

## **PORPHYRY CU DEPOSITS** **(MODEL 17; Cox, 1986)**

by Leslie J. Cox, Maurice A. Chaffee, Dennis P. Cox, and Douglas P. Klein

### SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

#### Deposit geology

Porphyry copper deposits contain copper, molybdenum, and gold minerals, disseminated or in a stockwork of small veinlets within a large mass of altered rock (Singer and Mosier, 1981). The host rock is commonly a pyrite-rich porphyry ranging in composition from granodiorite to tonalite, but alkalic porphyries are locally important. In the southwestern United States, where porphyry copper deposits are abundant, associated igneous rocks are mainly Mesozoic and Cenozoic. Older plutonic, volcanic, sedimentary, and metamorphic rocks intruded by these porphyries also host ore minerals; the highest grades are found in reactive rocks such as limestone, or rocks, such as diabase, which contain abundant iron-rich minerals prior to alteration. Porphyry deposits exhibit a characteristic pattern of hydrothermal alteration, which includes biotite and K-feldspar assemblages in the center and grades outward to chlorite, actinolite, and epidote assemblages. Most deposits have a late-stage alteration assemblage that contains abundant white mica, clay, and carbonate minerals.

#### Examples

Bingham, Utah (Lanier and others, 1978); San Manuel, Ariz. (Lowell and Guilbert, 1970); El Salvador, Chile (Gustafson and Hunt, 1975).

#### Spatially and (or) genetically related deposit types

Related deposit types (Cox and Singer, 1986) include porphyry copper, skarn-related (Model 18a), base-metal skarn (Model 18c), porphyry copper-gold (Model 20c), porphyry copper-molybdenum (Model 21a), polymetallic vein (Model 22c), polymetallic replacement (Model 19a), volcanic-hosted copper-arsenic-antimony (Model 22a), quartz-alunite gold (Model 25e), distal disseminated silver-gold (Model 19c; Cox, 1992), and gold-skarn deposits.

#### Potential environmental considerations

Visual considerations include open pits and waste dumps from open-pit mining and from subsidence areas produced by underground block caving. Tailings from milling of ore can cause release of acid mine drainage from mine and waste dumps. Mill tailings are a source of dust. Emissions from smelters, mainly SO<sub>2</sub>, are a significant concern; many smelters are located considerable distances from deposits.

Statistical summaries (tables 1-11) show that, relative to commonly accepted crustal abundances, as many as 28 porphyry copper deposit-related elements (Ag, As, Au, B, Cd, Co, Cu, Cs, Fe, Hg, K, La, Li, Mn, Mo, Ni, Pb, Rb, S, Sb, Se, Sn, Sr, Te, Tl, U, V, W, and Zn) are locally to generally enriched in and around these deposits. Although any of these 28 elements might be deemed to be sufficiently enriched to produce potential environmental problems when dispersed into the area around a deposit, many of these enrichments are probably not important. In fact, only 10 of these elements (As, Cd, Cu, Fe, Mo, Pb, S, Sb, Te, and Zn) are likely to be present in sufficiently elevated concentrations to have associated environmental impact.

#### Exploration geophysics

The distribution of disseminated copper sulfide minerals and pyrite can be mapped using induced polarization; resistivity surveys may define low resistivity areas associated with altered sulfide-mineral-bearing rock (Elliot and MacLean, 1978; Pelton and Smith, 1976). Detailed magnetic surveys may also help delineate altered rock if contained magnetic minerals have been destroyed by alteration. Peripheral magnetite-bearing rocks, including magnetite-rich skarns, may produce magnetic anomaly highs around porphyry copper deposits (Grant, 1985). Regional magnetic and gravity anomalies may identify intrusions that host porphyry copper deposits; magnetic and gravity maps, as well as remote sensing images may show lineaments, associated with large faults, and clusters of intrusions that may host porphyry copper deposits (Carlson and Mabey, 1963; Raines, 1978; Turner and others, 1982; Abrams and others, 1983). Large alteration halos surrounding exposed porphyry copper deposits are easily identified on remote sensing images. Vegetation in the vicinity of buried porphyry copper deposits may be stressed by metal uptake. Remote sensing may identify buried deposits if associated stressed vegetation produces reflectance anomalies (Birnie and Francica, 1981; Knepper, 1989).

**Table 1.** Summary statistics for 326 samples of mostly unoxidized rocks from the hypogene zone of porphyry copper deposits, southern Arizona, with Cu  $\geq$  1,000 ppm (Maurice Chaffee, unpub. data).

[Most concentrations in parts per million; % following an element indicates weight percent data. N, not detected at lower limit of determination, in parentheses. L, detected at concentration less than lower limit of determination, in parentheses. Mean values based on unqualified values only. Most elements determined by semiquantitative spectroscopic analysis; except, "aa" following element symbol indicates atomic-absorption analysis; "inst" indicates specific-ion electrode (F), titrimetric (S), fluorometric (U) analysis. Leaders (--) indicate no meaningful value]

Element	Range of values		Geometric mean	Number unqualified	Percent unqualified
	Minimum	Maximum			
Ag	N(0.5)	30	1.3	308	94
As-aa	N(1)	500	5.5	296	91
Au-aa	N(0.002)	1.1	0.031	325	99.6
B	N(10)	200	18	269	83
Ba	150	3,000	740	326	100
Be	L(1)	2	1.1	250	77
Bi	N(10)	500	--	16	4.9
Ca %	L(0.05)	5.0	0.51	325	99.6
Cd	N(20)	150	--	4	1.2
Co	N(5)	70	18	319	98
Cr	N(10)	300	33	275	84
Cu	1,000	20,000	2,000	326	100
Cs	N(10)	150	20	233	71
F-inst <sup>1</sup>	300	1,000	440	32	100
Fe %	0.7	10	4.1	326	100
Hg-aa	N(0.02)	1.1	0.04	279	86
K-aa %	0.70	8.7	2.9	326	100
La	N(20)	150	46	323	99
Li	L(1)	200	11	323	99
Mg %	0.15	3.0	0.86	326	100
Mn	50	>5,000	630	325	99.6
Mo	N(5)	2,000	20	225	69
Na-aa %	N(0.1)	3.7	0.65	288	88
Ni	N(5)	150	22	311	95
Pb	10	5,000	49	326	100
Rb	70	70	170	326	100
S-inst	0.02	15.5	1.2	326	100
Sb-aa	N(1)	600	3.2	211	65
Sc	L(5)	50	13	325	99.6
Sn	N(10)	70	--	34	10
Sr	N(100)	1,000	260	286	88
Te-aa	N(0.01)	6,000	0.20	322	99
Ti %	0.10	1.0	0.41	326	100
Tl-aa	0.30	56	1.2	326	100
U-inst	0.14	30	1.2	326	100
V	20	700	110	326	100
W	N(50)	150	--	17	5.2
Y	N(10)	70	19	322	99
Zn-aa	5	17,000	130	326	100
Zr	30	500	140	326	100

<sup>1</sup>Fluorine determined in only 32 samples.

## References

Lowell and Guilbert (1970), Gustafson and Hunt (1975), Lanier and others (1978), and Titley, (1982).

## GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

### Deposit size

Tonnage estimates for the 90th, 50th, and 10th percentiles are respectively 19, 140, and 1,100 million metric tons (Singer and others, 1986).

### Host rocks

Host rocks include tonalite to monzogranite or syenitic porphyry and associated breccia pipes intruding granitic,

**Table 2.** Summary statistics for 247 samples of mostly unoxidized rocks from the hypogene zone of porphyry copper deposits, southern Arizona, with Cu <1,000 ppm (Maurice Chaffee, unpub. data).

[Most concentrations in parts per million; % following an element indicates weight percent data. N, not detected at lower limit of determination, in parentheses. L, detected at concentration less than lower limit of determination, in parentheses. Mean values based on unqualified values only. Most elements determined by semiquantitative spectroscopic analysis; except, "aa" following element symbol indicates atomic-absorption analysis; "inst" indicates specific-ion electrode (F), titrimetric (S), fluorometric (U) analysis. Leaders (--) indicate no meaningful value]

Element	Range of values		Geometric mean	Number unqualified	Percent unqualified
	Minimum	Maximum			
Ag	N(0.5)	7	0.71	115	47
As-aa	N(1)	650	6.2	240	97
Au-aa	N(0.002)	3.0	0.018	215	87
B	N(10)	150	17	209	85
Ba	100	3,000	660	247	100
Be	N(1)	2	1.1	220	89
Bi	N(10)	15	--	7	2.8
Ca %	L(0.05)	3.0	0.40	243	98
Cd	N(20)	20	--	1	0.4
Co	N(5)	150	17	241	98
Cr	N(10)	300	44	182	74
Cu	5	700	210	247	100
Cs	N(10)	100	23	202	82
F-inst <sup>1</sup>	300	600	420	11	100
Fe %	L(0.05)	10	3.6	246	99.6
Hg-aa	N(0.02)	0.60	0.04	201	81
K-aa %	L(0.1)	5.6	2.7	244	99
La	L(20)	100	45	245	99
Li	L(1)	100	13	245	99
Mg %	0.05	3.0	0.80	247	100
Mn	15	5,000	700	247	100
Mo	N(5)	300	12	91	37
Na-aa %	N(0.1)	2.7	0.61	211	85
Ni	N(5)	150	24	214	87
Pb	N(10)	1,500	42	245	99
Rb	70	500	170	247	100
S-inst	0.005	17.4	0.89	247	100
Sb-aa	N(1)	200	2.4	140	57
Sc	L(5)	30	13	245	99
Sn	N(10)	10	--	8	3.2
Sr	N(100)	1,000	260	175	71
Te-aa	N(0.01)	4.5	0.14	241	98
Ti %	0.10	1.0	0.39	247	100
Tl-aa	0.20	4.4	1.3	247	100
U-inst	0.09	7.4	1.0	247	100
V	10	300	87	247	100
W	N(50)	100	--	9	3.6
Y	N(10)	50	20	245	99
Zn-aa	L(5)	1,900	140	246	99.6
Zr	50	300	140	247	100

<sup>1</sup>Fluorine determined in only 11 samples.

volcanic, calcareous sedimentary, and other reactive rocks.

#### Surrounding geologic terrane

Porphyry copper deposits are in terranes composed of high-level intrusive rocks contemporaneous with abundant dikes, cupolas of batholiths, breccia pipes, and faults. Deposits may be covered by younger volcanic rocks or sedimentary basin fill.

#### Wall-rock alteration

Alteration zones (and mineral assemblages), from bottom, innermost zones outward are: sodic-calcic (oligoclase or albite, actinolite, and sphene), potassic (potassium feldspar, biotite, rutile, and pyrite or magnetite), to propylitic

**Table 3.** Summary statistics for 75 partly to completely oxidized rock samples from the supergene zone of porphyry copper deposits, southern Arizona, with Cu  $\geq$  1,000 ppm (Maurice Chaffee, unpub. data).

[Most concentrations in parts per million; % following an element indicates weight percent data. N, not detected at lower limit of determination, in parentheses. L, detected at concentration less than lower limit of determination, in parentheses. Mean values based on unqualified values only. Most elements determined by semi-quantitative spectroscopic analysis; except, "aa" following element symbol indicates atomic-absorption analysis; "inst" indicates specific-ion electrode (F), titrimetric (S), fluorometric (U) analysis. Leaders (--) indicate no meaningful value]

Element	Range of values		Geometric mean	Number unqualified	Percent unqualified
	Minimum	Maximum			
Ag	N(0.5)	150	1.2	70	93
As-aa	N(1)	400	31	72	96
Au-aa	0.002	0.11	0.017	75	100
B	10	300	31	75	100
Ba	200	5,000	630	75	100
Be	N(1)	2	1.1	52	69
Bi	N(10)	70	--	5	6.7
Ca %	L(0.05)	0.15	0.06	39	52
Cd	N(20)	100	--	9	12
Co	N(5)	150	32	74	99
Cr	N(10)	200	38	66	88
Cu	1,000	5,000	1,500	75	100
Cs	N(10)	50	15	34	45
F-inst <sup>1</sup>	100	800	380	9	100
Fe %	1.0	10	4.1	75	100
Hg-aa	N(0.02)	0.64	0.05	69	92
K-aa %	1.4	5.5	2.7	75	100
La	20	200	52	75	100
Li	L(1)	30	2.7	64	85
Mg %	0.02	2.0	0.29	75	100
Mn	10	1,000	63	75	100
Mo	N(5)	300	28	66	88
Na-aa %	N(0.1)	1.8	0.18	68	91
Ni	L(5)	200	32	73	97
Pb	20	10,000	150	75	100
Rb	70	300	160	75	100
S-inst	0.10	11.7	4.1	75	100
Sb-aa	N(1)	60	4.8	63	84
Sc	5	50	14	75	100
Sn	N(10)	20	12	50	67
Sr	N(100)	1,000	250	66	88
Te-aa	N(0.01)	3,000	1.0	74	99
Ti %	0.10	1.0	0.45	75	100
Tl-aa	1.1	140	2.9	75	100
U-inst	0.13	36	1.0	75	100
V	20	300	110	75	100
W	N(50)	50	--	2	2.7
Y	N(10)	70	18	59	79
Zn-aa	L(5)	9,000	230	74	99
Zr	70	300	150	75	100

<sup>1</sup>Fluorine determined in only 9 samples.

(oligoclase or albite, epidote or calcite, chlorite, rutile, and magnetite or pyrite). Phyllic (sericite, chlorite, rutile, and pyrite) and argillic (clay, sericite, chlorite, and pyrite) alteration may overprint early potassic assemblages. High-alumina alteration (pyrophyllite, alunite, andalusite, corundum, diaspore, clay, and sericite) may be present in upper part of some deposits. Propylitic or phyllic alteration zones commonly lie on the flanks of deposits.

#### Nature of ore

Ore consists of stockwork veinlets and disseminated copper minerals.

#### Deposit trace element geochemistry

Statistical summaries that provide elemental concentration ranges in hypogene and supergene zone rocks from

**Table 4.** Summary statistics for 168 partly to completely oxidized rock samples from the supergene zone of porphyry copper deposits, southern Arizona, with Cu <1,000 ppm (Maurice Chaffee, unpub. data).

[Most concentrations in parts per million; % following an element indicates weight percent data. N, not detected at lower limit of determination, in parentheses. L, detected at concentration less than lower limit of determination, in parentheses. Mean values based on unqualified values only. Most elements determined by semiquantitative spectroscopic analysis; except, "aa" following element symbol indicates atomic-absorption analysis; "inst" indicates specific-ion electrode (F), titrimetric (S), fluorometric (U) analysis. Leaders (--) indicate no meaningful value]

Element	Range of values		Geometric mean	Number unqualified	Percent unqualified
	Minimum	Maximum			
Ag	N(0.5)	15	1.0	118	70
As-aa	N(1)	450	20	166	99
Au-aa	N(0.002)	0.61	0.014	148	88
B	10	700	27	168	100
Ba	200	5,000	810	168	100
Be	N(1)	2	1.1	82	49
Bi	N(10)	20	--	10	6.0
Ca %	L(0.05)	0.5	0.07	80	48
Cd	N(20)	300	--	8	4.8
Co	N(5)	300	28	142	85
Cr	N(10)	300	51	153	91
Cu	10	700	190	168	100
Cs	N(10)	100	18	80	48
F-inst <sup>1</sup>	100	1,000	400	21	100
Fe %	1.0	15	3.6	168	100
Hg-aa	N(0.02)	0.60	0.06	149	89
K-aa %	0.7	5.0	2.5	168	100
La	20	100	48	168	100
Li	L(1)	50	3.0	130	77
Mg %	0.02	3.0	0.24	168	100
Mn	10	1,500	42	168	100
Mo	N(5)	300	12	118	70
Na-aa %	N(0.1)	2.3	0.20	142	85
Ni	N(5)	150	35	141	84
Pb	10	2,000	130	168	100
Rb	30	500	150	168	100
S-inst	0.030	12.7	2.7	168	100
Sb-aa	N(1)	140	3.1	141	84
Sc	L(5)	70	14	167	99
Sn	N(10)	50	13	66	39
Sr	N(100)	2,000	240	152	90
Te-aa	N(0.01)	2,000	0.48	166	99
Ti %	0.15	1.0	0.45	168	100
Tl-aa	0.55	80	2.7	168	100
U-inst	0.06	5.2	0.67	168	100
V	20	500	110	168	100
W	N(50)	100	--	13	7.7
Y	N(10)	150	17	154	92
Zn-aa	L(5)	22,000	74	166	99
Zr	70	500	160	168	100

<sup>1</sup>Fluorine determined in only 21 samples.

porphyry copper deposits of the western United States are presented in tables 1-8. The summaries have been constructed for subsets containing samples with either  $\geq 1,000$  or  $<1,000$  ppm copper; samples with copper contents  $\geq 1,000$  ppm are assumed to come from copper deposits and those with copper values  $<1,000$  ppm are assumed to be from areas surrounding the deposits (outer haloes). Data summarized are from published (Chaffee, 1992; 1994) and unpublished compilations (M.A. Chaffee, unpub. data, 1995).

A comparison of mean values for hypogene samples shows that Ag, Au, Cu, Fe, Mo, S, Sb, Te, and V have significantly higher mean values in the "ore" zone, whereas chromium and manganese have significantly higher values in the areas surrounding the "ore" zones (tables 1 and 2). Other elements considered are not significantly enriched or depleted in either zone. A similar comparison of mean values for samples from areas influenced by weathering and supergene enrichment shows a significant enrichment of Ag, As, Cu, Mn, Mo, S, Sb, Te, U, and Zn in secondarily-enriched ( $\geq 1,000$  ppm copper) copper zones, whereas barium and chromium are higher in the sur-

**Table 5.** Summary statistics for 39 rock samples from the Mount Margaret, Wash., porphyry copper deposit with Cu $\geq$ 1,000 ppm (Chaffee, 1994).

[Most concentrations in parts per million; % following an element indicates weight percent data. N, not detected at lower limit of determination, in parentheses. L, detected at concentration less than lower limit of determination, in parentheses. Mean values based on unqualified values only. Most elements determined by semi-quantitative spectroscopic analysis; except, "aa" following element symbol indicates atomic-absorption analysis; "cm" indicates colorimetric analysis. Leaders (--) indicate no meaningful value]

Element	Range of values		Geometric mean	Number unqualified	Percent unqualified
	Minimum	Maximum			
Ag	L(0.5)	5	1.1	38	97
As-aa	N(10)	50	19	9	23
Au-aa	N(0.002)	2.4	0.105	37	95
B	10	2,000	64	39	100
Ba	50	500	94	39	100
Be	N(1)	1	--	3	7.7
Bi-aa	N(1)	80	--	3	7.7
Ca %	0.05	1.0	0.60	39	100
Cd-aa	N(0.10)	1.7	0.23	25	64
Co	5	50	14	39	100
Cr	N(10)	30	16	37	95
Cu	1,000	15,000	2,000	39	100
Fe %	1.0	5.0	2.0	39	100
La	N(20)	200	38	19	49
Mg %	0.30	1.0	0.73	39	100
Mn	100	300	170	39	100
Mo	N(5)	300	38	35	90
Ni	10	70	22	39	100
Pb	N(10)	100	21	18	46
Sb-aa	N(1)	12	3.3	18	46
Sc	5	15	8.8	39	100
Sn	N(10)	10	10	9	23
Sr	N(100)	500	170	33	85
Te-aa	N(0.005)	0.60	0.035	26	67
Ti %	0.20	0.50	0.34	39	100
Tl-aa	0.05	0.70	0.21	39	100
V	50	200	81	39	100
W-cm	3	24	7.4	39	100
Y	L(10)	30	13	31	79
Zn-aa	5	170	43	39	100
Zr	30	200	69	39	100

rounding areas.

Elements with significantly higher concentrations in the supergene environment (table 3) with copper  $\geq$ 1,000 ppm, as compared to the high copper subset in the hypogene zone (table 1), include As, B, Co, Mo, Ni, S, Sb, Te, Tl, and Zn. Those significantly higher in the hypogene zone subset include Ba, Ca, Cu, Cs, F, Li, Mg, Mn, and Na.

Elemental abundances in hypogene and supergene samples from halo areas (tables 2 and 4) are very similar; As, B, Ba, Co, Ni, Pb, S, Sb, Te, Tl, and V have significantly higher mean values in the supergene zone and Ca, Cu, Cs, Li, Mg, Mn, Na, U, and Zn have higher mean values in the hypogene zone.

Samples from the Mount Margaret, Wash. deposit (tables 5 and 6), were mostly unaffected by weathering. Ag, Au, B, Cu, Mo, Pb, and W have significantly higher values in samples containing greater than 1,000 ppm copper, whereas As, Cd, Sb, Sr, and Te are higher in samples from outside the "ore" zone. Similarly, samples from the Kalamazoo deposit, Ariz. (tables 7 and 8), were almost unaffected by weathering. Ag, Au, B, Ce, Cu, F, Li, Mg, Mo, S, Sb, Se, V, and CO<sub>2</sub> abundances are significantly higher in the subset of samples that contains  $\geq$ 1,000 ppm copper, whereas Fe, Hg, Mn, Pb, Rb, Te, Tl, and Zn abundances are greater in samples from areas surrounding the "ore" zone.

One sample from Tanamá (table 9), Puerto Rico (Cox, 1985), with more than 4,000 ppm copper, have different metal concentrations in different mineral zones. The potassically altered chalcopyrite-magnetite zone (table 9) has higher manganese (700 ppm) and zinc (60 ppm) than the phyllic-altered chalcopyrite-pyrite zone (table 10), which has higher sulfur (2.3 weight percent) and selenium (6 ppm).

**Table 6.** Summary statistics for 28 rock samples from the Mount Margaret, Wash., porphyry copper deposit with Cu <1,000 ppm (Chaffee, 1994).

[Most concentrations in parts per million; % following an element indicates weight percent data. N, not detected at lower limit of determination, in parentheses. L, detected at concentration less than lower limit of determination, in parentheses. Mean values based on unqualified values only. Most elements determined by semi-quantitative spectroscopic analysis; except, "aa" following element symbol indicates atomic-absorption analysis; "cm" indicates colorimetric analysis. Leaders (--) indicate no meaningful value]

Element	Range of values		Geometric mean	Number unqualified	Percent unqualified
	Minimum	Maximum			
Ag	N(0.5)	3	0.70	18	64
As-aa	N(10)	100	23	12	43
Au-aa	N(0.002)	0.15	0.033	26	93
B	10	>2,000	37	27	96
Ba	30	200	86	28	100
Be	N(1)	N(1)	--	0	0
Bi-aa	N(1)	1	--	1	3.6
Ca %	L(0.05)	1.0	0.73	25	89
Cd-aa	N(0.10)	6.7	0.39	7	25
Co	N(5)	30	11	26	93
Cr	10	20	13	28	100
Cu	100	700	340	28	100
Fe %	0.7	5.0	1.9	28	100
La	N(20)	100	33	4	14
Mg %	0.10	1.0	0.57	28	100
Mn	50	500	150	28	100
Mo	N(5)	200	20	18	64
Ni	L(5)	30	17	27	96
Pb	N(10)	30	11	8	29
Sb-aa	N(1)	84	6.2	9	32
Sc	5	15	7.3	28	100
Sn	N(10)	20	11	6	21
Sr	N(100)	500	220	23	82
Te-aa	N(0.005)	0.80	0.062	18	64
Ti %	0.20	0.50	0.30	28	100
Tl-aa	N(0.05)	0.65	0.25	26	93
V	50	100	67	28	100
W-cm	2	15	5.6	28	100
Y	N(10)	20	11	14	50
Zn-aa	N(5)	1,100	40	27	96
Zr	50	500	87	28	100

#### Ore and gangue mineralogy and zonation

Primary minerals include chalcopyrite + pyrite ± bornite ± molybdenite. Gangue and alteration minerals are potassic (quartz + K-feldspar + biotite + anhydrite), grading outward to propylitic (albite, chlorite, epidote, calcite). Plagioclase in these assemblages can neutralize acid. Late-stage assemblages, which have significant acid generation capacity, include quartz + sericite + clay + pyrite ± alunite ± pyrophyllite. Assemblages commonly are superimposed. Late veins of chalcopyrite, bornite, enargite, tetrahedrite, galena, sphalerite, and barite are present in some deposits.

Important exceptions: Most porphyry copper-gold deposits contain chalcopyrite + magnetite ± bornite (Cox and Singer, 1992). Pyrite is abundant only in the outer phyllic alteration halo, or in the upper part of some deposits, in late-stage phyllic-altered rock. A breccia pipe in Oregon with porphyry copper affinities contains bornite, chalcopyrite, and essentially no pyrite; the main ferrous iron mineral is siderite (Stone, 1992).

#### Mineral characteristics

Porphyry has closely spaced quartz and feldspar phenocrysts in a fine grained, aplitic quartz-feldspar groundmass. Ore minerals are present in stockwork veinlets and as disseminated sulfide grains.

#### Secondary mineralogy

Weathered outcrops in high pH environments include copper carbonate, oxide, and silicate minerals. Most deposits that include abundant pyrite, create low pH environments in which leaching is intense; outcrops are greatly depleted

**Table 7.** Summary statistics for 121 rock samples from the Kalamazoo porphyry copper deposit, Ariz., with Cu>1,000 ppm (Chaffee, 1992).

[Most concentrations in parts per million; % following an element indicates weight percent data. N, not detected at lower limit of determination, in parentheses. L, detected at concentration less than lower limit of determination, in parentheses. Mean values based on unqualified values only. Most elements determined by semi-quantitative spectroscopic analysis; except, "aa" following element symbol indicates atomic-absorption analysis; xrf, indicates X-ray fluorescence analysis; inst indicates volumetric analysis (CQ, specific-ion electrode (F), titrimetric (S), colorimetric (Se). Leaders (--) indicate no meaningful data]

Element	Range of values		Geometric mean	Number unqualified	Percent unqualified
	Minimum	Maximum			
Ag	N(0.5)	15	1.1	59	49
Al-xrf %	4	9.5	6.5	121	100
As-cm	N(10)	1,200	16	49	40
Au-aa	N(0.02)	0.40	0.053	92	76
B	N(20)	200	49	22	18
Ba	100	2,000	660	121	100
Be	N(1.5)	3	1.7	81	67
Bi	N(10)	10	--	1	0.8
CO <sub>2</sub>	N(0.0003)	3.6	0.63	119	98
Ca %	0.07	3.0	0.56	121	100
Cd-aa	N(0.10)	25	0.37	102	84
Ce	N(200)	200	--	4	3.3
Co	L(5)	100	15	120	99
Cr	5	300	21	121	100
Cs	N(20)	30	8.3	27	22
Cu	1,000	30,000	2,800	121	100
F-inst	100	940	410	121	100
Fe %	0.7	7.0	2.3	121	100
Ga	15	30	19	121	100
Hg-aa	0.02	0.80	0.08	121	100
K-aa %	1.0	5.0	2.5	121	100
La	N(50)	100	61	61	50
Li-aa	15	1,100	47	121	100
Mg %	0.20	1.5	0.63	121	100
Mn	7	700	100	121	100
Mo	N(3)	1,000	22	104	86
Na-aa %	0.10	3.2	0.92	121	100
Nb	N(10)	30	12	57	47
Ni	L(5)	150	15	116	96
P-xrf	L(440)	2,400	1,100	106	88
Pb	N(10)	70	14	95	79
Rb	20	200	55	121	100
S-inst	0.29	9.4	1.69	121	100
Sb-cm	N(1)	1,500	10	49	40
Sc	L(5)	30	10	120	99
Se-inst	0.10	16	2.7	121	100
Si-xrf %	21	35	31	121	100
Sn	N(10)	15	10	15	12
Sr	50	700	150	121	100
Te-aa	N(0.10)	2.0	0.30	16	13
Ti %	0.15	0.50	0.26	121	100
Tl-aa	N(0.20)	4.2	0.47	104	86
V	30	300	90	121	100
W	N(100)	L(100)	--	0	0
Y	N(10)	70	23	97	80
Yb <sup>1</sup>	N(1)	7	2.3	105	95
Zn-aa	N(5)	1,100	21	118	98
Zr	30	300	93	121	100

<sup>1</sup>Yb determined in only 110 samples.



**Table 8.** Summary statistics for 162 rock samples from the Kalamazoo porphyry copper deposit, Ariz., with Cu <1,000 ppm (Chaffee, 1992).

[Most concentrations in parts per million; % following an element indicates weight percent data. N, not detected at lower limit of determination, in parentheses. L, detected at concentration less than lower limit of determination, in parentheses. Mean values based on unqualified values only. Most elements determined by semi-quantitative spectroscopic analysis; except, "aa" following element symbol indicates atomic-absorption analysis; xrf, indicates X-ray fluorescence analysis; inst indicates volumetric analysis (CQ, specific-ion electrode (F), titrimetric (S), colorimetric (Se). Leaders (--) indicate no meaningful data]

Element	Range of values		Geometric mean	Number unqualified	Percent unqualified
	Minimum	Maximum			
Ag	N(0.5)	3.0	0.83	13	8.0
Al-xrf %	3.3	11	5.5	162	100
As-cm	N(10)	80	15	46	28
Au-aa	N(0.02)	1.2	0.034	75	46
B	N(20)	70	28	15	9.3
Ba	70	3,000	590	162	100
Be	N(1.5)	7	2.0	140	86
Bi	N(10)	30	--	1	0.6
CO <sub>2</sub> -inst <sup>1</sup>	N(0.0003)	2.3	0.48	161	100
Ca %	0.05	3.0	0.46	162	100
Cd-aa	N(0.10)	2.0	0.33	141	87
Ce	N(200)	700	--	2	1.2
Co	N(5)	70	10	158	98
Cr	5	150	17	162	100
Cs	N(20)	30	7.1	45	28
Cu	10	700	270	162	100
F-inst	140	840	310	162	100
Fe %	0.3	10	3.3	162	100
Ga	7	30	18	162	100
Hg-aa	0.02	0.65	0.11	162	100
K-aa %	0.8	4.6	2.5	162	100
La	N(50)	300	62	80	49
Li-aa	10	770	31	162	100
Mg %	0.05	2.0	0.54	162	100
Mn	7	1,500	200	162	100
Mo	N(3)	30	4.2	96	59
Na-aa %	0.10	2.6	0.91	162	100
Nb	N(10)	30	15	110	68
Ni	N(5)	70	13	153	94
P-xrf	L(440)	2,200	1,000	152	94
Pb	N(10)	1,000	27	151	93
Rb	30	200	96	162	100
S-inst	0.010	22	0.98	161	99
Sb-cm	N(1)	20	2.1	80	49
Sc	N(5)	30	11	160	99
Se-inst	L(0.10)	10	1.0	159	98
Si-xrf %	20	37	31	162	100
Sn	N(10)	10	--	3	1.9
Sr	30	700	120	162	100
Te-aa	N(0.10)	3.5	0.62	63	39
Ti %	0.03	1.0	0.27	162	100
Tl-aa	L(0.20)	3.3	0.74	160	99
V	L(7)	150	71	160	99
W	L(100)	200	--	5	3.1
Y	L(10)	150	28	148	91
Yb <sup>2</sup>	N(1)	10	3.9	140	86
Zn-aa	N(5)	900	38	160	99
Zr	30	500	110	162	100

<sup>1</sup>CO<sub>2</sub> determined in only 161 samples.

<sup>2</sup>Yb determined in only 143 samples.

**Table 9.** Summary statistics for 18 samples of mostly unoxidized rocks from the chalcopyrite-magnetite zone of the Tanamá porphyry copper deposit, Puerto Rico. Data, in ppm unless otherwise noted, from Cox (1985); N, not detected at indicated abundance.

Element	Minimum	Maximum	Median	Number unqualified	Percent unqualified
Ag	1	5	1.5	18	100
Au	0.2	0.95	0.36	18	100
Ba	150	500	200	18	100
Cu	4,400	15,600	6,700	18	100
Co	7	30	15	18	100
Cr	20	1,000	50	18	100
Mn	150	>5,000	700	18	100
Mo	N5	70	15	14	78
Ni	10	70	15	18	100
Pb	4	21	8	18	100
S %	0.4	8	1.5	18	100
Se	2	8	3	18	100
Te	<0.1	0.7	0.12	9	50
Ti	<0.2	0.76	0.3	12	67
Zn	17	2,300	60	18	100

**Table 10.** Summary statistics for 15 samples of mostly unoxidized rocks from the chalcopyrite-pyrite zone of the Tanamá porphyry copper deposit, Puerto Rico. Data, in ppm unless otherwise noted, from Cox (1985); N, not detected at indicated abundance.

Element	Minimum	Maximum	Median	Number unqualified	Percent unqualified
Ag	0.7	2	1.5	15	100
Au	0.18	0.65	0.36	15	100
Ba	150	500	200	15	100
Cu	4,300	13,000	8,400	15	100
Co	10	30	15	15	100
Cr	N20	70	30	14	93
Mn	50	700	200	15	100
Mo	N5	70	5	8	57
Ni	10	30	15	15	100
Pb	2	13	7	15	100
S %	0.6	5.6	2.3	15	100
Se	4	9	6	8	53
Te	<0.1	0.79	0.11	8	50
Ti	<0.2	0.68	0.34	10	67
Zn	9	270	36	15	100

**Table 11.** Summary statistics for soil samples from the B horizon above two distinct mineral zones in the Tanamá porphyry copper deposit, Puerto Rico. Data, in ppm, from Learned and others (1992).

Element	Magnetite zone				Pyrite zone			
	Maximum	Minimum	Median	Number of samples	Maximum	Minimum	Median	Number of samples
Cu	2,000	150	510	12	400	71	160	12
Pb	19	5	10	12	23	1	4	12
Zn	17	2	8	12	11	<1	5	12
Mo	50	<5	5	12	300	<5	20	12
Cd	2.4	0.7	1.4	12	3.5	0.4	1	12

in copper; other metals may be similarly affected. Leached copper is transported downward and deposited as secondary sulfide minerals at the water table or paleowater table. Deposits of secondary sulfide minerals contain chalcocite, covellite, as well as other  $\text{Cu}_2\text{S}$  and  $\text{CuS}$  minerals that replace pyrite and chalcopyrite.

#### Topography, physiography

Deposits are mainly in mountainous terrain, but in the southwestern United States they commonly are found partially or completely buried under Cenozoic basin fill deposits.

#### Hydrology

Potassic zone is commonly weakly jointed; phyllic and argillic zones are generally highly jointed and permeable to ground water.

#### Mining and milling methods

Deposits are generally mined by open pit methods; on average, about 1.49 tonnes of waste rock and overburden must be removed to obtain one tonne of ore (Phillips and Niemuth, 1993). Deep deposits are exploited by underground block caving. Oxidized ore buried by Cenozoic alluvium may be exploited by in-place leaching. Experiments with in-place leaching are being carried out at the Santa Cruz, Ariz., deposit which is buried beneath as much as 445 m of Cenozoic basin-fill sediment and conglomerate (Dillard, 1995).

During open pit mining, rock with low copper content that must be removed to recover ore is placed on waste dumps. Slightly higher grade rock is placed in dumps and leached with acid so that copper can be recovered from solutions collected at the toe of the dump. Richer ore is treated in several ways depending on its mineralogy. To recover copper from chalcopyrite ore, the ore is crushed and ground, mixed with organic compounds and water, and frothed by a stream of air bubbles Parsons (1933). Chalcopyrite adheres to surfaces of bubbles and floats to the surface where it is separated from pyrite and silicate and other minerals. Fine waste material is then circulated to tailings ponds. Chalcopyrite concentrate is roasted in a smelter to remove its sulfur. The resulting copper matte, containing about 99 weight percent copper, is sent to a refinery where it is dissolved electrolytically and reprecipitated as cathode copper, about 99.99 percent pure. Sulfur, produced in the smelter, is converted to acid and commonly recycled to leach copper from dumps.

Deeply oxidized porphyry copper deposits commonly have a leached, copper-poor cap underlain by an enriched zone amenable to acid leaching and recovery of copper by solvent extraction and electrowinning (SX-EW). This process (Lynch and others, 1994) produces cathode copper directly without fine grinding and attendant production of tailings, and without smelting and attendant release of sulfur-rich gas. Ore is leached in place, or mined, crushed, and placed on a leach pad on an impermeable base surface. Acid is applied at the top and copper-rich solution is extracted at the bottom. This solution is mixed with a synthetic organic compound that selectively extracts copper. Barren acid leach solutions are returned to the leach pad and the organic compound is mixed with concentrated acid that recovers copper. The organic compound is returned and mixed with more copper-rich leach solution. The copper-rich acid is sent to the electrowinning cell where pure copper is electroplated onto a cathode. Sulfur resulting from this process is converted to acid and returned to the leach pad.

Application of the SX-EW process depends on ore mineralogy (Lynch and others, 1994). Ore that contains azurite, malachite, tenorite, brochantite, and atacamite can be leached with dilute sulfuric acid. Ore with chalcocite, covellite, cuprite, native copper, and bornite can be leached with acid-ferric iron solutions into which sulfur-oxidizing bacteria are introduced. Chalcopyrite is leached slowly by strong acids and bacteria. Ore that contains acid-consuming minerals such as calcite can be leached with ammonia. Production of by-product molybdenum or gold by acid leaching copper-molybdenum or copper-gold porphyry ore has not yet been achieved, but might be possible in the future.

### ENVIRONMENTAL SIGNATURES

#### Drainage signatures and metal mobility from solid mine wastes

Elements in surface materials may be remobilized by chemical leaching or mechanical weathering processes; those whose abundances in rock or soil are elevated can become similarly elevated in derivative materials. All elements present are transported away from porphyry system exposures by mechanical erosion; in addition, elements can be remobilized from subsurface rock by flowing ground water. However, three factors particularly influence the chemical environment in and around porphyry copper deposits: (1) host-rock chemistry, (2) the level of erosion in a given deposit, (3) the abundances of elements and various mineral species at a given erosion level.

The chemical, as well as the physical, nature of the host rocks in the vicinity of porphyry copper deposits influence the extent of associated chemical dispersion. Chemically reactive host rocks, such as limestone and dolomite, react with acidic solutions containing elements, such as copper and zinc, that are mobile in the low-pH environment commonly associated with a weathering porphyry copper deposit. Most other host-rock lithologies are relatively non-reactive to low-pH solutions and do not much affect solution-borne elements.

Porphyry copper deposit genesis typically produces zones containing concentrations of various elements and minerals (Chaffee, 1976a, 1982). Some elements and minerals tend to be concentrated in the core of a deposit, some in the main chalcopyrite zone, some in the pyrite halo, and some in the outermost parts of a deposit. Data in tables 1-8, for instance, indicate that the outer halo around the chalcopyrite zone may be enriched in the elements Ag, As, Au, B, Cu, Fe, B, Mo, Pb, S, Se, Te, Tl, and (or) Zn, whereas the inner parts of the same system have different abundances and distributions of ore-related elements. Thus, the environmental effects of a given porphyry copper deposit depend on the level of erosion.

Porphyry copper deposits commonly contain significant pyrite abundances. Pyrite is usually concentrated in a zone that is generally at the outer edge of the chalcopyrite zone. During weathering, pyrite decomposition produces a low pH environment and many mineral deposit-related elements react with the resulting acidic solutions and, in the absence of carbonate rocks, (1) co-precipitate locally with iron-oxide phases (for instance, molybdenum and tellurium), (2) form new minerals (for instance, chalcocite, covellite, native copper, malachite), or (3) precipitate on unweathered sulfide grains (chalcocite, covellite). All of these reactions significantly restrict dispersion of the elements affected. This process results a zone of supergene-enriched metals. In the absence of significant pyrite, weathering leaches Cu, Mo, and Zn, as well as B, Co, Mn, S, Se and major rock-forming elements such as Ca, Mg, and Na, from near-surface rocks and disperses them into the surrounding environment.

The interaction between a porphyry copper deposit and the environment is illustrated by a stream in the Globe mining district, Ariz. that was blocked by mill tailings, causing a lake to form. Water from this lake entered an alluvial aquifer by seepage; the aquifer and a stream to the north were contaminated. The results, as reported by Eychaner (1991) and Stollenwerk (1994), represent the chemical signature of a pyrite-rich porphyry copper deposit in the natural environment, although the pH in this case is much lower, and the dissolved metal content much higher, than would be expected in a natural weathering situation. The most contaminated ground water in the aquifer had a pH of 3.3, and contained about 9,600 mg/l sulfate, 2,800 mg/l iron, 300 mg/l aluminum, and 190 mg/l copper. As the plume traveled north through the aquifer, the concentration of constituents decreased as the plume interacted with alluvium and was diluted by uncontaminated water (ground water flowing upwards from lower basin-fill, water in uncontaminated streams that join the contaminated wash, and surface rain water). In all cases, mixing was not necessarily instantaneous, and uncontaminated water could flow parallel to the plume for hundreds of meters before mixing was complete. The large concentration of sulfate in acidic ground water has a significant effect on the speciation of aqueous cations: about 50 percent of Ca, Mg, Fe, Mn, Cu, Co, Ni, and Zn, and more than 80 percent of the aluminum, are transported as sulfate-ion pair complexes. The acid-water front, pH <5, has advanced through alluvium, which contained about 0.4 weight percent carbonate minerals, at a rate of 0.2 to 0.3 km/yr during the past several decades. One of the reactions modeled by Stollenwerk (1994) is dissolution of calcite and dolomite by acidic water and precipitation of large amounts of calcium as gypsum. Stollenwerk (1994) concluded that aluminum and pH exhibit the greatest potential for continued adverse effects to ground water quality. In a work plan written by Eychaner (unpublished data, 1989), he states, "In ground water systems the movement of acidic water is retarded by chemical reactions with the aquifer material, but the same reactions transform the aquifer and decrease its capacity to retard future contamination."

#### Soil, sediment signatures prior to mining

Data from Tanamá, Puerto Rico (Learned and others, 1992) show different metal abundances in the B-horizon of residual soil over magnetite-rich (1.4 weight percent S) and pyrite-rich (2.5 weight percent S) copper ore zones (table 11). These data illustrate how acid, which is released as pyrite oxidizes, leaches metals from soil. An exception is molybdenum, which is not readily leached in low pH environments. Chaffee and others (1981) indicate that stream sediment from the area draining the unmined Red Mountain porphyry copper deposit in arid southeastern Arizona contains elevated abundances of molybdenum, lead, and tellurium. The Mineral Butte and Vekol, Ariz., deposits are other, arid-climate porphyry copper deposits for which pre-mining geochemical data are available. Chaffee (1976b; table 1 and 1977; table 3) presents ranges, backgrounds, and geochemical anomaly thresholds for Mn, Cd, Cu, Co, F, Au, Pb, Bi, Hg, Mo, Ag, and Zn abundances in bedrock and residual soil samples collected in the vicinity of these deposits. Abundances of most of these elements are elevated in the vicinity of these deposits relative to

those characteristic of other geologic environments; these elevated abundances identify appropriate baseline geochemical values that may be useful in setting remediation standards for mines associated with this deposit type.

#### Potential environmental concerns associated with mineral processing

Acid drainage from waste dumps and dust from mill tailings are among the potential environmental concerns associated with mineral processing. Very few concerns are associated with SX-EW processing.

#### Smelter signatures

No data specific to the environmental effects of smelting ore from deposits of this type were identified. However, copper sulfide minerals are typically smelted and may produce SO<sub>2</sub>-rich and metal-rich emissions, which may increase acidity and foster accumulation of heavy metals in downwind areas.

#### Climate effects on environmental signatures

The effects of various climate regimes on the geoenvironmental signature specific to porphyry 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. Present surface and near-surface chemical relations and mineral assemblages may reflect pre-existing (wetter) climate in the southwest United States.

#### Geoenvironmental geophysics

Detailed induced polarization and (or) resistivity or electromagnetic surveys can identify low resistivity rocks associated with porous and permeable, clay-altered sulfide-mineral-bearing veins, fractures and faults, and breccia pipes that may be a source of acidic, metal-bearing water that results from oxidation of iron or copper sulfide minerals (King and Pesowski, 1993). Oxidation of sulfide minerals may create thermal anomalies identifiable by infrared surveys, shallow heat-flow probes, or self potential (Strangway and Holmer, 1966; Corry, 1985; Corwin, 1990). Acid- or metal-bearing water has low resistivity that can be identified with electromagnetic or direct current induced polarization and (or) resistivity surveys and ground penetrating radar (Greenfield and Stoyer, 1976; Davis and Annan, 1992; King and Pesowski, 1993). Structural and stratigraphic features such as bedrock topography, buried channels, permeable fault zones, and aquitards that affect water flow away from mine areas may be studied with electromagnetic, direct current resistivity, seismic refraction, and gravity surveys (Paterson 1995). Water flow may be monitored using self potential techniques (Corwin, 1990). Carefully designed and interpreted self potential surveys also may be useful in defining reduction-oxidation centers in tailings (Paterson, 1995). Remote sensing images derived from satellite or airborne surveys can be used to identify the distribution of alteration assemblages, which in turn help identify areas that may be sources of acidic and metal-bearing water; images derived from airborne surveys, such as AVIRIS, also may indicate the distribution of minerals that provide acid buffering capacity. Remote sensing can also be used to evaluate effects related to large scale open pit mining.

#### REFERENCES CITED

- Abrams, M.J., Brown, David, Lepley, Larry, and Sadowski, Ray, 1983, Remote sensing for porphyry copper deposits in southern Arizona: *Economic Geology*, v. 78, p. 591-604.
- Birnie, R.W., and Francica, J.R., 1981, Remote detection of geobotanical anomalies related to porphyry copper mineralization: *Economic Geology*, v. 76, p. 637-647.
- Carlson, J.E., and Mabey, D.R., 1963, Gravity and aeromagnetic maps of the Ely area, White Pine County, Nevada: U.S. Geological Survey Geophysical Investigations Map GP-392, scale 1:250,000.
- Chaffee, M.A., 1976a, The zonal distribution of selected elements above the Kalamazoo porphyry copper deposit, San Manuel district, Pinal County, Arizona: *Journal of Geochemical Exploration*, v. 5, no. 2, p.145-165.
- \_\_\_\_\_, 1976b, Geochemical exploration techniques based on distribution of selected elements in rocks, soils, and plants, Mineral Butte copper deposit, Pinal County, Arizona: U.S. Geological Survey Bulletin 1278-D, p. D1-D55.

- \_\_\_\_\_, 1977, Geochemical exploration techniques based on distribution of selected elements in rocks, soils, and plants, Vekol porphyry copper deposit, Pinal County, Arizona: U.S. Geological Survey Bulletin 1278-E, p. E1-E78.
- \_\_\_\_\_, 1982, A geochemical study of the Kalamazoo porphyry copper deposit, Pinal County, Arizona, *in* Titley, S.R., ed., *Advances in Geology of the Porphyry Copper Deposits, Southwestern North America*: Arizona University Press, Tucson, p. 211-224.
- \_\_\_\_\_, 1992, Data for four drill holes, Kalamazoo porphyry copper deposit, Pinal County, Arizona: U.S. Geological Survey Open-File Report 92-238-A, 50 p., and Report 92-238-B (diskette).
- \_\_\_\_\_, 1994, Data for four drill holes, Mount Margaret copper-molybdenum-gold deposit, Skamania County, Washington: U.S. Geological Survey Open-File Report 94-2-A, 10 p., and Report 94-2-B (diskette).
- Chaffee, M.A., Hill, R.H., Sutley, S.J., and Waterson, J.R., 1981, Regional geochemical studies in the Patagonia Mountains, Santa Cruz County, Arizona: *Journal of Geochemical Exploration*, v. 14, p. 135-153.
- Corry, C.E., 1985, Spontaneous polarization associated with porphyry sulfide mineralization: *Geophysics*, v. 50, no. 6 p. 1020-1034.
- Corwin, R.F., 1990, The self-potential method for environmental and engineering applications, *in* Ward, S.H., ed., *Geotechnical and environmental geophysics*, v.I: Tulsa, OK, Society of Exploration Geophysicists, p.127-145.
- Cox, D.P., 1985, Geology of the Tanama and Helecho porphyry copper deposits and their vicinity, Puerto Rico: U.S. Geological Survey Professional Paper 1327, 59 p.
- \_\_\_\_\_, 1986, Descriptive model of porphyry copper, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models*: U.S. Geological Survey Bulletin 1693, p. 76.
- \_\_\_\_\_, 1992, Descriptive model of distal disseminated Ag-Au deposits, *in* Bliss, J.D., ed., *Developments in mineral deposit modeling*: U.S. Geological Survey Bulletin 2004, p. 20-22.
- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- \_\_\_\_\_, 1992, Distribution of gold in porphyry copper deposits, *in* DeYoung, J.H., Jr., and Hammarstrom, J.M., eds., *Contributions to commodity geology research*: U.S. Geological Survey Bulletin 1877, p. C1-C14.
- Davis, J.L., and Annan, A.P., 1992, Applications of ground penetrating radar to mining, groundwater, and geotechnical projects: selected case histories: *in* Pilon, J., *Ground Penetrating Radar*: Geological Survey of Canada, Paper 90-4, p. 49-55.
- Dillard, Gary, 1995, Industry-government project has big potential: *Southwestern Paydirt*, no. 668, Feb. 1995, p. 4A-9A.
- Elliot, C.L., and MacLean, H., 1978, Induced-polarization depth penetration in exploring for porphyry coppers: *Arizona Geological Society Digest*, v. 11, p. 37-48.
- Eychaner, J.H., 1991, The Globe, Arizona, research site--contaminants related to copper mining in a hydrologically integrated environment, *in* Mallard, G.E., and Aronson, D.A., eds., *U.S. Geological Survey Toxic Substances Hydrology Program--Proceedings of the technical meeting*, Monterey, California, March 11-15, 1991: U.S. Geological Survey Water-Resources Investigations Report 91-4034, p. 439-447.
- Grant, F.S., 1985, Aeromagnetism, geology, and ore environments: *Geoexploration*, v. 23, no. 3, p. 303-362.
- Greenfield, R.J., and Stoyer, C.H., 1976, Monitoring ground-water contamination with geophysical methods: *Society of Mining Engineers, Transactions, American Institute of Mining Engineering*, v. 260, p. 20-28.
- Gustafson, L.B., and Hunt, J.P., 1975, The porphyry copper deposit at El Salvador, Chile: *Economic Geology*, v. 70, p. 857-912.
- King, A., and Pesowski, 1993, Environmental applications of surface and airborne geophysics in mining: *Canadian Institute of Mining and Metallurgy Bulletin*, v. 86, p. 58-67.
- Knepper, D.H., 1989, Mapping hydrothermal alteration with Landsat thematic mapper data, *in* Lee and others, eds., *Mineral deposits of North America*, v. 1, *Remote sensing in exploration geology*, Field trips for the 29th International Geological Congress: Washington, DC, American Geophysical Union, p. 13-21.
- Lanier, George, John, E.C., Swenson, A.J., Reid, Julia, Bard, C.E., Caddy, S.W., and Wilson, J.C., 1978, General geology of the Bingham mine, Bingham Canyon, Utah: *Economic Geology*, v. 73, p. 1228-1241.
- Learned, R.E., Pierce, H.A., and Pérez, Ileana, 1992, Analytical results and sample locality map of soil samples from the Tanama and Helecho porphyry copper deposits district, Municipios of Utuado and Adjuntas, Puerto Rico: U.S. Geological Survey Open-File Report 93-179, 34 p.
- Lowell, J.D., and Guilbert, J.M., 1970, Lateral and vertical alteration-mineralization zoning in porphyry copper deposits: *Economic Geology*, v. 65, p. 363-408.

- Lynch, A.J., Taylor, Alan, and Avendaño Varas, Carlos, 1994, Solvent extraction boom in Latin America: *Engineering and Mining Journal*, Dec. 1994, p. 18-21.
- Parsons, A.B., 1933, *The porphyry coppers*: New York, American Institute of Mining and Metallurgical Engineers, 581 p.
- Paterson, 1995, Application of geophysical methods to the detection and monitoring of acid mine drainage: *in* Bell, R.S., *Proceedings of the Symposium on the application of geophysics to engineering and environmental problems*: Orlando, Florida, April 23-26, Environmental and Engineering Geophysical Society, p. 181-189.
- Pelton, W.H., and Smith, P.K., 1976, Mapping porphyry copper deposits in the Philippines with IP: *Geophysics*, v. 41, no. 1, p. 106.
- Phillips, K.A., and Niemuth, N.J., 1993, *The primary copper industry of Arizona in 1991*: Phoenix, Arizona, Department of Mines and Mineral Resources, Special Report No. 18, 53 p.
- Raines, G.L., 1978, Porphyry copper exploration model for northern Sonora, Mexico: *U.S. Geological Survey Journal of Research*, v. 6, no. 1, p. 51-58.
- Singer, D.A., and Mosier, D.L., 1981, The relation between exploration economics and the characteristics of mineral deposits, *in* Ramsey, J.B., ed., *The economics of exploration for energy resources*: Greenwich, Conn., Jai Press Inc., p. 313-326.
- Singer, D.A., Mosier, D.L., and Cox, D.P., 1986, Grade-tonnage model of porphyry copper, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models*: U.S. Geological Survey Bulletin 1693, p. 77-81.
- Stollenwerk, K.G., 1994, Geochemical interactions between constituents in acidic ground water and alluvium in an aquifer near Globe, Arizona: *Applied Geochemistry*, v. 9, p. 353-369.
- Stone, B.G., 1992, *The Bornite project, Oregon: geology, technology and serendipity*: Northwest Mining Association 1992 Short Course, Tucson, Ariz., and Spokane, Wash., Porphyry copper model--regional talks and settings, 22 p.
- Strangway, D.W., and Holmer, R.C., 1966, The search for ore deposits using thermal radiations: *Geophysics*, v. 31, p. 225-224.
- Titley, S.R., 1982, *Advances in the geology of porphyry copper deposits, southwestern North America*: Tucson, University of Arizona Press, 555 p.
- Turner, R.L., Raines, G.L., Kleinkopf, M.D., 1982, Regional northeast-trending structural control of mineralization, northern Sonora, Mexico: *Economic Geology*, no. 77, v. 1, p. 25-37.