Oolitic ironstone and ferruginous rocks occur in six zones on Bell Island and are described in order from the upper to the lower parts of the stratigraphic column in Table 3.3-2.

Sedimentary features of ore

Beds of ironstone in the ore zones that are less than one metre thick are separated by thin beds of ferruginous shale that contain isolated iron-rich granules or oolites. Transitional zones between ironstone and shale consist of interbedded shale and oolitic hematite. Sandy beds containing chamosite granules in a matrix of siderite and fine clastic mud are commonly interlayered with shale and ferruginous beds. The oolitic hematite beds show many sedimentary features that formed in shallow water such as crossbedding, ripple-marks, scour-and-fill structures, worm burrows, and abraded fossil fragments.

Oolites and ooids in the ironstone consist of alternating concentric rings of siderite or mixtures of siderite, hematite, and chamosite surrounding nuclei of fossil fragments, sand grains, or granules, and are distributed in a matrix of hematite or siderite. The average size of the oolites is about 0.5 mm and their outer rings usually consist of hematite. Hayes (1915) described delicate, well-preserved algal borings that cut across some of the oolite rings and showed that there has been little alteration of the oolites, ooids, or spherules since they were formed.

Stratigraphic features of ore

The lenticular nature of the ironstone beds is shown in Figure 3.3-1. Iron-rich beds, less than 10 m thick, extend along strike for more than 1000 m and appear to have been sand bars that were parallel to the ancient shoreline (Fig. 3.3-2).

Ironstone ore was mined from three stratigraphic units, which were less than 12 m thick, typically massive, deep red to purplish red, and composed of oolites or spherules consisting of hematite, chamosite, and siderite. The ore broke into rectangular blocks along well developed sets of joints and fractures.

The "Lower" ironstone ore zone, the Dominion bed, maximum thickness about 12 m, was the thickest of the three zones mined, and provided most of the ore. It consisted of several hematite-rich lenses separated by lenses of leaner shale or sandstone. The upper part of this zone was rich in siderite and similar to the Upper bed, probably recording a change in sedimentation with deeper submergence of the depositional basin. Good quality hematite-chamosite ore, present mainly in the upper and lower parts of this ore zone, graded laterally over a distance of 30 to 100 m into leaner siliceous material in the main bar or lens of iron-rich sediment (Fig. 3.3-2). The top of the Lower bed

was defined by a disconformity, and by a persistent bed of sandy conglomerate less than 2 m thick that contains nodules of black shale and pyrite in a cherty matrix. A pyrite bed (Zone 3, 0.5 m thick), composed of oolites and spherules of pyrite in a cherty matrix, lies above the sandy bed.

The "Middle" ironstone ore zone, Scotia bed, was mineralogically and texturally like the Lower bed but richer in iron. The average thickness mined was about 2.5 m. It contained 59.6 to 51.5% iron and 6.4 to 12.0% SiO₂. The lenses of oolitic hematite, 1-2 m thick, strike northwest and are parallel to the present shoreline. They thin to less than one metre in areas one to two kilometres from the shore.

The "Upper" ironstone ore zone (5), marks the upper limits of iron deposition in the basin. It is located 10 to 15 m above the Middle zone, and is characterized by the lency, erratic distribution of hematite-chamosite-siderite facies interbedded with sand and shale, a lower iron content, and siderite present in wavy bands and as matrix to the oolites.

Structure in ore zones

Two prominent sets of faults with parallel sets of joints are developed in the east limb of the Conception Bay Syncline. One set strikes 030° and dips 85°SE and the other set strikes 290° and dips 85°SW. The ore breaks into rectangular

fragments along joints spaced 10 to 30 cm apart. Both strike-slip and dip-slip movement took place along most faults; right-hand displacement was along northwest-trending faults; and left-hand displacement was along the northeast-trending faults. The northeast-trending faults appear to have developed somewhat later than the north-westerly faults, but movement along the faults caused very little brecciation or contraction of adjacent beds. Vertical movement of 30 m has taken place on some of the major faults that pass through the three ore zones (Fig. 3.3-3).

DEFINITIVE CHARACTERISTICS OF IRONSTONE IRON ORE

The most desirable ironstone beds at Wabana had a minimum of shale and clay intermixed with the iron-rich oolites and spherules, a high proportion of iron as hematite and hydrated iron oxide minerals relative to siderite and chamosite, and iron distributed in discrete mineral grains, oolites, and spherules, rather than intermixed in clay-sized or amorphous aggregates. Facies rich in siderite frequently contained an undesirably high content of manganese. Beds of well-sorted hematite, siderite, and chamosite oolites and granules, of a mineable thickness, 2 to 10 m, provided the best ore in Wabana mine. Sharp boundaries between the

Table 3.3-1. Regional stratigraphy of the Wabana mine area (based on data from Rose, 1952; Hutchinson, 1953; and Gross, 1967a).

<p>WABANA GROUP – Lower Ordovician, >300 m thick.</p> <p>This group overlies the Dominion or "Lower ore bed". Lithofacies are similar to those in the Bell Island Group, except that black shale units containing beds of oolitic pyrite and pyrite-bearing shale associated with oolitic hematite-chamosite-siderite ironstone are more abundant in basal part of unit.</p>
<p>BELL ISLAND GROUP – Lower Ordovician, estimated thickness >1220 m.</p> <p>Composed of massive red oolitic hematite-chamosite beds, ferruginous sandstone, and shale; thin-bedded, grey, grey-brown, and greenish sandstone; grey, brown, and black shale; light micaceous sandy shale and sandstone. Sandstone beds consist of subangular quartz grains, glauconite, chamosite, altered feldspar, ferromagnesian minerals, and accessory zircon, sphene, and magnetite, which are enclosed in a matrix of siderite in some of the beds. Deposition of the ironstone and clastic sediments in shallow water is indicated by numerous sedimentary features – crossbedding, ripple-marks, rain-drop impressions, worm burrows, algae tubes, and fossil fragments.</p>
<p>ELLIOT COVE GROUP – Upper Cambrian, >150 m thick.</p> <p>Composed of thin-bedded, dark grey and black shale with nodules of pyrite, and lenses of limestone and sandstone.</p>
<p>ACADIAN GROUP – Middle Cambrian, 150 m thick.</p> <p>Composed of black and green shale, slate, and siltstone with nodules, lenses, and thin beds of red and grey limestone, pyritic slate, and manganiferous and phosphatic beds.</p>
<p>LOWER CAMBRIAN GROUP – 150 to 245 m thick.</p> <p>Red to pink to green wavy banded limestone interbedded with red or green slate. Quartz-pebble conglomerate cemented by red limestone at the base of the section is in angular unconformity with Precambrian rocks.</p>

TYPE 3

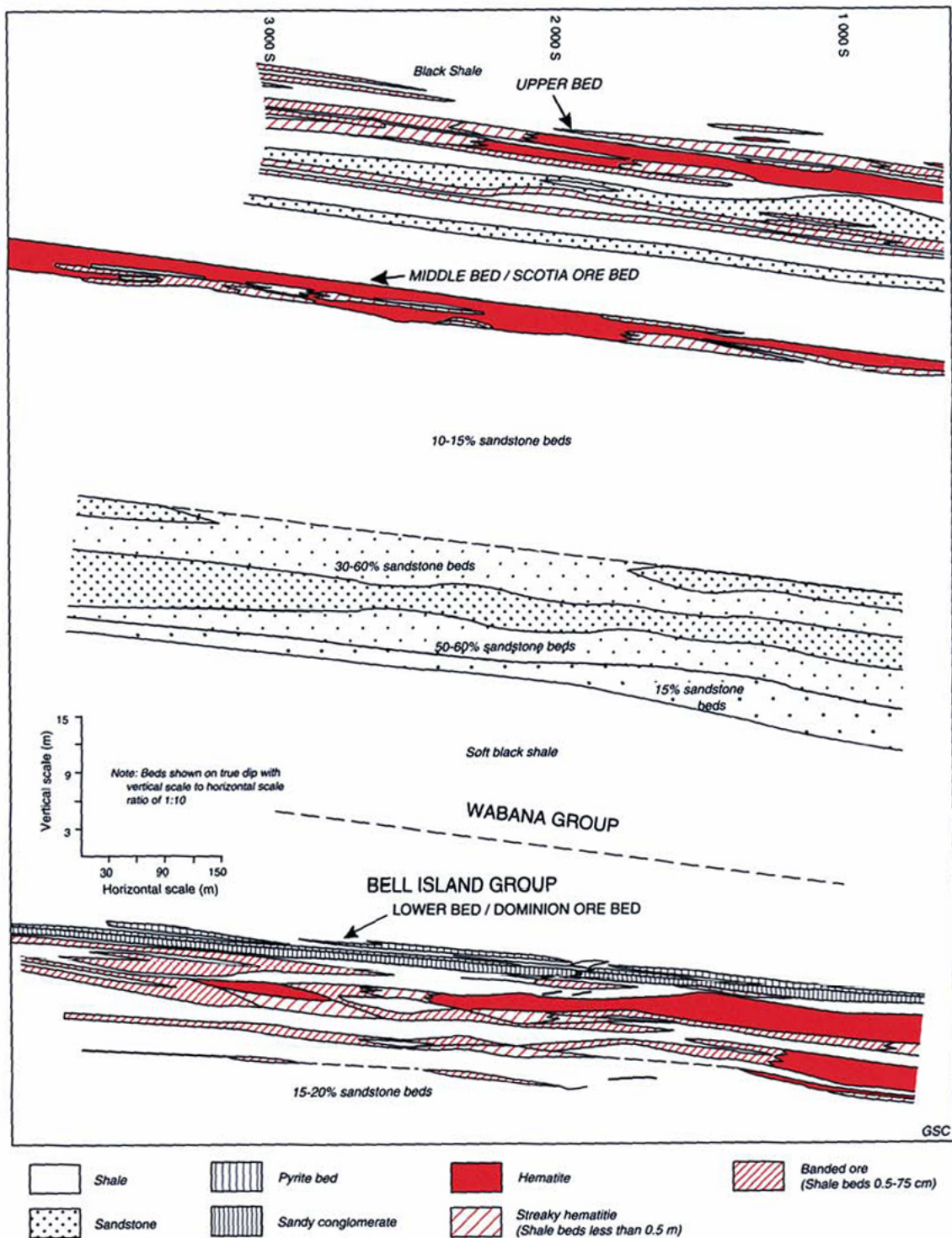


Figure 3.3-1. Section A, through Upper, Middle, and Lower beds, facing west, Wabana, Newfoundland (after Lyons, 1957).

Table 3.3-2. Stratigraphy of the Wabana ironstone within the Lower Ordovician Wabana and Bell Island groups.

Zone 5, Upper bed. The lowest ironstone bed of this zone is separated from the Scotia bed by about 12 m of sandstone and shales, and oolitic ironstone beds are prominent throughout the upper 15 m of this stratigraphic zone.
Zone 4, Middle "Scotia" bed ironstone, ore zone. This zone is about 4.5 m thick and is 60 m stratigraphically above zone 3.
Zone 3, Pyrite beds. Three beds of oolitic pyrite, ranging in thickness from 5 cm to 1.2 m, are interbedded with black shale in 3 m of the stratigraphic succession immediately above the oolitic hematite beds of zone 2.
Zone 2, Dominion bed, the main ore zone. This is about 30 m thick and consists of a series of oolitic hematite ironstone beds interbedded with shale and crossbedded, fine grained sandstone. The main Dominion ore bed in the upper 10.5 m of zone 2 is composed of thick beds of oolitic hematite separated by thin layers of ferruginous sandstone and shale. The lowest oolitic hematite beds in the Dominion zone are 180 m stratigraphically above zone 1.
Zone 1. This zone is partially exposed by shallow cuttings along the tramways at the mine. It contains bands of oolitic hematite, two of which appear to be continuous, one attaining a thickness of about 60 cm.
Zone 0. This consists of a thin ferruginous band located in the extreme southwestern part of the island.

ironstone and associated sediments, shallow-dipping to flat-lying strata, and a minimum of disruption of the ore strata by faults, were favourable factors in defining ore zones.

GENETIC MODEL FOR IRONSTONE

The oolitic iron ore, ferruginous shale, and sandstone form part of a series of sedimentary rocks of Lower Ordovician age. Three stages in the deposition of the Lower ironstone bed at Wabana were described by Lyons (1957):

1. deposition of a thin bed of oolitic hematite, 30 to 60 cm thick, was followed by deposition of ferruginous shale beds, 30 cm to 3 m thick;
2. development in favourable areas of a complex zone of hematite- and chamosite-rich beds, 1 to 5 m thick, that were relatively free from shale partings, except at the base and top of the zone; and
3. the iron-rich beds were succeeded by another unconformity zone (reactivation surface) in which iron deposition was much more limited and a bed of mud 10 cm to 2 m thick accumulated. Hematite and chamosite beds deposited above this unconformity zone are 2.5 to 5 m thick.

Precipitation of iron took place separately or during the normal deposition of mud, silt, shale, sand, and some limestone. Observations by Hayes (1915) on the Wabana beds outlined features of special genetic significance which are summarized below.

The ore beds are characterized by ripple-marked surfaces and crossbedded layers, and contain remains of organisms which lived in shallow water. The spherules, oolites, and granules in the ore range in size from 0.1 to 0.5 mm and are composed of alternating concentric layers of hematite and chamosite. Some of the oolites were pierced by living, boring algae that flourished on the sea bottom, which suggests that precipitation of iron and the development of the oolites took place near the sediment-water interface.

Chamosite appears to have formed in advance of the other iron-rich minerals. The conspicuous increase in hematite in the outer parts of oolites suggests that part of

it may have formed by oxidation of chamosite or during a later stage of precipitation. Ferrous iron in solution reacted with complexes of clay and colloidal clay particles to form chamosite on the surface of convenient nuclei.

Much of the siderite appears to have formed during diagenesis of the beds. Siderite is less abundant than hematite and chamosite and replaces these minerals and some of the detrital quartz in the ironstone. Fossilized algae is found in all parts of the ore beds and evidently algae were very abundant in the marine plant life growing on the sea bottom. Tubules of the algae preserved in the siderite are usually coated on the exterior with hematite. The siderite was probably precipitated below the sediment-water interface where concentrations of ammonia and carbon dioxide were produced from decaying organic matter. Evidently hematite and chamosite formed on the surface of the sediment whereas siderite formed contemporaneously during early diagenesis of the underlying sediments.

The iron ore beds occur as primary sedimentary deposits that are essentially in the same condition today as when they were deposited, except for induration, faulting, and the addition of small amounts of secondary calcite and quartz in joints and fractures. Limestone is not associated with the ore beds and all of the original calcium in the ore, average content about 2.5%, is present in the fossils, which are composed largely of calcium phosphate, or calcium phosphate derived from organic matter. The phosphorus in the iron ore is also distributed in the fossil material. No evidence of diagenetic transformation from an original oolitic limestone to an oolitic iron ore has been found and there is no evidence that addition or concentration of iron has occurred since the deposition of these ferruginous sediments.

Oolitic pyrite beds in the same sedimentary succession as the hematite ore beds are characterized by a planktonic fauna indicative of open ocean currents and deeper water. The layers of pyrite show distinct stratification and are probably similar in origin to modern deposits of pyrite now forming in the Black Sea. The pyrite oolites and spherules are composed of fine concentric laminae of pyrite, and some oolites have alternate fine laminae of phosphatic material and pyrite. Pyritized and unpyritized graptolites and

brachiopod remains occur together in contact with the spherules, indicating that some mechanical mixing took place on the depositional surfaces.

It is evident that complex and delicate adjustments of the composition and chemistry of the basin water, water depth, distribution of clastic material, and of Eh and pH of the seawater were required for the formation of this ironstone. The oolites are evidence of agitation and disturbance of the water, probably by wave or tidal action, in a shallow bay or shelf.

The source of the iron in the Wabana ironstone has not been established with any degree of certainty. Many have inferred that the iron was derived by weathering processes and transported in solution as inorganic and organic acid compounds. The imposition of chemically precipitated iron at specific intervals and locations in the sequence of ordinary shelf sediments, and the abundance of shales and coarse grained clastic material intimately associated with these hydrolithic ironstones, raises some doubt as to

whether sedimentation factors in a basin and weathering of terrestrial rocks can solely account for, or are compatible with, the concentration of iron as found in ironstones.

The iron in some of the ironstones may have come from submarine volcanic emanations which could have been transported by currents to the sedimentary basin where it was oxidized and precipitated in shallow water near the shore (Gross, 1965; see also Kimberley, 1979, 1994). The large deposits of oolitic brown hematite, goethite, and silicate ironstones deposited on river beds and flats in Oligocene time at Lisakov in the southern Ural Mountains (Gross, 1967b), and the large Oligocene ironstone deposits around Kerch near the Black Sea and Sea of Azov, clearly show that the iron in large ironstone deposits can be derived by sedimentary processes, since evidence of hot springs and effusive sources of iron at these sites has not been reported. On the other hand, iron from hydrothermal sources is being deposited in the hydrolithic sediments forming along the shore of Santorini Island, Greece, and

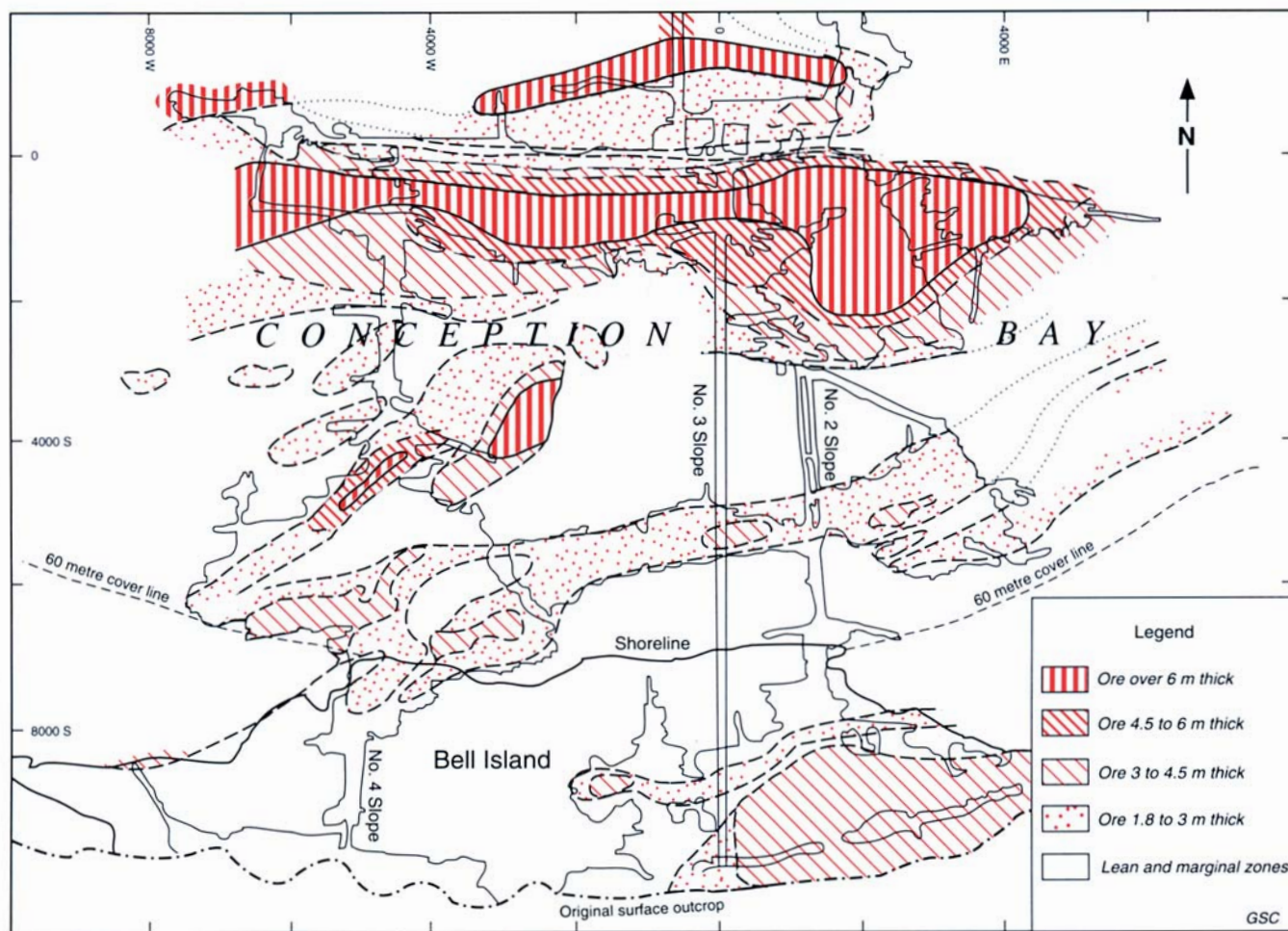


Figure 3.3-2. Plan showing ore trends and thickness, Lower bed, Wabana, Newfoundland (after Lyons, 1957).

Volcano Island in the Tyrrhenian Sea. Jenkyns (1970) concluded that exhalations associated with volcanism were the most likely source of iron in Jurassic ferruginous pisolitic sediments in western Sicily.

A fundamental difference between ironstones and iron-formation may be a land source for some of the iron and most of the other constituents in ironstones, as opposed to hydrothermal-effusive sources for the iron and silica in iron-formations and other stratafer lithofacies. The bulk chemistry of most ironstones is compatible with a land source for their components but the content of minor elements is not well known. Iron may have been derived from either one of these sources, but environmental factors controlled the composition and the kinds of lithofacies that developed.

The genetic relationship between ironstones and iron-formations or other stratafer rocks is not clearly understood, and a distinction between them is maintained because of marked differences in their composition, lithology, and

mineralogy, and their qualities as iron ore. Because of the high contents of alumina and clay material in the ironstones and the high content of silica in the form of chert and quartz in iron-formation, it has generally been accepted that these two main groups of iron-rich hydrolithic sediments were formed by different processes in different environments and that deposition of silica and alumina in large quantities in the same basin environment was chemically incompatible. Banded chert is found occasionally in sequences of ironstone, but an exclusive hydrogenous-sedimentary or hydrothermal genesis has not been demonstrated.

RELATED TYPES OF DEPOSITS

Possible genetic relationships between ironstones and manganese-, copper-, and zinc-rich metalliferous sediments require further investigation.

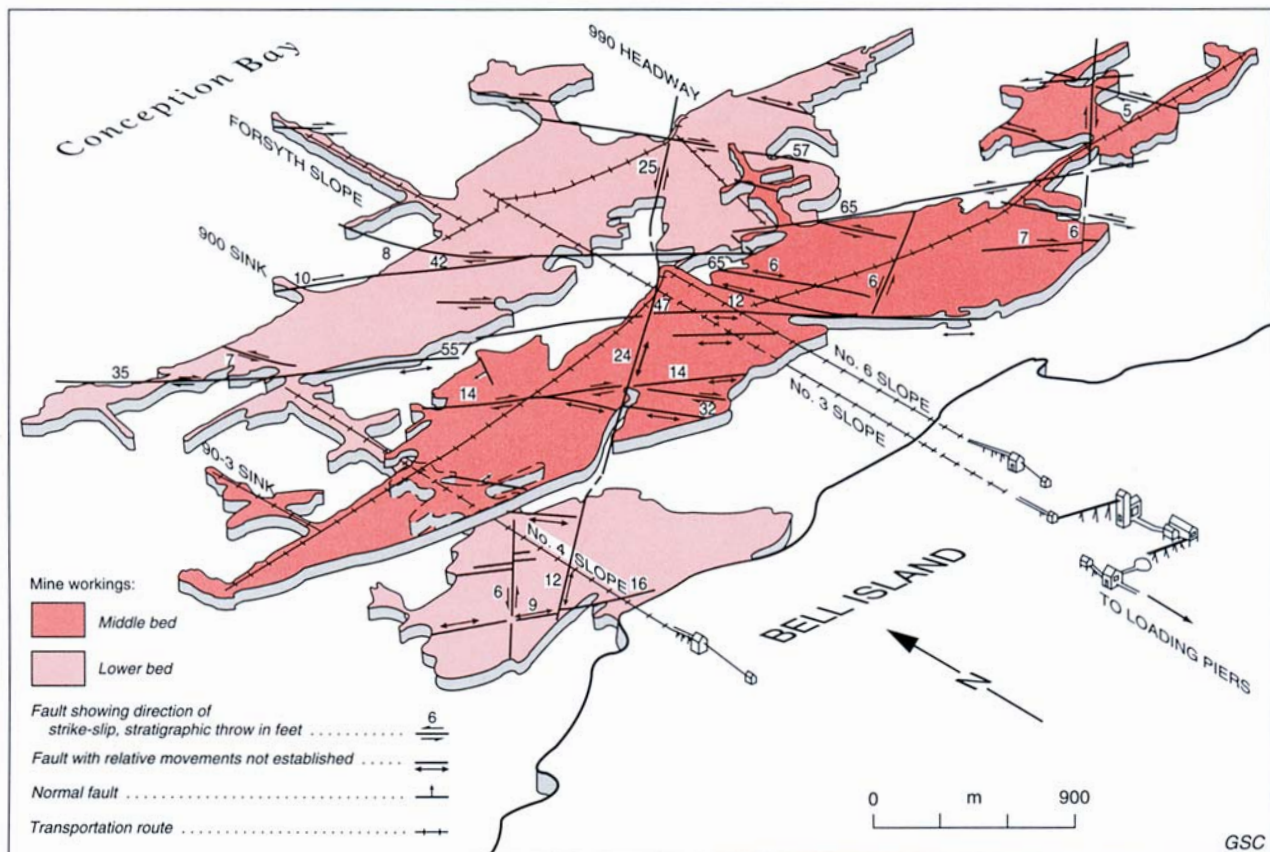


Figure 3.3-3. Schematic drawing of mine workings, Wabana, Newfoundland (from D.K. Norris, 1957, GSC; courtesy Dominion Wabana Ore Limited).

The typically high content of phosphorus in ironstones suggests that some facies of ironstone might be used as metallogenetic markers for locating beds and nodules rich in phosphate.

Manganese-rich facies stratigraphically equivalent to ironstone have not been described as such and apparently are not an important source of manganese. This suggests further differences between ironstone and iron-formations (see iron-formations and residual-enriched iron ore subtypes 3.1, 3.2, and 4.1).

Ironstones provide a source of ferrous iron in the preparation of fertilizer products for application in tropical areas where the iron is oxidized by weathering processes and the soils become depleted in essential ferrous iron compounds.

EXPLORATION GUIDELINES

1. Most of the ironstone facies selected for ore should be sought in strata which record neritic to estuarine environments, have a predominance of chemically precipitated material, a minimum of clastic material, and distinctive mineral assemblages and textures that are conducive to beneficiation and smelting.
2. Ironstone facies suitable for iron ore usually contain 30% or more iron, and the acceptable ranges of contents of other constituents have been indicated above.
3. The bulk of the iron should be in discrete coarse granular aggregates of iron oxide and carbonate minerals, with a minimum of associated fine grained admixtures of clay and complex iron-silicate or carbonate minerals.
4. Ironstone selected for ore should consist of well defined, uniform lithofacies that are relatively free from interbedded shale and other kinds of sediment, and have an adequate thickness to meet requirements for mining.
5. Intense folding, steep dips, and excessive structural disruption adversely affect mining feasibility.
6. Location of the ore with respect to the smelter site or shipping routes is important, as a large proportion of the cost of bulk commodities is usually attributable to transportation.
7. Phosphate minerals usually associated with organic debris, and other constituents, such as sulphide minerals, which necessitate a high slag volume in the furnaces, should be kept to a minimum in the ore.

ACKNOWLEDGMENTS

This paper was reviewed by R.T. Bell, R.I. Thorpe, and C.W. Jefferson. Assistance in word processing was provided by Lara O'Neill and Carol Plant. Figures were expedited by R. Lancaster.

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