



The Importance of Geology

Sharon F. Diehl, USGS

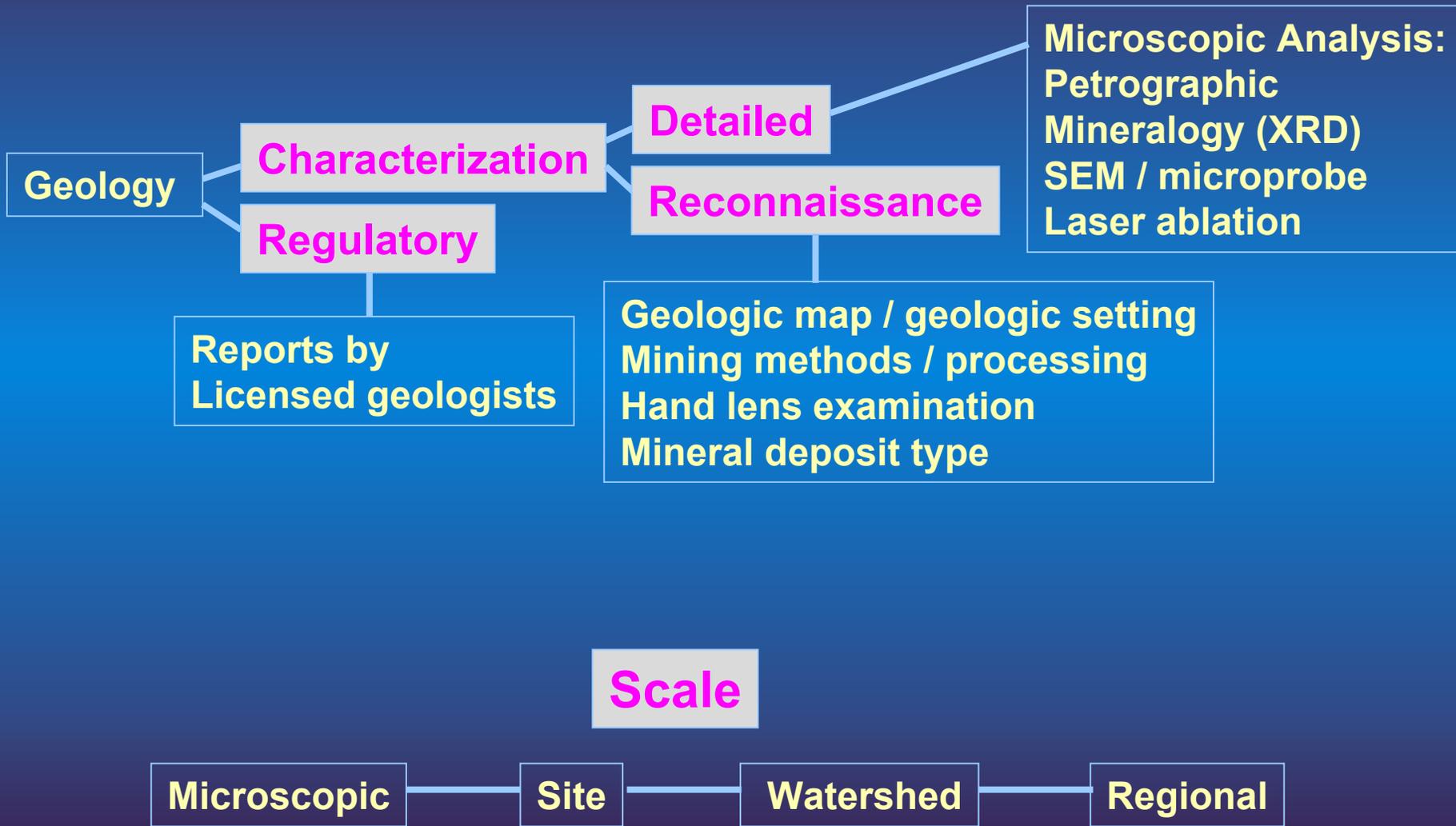
Billings Symposium / ASMR Annual Meeting

**Assessing the Toxicity Potential
of Mine-Waste Piles Workshop**

June 1, 2003

**U.S. Department of the Interior
U.S. Geological Survey**

Flow Chart for Ranking and Prioritization



Potential Environmental Impact

A complex function of:

- **Geology**
- **Geochemical and biogeochemical processes**
- **Climate**
- **Topography**
- **The mining and mineral processing methods used**

Environmental Geology of Mineral Deposits

Acid generation:

- Iron sulfide content
 - Other sulfide content
- Many sulfides (not all) generate acid when oxidized

Acid consumption:

- Host rock
 - Wallrock alteration
 - Gangue mineralogy
- Minerals and weathering products may consume or generate acid

Trace element release:

- Abundance (deposit, host rocks)
 - Access of weathering agents
 - Susceptibility of source mineral phases to weathering
- Often results in a characteristic geochemical signature (depending upon type of mineral deposit)

Acid-Generating Minerals

Pyrite (FeS_2)

Marcasite (FeS_2)

Pyrrhotite (Fe_{1-x}S)

Arsenopyrite (FeAsS)

Enargite (Cu_3AsS_4)

Tennantite ($\text{Cu}_{12}\text{As}_4\text{S}_{13}$)

Realgar (As_2S_3)

Orpiment (AsS)

Others

If ferric iron is oxidant, above minerals plus:

Chalcopyrite (CuFeS_2)

Covellite (CuS)

Sphalerite (ZnS)

Chalcocite (Cu_2S)

Acanthite (Ag_2S)

Galena (PbS)

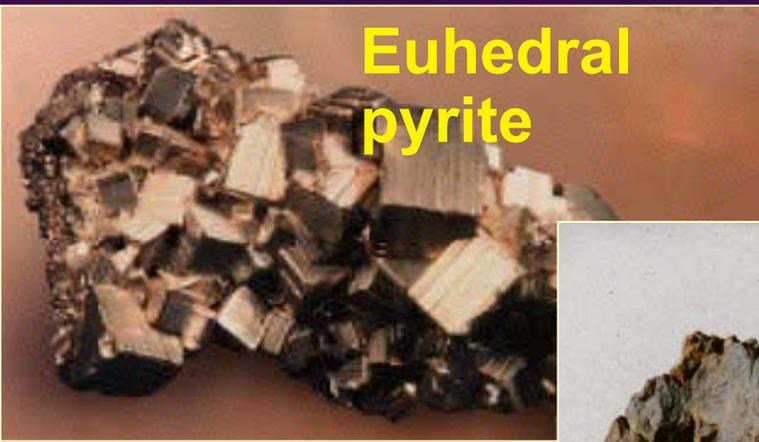
If metal hydroxides (solid or aqueous) form, above minerals plus:

Siderite (FeCO_3)

Rhodochrosite (MnCO_3)

Sulfide Texture and Resistance to Weathering

**Euhedral
pyrite**



Less
easily
weathered

**Massive
pyrite**



More
easily
weathered

**Colloform
pyrite**



Acid-Consuming Minerals

Carbonate minerals and some other minerals (some silicates, volcanic glasses) in mineral deposits, their host rocks, and watershed rocks:

- **Can help consume acid generated by sulfide oxidation**
- **Can generate alkalinity in ground and surface waters, thereby increasing the waters' ability to buffer acid**

Acid-Consuming Minerals

(after Sverdup, 1990; Kwong, 1993)

Most Effective:

aragonite, calcite

Other Carbonates (may consume acid):

**dolomite, rhodochrosite, magnesite, ankerite,
brucite**

Rapidly Weathering Minerals:

**anorthite, nepheline, olivine, garnet, jadeite,
leucite, spodumene, diopside, wollastonite,
poorly-welded volcanic glass**

Less-Effective Acid-Consuming Minerals

(after Sverdup, 1990; Kwong, 1993)

Intermediate weathering:

Epidote, zoisite, enstatite, hypersthene, augite, hedenbergite, hornblende, glaucophane, talc, chlorite, biotite, welded “volcanic glass”

Slow weathering:

Albite, oligoclase, labradorite, vermiculite, montmorillonite, gibbsite, kaolinite

Very slow weathering:

K-feldspar, muscovite

Inert:

Quartz, rutile, zircon

Host Rock Characteristics

- **May consume or generate acid**
- **May contribute trace elements to the deposit's environmental signature**
- **Their physical characteristics (i.e., porosity, permeability, fractures) control access of weathering agents to the deposit (e.g. water, oxygen, CO₂, acid)**

Hydrologic Characteristics

- **Potential interactions of ground water with the mineral deposit during and after mining**
- **Potential impacts of the mineral deposit on water quality down gradient from a mine**
- **Must be considered when determining remediation approaches**

Influence of Alteration Zones/Characteristics of Ore Deposits

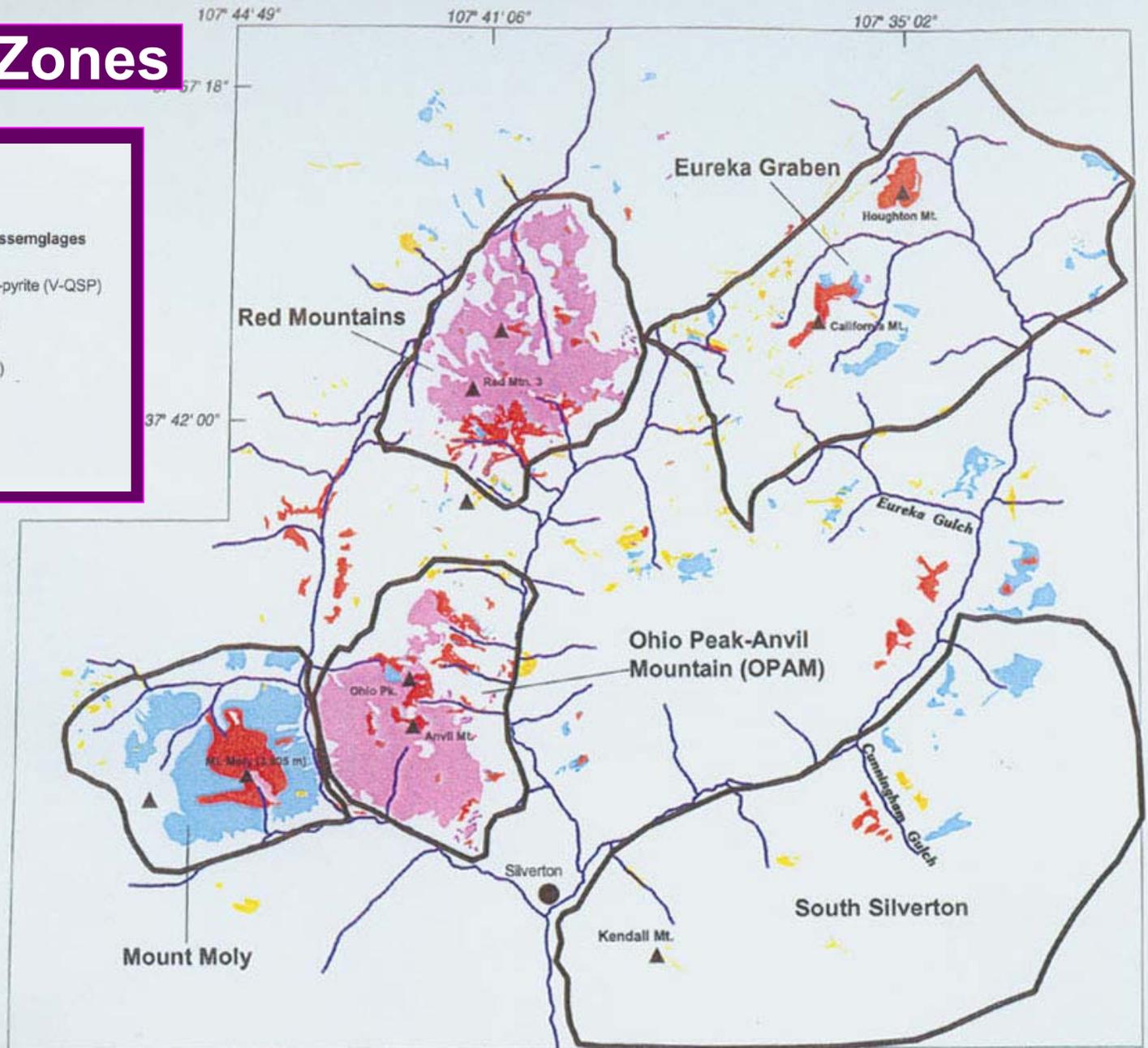
- **Mineralizing processes modify an ore deposit's host-rock mineral assemblage to a new mineral assemblage**
 - **Results in different acid-generating and acid-consuming capacities**
- **Can strongly influence the environmental signature of a mineral deposit**
- **Can modify the physical characteristics of the host rocks (porosity, permeability, fractures, strength)**

Alteration Zones

EXPLANATION

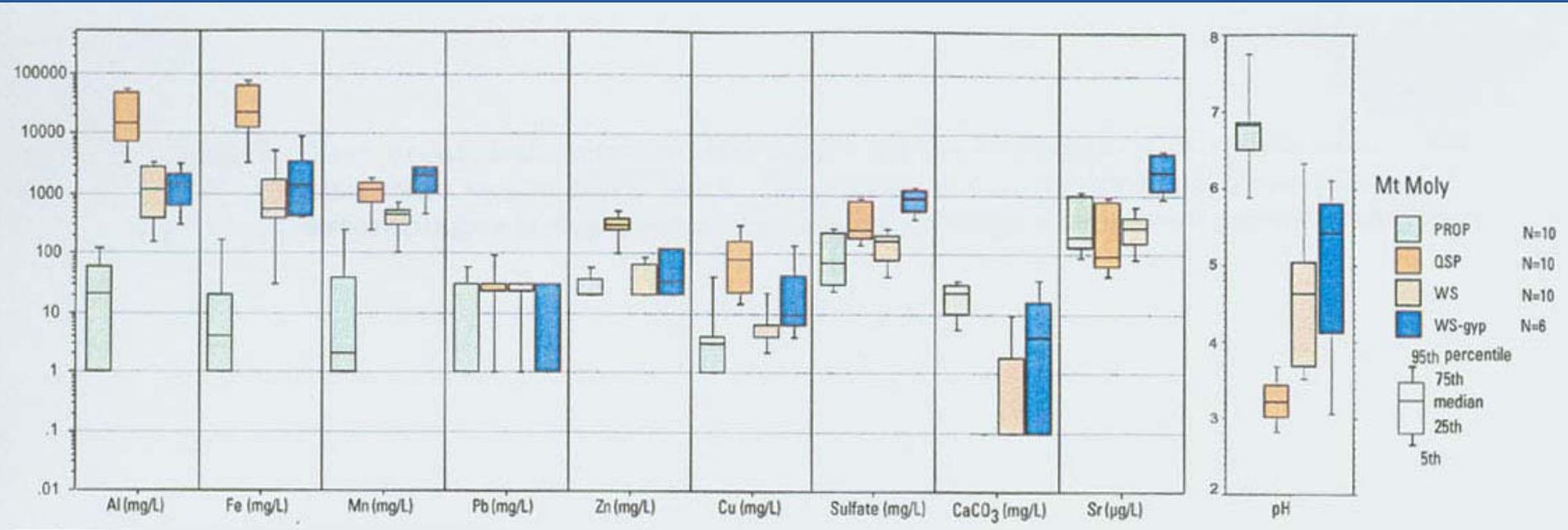
Hydrothermal Alteration Assemblages

-  Vein-related quartz-sericite-pyrite (V-QSP)
-  Weak sericite-pyrite (WSP)
-  Quartz-sericite-pyrite (QSP)
-  Acid-sulfate
-  Regional Propylitic



Bove, D.J. et al., in press

TRACE METAL ENRICHMENT IN WATERS DRAINING FROM ALTERATION ZONES



[Bove, D.J., in press]

Acid buffering capacity: Propylitic >Weak Sericite Pyrite >Qtz-Pyrite

Mining and Processing Methods

- **Influenced by the geologic characteristics of the mineral deposit**
- **Dictates the amount of rock surface exposed to weathering**
 - **Accessibility of weathering agents**
 - **Opportunities for evaporative concentration**
- **In general, for the same geologic characteristics, degradation of mine-water quality decreases from:**
open-pit > mine dumps > underground mine workings

Climate

➤ **Weathering Rates**

- Weathering is faster and more intense in wetter, warmer climates

➤ **Acid-Buffering Capacity of Soils, Alluvium, and Waters**

- Carbonate-rich soils and rock coatings in dry climates
- Surface and ground waters have higher acid-buffering capacity in drier climates
- Organic acids in high-vegetation areas

Climate, cont.

➤ Depth of Oxidation

- Water table is deeper in drier climates, thus deeper oxidation

➤ Evaporation

- Somewhat increases acidity and metal content of acid waters
- Dry periods lead to formation of soluble salts; wet periods lead to flushing of soluble salts

➤ Metal Transport

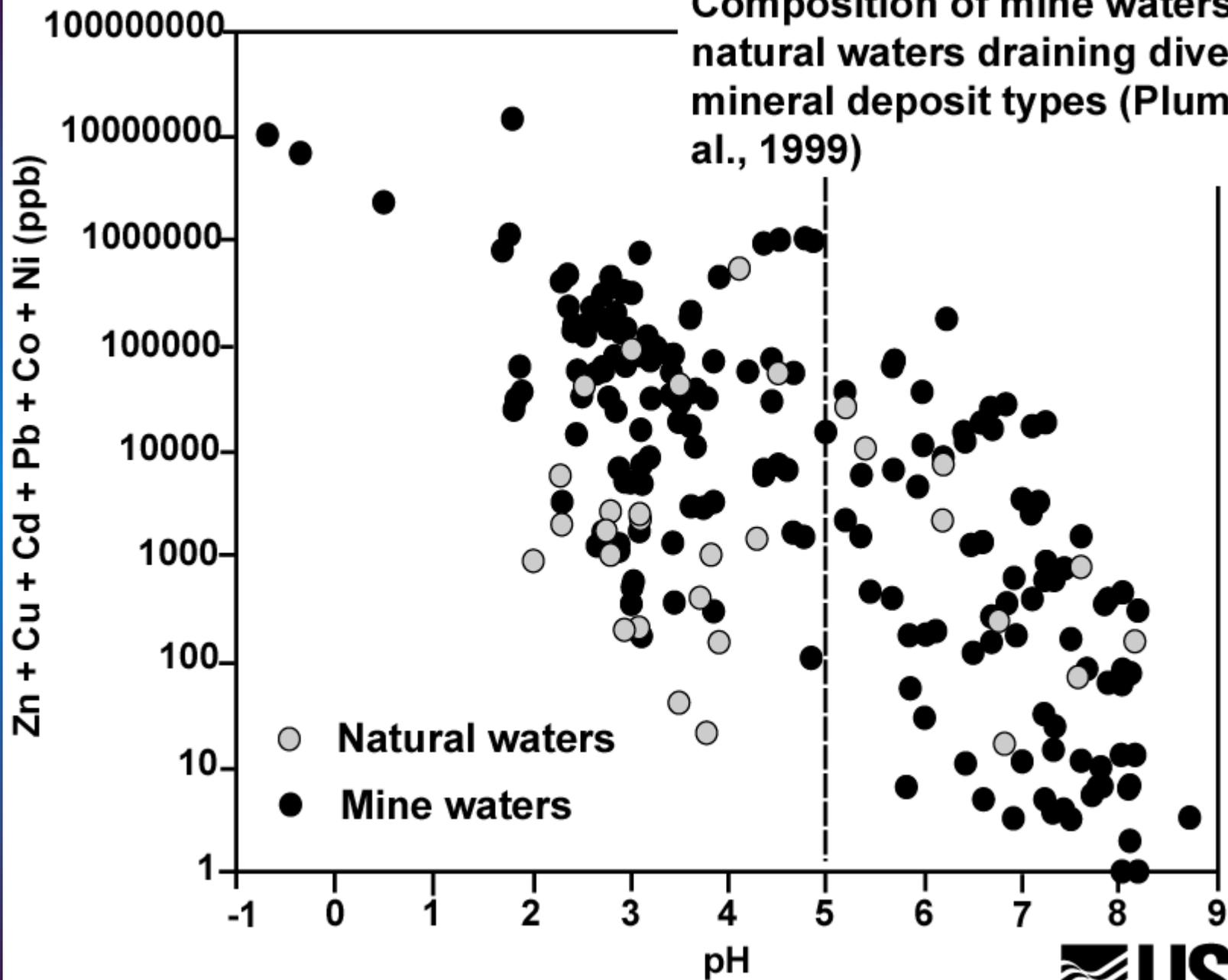
- Dilution greatest in wet climates

Geoenvironmental Models

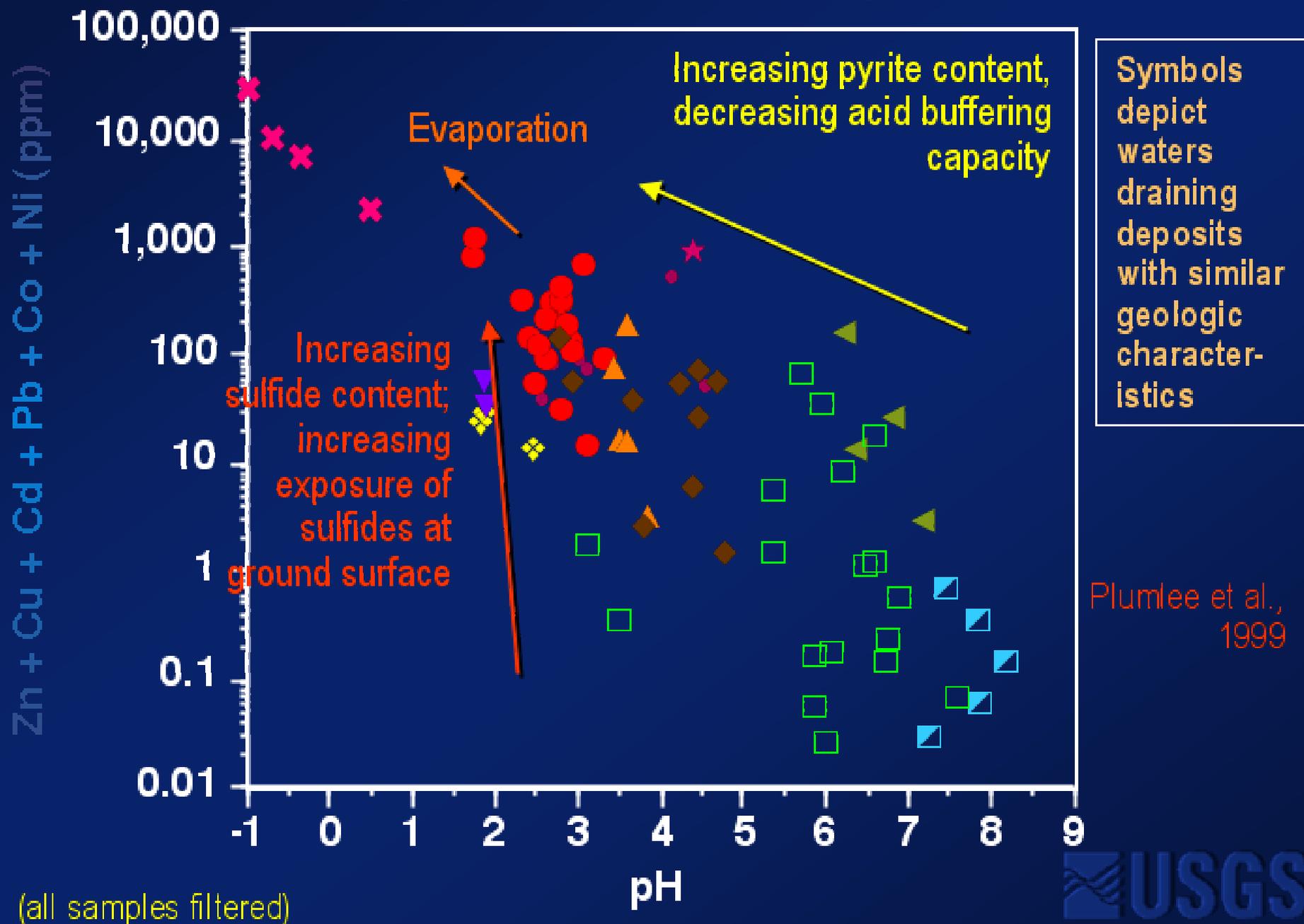
(Plumlee and Nash, 1995; du Bray, 1995)

A compilation of geologic, geochemical, geophysical, hydrologic, and engineering information pertaining to the environmental behavior of geologically similar mineral deposits (1) prior to mining, and (2) resulting from mining, mineral processing, and smelting.

Composition of mine waters and natural waters draining diverse mineral deposit types (Plumlee et al., 1999)



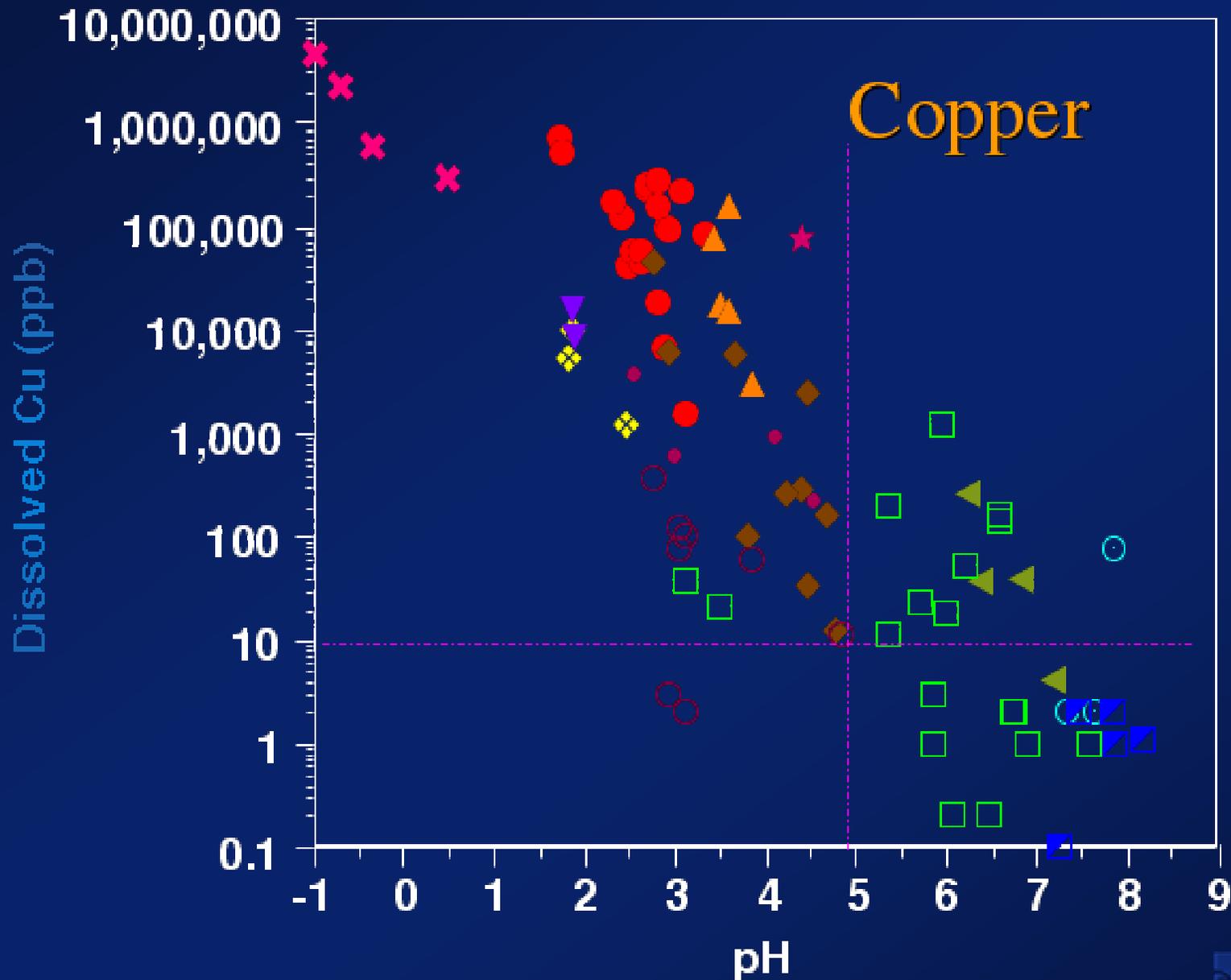
Geologic controls on mine-drainage composition



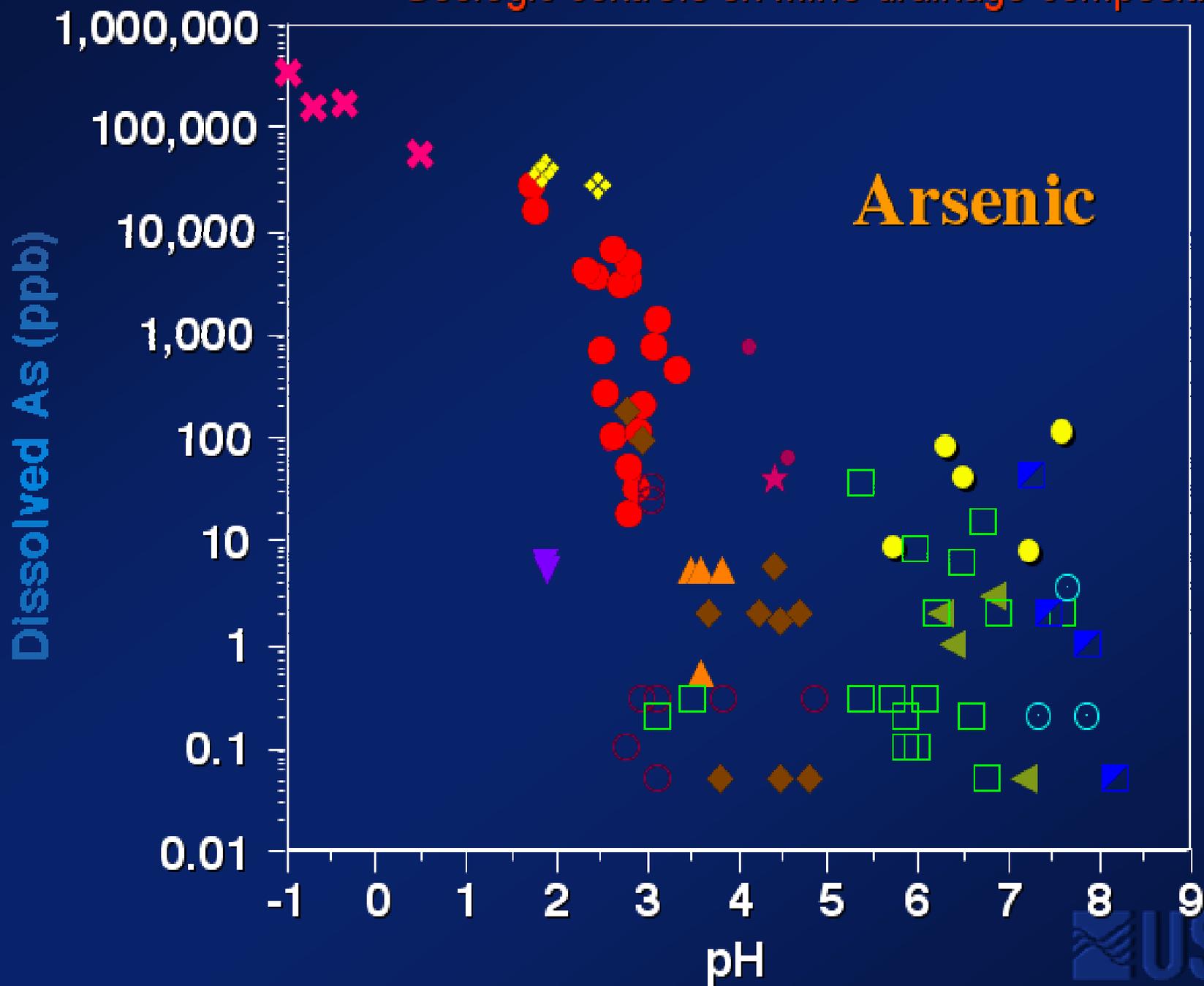
Legend

- ✱ Massive pyrite, sphalerite, galena, chalcopyrite
- ★ Cobalt-rich massive sulfides
- Massive pyrite-sphalerite-galena in black shales
- Pyrite-enargite-chalcocite-covellite ores in acid-altered rocks
- ◆ Pyrite-native sulfur in acid altered wallrocks
- ▼ Molybenite-quartz-fluorite veins, disseminations in U-rich igneous intrusions
- ▲ Pyrite-chalcopyrite disseminations in quartz-sericite-pyrite altered igneous rocks
- ◆ Pyrite-sphalerite-galena-chalcopyrite in carbonate-poor rocks
- Pyrite veins and disseminations with low base metals in carbonate-poor rocks
- ◀ Pyrite-sphalerite-galena-chalcopyrite veins, replacements in carbonate-rich sediments
- ◻ Pyrite-sphalerite-galena-chalcopyrite veins with high carbonates or in rocks altered to contain carbonates
- Pyrite-poor gold-telluride veins, breccias with high carbonates
- ▣ Pyrite-poor sphalerite-galena veins, replacements in carbonate sediments

Geologic controls on mine-drainage composition

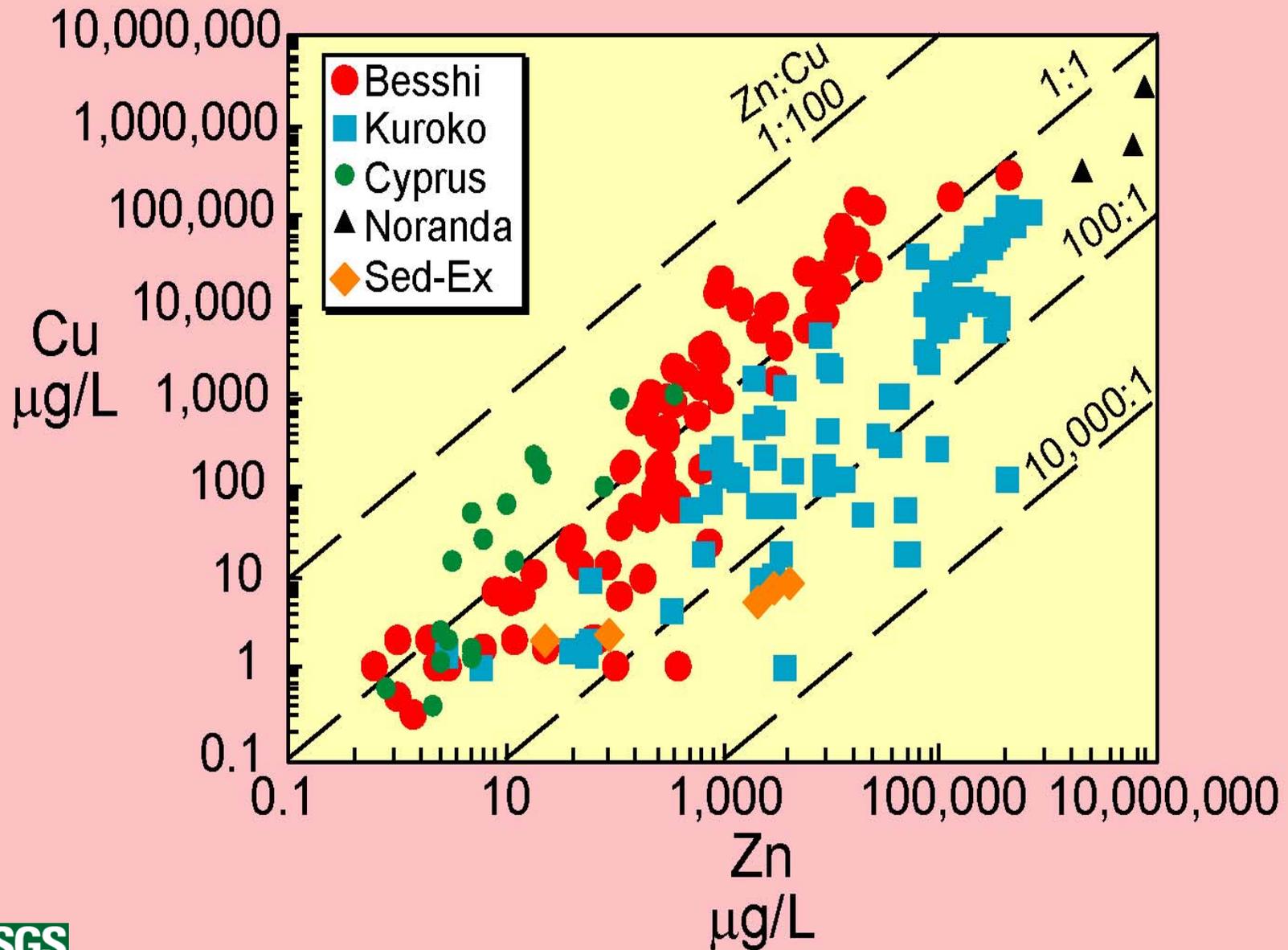


Geologic controls on mine-drainage composition



Types of Massive Sulfide Deposits

(Seal and Hammarstrom, 2003)





REVIEWS IN ECONOMIC GEOLOGY

Volume 6A

THE ENVIRONMENTAL GEOCHEMISTRY OF MINERAL DEPOSITS

Part A: Processes, Techniques, and Health Issues

Volume Editors: Geoffrey S. Plumlee and Mark J. Logsdon

CONTENTS

INTRODUCTION AN EARTH-SYSTEM SCIENCE TOOLKIT FOR ENVIRONMENTALLY FRIENDLY MINERAL RESOURCE DEVELOPMENT	<i>G.S. Plumlee and M.J. Logsdon</i>
AN OVERVIEW OF THE ABUNDANCE, RELATIVE MOBILITY, BIOAVAILABILITY, AND HUMAN TOXICITY OF METALS	<i>Kathleen S. Smith and Holly L.O. Huyck</i>
PROCESSES THE ENVIRONMENTAL GEOLOGY OF MINERAL DEPOSITS	<i>G.S. Plumlee</i>
SOME FUNDAMENTALS OF AQUEOUS GEOCHEMISTRY	<i>D. Kirk Nordstrom</i>
THE ROLE OF BACTERIA IN ENVIRONMENTAL GEOCHEMISTRY	<i>A.L. Mills</i>
GEOCHEMISTRY OF ACID MINE WATERS	<i>D. Kirk Nordstrom and C.N. Alpers</i>
METAL SORPTION ON MINERAL SURFACES: AN OVERVIEW WITH EXAMPLES RELATING TO MINERAL DEPOSITS	<i>Kathleen S. Smith</i>
GENERAL ASPECTS OF AQUATIC COLLOIDS IN ENVIRONMENTAL GEOCHEMISTRY	<i>J.F. Ranville and R.L. Schmiermund</i>
GEOCHEMICAL PROCESSES CONTROLLING URANIUM MOBILITY IN MINE DRAINAGES	<i>R.B. Wanty, W.R. Miller, P.H. Briggs, and J.B. McHugh</i>
GEOCHEMISTRY OF THE PROCESSES THAT ATTENUATE ACID MINE DRAINAGE IN WETLANDS	<i>Katherine Walton-Day</i>
THE ENVIRONMENTAL GEOCHEMISTRY OF CYANIDE	<i>A.C.S. Smith and T.I. Mudder</i>
TECHNIQUES FIELD METHODS FOR SAMPLING AND ANALYSIS OF ENVIRONMENTAL SAMPLES FOR UNSTABLE AND SELECTED STABLE CONSTITUENTS	<i>W.H. Ficklin and E.L. Mosier</i>
LABORATORY METHODS FOR THE ANALYSIS OF ENVIRONMENTAL SAMPLES	<i>J.G. Crock, B.F. Arbogast, and P.J. Lamothe</i>
GEOCHEMICAL MODELING OF WATER-ROCK INTERACTIONS IN MINING ENVIRONMENTS	<i>C.N. Alpers and D. Kirk Nordstrom</i>
STATIC-TEST METHODS MOST COMMONLY USED TO PREDICT ACID-MINE DRAINAGE: PRACTICAL GUIDELINES FOR USE AND INTERPRETATION	<i>W.W. White III, K.A. Lapakko, and R.L. Cox</i>
HEALTH ISSUES THE HEALTH EFFECTS OF MINERAL DUSTS	<i>Malcolm Ross</i>
BIOAVAILABILITY OF METALS IN THE ENVIRONMENT: IMPLICATIONS FOR HEALTH RISK ASSESSMENT	<i>G.R. Krieger, H.A. Hattemer-Frey, and J.E. Kester</i>
EFFECTS OF HEAVY METALS ON THE AQUATIC BIOTA	<i>M.G. Kelly</i>

SOCIETY OF ECONOMIC GEOLOGISTS, INC.



REVIEWS IN ECONOMIC GEOLOGY

Volume 6B

THE ENVIRONMENTAL GEOCHEMISTRY OF MINERAL DEPOSITS

Part B: Case Studies and Research Topics

Volume Editors: Lorraine H. Filipek and Geoffrey S. Plumlee

CONTENTS

GEOLOGIC CONTROLS ON THE COMPOSITION OF NATURAL WATERS AND MINE WATERS DRAINING DIVERSE MINERAL-DEPOSIT TYPES	<i>G.S. Plumlee, K.S. Smith, M.R. Montour, W.H. Ficklin, and E.L. Mosier</i>
A MULTI-PHASED APPROACH TO PREDICT ACID PRODUCTION FROM PORPHYRY COPPER-GOLD WASTE ROCK IN AN ARID MONTANE ENVIRONMENT	<i>L.H. Filipek, T.J. VanWyngharden, C.S.E. Papp, and J. Curry</i>
THE HYDROGEOCHEMISTRY OF A NICKEL-MINE TAILINGS IMPOUNDMENT— COPPER CLIFF, ONTARIO	<i>C.J. Coggans, D.W. Blowes, W.D. Robertson, and J.L. Jambor</i>
SEASONAL VARIATION IN METAL CONCENTRATIONS IN A STREAM AFFECTED BY ACID MINE DRAINAGE, ST. KEVIN GULCH, COLORADO	<i>B.A. Kimball</i>
NATURAL ATTENUATION OF ACIDIC DRAINAGE FROM SULFIDIC TAILINGS AT A SITE IN WASHINGTON STATE	<i>R.H. Lambeth</i>
THE BEHAVIOR OF TRACE METALS IN WATER DURING NATURAL ACID SULFATE WEATHERING IN AN ALPINE WATERSHED	<i>W.R. Miller, R.L. Bassett, J.B. McHugh, and W.H. Ficklin</i>
CALCULATIONS OF GEOCHEMICAL BASELINES OF STREAM WATERS IN THE VICINITY OF SUMMITVILLE, COLORADO, BEFORE HISTORIC UNDERGROUND MINING AND PRIOR TO RECENT OPEN-PIT MINING	<i>W.R. Miller and J.B. McHugh</i>
A CASE STUDY ON THE AEROBIC AND ANAEROBIC REMOVAL OF MANGANESE BY WETLAND PROCESSES	<i>L.A. Clayton, J.L. Bolis, T.R. Wildeman, and D.M. Updegraff</i>
GEOCHEMICAL AND BIOGEOCHEMICAL CONTROLS ON ELEMENT MOBILITY IN AND AROUND URANIUM MILL TAILINGS	<i>E.R. Landa</i>
BIOOXIDATION PRETREATMENT OF REFRACTORY SULFIDIC AND SULFIDIC-CARBONACEOUS GOLD ORES AND CONCENTRATES	<i>J.A. Brierley</i>
DETERMINATION OF THE SOURCE AND PATHWAY OF CYANIDE-BEARING MINE WATER SEEPAGE	<i>L.H. Filipek</i>
USE OF LEAD ISOTOPES AS NATURAL TRACERS OF METAL CONTAMINATION—A CASE STUDY OF THE PENN MINE AND CAMANCHE RESERVOIR, CALIFORNIA	<i>S.E. Church, C.N. Alpers, R.B. Vaughn, P.H. Briggs, and D.G. Slotton</i>

SOCIETY OF ECONOMIC GEOLOGISTS, INC.

\$55 for the 2-volume set. For ordering info: www.segweb.org

Microscopic Analytical Methods

Parameter:

Method:

Result:

Mineralogy

**Petrographic Microscope
Scanning Electron Microscope**

**Mineral Species;
acid or non-acid
generating;
Mineral Textures;
particle size,
cleavage
Structure**

Trace Metals

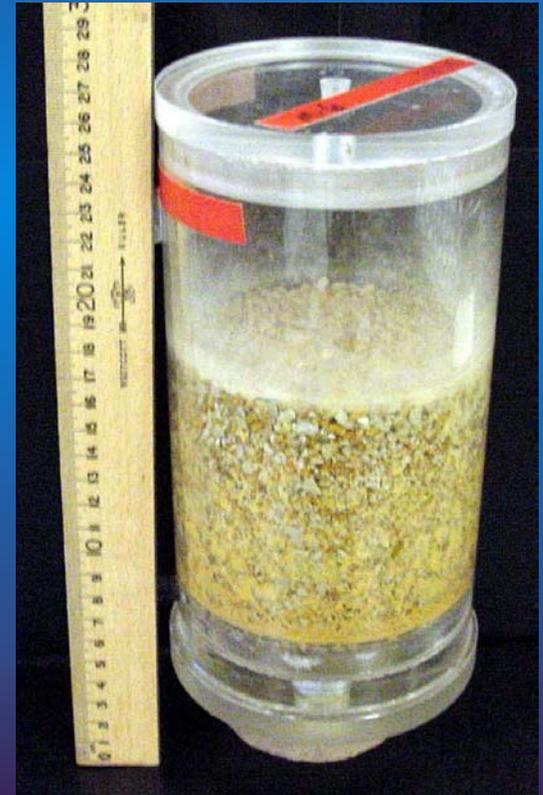
**Microprobe
Laser Ablation Mass Spectrometry**

**Exact Residence of
trace metals
Spatial Distribution
of trace metals
Quantitative data**

Case Studies

1. Hard-Rock Mine Waste in Humidity Cell Tests (Lapakko, 1999; Lapakko and White, 2000; White and Lapakko, 2000)

2. Pyrite-Rich Coal Samples



Mineralogical Characterization

Elemental Residence Phases

Jarosite [$\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$]	Pb, Ag, Cu, Bi
Pyrite [FeS_2]	Cu, Bi, Ag, As
Sphalerite [ZnS]	Cd, Cu, Mn, Ag
Galena [PbS]	Ag, Bi
Anglesite [PbSO_4]	Zn, Cd, Bi, Cu
Tennantite-Tetrahedrite [$(\text{Ag, Cu, Fe})_{12}(\text{Sb, As})_4\text{S}_{13}$]	Cu, Zn, Sb, As



Case Study 1: Bulk Mineralogy of Mine Waste Samples

SEMI-QUANTITATIVE MINERALOGY (sample 99.1, wt. %)

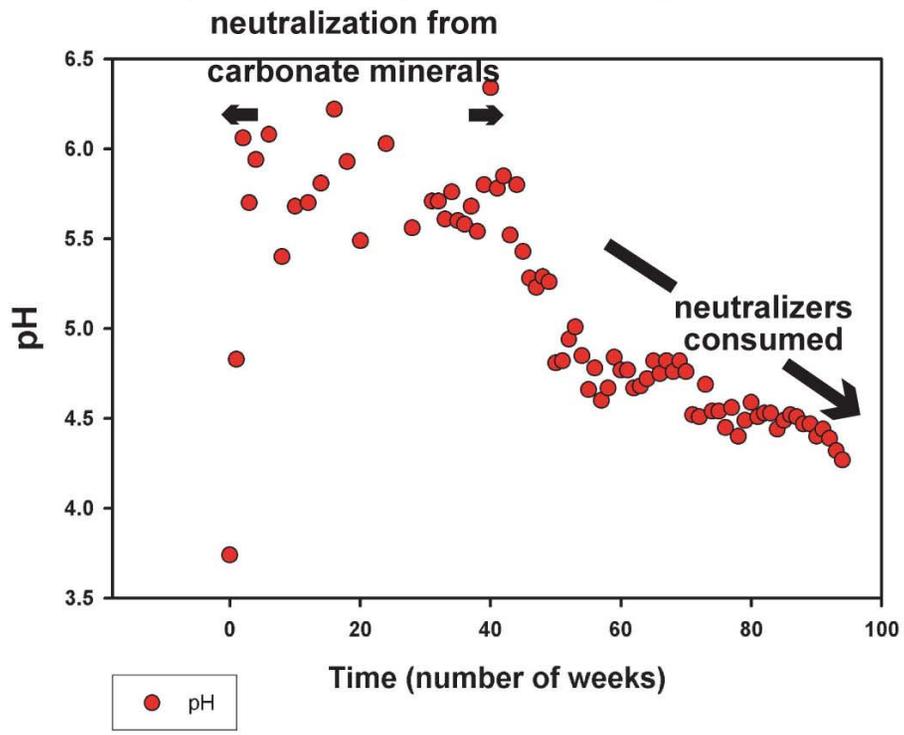
	Before Leaching	After Leaching
Quartz	32	30
Amorphous	23	28
Potassium Feldspar	10	13
Muscovite	9	7
Plagioclase Feldspar	8	8
Siderite	7	--
Pyrite	6	6
Kaolinite	2	2
Gypsum	1	3

SEMI-QUANTITATIVE MINERALOGY (sample 81196, wt. %)

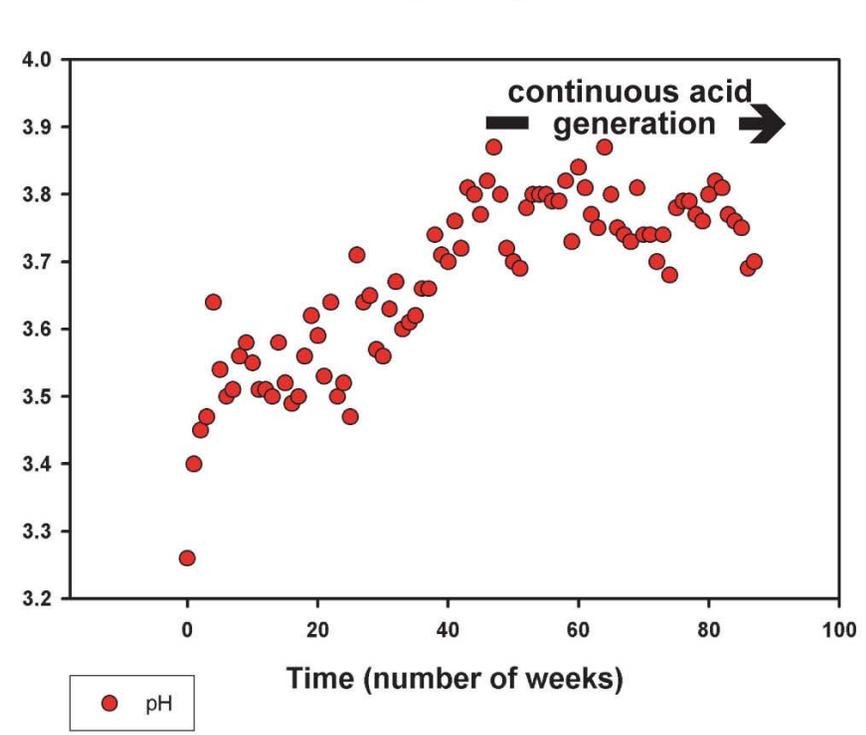
	Before Leaching	After Leaching
Quartz	33	32
Amorphous	33	34
Jarosite	16	17
Potassium Feldspar	15	15
Muscovite	2	2
Gypsum	1	--

pH

A Pyrite-Bearing Sample 99.1; pH



B Jarosite-Bearing Sample 81196; pH



500µm

Microstructure; Sample 99.1

early, etched
dolomite and
silica-filled vein →

pyrite

younger
silica-filled vein

↑
Cu, Sb, As sulfides

older
carbonate-filled
vein

↑
pyrite

siderite →

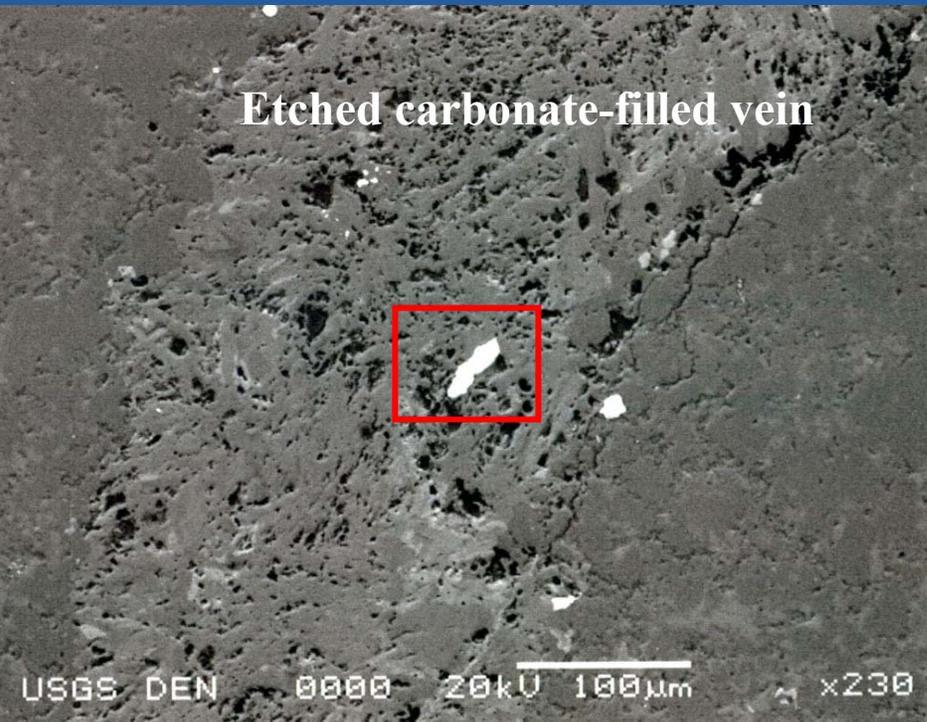
kspar →
↓

early, etched
dolomite and
silica-filled vein

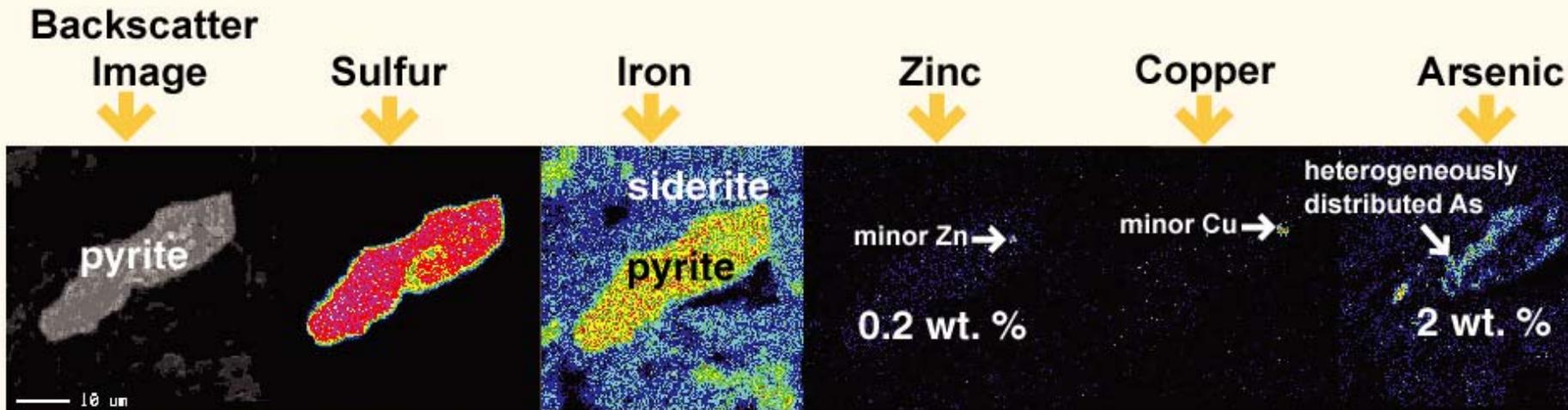
pyrite

quartz

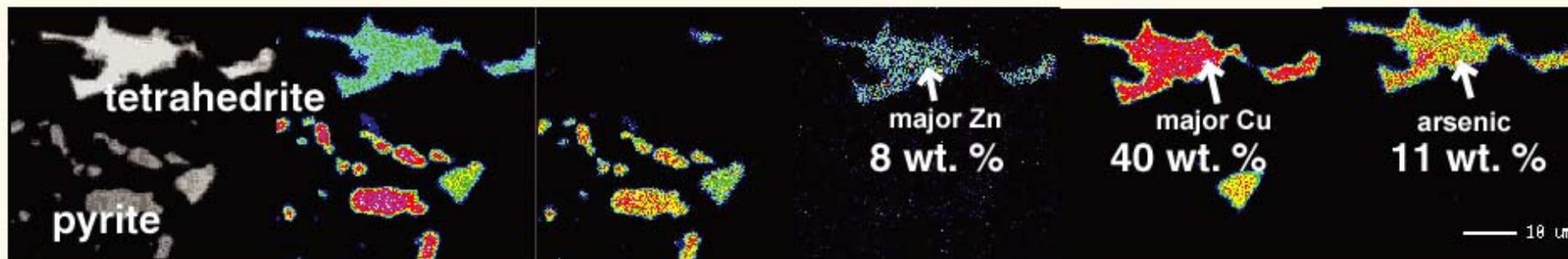
Microstructure; Sample 99.1



Microprobe Element Distribution Maps



Sulfides in Carbonate-filled Vein

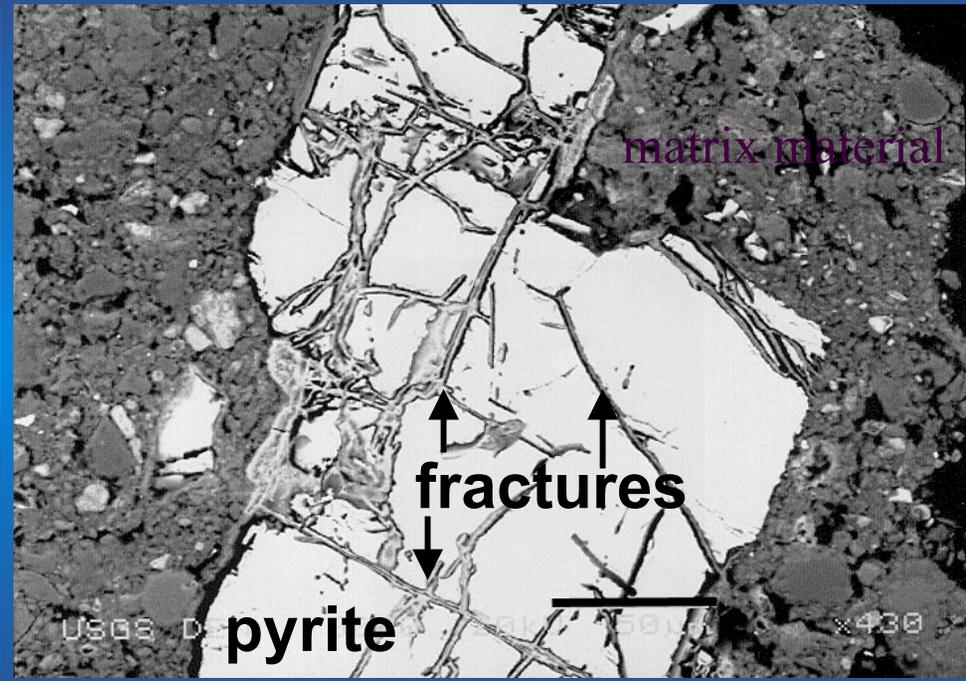


Sulfides in Silica-filled Vein

Pyrite-bearing Sample 99.1

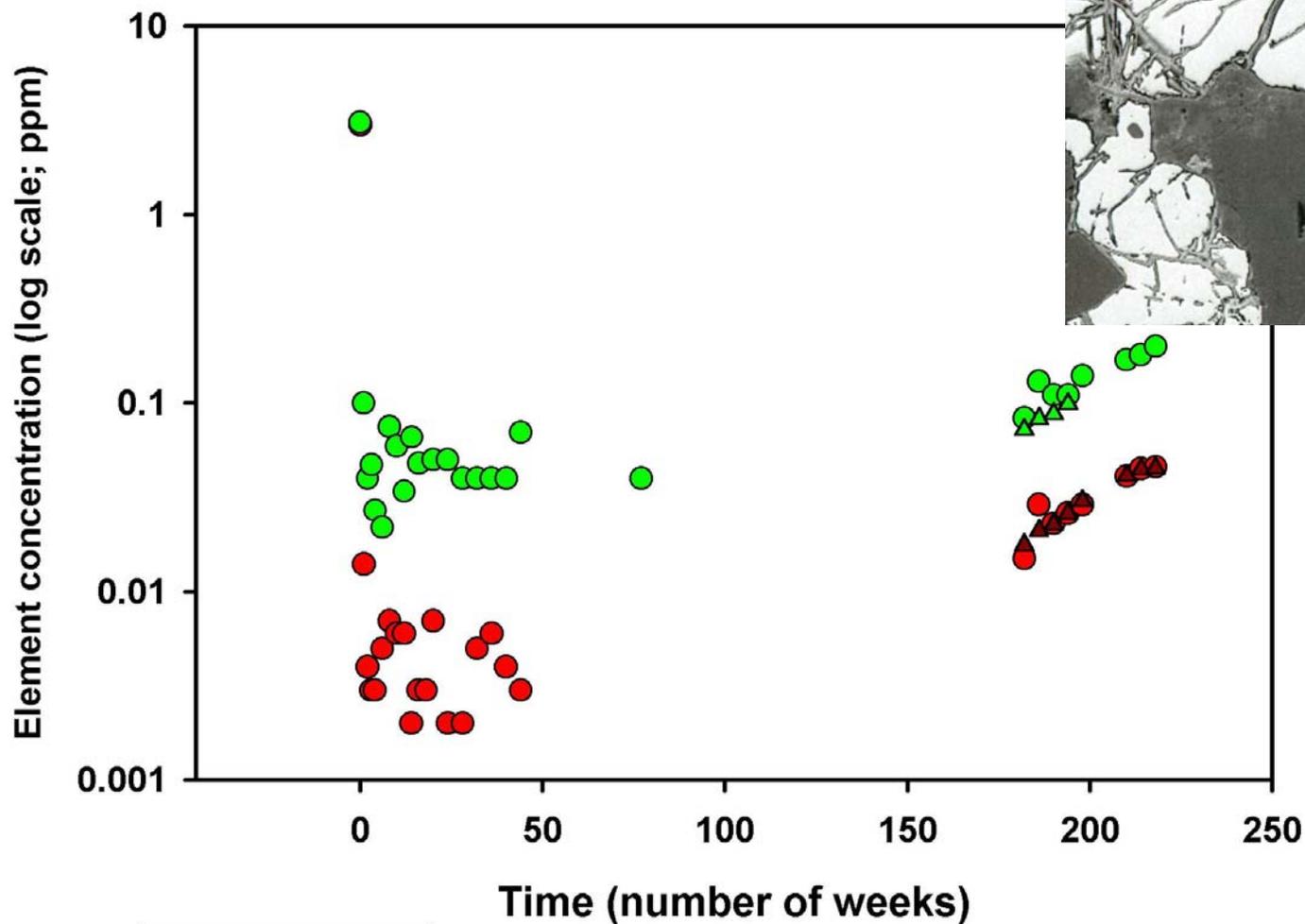
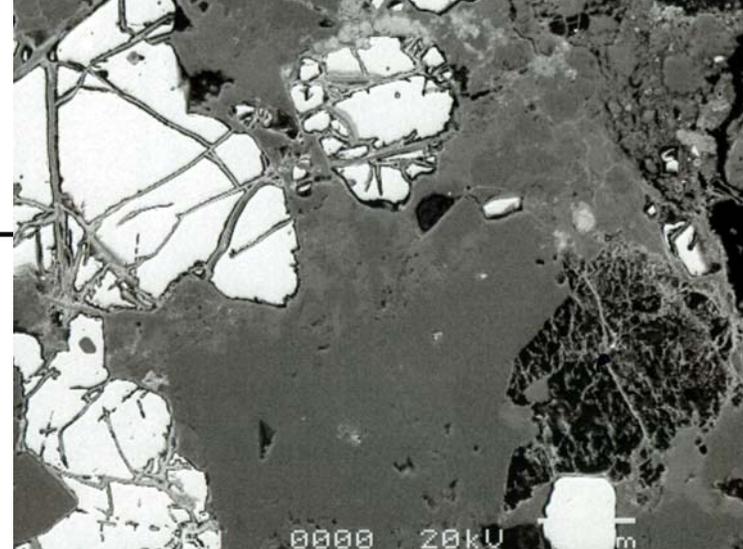


**Pyrite Before
Leaching**



Pyrite After Leaching

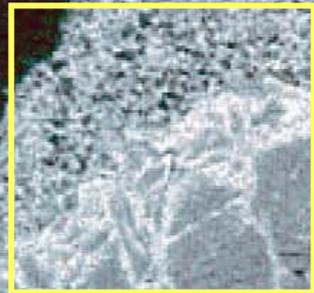
Pyrite-Bearing Sample 99.1 Cu and Zn from sulfides



- Cu
- ▲ ICP_MS Cu
- Zn
- ▲ ICP_MS Zn

Sample 81196

jarosite



Fe
oxides

micaceous
minerals

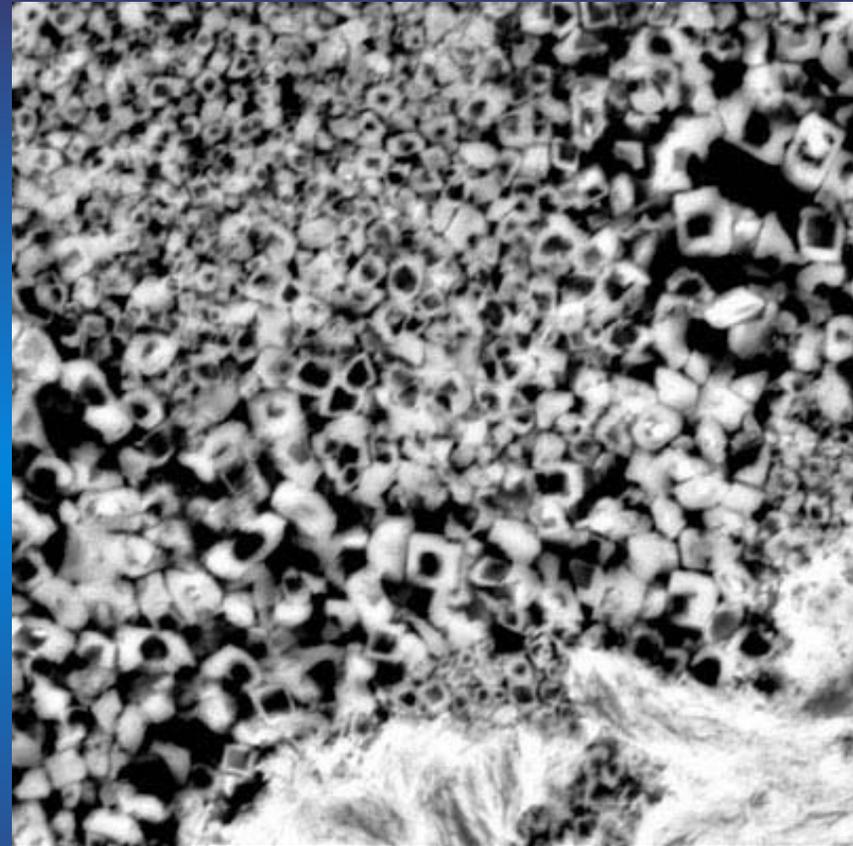
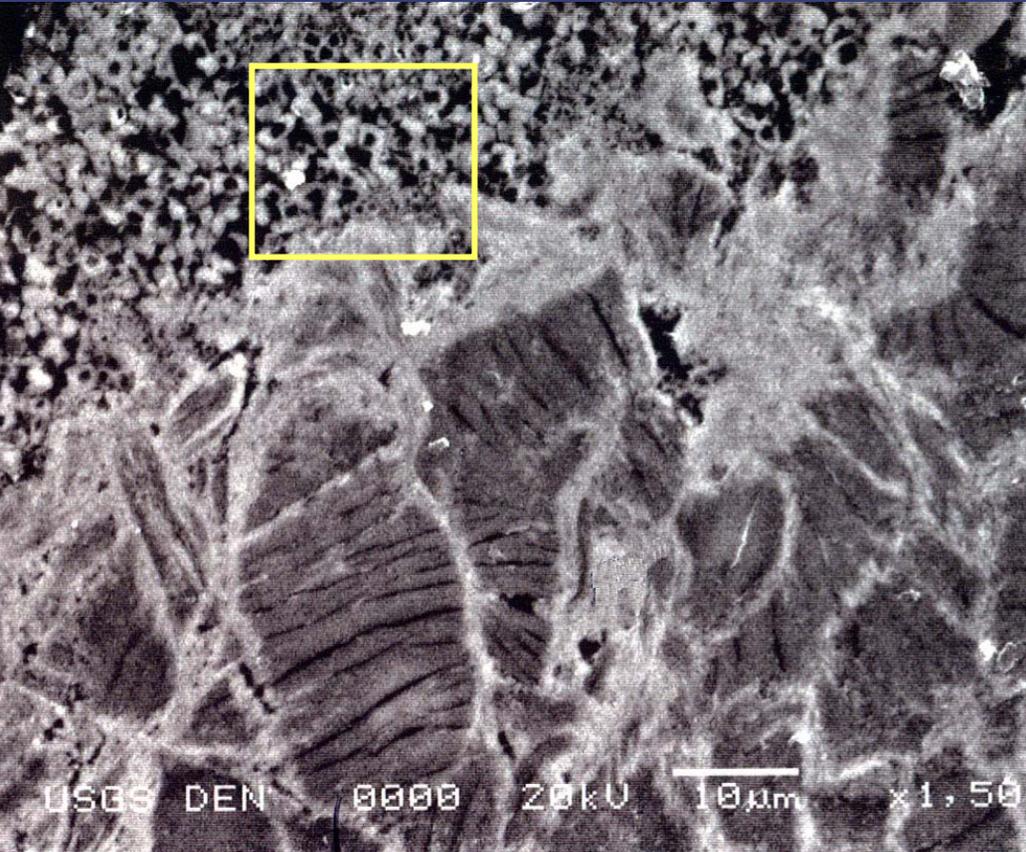
Quartz



Textures

Zoned Jarosite

Cleavage/Shrinkage Cracking (?) in Mica

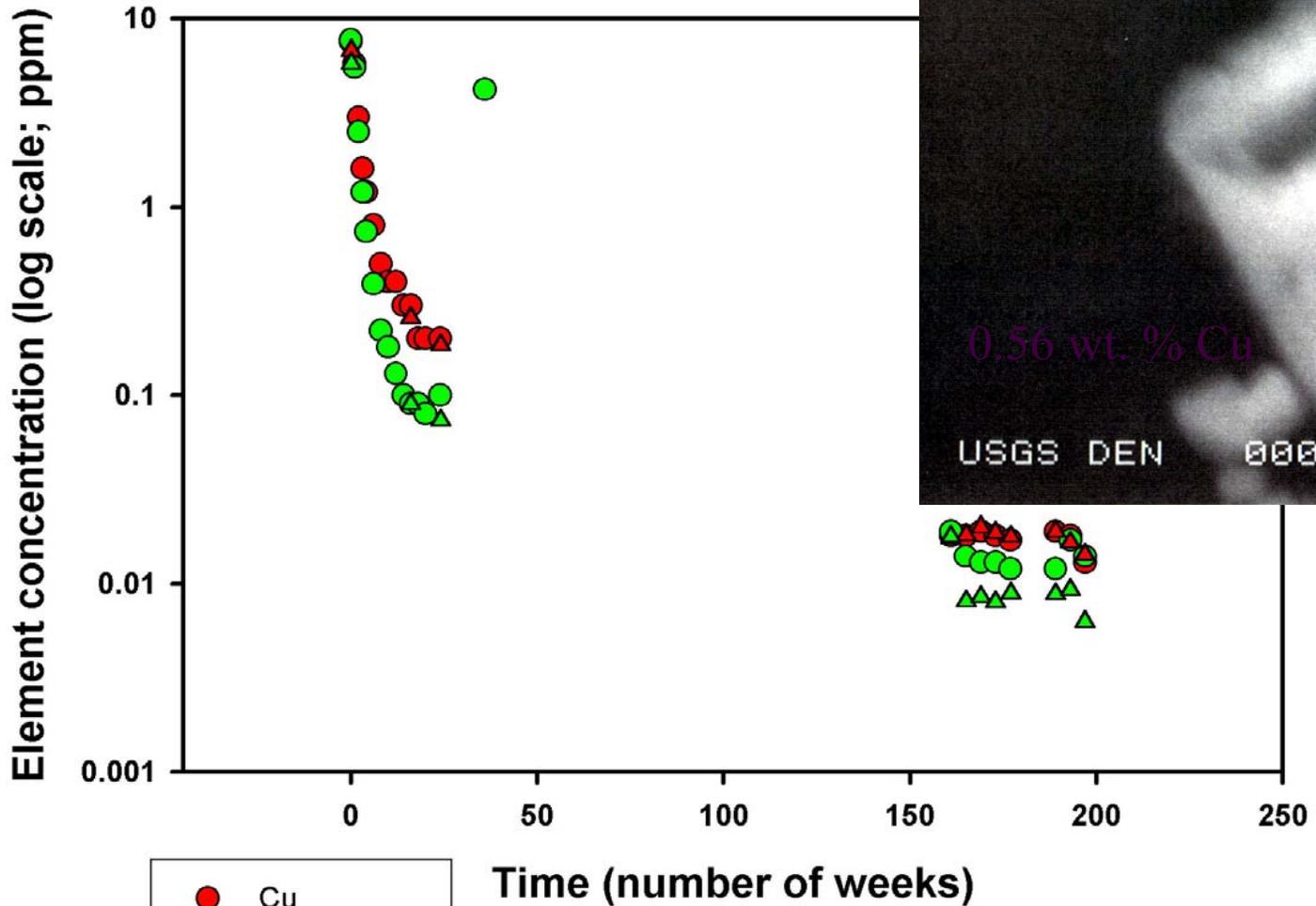


Cleavage in mica is a highly porous structure and a viable pathway for fluid infiltration and migration.

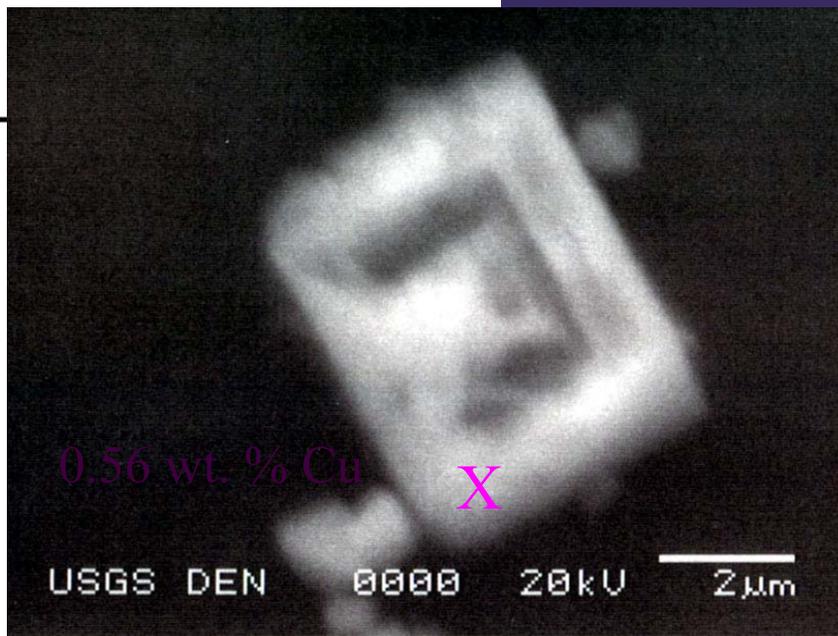
Jarosite crystals exhibit a chemical zonation evidenced by dissolution of the crystal cores.

Sample 81196; Trace Metals in Jarosite-Bearing Mine Waste

Trace elements in Jarosite



- Cu
- Zn
- ▲ ICP_MS Cu
- ▲ ICP_MS Zn



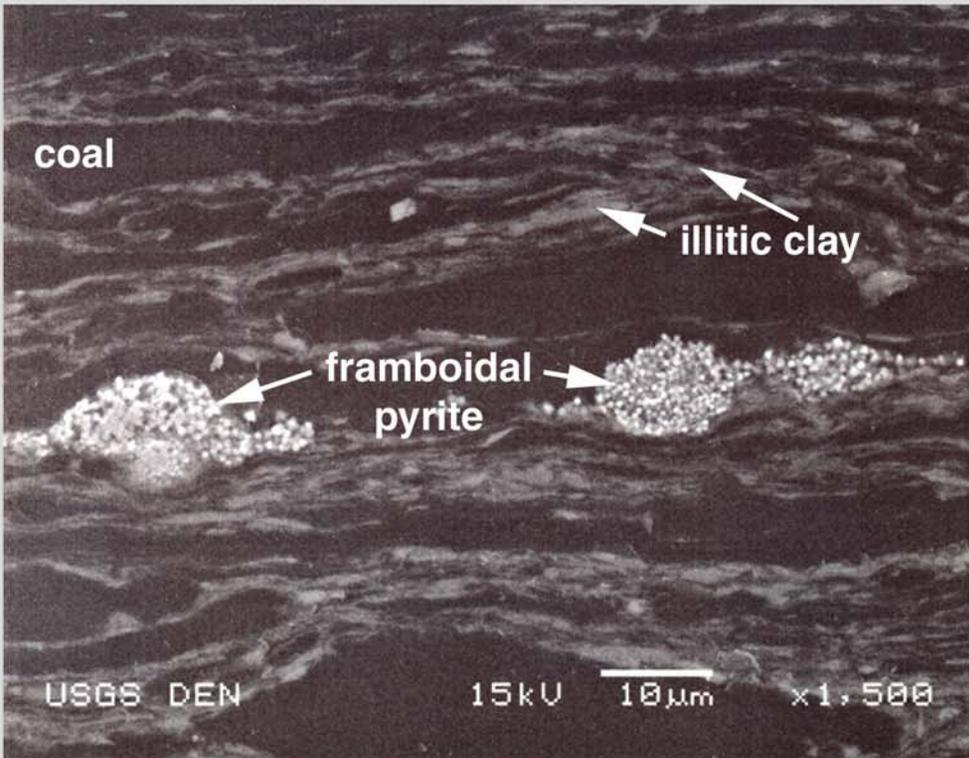
Case Study 2:

Trace Elements in Coal/Pyrite from the Lost Creek Mine, Warrior Basin, Alabama

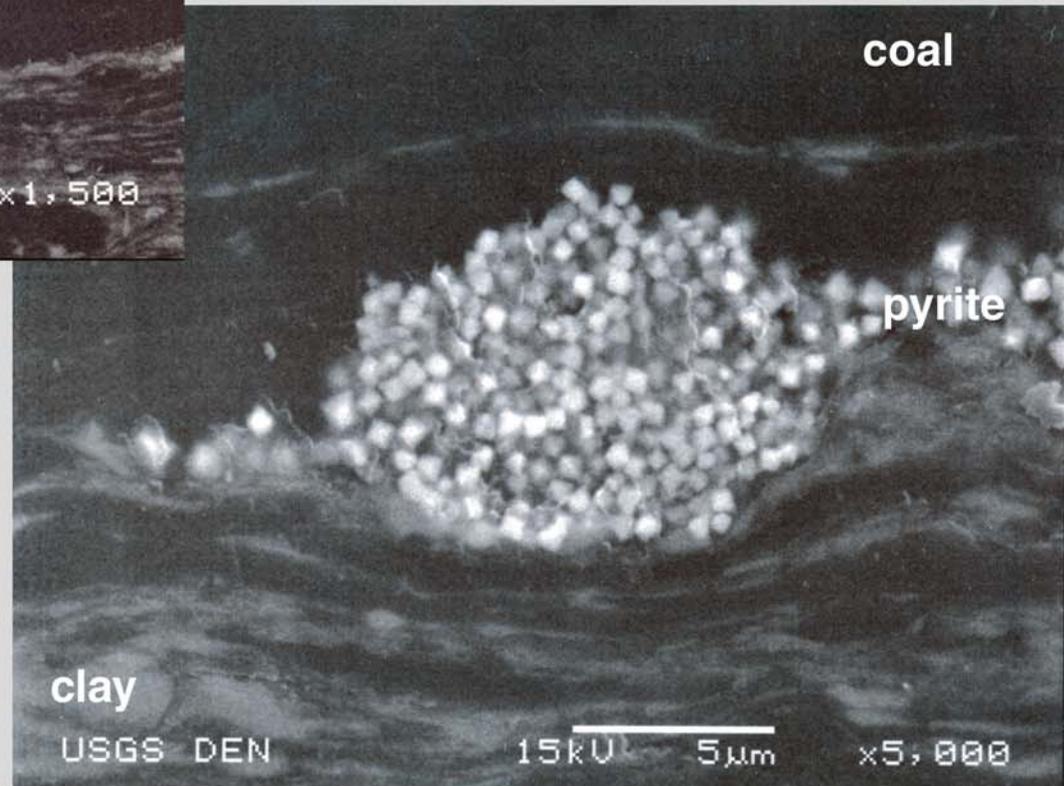


Framboidal Pyrite

Framboidal pyrite is an early form of arsenic-poor pyrite that occurs as microcrystalline cubes in lens and spheres.



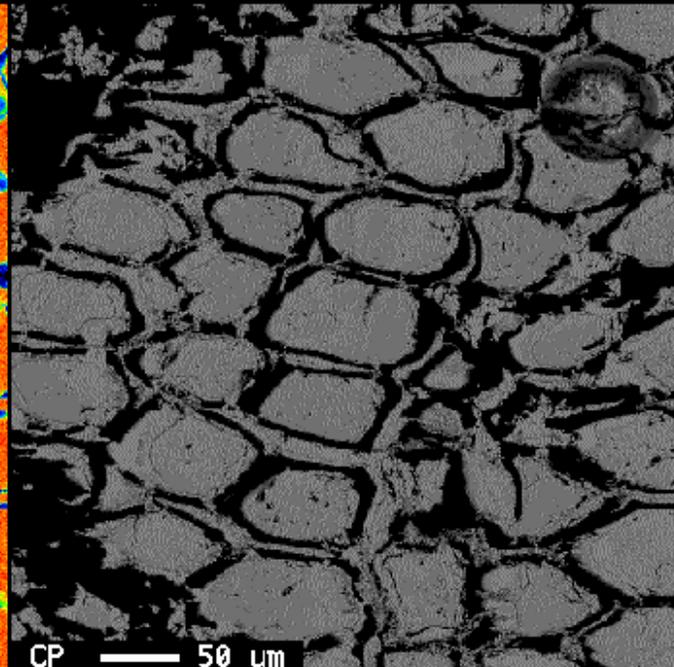
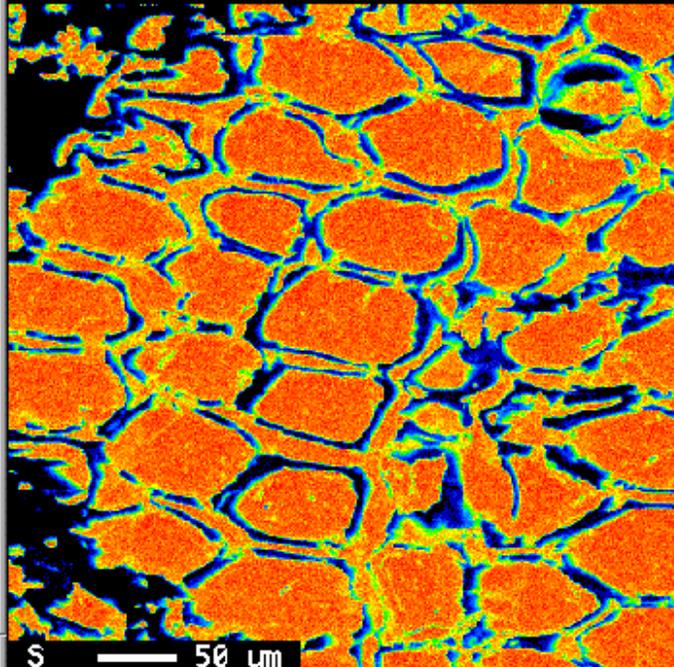
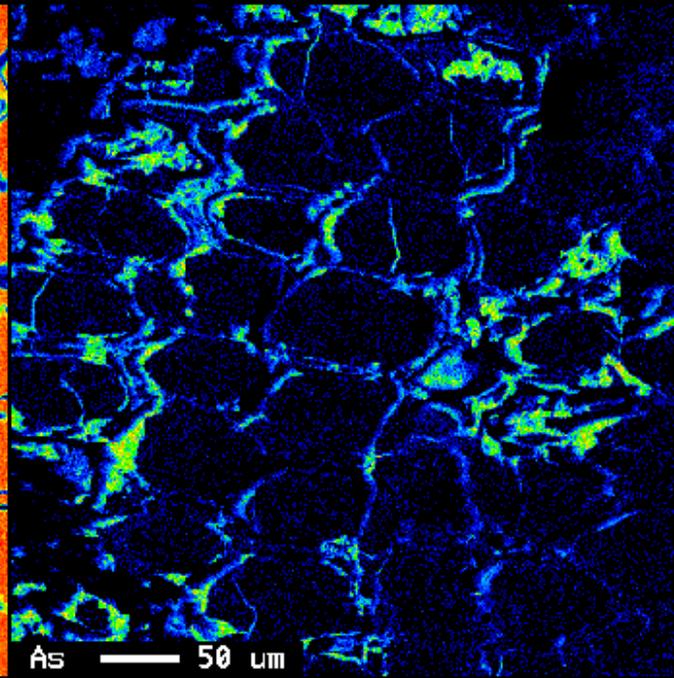
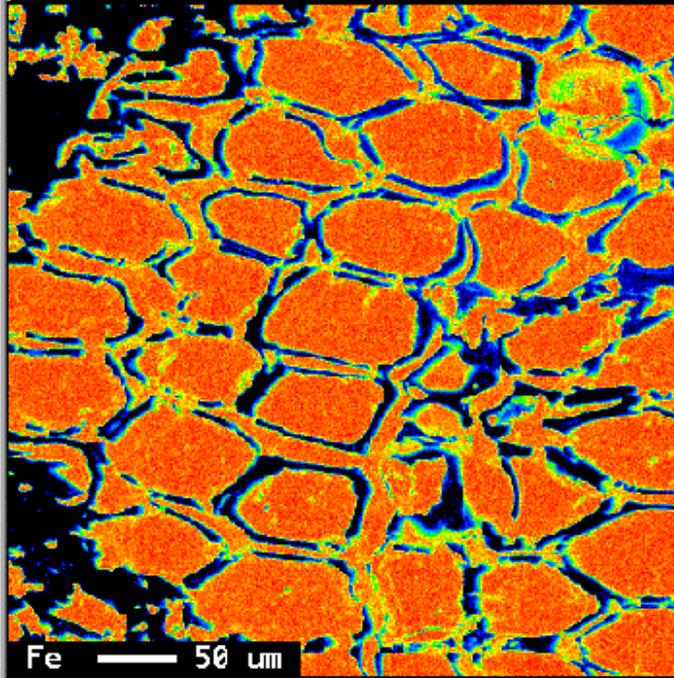
Framboidal pyrite is commonly enriched in trace metals, such as Pb, Ni, and Cu.



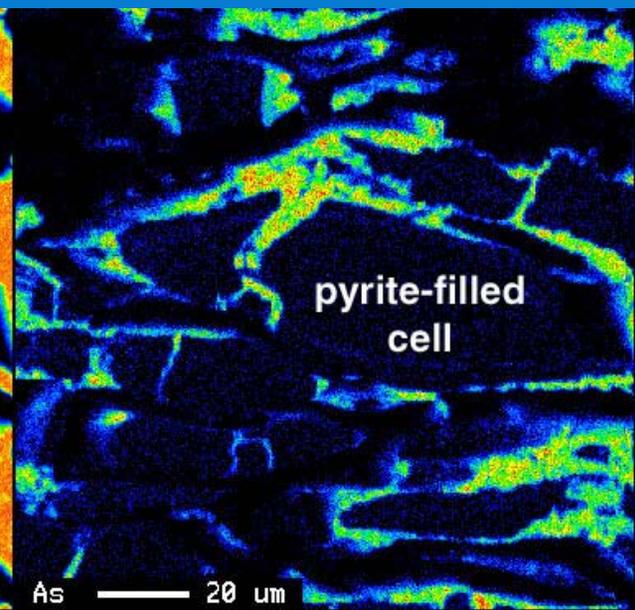
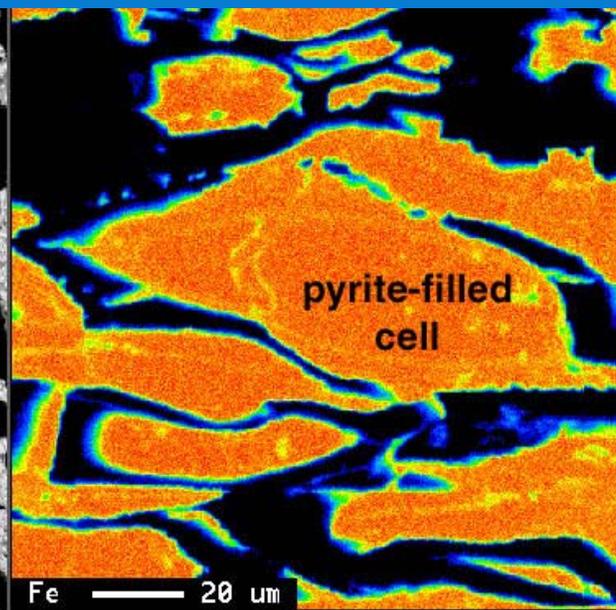
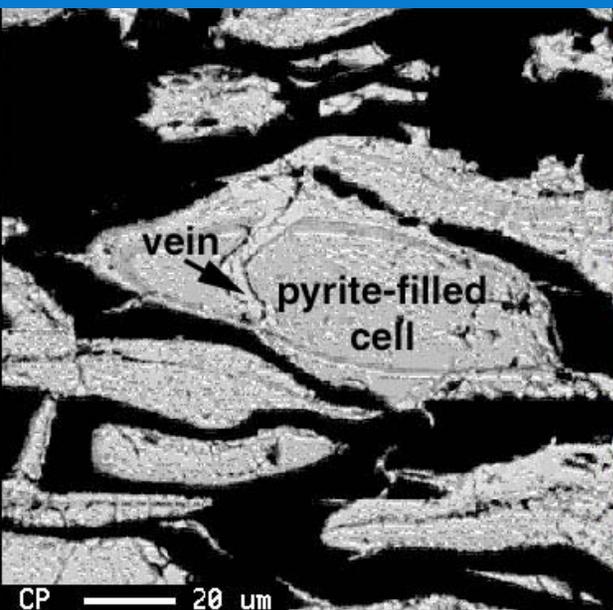
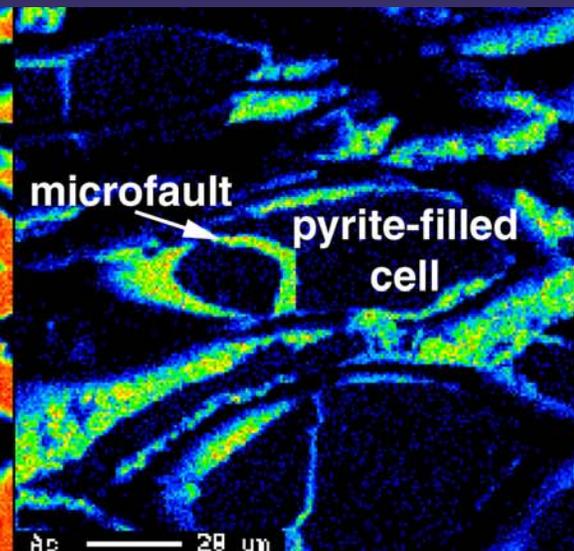
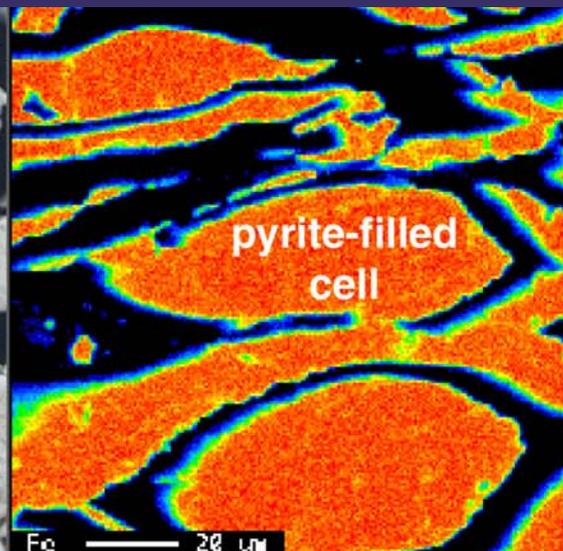
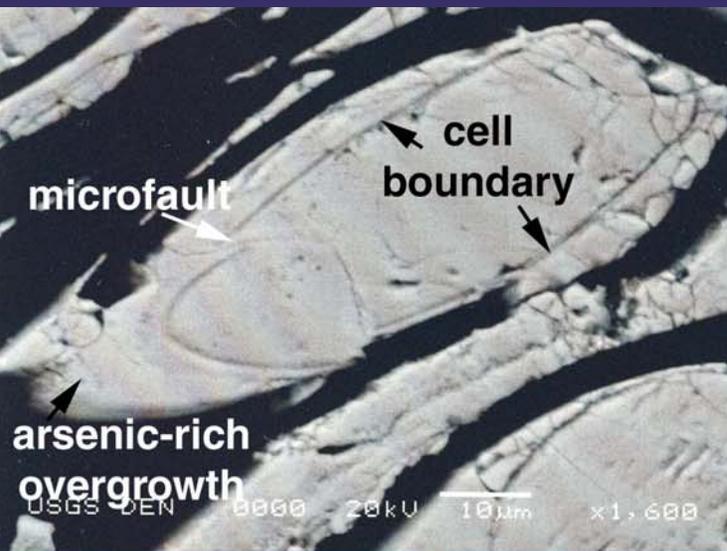
Lost Creek Mine

Pyrite fills woody cell structures.

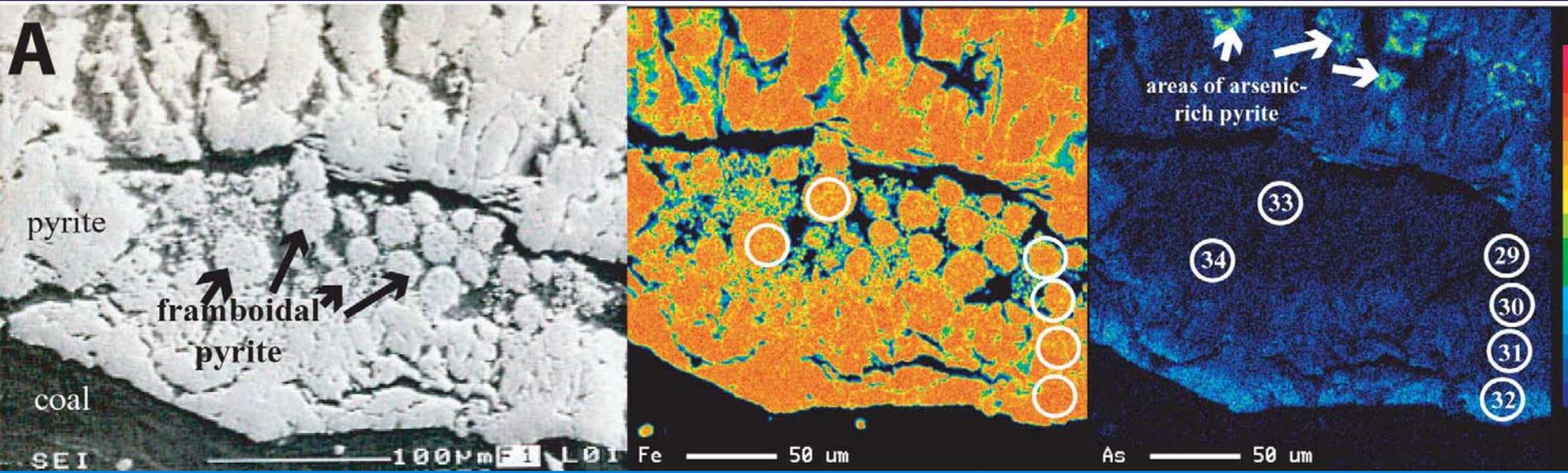
Arsenic-rich pyrite replaces early arsenic-poor pyrite in lumens, occurs as overgrowths, and along microfaults.



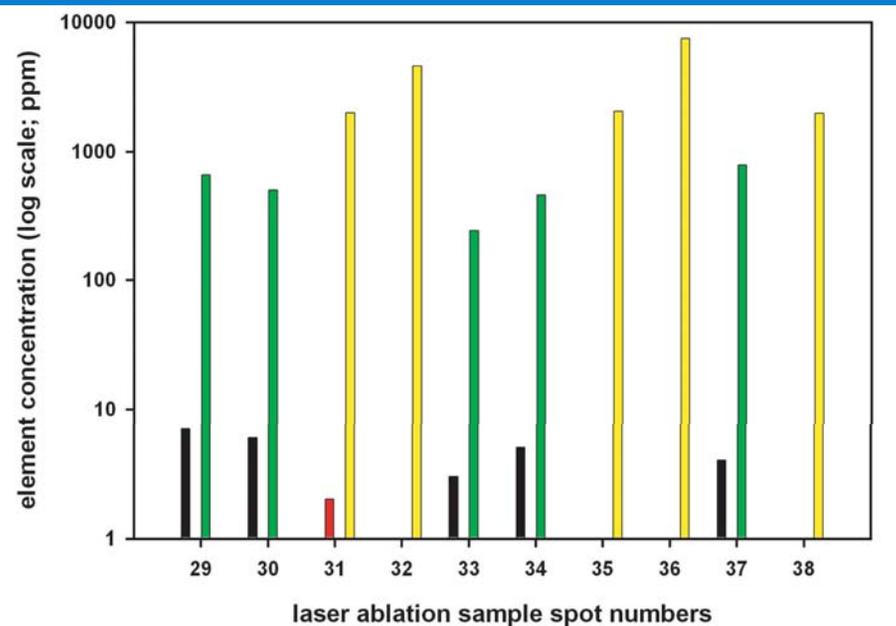
Element Maps of Arsenic in Microstructures

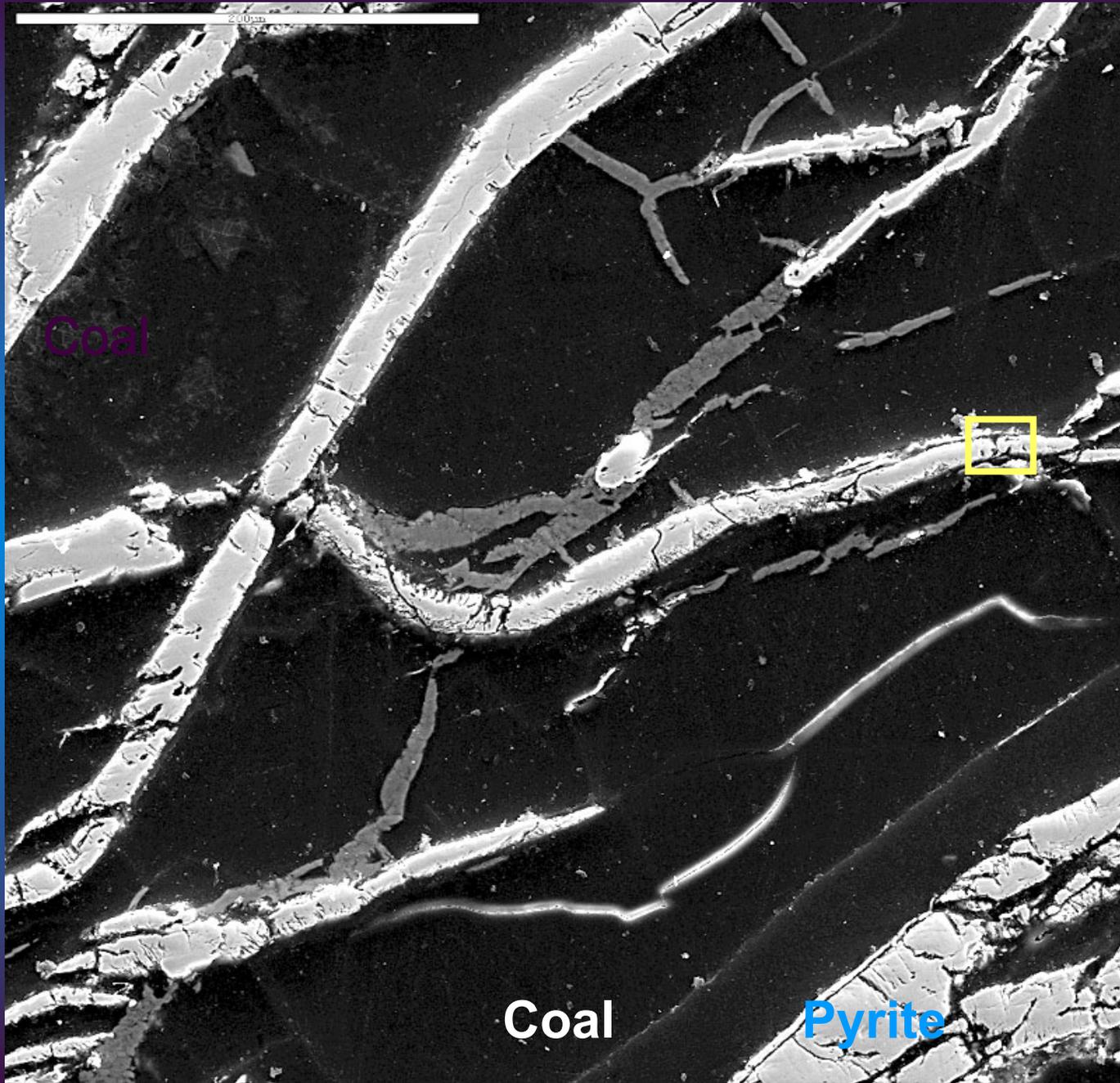


Arsenic Element Distribution Map; Framboidal vs. Coarse-Grained Pyrite



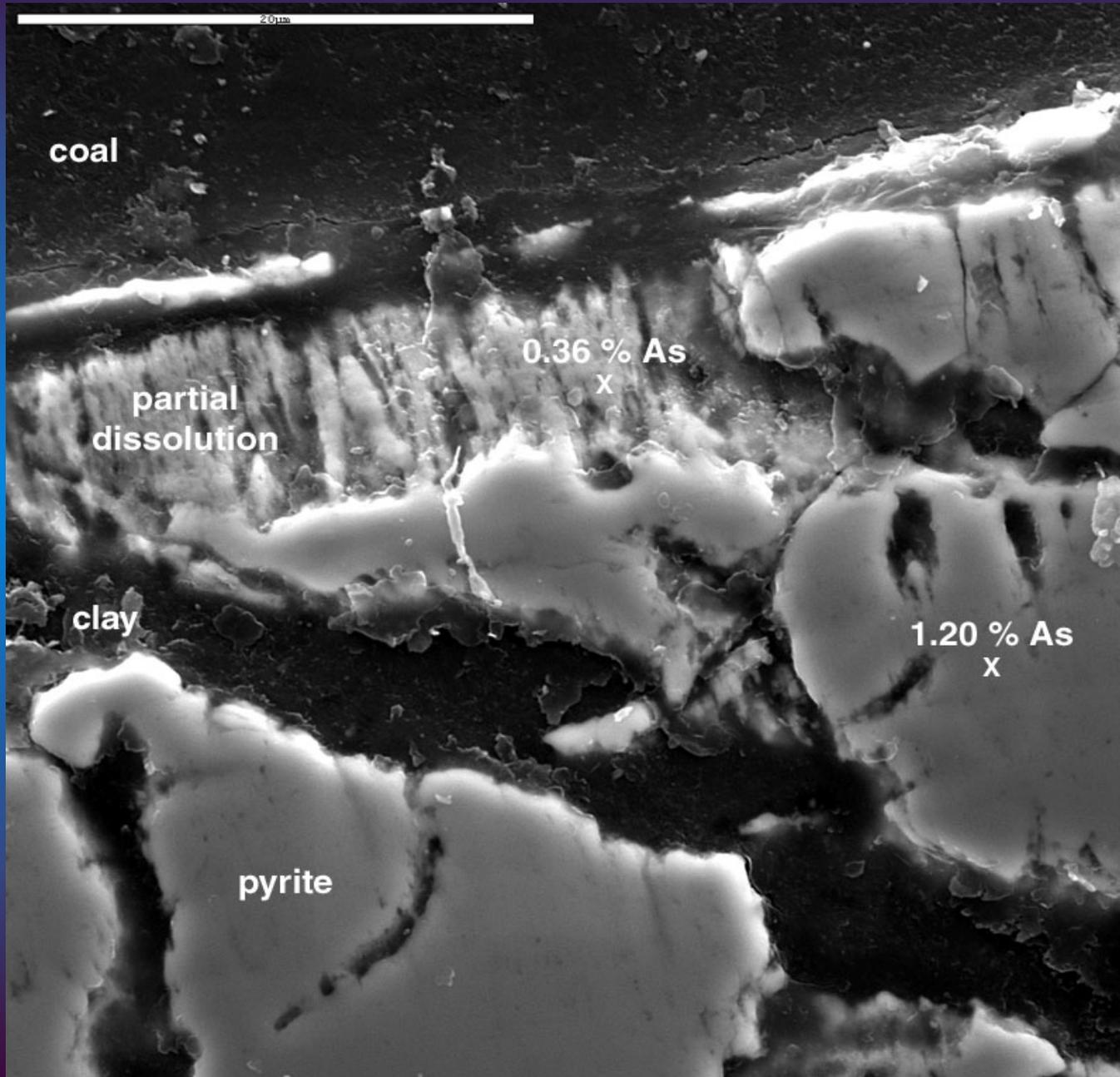
- Cu in framboidal pyrite
- Cu in coarse-grained pyrite cement
- As in framboidal pyrite
- As in coarse-grained pyrite cement





Arsenic-rich Pyrite and Clay-filled Fractures

Arsenic-rich Pyrite-filled Veins



Arsenic-rich pyrite goes into solution more readily than arsenic-poor pyrite.

Summary

Trace metals are associated with characteristic geologic settings and their mineral assemblages.

Therefore, trace metal release and acid mine drainage can be predicted from the mineralogy in mine waste.