

FE SKARN DEPOSITS (MODEL 18d; Cox, 1986)

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SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

See general comments in the section entitled "Deposit Characterization" of the CU, AU, ZN-PB Skarn Deposits model (Hammarstrom and others, this volume).

Deposit geology

These deposits principally consist of magnetite in calc-silicate contact metasomatic rocks. Calcic magnetite skarns form in island-arc settings associated with relatively mafic (diorite) intrusions. Magnesian magnetite skarns form in orogenic belts along continental margins and are associated with felsic plutons in dolomitic host rocks as transitional zones, or in districts that contain copper-rich or tungsten skarn deposits. Most scapolite-(albite) iron skarn deposits are localized in basinal volcanic-sedimentary strata and are genetically related to late-stage phases of gabbroic and dioritic magmas.

Examples

Calcic iron skarn: Daquiri, Cuba; Empire, Vancouver Island, Canada; Shinyama, Japan.
Magnesian iron skarn: Fierro-Hanover, N. Mex.; Cornwall, Pa.; Eagle Mountain, Calif.
Scapolite-(albite) iron skarn: Kachar and Sarbay, U.S.S.R.; West Humboldt, Nev.

Worldwide, some of the largest iron skarn deposits are of the scapolite-(albite) variety (Zitzmann, 1977; Sokolov and Grigorev, 1977; Einaudi and others, 1981). In the classification scheme of Einaudi and others (1981), these deposits are categorized as the calcic-iron part of the twofold calcium-magnesium scheme. However, because of notable differences between scapolite-(albite) iron skarns and calcic and magnesian iron skarns we herein describe the scapolite-(albite) iron skarns separately, somewhat along the lines adopted by Zitzmann (1977). These differences include (1) the presence of widespread albite-(scapolite) assemblages in addition to garnet-pyroxene, (2) common development of endoskarn in contrast to calcic exoskarn, (3) extremely large tonnages, and (4) development in basinal volcanogenic strata as opposed to platform sequences consisting of thick miogeoclinal micrites.

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include base and precious metal skarns (Models 18b and c), tungsten skarns (Model 14a), porphyry copper deposits (Model 17). Magnetite-rich ore is mined as a by-product at a number of deposits. Examples include some of the Malaysian tin skarns, calcic zinc skarns in New Mexico, copper skarns at OK Tedi, Papua, New Guinea and Craigmont, British Columbia (Ray and Webster, 1990).

Potential environmental considerations

Magnetite is the principal ore mineral in iron skarns. Ore grades are typically 40 to 50 weight percent iron but these deposits have relatively low sulfide mineral contents and therefore relatively low acid-generating potential. In addition to the acid-buffering potential afforded by the common presence of carbonate-bearing strata, epidote (propylitic alteration of host rocks) also consumes acid. Magnetite is generally stable in the surface environment and persists as a heavy mineral in stream sediment during mechanical erosion. Furthermore, metals, including mercury, selenium, cadmium, and arsenic, that pose the most significant threats to the environment when they become bioavailable are not associated with most magnetite skarns. However, some scapolite-(albite) iron skarn in the West Humboldt, Nev., deposits contain as much as 15 ppm cadmium.

Exploration geophysics

Strong magnetic anomalies may be associated with these deposits; these anomalies become attenuated with increasing depth of burial or if magnetite has been converted to hematite. Airborne magnetic surveys have been used to identify large scapolite-(albite) iron skarn deposits in the U.S.S.R. In extremely weathered terranes, exposures of limonite, iron hydroxide, iron sulfate gossan, clay, or carbonate rock associated with these deposits may be identified by Landsat Thematic Mapper reflectance imagery. Very low frequency electromagnetic and induced polarization surveys may be used to identify magnetite and associated disseminated sulfide bodies. Resistivity surveys can be used to

model the distribution of alteration zones as indicated by ion content of water saturated rocks. Because of density contrasts between alteration mineral assemblages and deposit host rocks, microgravity surveys may be used to delineate the distribution of skarn deposits.

References

Einaudi and others (1981), Zitzmann (1977), and Cox (1986).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Mosier and Menzie (1986) present a deposit size range for iron skarns, undivided, expressed as percentiles of tonnages (in millions of metric tons) for a population of N deposits, whereas Einaudi and others (1981) present sizes for two iron skarn subtypes:

iron skarns, undivided (N=168):	0.33 (90th percentile)	7.2 (50th percentile)	160 (10th percentile)
Calcic iron skarn:	5 to 200 million t.		
Magnesian iron skarn:	5 to 100 million t. Largest known deposit (234 million t) is Sherogesh, USSR.		
Scapolite-(albite) iron skarn:	1 to 6,200 million t.		

The 50th percentile value is the median deposit size for the population.

Scapolite-(albite)-magnetite iron skarns at Sarbay (Sarbai), in the Turgai Iron Province or mining district, U.S.S.R. (Sokolov and Grigorev, 1977), are among the largest iron skarns known: a geologic resource of approximately 2,894 million tonnes (t) of ore at a grade of about 43 weight percent iron was present prior to the onset of mining (D.L. Mosier, written commun., 1995). In addition, the nearby South Sarbay deposit contained 282 million t at 44 weight percent iron (Zitzmann, 1977). However, the scapolite-(albite)-magnetite iron skarn at Kachar, U.S.S.R., is even larger than those at Sarbay, and includes approximately 6,200 million t as a geologic resource to depths of 2.5 km at average grades of about 39 weight percent iron (Zitzmann, 1977).

The scapolite-(albite)-magnetite skarns at West Humboldt, Nev., are significantly smaller than those at Sarbay and Kachar: the largest deposits at West Humboldt are approximately 18 million t at about 47 weight percent iron (Reeves and Kral, 1955; Lowe and others, 1985).

Host rocks

Calcic iron skarn: Host rocks include limestone, sandstone, volcanic rocks, graywacke, dolomite at contacts of dioritic intrusions, within diorite, or at contacts of carbonate-bearing rocks with diabase flows.

Magnesian iron skarn: Host rocks are typically dolomite, or limestone, quartzite, and schist associated with dolomitic rocks.

Scapolite-(albite) iron skarn: Host rocks are andesite, tuff, limestone, argillite; endoskarn forms in gabbroic to dioritic intrusions.

Surrounding geologic terrane

Surrounding geologic terrane consists of batholiths, stocks, or plutons that intrude sedimentary sequences; scapolite-(albite)-magnetite iron skarns are present in volcanic-sedimentary basins.

Wall-rock alteration

Wall-rock alteration associated with calcic iron skarns involves extensive endoskarn development, which is characterized by albite, orthoclase, epidote, quartz, and scapolite, in plutons and volcanic rocks. Endoskarn associated with magnesian iron skarns is minor; propylitic alteration assemblages are characteristic.

Nature of ore

Ore consists of massive magnetite layers or lenses; orebodies are spatially associated with garnet zones or form in limestone beyond calc-silicate skarn zones. Calcic magnetite skarns and scapolite-(albite) iron skarns may be present within diorite stocks as replacements of gabbro and diorite or of limestone xenoliths (Einaudi and others, 1981). Stockwork veins may also be present in mafic volcanic rocks overlying altered gabbro. Orebodies may be lenticular, lensoid, tabular, contact-controlled deposits extending hundreds of meters to 4 km or more along strike and having thicknesses of tens to hundreds of meters, as well as irregular and pipelike, replacement of mafic intrusions and stockworks. Ore may be nearly monomineralic veins, pods, layers, or lenses of magnetite or may consist of magnetite-rich laminae or layers alternating with, or intergrown with gangue minerals. Ore mineral associations in

Table 1. Geochemical data for rock samples from the Hancock magnetite skarn, McCoy district, Lander County, Nev.

[Analyses by inductively coupled plasma and atomic absorption spectrophotometry; D. Fey, analyst. Oxides, in weight percent; trace elements, in ppm (Au, in ppb). N.d., not determined; FeTO3, total iron reported as FeO₃]

Sample	1	2	3	4	5
TiO ₂	.20	.03	.12	.17	.17
Al ₂ O ₃	3.59	.36	1.13	3.02	1.08
FeTO ₃	93.0	102	41.6	47.2	5.01
MgO	5.64	1.82	2.65	6.14	14.9
CaO	.06	.04	28.0	15.5	12.0
Na ₂ O	.04	.03	.03	.19	1.05
K ₂ O	.77	<.06	.51	1.69	.20
P ₂ O ₅	<.01	<.01	<.01	<.01	.02
As	<10	<10	<10	<10	<10
Au	<50	<50	<50	<50	<50
Ba	270	21	81	320	49
Be	<1	<1	<1	<1	2.00
Cd	<2	<2	<2	<2	<2
Ce	<4	<4	38	19	30
Co	51	31	120	31	15
Cr	7	39	23	12	7
Cu	17	25	260	5	9
Ga	15	8	10	6	<4
La	<2	<2	36	18	20
Li	9	<2	5	15	16
Mn	930	736	646	375	504
Mo	<2	<2	<2	<2	<2
Nb	N.d.	N.d.	N.d.	N.d.	N.d.
Nd	<4	<4	10	5	13
Ni	51	<2	18	<2	120
Pb	28	6	9	7	33
Sc	4	<2	<2	<2	<2
Sn	<10	<10	<10	<10	<10
Sr	11	16	130	39	39
Th	8	9	<4	5	<4
V	300	280	370	88	100
Y	<1	<1	<1	<1	<1
Zn	120	20	16	8	13

1. Sample 85JH189- massive magnetite ore.
2. Sample 85JH190- massive magnetite ore.
3. Sample 85JH193- sulfide-mineral-rich magnetite ore.
4. Sample 85JH195- layered magnetite-tremolite-carbonate skarn.
5. Sample 85JH199- tremolite-magnetite skarn.

the Cornwall, Pa., skarn include magnetite-chalcopyrite-pyrite, magnetite-pyrite-actinolite, magnetite-chlorite, magnetite-hematite-calcite, and magnetite alone. Magnetite varies from anhedral and granular to euhedral and forms platy pseudomorphs after hematite (Lapham, 1968).

Deposit trace element geochemistry

Calcic iron skarn: iron, copper, cobalt, gold, and nickel.

Magnesian iron skarn: iron, copper, zinc.

Scapolite-(albite) iron skarn: iron, copper, zinc, lead, and arsenic, as well as trace amounts of cadmium.

See tables 1-3 for geochemical analyses of magnetite skarn ore and associated rocks. Table 1 presents previously unpublished data for magnesian magnetite skarn in dolomite adjacent to the Jurassic diorite stock at McCoy, Nev. (Stager, 1977). This skarn is older than the nearby copper-gold skarn deposit, which is associated with

Table 2. Geochemical data for rock samples from magnesian iron skarns, western Montana. [Analyses by inductively coupled plasma and atomic absorption spectrophotometry; B. Adrian, analyst. Oxides in weight percent; trace elements in ppm. FeTO₃, total iron reported as Fe₂O₃].

Sample	1	2	3
TiO ₂	<.01	.02	.23
Al ₂ O ₃	.62	.40	.60
FeTO ₃	44.2	38.8	33.9
MgO	3.76	9.69	11.4
CaO	1.16	.07	.63
Na ₂ O	.01	.01	.01
K ₂ O	<.06	<.06	<.06
P ₂ O ₅	<.01	.02	.21
As	<10	<10	<10
Au	<.05	<.05	<.05
Ba	5	2	2
Be	<1	<1	<1
Cd	<2	<2	<2
Ce	<4	<4	<4
Co	26	36	58
Cr	<1	2	7
Cu	4	2	3
Ga	10	10	6
La	<2	<2	<2
Li	2	3	3
Mn	988	1,640	1,821
Mo	<2	<2	<2
Nb	<4	5	11
Sn	<10	40	40
Sr	4	<2	<2
Th	4	4	7
Nd	<4	<4	<4
Ni	<2	11	6
Pb	<4	<4	<4
Sc	<2	<2	<2
V	13	35	17
W	2	5	2
Y	<2	<2	<2
Yb	<1	<1	<1
Zn	38	103	97

1. Pomeroy Mine, Southern Cross district, South Flint Creek Range, Mont., sample 89MT152 - massive magnetite.

2. Jumbo Mine, Beaverhead County, Mont., sample 89MT059 - magnetite ore.

3. Jumbo Mine, Beaverhead County, Mont., sample 89MT061-apatite-rich magnetite ore.

a 39-38 Ma granodiorite stock, currently being mined in the McCoy district. Minor amounts of pyrite and chalcopyrite are present in the magnetite skarn. Table 2 presents three previously unpublished analyses of magnetite

Table 3. Summary statistics for iron skarn analyses.

[Data from tables 1, 2, and Hammarstrom and Gray (1993, tables 2 and 3); N, number of analyses used to calculate means; qualified values were omitted from calculations. Oxides (in weight percent); trace elements in ppm (Au, in ppb)]

	N	Minimum	Maximum	Mean
TiO ₂	18	<.01	.78	.18
Al ₂ O ₃	19	0	17	5
FeTO ₃	19	3	102	44
MgO	19	0	15	4
CaO	19	0	28	8
Na ₂ O	18	<0.01	6	1
K ₂ O	14	<0.02	6	1
P ₂ O ₅	12	<0.01	.23	.10
As	2	<10	50	40
Au	9	<2	750	181
Ba	19	2	2,700	316
Be	2	<1	3	3
Cd	4	<2	6	5
Ce	7	<4	76	44
Co	19	6	120	44
Cr	14	<1	210	32
Cu	18	<2	2,100	432
Ga	16	6	28	15
La	7	<2	51	32
Li	15	<2	29	10
Mn	19	375	6,199	1,466
Mo	7	<2	22	10
Nb	3	<4	24	13
Nd	7	<4	46	21
Ni	15	<2	170	35
Pb	9	<4	40	17
Sc	10	<2	33	11
Sn	2	<10	40	40
Sr	16	<2	750	170
Th	7	<4	20	8
V	19	10	610	139
W	3	2	5	3
Y	5	<2	38	14
Yb	3	<1	4	3
Zn	19	8	310	94

skarn ore from two different deposits in western Montana--the Pomeroy Mine, a magnesian magnetite skarn along a contact between Upper Cambrian Pilgrim Dolomite and the Cretaceous Uphill Creek Granodiorite pluton of the Pioneer batholith. This pluton is associated with tungsten and copper-silver-gold skarns, including deposits of the Rock Creek district (see also, SN and (or) W skarn and replacement deposits model, Hammarstrom and others, this volume), that formed along contacts with limestone (Geach, 1972; Pearson and others, 1988). Ranges of iron skarn compositions from tables 1 and 2, for magnetite skarns in roof pendants of Mississippian Madison Limestone in the Sliderock Mountain area, Sweet Grass County, Mont., and data for iron-copper skarns in Cambrian Meagher Limestone along a granodiorite sill in the Independence mining district, Park County, Mont. (Hammarstrom and Gray, 1993), are summarized in table 3. These data represent nineteen samples from six different deposits, including magnesian as well as calcic skarn. No systematic differences in trace element content are apparent in the data set for dolomite- versus limestone-hosted skarn, so the data sets were combined. Table 4 summarizes previously unpublished data for the West Humboldt, Nev., scapolite-(albite) iron skarn deposits.

Table 4. Summary statistics for scapolite-(albite) iron skarn analyses for West Humboldt, Nev. [Data from G.B. Sidder, M.L. Zientek, and R.A. Zierenberg (written commun., 1995). Analyses by DC arc emission spectrography except for As, Bi, Cd, Sb, and Zn by inductively coupled plasma atomic emission spectrometry]

Sample type	Iron ore	Altered igneous wall rock
No. analyses ¹	17 (12)	29 (10)
Major elements, in weight percent ²		
Ca	.1-10 (1)	1-10 (3)
Fe	5->20 (>20)	3-15 (5)
Mg	.3-3 (1)	.7-3 (3)
Na	<.2-5 (<.2)	1.5-5 (3)
P	<.2	<.2
Ti	.07-.5 (.2)	.15-1 (1)
Trace elements, in ppm		
Ag	<.5-5 (<.5)	<.5-1.5 (<.5)
As	<5	<5
B	<10-30 (<10)	<10-200 (30)
Ba	<20-2,000 (50)	<20-300 (300)
Be	<1	<1-1.5 (<1)
Bi	<2-5 (<2)	<2
Cd	2.1-14 (12)	.6-7.3 (1.2)
Co	15-100 (30)	<10-200 (20)
Cr	<10-100 (10)	30-300 (150)
Cu	<5-30 (7)	<5-300 (10)
Ga	30-50 (30)	30-50 (30)
Mn	50-700 (150)	150-700 (500)
Mo	<5	<5
Nb	<20	<20
Ni	70-200 (150)	15-100 (50)
Pb	<10-30 (<10)	<10-20 (10)
Sb	<2-350 (<2)	<2-7 (<2)
Sc	<10-20 (<10)	10-30 (20)
Sn	<10	<10
Sr	<100-1,000 (<100)	<100-700 (500)
V	150-700 (300)	30-700 (150)
W	<20	<20
Y	15-70 (20)	15-50 (30)
Zn	8-37 (13)	<2-25 (8)
Zr	<10-100 (10)	30-150 (100)

¹Total number of analyses (number of analyses for As, Bi, Cd, Sb, and Zn).

²Range and (median) values.

Ore and gangue mineralogy and zonation

Calcic iron skarn:	Prograde- Garnet (grossular-andradite), pyroxene (ferrosalite). Retrograde- Amphibole, chlorite, epidote. Ore- Magnetite, chalcopyrite, cobaltite, pyrrhotite.
Magnesian iron skarn:	Prograde- Forsterite, calcite, spinel, diopside, magnetite, apatite, ludwigite-group minerals. Retrograde- Amphibole, humite, serpentine, phlogopite, talc, chlorite, chondrodite, magnesite, clinohumite. Ore- Magnetite, pyrite, chalcopyrite, sphalerite, pyrrhotite, arsenopyrite.
Scapolite-(albite) iron skarn:	Prograde- Garnet, pyroxene. Retrograde- Scapolite, albite, chlorite, calcite, zeolites, actinolite, epidote, apatite, quartz, prehnite, and sphene. Ore- Magnetite, hematite, pyrite, marcasite, chalcopyrite, sphalerite, pyrrhotite, and arsenopyrite.

Mineral characteristics

Magnetite typically forms massive layers or lenses. Sulfide mineral contents of magnetite skarns are generally low, but can be quite variable. Reported magnetite-pyrite ratios range from 100:1 to 3:1 for the Larap deposit in the Philippines; Larap is somewhat atypical of iron skarns because it contains economic concentrations of Cu, Mo, Au, Ag, Co, and Ni as well as Fe (Einaudi and others, 1981). At the Cornwall, Pa., magnetite mines, sulfide minerals were separated from magnetite; copper, gold, and silver were recovered from chalcopyrite and cobalt was recovered from pyrite.

Secondary mineralogy

Magnetite may alter to hematite, maghemite, goethite, limonite, or lepidocrocite during oxidation and weathering.

Topography, physiography

Iron skarns have little or no surface expression; however, in most cases, this depends on their resistance to weathering relative to adjacent rocks and on climatic setting.

Hydrology

These deposits have no known control on the local hydrologic regime.

Mining and milling methods

Most of these deposits have been exploited by open-pit methods; run-of-mine ore is fed directly to variable types of crushers and then sized through vibrating screens to mesh fractions appropriate for shipping. Comminuted ore is shipped as a concentrate and may be agglomerated by pelletizing or sintering prior to further processing (Ripley and others, 1995).

ENVIRONMENTAL SIGNATURES

Drainage signatures

No data are available for iron skarn deposits. However, chemical analyses of water from iron ore mines and milling operations in Canada (Ripley and others, 1995) are probably reasonable indicators of mine water discharge characteristics applicable to iron skarn deposits because Canadian iron ore has a low sulfide-mineral content and is dominated by magnetite, hematite, and siderite. This mine water and direct-discharge tailings effluent have pH of 6.4 to 9 and relatively low dissolved metal contents, including 0.01 to 0.4 mg/l copper, 0.05 to 1.3 mg/l iron, <1 mg/l lead, and 0.01 to 0.15 mg/l zinc. Much higher dissolved metal concentrations, including >40 mg/l copper and >6,000 mg/l iron, were reported for marine-discharge tailings effluent. Suspended solids may contribute to stream turbidity. Although iron is an essential nutrient for plants and animals, extreme iron concentrations downstream from historic, large-scale iron ore operations can be harmful to salmon and benthic organisms. However, residual materials from iron ore mining are generally considered to have minor toxicity.

Metal mobility from solid mine wastes

Typical final tailings associated with calcic iron skarn ore at Cornwall, Pa., which contains 40 to 42 percent iron, contain 7.7 weight percent iron, 0.61 weight percent sulfur, and 0.04 weight percent copper (Lapham, 1968). This iron concentration is similar to that, 7 to 9 weight percent, characteristic of typical iron ore tailings reported by Andrews (1975). Weathering of these tailings yields insoluble iron hydroxides.

Soil, sediment signatures prior to mining

Magnetite is commonly recovered as a heavy mineral in stream-sediment surveys. In industrialized areas in the Central Pyrenees Mountains, magnetite spheres were recovered in panned stream-sediment concentrates, and they have been interpreted as anthropogenic contaminants resulting from ash emission from an electric plant (Soler, 1991). In soil, magnetite is usually considered to be lithogenic rather than pedogenic although a number of studies suggest that magnetite may precipitate as a consequence of bacterial activity (Schwertmann, 1988).

Soil: The rate of iron oxide dissolution in soil is a function of mineralogy, particle size, and degree of crystallinity; in general, the reactivity of the iron oxide minerals in soil decreases as follows: ferrihydrate > lepidocrocite > magnetite > akageneite > hematite > goethite (Loeppert, 1988).

Potential environmental concerns associated with mineral processing

The relatively low sulfide mineral content of iron skarn deposits suggests that these deposits have relatively low acid-generating potential. Carbonate mineral-bearing strata that frequently host these deposits can buffer most of the acid generated by these deposits. Elevated abundances of metals that pose the most significant threats to the environment are not associated with most magnetite skarn deposits.

Smelter signatures

Iron ore is converted to iron by reduction to pig iron in blast furnaces or by direct reduction. The major impurities in iron ore result in relatively inert acidic (silica, alumina) or basic (lime, magnesia) slag during smelting.

Climate effects on environmental signatures

The effects of various climatic regimes on the geoenvironmental signature specific to iron skarn deposits are not known. Because these deposits have relatively low sulfide mineral contents and because many are hosted by carbonate mineral-bearing strata that have abundant acid consumption potential, environmental signatures associated with iron skarn deposits are probably not much affected by climatic regime variation. The major effect of climate is probably the potential for physical disruption of tailings impoundments by flooding or wind.

Geoenvironmental geophysics

Low spectral resolution reflectance imagery can be used to delineate the distribution of limonite, iron hydroxide, and iron sulfate gossan mineral assemblages in soil and water associated with iron skarn deposits. Similarly, magnetic surveys can be used to define the distribution of magnetite and pyrrhotite. Sulfide- mineral-rich bodies, whose oxidation may generate acid, metal-charged water, may be located using electromagnetic, induced polarization, and self potential surveys. Zones of leached rock altered to clay, mica, epidote, chlorite, and pyroxene may be delineated by resistivity surveys and using Landsat thematic mapper imagery and imaging spectrometer data. Remote sensing may be used to identify acid buffering carbonate rocks and stressed vegetation indicative of contaminated soil.

PERSPECTIVE

See section entitled "Perspective" in the CU, AU, ZN-PB skarn deposits model (Hammarstrom and others, this volume).

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