SUPERIOR FE DEPOSITS
(MODEL 34a; Cannon, 1986)

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SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Superior-type iron-formation consists of extensive stratigraphic units of iron-rich rocks interbedded with a variety of shallow water marine sedimentary rocks, including quartzite, shale, and dolomite, that are part of sedimentary sequences that lie unconformably on older crystalline basement rocks, either in passive margin or foreland basin settings. Some Superior-type iron-formation interfingers with or grades laterally into volcanic rocks; most is Early Proterozoic or very late Archean in age. Oxide, carbonate, and silicate facies are commonly interbedded, and sulfide facies is present in some cases. Economic deposits are restricted to oxide facies ore, commonly referred to as taconite in North America (in some areas "taconite" has a specific legal definition for taxation purposes), from which concentrates of magnetite and less commonly hematite can be produced. All ore requires concentration, done at or near the mine site, to produce a marketable product. Individual mines generally exploit only a small part of the iron-formation. Mine boundaries may be determined by subtle features of mineralogy, structure, or other geologic and geotechnical factors, or by property or political boundaries. In some cases, as on the Mesabi Iron Range, Minn., a series of mines forms nearly continuous workings for many kilometers along strike of the iron-formation. Deposits of this type provide nearly all domestic iron production; the Mesabi Range, Minn., and Marquette Range, Mich., are the major producing districts. Their combined production is about 50 million tonnes per year.

Examples

Mesabi Iron Range, Minn. (Biwabik Iron-Formation); Marquete Iron Range, Mich. (Negaunee Iron-Formation); Minas Gerais area, Brazil; Wabush Lake area, Canada

Spatially and (or) genetically related deposit types

Some Superior-type iron-formation, such as the Kalahari district of South Africa, includes interbedded manganese-rich strata that may constitute important manganese ore.

Potential environmental considerations

Geoenvironmental concerns are almost entirely related to physical redistribution of earth materials; concerns related to acid water generation and metal mobility are minor. Many taconite mines in Superior-type iron-formation rank among the worlds largest mines. Exceptionally large open pits, waste rock dumps, and tailings impoundments produce long-term modifications of the Earth's surface.

Processing taconite to concentrate iron minerals produces large volumes of fine-grained tailings that must be permanently stored. The tailings consist of quartz, a variety of silicate minerals, some of which may be fibrous, iron carbonate minerals, and iron oxide minerals. Potential environmental concerns related to tailings include: (1) silica-rich wind-borne dust, (2) fibrous silicate minerals in air and water, (3) particulate and colloidal iron compounds in discharge water, (4) exchange of water in tailings impoundments with ground water, (5) long-term stability of tailings impoundments, and (6) mineral dusts in stack emissions from kilns.

Ore that contains amphibole minerals is a particular concern because it has the potential to generate fine-grained acicular cleavage fragments that meet some legal definitions of asbestos; natural amphibole asbestos poses similar problems. Crocidolite, the fibrous variety of riebeckite, and amosite, the fibrous variety of grunerite-cummingtonite amphibole, are known carcinogens of both the lungs and digestive tract and can be harmful, even with less than occupational exposure. Both minerals are present in some iron-formation but are far from ubiquitous. The non-asbestiform variety of grunerite-cummingtonite amphibole is common in iron-formation, including much that is mined and processed. Fine acicular particles, legally classed as asbestos, that are produced by grinding are potentially harmful. However, epidemiological studies of taconite miners and mill workers at a taconite mine in Minnesota, where the ore contains abundant grunerite-cummingtonite, found no evidence of excess cancer of the type related to asbestos exposure (Ross, 1984). Nevertheless, any iron-formation containing amphibole probably requires special consideration with regard to mine design, milling, and waste disposal practices to minimize discharge of amphibole particles into the environment. All of these hazards are successfully mitigated at numerous large mining and processing operations.

Superior-type deposits are invariably mined from open pits resulting in large, and partly permanent surface disturbance. Reclamation after mining generally only partly restores pre-mining surface configuration.

Exploration geophysics

Gravity and magnetic methods can be used to delineate greenstone belts within granite-greenstone terranes at provincial to regional scales. Magnetic low and gravity high anomalies are usually associated with relatively nonmagnetic, dense greenstone terranes, whereas magnetic high and gravity low anomalies are usually associated with magnetic, low-density granitic terranes (Innes, 1960; Bhattacharya and Morely, 1965; McGrath and Hall, 1969; Tanner, 1969; and Condie, 1981). Gravity and magnetic methods can also be used for deposit-scale iron-formation studies. Most iron-formation is associated with positive, high-amplitude gravity anomalies because it contains elevated abundances of high-density iron minerals, including magnetite and hematite. The magnetic signature of iron-formation is usually one to two orders of magnitude greater than that of its host rock (Bath, 1962; Sims, 1972). Remote sensing imaging spectroscopy can also be used in regional exploration (Hook, 1990) because iron ore minerals and their alteration products have distinct spectral signatures (Clark and others, 1993).

The magnetic character of iron-formation is dependent on magnetic mineral content, alteration, structural attitude, and remanent magnetization. Iron-formation with low magnetite content, or deposits in which magnetite has been oxidized to non-magnetic hematite, produce low-amplitude anomalies of tens to hundreds of nanoTeslas. Flat-lying deposits with normal magnetic polarization typically produce positive anomalies of about several thousand nanoTesla. Steeply dipping or folded iron-formation dominated by remanent magnetic polarization can produce anomalies with extremely high positive amplitudes of as much as tens of thousands of nanoTesla.

Electrical and electromagnetic methods are generally not applied to iron-formation exploration because the ore is resistive owing to high silica (chert) content. However, electrical techniques could be used to delineate conductive sulfide facies associated with ore deposits.

References

Geology: James (1954), Beukes (1983), Morey (1983), and Trendall (1983).
Environment: Bartlett (1980), Ross (1984), Gross (1988), Myette (1991), and Ross and others (1993).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Superior-type iron-formation forms extensive stratigraphic units, some containing tens of trillions of tons of material averaging about 30 percent iron. Individual mining blocks outlined within iron-formation, based largely on metallurgical characteristics related to grinding and concentration, commonly exceed a billion tons of reserves and seldom are less than 100 million tons. Median deposit size is 170 million tonnes (Mosier and Singer, 1986).

Host rocks

Superior-type iron-formation is interbedded with marine shale, quartzite, carbonate rocks, and in some cases mafic to felsic volcanic rocks. Some contain extensive diabase sills.

Surrounding geologic terrane

Superior-type iron-formation is present in shallow marine sequences deposited on continental margins, either during passive margin phases or in foreland basins adjacent to collisional orogens. All have basement of older, generally Archean crystalline rocks. Deformation varies from mild to intense as does metamorphic grade. In some cases submarine volcanic rocks form interbeds or lateral facies equivalents.

Wall-rock alteration

No wall rock alteration is associated with Superior iron deposits. Formation of Superior-type iron-formation results from processes involving chemical sedimentation.

Nature of ore

Most ore is banded rock in which iron-rich bands are interlayered with chert bands on a scale of less than a millimeter to a few centimeters. Several depositional facies are common, including oxide, silicate, and carbonate facies. The facies may be in stratigraphic superposition within iron-formation or form lateral equivalents; sulfide facies ore is present in some cases. Oxide facies ore consists of both magnetite- and hematite-bearing rocks, and is the only economically important facies. Grade is relatively uniform, typically about 30 to 35 weight percent iron for all facies, but may vary from 15 to 45 weight percent. Grain size and the nature of gangue minerals vary according to degree of metamorphism. A critical factor for environmental consideration is the metamorphic development of iron-amphibole, which may be released as discrete fibrous particles during processing. Iron amphibole commonly is present in middle greenschist facies or higher metamorphic grade rocks.

Deposit trace element geochemistry

The composition of Superior-type iron-formation is remarkably simple. Except for its essential constituents, iron and silica, iron-formation characteristically has very low abundances of other elements, nearly all of which are present at concentrations below average crustal abundances. Some iron-formation has somewhat elevated concentrations of phosphorous, which are present in apatite. Because phosphorous is extremely detrimental in steel manufacture, its concentration is carefully monitored during mining and high-phosphorous material is avoided.

Ore and gangue mineralogy and zonation

Ore minerals are magnetite and hematite. Gangue is mostly quartz in the form of variably metamorphosed chert beds. Other gangue minerals include, depending on original facies of deposition and degree of metamorphism, siderite or other ferruginous carbonate minerals, greenalite, minnesotaite, stilpnomelane, iron-amphibole, iron-pyroxene, garnet, and pyrite, generally present in only trace amounts. Magnetically concentrated ore may include hematite as gangue.

Mineral characteristics

The most important mineral characteristic is the presence or absence of amphibole that might contribute natural asbestos fibers or asbestos-like grains produced during processing. Amphibole is a common metamorphic mineral in iron-formation and may be present in middle greenschist or higher metamorphic grade rocks. Original grain size is also important and varies as a function of metamorphic grade. Weakly metamorphosed iron-formation is extremely fine grained and requires very fine grinding (as fine as 0.03 mm in some cases) to liberate iron minerals from gangue. More intensely metamorphosed ore is coarser grained and requires less grinding. Maximum grain size after grinding is generally about 0.1 mm, even for the most coarse grained ore. Grain size fineness is positively correlated with increased potential for problems with dust from tailings basins, colloidal and particulate suspensions of ore and gangue minerals in released process water, and higher tailings weathering rates.

Secondary mineralogy

Because tailings are generally very-fine grained, weathering and formation of secondary minerals may proceed quickly. Iron oxide minerals alter to iron hydroxide minerals. Iron silicate minerals alter to iron hydroxide minerals and clay. Most alteration minerals are highly insoluble. Sulfide minerals, mainly pyrite, may also quickly alter and generate small amounts of acid. Much ore also contains at least trace amounts of carbonate minerals, which, when present, are probably adequate to neutralize any acid generated.

Topography, physiography

Superior-type iron-formation can be present in a variety of physiographic settings. They are characteristic deposits of Precambrian shields, so many are in areas of low to moderate relief. They may also be present in high relief areas, particularly where older shields have been incorporated in younger orogenic belts. The principal topographic and physiographic concern relates to large volumes of tailings that are characteristically produced. In areas of high relief it may be difficult to site tailings impoundments with adequate volume. In settings where rapid runoff can produce flash flood hazards, impoundments must be protected from failure.

Hydrology

Hydrologic communication between ground water, waste piles, and tailings is a predictable consequence of mining. A detailed study of a taconite tailings basin in Minnesota (Myette, 1991) and its surroundings suggests that associated environmental problems are minimal. Abundances of components dissolved in water from a tailings test well are well below maximum abundances permitted by state standards for drinking water, except those for fluoride, which are about at the maximum permitted abundance. Particulate abundances in discharge water are also low except during occasional periods of very high precipitation or snow melt.

Mining and milling methods
Superior-type iron-formation is mined in open pits, and processed to high-grade concentrates that are pelletized and fire hardened in kilns at or near mine sites. Open pit mining produces relatively large volumes of waste rock that must be disposed of near mines. Mine waste generally includes shale and quartzite with which iron-formation is interlayered, and in some cases mafic rocks that intrude the iron-formation. Ore concentration generates large volumes of tailings, mostly composed of silica and lesser iron silicate and iron carbonate minerals. Stack emissions of mineral dust might also be a concern; scrubbing or filtering might be required to eliminate dust problems.

ENVIRONMENTAL SIGNATURES

Drainage signatures
Pre-mining drainage signatures for Superior-type iron-formation deposits are unknown. In virtually all weathering regimes, original iron minerals break down to iron hydroxide minerals and clay which are highly insoluble. With intense weathering silica is lost, but not in concentrations that produce a detectable geochemical signature. Some asbestos-like particles may be released into surface water; however, the U.S. Environmental Protection Agency has concluded that ingestion of asbestos fibers poses no significant cancer risk (U.S. Environmental Protection Agency, 1991).

Metal mobility from solid mine wastes
Except in special cases, in which sulfide-mineral-rich rocks might be included in waste rock, metal mobility is probably negligible. Iron weathers to largely insoluble compounds and iron-formation contains concentrations of other metals that are at or below average crustal abundances.

Soil, sediment signatures prior to mining
Pre-mining soil and sediment signatures for Superior-type iron-formation deposits are unknown but stream sediments probably contain high iron abundances. In areas of intense weathering, very iron-rich laterite, some of which may itself be iron-ore, may develop on iron-formation. In glaciated areas, most iron formation is virtually unweathered and has no associated characteristic soil signature.

Potential environmental concerns associated with mineral processing
Most Superior-type iron-formation ore is ground to 0.1 mm or finer, concentrated by magnetic or specific gravity techniques, and formed into pellets that are then fire hardened in kilns at or near mine sites. The large volume of tailings generated are stored in nearby impoundments. The principal environmental concern involves continued physical isolation of tailings, particularly fine-grained silica and fibrous silicate minerals. Redistribution by wind can be mitigated by wetting and vegetating abandoned tailings areas. Redistribution in surface water can be minimized at active mines by reuse of tailings water so that outflow is restricted to periods of very high precipitation or snow melt. The long term, post-mining stability of tailings impoundments must be assured in their design.

Combustion products from rotary kilns are generally vented through stacks and may carry fine ore particles that should be removed by scrubbing or filtering before combustion products are released to the atmosphere.

Smelter signatures
No smelting is required to process Superior-type iron ore.

Climate effects on environmental signatures
Principal climatic concerns relate to the continued integrity of tailings impoundments in climates with high annual or seasonal precipitation and with airborne redistribution of tailings in dry climates. Even in humid climates, milling operations generally reuse nearly all process water to minimize water outflow through tailings basins. In climates susceptible to extreme precipitation, however, measures are required to assure that flooding does not compromise the containment of tailings either during or after mining.

Geoenvironmental geophysics
Electrical methods can be used to identify conductive ground water plumes produced by high abundances of dissolved solids and colloidal suspensions. The self potential method can detect leaks in tailings impoundment dikes. Remote sensing methods can be used to quantify areas of permanent surface disturbance related to mining and ore processing. Remote sensing methods may also be used to identify areas of stressed vegetation related to sulfur and fugitive-metal

stack emissions, and contaminated surface water.

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