STRATABOUND AU IN IRON-FORMATIONS
(MODEL 36b; Berger, 1986)

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SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Deposits are concentrations of electrum and the sulfide minerals troilite, pyrrhotite, pyrite, and arsenopyrite, and include electrum in carbonate-facies iron-formations, and are mined for gold and silver. Notably lacking are base-metal sulfide minerals. Bed-controlled ore predominates; subsequent regional metamorphism of stratabound deposits can result in ore redistribution and concentration in quartz vein-related deposits.

Most large gold deposits in iron-formation (GDIF) are strata-bound, bed-controlled concentrations of sulfide minerals and gold that were probably formed by syngenetic, hot-spring processes during deposition of iron-formation. Iron-formation and layered, bed-controlled sulfide mineral deposits were deposited on the seafloor under extremely reducing conditions, in an environment that contained abundant organic carbon and iron and variable amounts of sulfur. Gold abundances are highly correlated with either those of pyrrhotite and troilite or with that of arsenopyrite, depending on the physical-chemical conditions of hot-spring activity. Obvious feeder zones and alteration halos within GDIF are not known.

Subsequent regional metamorphism of most GDIF has generated, *in situ*, quartz veins that may locally reconcentrate gold within iron-formation. Mobility of gold and sulfide minerals during regional metamorphism is normally restricted to the immediate thickness of the iron-formation. Quartz veins contain very few sulfide minerals, but do contain visible electrum and have selvages rich in pyrrhotite, chlorite, pyrite, ankerite, and electrum. Arsenopyrite may or may not be present in vein selvages. Because veins developed during regional metamorphism, they may be deformed or they may post-date the last folding event. Available evidence indicates that fluids responsible for quartz vein generation were not transported into the iron-formation from external sources.

The Homestake Mine produces about 350,000 ounces of gold each year, which makes it one of the five largest individual gold mines in the United States. Until the late 1980s, Homestake produced more gold than any other mine in the western hemisphere.

Examples

Homestake, S. Dak.; Jardine, Mont.; Lupine, Northwest Territories; São Bento, Brazil; Cuiaba, Brazil; Champion, India.

Spatially and (or) genetically related deposit types

Morro Velho, Brazil, may be a spatially related deposit, but data necessary to evaluate this possibility are incomplete.

Potential environmental considerations

The two mining operations in the United States that exploit examples of this deposit type, Homestake, S. Dak., and Jardine, Mont., comply with existing state, federal, and local environmental regulations. They pose no potential environmental risks.

Exploration geophysics

Oxide-facies iron-formation has high magnetization and density; consequently, its presence can commonly be delineated by aeromagnetic and gravity studies (Kleinkopf and Redden, 1975; Hildenbrand and Kucks, 1985). However, carbonate-facies iron-formation that hosts these gold deposits commonly contains no magnetite and is weakly magnetic, except where it contains abundant pyrrhotite. In carbonate-facies iron-formation, aeromagnetic highs are best developed in association with pyrrhotite- or troilite-rich deposits. Ground magnetic surveys have been used to delineate oxide-facies iron-formation and predict strike extensions, bed thickness, and dip of magnetic zones within stratigraphic sequences (Lindeman, 1984). Induced polarization and a variety of electromagnetic surveys, which can help identify concentrations of disseminated, conducting minerals, can be used to refine the location of disseminated, sulfide-mineral bearing deposits and to project the extent of known deposits (Lindeman, 1984). Potential host rocks that contain iron oxide and carbonate minerals can be identified with high resolution imaging spectrometers where vegetation does not obscure rock reflectance characteristics (Clark and others, 1990).

References

Rye and others (1974), Rye and Rye (1974), Bidgood (1978), Hallager (1980), Ladeira (1980), Kath (1990), Caddey and others (1991), and Kerswill (1993).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Deposits mined in the past and those currently being mined range from as small as several hundred metric tons to 150 million metric tons.

Host rocks

Most GDIF are contained within carbonate-facies iron-formation or their metamorphosed equivalents. Oxide-facies iron-formations host very few gold deposits. Minor amounts of silicate-facies and oxide facies iron-formation are known. Host iron-formation may or may not be laterally continuous within the shale-dominant sedimentary sequence. Transitions within iron-formation from one facies to another are known, and range from carbonate- to oxide-, silicate-, and sulfide-facies. Typically, the iron-formations are less than 30 meters thick but quite continuous along strike. Minor tuffaceous rocks are associated with some iron-formation, but this component does not appear to be a prerequisite for GDIF. Clay-rich layers in the iron-formation may have formed by submarine weathering of basaltic material or direct hydrothermal precipitation of iron-rich material.

Surrounding geologic terrane

Iron-formation is most commonly developed within shale and graywacke terrane. Gold deposits within iron-formations (GDIF) are commonly restricted to epicratonic basins formed within foundered Archean or Proterozoic cratons. Deposits are typically contained within shale-dominated environments that lack volcanic input. A few small deposits are within relatively high energy environments typified by graywacke. Arc-related rocks are unknown in environments that contain GDIF, as are very high-energy sedimentary rocks such as conglomerate, sandstone, and breccia. A slowly subsiding, continually rifting, epicratonic basin setting appears most favorable for GDIF genesis. Underlying and overlying contacts with shale-dominant rocks are transitional over distances of less than 10 m.

Wall-rock alteration

No wall-rock alteration is associated with bedded ore. Chloritization is associated with vein-related ore.

Nature of ore

Typical bedded ore contains 1 to 15 volume percent sulfide minerals, including troilite, pyrrhotite, pyrite, arsenopyrite. Electrum is associated with various sulfide minerals. Ore may be pyrrhotite rich, pyrite rich, or arsenopyrite rich. Typical quartz vein ore contains 0.5 to 10 volume percent sulfide minerals, including pyrrhotite, pyrite, and arsenopyrite. Electrum is again associated with various sulfide minerals or with quartz.

Deposit trace element geochemistry

Relative to underlying and overlying shale and graywacke, deposits are enriched in iron (in carbonate and sulfide minerals), carbon dioxide (in carbonate minerals), gold and silver (in electrum), and may or may not be enriched in arsenic (in arsenopyrite and loellingite).

Ore and gangue mineralogy and zonation

Bedded ore contains the above-mentioned sulfide minerals and electrum within strata of siderite, ankerite, quartz, chlorite, biotite, and stilpnomelane. Quartz-vein ore contains pyrrhotite, pyrite, electrum, and may or may not contain arsenopyrite within veins or marginal to veins. Common gangue minerals associated with veins include quartz, chlorite, biotite, calcite, and ankerite. Silicate-facies iron-formation contains additional phyllosilicate minerals; metamorphism at higher grade conditions yields iron-formation that contains orthoamphibole and pyroxene-group minerals. Sulfide-facies minerals are commonly troilite and varieties of FeS more iron-rich than troilite, pyrrhotite, arsenopyrite, and pyrite, as well as electrum. Pyrrhotite and troilite are more abundant than pyrite and arsenopyrite, but the latter minerals can be highly concentrated in certain parts of GDIF.

Mineral characteristics

Pyrrhotite and troilite in non-metamorphosed, bed-controlled ore are fine-grained to very fine-grained.

Metamorphism of GDIF increases grain size to medium grained. Arsenopyrite and pyrite in non-metamorphosed, bed-controlled ore are coarser (medium-grained) than pyrrhotite and troilite. Metamorphism of pyrite and arsenopyrite does not increase their grain size. Electrum in bed-controlled ore may form very fine-grained inclusions in either pyrrhotite or arsenopyrite. Elemental gold and silver are also present in solid substitution for iron in arsenopyrite. Quartz-vein-controlled sulfide minerals are notably coarser grained than those in bed-controlled ore. Arsenopyrite and pyrrhotite in vein-controlled ore are commonly coarse-grained. Electrum in vein-controlled ore may be visible to fine-grained.

Secondary mineralogy

Surface weathering of all minerals is highly dependent on local climate. Weathering of siderite, ankerite, and calcite typically produces pits filled with iron oxide minerals. Weathering of pyrrhotite and arsenopyrite typically results in tarnished grains that are partially replaced by pyrite. Carbonate minerals in GDIF are highly capable of buffering oxidation reactions due to surface weathering.

Topography, physiography

Deposits are in desert, steppe, temperate forest, tundra, and tropical forest areas. Carbonate-rich rocks weather differently in each terrane, from prominent ridges in deserts to topographically low areas in tropical environments.

Hydrology

Water flow through metamorphic rocks is typically controlled by shear zones and fractures. Porosity of all host rocks is very low to nonexistent. Hydrologic flow models probably are not relevant for GDIF. Most existing deposits are exploited in underground mines that have complex dewatering systems and sophisticated water treatment plants.

Mining and milling methods

Open-pit mining is minor. Most deposits are exploited by underground mining involving block-caving, vertical crater retreat, small width stoping, or a combination of these techniques. Milling commonly involves gravity concentration and carbon-in-pulp extraction. Various specific metallurgical techniques are applied to specific ore types.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Very few or no GDIF in the United States are contained in drainage basins that have only iron-formation-type deposits. Homestake, S. Dak., is surrounded by Tertiary, epithermal vein and replacement deposits that contribute metals to the drainage basin of Whitewood Creek. Jardine, Mont., is in an area covered by extensive Tertiary volcanic rocks; contributions from minor vein deposits in the Bear Creek drainage at Jardine may obscure the geochemical signatures attributable to Jardine. Metal contributions from the Yellowstone area hot springs above Jardine probably also overprint drainage signatures from the GDIF below Jardine.

Deposits in the Northwest Territories, Canada, are probably the best candidates for accurate definition of drainage signatures associated with GDIF, but topography, and therefore drainage net development, is negligible near Lupine and surrounding deposits. Soil geochemistry surrounding these deposits might accurately reflect pre-mining conditions, as the deposits were discovered in the early 1960s.

Metal mobility from solid mine wastes

Most mine waste is used for fill in underground mines. Open-pit dumps typically contain shale and graywacke that pose no environmental problems. Tailings of operating mines are contained within ponds that comply with federal, state, and local environmental regulations. Because ore contains no base metals and extraction of sulfide minerals during ore processing is extremely efficient, modern tailings contain virtually no metals that might pose environmental problems. Depending on the type of ore processing technique used, tailings may or may not contain sodium cyanide in dilute concentrations. Gold is routinely extracted from these solutions during the life of the tailings pond. Monitoring equipment is installed to ensure no adverse environmental effects.

Soil, sediment signatures prior to mining

Soil is probably enriched in iron, gold, and carbon dioxide; soil may be enriched in arsenic. No data applicable to definition of pre-mining soil geochemistry are available for deposits in the United States. Deposits in the Northwest Territories, Canada, are probably the best candidates for accurate definition of pre-mining soil geochemistry in an

Arctic environment, as these deposits were not discovered until the 1960s. Similarly, newly discovered deposits in the Amazon region of Brazil could be utilized to define pre-mining conditions in a tropical environment.

Potential environmental concerns associated with mineral processing

Currently operating mines comply with federal, state, and local environmental regulations. Details of some mineral processing techniques are confidential; state regulatory boards may have information on patented techniques.

Smelter signatures

No currently operating mines use smelters to process ore. Historic smelters may or may not have been numerous in different districts, depending on the number of individual mines. Smelters undoubtedly serviced many types of ore deposits, not only those from GDIF. Soil contamination from any one or group of smelters is not directly attributable to any one GDIF deposit.

Climate effects on environmental signatures

Deposits are found in climates ranging from tropical to tundra. The effects of various climatic regimes on the geoenvironmental signature specific to stratabound gold deposits are not known. Although deposits in areas of higher precipitation have enhanced potential for associated acid mine drainage, the low base-metal sulfide content of these deposits inhibits the development of significantly metal-enriched water.

Geoenvironmental geophysics

Detailed magnetic and electromagnetic surveys can delineate fluid migration paths along geologic contacts, faults, and fractures (Paterson, 1995) but application of these techniques in crystalline rocks can be difficult. Electrical and electromagnetic surveys can be used to trace and monitor acidic, metal-enriched ground water plumes (Ebraheem and others, 1990; McNeill, 1990) in horizontally stratified rocks, but with difficulty in crystalline terranes. Hot spots in tailings piles that result from ongoing redox reactions can be located using self potential methods. Induced polarization surveys can be used to discriminate between environmentally benign electrical conductors, such as clay bodies, and metal-enriched ground water (Paterson, 1995).

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