SEDIMENT-HOSTED CU DEPOSITS
(MODEL 30b; Cox, 1986)

by David A. Lindsey, Laurel G. Woodruff, William F. Cannon,
Dennis P. Cox, and William D. Heran

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

The sediment-hosted copper model (Cox, 1986, Model 30b) has been subdivided into three models having different geologic features, grades and tonnages, and anticipated environmental effects associated with mining and processing. The reduced-facies model (RF) includes deposits in widespread reduced-facies sedimentary rocks, is relatively high-tonnage, and has been mined mostly underground. The only major, reduced facies deposit mined in the United States, White Pine, Mich., produced 138 million tonnes of ore that contained 1.14 weight percent copper and 8 g/t silver between 1953 and 1982 (Kirkham, 1989). The redbed model (RB) includes deposits in local areas of reduced rocks in redbed sequences, is low-tonnage, and has been mined near the surface by open-pit and small underground mines. Redbed deposits have not been a major source of copper. The Revett model (RV; Spanski, 1992), based on deposits restricted to the Proterozoic Revett Formation of the Belt Supergroup of Montana and Idaho, is intermediate in tonnage and has been mined entirely underground. The now-closed Spar Lake, Mont., mine produced 44 million tonnes of ore that contained 0.74 weight percent copper and 53 g/t silver (Balla, 1992). Production from either one of two mines under development would exceed that of the Spar Lake mine. The silver-rich character of Revett ore makes it the largest producer of silver in the United States (E&MJ, 1982; 1989).

New geologic information and mining technology may change the classification, grade and tonnage, and environmental effects of sediment-hosted copper models in the future. Variation in geology and coproduct metals among reduced-facies deposits may require development of additional models for White Pine-, Kupferschiefer-, and Zambian-type deposits. The distinction between the Revett and redbed models may be unduly arbitrary (Lange, 1975). Sandstone-hosted deposits like those in the Revett Formation may reach gargantuan tonnages exploitable by open-pit mining (Udokan, Siberia; Volodin and others, 1994). Some deposits in Phanerozoic rocks, now included in the redbed model, may belong to the same genetic class as the Revett deposits. However, examination of environmental effects is facilitated by the present classification of all Devonian and later sandstone-hosted copper deposits in the redbed model because they share a common mineralogical association and are commonly associated with fossil plant matter. Finally, the advent of solvent extraction-electrowinning (SX-EW) mining may lead to *in situ* solution mining of underground workings in chalcocite-rich reduced facies deposits and to open-pit, heap-leach mining of previously uneconomic, near-surface oxidized and chalcocite ore in the largest redbed deposits.

Deposit geology

Principal features of the three sediment-hosted copper models are shown diagrammatically in figure 1. These models portray dimensions, stratigraphic settings, favorable host rocks, mineral zones, degree of oxidation, fractures, ground water flow, and mining methods of known deposits. Ore fluids were warm (50 to 150°C), oxidizing (hematite-buffered), and rich in sulfate and chloride ions (to complex Cu^{+}) (Jowett, 1986; Hayes, 1990).

RF: Deposits of the reduced-facies model are present where continental clastic sedimentary rocks are overlain by regionally extensive marine or lacustrine shale or carbonate rocks, rich in organic material, that act as traps for mineral deposition (Ensign and others, 1968; Oszczepalski, 1989). Host rocks may be shale or adjacent limestone, sandstone, or conglomerate. Commonly, the reduced facies overlies basaltic volcanic rocks in rift environments. Where evidence for a rift is lacking, reduced facies overlie coarse clastic sedimentary rocks derived from older terranes that contain mafic rocks. Evaporite deposits overlie, or are believed to have once overlain, copper deposits of the reduced-facies model.

RB: Deposits of the redbed model are in the same geologic setting as those of the reduced-facies model but lack regionally extensive reduced strata. In Devonian and later strata, copper commonly replaces local accumulations of fossil plant matter (LaPoint, 1976). Redbed copper deposits may be present in rifts or intracratonic basins.

RV: Deposits of the Revett model are in thick beds of reduced (pyritic) quartzite (properly, metasandstone) near pre-ore redox fronts (Hayes and Einaudi, 1986; Hayes, 1990). Orebodies may be stacked, especially near faults (Balla, 1993). Copper is not associated with solid organic matter in Revett deposits, but copper may have been deposited by a transient gas reductant generated by decay of organic matter.

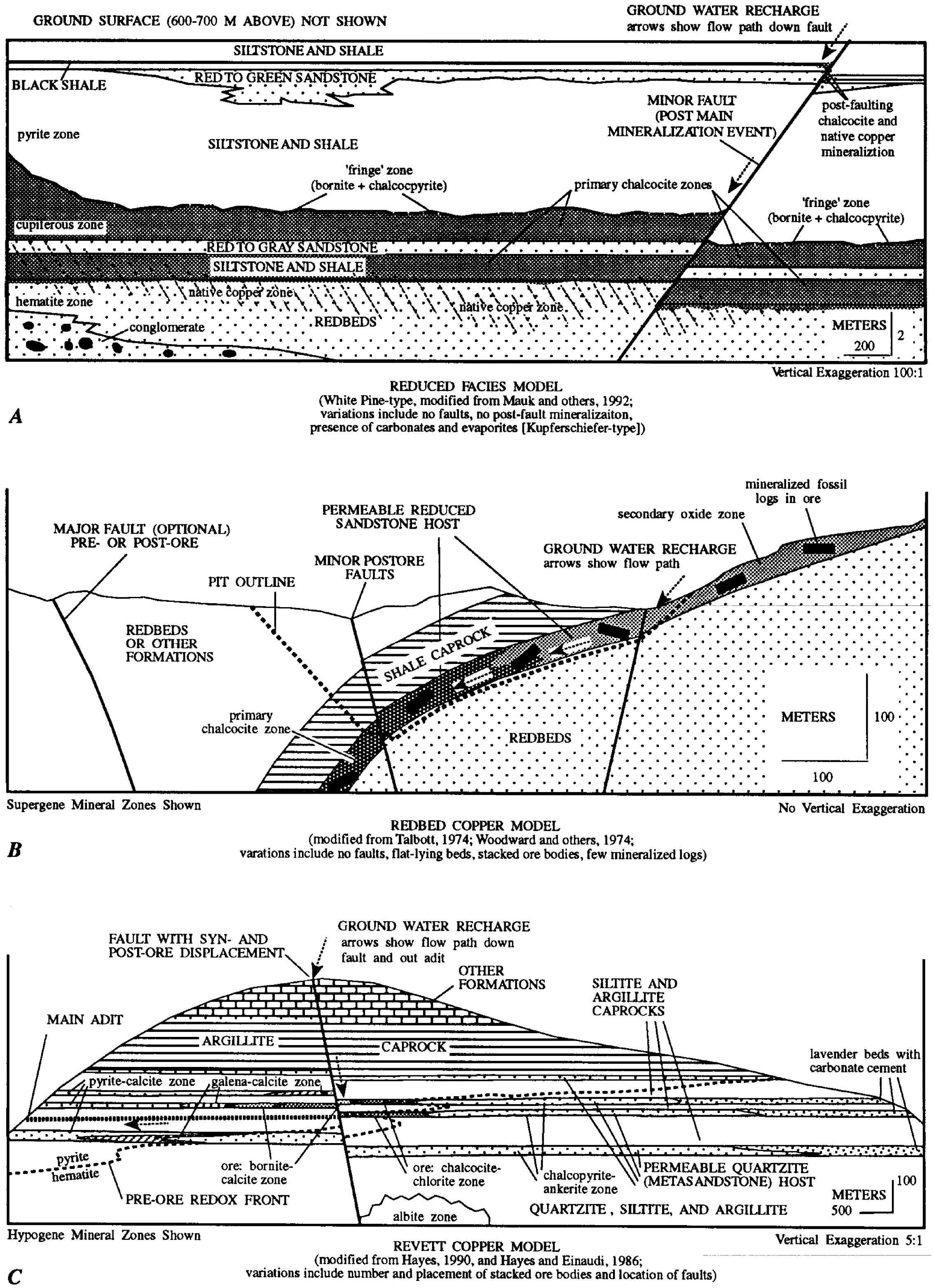

Figure 1. Simplified cross-sections of sediment-hosted copper deposits: *A*, reduced facies, *B*, redbed, and *C*, Revett models. Note scale variations and vertical exaggeration.

Examples
RF: White Pine, Mich.; Creta, Okla.; Kupferschiefer, Germany and Poland; and African copperbelt, Zaire and Zambia.
RB: Nacimiento, Scholle, and Stauber, N. Mex.; and Paoli, Okla.
RV: Spar Lake, Rock Creek, and Montanore, Mont.

Spatially and (or) genetically related deposit types
The three sediment-hosted deposit types are genetically related and may be present in the same terrane. Hypothetically, all three deposit types might form from a single ore-forming fluid that invaded reduced rocks. Deposits belonging to the three models represent ore deposition in different reducing environments: laterally extensive reduced black shale and carbonate rock (reduced facies model, RF), local areas of reduced rock and plant matter in redbeds (redbed model, RB), and large reduced areas in sandstone (Revett model, RV). Where sediment-hosted copper deposits form in a rift environment, as for example in the Keweenaw peninsula, Mich., large deposits of native copper are present in vesicular basalt flows (Model 23; Cox and Singer, 1986).

Potential environmental concerns
Surface disturbance: Mines, including open pits, and mineral processing facilities occupy areas ranging from a few to many square kilometers.
Water quality: Potential for acid drainage and dissolved metals associated with these deposits is minimized by low pyrite and chalcopyrite contents and by widespread presence of carbonate minerals in ore and waste rock. Heavy metal (including arsenic, cadmium, chromium, copper, mercury, and lead) abundances downstream from mining and milling operations may be elevated; however, undesirable environmental effects have not been reported (U.S Forest Service and others, 1992). Anomalous quantities of some elements may also be present in ground and surface water downdip or downslope from undisturbed sediment-hosted copper deposits; anomalies in ground water have been traced to small concentrations in associated rock (Mosier, in press). Lead in ore can be recovered by smelting (E&MJ, 1986a), and lead in tailings and waste rock can be minimized during mining by avoiding lead-rich zones near ore. Metals in surface water may be sorbed by particulate oxyhydroxide minerals, which can be removed by filtration through soil. Acid water may drain from tailings and waste, particularly from friable or permeable pyrite-bearing waste rock that is removed to the surface, but the presence of carbonate rock may significantly mitigate these effects. Elevated ammonia and nitrates from blasting may affect aquatic life.
Air quality: Particulate emissions from mineral processing, including smelting, may exceed air quality standards. Sulfur dioxide is a product of copper smelting, but emissions can be controlled by collection and production of sulfuric acid. Copper recovery by SX-EW instead of smelting greatly reduces impact on air quality.

Exploration geophysics
Major structural features (Unrug, 1989) and bleached redbeds (Conel and Alley, 1984) associated with uranium and copper deposits can be delineated by the Landsat Multispectral Scanner. Integrated studies of basin structure, thickness, and lithology, which may be applicable to sediment hosted copper deposits, have been conducted using electrical, electromagnetic, gravity, and seismic methods (Zohdy and others, 1974; Gomez-Trevino and Edwards, 1983; Horscroft and Nettleton, 1989; Sinha, 1990).

References
Geology General: Kirkham (1984, 1989), and Cox (1986). RF--Ensign and others (1968), Dingess (1976), Oszczepalski (1989), and Mauk and others (1992). RB--Woodward and others (1974) and LaPoint (1976). RV--Hayes and Einaudi (1986), Hayes (1990), and Balla (1993).
Environmental geology, geochemistry: RV--Balla (1992) and U.S. Forest Service and others (1992).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS
Deposit size
Size and grade of deposits vary by model (table 1). Median deposit size is related to the average size of the area potentially impacted by nearby mining; maximum deposit size indicates the size of the largest, potentially impacted area. The maximum-size reduced facies copper deposit in the United States is White Pine, Mich., which contains 560 million tonnes of 1.2 weight percent copper (Kirkham, 1989). The largest redbed copper deposit is Nacimiento, N. Mex. (Talbott, 1974). If Lisbon Valley, Utah, is included in the redbed model, maximum size is 35 million tonnes

Table 1.--Estimated median and maximum ore tonnages (reserves plus production) and copper grades of each sediment-hosted copper model type

Model	Number of deposits in model	Median size (tonnes X 10^6)	Copper grade (percent)	Maximum size (tonnes x 10^6)	Grade of maximum-tonnage deposit (percent)
Reduced (RF)[1]	43	32	2.3	2,600[2]	>2[2]
Redbed (RB)[1]	17	0.12	2.8	10	0.67
Revett (RV)[1,3]	7	19	0.86	147	0.68

[1]Cox and others (1992).
[2]Kirkham (1989).
[3]Spanski (1992).

of 0.49 weight percent copper (Mining Record, 1995). If Udokan, Siberia, is included in the Revett model, maximum size is 1,200 million tonnes of 1.5 weight percent copper (Volodin and others, 1994).

Host rocks
RF: Shale, argillite, siltstone, and their calcareous variants; adjacent rocks that may be important hosts locally include limestone, dolomite, sandstone, and conglomerate.
RB: Sandstone; locally, siltstone and shale.
RV: Metasandstone.

Surrounding geologic terrane
Most sediment-hosted copper deposits are in terranes principally composed of sedimentary rocks.
RF: Alluvial clastic redbeds and rift-related volcanic rocks; may contain evaporites in subsurface.
RB: Alluvial clastic redbeds with or without evaporites.
RV: Precambrian alluvial and shallow marine sedimentary rocks of low metamorphic grade.

Wall-rock alteration
All models: Zones of reduced rock predate ore deposition and range from regional features extending many kilometers to local features (Shockey and others, 1974; Oszczepalski, 1989; and Hayes, 1990). Reduced zones in sandstone are bleached and contain pyrite or iron oxide pseudomorphs after pyrite; possibly formed by reducing action of fluid hydrocarbons (for example, Conel and Alley, 1984). Reduced rock is separated from oxidized rock by redox fronts (pyrite to hematite-magnetite boundaries).

Nature of ore
RF: Most ore in shale is fine-grained (typically 2 to 20 microns at White Pine, Mich., and less than 50 microns in Kupferschiefer, Poland) disseminated chalcocite accompanied by lesser amounts of native copper (White Pine) and chalcopyrite and bornite (Kupferschiefer); disseminated ore is accompanied by coarse-grained aggregates, lenses, and veinlets of native copper (White Pine) and chalcocite (Kupferschiefer) (Ensign and others, 1968; Haranczyk, 1972; Oszczepalski, 1989); Kupferschiefer sandstone ore contains pore-filling cement of copper sulfide minerals, commonly chalcocite (Tomaszewski, 1986). Weakly metamorphosed ore is impermeable; shale ore is fissile and friable.
RB: Most ore is composed of malachite, azurite, and chalcocite in sandstone pore space; some ore minerals replace fossil plant remains; most ore is porous and friable (Woodward and others, 1974; LaPoint, 1976).
RV: Ninety percent of ore contains disseminated sulfide minerals, including chalcocite and bornite, that replace sandstone cement or fill pore space; crowded, disseminated sulfide minerals form clots that replace sand grains, follow bedforms, and form ore rods across stratification; minor amount of ore is present in veins; ore is hosted by refractory quartzite (Hayes and Einaudi, 1986).

Deposit trace element geochemistry
RF: Lead, silver, and zinc abundances are locally significantly elevated; cobalt is a coproduct in Zaire-Zambian deposits; metals associated with organic matter in Kupferschiefer, Poland, include arsenic, bismuth, chromium, cobalt, gold, molybdenum, nickel, uranium, and platinum-group elements (Przybylowicz and others, 1990).
RB: Lead, silver, uranium, and vanadium are locally abundant in individual deposits; trace elements present in

Table 2.--Ore and gangue mineralogy for representative deposits of RF-, RB-, and RV-models; all data expressed as volume percent. c, common; p, present; --, not reported

Mineral	White Pine (RF)[1]	Creta (RF)[2]	1-New Mexico (RB)[3]	2-New Mexico (RB)[3]	Spar Lake (RV)[4]
Quartz	20-30	10-20	35-51	63-66	60-70
1-Silicate[5]	30-35	45-63	21-39	8-17	10-20
2-Silicate[6]	24-34	5-6	c	c	1-4
Carbonate	c	0.1-3	2-11	1-6	0.1-4
Sulfate	--	3-28	0-10	0-1	p
Hematite	0-5	--	2-9	2-8	<0.5[7]
Carbonaceous matter	0.5	0.3	c	c	--
Oxidized ore minerals	-	c	1-11	3-10	p[8]
Sulfide	0-8	2-4	0-7	2-7	0.2-0.7[8]

[1]Ensign and others (1968); in addition, they list 7 percent as "other", which includes laumontite cement and trace amounts of zircon and tourmaline (Daniels, 1982).
[2]Johnson (1976).
[3]1-N. Mex., Permian host rocks; 2-N. Mex., Triassic host rocks; data from LaPoint (1979, tab. 1); includes carbonate clasts in Permian rocks.
[4]Hayes and Einaudi (1986); quartz and feldspar from author's data on unmineralized Revett Formation.
[5]Minerals that weather at slow to very slow rates: mainly plagioclase, K-feldspar, muscovite, and clay minerals.
[6]Minerals that weather at intermediate rates: mainly chlorite, epidote, biotite, and hornblende.
[7]Also includes authigenic magnetite and leucoxene.
[8]Oxidized ore confined to outcrops and fractures; sulfide minerals adjacent to ore include as much as 0.3 percent chalcopyrite.

anomalous abundances include arsenic, barium, chromium, cobalt, molybdenum, nickel, selenium, strontium, tin, vanadium, and zinc (Lange, 1975).
RV: Lead and silver are abundant; silver is a coproduct; trace elements present in anomalous abundances include barium, boron, cadmium, chromium, cobalt, mercury, nickel, scandium, vanadium, and zinc (Lange, 1975).

Ore and gangue mineralogy, zoning

Ore and gangue mineralogy: Gangue assemblages associated with these deposits are summarized in table 2. The abundance of carbonate minerals and minerals that weather at intermediate rates, principally chlorite- and epidote-group minerals, define the acid-neutralizing capacity of these deposits (Kwong, 1993). Exceptional among RB deposits, those at Nacimiento, N. Mex., contain very small amounts (0 to 1 volume percent) of carbonate minerals (LaPoint, 1979).

Sulfide ore mostly consists of chalcocite with or without minor to locally abundant bornite, chalcopyrite, native copper, galena, sphalerite, and silver minerals. Oxidized ore, abundant only in near-surface RB deposits, is composed of malachite, azurite, chrysocolla, and cuprite.

Pyrite content: RF--Most ore has low pyrite content; beyond ore, reduced shale and siltstone may contain 1 volume percent or more pyrite. The Precambrian Nonesuch Formation near White Pine, Mich., contains 0.5 to 3 volume percent pyrite (Daniels, 1982, p. 120)). RB--Ore has low pyrite content; no reliable data. RV--Ore has low pyrite content; beyond ore, reduced Revett Formation contains about 0.1 to 0.2 volume percent pyrite (Hayes and Einaudi, 1986).

Zoning: Three types of zoning have been identified: (1) preore reduced and oxidized zones in host formations, described in section above entitled "Wall-rock alteration", (2) mineralogical zoning in primary ore, formed during hypogene deposition of sulfide minerals, and (3) secondary ore zones above primary ore, formed by near surface supergene alteration, described below in section entitled "Secondary mineralogy."

Preore redox fronts control location of some deposits; richest sulfide ore is in reduced rock near redox fronts in RF Kupferschiefer, Poland, deposits (Oszczepalski, 1989), RB Paoli, Okla., deposit (Shockey and others, 1974), and RV Spar Lake, Mont., deposit (Hayes, 1990). Primary ore zoning is observed mainly in RF and RV deposits; zoning upward and outward from the bottom of the orebody is defined by increasing solubility in the sequence chalcocite-bornite-chalcopyrite-galena-sphalerite. In some reduced facies deposits, such as White Pine, Mich., native copper is present at the base. Primary zoning commonly is attenuated laterally along bedding and condensed vertically across bedding; successively higher and distal zones in single mine faces are persistent for many kilometers laterally. Primary sulfide mineral distribution zonation generally is not reported for RB deposits, perhaps because it has been overprinted by secondary ore.

Mineral characteristics

Textures: Sulfide minerals, interlocked with gangue (see section above entitled "Nature of ore") range from 2 to 50 microns in shale to 2 to 4 mm in sandstone ore; shale ore must be milled to fine particle size to enable metal recovery by flotation (Finlay, 1968, p. 171).

Trace element contents: RV--Trace amounts of cobalt and zinc are present in pyrite and sphalerite, respectively (Hayes and Einaudi, 1986).

General rates of weathering: Weathering rates depend on overall physical characteristics of rock: RB sandstone ore (fast) > RF shale ore > RF metamorphosed shale ore > RV quartzite ore (slow).

Secondary mineralogy

RF and RV: Outcrops include sparse stains and fracture fillings of malachite and azurite.

RB: Secondary ore, formed above water table, consists mainly of malachite, azurite, and chrysocolla. A thin zone that contains minor amounts of cuprite, native copper, native silver, and other minerals has been reported at the interface between oxidized and chalcocite ore at Nacimiento, N. Mex. (Woodward and others, 1974). Zones of chalcocite enrichment below the water table have not been reported. Jarosite and natrojarosite are present along faults at Lisbon Valley, Utah (Schmitt, 1967), but a supergene origin has not been established.

Topography, physiography

RF: Shale hosts are poorly exposed and do not form topographic features.

RB and RV: Some sandstone host rocks form cliffs and escarpments. RV deposits are in mountainous terrane.

Hydrology

RF: Ore deposits and host formations have low permeability and therefore do not channel water flow. Fracture zones along faults and permeable aquifer beds above and below ore may allow high-volume water entry from rivers, lakes, and tailings ponds. Examples: White Pine, Mich., mine pumps 3.8 million liters/day; Konkola, Zambia, mine receives major inflow from fracture zones that connect with a river and a tailings lake; it is one of the world's wettest mines (Mulenga and de Freitas, 1991).

RB: Near-surface deposits are permeable, which allows direct recharge. Faults may focus ground water flow locally. Permeable sandstone hosts may serve as regional aquifers (for example see, Mosier and Bullock, 1988).

RV: Ore deposits and host formations have low permeability and therefore do not focus flow; surface recharge is limited to fractured zones along faults; water flows down fractures and out mine workings.

Mining and processing methods

RF: These deposits are mined by underground room-and-pillar method to depths of 1,000 m; in a few old mines, longwall methods were employed. Ore is processed by pulverizing and flotation; concentrates are smelted nearby or shipped to distant smelters (E&MJ, 1979a; 1986a,b). Some Zambian ore is mined by open-pit methods and processed by combination of flotation-smelting and SX-EW methods (E&MJ, 1979a). Chalcocite in fractured and vesicular basalt flows (Model 23, Cox and Singer, 1986) has been successfully processed by *in situ* leaching (Johnson and others, 1988).

RB: These deposits are mined in small adits, inclines, and shafts; larger deposits are mined by open-pit methods. Historically, ore has been processed by pulverizing and flotation; concentrates were shipped to smelters (Soule, 1956; Talbott, 1974). Ore produced in the future will probably be processed by heap leach-SX-EW recovery of copper metal on site (for example, Mining Record, 1995).

RV: These deposits are mined by underground room-and-pillar methods; ore has been processed by pulverizing and flotation near mine site; concentrates have been shipped to smelters (E&MJ, 1979b; U.S. Forest Service and others, 1992).

ENVIRONMENTAL SIGNATURES

Drainage signatures

Mine and processing facilities: All models--These deposits resemble low-sulfide mineral, carbonate-hosted ore described by Plumlee and others (1993). Accordingly, as might be predicted from the mineralogy of these deposits, water draining mines and tailings has near-neutral to moderately alkaline pH and low dissolved metal contents (table

Table 3.--pH and dissolved metal content of mine and tailings water from some sediment-hosted copper deposits.

Mine (deposit model)	Water source	pH	Zn (µg/l)	Pb(µg/l)	Cu (µg/l)
White Pine, Mich. (RF)	tailings basin[1]	7.2	--	--	--
Kupferschiefer, Germany (RF)[2]	mine	6.9-7.7	--	--	--
Spar Lake, Mont. (RV)[3]	mine	7.2-7.6	10-40	10	10-280
Montanore, Mont. (RV)[3]	mine	7.5-8	10-20	<10	<10
Montanore, Mont. (RV)[3]	settling pond	7.7-10.9	<20-50	<10	<10-20

[1]Basin also receives drainage from smelter slag pile and water pumped from mine.
[2]Knitzschke and Kahmann (1990).
[3]U.S. Forest Service and others (1992, tabs. 6-10, 6-11, 6-12, and 6-14); they also report <5 µg/l dissolved arsenic, <1 µg/l dissolved cadmium, and <0.2 µg/l mercury.

3). RF--Where mining, milling, and smelting are conducted on-site, water from multipurpose basins (tailings, mine, and slag pile drainage) may contain mercury, copper, cadmium, and arsenic. RB--Visually obvious suspended iron oxyhydroxide particulates, which usually indicate acid drainage, are present at some deposits. Natural concentrations of arsenic, chromium, selenium, and uranium in redbed hosts of central Oklahoma aquifer are probable sources of drinking water contamination (Mosier, in press). RV--These deposits have low dissolved metal (Al, As, Cd, Cr, Cu, Fe, Pb, Mn, Hg, Ag, and Zn) abundances but elevated total metal (including iron, manganese, and aluminum as particulate oxyhydroxide minerals; and particulate-sorbed copper, cadmium, lead, and zinc) abundances in adit drainage and water from tailings and settling ponds (U.S. Forest Service and others, 1992). Blasting operations have contributed nitrates and ammonia to stream water.
Natural drainage: Data from streams draining Revett and other formations of Belt Supergroup suggest near-neutral pH and low dissolved metals (U.S. Forest Service and others, 1992).

Metal mobility from solid mine waste

All models: Metal mobility from these deposits is low to moderate, primarily because of acid buffering capacity provided by associated carbonate rocks. Dissolved metals may be sorbed from acid drainage by suspended iron oxyhydroxide particulates (Smith and others, 1993) in drainage from open pits and mill tailings. Particulates and sorbed metals are subsequently removed from water by filtration through soil and by plant uptake (U.S. Forest Service and others, 1992).

Soil, sediment signatures prior to mining

All models: Soil and stream sediment associated with some of these deposits contains anomalous abundances of copper, lead, silver, and possibly arsenic, mercury, and zinc. Copper clearings, in which soil is copper rich and normal vegetation is replaced by copper-resistant and copper-accumulating plants, are present in the vicinity of Zaire-Zambian deposits (Reilly, 1967; Reilly and Stone, 1971; Malaisse and others, 1978). Copper (Cu^{++}) is preferentially adsorbed by organic matter and manganese in mildly acid soil (McLaren and Crawford, 1973).
RV: Soil and sediment associated with some of these deposits contain anomalous metal abundances, including >50 to as much as 2,000 ppm copper, >150 ppm lead, and >0.5 ppm silver (Cazes and others, 1981; Wells and others, 1981).

Potential environmental concerns associated with mineral processing

All models: Surface disturbance results from construction of facilities including conveyors, roads, transmission lines, mills, and tailings ponds. Local surface water may be diverted by facilities or used for milling. Drainage from processing sites may contain elevated concentrations of arsenic, cadmium, chromium, copper, mercury, and lead. Ammonia and nitrate contributed by blasting are of less concern. Acid mine and mill tailings drainage may develop if inadequate buffering capacity is provided by available carbonate rock. Organic compounds used as flocculents during milling may be toxic (for example see, U.S. Forest Service and others, 1992, p. 262). Air quality in vicinity of facilities may be affected by significant emission of suspended particulates, nitrogen oxides, sulfur dioxide, carbon monoxide, and hydrocarbons (for example see, U.S. Forest Service and others, 1992, tab. 6-2).
RF and RV: Lake levels may be disturbed if underground workings intersect fractured rock beneath lakes (U.S. Forest Service and others, 1992).
RF and RB: Additional surface disturbance may result from open pits and leaching facilities.

Smelter signatures

Smelters associated with these deposits may contribute particulates, metals, and sulfur dioxide to the environment. At White Pine, Mich., 1990 emissions were approximately 900 tonnes/year (t/yr) of particulates and about 225 t/yr of metal. Estimated outputs include 198 t/yr copper, 25 t/yr lead, 9 t/yr arsenic, 1.8 t/yr cadmium, and <1 t/yr each of chromium, mercury, and nickel (Anonymous, 1990). The stack plume at White Pine had 60 to 80 percent opacity in 1990. Most smelters control sulfur dioxide emissions by recovery as sulfuric acid (E&MJ, 1986a). Some ore is amenable to SX-EW, which avoids smelting. RB and RV ore concentrates are shipped to distant smelters.

Climate effects on environmental signatures

The effects of various climate regimes on the geoenvironmental signature specific to sediment-hosted copper deposits are not known. However, in most cases the intensity of environmental impact associated with sulfide-mineral-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-salt 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. Extreme leaching of heavy metals from soil is expected in tropical environments.

Geoenvironmental geophysics

Naturally heavy-metal-distressed areas (Bolviken and others, 1977) associated with uranium and copper deposits have been delineated by the Landsat Multispectral Scanner. Airborne remote sensing (Watson and Knepper, 1994) should be applicable to mapping environmental effects of mining and processing. A variety of methods, including gravity, magnetics, electrical, and electromagnetics can be employed to define fluid migration pathways such as buried stream channels or fault zones. Induced polarization methods can be used to estimate sulfide mineral content of unmined rock. Plumes with sufficiently high metal contents can be traced using electrical or induced polarization surveys.

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