

CU, AU, AND ZN-PB SKARN DEPOSITS
(MODELS 18b,c; Cox and Theodore, 1986; Cox, 1986; Theodore and others, 1991)

by Jane M. Hammarstrom, Boris B. Kotlyar, Ted G. Theodore, James E. Elliott, David A. John,
Jeff L. Doebrich, J. Thomas Nash, Robert R. Carlson, Gregory K. Lee, K. Eric Livo, and Douglas P. Klein

INTRODUCTION

The general description of skarns given below is also applicable to the SN and (or) W skarn and replacement deposits and Fe skarn deposits geoenvironmental models.

Skarns are coarse-grained metamorphic rocks composed of calcium-iron-magnesium-manganese-aluminum silicate minerals (commonly referred to as "calcsilicate" minerals) that form by replacement of carbonate-bearing rocks (in most cases) during contact or regional metamorphism and metasomatism. The majority of the world's major skarn deposits are thought to be related to hydrothermal systems (Einaudi and others, 1981). Skarns can be barren or contain metals with economic value. Skarn deposits are important sources of base and precious metals as well as tin, tungsten, and iron. Skarns are relatively high-temperature mineral deposits related to magmatic-hydrothermal activity associated with granitoid plutons in orogenic tectonic settings; skarns generally form where a granitoid pluton has intruded sedimentary strata that include limestone or other carbonate-rich rocks. The processes that lead to formation of all types of skarn deposits include: (1) isochemical contact metamorphism during pluton emplacement, (2) prograde metasomatic skarn formation as the pluton cools and an ore fluid develops, and (3) retrograde alteration of earlier-formed mineral assemblages. Deposition of ore minerals accompanies stages 2 and 3. Skarn deposits are typically zoned mineralogically with respect to pluton contacts, original lithology of host rocks, and (or) fluid pathways. Later petrogenetic stages may partly or completely obliterate earlier stages of skarn development. Skarn deposits commonly are also associated with many other types of magmatic-hydrothermal deposits in mineral districts. In fact, distinction between skarn and other deposit types is not always apparent, and in many districts, skarns form an intermediate "zone" between porphyry deposits in the center of mining districts and peripheral zones of polymetallic vein and replacement and distal disseminated deposits. In many cases, geochemical signatures in stream sediment or water may reflect mixtures of several deposit types.

Skarns are classified as calcic if the protolith was limestone and as magnesian if the protolith was dolomite; they are also classified by the most economically important metal present (copper, iron, lead-zinc, gold, tin, tungsten, etc.). Each class of skarn deposit has a characteristic, though not necessarily unique, size, grade, tectonic setting, granitoid association, and mineralogy (Einaudi and Burt, 1982; Einaudi and others, 1981; Meinert, 1983). Not surprisingly, therefore, the various classes of skarn deposits have different geochemical signatures and oxidation-sulfidation states. Most economic skarn ore is present as exoskarn, which forms in carbonate rock that hosts a mineralizing intrusion. Endoskarn, which is variably developed on the intrusion side of intrusion-wallrock contacts, can be important when fluid flow was directed into the intrusion or channelized along the intrusion-wall rock contact.

Separate geoenvironmental models for three groups of skarn deposits are presented below: (1) base and precious metal, (2) tin and tungsten, and (3) iron skarns. These groupings are based on geologic setting, associated igneous rock compositions, skarn mineralogy and sulfide mineral content, and characteristic geochemical and geophysical signatures (fig. 1). Differences among these groups of deposits indicate different potentials for acid mine drainage and differences in geoavailability of potentially toxic substances. For example, the principal ore minerals in base and precious metal skarns are sulfide minerals, whereas the principal tin and tungsten ore minerals are the oxide and tungstate minerals cassiterite and scheelite, respectively. Data tables illustrate observed ranges of composition for skarn, stream-sediment, soil, water, and mine waste. Much of these data reflect the authors' unpublished and published work in north-central Nevada and in southwestern Montana. Both areas contain examples of skarn deposits from each model group. No new data were acquired for this model development effort, but some previously unpublished geochemical data are included. These models are preliminary compilations based on existing data from a variety of sources.

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

These deposits consist of base- and precious-metal minerals in calcsilicate rocks. Copper skarn generally consists of chalcopyrite in contact metasomatic rocks. Zinc-lead skarns are composed of sphalerite and galena in calc-silicate rocks that may represent contact metasomatism by nearby granitoid intrusions or they may form hundreds of meters from intrusions inferred to be sources of metasomatizing fluids. Gold-bearing skarns are generally calcic exoskarns

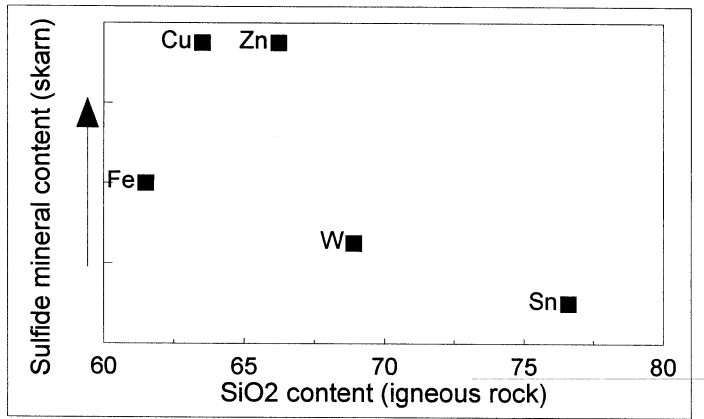


Figure 1. Schematic diagram showing relative positions of different classes of skarns as a function of associated igneous rock composition and skarn sulfide mineral content. Mean silica content, in weight percent, for igneous rocks from Meinert (1983).

that contain average ore grades greater than 1 gram of gold per tonne and are usually associated with intense retrograde alteration. Gold-bearing skarns may contain significant amounts of numerous other commodities, including copper, lead, zinc, and iron and (or) they may have been mined in the past for these or other metals.

Examples

Copper skarns: Carr Fork, Utah; Meme, Haiti; Cananea, Sonora, Mexico.

Gold-bearing skarns: Fortitude, Nev.; McCoy, Nev.; Nickel Plate-Hedley, British Columbia, Canada; Red Dome, Australia.

Zinc-lead skarns: Groundhog, N.Mex.; Bismark, Chihuahua, Mexico.

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include porphyry copper (Model 17), iron skarn (Model 18d), polymetallic vein (Model 22c) and replacement (Model 19a), placer gold deposits (Model 39a), and distal disseminated silver-gold (Model 19c; Cox, 1992).

Potential environmental considerations

Surface and ground water associated with sulfide-mineral-rich tailings and waste piles or ponds may develop elevated concentrations of dissolved iron, aluminum, lead, copper, and zinc, especially if snowmelt and rain pond in tailings areas. At some inactive and abandoned historic mine workings where tailings are dispersed into streams, aquatic and plant communities may be impacted for as much as tens of km downstream by acidic conditions and (or) elevated metal concentrations. Sulfide mineral contents for these skarns are highly variable, and sulfide minerals may represent as much as 50 to 70 volume percent in parts of some deposits.

Exploration geophysics

Local magnetic highs may indicate skarn deposits with significant abundances of pyrrhotite and (or) magnetite. Precious metal skarns that contain abundant pyrite and quartz may lack this distinctive magnetic signature. In extremely weathered terranes, exposures of limonite, iron hydroxide, iron sulfate gossan, clay, or carbonate rock associated with these deposits may be identified by analyzing spectral features on 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 concentrations 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

Geology: Einaudi and others (1981), Cox (1986), Cox and Theodore (1986), and Theodore and others (1991).
Environmental signature: Ficklin and others (1992), Smith and others (1994), Apte and others (1995), and Salomons (1995).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Mosier (1986), Cox and Theodore (1986), Jones and Menzie (1986), and Theodore and others (1991) present deposit size ranges, expressed as percentiles of tonnages (million metric tonnes) for populations of N deposits:

| | | | |
|----------------------|--------------------------|------------------------|-----------------------|
| Cu skarns (N=64): | 0.03 (90th percentile) | 0.56 (50th percentile) | 9.2 (10th percentile) |
| Au skarns (N= 90): | 0.0013 (90th percentile) | 0.28 (50th percentile) | 9.8 (10th percentile) |
| Zn-Pb skarns (N=34): | 0.16 (90th percentile) | 1.40 (50th percentile) | 12 (10th percentile) |

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

Host rocks

These deposits are in carbonate rocks, including limestone or marble, dolomite, and calcareous and dolomitic marble, pelite, argillite, shale, graywacke, and other clastic rocks. In terms of the bedrock type classification of Glass and others (1982), most host rocks for these deposit types are type IV; they are highly calcareous sedimentary rocks or metamorphosed calcareous sedimentary rocks that have extensive buffering capacity. Less common host rocks include chert, volcanic flows (dacite, andesite, or basalt) and volcanoclastic rocks, and metamorphic rocks such as slate or phyllite, quartzite, and amphibolite. These less common host rocks provide low to medium buffering capacity. At the Beal Mountain, Mont., gold deposit, gold-bearing rock is entirely in calcsilicate-bearing hornfels in clastic, quartz-rich host rocks. This deposit is atypical of skarns and may represent a distinct, but related type of disseminated gold deposit in contact metamorphosed rocks (Hastings and Harrold, 1988; Meinert, 1989).

Surrounding geologic terrane

These deposits are typically associated with contact zones around batholiths or plutons, including some relatively isolated small bodies, that intrude sedimentary strata. Zn-Pb skarns may lack spatial associations with intrusions.

Wall-rock alteration

Wall rock is altered to hornfels (quite widespread in places, and present throughout areas as large as 15 to 20 km²), marble, bleached limestone, and skarn zones; potassic, sericitic, argillic, propylitic alteration assemblages are developed and plutons may contain endoskarn. Silica and marble "fronts" (sharp boundaries between unreplaced rock and altered rock) may be present.

Nature of ore

Ore minerals may be present in massive, stratiform, vein, and (or) disseminated form; grain size is highly variable and ranges from fine to very coarse. Ore may be present in sulfide mineral zones, oxide zones, and in supergene, clay-rich oxidized zones. Sulfide minerals and gold generally are deposited during late, retrograde alteration within zones characterized by hydrous calcsilicates. Retrograde alteration may be best developed along faults cutting paragenetically earlier assemblages. Gold is commonly associated with a late pyrite + quartz assemblage (veins or disseminated). Note that many of these skarns contain zones that have been or could be mined for magnetite (see Fe skarn model, Hammarstrom and others, this volume). Total sulfide mineral content at the McCoy, Nev., gold skarn is low (<2 volume percent) and many sulfide minerals are oxidized. In contrast, at the Fortitude, Nev., gold skarn about 30 km to the north, high grade ore is sulfide mineral rich, and includes mostly pyrrhotite as well as lesser amounts of chalcopyrite, pyrite, arsenopyrite, and native bismuth.

Deposit trace element geochemistry

Cu skarns: Cu, Au, Ag in proximal zones; Pb, Zn, and Ag in distal zones; Co, As, Sb, Bi, and Mo anomalies in some deposits; calcic exoskarns are generally high in iron and sulfur; low in aluminum and manganese.

Au skarns: Au, Ag, Cu, As, Pb, and Zn; as well as Bi, Co, Sb, Te, Se, and Cd for some deposits.

Zn-Pb skarns: Zn, Pb, Mn, Cu, Co, Au, Ag, As, W, Sn, F, possibly Be; exoskarn, high in iron, sulfur, and manganese and low in aluminum.

Additional trace element data, including that pertaining to the geometry of their halos and distribution, for mineralized skarns are presented by Beus and Grigorian (1977). These data confirm the widespread natural distribution of many metals in these types of skarns.

Summary statistics for trace elements associated with selected Cu-Au skarn deposits are presented in tables 1 to 3. Ranges and means for elements (As, Cd, Se, Pb, Cr, and Hg) that are potentially harmful to aquatic biota are highly variable among deposits of the same type, and within different parts of single deposits (table 1A-C).

Table 1A. Data summary for drill core samples, provided by Battle Mountain Gold Company, from Fortitude, Nev. gold skarn deposit; tabulated by J.L. Doebrich. [Samples from border zone immediately surrounding Lower Fortitude ore zone (hosted by Pennsylvanian and Permian Antler Peak Limestone; Au <0.02 oz/t; N, number of samples)]

| Element (unit) | N | Minimum | Maximum | Mean |
|----------------|-----|---------|---------|------|
| Si (%) | 185 | 5.5 | 36.8 | 15.8 |
| K (%) | 138 | .002 | 3.2 | .41 |
| Al (%) | 185 | .60 | 4.4 | 1.7 |
| Ca (%) | 185 | 1.1 | 48.2 | 17.5 |
| Mg (%) | 185 | .15 | 12.8 | 4.1 |
| Mn (%) | 104 | .007 | .88 | .14 |
| Ti (%) | 185 | .005 | .49 | .11 |
| S (%) | 185 | .002 | 30.4 | 3.6 |
| Fe (%) | 138 | .002 | 32.2 | 5.1 |
| Rb (ppm) | 96 | 1 | 241 | 24 |
| Sr (ppm) | 127 | 36 | 329 | 125 |
| Ba (ppm) | 138 | 3 | 3,830 | 272 |
| Se (ppm) | 128 | 1 | 124 | 11 |
| As (ppm) | 135 | 2 | 2,113 | 96 |
| Sb (ppm) | 114 | 1 | 47 | 11 |
| Bi (ppm) | 138 | 1 | 200 | 19 |
| Mo (ppm) | 101 | 1 | 68 | 5 |
| Cu (ppm) | 147 | 100 | 6,900 | 522 |
| Pb (ppm) | 26 | 3 | 7,300 | 138 |
| Zn (ppm) | 262 | 7 | 14,000 | 207 |
| Ag (oz/t) | 250 | .01 | 9.4 | .22 |
| Au (oz/t) | 210 | .001 | .02 | .006 |

Table 1B. Data summary for drill core samples, provided by Battle Mountain Gold Company, from Fortitude, Nev. gold skarn deposit; tabulated by J.L. Doebrich. [Samples from Lower Fortitude ore zone (hosted by Pennsylvanian and Permian Antler Peak Limestone; Au ≥0.02 oz/t; N, number of samples); --, not detected]

| Element (unit) | N | Minimum | Maximum | Mean |
|----------------|-----|---------|---------|-------|
| Si (%) | 208 | 6.0 | 27.1 | 15.7 |
| K (%) | 173 | .0003 | 4.3 | .23 |
| Al (%) | 208 | .7 | 14.3 | 1.8 |
| Ca (%) | 208 | .21 | 22.1 | 7 |
| Mg (%) | 208 | .29 | 13.0 | 2.9 |
| Mn (%) | 173 | .05 | .94 | .19 |
| Ti (%) | 208 | .0002 | .47 | .1 |
| S (%) | 208 | .13 | 32.5 | 9.1 |
| Fe (%) | 173 | .02 | 39.2 | 18.6 |
| Rb (ppm) | 173 | -- | 85 | 7 |
| Sr (ppm) | 173 | -- | 236 | 64 |
| Ba (ppm) | 173 | -- | 1,289 | 135 |
| Se (ppm) | 173 | -- | 169 | 15 |
| As (ppm) | 173 | 3 | 29,100 | 1,732 |
| Sb (ppm) | 173 | -- | 47 | 7 |
| Bi (ppm) | 173 | 7 | 1,730 | 114 |
| Mo (ppm) | 130 | -- | 19 | 4 |
| Cu (ppm) | 301 | -- | 12,800 | 1,334 |
| Pb (ppm) | 301 | 8 | 7,400 | 261 |
| Zn (ppm) | 301 | 5 | 14,800 | 361 |
| Ag (oz/t) | 301 | -- | 12.7 | 1.1 |
| Au (oz/t) | 301 | .02 | 5.2 | .36 |

Table 1C. Data summary for drill core samples, provided by Battle Mountain Gold Company, from Fortitude, Nev. gold skarn deposit; tabulated by J.L. Doebrich.

[Analyses from Upper Fortitude ore zone (hosted by Middle Pennsylvanian Battle Formation; Au <0.02 oz/t; N, number of samples)]

| Element (unit) | N | Minimum | Maximum | Mean |
|----------------|-----|---------|---------|-------|
| Si (%) | 109 | 17.9 | 40.3 | 26.8 |
| K (%) | 109 | .01 | 6.1 | 2.4 |
| Al (%) | 109 | 1.2 | 13.8 | 4.2 |
| Ca (%) | 109 | .003 | 5.9 | 1.2 |
| Mg (%) | 109 | .01 | 8.8 | 2.9 |
| Mn (%) | 109 | .01 | .18 | .05 |
| Ti (%) | 109 | .11 | .56 | .29 |
| S (%) | 109 | .09 | 17.1 | 5 |
| Fe (%) | 109 | 2.7 | 22.5 | 8.9 |
| Rb (ppm) | 101 | 6 | 253 | 98 |
| Sr (ppm) | 94 | 31 | 134 | 65 |
| Ba (ppm) | 109 | 50 | 4,127 | 1,784 |
| Se (ppm) | 109 | 3 | 117 | 18 |
| As (ppm) | 107 | 2 | 19,700 | 633 |
| Sb (ppm) | 95 | 1 | 74 | 7 |
| Bi (ppm) | 107 | 2 | 332 | 63 |
| Cu (ppm) | 610 | 100 | 49,800 | 1,704 |
| Pb (ppm) | 614 | 3 | 8,780 | 147 |
| Zn (ppm) | 614 | 3 | 7,400 | 274 |
| Ag (oz/t) | 614 | .01 | 9.7 | .35 |
| Au (oz/t) | 614 | .02 | .48 | .06 |

Table 2. Summary ranges of trace element data for some precious metal-enriched skarns in British Columbia.

[Data from Ettliger and Ray (1989, Appendix 7). Data represent 76 samples of skarn, endoskarn, and associated rocks from skarn deposits in Banks Island, Oka, Benson Lake, Nanaimo Lakes, Dividend-Lakeview, Texada Island, and Greenwood mining districts. Analyses by atomic absorption spectrometry]

| Element | Detection limit | Minimum | Maximum |
|----------|-----------------|---------|---------|
| Au (ppb) | 20 | <20 | 103,000 |
| Ag (ppm) | .5 | <.5 | 200 |
| Cu (ppm) | 10 | 7 | 193,000 |
| Pb (ppm) | 5 | <5 | 1,500 |
| Zn (ppm) | 5 | 8 | 29,000 |
| Co (ppm) | 3 | <3 | 17,000 |
| Mo (ppm) | 10 | <10 | 248 |
| As (ppm) | 3 to 10 | <1 | 445,000 |
| Bi (ppm) | 3 | <3 | 32,000 |

The Copper Canyon area, Nev., (fig. 2) contains copper, gold, lead-zinc skarns whose geochemical signatures are characteristic of those associated with these deposit types. Skarn deposits in the central part of the map area (fig. 2A) were unexposed prior to mining. Broad areas of outcrop had elevated abundances of copper (>700 ppm) prior to large-scale mining activity (fig. 2B). Concentrations of lead, mercury, arsenic, and cadmium are controlled strongly

Table 3. Summary ranges of geochemical data for trace elements in fresh and variably altered rocks from northern part of New World Cu-Ag-Au district, Mont.

[Data, in ppm unless otherwise noted, from Johnson (1991, Table F-1). Samples include drill core, outcrops, and ore dumps. Fire assay and atomic absorption methods. Mean based on number of samples in which element was detected at concentrations above detection limits; --, not detected]

| Element | Detection Limit | Number of Samples | Minimum | Maximum | Mean |
|---------|-----------------|-------------------|---------|---------|-------|
| Au | 0.005 | 108 | 0.006 | 176 | 3 |
| Cu | 1 | 110 | -- | 135,300 | 6,366 |
| Ag | .2 | 105 | -- | 300 | 14 |
| Te | .2 | 102 | -- | 76 | 6 |
| Bi | 1 | 85 | 2 | 1,505 | 46 |
| As | 5 | 78 | <5 | 289 | 69 |
| Pb | 2 | 96 | 3 | 132,000 | 1,610 |
| Zn | 1 | 111 | 4 | 132,700 | 1,669 |
| Ni | 1 | 102 | 1 | 152 | 34 |
| Co | 1 | 93 | 1 | 275 | 22 |
| Mo | 1 | 94 | 1 | 62 | 7 |
| Cr | 1 | 111 | 2 | 674 | 105 |
| Se | 5 | 43 | 5 | 420 | 31 |
| Hg(ppb) | 5 | 108 | <5 | 1,900 | 58 |
| Sb | 5 | 43 | .6 | 580 | 25 |
| W | 10 | 46 | 5 | 316 | 41 |
| Ba | 20 | 73 | 30 | 2,200 | 645 |
| Mn | 1 | 111 | -- | 4,670 | 848 |
| Tl | .5 | 38 | .1 | 2.3 | .78 |

by surface distribution of pre- and syn-mineralization faults that acted as conduits for mineralizing fluids. Most rocks with anomalous cadmium abundances are north of the outer limit of the dispersed iron sulfide halo that surrounds almost all of the large disseminated deposits (fig. 2F). In addition, mercury, and to a lesser degree tin abundances, appear to be sharply zoned relative to some of the most intensely mineralized skarns (B.B. Kotlyar, unpub. data, 1995). Similar relations characterize soil geochemistry around the McCoy deposit, Nev. (fig. 3). Summary statistics for the Fortitude, Nev., gold-rich skarn in the Copper Canyon area are shown in table 1.

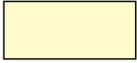





Summary ranges of trace element geochemical data for fresh and variably altered rocks from the northern part of the New World, Mont., copper-gold-silver district (Johnson, 1991), which includes the historic McLaren Mine are listed in table 3. In addition, Van Gosen (1994) analyzed 100 samples from the Homestake breccia deposit, one of five copper-gold-silver skarn and replacement deposits recently delineated by exploration in the New World district, and located less than 1 km southeast of the McLaren Mine. Van Gosen (1994) demonstrated that the Homestake orebodies are best categorized as gold-bearing skarns in the upper parts of a porphyry copper system. By comparing metal concentrations in samples of ore (Au >3,125 ppb), sub-ore (3 ppb < Au <3125 ppb), and background rock (Au <3 ppb), Van Gosen (1994) computed enrichment-depletion ratios for 24 selected metals in the Homestake deposits. Relative to background, the following elements are enriched in ore and sub-ore: Au, Ag, Cu, Mg, As, Bi, Co, Cr, Ga, Mn, Nb, Ni, Pb, and Zn. Barium, lithium, strontium, and zirconium are depleted in ore and sub-ore samples relative to background samples, whereas aluminum, potassium, sodium, titanium, and vanadium are depleted in ore samples but enriched or unchanged relative to background in sub-ore samples.







Ore and gangue mineralogy and zonation

Skarn deposits exhibit temporal and spatial zoning that reflects various stages of skarn development. Early formed prograde mineral assemblages are variably overprinted and crosscut by retrograde assemblages. Initial metamorphism forms marble and hornfels, which may be present in extensive surrounding halos. Subsequent metasomatism forms high-temperature, anhydrous calcsilicate assemblages that may be overprinted or cut by lower temperature hydrous assemblages including sulfide minerals (mainly pyrite) deposited under conditions of increased sulfur concentrations.




Cu skarns: Prograde- Pyroxene (diopside-hedenbergite), garnet (andradite-grossular), wollastonite.
Retrograde- Actinolite, chlorite, clay, epidote.
Ore- Chalcopyrite, pyrite, hematite, magnetite, sphalerite, galena, arsenopyrite; less common, bornite, pyrrhotite, molybdenite, tennantite, bismuthinite, enargite, cobaltite, and tetrahedrite.

EXPLANATION

-  Younger alluvium and fanglomerate deposits (Quaternary)
-  Altered granodiorite and quartz diorite (Tertiary)
-  Havallah sequence (Permian, Pennsylvanian, and Missisipian) -- In this area includes only lithotectonic unit 1 of Murchey (1990) (Permian and Pennsylvanian); argillite, shale, and chert
-  Antler sequence of Roberts (Permian and Pensylvanian) -- Includes conglomerate of Middle Pennsylvanian Battle Formation, limestone of Pennsylvanian and Permian Antler Peak Limestone, and sandstone and conglomerate of Permian Edna Mountain Formation
-  Scott Canyon Formation (Devonian) -- Chert, shale, argillite
-  Harmony Formation (Upper Cambrian)-- Mostly feldspathic sandstone

-  Geological contacts
-  High angle fault -- bar and ball on side of down-dropped block
-  Thrust fault -- sawteeth on upper plate
-  Outer limit of pyritized rocks, hachures on side of pyritized rock
-  Projection to the surface of outer limit of large disseminated deposits
-  Small vein deposits and occurrences

Projection to the surface in *B-F* of outer limit of :

-  Cu, Au, Ag altered porphyry deposits
-  Cu, Au, Ag skarn deposits, unexposed prior to mining, sulfide
-  Au, Ag (Pb, Zn, Cu) skarn deposits, exposed prior to mining, sulfide
-  Au, Ag (Cu, Pb, Zn) skarn deposits, oxidized, exposed prior to mining

 Trend of major drainages showing stream-flow direction

Concentrations of select metals in 2,927 rock samples
(in parts per million; N.A., not applicable)

| | Copper | Lead | Mercury | Arsenic | Cadmium |
|--|---------|---------|----------|---------|---------|
| | <50 | <10 | <0.02 | <200 | <20 |
| | 50-150 | 10-70 | 0.02-0.2 | N.A. | N.A. |
| | 200-700 | 100-700 | 0.2-1 | 200-700 | 20-50 |
| | >700 | >700 | >1 | >1000 | >70 |

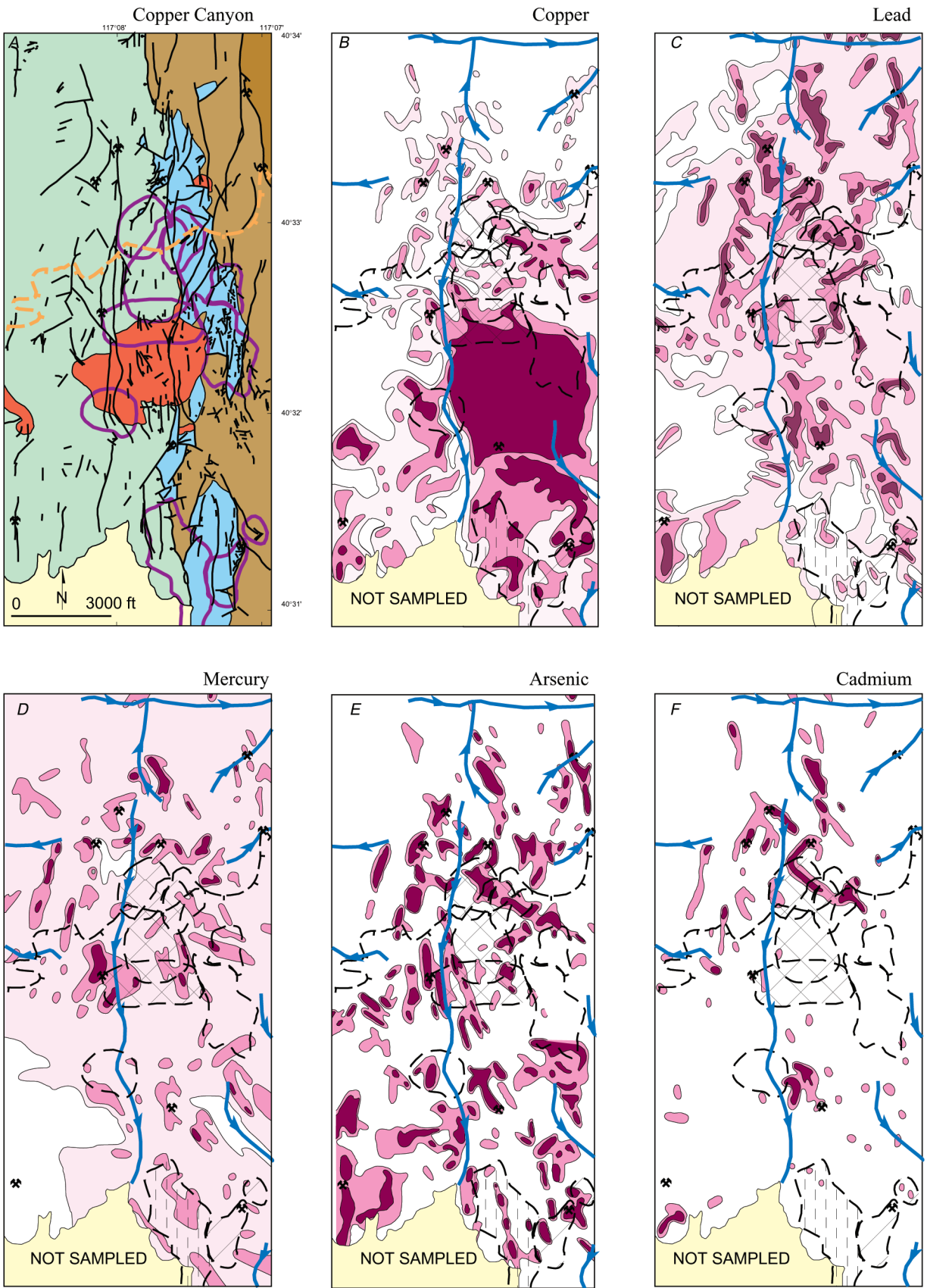




Figure 2. Maps showing *A*, geology; and contoured distributions of *B*, copper; *C*, lead; *D*, mercury; *E*, arsenic; and *F*, cadmium in 2,924 rock samples at Copper Canyon, Battle Mountain district, Nev. Geochemical data from Theodore (1969), geology modified from Theodore and Blake (1975), and surface projections of ore deposits from Doebrich and others (1995).

EXPLANATION

 Alluvium (Quaternary)

 Felsite porphyry (Tertiary)


 Granodiorite (Oligocene) -- Brown stock, 38-39 Ma

Cane Spring Formation (Upper Triassic) -- In this area includes:

 Limestone Member

 Clastic Member

 Osobb Formation (Upper Triassic)

 Augusta Mountain Formation (Middle and Upper Triassic)
-- In this area includes Smelser Pass Member

 Skarn, marble, and jasperoid

 Open pit

 Contacts

 High angle fault

Concentrations of select metals in soil samples
(in parts per million; --, not detected)

| | Gold | Copper | Arsenic |
|--|---------|---------|---------|
| | <0.1 | <50 | <5 |
| | 0.1-0.2 | 50-100 | 5-10 |
| | 0.2-0.3 | 100-200 | 10-15 |
| | 0.3-0.4 | 200-300 | 15-20 |
| | >0.4 | >300 | -- |

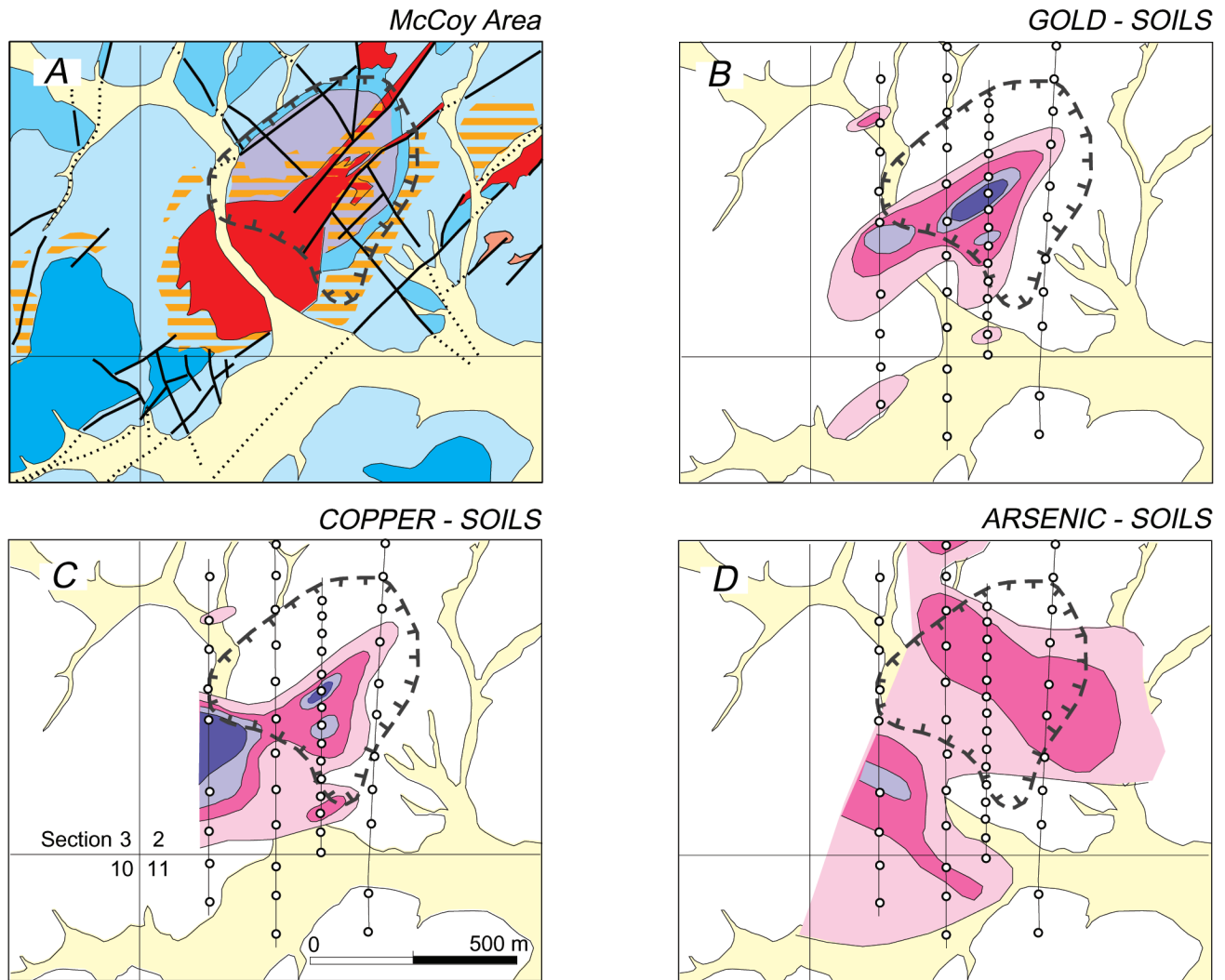


Figure 3. Maps showing *A*, geology, and contoured distributions of *B*, gold; *C*, copper; *D*, arsenic in soil at McCoy, Nev. gold skarn deposits. Geochemical data from Echo Bay Corporation (written commun., 1995); geology from Emmons and Eng (1995).

- Au-bearing skarns:** Prograde—Garnet (andradite-grossular), pyroxene (diopside-hedenbergite), idocrase, wollastonite. Retrograde—Epidote, amphibole, chlorite, prehnite, scapolite, boron minerals, potassium feldspar, clay, siderite. Ore—Gold (electrum), pyrite, pyrrhotite, chalcopyrite, arsenopyrite, magnetite, hematite (specularite), sphalerite, galena, bismuthinite or native bismuth, hedleyite, telluride minerals, molybdenite, and scheelite; gold is present as native gold or electrum associated with pyrrhotite, chalcopyrite, or with quartz-pyrite assemblages.
- Zn-Pb skarns:** Prograde—Pyroxene (hedenbergite-johannsenite), garnet (andradite-spessartine), bustamite, rhodonite. Retrograde—Actinolite (Mn-rich), ilvaite, chlorite, dannemorite, rhodochrosite, epidote. Ore—Sphalerite, galena, pyrrhotite, pyrite, magnetite, chalcopyrite, arsenopyrite; manganese-rich silicate and carbonate minerals are a distinctive characteristic of Zn-Pb skarn deposits.

Mineral characteristics

Ore may be present in sulfide-mineral-rich, massive lenses or pods or it may be disseminated. At the Nickel Plate mine in Canada, <25-micron-diameter grains of native gold associated with hedleyite are adjacent to arsenopyrite and gersdorffite. In other parts of the same deposit, electrum is concentrated in microfractures in and around chalcopyrite, pyrrhotite, sphalerite, and bismuth (Ettlinger and Ray, 1989). In contrast, gold at the McCoy, Nev., skarn is spatially and paragenetically associated with late-stage pyrite and forms 20- to 100-micron-diameter grains

bordering pyrite cubes. Mineral characteristics in skarns are likely to vary considerably within a single deposit due to the zoned nature of skarns and replacement of early-formed minerals by later mineral assemblages. In zinc-lead skarns, ore commonly forms massive pods of pyrrhotite, sphalerite, galena, and chalcopyrite in pyroxene zones.

Secondary mineralogy

Gossans develop over sulfide-mineral-rich parts of skarn deposits and may concentrate metals. Manganese oxide rich gossans are associated with zinc-lead skarns. Supergene alteration (oxidation) leads to formation of clays, hematite and goethite (after pyrite and other sulfide minerals), and secondary copper minerals (after chalcopyrite). Gold-rich skarn at the McCoy, Nev., deposit is highly oxidized and argillized to as much as 245 m below the present surface (Brooks and others, 1991). Minerals in these argillized zones include a variety of clays (montmorillonite, nontronite, smectite, and illite), manganese oxide minerals, supergene copper oxide minerals, claudetite (As_2O_3), willemite (Zn_2SiO_4), marcasite, and hydrated iron oxide minerals. At the Red Dome Au skarn deposit in North Queensland, Australia, high-grade gold ore is concentrated in highly oxidized karst-collapse breccia which formed during post-mineralization uplift and erosion; oxidation of primary tellurium-rich hypogene sulfide ore promoted karst formation and concentration of free gold (Torrey and others, 1986). Mineralogy and zoning that develops during supergene alteration of zinc-lead-silver sulfide ore in carbonate rocks depends on local Eh and pH conditions, permeability, and relative activities of carbonate species and sulfate ions in leaching ground water (Sangameshwar and Barnes, 1983). For example, cerussite is the first lead mineral to precipitate where dissolved carbonate is more abundant than sulfate, but anglesite precipitates if the situation is reversed. Supergene minerals associated with copper-lead-zinc-silver ore include azurite, malachite, smithsonite, cerargyrite as well as cerussite, anglesite, manganese minerals (pyrolusite, groutite), goethite and sulfide mineral products from bacterial reduction.

Topography, physiography

Skarn deposits in the western conterminous United States typically are present in mountainous areas, but can be present in a variety of settings; some are buried in fault blocks under Tertiary or Quaternary basin fill. Skarns also may be present in roof pendants in plutons, as well as at contacts with plutons. These types of skarns are in continental margin, syn- to late-orogenic tectonic settings such as those exposed in British Columbia, Peru, Japan, and the western Cordillera of the United States and Mexico.

Hydrology

In some deposits, shear zones and faults are important structural controls for channeling hydrothermal fluids and subsequent mineralization. In other deposits, lithologic contacts serve as fluid conduits. Post-mineralization faults may also channel fluids. At Minera Bismark, a zinc-lead skarn deposit in northern Mexico, water flows continuously along a major post-mineralization fault, as well as along other faults and fractures in granitic rock, necessitating a pumping system to dewater the orebody (Mining Magazine, 1994). Ferricrete deposits represent iron remobilized from weathered sulfide minerals by surface and subsurface water and indicate locations of former springs or drainage seepages. Manganese or iron bog deposits may provide clues to paleohydrology in the vicinity of base and precious metal skarn deposits. Faults at Copper Canyon, Nev., are known to have channeled ground water for several km during periods of enhanced ground-water availability.

Mining and milling methods

These deposits have been exploited by open pit and underground mining methods. Copper-gold ore is milled primarily by gravity and flotation methods. Copper is usually recovered by flotation. Gold is commonly recovered by cyanide leaching of crushed ore using carbon adsorption, carbon stripping at elevated temperatures and pressures, electrowinning and refining to produce dore bullion. Crushed ore may be agglomerated with cement and lime before leaching to stabilize it and promote thorough leaching. A new pyrite flotation process is available as a substitute for cyanide processing of pyrite-rich gold ore to produce tailings that have negligible acid generation potential. Resulting gold-rich pyrite concentrates are dewatered and shipped to smelters for refining. Differential flotation and separation processes are used to recover metals from complex polymetallic ore (for example, the zinc-lead skarn at Minera Bismark, Mexico) after crushing and milling to produce concentrates for shipment to smelters.

ENVIRONMENTAL SIGNATURES

Surface disturbance

Surface disturbance associated with mining these deposits is variable. Historic deposits were typically mined by hand

Table 4A. Summary of water analyses associated with historic mining of the McLaren sulfide mineral-rich Cu-Au-Ag skarn deposit in the New World district, Mont. Surface water stations and ground water observation wells.

[The McLaren open pit mine and mill operated from 1934 to 1953. Data compiled from reports cited in SCS Engineers, 1984; N, number of observations; flow, in cubic feet per second; SC, specific conductance in micromhos/cm; other measurements in mg/l. Samples were collected and analyzed in 1973 to 1975 and in 1983. N.d., not determined]

| Parameter measured | Ground water analyses | | | Surface water analyses | | |
|--------------------|-----------------------|---------|---------|------------------------|---------|---------|
| | N | Minimum | Maximum | N | Minimum | Maximum |
| Flow | N.d. | N.d. | N.d. | 21 | 0.06 | 293 |
| pH | 47 | 2.22 | 8.03 | 29 | 3.69 | 8.17 |
| SC | 47 | 103 | 26,300 | 29 | 104 | 1,480 |
| Acidity | 16 | 123 | 13,200 | 9 | 14.2 | 176 |
| Alkalinity | 42 | 0 | 469 | 24 | 0 | 118 |
| SO ₄ | 42 | 1.6 | 49,900 | 25 | 7.2 | 854 |
| Si | 41 | 2.2 | 62 | 25 | 5.6 | 29.6 |
| Fe ¹ | 20 | <.02 | 3,660 | 10 | 0.09 | 143 |
| Fe ² | 42 | <0.03 | 20,600 | 24 | <0.03 | 198 |
| Al | 35 | <0.1 | 21.4 | 21 | <0.01 | 4.56 |
| Pb | 24 | <0.02 | 0.74 | 19 | <0.003 | 0.07 |
| Cu | 23 | <0.01 | 15.93 | 21 | <0.01 | 0.5 |
| Zn | 22 | <0.01 | 2.69 | 20 | <0.005 | 0.3 |
| Cd | 23 | <0.02 | 0.1 | 19 | <0.001 | 0.02 |

¹ Total recoverable iron

² Total dissolved iron

Table 4B. Summary of water analyses associated with historic mining of the McLaren sulfide mineral-rich Cu-Au-Ag skarn deposit in the New World district, Mont. Total recoverable metals in mine and mill site drains; measured in September, 1979. Data in mg/l. [--, not detected]

| Parameter measured | Mine site | Mill site |
|--------------------|-----------|-----------|
| pH | 4.5 | 5.0 |
| Cu | 3.56 | -- |
| Zn | 0.14 | 0.12 |
| Fe | 33.7 | 17.2 |
| Mn | 1.01 | 2.94 |

in underground workings. Multiple adits, pits, and tailings piles are commonly present at inactive and abandoned workings because skarn deposits were often explored or worked at different sites, and at different times in the past, along limestone-pluton contacts. Placer gold workings are downstream from many gold-bearing skarn deposits. Some placer gold workings have affected areas of as much as 5 km².

Drainage signatures

Analogies with mine drainage compositions for polymetallic replacement deposits characterized by pyrite +chalcopyrite + sphalerite + galena veins or replacements in carbonate-rich host rocks (for example, Leadville, Colo.), indicate that mine drainages are likely to exhibit near-neutral pH ranges, carry moderate concentrations of dissolved metals (10 to 100 mg/l total Zn+Cu+Cd+Pb+Co+Ni), but may contain elevated (as much as 100,000 mg/l) amounts of zinc. Dissolved aluminum and iron concentrations are both likely to about 100 mg/l, but can be much less (Smith and others, 1994). Parts of deposits that are not in contact with carbonate rocks may cause associated drainages to be more acidic and metal rich. See tables 4 and 5 for examples of compositions of surface and ground

Table 5. Chemical analysis of a water sample from the Cananea Cu skarn deposit, 275 m level, Sonora, Mexico; all data in mg/l. [Data from White and others (1963, Table 24). Water affected by oxidation of disseminated sulfide minerals]

| | |
|------------------|-------|
| SiO ₂ | 56 |
| Al | 22 |
| Fe ²⁺ | 524 |
| Mn | 153 |
| Cu | 60 |
| Zn | 252 |
| Ca | 753 |
| Mg | 86 |
| Na + K | 198 |
| SO ₄ | 4,460 |
| Cl | 22 |

water associated with selected sulfide-mineral-rich copper skarn deposits. These data indicate total recoverable metals and, therefore, provide no information concerning dissolved versus suspended metals or metal speciation. Seasonal fluctuations affect flow and pH in some climates, especially where snow melt affects surface water during summer months (fig. 4). Various parameters of surface and ground water from monitoring sites in the New World, Mont., copper-silver-gold district are plotted in figure 5. These sites are on, or immediately adjacent (within 100 m) to, an 87,000 km³ tailings pile removed from the mine site. These data (table 4A) for water samples collected in the 1970s and early 1980s (SCS Engineers, 1984), reflect signatures that developed from mine tailings at a mill site for ore from the McLaren mine, a skarn that was worked as an open pit mine from 1934 to 1953. At the time of the analyses, a stream flowed directly over part of the tailings pile. The stream ran red and was impacted for about 16 km. The stream contained no fish and was characterized by reduced benthic organism populations mainly due to high dissolved iron and relatively high aluminum concentrations. Rock geochemical data (table 3) from the New World district include samples from in and around the historic McLaren mine. Water data from mine and mill site drainages are cited in table 4B. Many surface and ground water samples have near-neutral pH values (6 to 8). Specific conductance (a measure of dissolved solid content), iron, and to a lesser extent aluminum, all increase dramatically with decreasing pH (fig. 5). Sulfate concentration increases with increasing specific conductance (fig. 5) in both surface and ground water. However, ground water has much higher sulfate concentrations and specific conductances than surface water for the same pH ranges (note the difference in scale on fig. 5). These same data are plotted on a modified Ficklin diagram to show base metal abundance ranges as a function of pH (fig. 6). Note that the original Ficklin diagram (Ficklin and others, 1992) was devised to show the variations in aqueous (not total) base metal concentrations for systematically sampled water draining diverse ore deposit types in Colorado and included nickel and cobalt. Nevertheless, the New World water data mainly plot (fig. 6) in the near-neutral to acid, low to high metal fields and are much less acidic than water that drains many other deposit types. As Ficklin and others (1992) noted, the ability of carbonate-hosted deposits to generate metal-rich water appears to be a function of sulfide mineral content. The unusually high pyrite content of skarn ore at New World, along with the unusual situation of stream flow directly over tailings, led to some relatively high metal abundances in water on a local scale. However, iron and aluminum, not base metals, were cited as the primary pollutants during a U.S. Environmental Protection Agency (EPA) investigation. Many skarns in Nevada, however, are in semi-arid to arid climatic environments where annual rates of evaporation exceed annual rainfall and commonly most stream flow is intermittent.

A variety of samples, including stream sediment, heavy-mineral concentrates, soil, pond and spring mud, and iron-rich stream and mine adit flocculent precipitates, were collected in September, 1993, as part of a geochemical baseline study of the New World, Mont., district and adjacent areas (R.R. Carlson and G.K. Lee, unpub. data, 1995). In addition, *in-situ* pH and conductivity readings of water in streams, ponds, springs, seeps, and mine

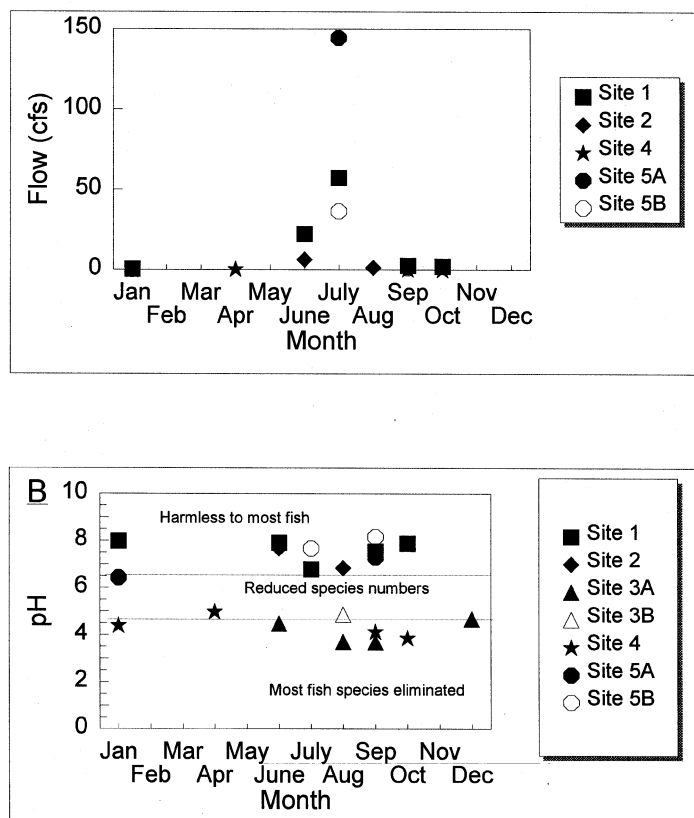


Figure 4. Seasonal variations in A, stream flow and B, pH for surface water from monitoring sites adjacent to a tailings pile at an historic mill site along Soda Butte Creek in the New World, Mont., district. These data reflect impacts caused by a tailings pile failure rather than drainage from a mine. The tailings were removed from the McLaren copper-gold-silver mine and placed at the mill site several km south of the mine. Two data sets, which represent sampling in 1974 (a) and 1975 (b), are plotted for sites 3 and 5. Dashed lines on B separate pH ranges in terms of generalized effects of pH on aquatic ecosystems (based on Potter and others, 1982). Note that the average pH value for precipitation in this area is 5.3. Water data from SCS Engineers (1984).

adits and open pits were made. Figure 7 is a preliminary contour map of pH ranges generated from the unpublished data and augmented by data from the National Uranium Resources Evaluation (Broxton, 1979). Areas characterized by high acidity (pH <5) represent water in a variety of settings. pH values in the area at the southeast end of Henderson Mtn. represent standing water in an inactive open-pit mine and low-volume seeps down hill from the pit. pH values for the area in the headwaters of the Stillwater River represent water draining recontoured mine waste rock. Most of the low pH values in the upper reaches of Fisher Creek represent discharge from abandoned adits; the remainder of these low pH values represent spring water. In all cases, highly acidic water appears to be ameliorated to near-neutral pH, probably as a consequence of buffering by water draining limestone and calc-alkaline intrusive rocks of the New World area, within 1000 meters of source areas.

In natural water, free metal ions such as Cu^{2+} are the most bioavailable and most toxic aqueous species; however, complexing with dissolved organic matter greatly reduces bioavailability.

Metal mobility from solid mine wastes

Oxide zone mine waste from skarn deposits may pass environmental monitoring tests for static acid generation potential and mobilization, whereas sulfide mineral zone wastes from the same deposit may fail such tests.

The mobility of metals from solid mine waste (tailings) varies as a function of pH, Eh, and the composition of tailings. Pathways for metal release from tailings include structural failure of tailings (for example, during a flood), direct discharge of tailings into surface water, dust, concentration in plants, erosion, and leaching into ground water (Andrews, 1975). The presence of sulfide minerals, especially pyrite, in tailings exposed to oxidation promotes development of acid mine drainage and concomitant metal mobility if carbonate mineral content and dissolution rates in tailings are insufficient to neutralize sulfide mineral oxidation (Ripley and others, 1995). Although carbonate rock

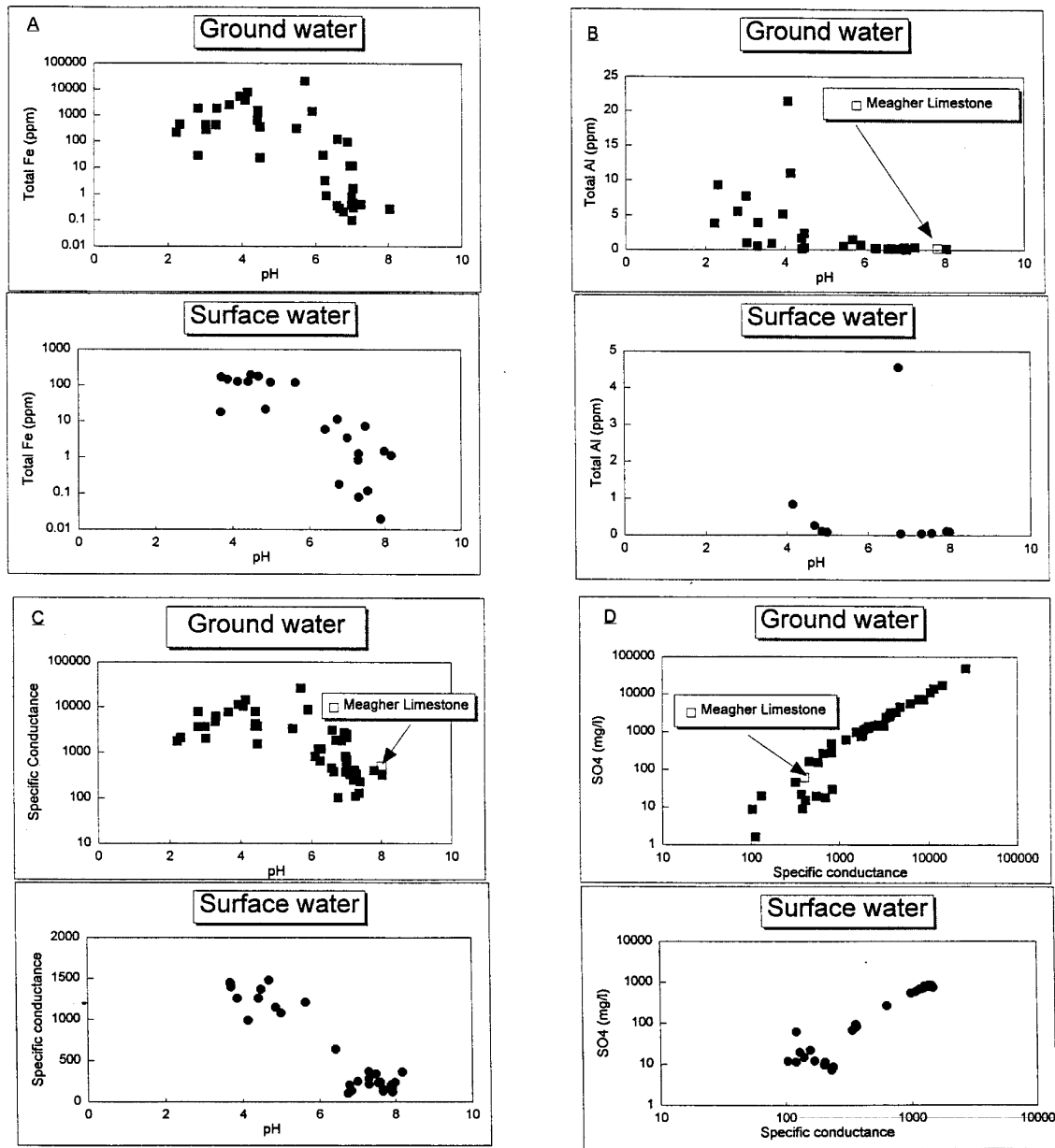


Figure 5. Plots showing A, relationships between pH and iron abundances; B, pH and aluminum abundances; C, specific conductance and pH; and D, between sulfate abundances and specific conductance for ground (squares) and surface (circles) water in the New World district, Mont. Water data from SCS Engineers (1984). Ground water chemistry for Middle Cambrian Meagher Limestone (at Ennis, about 130 km north-northwest of the New World district) reported by White and others (1963, table 6) is shown for reference (open square). The Meagher Limestone is the most important host rock for skarn deposits in the New World district (Johnson, 1991).

is commonly present in skarn deposits, waste rock may include less reactive gangue minerals, including silicate minerals, and tailings may have highly variable acid-buffering capacity. Andrews (1975) reports typical abundances for a number of metals, including 6 to 38 ppm lead, 10 to 65 ppm zinc, and 1 to 35 ppm copper, in tailings associated with a number of deposit types.

Metals released from weathered primary (hypogene sulfide ore) and secondary (supergene oxide and sulfide) minerals in tailings at the Kelley zinc-lead skarn deposit in the Magdalena, New Mex., district are fixed by precipitation of tertiary minerals and by ion exchange into phyllosilicate minerals on grain surfaces and along

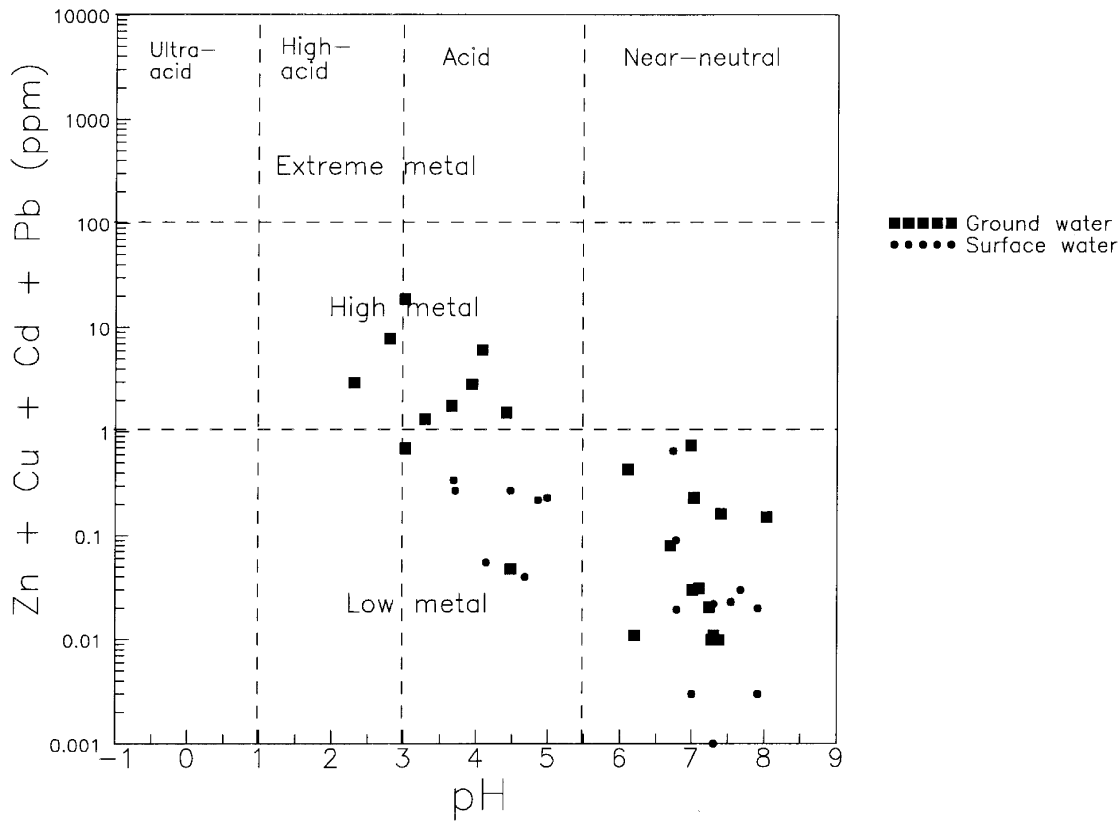


Figure 6. Variations in base metal concentrations (Zn+Cu+Cd+Pb) versus ground and surface water pH, New World district, Mont. Water data from SCS Engineers (1984). Classification scheme modified from Ficklin and others (1992).

fractures. Primary sulfide minerals persist as the main source of metals in sediments derived from tailings; these sediments contain as much as 1.9 weight percent lead, 6.2 weight percent zinc, and 279 ppm cadmium (Larocque and others, 1995).

Soil, sediment signatures prior to mining

Soil sampling has been proven useful as an exploration tool for delineating exploration targets for gold-bearing skarn systems. Hastings and Harrold (1988, fig. 7) showed that ranges for selected trace elements in rocks and soil at the Beal gold-skarn(?) deposit generally overlap. Arithmetic means for trace element concentrations in soil samples are similar to means for rock samples with the exception of gold (0.05 ppm in soil, 1 ppm in rock). Means for both soil and rock for arsenic, copper, and zinc at the Beal deposit are between 10 and 100 ppm; soil appears to be slightly enriched in arsenic and zinc relative to rocks.

The geology of the McCoy gold-silver-copper skarn deposit is shown in figure 3, along with contoured distributions of a number of metals (copper, arsenic, and gold) in soil samples. The operations at Cove, Nev., which are part of the mineralized system at McCoy, were the leading producer of silver in Nevada in 1994. The data illustrate the pre-mining distribution of metals, that is, background (natural concentrations of elements in natural materials that exclude human influence) geochemistry for soil in the area (fig. 3). These data were collected during exploration for the present McCoy mine, prior to large-scale mining (figure 3 provided by Echo Bay Minerals, written commun., 1995). Soil in the general area of the McCoy, Nev., gold skarn deposit includes as much as 15 to 20 ppm arsenic and as much as 200 to 300 ppm copper (fig. 3C-D). At McCoy, an area as much as 750 m wide contained soil with more than 5 ppm arsenic prior to large-scale mining. Analyses of the minus-80-mesh fraction of 140 soil samples in the general area of the copper-gold-silver West orebody, Copper Canyon, Nev., reveal that the soil is alkaline (pH typically 9.0 to 9.6). Calcite was present in about one-third of the samples (Theodore and Blake, 1978). Contents of silver, arsenic, gold, copper, lead, and mercury in soil above skarn are generally anomalous. Median values are: 3 ppm silver, 0.15 ppm gold, 150 ppm copper, 50 ppm lead, and 0.7 ppm mercury. Mercury contents in the soil appear to be higher along some traverses just outside or beyond the surface projection of underlying ore. Arsenic is >160 ppm in some soil samples. These are natural concentrations, uncontaminated

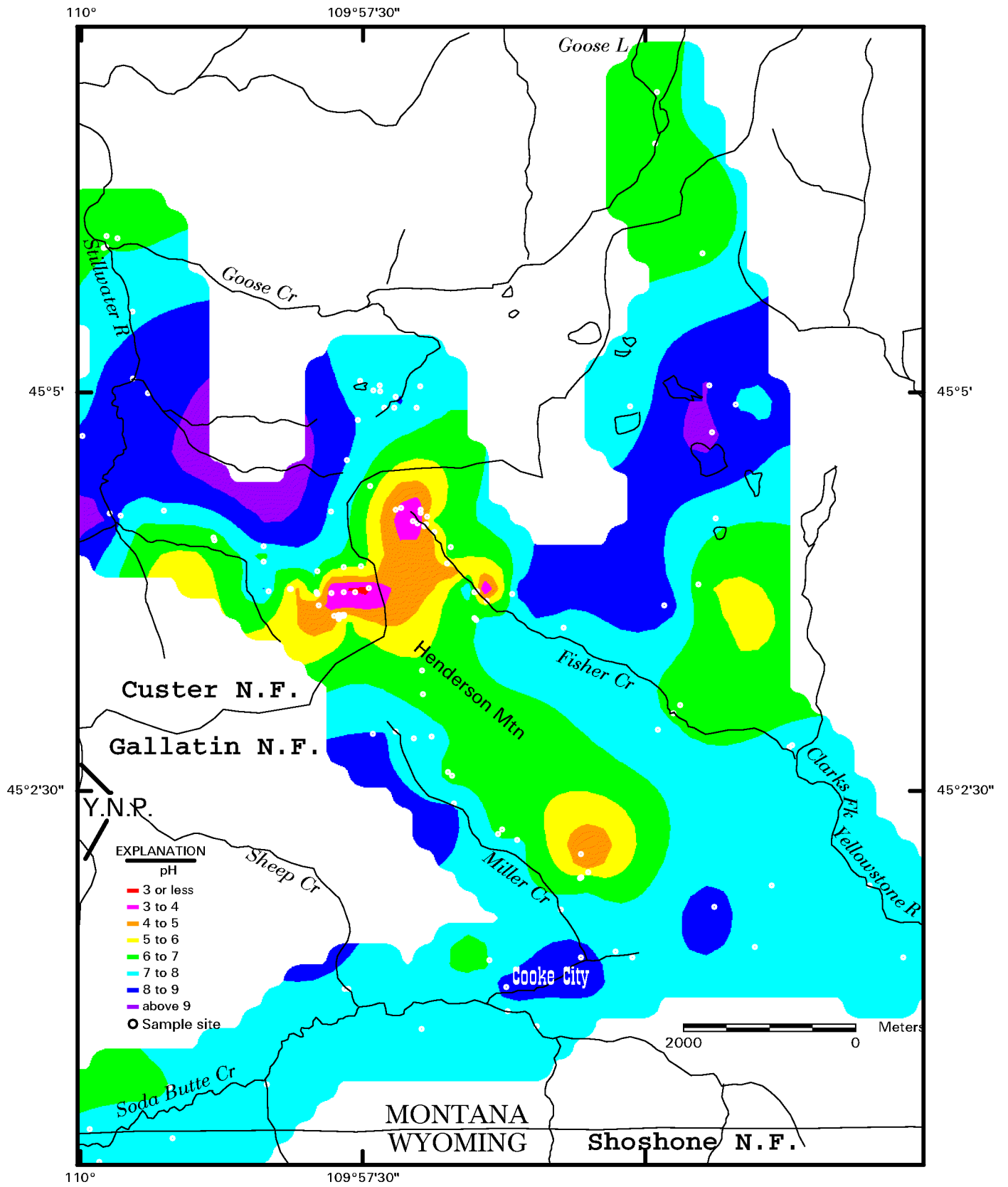


Figure 7. Contoured pH ranges in surface and ground water of the New World, Mont., district (R.R. Carlson and G.K. Lee, unpub. data, 1995).

by mining activities.

The contrast between arsenic abundances in soil at the McCoy (15 to 20 ppm) and West (>160 ppm) orebodies shows that similar deposits in similar geologic and climatic conditions can have distinctly different geochemical signatures. Although these two deposits formed in different carbonate strata, in different tectonic blocks, both are copper-gold-silver skarn deposits associated with 39 Ma granitoid intrusions in north-central Nevada and both deposits are in arid-climate settings (Bailey and others, 1994) where precipitation averages 100 to 300 mm and elevations range from 1,200 to 3,000 m.

Potential environmental concerns associated with mineral processing

Poor site selection for tailings piles or mineral processing operations, leach pads, and settling ponds can lead to chemical (acid or metal loading) or physical (increased turbidity or sedimentation) degradation of surface and ground water and soil. Potential problems associated with cyanide heap leach operations include leach solution overflow during heavy rains and rapid snowmelt, liner failures in pads or ponds, and inadequate neutralization of cyanide solutions and cyanide-treated heap-leach pads at mine closure (Norman and Raforth, 1995). Free cyanide degrades naturally by volatilization, especially at elevated temperatures with ultraviolet radiation in solutions enriched in dissolved oxygen or CO₂. These favorable conditions may not obtain in areas where winters are long and severe, or in ground water. In such cases, heap detoxification may be accomplished by a variety of chemical or biological processes.

Smelter signatures

Copper smelters release SO₂ gas and represent the largest single source of arsenic emission from industrial processing of non-ferrous metals (Loebenstein, 1994). Flue dusts from copper smelters commonly contain lead, zinc, arsenic, and other metals. Copper concentrations in air near copper smelters may be elevated from normal abundances of a few to 200 ng/m³ to abundances on the order of 5,000 ng/m³. Smelters (copper, zinc, and lead) in the United States have been regulated for emissions and metal effluents since the mid 1970s.

Climate effects on environmental signatures

The effects of various climatic regimes on the geoenvironmental signature specific these deposits are not known. However, in most cases the intensity of environmental impact associated with sulfide-bearing mineral deposits is greater in wet climates than in dry climates. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-alt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell.

Geoenvironmental geophysics

Multispectral remote imaging over sparsely vegetated areas can help identify oxidized mine tailings. Ongoing heat evolution associated with sulfide mineral oxidation can be identified by airborne infrared surveys. Electromagnetic or direct current resistivity surveys can be used to identify and track metal-contaminated ground water flowing from tailings or mine shafts. Self potential, shallow seismic, and electrical surveys can be combined to provide information on the thickness, structure, and possibly the presence of oxidation-reduction centers associated with tailings and mine waste.

Examples of case studies of the environmental impact of skarn deposits

New World district, Mont.: Mine tailings from historic mining in the New World district have been washed downstream during large floods and especially during failure of the McLaren mine tailings impoundment along Soda Butte Creek in 1950 (Meyer, 1995). The site is along Soda Butte Creek, not at the McLaren mine itself, which is a few km to the north. The site has been investigated by EPA for remediation of acid mine drainage (SCS Engineers, 1984). Redeposited sand to clay-size sediment thins from a 35 cm-thick layer near the tailings failure to a layer a few cm thick 30 km downstream; lead and copper abundances in sediment decrease (from 1,200 to 300 ppm) downstream (Meyer, 1995). Preliminary studies of soil samples from meadows downstream from the tailings indicate patchy areas of low soil pH (3.5 to 4.0), low species diversity, and high abundances of toxic elements (Stoughton, 1995). Water data collected for the EPA site investigation are summarized above (see section entitled

"Drainage signatures).

Ok Tedi, Papua New Guinea: A number of recent studies address behavior of metals discharged in particulate form directly into the Fly River from mine tailings from the Ok Tedi porphyry copper and copper-gold skarn deposit (Salomons and Eagle, 1990; Apte and others, 1995). Mine tailings enter an upper tributary of this large tropical river because high rainfall and site instability preclude construction of adequate waste-retention structures. In water draining this area, calcium and bicarbonate ion concentrations are elevated because of abundant carbonate rock in the drainage area; bicarbonate ions buffer pH levels. Copper solubility is controlled by high concentrations of dissolved organic carbon and high alkalinity of the system; copper largely remains in particulate form (Salomons and Eagle, 1990). Copper-enriched sediment that is transported to an estuarine environment interacts with water having a different chemistry (greater concentrations of magnesium, calcium, and sodium) that leads to cation exchange reactions and release of copper in soluble forms.

Effects of metals associated with these deposits types on life

Plants: Copper is an important nutrient for plants; low soil copper contents (<10 ppm) may stress vegetation whereas high copper contents may be toxic.

Animals: Copper, iron, and zinc are essential elements for all animals. The effects of metals on animals depends on the bioavailability of metals ingested, and therefore, on the behavior of the metals in soil, plants, and water. Elevated metal concentrations in soil and plants, especially lead and arsenic can cause chronic toxicity. Metal deficiencies in ruminant animals are well-documented. Regional stream sediment geochemical surveys have been used in Great Britain to explore possible relations between geochemical environment and disease in animals due to inorganic element deficiencies or excesses (Bowie and others, 1985). The effects of metals are complex, because chemically similar elements, or elements that share metabolic pathways, may interact in the digestive tract.

Absorption of copper as a nutrient, for example, can be inhibited by intake of high concentrations of zinc, cadmium, molybdenum, sulfur, iron, or silver and result in a copper deficiency syndrome.

Humans: Copper compounds in air, water, soil, sediment, and rocks are generally not harmful to humans because copper is strongly bound to soil or particles, or incorporated in insoluble minerals. Soluble forms of copper released into rivers and lakes are readily sorbed to particles. Copper is essential for human health and is not known to be a carcinogen (Agency for Toxic Substances and Disease Registry, 1989). Although cadmium is extremely toxic to animals and plants (as little as 1 to 10 ppm cadmium affects plant growth), much cadmium also apparently enters the human environment in cigarette smoke (Francis, 1984).

PERSPECTIVE

The following commentary is generally applicable to all three skarn-related geoenvironmental models.

Extensive buffering capacity afforded by limestone suggests that skarn deposits should be less likely point sources of acid mine drainage than many other deposit types. The efficacy of limestone as a natural mitigant for acid mine drainage depends on its availability and on economic considerations. Some limestone is commonly present near most skarn deposits, but some roof pendants in granitoids, originally composed of limestone, are completely converted to skarn. In many skarn deposits, calcite and other minerals, such as epidote and chlorite, characteristic of propylitic alteration are disseminated or vein gangue minerals in ore zones. These minerals also increase the ability of the host rock to consume acid (Smith and others, 1994).

In their study of factors controlling acidity and metal concentrations in water draining mines developed in various types of mineral deposits in Colorado, Plumlee and others (1993) showed that important factors include acid-buffering capacity of ore deposit gangue minerals and host rocks, types and abundances of sulfide minerals and their exposure to weathering processes, and availability of dissolved oxygen. No skarn deposits were included in their study; however, their results, with regard to variations in aqueous base-metal concentrations as a function of pH for high-sulfide mineral, carbonate-hosted deposits and low-sulfide mineral carbonate-hosted deposits, represent the most appropriate available analog for predicting mine drainage signatures for skarn deposits. The length of time that sulfide-mineral-bearing deposits are exposed to oxidation may play a significant role in their eventual contribution to local, undisturbed environments as well as environments disturbed by mining. Some originally sulfide-mineral-bearing skarns have been thoroughly oxidized as a result of having been exposed during the last 35 million years.

Many mineralized skarn deposits are point sources for metals within much more widely altered mineralized systems, particularly porphyry systems. Some mineralized skarns may have potential for significant acid mine water development. However, none of the 61 mining-related sites on the Environmental Protection Agency (1995) National Priority List (Superfund) include skarn deposits. A number of skarn deposits, however, appear on lists of legal cases

that resulted from reported environmental damage (SCS Engineers, 1984). These include deposits where historic mine tailings contribute to water quality degradation and, in some cases, affected aquatic life. The extent of degradation from historic mining appears to be related to the magnitude and duration of operations as well as deposit type and climate. Any area that was extensively mined for long periods of time is likely to have experienced some environmental impact.

Skarn deposits that enter production today cannot be compared with skarn deposits worked a hundred, or even twenty, years ago. Many currently active mining or exploration projects involving skarn deposits operated at some time in the past at a smaller scale and are currently being re-evaluated for different metals (gold, silver) than were sought in past enterprises. Many abandoned or inactive skarn deposits are the focus of recent exploration because of economic changes or development of modern technology that allows previously uneconomic ore to be mined. For example, skarns that were mined in the past for base metals or tungsten may now constitute exploration targets for gold. Known or potential environmental hazards from historic mining can, in some cases, be mitigated by reopening the site to mining activity that involves reprocessing historic tailings using modern mining practices.

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