The environmental geochemistry of mineral deposits

ΠΜΣ - ΕΦΑΡΜΟΣΜΕΝΗ ΓΕΩΧΗΜΕΙΑ – ΜΕΤΑΛΛΕΥΤΙΚΗ ΔΡΑΣΤΗΡΙΟΤΗΤΑ

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16-12-2016

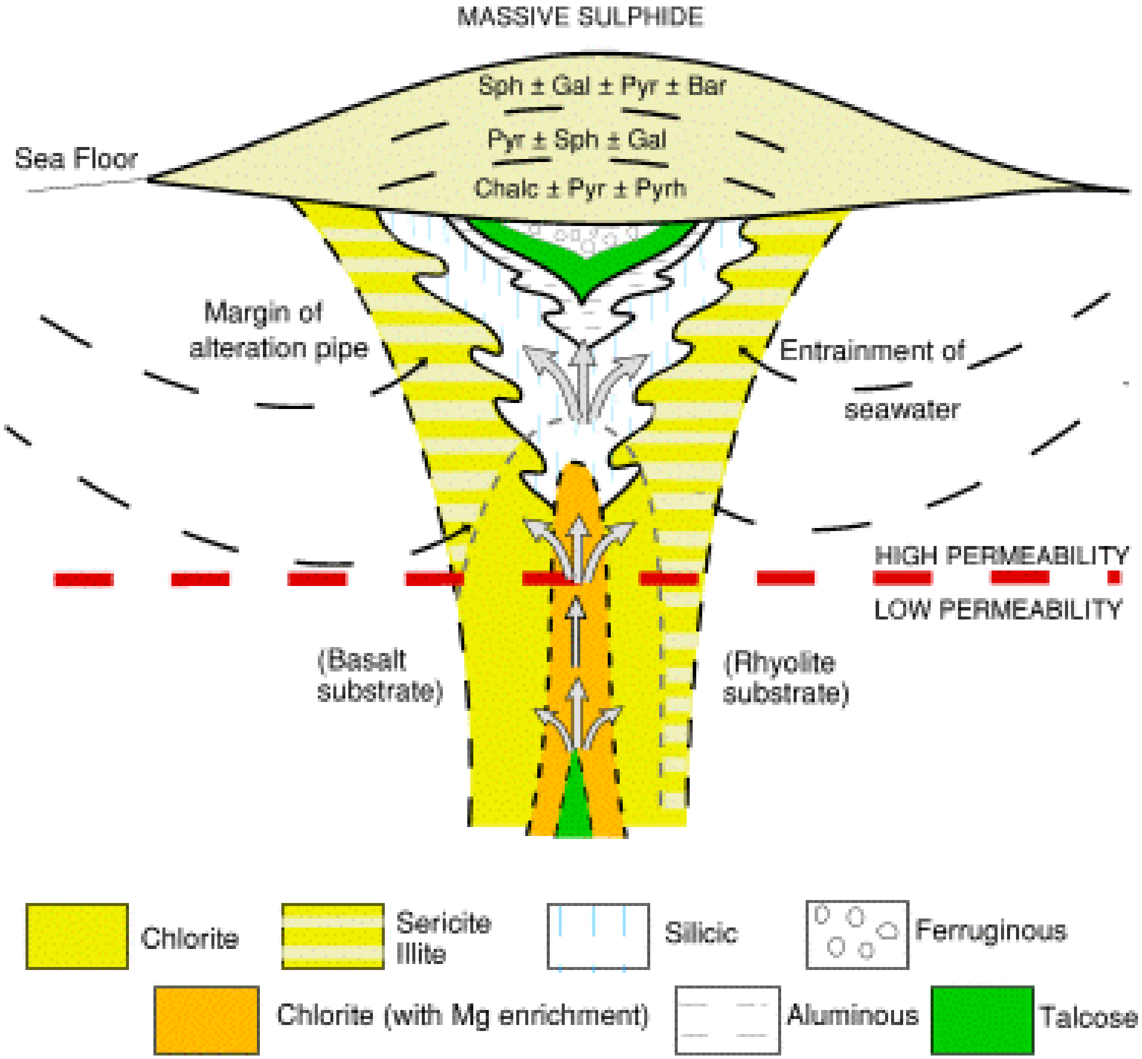
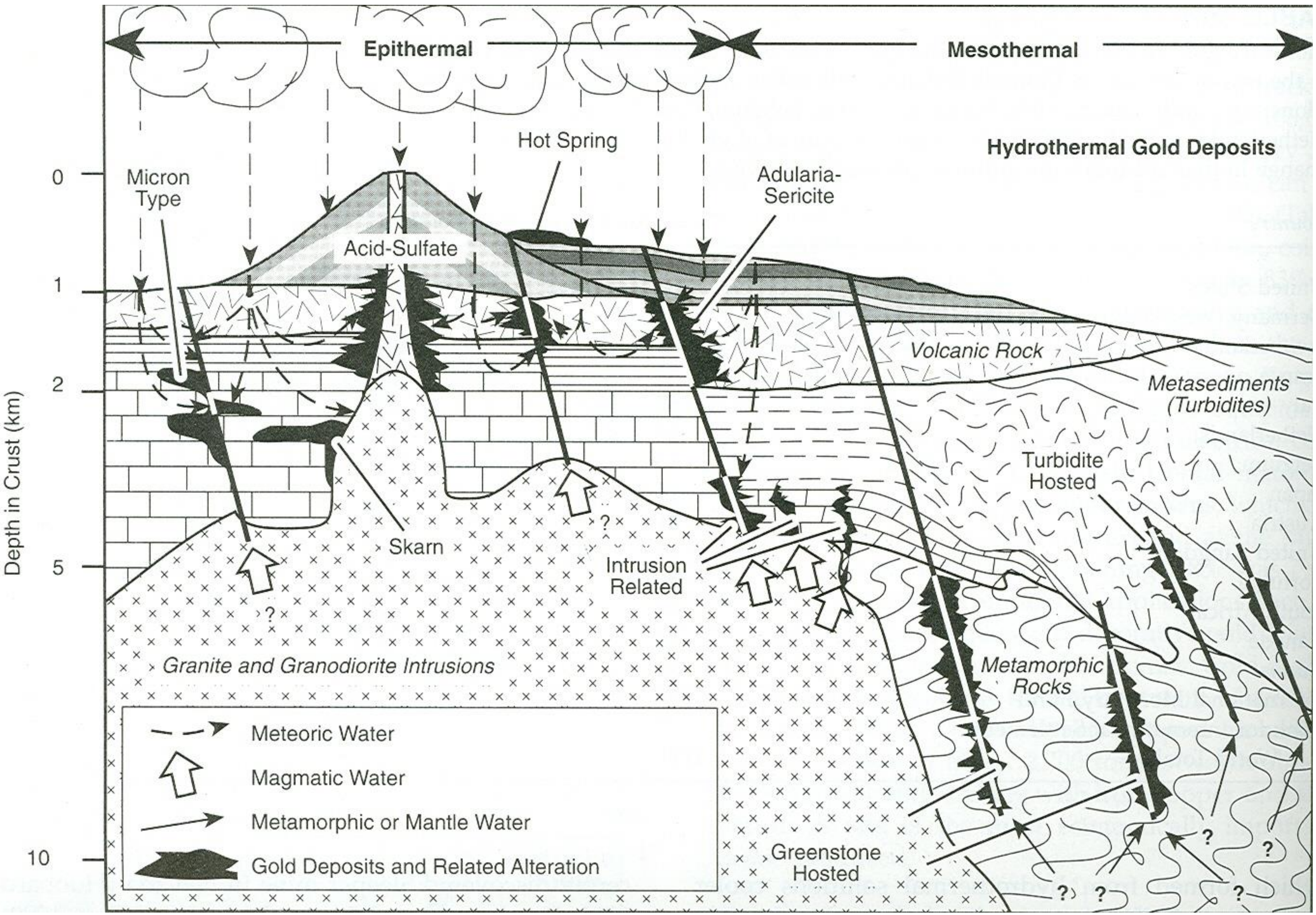


Fig. 1. The diagram illustrate some of the processes of convective seawater circulation and the respective mineral zones in the formation of hydrothermal mounds on the ocean floor


Epithermal
Mesothermal
Hydrothermal Gold Deposits
Hot Spring
Micron Type
Acid-Sulfate
Adularia-Sericite
Volcanic Rock
Metasediments (Turbidites)
Turbidite Hosted
Skarn
Intrusion Related
Metamorphic Rocks
Granite and Granodiorite Intrusions
Greenstone Hosted
?
Depth in Crust (km)
0
1
2
5
10
Meteoric Water
Magmatic Water
Metamorphic or Mantle Water
Gold Deposits and Related Alteration

Introduction

What are the geological controls?

- mineral deposit types

empirical geoenvironmental models of various mineral deposit types

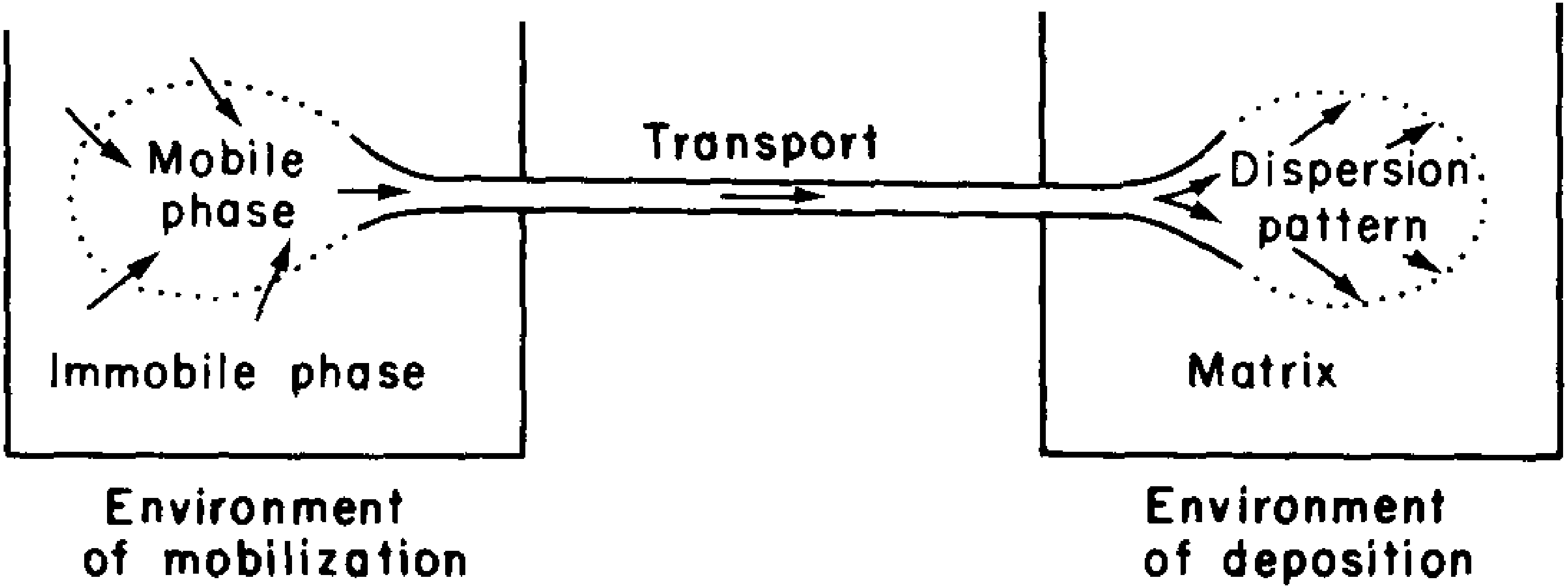


Fig. 2.2. The dispersion process.

Principle

The geologic characteristics of mineral deposits exert important and predictable controls on the natural environmental signatures of mineralized areas prior to mining, and on the environmental signatures that could result from mining and mineral processing if appropriate preventive and mitigative practices were not followed.

A good understanding of the environmental geology of mineral deposits is therefore crucial to the development of effective mining-environmental prediction, mitigation, and remediation practices.

Ορισμοί

- **Μετάλλευμα (Ore):** Ονομάζουμε μετάλλευμα, τον ειδικό τύπο πετρώματος που στη σύνθεσή του υπάρχουν ωφέλιμα ορυκτά, σε αναλογία τέτοια ώστε να μπορεί να αποκτήσει βιομηχανική σημασία και να εκμεταλλευθεί.

- **Εμφάνιση (mineral occurrence)**: Μη οικονομικά συμφέρουσα συγκέντρωση μεταλλικών ορυκτών, βιομηχανικών ορυκτών ή βιομηχανικών πετρωμάτων.

- **Κοίτασμα (ore deposit)**: Οικονομικά συμφέρουσα συγκέντρωση μεταλλικών ορυκτών, βιομηχανικών ορυκτών ή βιομηχανικών πετρωμάτων, ή γεωμετρικός χώρος που καταλαμβάνει μια οικονομικά συμφέρουσα μεταλλοφορία.

Ορισμοί

- **Τύπος κοιτάσματος**: Ομάδα κοιτασμάτων που έχουν παρόμοια γεωλογικά χαρακτηριστικά, γεωλογικά περιβάλλοντα εμφάνισης και γεωλογικές διεργασίες σχηματισμού (Gilbert and Park, 1986; Cox and Singer 1986; Bliss 1992).

1. Metallic Mineral Deposits

 # Magmatic deposits (e.g Ni-sulfides)

 # Magmatic hydrothermal deposits

- **porphyric**
- **skarn**
- **polymetalic replacement deposits**

 # Hydrothermal deposits

- **VMS**
- **Epithermal**
- **polymetalic vein**
- **Carlin-type sediment hosted Au**

1. Metallic Mineral Deposits

Supergene

Residual deposits

Placer deposits

Environmental geology characteristics of mineral deposits

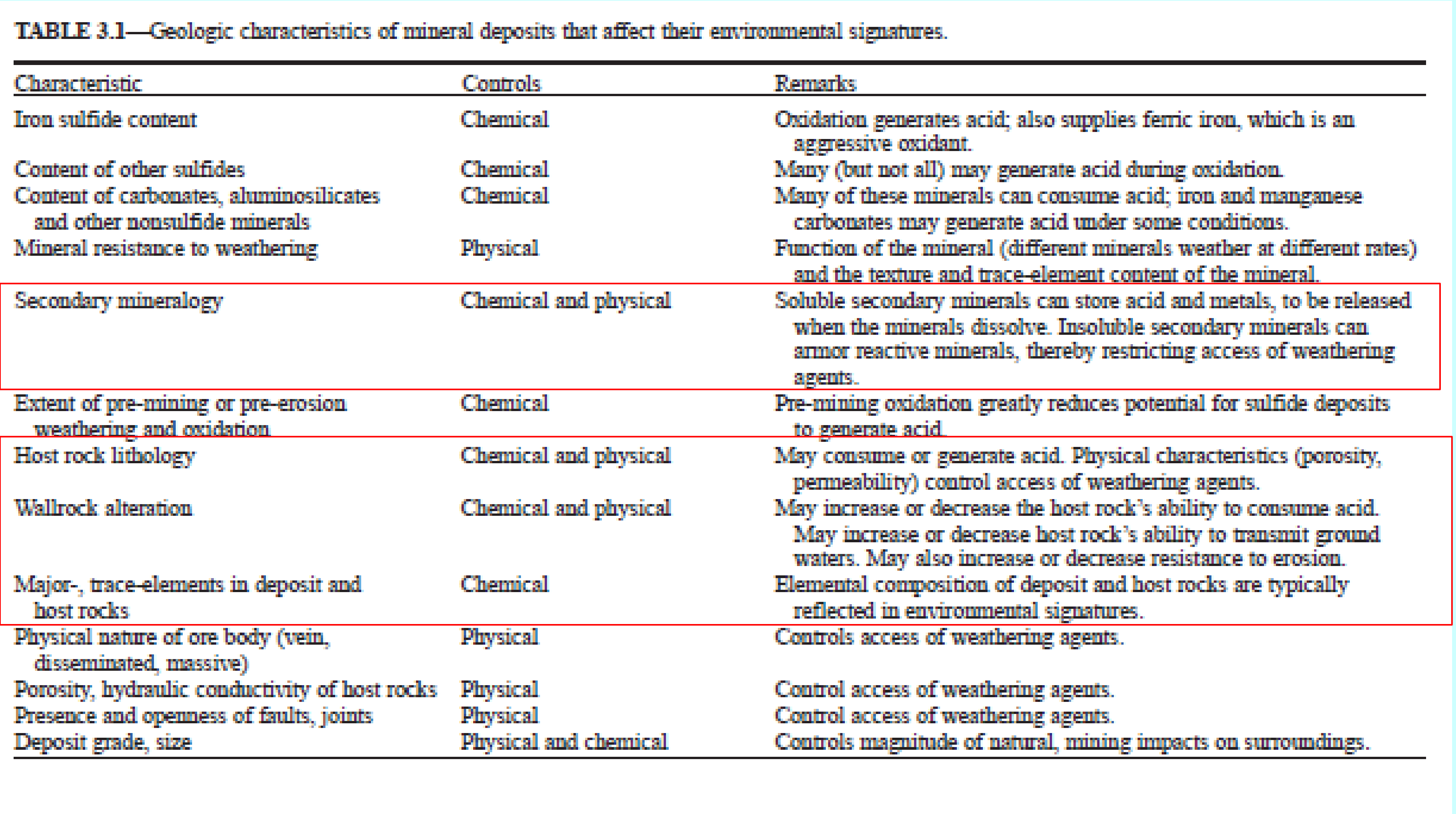


TABLE 3.1—Geologic characteristics of mineral deposits that affect their environmental signatures.

Characteristic	Controls	Remarks
Iron sulfide content	Chemical	Oxidation generates acid; also supplies ferric iron, which is an aggressive oxidant.
Content of other sulfides	Chemical	Many (but not all) may generate acid during oxidation.
Content of carbonates, aluminosilicates and other nonsulfide minerals	Chemical	Many of these minerals can consume acid; iron and manganese carbonates may generate acid under some conditions.
Mineral resistance to weathering	Physical	Function of the mineral (different minerals weather at different rates) and the texture and trace-element content of the mineral.
Secondary mineralogy	Chemical and physical	Soluble secondary minerals can store acid and metals, to be released when the minerals dissolve. Insoluble secondary minerals can armor reactive minerals, thereby restricting access of weathering agents.
Extent of pre-mining or pre-erosion weathering and oxidation	Chemical	Pre-mining oxidation greatly reduces potential for sulfide deposits to generate acid.
Host rock lithology	Chemical and physical	May consume or generate acid. Physical characteristics (porosity, permeability) control access of weathering agents.
Wallrock alteration	Chemical and physical	May increase or decrease the host rock's ability to consume acid. May increase or decrease host rock's ability to transmit ground waters. May also increase or decrease resistance to erosion.
Major-, trace-elements in deposit and host rocks	Chemical	Elemental composition of deposit and host rocks are typically reflected in environmental signatures.
Physical nature of ore body (vein, disseminated, massive)	Physical	Controls access of weathering agents.
Porosity, hydraulic conductivity of host rocks	Physical	Control access of weathering agents.
Presence and openness of faults, joints	Physical	Control access of weathering agents.
Deposit grade, size	Physical and chemical	Controls magnitude of natural, mining impacts on surroundings.

Reference: Reviews in economic geology, Volume 6, Part A (1999)

1. Primary mineralogy

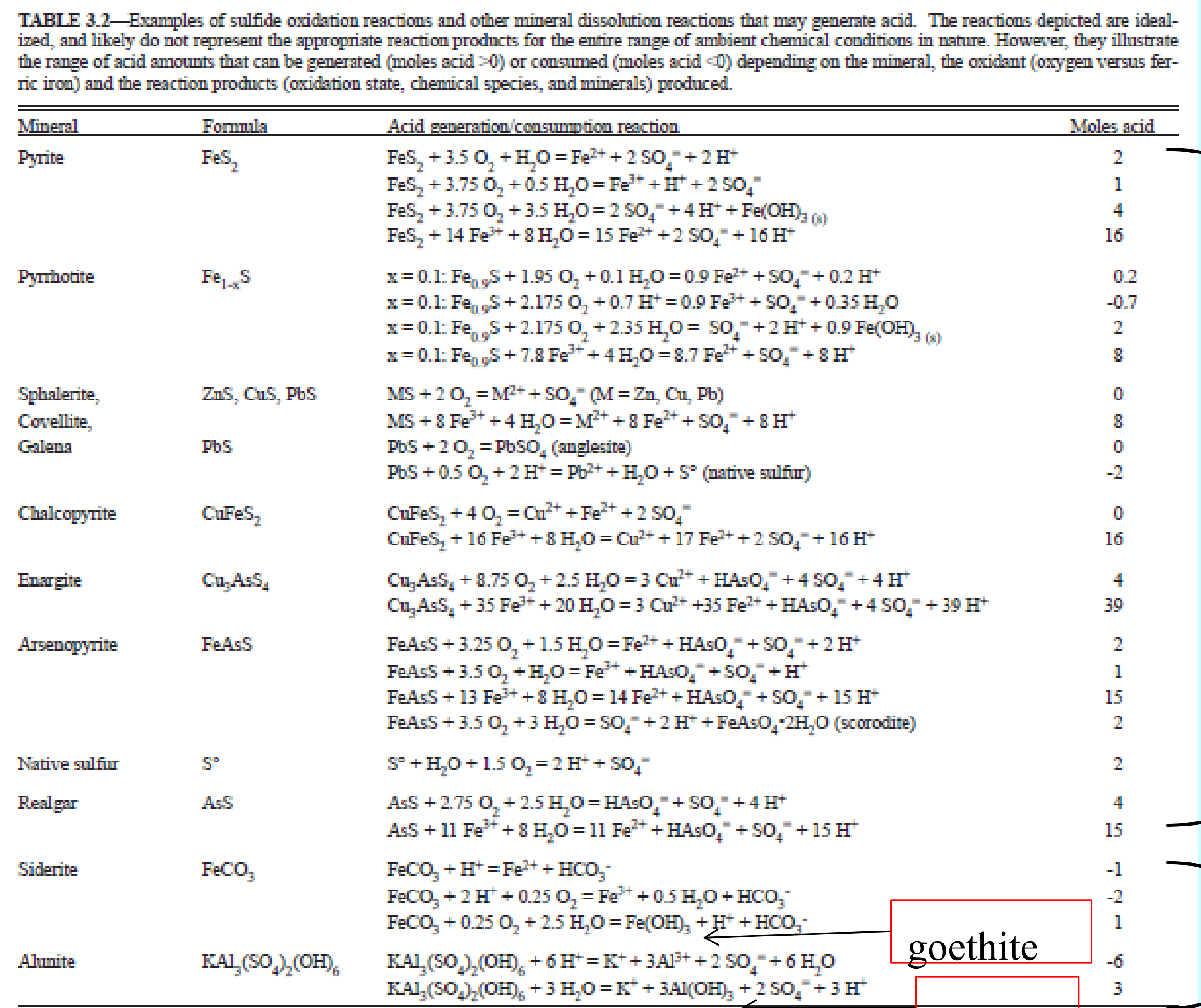


TABLE 3.2—Examples of sulfide oxidation reactions and other mineral dissolution reactions that may generate acid. The reactions depicted are idealized, and likely do not represent the appropriate reaction products for the entire range of ambient chemical conditions in nature. However, they illustrate the range of acid amounts that can be generated (moles acid >0) or consumed (moles acid <0) depending on the mineral, the oxidant (oxygen versus ferric iron) and the reaction products (oxidation state, chemical species, and minerals) produced.

Mineral	Formula	Acid generation/consumption reaction	Moles acid
Pyrite	FeS_2	$FeS_2 + 3.5\ O_2 + H_2O = Fe^{2+} + 2\ SO_4^{=} + 2\ H^+$	2
		$FeS_2 + 3.75\ O_2 + 0.5\ H_2O = Fe^{3+} + H^+ + 2\ SO_4^{=}$	1
		$FeS_2 + 3.75\ O_2 + 3.5\ H_2O = 2\ SO_4^{=} + 4\ H^+ + Fe(OH)_{3\ (s)}$	4
		$FeS_2 + 14\ Fe^{3+} + 8\ H_2O = 15\ Fe^{2+} + 2\ SO_4^{=} + 16\ H^+$	16
Pyrrhotite	$Fe_{1-x}S$	$x = 0.1$: $Fe_{0.9}S + 1.95\ O_2 + 0.1\ H_2O = 0.9\ Fe^{2+} + SO_4^{=} + 0.2\ H^+$	0.2
		$x = 0.1$: $Fe_{0.9}S + 2.175\ O_2 + 0.7\ H^+ = 0.9\ Fe^{3+} + SO_4^{=} + 0.35\ H_2O$	-0.7
		$x = 0.1$: $Fe_{0.9}S + 2.175\ O_2 + 2.35\ H_2O = SO_4^{=} + 2\ H^+ + 0.9\ Fe(OH)_{3\ (s)}$	2
		$x = 0.1$: $Fe_{0.9}S + 7.8\ Fe^{3+} + 4\ H_2O = 8.7\ Fe^{2+} + SO_4^{=} + 8\ H^+$	8
Sphalerite,	ZnS, CuS, PbS	$MS + 2\ O_2 = M^{2+} + SO_4^{=}$ (M = Zn, Cu, Pb)	0
Covellite,		$MS + 8\ Fe^{3+} + 4\ H_2O = M^{2+} + 8\ Fe^{2+} + SO_4^{=} + 8\ H^+$	8
Galena	PbS	$PbS + 2\ O_2 = PbSO_4$ (anglesite)	0
		$PbS + 0.5\ O_2 + 2\ H^+ = Pb^{2+} + H_2O + S°$ (native sulfur)	-2
Chalcopyrite	$CuFeS_2$	$CuFeS_2 + 4\ O_2 = Cu^{2+} + Fe^{2+} + 2\ SO_4^{=}$	0
		$CuFeS_2 + 16\ Fe^{3+} + 8\ H_2O = Cu^{2+} + 17\ Fe^{2+} + 2\ SO_4^{=} + 16\ H^+$	16
Enargite	Cu_3AsS_4	$Cu_3AsS_4 + 8.75\ O_2 + 2.5\ H_2O = 3\ Cu^{2+} + HAsO_4^{=} + 4\ SO_4^{=} + 4\ H^+$	4
		$Cu_3AsS_4 + 35\ Fe^{3+} + 20\ H_2O = 3\ Cu^{2+} + 35\ Fe^{2+} + HAsO_4^{=} + 4\ SO_4^{=} + 39\ H^+$	39
Arsenopyrite	FeAsS	$FeAsS + 3.25\ O_2 + 1.5\ H_2O = Fe^{2+} + HAsO_4^{=} + SO_4^{=} + 2\ H^+$	2
		$FeAsS + 3.5\ O_2 + H_2O = Fe^{3+} + HAsO_4^{=} + SO_4^{=} + H^+$	1
		$FeAsS + 13\ Fe^{3+} + 8\ H_2O = 14\ Fe^{2+} + HAsO_4^{=} + SO_4^{=} + 15\ H^+$	15
		$FeAsS + 3.5\ O_2 + 3\ H_2O = SO_4^{=} + 2\ H^+ + FeAsO_4 \cdot 2H_2O$ (scorodite)	2
Native sulfur	S°	$S° + H_2O + 1.5\ O_2 = 2\ H^+ + SO_4^{=}$	2
Realgar	AsS	$AsS + 2.75\ O_2 + 2.5\ H_2O = HAsO_4^{=} + SO_4^{=} + 4\ H^+$	4
		$AsS + 11\ Fe^{3+} + 8\ H_2O = 11\ Fe^{2+} + HAsO_4^{=} + SO_4^{=} + 15\ H^+$	15
Siderite	$FeCO_3$	$FeCO_3 + H^+ = Fe^{2+} + HCO_3^-$	-1
		$FeCO_3 + 2\ H^+ + 0.25\ O_2 = Fe^{3+} + 0.5\ H_2O + HCO_3^-$	-2
		$FeCO_3 + 0.25\ O_2 + 2.5\ H_2O = Fe(OH)_3 + H^+ + HCO_3^-$	1
Alunite	$KAl_3(SO_4)_2(OH)_6$	$KAl_3(SO_4)_2(OH)_6 + 6\ H^+ = K^+ + 3Al^{3+} + 2\ SO_4^{=} + 6\ H_2O$	-6
		$KAl_3(SO_4)_2(OH)_6 + 3\ H_2O = K^+ + 3Al(OH)_3 + 2\ SO_4^{=} + 3\ H^+$	3

goethite

I. Οξείδωση των σουλφιδίων παράγει οξύτητα

II. Σχηματισμός ένυδρων οξειδίων παράγει οξύτητα

Common acid generating minerals

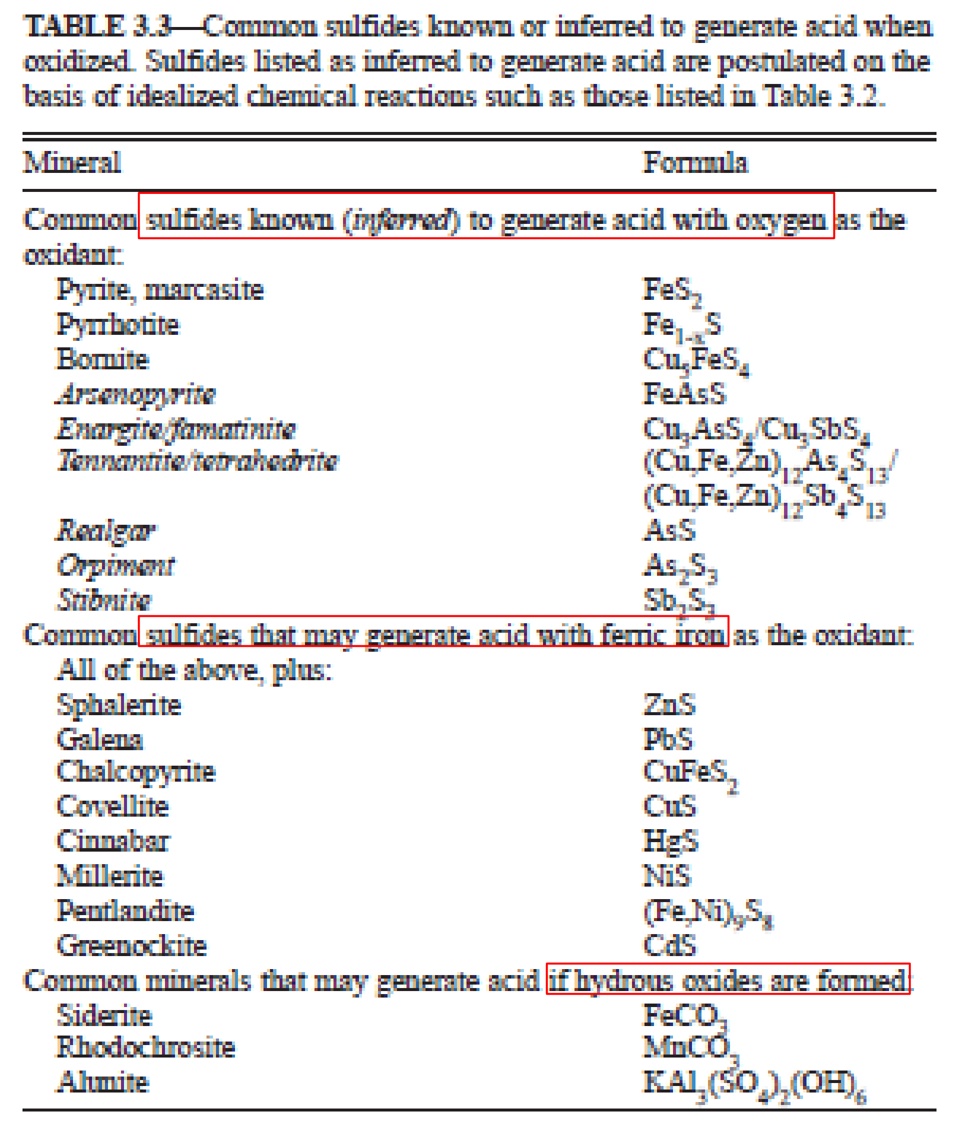
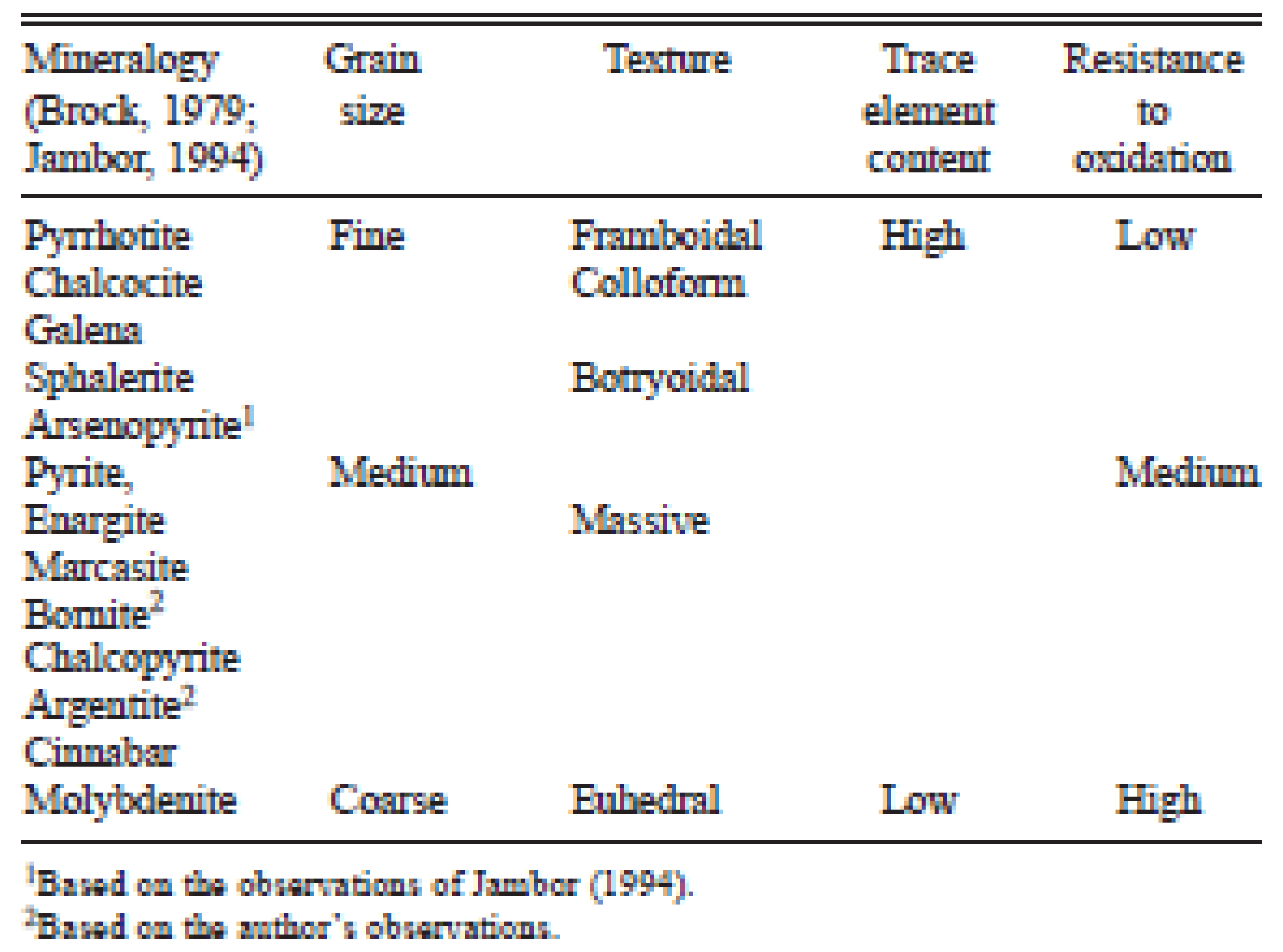


TABLE 3.3—Common sulfides known or inferred to generate acid when oxidized. Sulfides listed as inferred to generate acid are postulated on the basis of idealized chemical reactions such as those listed in Table 3.2.

Mineral	Formula
Common sulfides known (*inferred*) to generate acid with oxygen as the oxidant:	
Pyrite, marcasite	FeS_2
Pyrrhotite	$Fe_{1-x}S$
Bornite	Cu_5FeS_4
Arsenopyrite	$FeAsS$
Enargite/famatinite	Cu_3AsS_4/Cu_3SbS_4
Tennantite/tetrahedrite	$(Cu,Fe,Zn)_{12}As_4S_{13}/$ $(Cu,Fe,Zn)_{12}Sb_4S_{13}$
Realgar	AsS
Orpiment	As_2S_3
Stibnite	Sb_2S_3
Common sulfides that may generate acid with ferric iron as the oxidant:	
All of the above, plus:	
Sphalerite	ZnS
Galena	PbS
Chalcopyrite	$CuFeS_2$
Covellite	CuS
Cinnabar	HgS
Millerite	NiS
Pentlandite	$(Fe,Ni)_9S_8$
Greenockite	CdS
Common minerals that may generate acid if hydrous oxides are formed:	
Siderite	$FeCO_3$
Rhodochrosite	$MnCO_3$
Alunite	$KAl_3(SO_4)_2(OH)_6$

Factors affecting resistance of sulfides to oxidation

TABLE 3.4—Factors affecting resistance of sulfide minerals to oxidation,

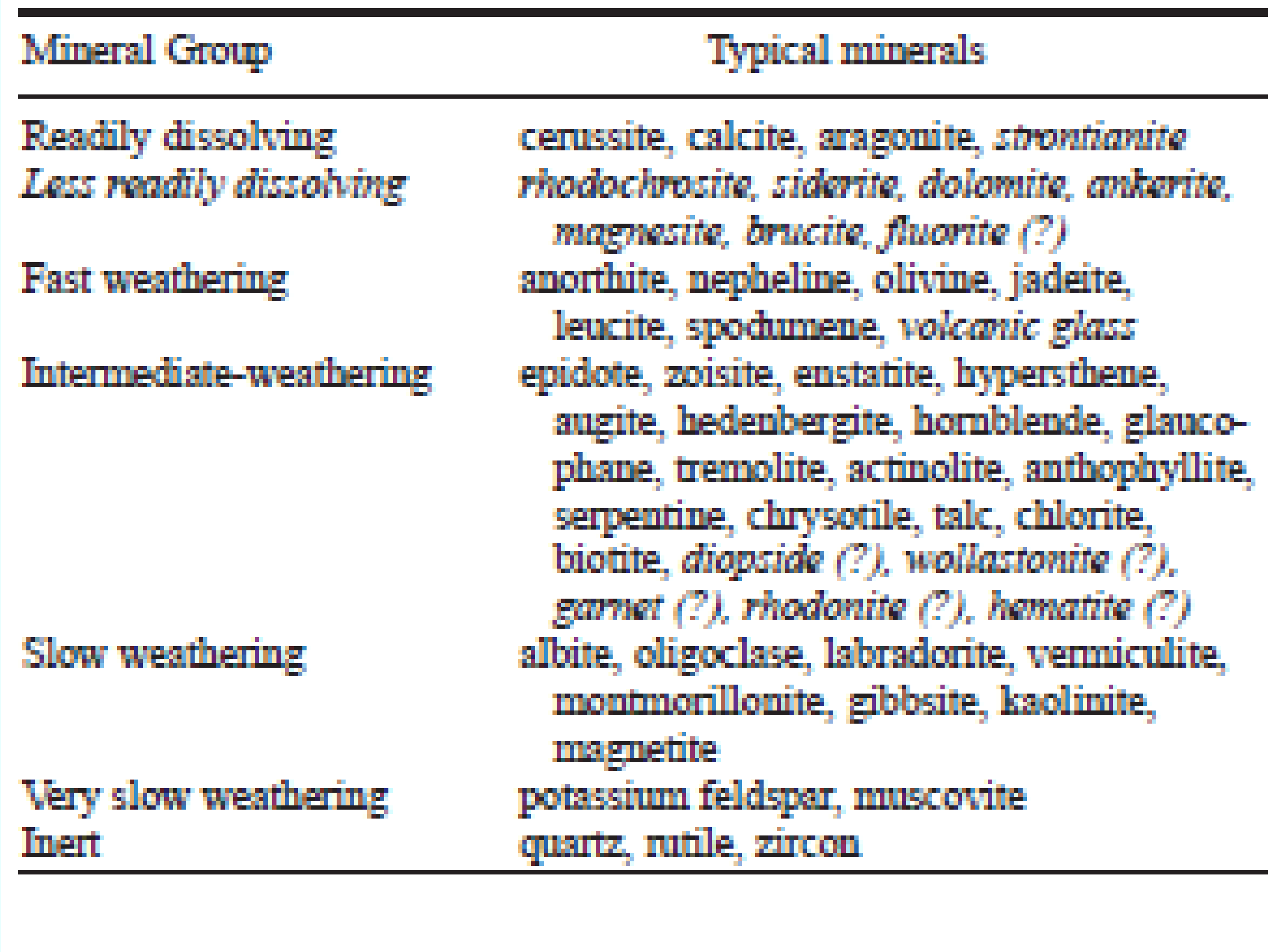


Mineralogy (Brock, 1979; Jambor, 1994)	Grain size	Texture	Trace element content	Resistance to oxidation
Pyrrhotite	Fine	Framboidal	High	Low
Chalcocite		Colloform		
Galena				
Sphalerite		Botryoidal		
Arsenopyrite[1]				
Pyrite,	Medium			Medium
Enargite		Massive		
Marcasite				
Bornite[2]				
Chalcopyrite				
Argentite[2]				
Cinnabar				
Molybdenite	Coarse	Euhedral	Low	High

[1] Based on the observations of Jambor (1994).

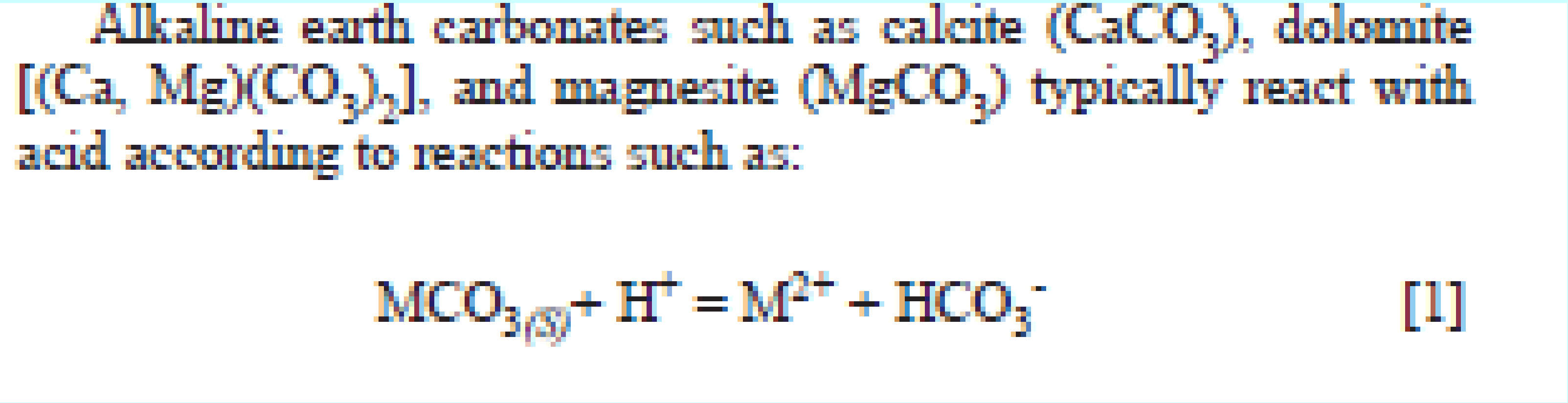
[2] Based on the author's observations.

Acid consuming minerals



Mineral Group	Typical minerals
Readily dissolving	cerussite, calcite, aragonite, *strontianite*
Less readily dissolving	*rhodochrosite, siderite, dolomite, ankerite, magnesite, brucite, fluorite (?)*
Fast weathering	anorthite, nepheline, olivine, jadeite, leucite, spodumene, *volcanic glass*
Intermediate-weathering	epidote, zoisite, enstatite, hypersthene, augite, hedenbergite, hornblende, glaucophane, tremolite, actinolite, anthophyllite, serpentine, chrysotile, talc, chlorite, biotite, *diopside (?), wollastonite (?), garnet (?), rhodonite (?), hematite (?)*
Slow weathering	albite, oligoclase, labradorite, vermiculite, montmorillonite, gibbsite, kaolinite, magnetite
Very slow weathering	potassium feldspar, muscovite
Inert	quartz, rutile, zircon

Acid consuming minerals



Alkaline earth carbonates such as calcite ($CaCO_3$), dolomite [(Ca, Mg)(CO_3)$_2$], and magnesite ($MgCO_3$) typically react with acid according to reactions such as:

$$MCO_{3(S)} + H^+ = M^{2+} + HCO_3^- \qquad [1]$$

Acid consuming minerals

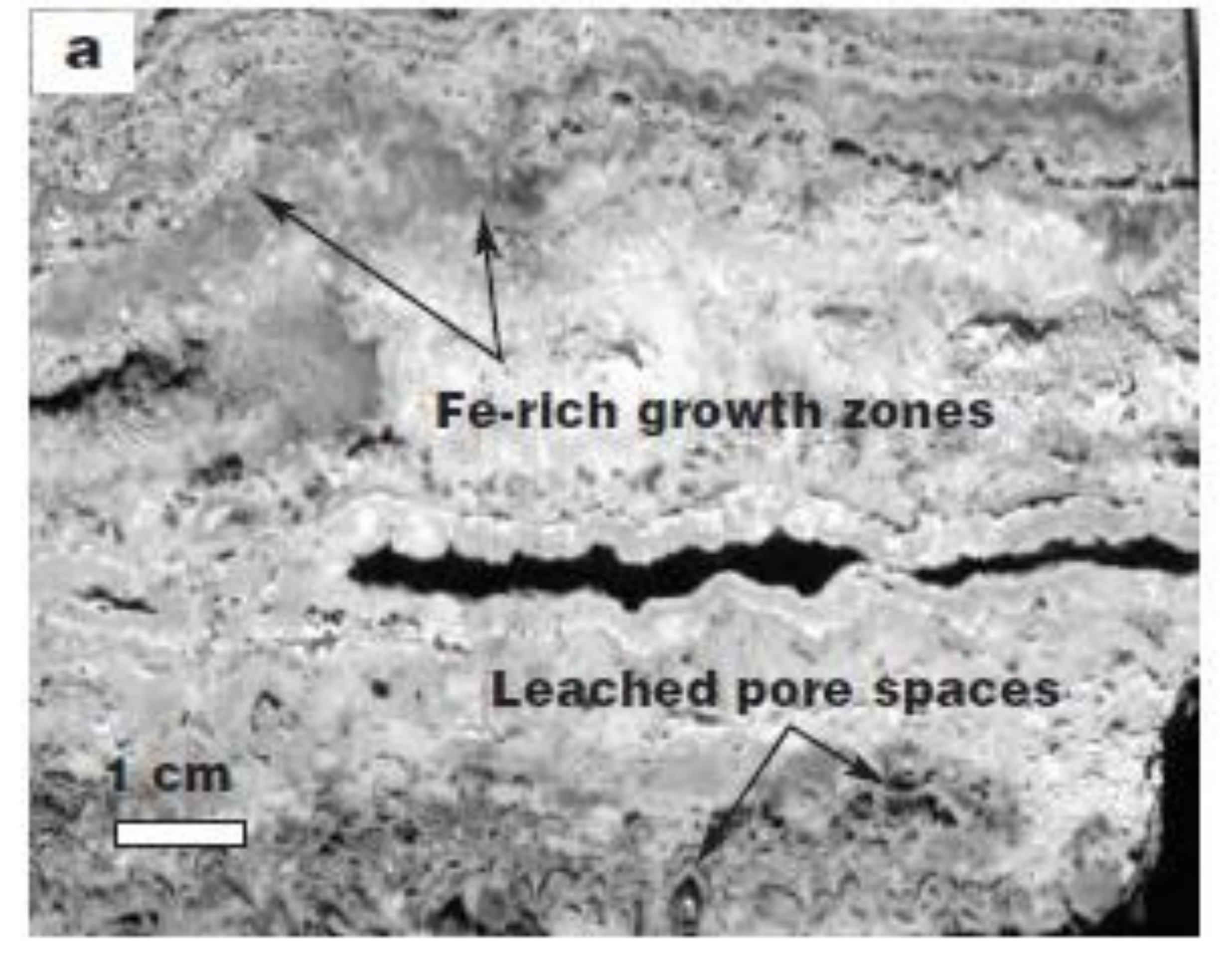
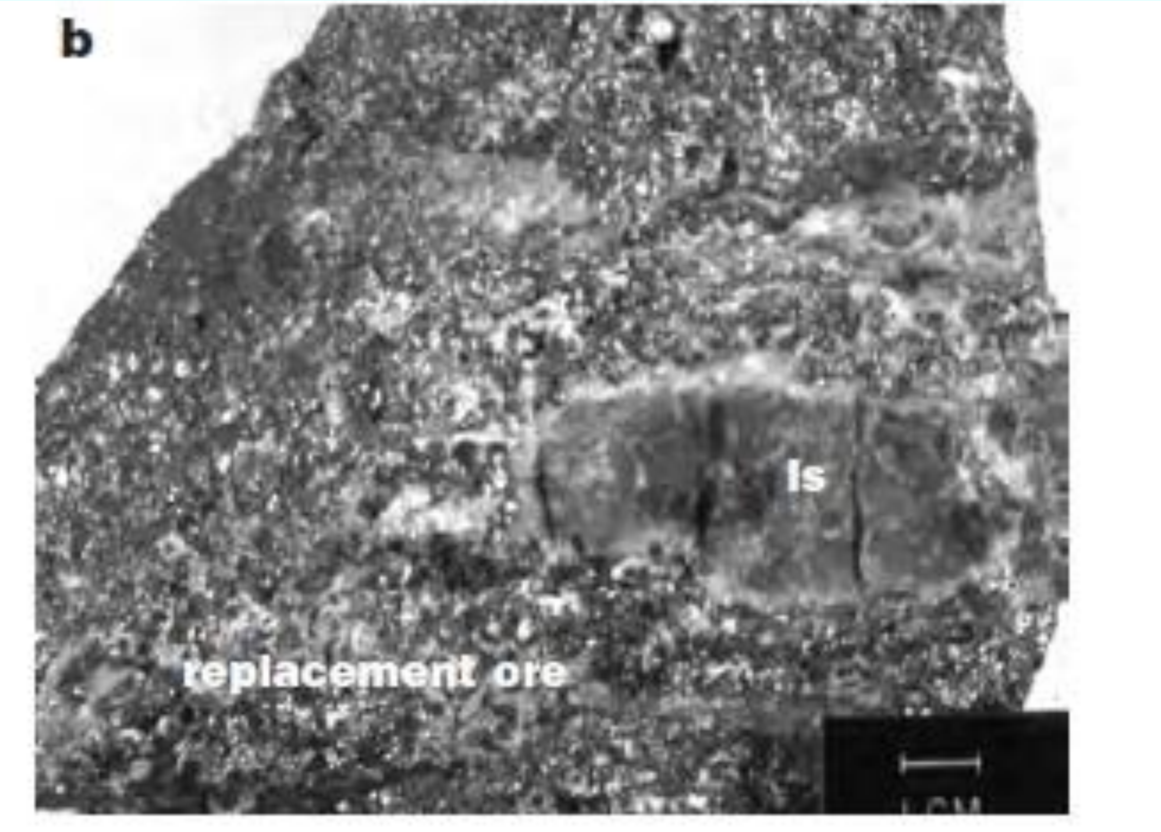


FIGURE 3.2—Examples of acid-consuming mineral assemblages. (a) Banded rhodochrosite, Creede, Colorado. Variations in color in part reflect va
ations in the Fe content of the rhodochrosite. The Fe preferentially oxidizes on the cut surface of the sample to form Fe-hydroxides. Some of t
rhodochrosite growth zones were subsequently leached by hydrothermal fluids, which produced the many dark pores in the sample. The dark open spa
stretching horizontally across the middle of the sample is a fracture with sides coated by later rhodochrosite that did not completely fill the fracture. (

Acid consuming minerals



b.

Sphalerite-galena-pyrite-calcite-silica ore (labeled replacement ore) replacing limestone, from the polymetallic replacement deposits at Leadvil Colorado. Remnant limestone fragment labeled ls. Due to the high pyrite and sphalerite content, this assemblage would most likely generate near-neutr pH drainage waters with elevated levels of zinc. Photograph by G. Landis.

2. Secondary mineralogy

- in the oxidized zone of weathering deposits

- below the water table of weathering sulfide deposits

-soluble secondary salts

- secondary ferricrete deposits

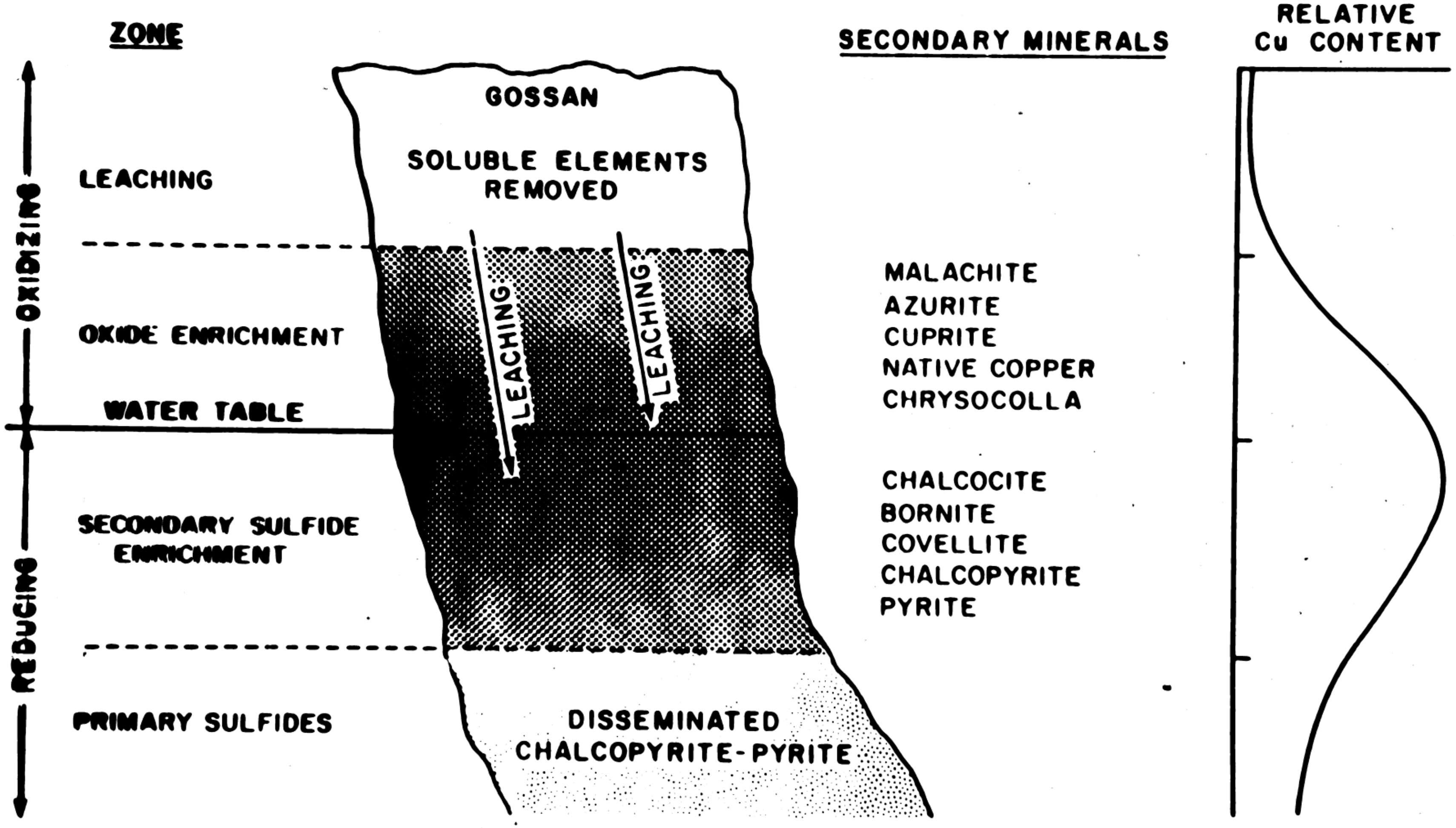


Fig. 3-1. Sketch of a gossan and zones of alteration after weathering of a copper sulfide vein. (Not shown is the thin layer of soil which is usually found over gossans except where they have been exposed by soil movement on slopes, glaciation, or other mechanisms.)

Mechanism of Supergene - hypogene enrichments

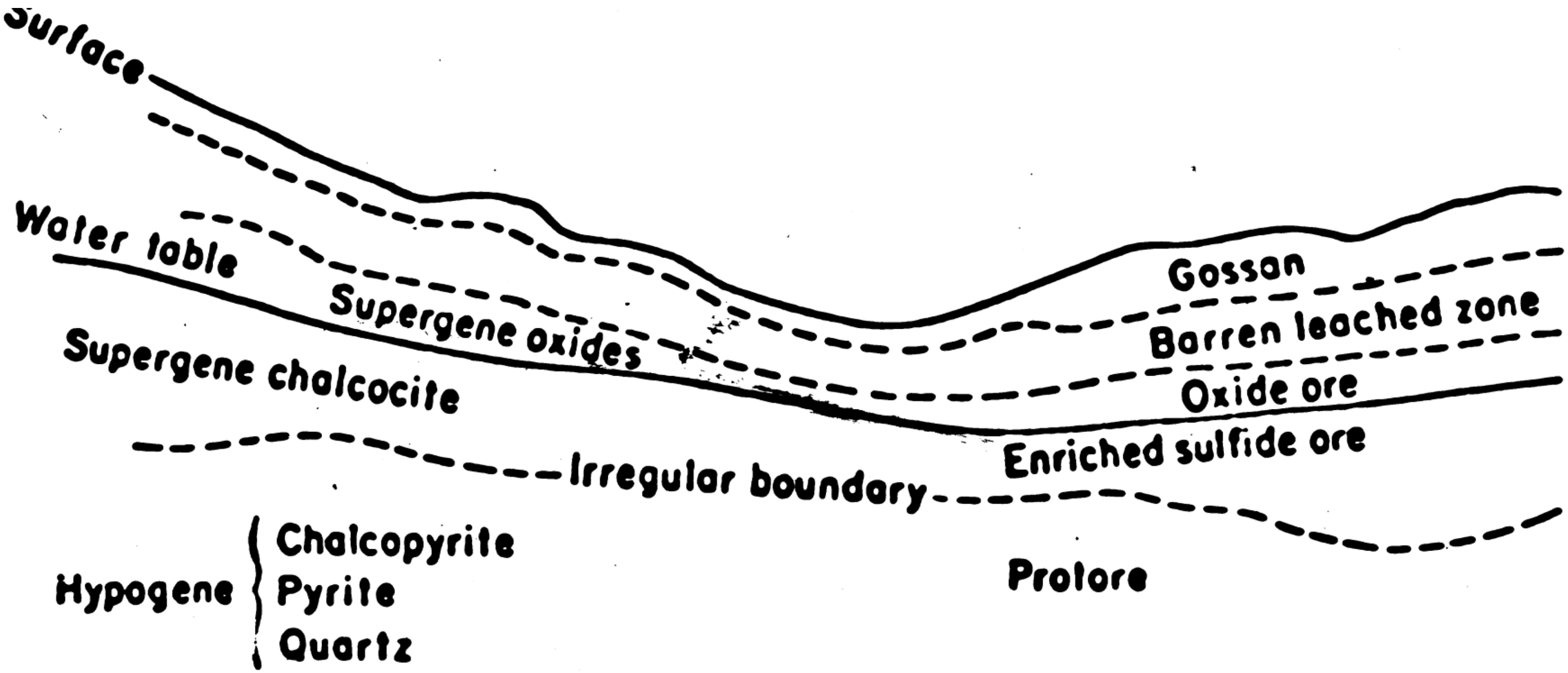


Figure 20-1
Diagrammatic sketch of a deposit containing chalcopyrite, pyrite, and quartz, showing the effects of weathering.

2. Secondary mineralogy

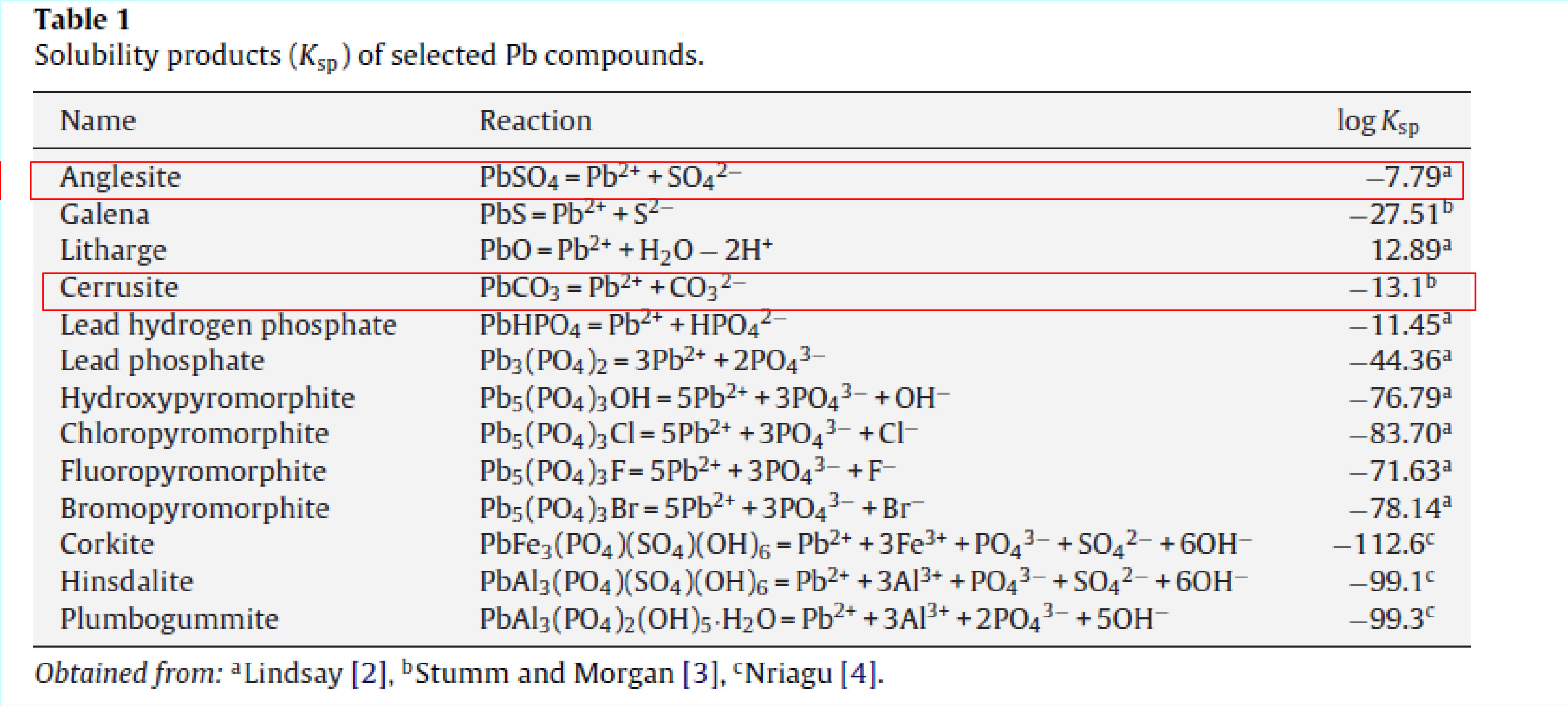


Table 1

Solubility products (K_{sp}) of selected Pb compounds.

Name	Reaction	log K_{sp}
Anglesite	$PbSO_4 = Pb^{2+} + SO_4{}^{2-}$	−7.79[a]
Galena	$PbS = Pb^{2+} + S^{2-}$	−27.51[b]
Litharge	$PbO = Pb^{2+} + H_2O - 2H^+$	12.89[a]
Cerrusite	$PbCO_3 = Pb^{2+} + CO_3{}^{2-}$	−13.1[b]
Lead hydrogen phosphate	$PbHPO_4 = Pb^{2+} + HPO_4{}^{2-}$	−11.45[a]
Lead phosphate	$Pb_3(PO_4)_2 = 3Pb^{2+} + 2PO_4{}^{3-}$	−44.36[a]
Hydroxypyromorphite	$Pb_5(PO_4)_3OH = 5Pb^{2+} + 3PO_4{}^{3-} + OH^-$	−76.79[a]
Chloropyromorphite	$Pb_5(PO_4)_3Cl = 5Pb^{2+} + 3PO_4{}^{3-} + Cl^-$	−83.70[a]
Fluoropyromorphite	$Pb_5(PO_4)_3F = 5Pb^{2+} + 3PO_4{}^{3-} + F^-$	−71.63[a]
Bromopyromorphite	$Pb_5(PO_4)_3Br = 5Pb^{2+} + 3PO_4{}^{3-} + Br^-$	−78.14[a]
Corkite	$PbFe_3(PO_4)(SO_4)(OH)_6 = Pb^{2+} + 3Fe^{3+} + PO_4{}^{3-} + SO_4{}^{2-} + 6OH^-$	−112.6[c]
Hinsdalite	$PbAl_3(PO_4)(SO_4)(OH)_6 = Pb^{2+} + 3Al^{3+} + PO_4{}^{3-} + SO_4{}^{2-} + 6OH^-$	−99.1[c]
Plumbogummite	$PbAl_3(PO_4)_2(OH)_5{\cdot}H_2O = Pb^{2+} + 3Al^{3+} + 2PO_4{}^{3-} + 5OH^-$	−99.3[c]

Obtained from: [a]Lindsay [2], [b]Stumm and Morgan [3], [c]Nriagu [4].

Secondary mineralogy

1. <u>Processes</u> leading to precipitation of secondary minerals (Alpers et al. 1994):

- evaporation
- oxidation
- reduction
- dilution
- mixing
- neutralization

2. Common secondary minerals (Seal and Foley 2002):

- efflorescent sulfate salts
- metal oxides, hydroxides
- hydrosulfates
- sulfides

Main processes

Dissolution and **precipitation** of secondary minerals is an important mechanism for recycling metals and acidity (H+) in surficial environments.

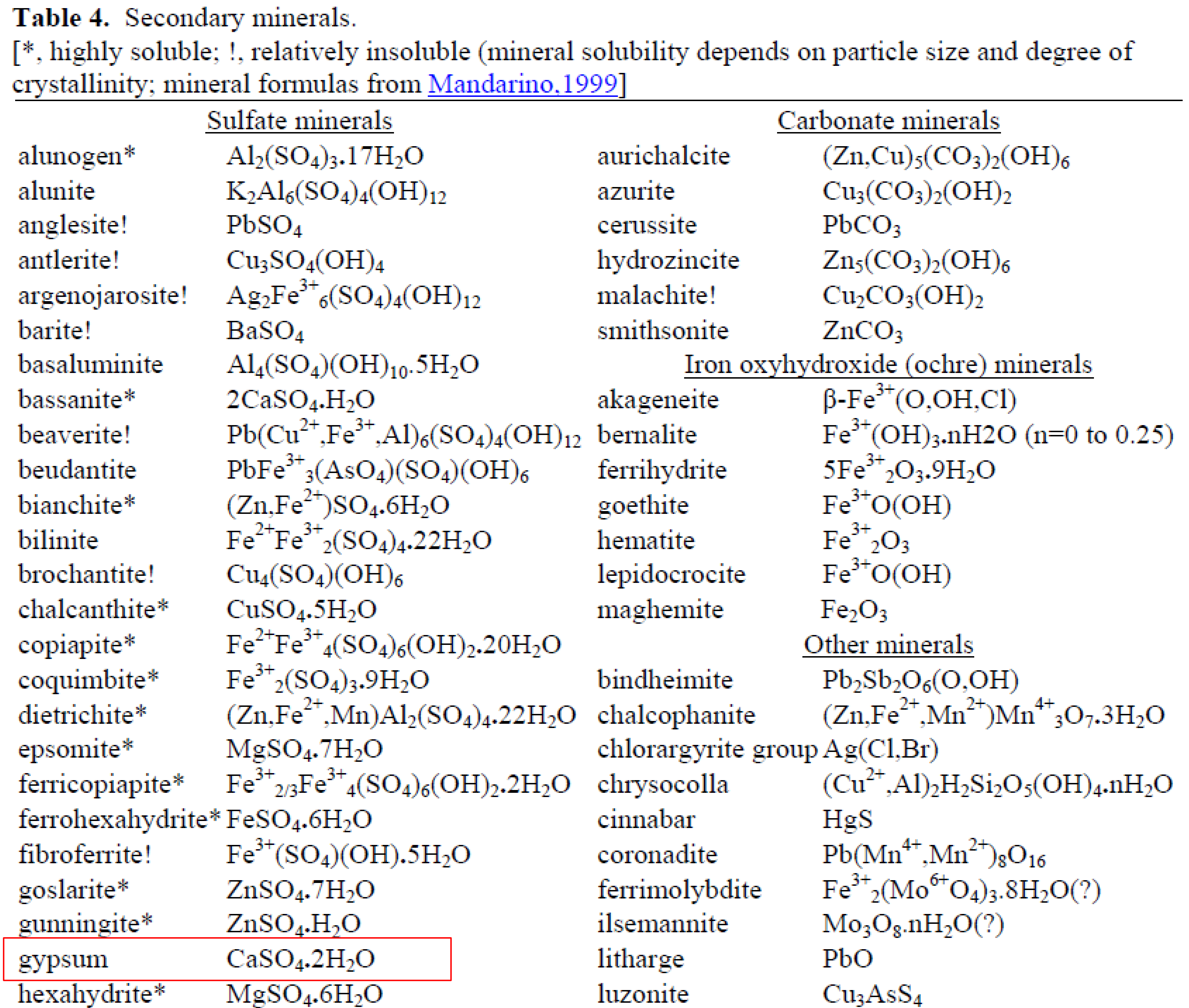


Table 4. Secondary minerals.

[*, highly soluble; !, relatively insoluble (mineral solubility depends on particle size and degree of crystallinity; mineral formulas from Mandarino,1999]

	Sulfate minerals		Carbonate minerals
alunogen*	$Al_2(SO_4)_3.17H_2O$	aurichalcite	$(Zn,Cu)_5(CO_3)_2(OH)_6$
alunite	$K_2Al_6(SO_4)_4(OH)_{12}$	azurite	$Cu_3(CO_3)_2(OH)_2$
anglesite!	$PbSO_4$	cerussite	$PbCO_3$
antlerite!	$Cu_3SO_4(OH)_4$	hydrozincite	$Zn_5(CO_3)_2(OH)_6$
argenojarosite!	$Ag_2Fe^{3+}{}_6(SO_4)_4(OH)_{12}$	malachite!	$Cu_2CO_3(OH)_2$
barite!	$BaSO_4$	smithsonite	$ZnCO_3$
basaluminite	$Al_4(SO_4)(OH)_{10}.5H_2O$		Iron oxyhydroxide (ochre) minerals
bassanite*	$2CaSO_4.H_2O$	akageneite	β-$Fe^{3+}(O,OH,Cl)$
beaverite!	$Pb(Cu^{2+},Fe^{3+},Al)_6(SO_4)_4(OH)_{12}$	bernalite	$Fe^{3+}(OH)_3.nH2O$ (n=0 to 0.25)
beudantite	$PbFe^{3+}{}_3(AsO_4)(SO_4)(OH)_6$	ferrihydrite	$5Fe^{3+}{}_2O_3.9H_2O$
bianchite*	$(Zn,Fe^{2+})SO_4.6H_2O$	goethite	$Fe^{3+}O(OH)$
bilinite	$Fe^{2+}Fe^{3+}{}_2(SO_4)_4.22H_2O$	hematite	$Fe^{3+}{}_2O_3$
brochantite!	$Cu_4(SO_4)(OH)_6$	lepidocrocite	$Fe^{3+}O(OH)$
chalcanthite*	$CuSO_4.5H_2O$	maghemite	Fe_2O_3
copiapite*	$Fe^{2+}Fe^{3+}{}_4(SO_4)_6(OH)_2.20H_2O$		Other minerals
coquimbite*	$Fe^{3+}{}_2(SO_4)_3.9H_2O$	bindheimite	$Pb_2Sb_2O_6(O,OH)$
dietrichite*	$(Zn,Fe^{2+},Mn)Al_2(SO_4)_4.22H_2O$	chalcophanite	$(Zn,Fe^{2+},Mn^{2+})Mn^{4+}{}_3O_7.3H_2O$
epsomite*	$MgSO_4.7H_2O$	chlorargyrite group	$Ag(Cl,Br)$
ferricopiapite*	$Fe^{3+}{}_{2/3}Fe^{3+}{}_4(SO_4)_6(OH)_2.2H_2O$	chrysocolla	$(Cu^{2+},Al)_2H_2Si_2O_5(OH)_4.nH_2O$
ferrohexahydrite*	$FeSO_4.6H_2O$	cinnabar	HgS
fibroferrite!	$Fe^{3+}(SO_4)(OH).5H_2O$	coronadite	$Pb(Mn^{4+},Mn^{2+})_8O_{16}$
goslarite*	$ZnSO_4.7H_2O$	ferrimolybdite	$Fe^{3+}{}_2(Mo^{6+}O_4)_3.8H_2O(?)$
gunningite*	$ZnSO_4.H_2O$	ilsemannite	$Mo_3O_8.nH_2O(?)$
gypsum	$CaSO_4.2H_2O$	litharge	PbO
hexahydrite*	$MgSO_4.6H_2O$	luzonite	Cu_3AsS_4

Sulfate salts

•Many of the sulfate minerals <u>are highly soluble</u>, and readily dissolve during rainstorms.

Examples:

Pure melanterite - $FeSO_4.7(H_2O)$

-> solubility of 15.65 grams/cc in cold water,

Gypsum – CaSO4

-> has a solubility of 0.241 grams/cc,

Ferric iron sulfate mineral coquimbite

-> is extremely soluble, at 440 grams/cc cold water (Weast, 1986).

Many of the minerals in table 4 are solid solutions.

3. Host rock lithology

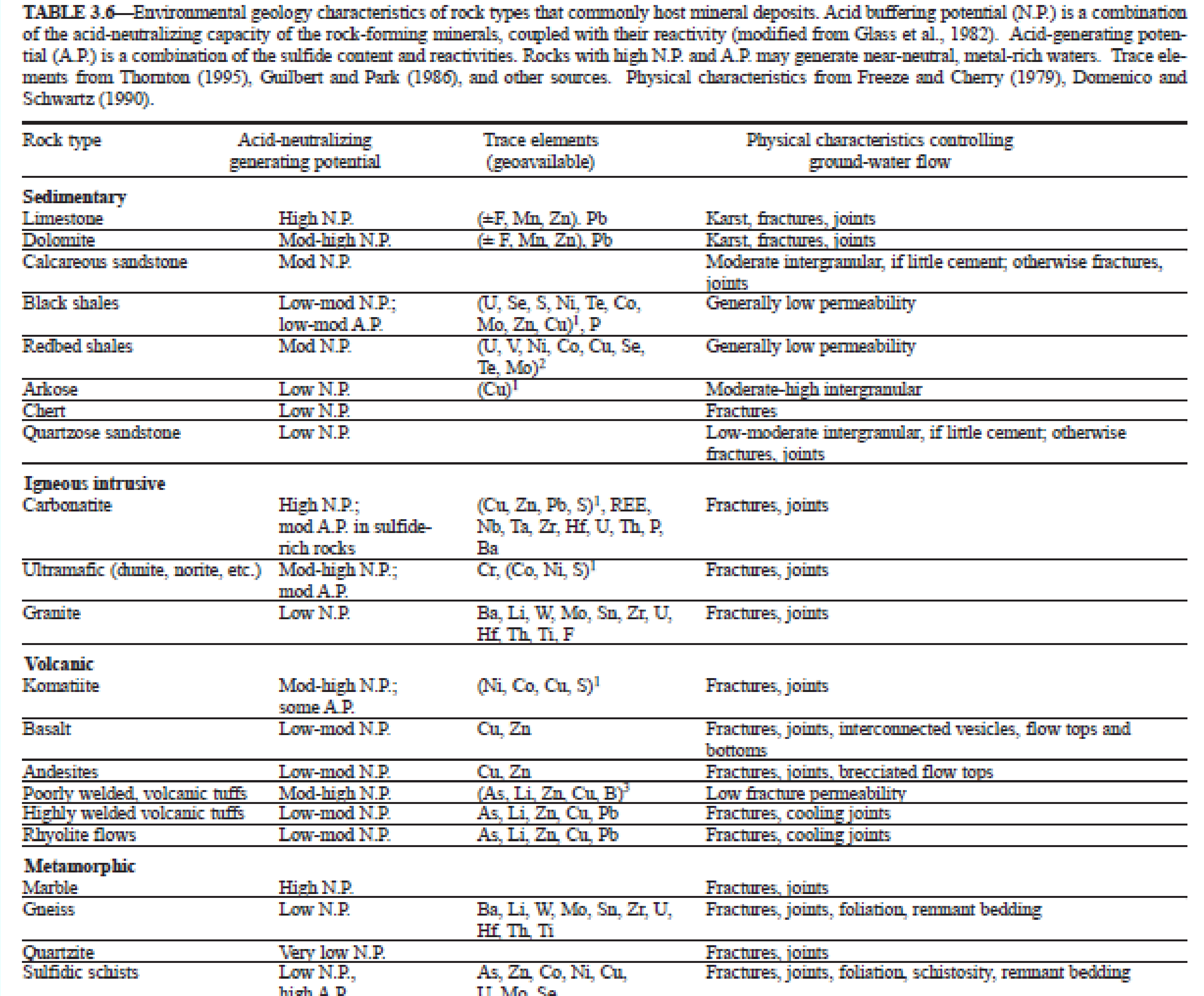


TABLE 3.6—Environmental geology characteristics of rock types that commonly host mineral deposits. Acid buffering potential (N.P.) is a combination of the acid-neutralizing capacity of the rock-forming minerals, coupled with their reactivity (modified from Glass et al., 1982). Acid-generating potential (A.P.) is a combination of the sulfide content and reactivities. Rocks with high N.P. and A.P. may generate near-neutral, metal-rich waters. Trace elements from Thornton (1995), Guilbert and Park (1986), and other sources. Physical characteristics from Freeze and Cherry (1979), Domenico and Schwartz (1990).

Rock type	Acid-neutralizing generating potential	Trace elements (geoavailable)	Physical characteristics controlling ground-water flow
Sedimentary			
Limestone	High N.P.	(±F, Mn, Zn), Pb	Karst, fractures, joints
Dolomite	Mod-high N.P.	(± F, Mn, Zn), Pb	Karst, fractures, joints
Calcareous sandstone	Mod N.P.		Moderate intergranular, if little cement; otherwise fractures, joints
Black shales	Low-mod N.P.; low-mod A.P.	(U, Se, S, Ni, Te, Co, Mo, Zn, Cu)^1, P	Generally low permeability
Redbed shales	Mod N.P.	(U, V, Ni, Co, Cu, Se, Te, Mo)^2	Generally low permeability
Arkose	Low N.P.	(Cu)^1	Moderate-high intergranular
Chert	Low N.P.		Fractures
Quartzose sandstone	Low N.P.		Low-moderate intergranular, if little cement; otherwise fractures, joints
Igneous intrusive			
Carbonatite	High N.P.; mod A.P. in sulfide-rich rocks	(Cu, Zn, Pb, S)^1, REE, Nb, Ta, Zr, Hf, U, Th, P, Ba	Fractures, joints
Ultramafic (dunite, norite, etc.)	Mod-high N.P.; mod A.P.	Cr, (Co, Ni, S)^1	Fractures, joints
Granite	Low N.P.	Ba, Li, W, Mo, Sn, Zr, U, Hf, Th, Ti, F	Fractures, joints
Volcanic			
Komatiite	Mod-high N.P.; some A.P.	(Ni, Co, Cu, S)^1	Fractures, joints
Basalt	Low-mod N.P.	Cu, Zn	Fractures, joints, interconnected vesicles, flow tops and bottoms
Andesites	Low-mod N.P.	Cu, Zn	Fractures, joints, brecciated flow tops
Poorly welded, volcanic tuffs	Mod-high N.P.	(As, Li, Zn, Cu, B)^3	Low fracture permeability
Highly welded volcanic tuffs	Low-mod N.P.	As, Li, Zn, Cu, Pb	Fractures, cooling joints
Rhyolite flows	Low-mod N.P.	As, Li, Zn, Cu, Pb	Fractures, cooling joints
Metamorphic			
Marble	High N.P.		Fractures, joints
Gneiss	Low N.P.	Ba, Li, W, Mo, Sn, Zr, U, Hf, Th, Ti	Fractures, joints, foliation, remnant bedding
Quartzite	Very low N.P.		Fractures, joints
Sulfidic schists	Low N.P., high A.P.	As, Zn, Co, Ni, Cu, U, Mo, Se	Fractures, joints, foliation, schistosity, remnant bedding

4. Wall rock alteration

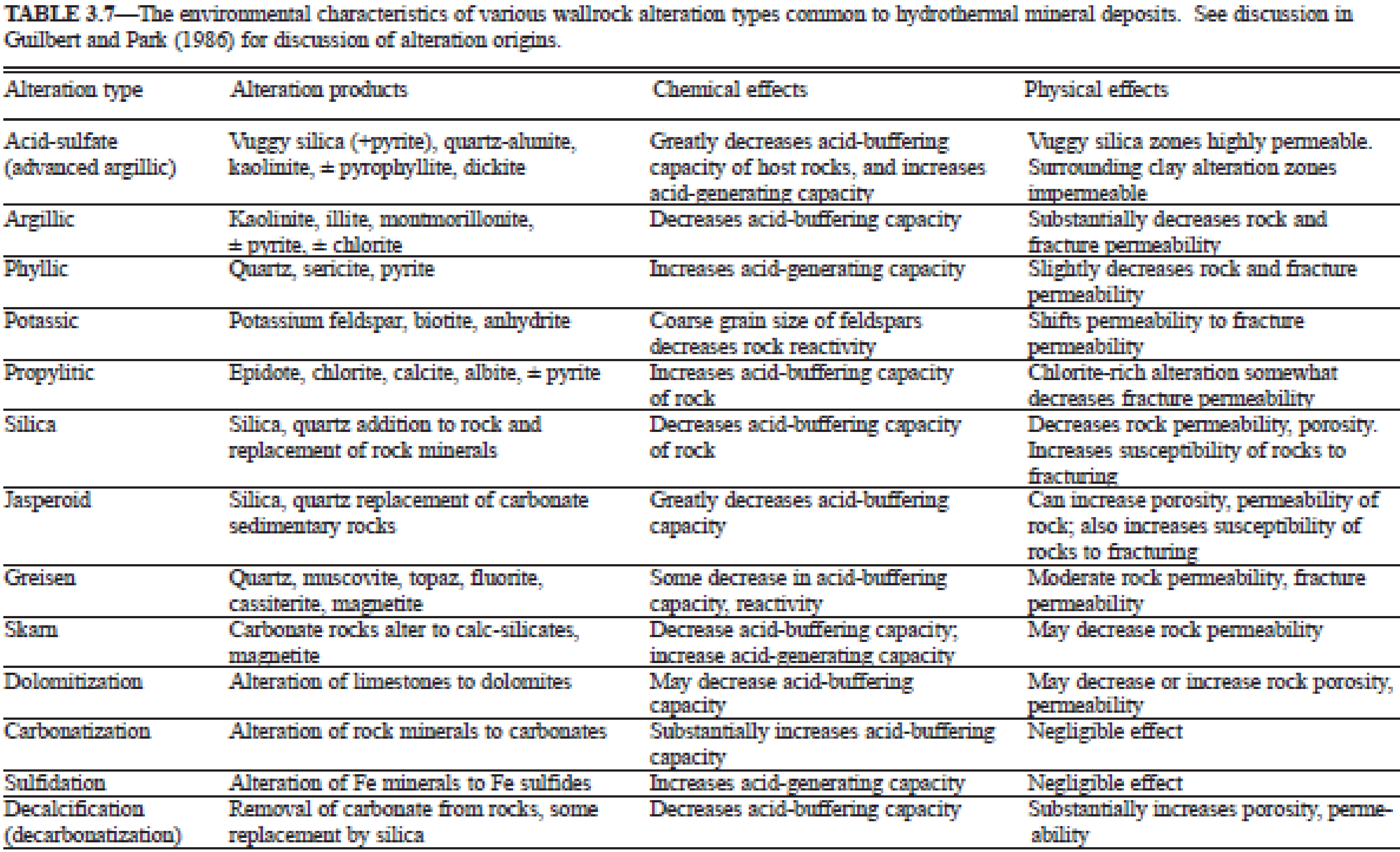


TABLE 3.7—The environmental characteristics of various wallrock alteration types common to hydrothermal mineral deposits. See discussion in Guilbert and Park (1986) for discussion of alteration origins.

Alteration type	Alteration products	Chemical effects	Physical effects
Acid-sulfate (advanced argillic)	Vuggy silica (+pyrite), quartz-alunite, kaolinite, ± pyrophyllite, dickite	Greatly decreases acid-buffering capacity of host rocks, and increases acid-generating capacity	Vuggy silica zones highly permeable. Surrounding clay alteration zones impermeable
Argillic	Kaolinite, illite, montmorillonite, ± pyrite, ± chlorite	Decreases acid-buffering capacity	Substantially decreases rock and fracture permeability
Phyllic	Quartz, sericite, pyrite	Increases acid-generating capacity	Slightly decreases rock and fracture permeability
Potassic	Potassium feldspar, biotite, anhydrite	Coarse grain size of feldspars decreases rock reactivity	Shifts permeability to fracture permeability
Propylitic	Epidote, chlorite, calcite, albite, ± pyrite	Increases acid-buffering capacity of rock	Chlorite-rich alteration somewhat decreases fracture permeability
Silica	Silica, quartz addition to rock and replacement of rock minerals	Decreases acid-buffering capacity of rock	Decreases rock permeability, porosity. Increases susceptibility of rocks to fracturing
Jasperoid	Silica, quartz replacement of carbonate sedimentary rocks	Greatly decreases acid-buffering capacity	Can increase porosity, permeability of rock; also increases susceptibility of rocks to fracturing
Greisen	Quartz, muscovite, topaz, fluorite, cassiterite, magnetite	Some decrease in acid-buffering capacity, reactivity	Moderate rock permeability, fracture permeability
Skarn	Carbonate rocks alter to calc-silicates, magnetite	Decrease acid-buffering capacity; increase acid-generating capacity	May decrease rock permeability
Dolomitization	Alteration of limestones to dolomites	May decrease acid-buffering capacity	May decrease or increase rock porosity, permeability
Carbonatization	Alteration of rock minerals to carbonates	Substantially increases acid-buffering capacity	Negligible effect
Sulfidation	Alteration of Fe minerals to Fe sulfides	Increases acid-generating capacity	Negligible effect
Decalcification (decarbonatization)	Removal of carbonate from rocks, some replacement by silica	Decreases acid-buffering capacity	Substantially increases porosity, permeability

Ζώνες παραγωγή όξινης απορροής

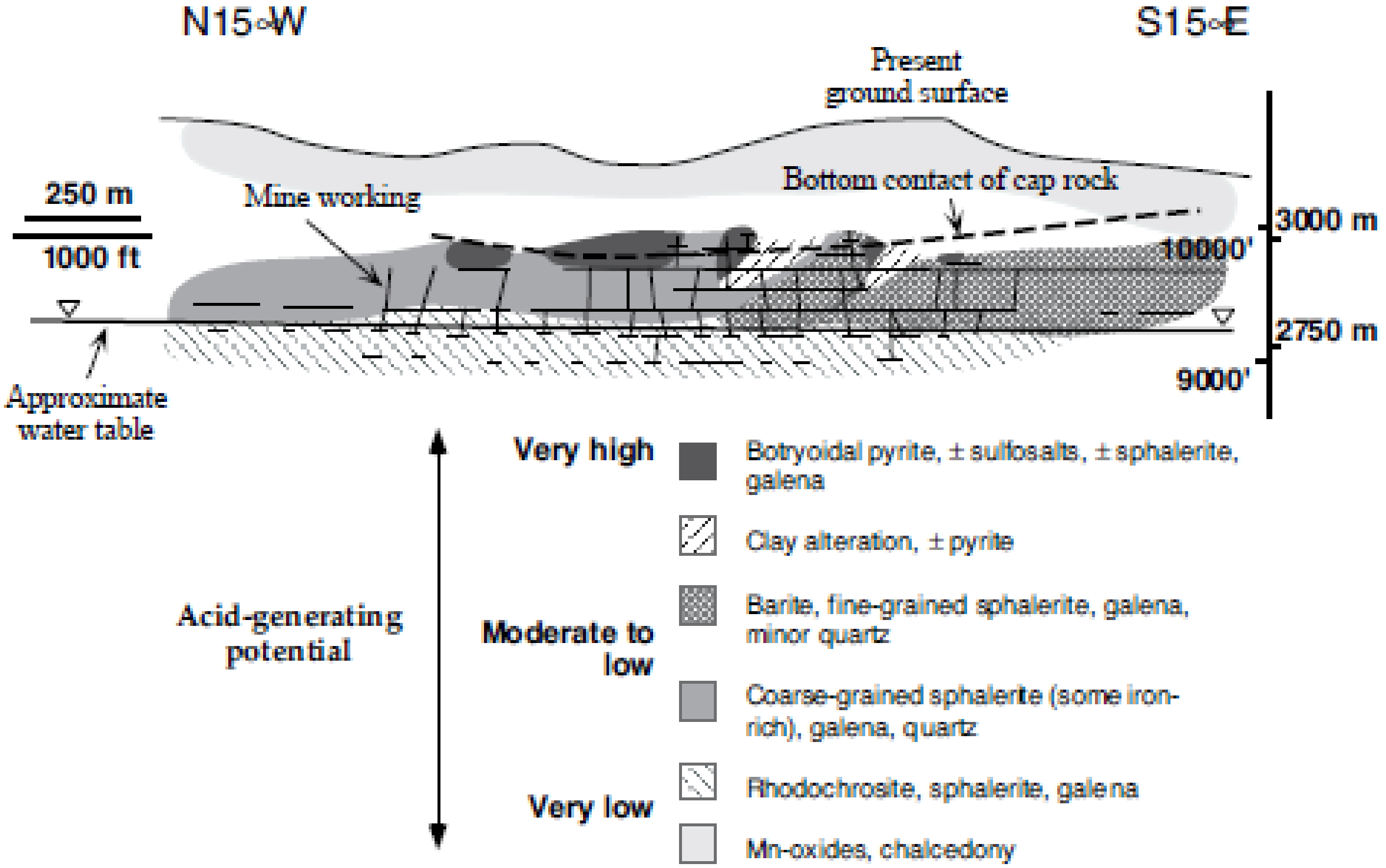


FIGURE 3.8—Longitudinal section of the A Vein, Bulldog Mountain Mine, Creede, Colorado, showing the distribution and environmental characteristics of dominant mineral assemblages along the vein. The pre-mining water table occurred primarily in acid-neutralizing rhodochrosite, and so the mine waters had near-neutral pH and relatively low levels of dissolved metals (R. Boppe, oral. commun., 1982). Acid-generating, arsenic-rich botryoidal pyrite (Figs. 3.3 and 3.7a) persists unoxidized above the water table due to the presence of an illite- and montmorillonite-rich hydrothermal alteration cap and a poorly welded ash-flow tuff above the main vein ore zone; these features combine to produce low hydraulic conductivity along the vein between the ground surface and the main ore zone. Figure modified from Plumlee and Whitehouse-Veaux (1994) and Plumlee and Nash (1995).

quartz-alunite epithermal, Au-Cu-Ag deposit (Summitville SW Colorado)

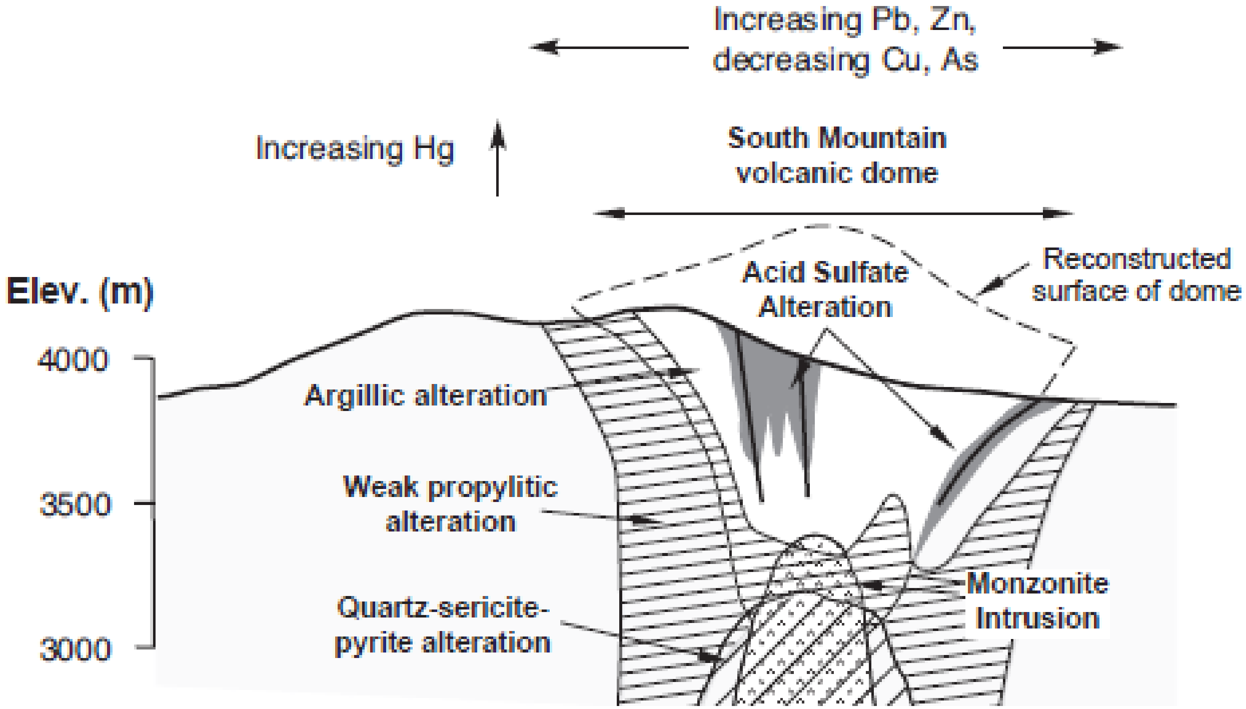


FIGURE 3.11—East-west geologic cross section of the Summitville deposit, SW Colorado, showing deposit-wide alteration and metal zoning. The quartz-sericite-pyrite alteration is associated with a low-grade porphyry-Cu deposit. Figure from Plumlee et al. (1995a), and originally modified from Rye et al. (1990).