The Importance of Geology

Sharon F. Diehl, USGS

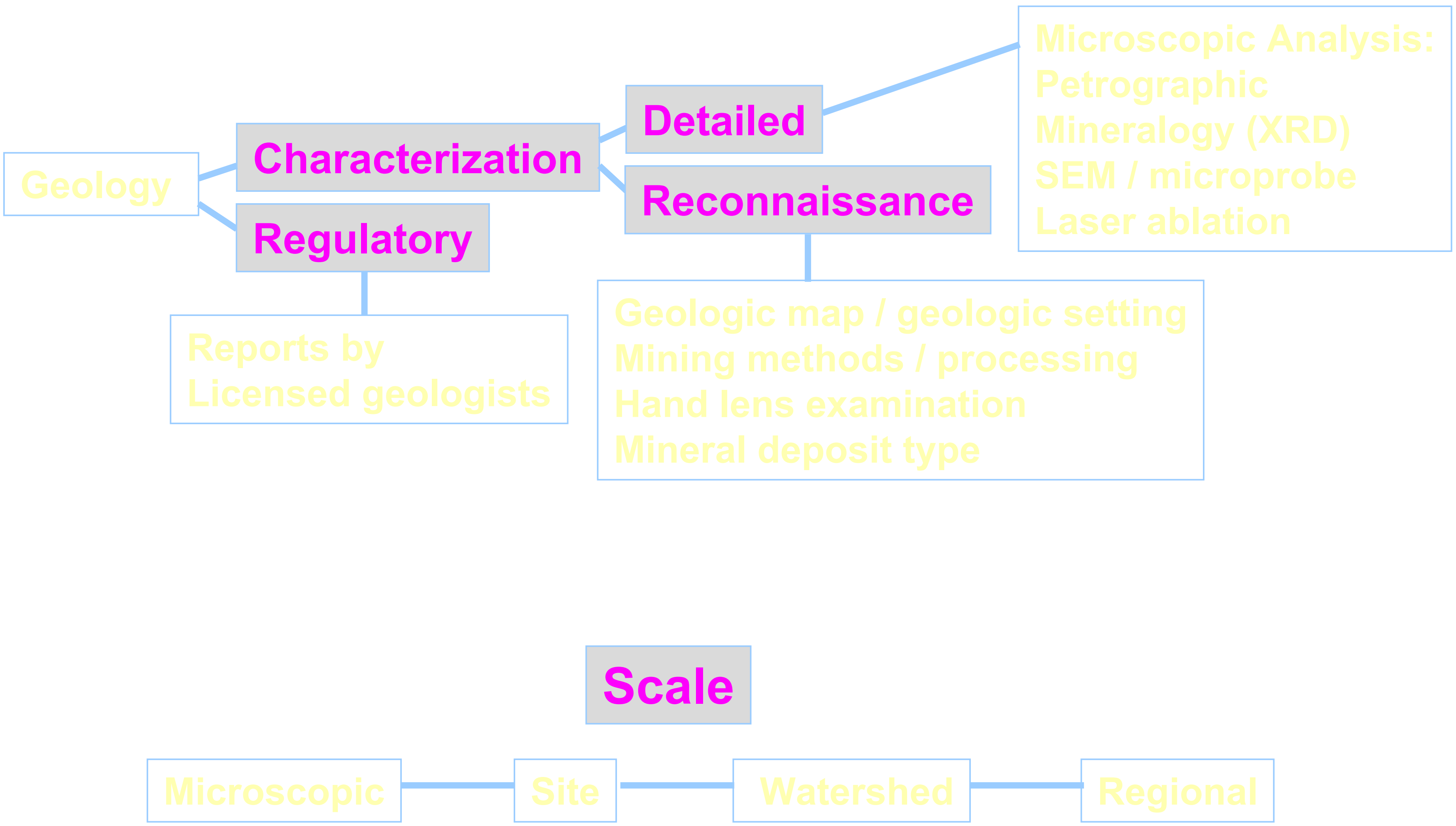
Billings Symposium / ASMR Annual Meeting

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

- Iron sulfide content
- Other sulfide content

Many sulfides (not all) generate acid when oxidized

- Host rock
- Wallrock alteration
- Gangue mineralogy

Minerals and weathering products may consume or generate acid

- 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)

USGS

Acid-Generating Minerals

Pyrite (FeS_2)
Marcasite (FeS_2)
Pyrrhotite ($Fe_{1-x}S$)
Arsenopyrite ($FeAsS$)
Enargite (Cu_3AsS_4)
Tennantite ($Cu_{12}As_4S_{13}$)
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)

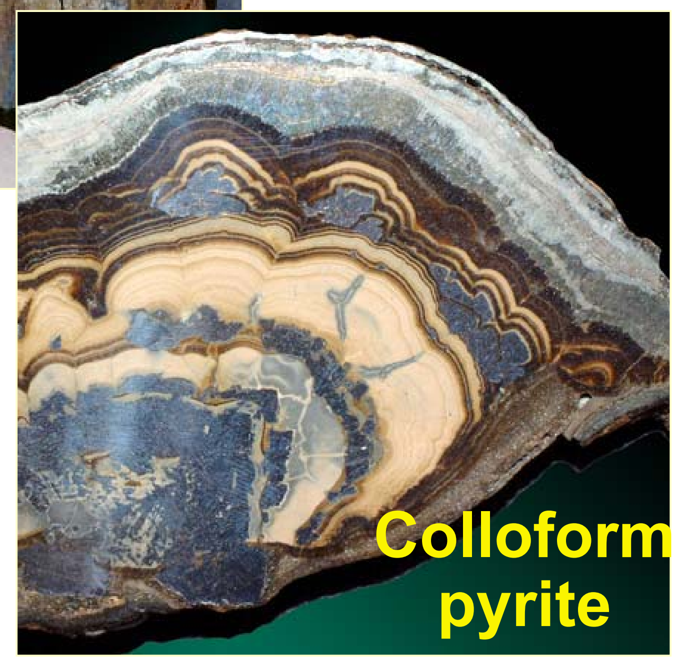
If metal hydroxides (solid or aqueous) form, above minerals plus:

Siderite ($FeCO_3$)
Rhodochrosite ($MnCO_3$)

USGS

Sulfide Texture and Resistance to Weathering

Less easily weathered



More easily weathered

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

USGS

- 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, CO_2, acid)

USGS

- 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

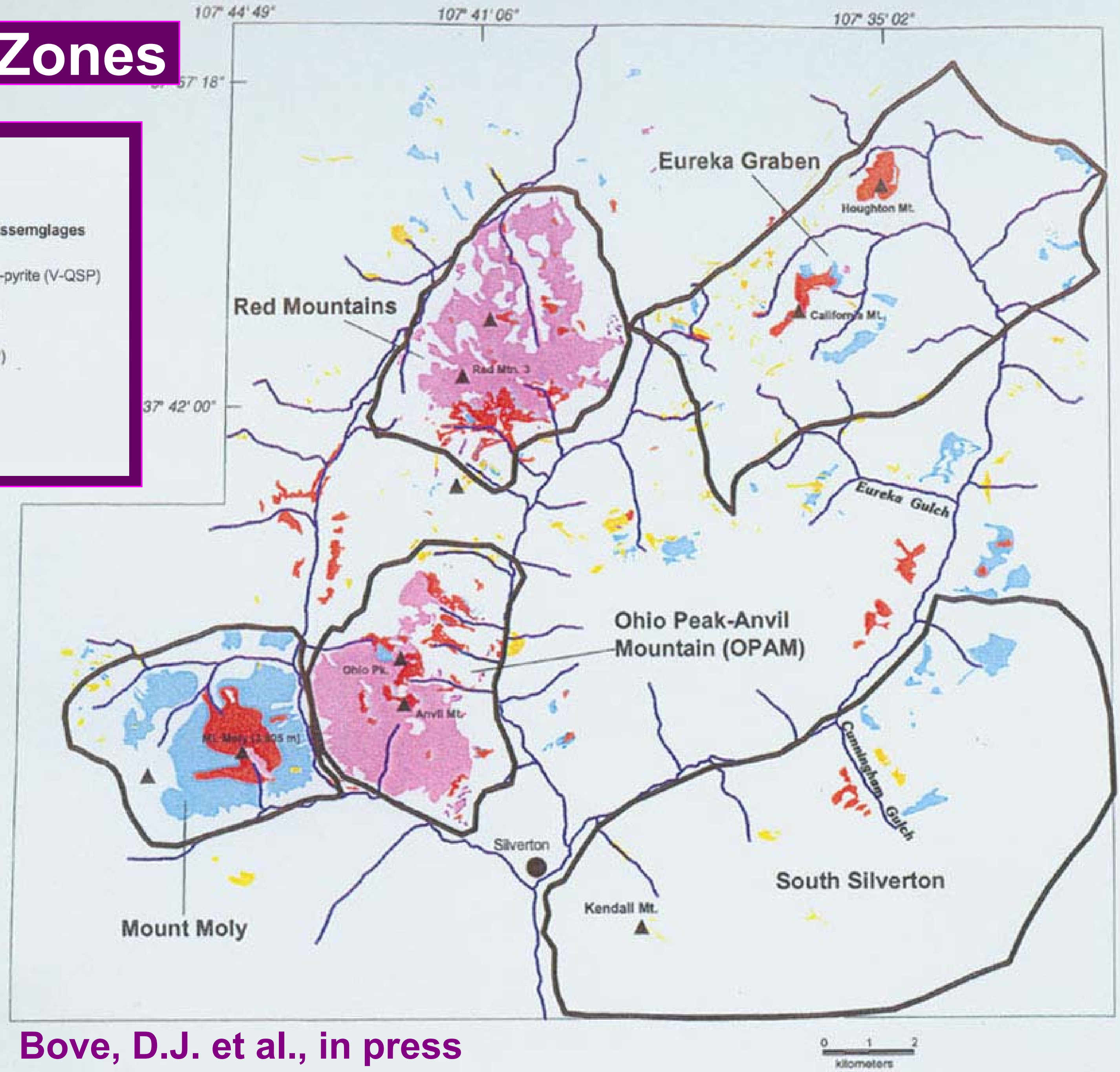
- Mineralizing processes modify an ore deposit's host-rock mineral assemblage to a new mineral assemblage
  - Results in different acid-generating and acid-consuming capacities
- Can strongly influence the environmental signature of a mineral deposit
- Can modify the physical characteristics of the host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

Alteration Zones

EXPLANATION

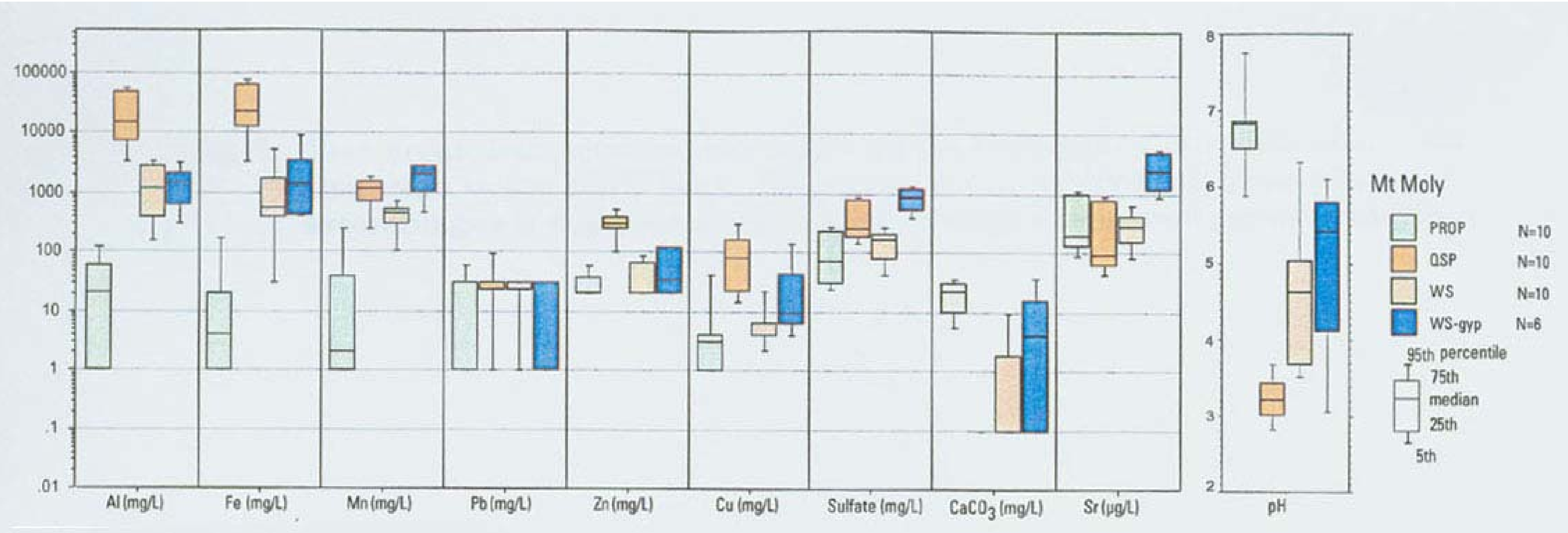
Hydrothermal Alterattion Assemglages

- 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

USGS

- 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:

- **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

USGS

- 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

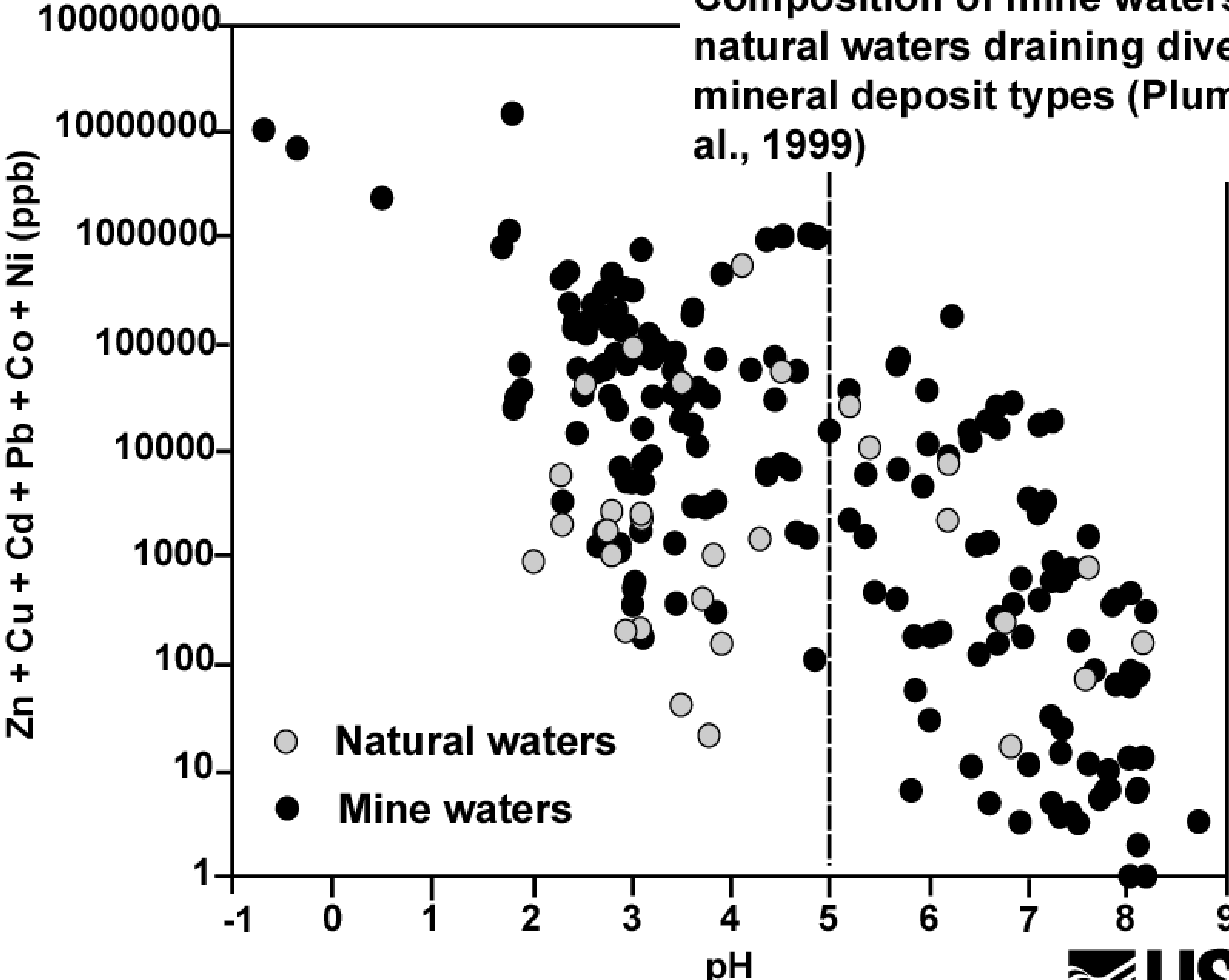
USGS

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

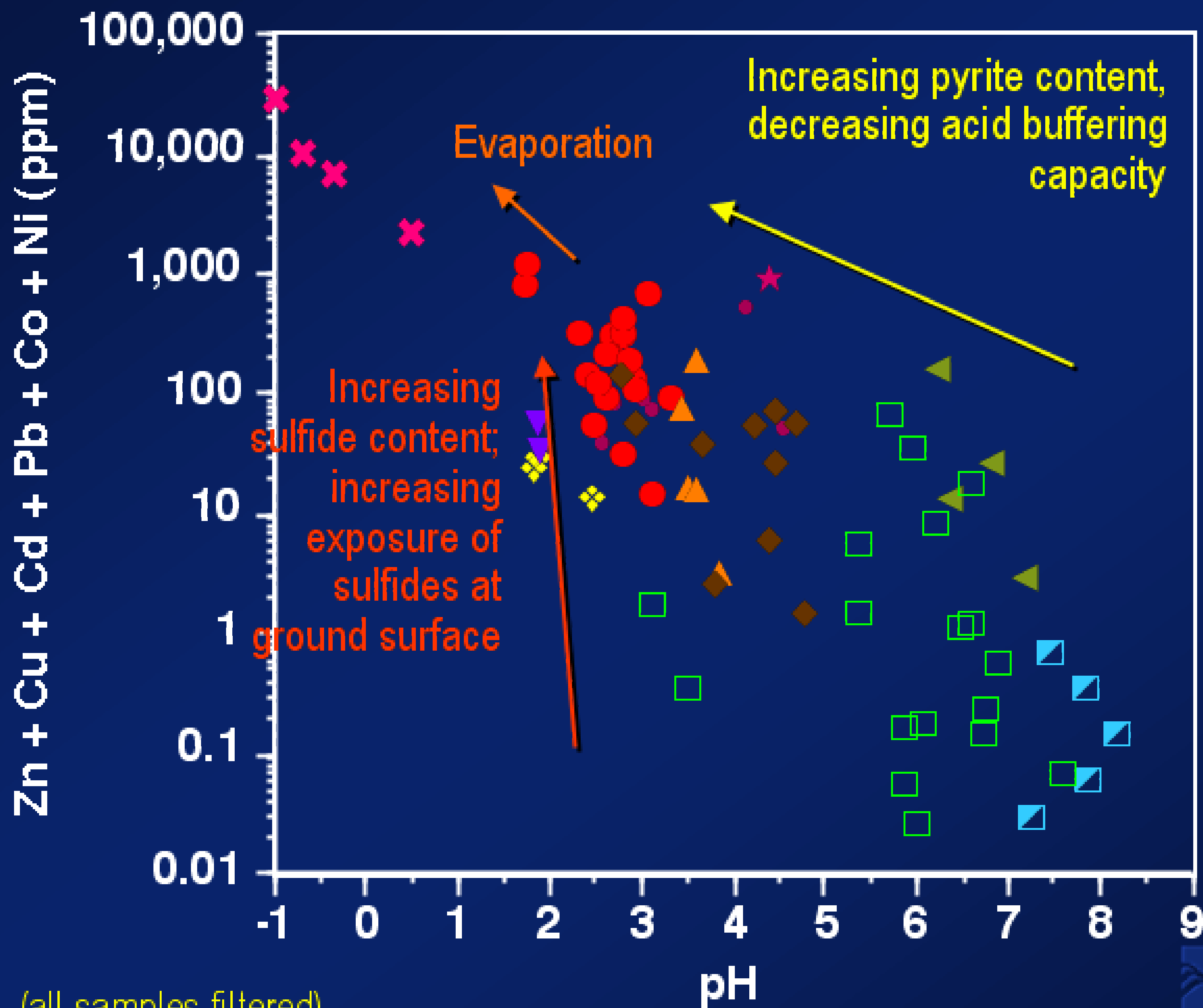
A compilation of geologic, geochemical, geophysical, hydrologic, and engineering information pertaining to the environmental behavior of geologically similar mineral deposits (1) prior to mining, and (2) resulting from mining, mineral processing, and smelting.

USGS

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



Geologic controls on mine-drainage composition



Symbols depict waters draining deposits with similar geologic character-istics

Plumlee et al., 1999

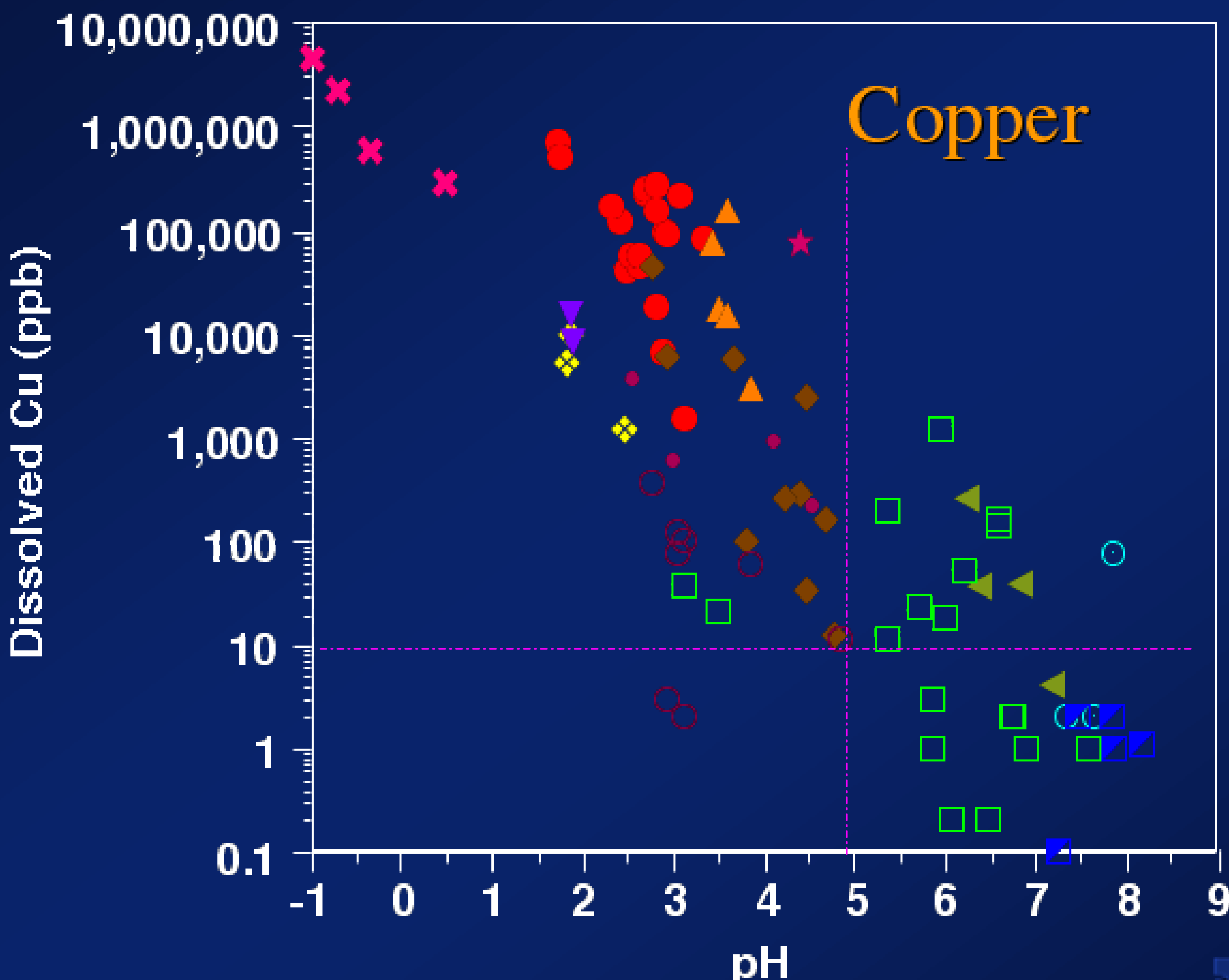
(all samples filtered)

USGS

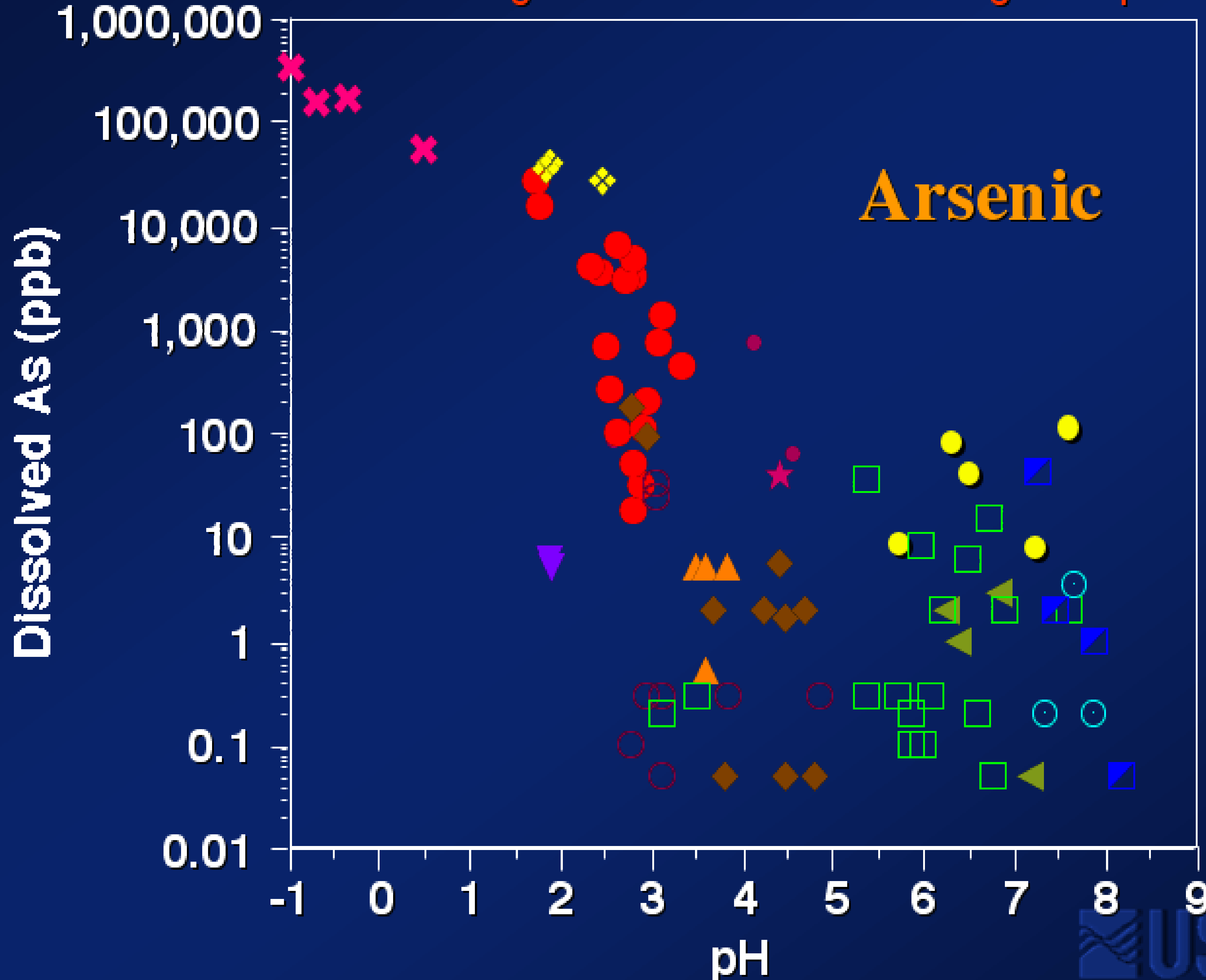
Legend

- 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

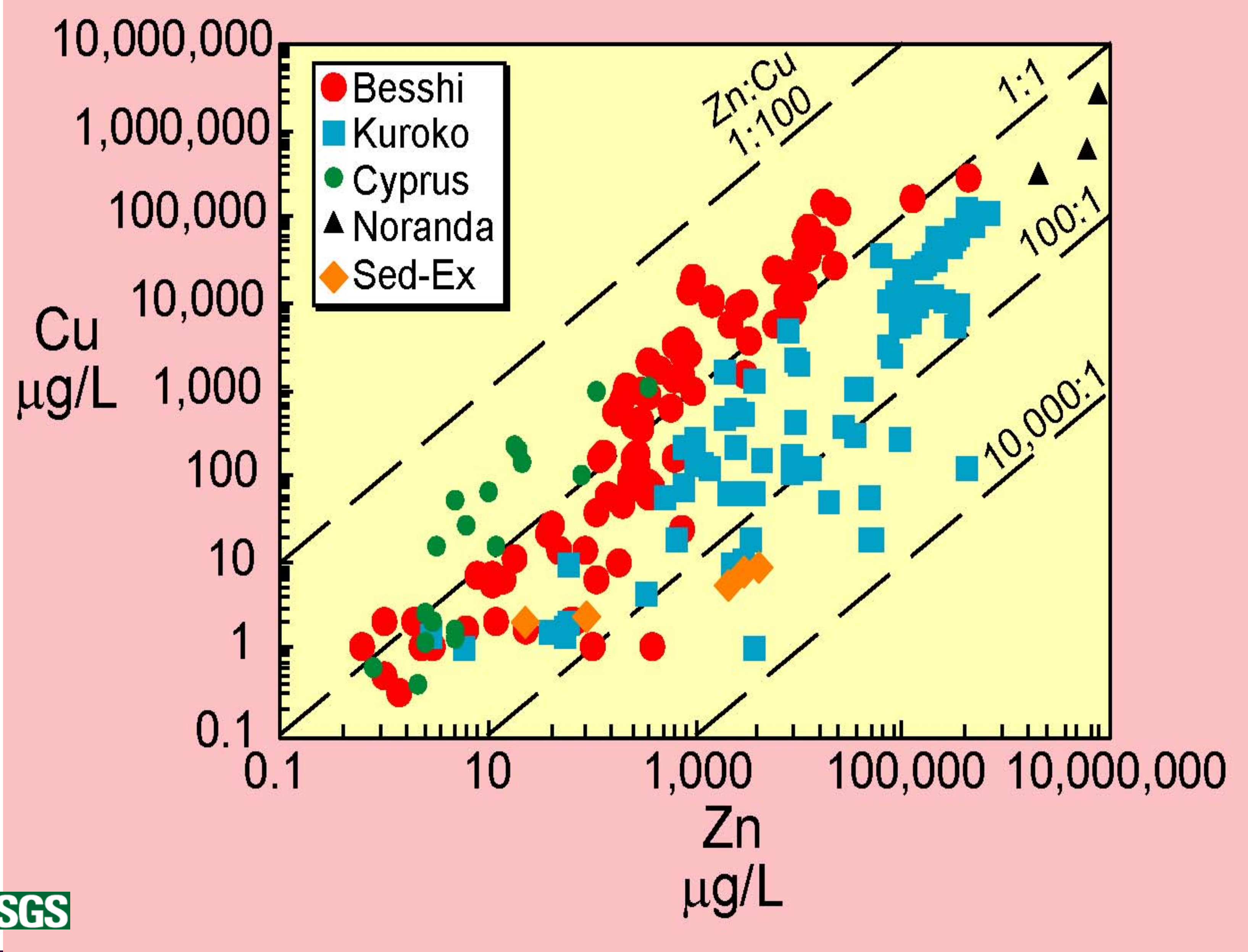
Geologic controls on mine-drainage composition



Geologic controls on mine-drainage composition



(Seal and Hammarstrom, 2003)



USGS

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

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

SOCIETY OF ECONOMIC GEOLOGISTS, INC.

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

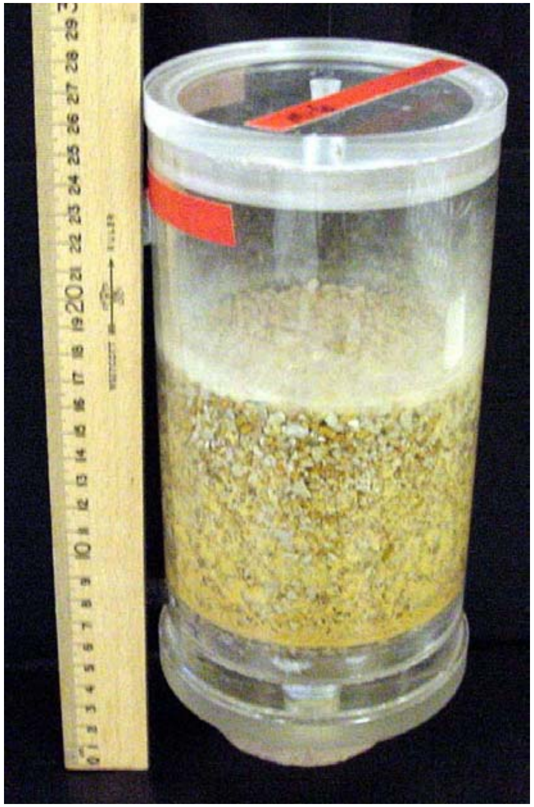
Microscopic Analytical Methods

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

USGS

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

[redacted]

Jarosite [$KFe_3(SO4)_2(OH)_6$]	**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 [$(Ag, Cu, Fe)_{12} (Sb, As)_4S_{13}$	**Cu, Zn, Sb, As**

USGS

Case Study 1:
Bulk Mineralogy of Mine Waste Samples

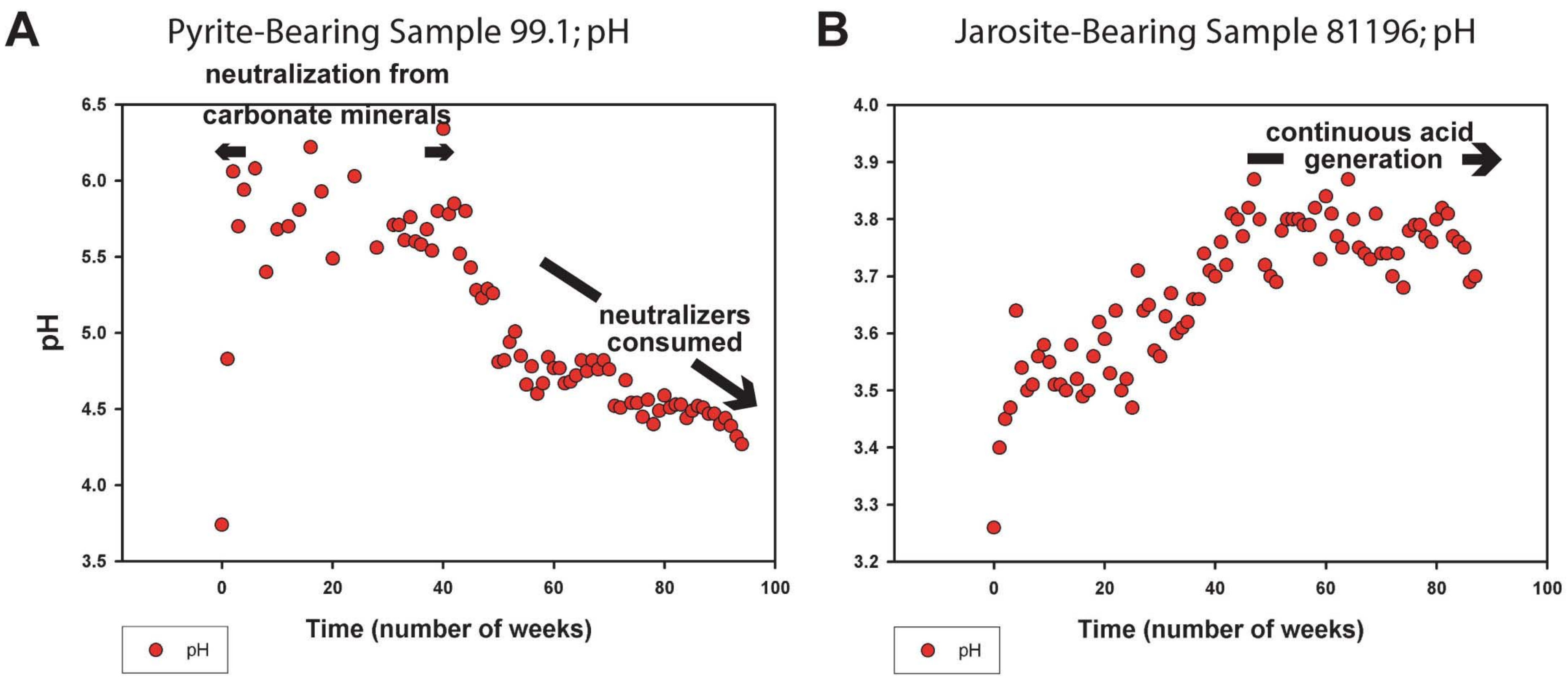
SEMI-QUANTITATIVE MINERALOGY (sample 99.1, wt. %)

	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

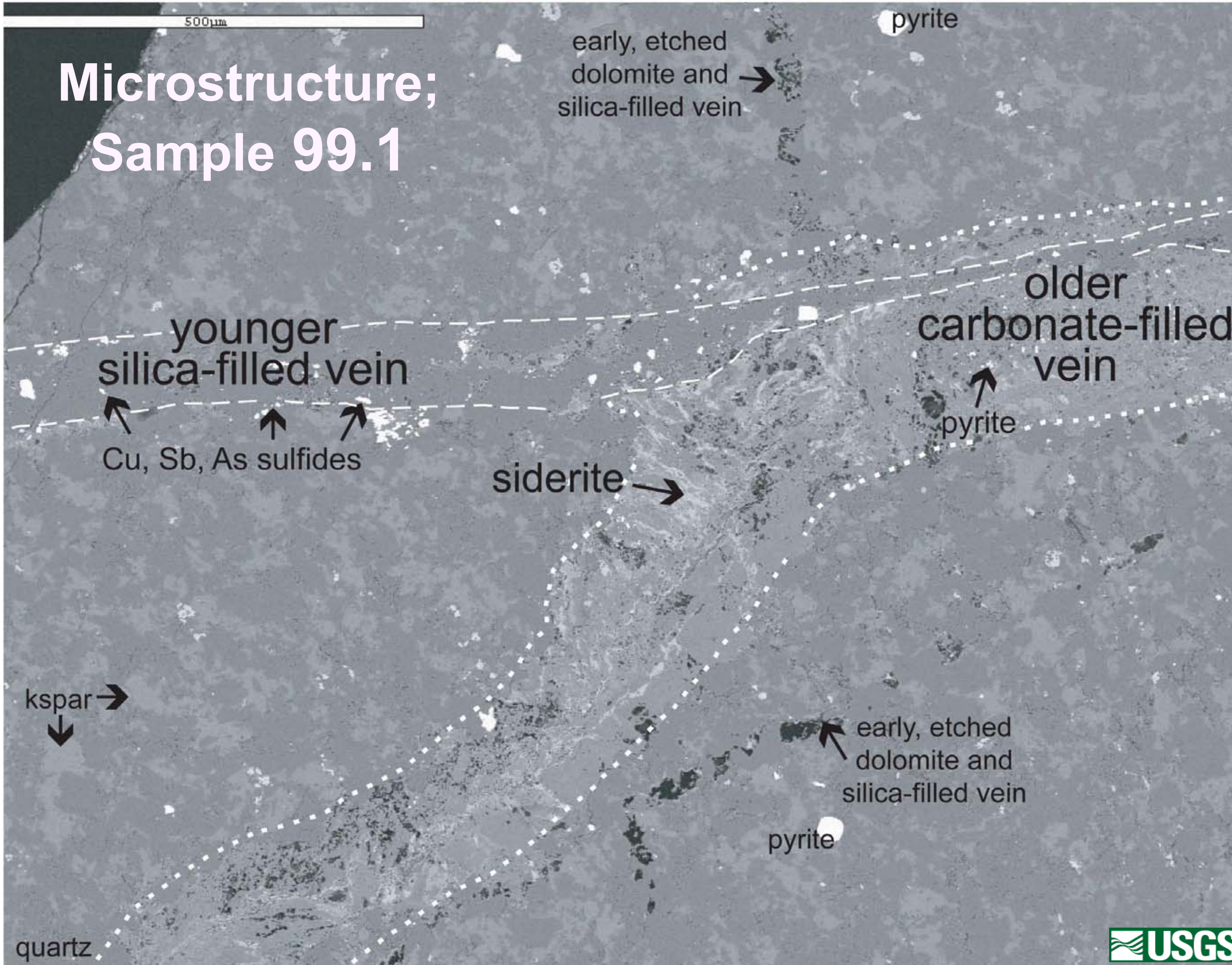
SEMI-QUANTITATIVE MINERALOGY (sample 81196, wt. %)

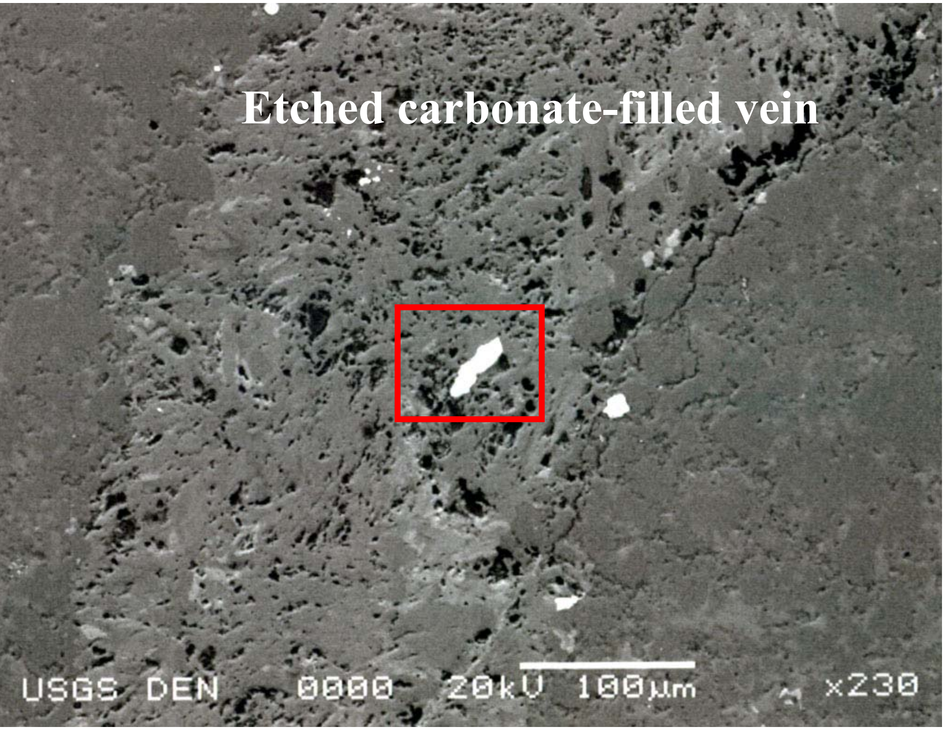
	Before Leaching	After Leaching
Quartz	33	32
Amorphous	33	34
Jarosite	16	17
Potassium Feldspar	15	15
Muscovite	2	2
Gypsum	1	--

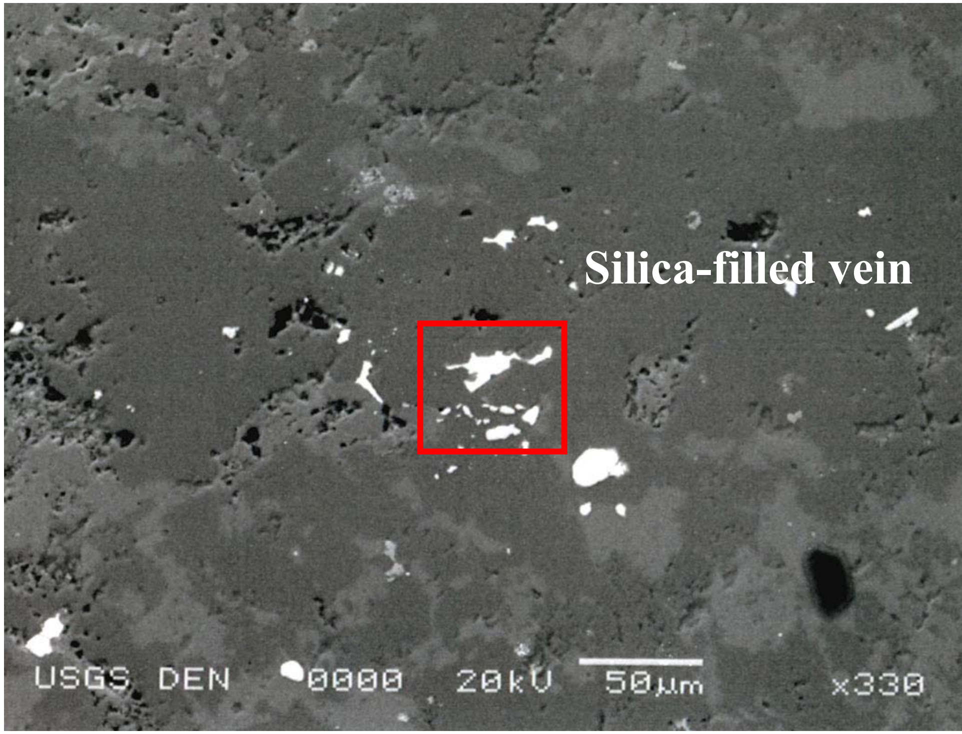
pH



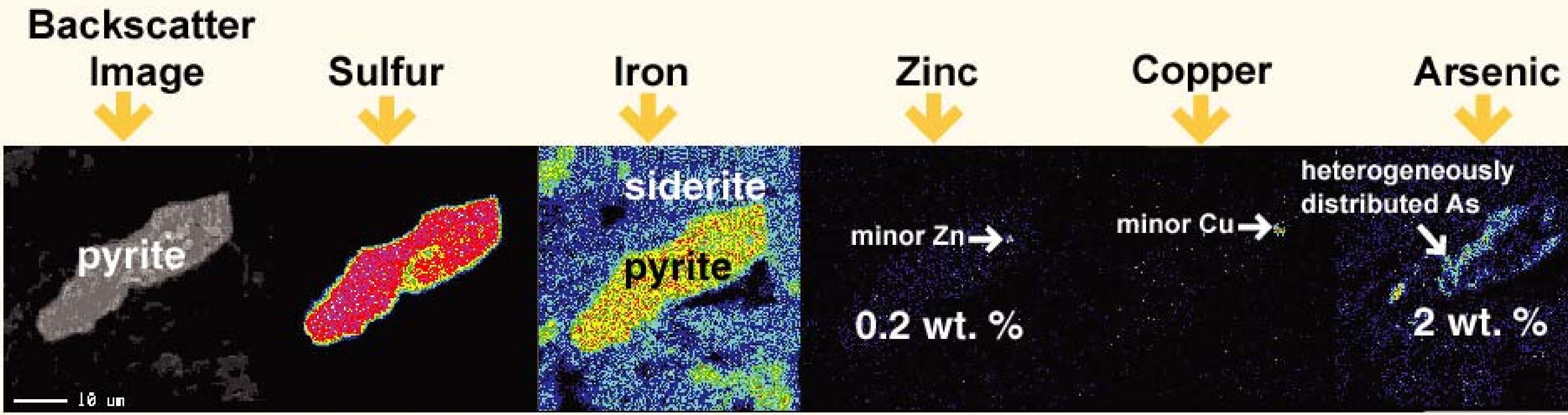
A
Pyrite-Bearing Sample 99.1; pH
neutralization from
carbonate minerals
neutralizers
consumed
pH
6.5
6.0
5.5
5.0
4.5
4.0
3.5
0
20
40
60
80
100
Time (number of weeks)
pH
B
Jarosite-Bearing Sample 81196; pH
continuous acid
generation
4.0
3.9
3.8
3.7
3.6
3.5
3.4
3.3
3.2
0
20
40
60
80
100
Time (number of weeks)
pH


500µm
Microstructure;
Sample 99.1
pyrite
early, etched
dolomite and
silica-filled vein
younger
silica-filled vein
Cu, Sb, As sulfides
older
carbonate-filled
vein
pyrite
siderite
kspar
early, etched
dolomite and
silica-filled vein
pyrite
quartz
USGS

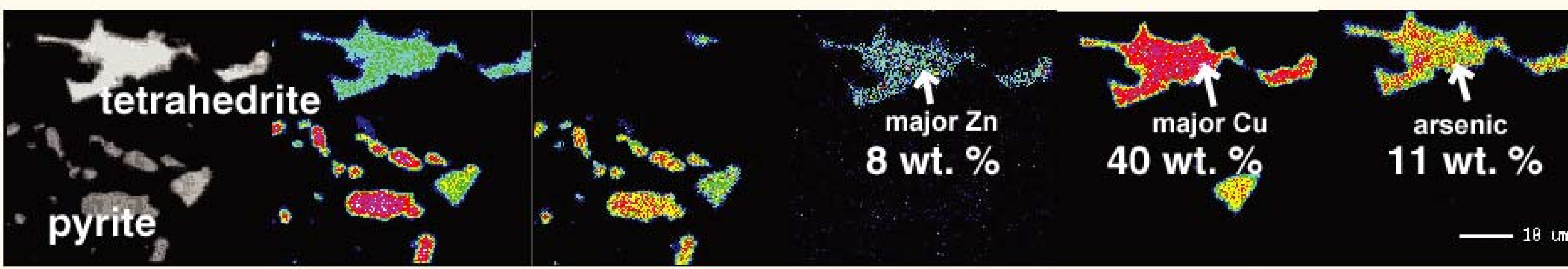

Etched carbonate-filled vein
USGS DEN 0000 20kV 100µm x230


Silica-filled vein
USGS DEN 0000 20kV 50µm x330

Microprobe Element Distribution Maps

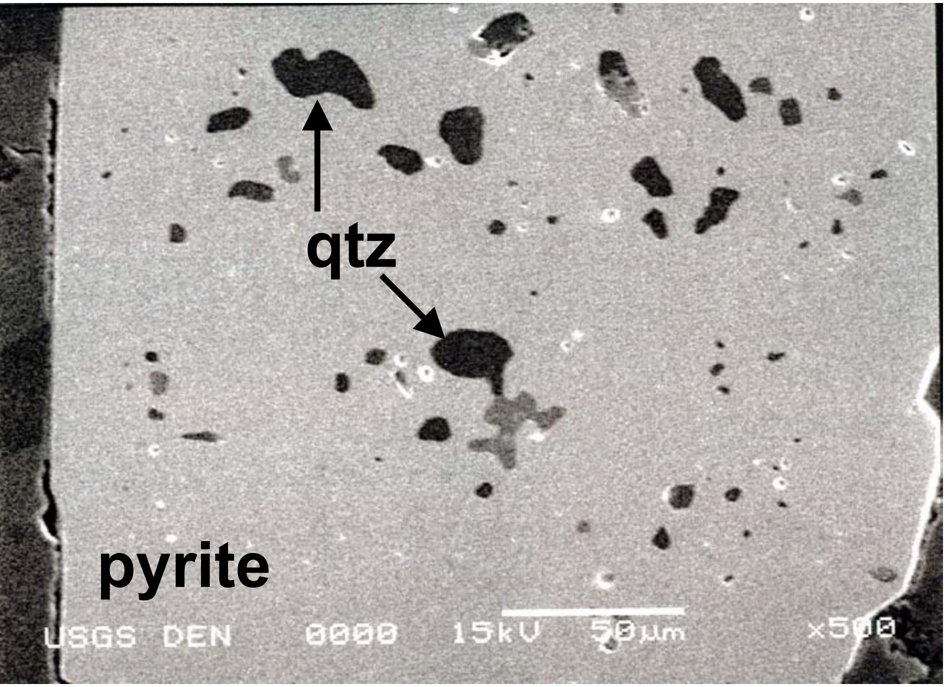


Sulfides in Carbonate-filled Vein

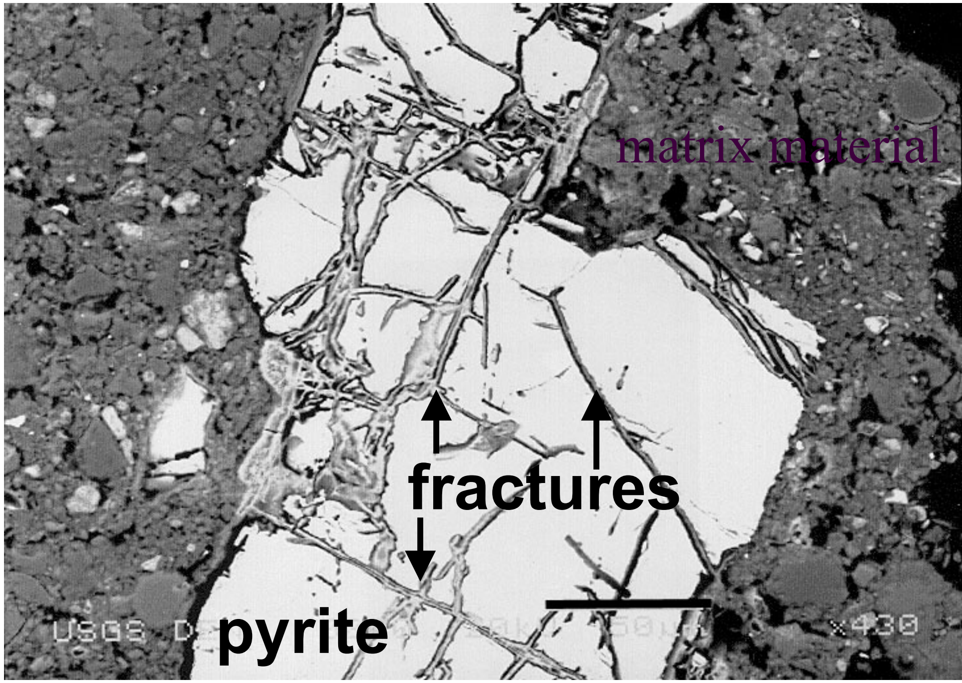


Sulfides in Silica-filled Vein

Pyrite-bearing Sample 99.1

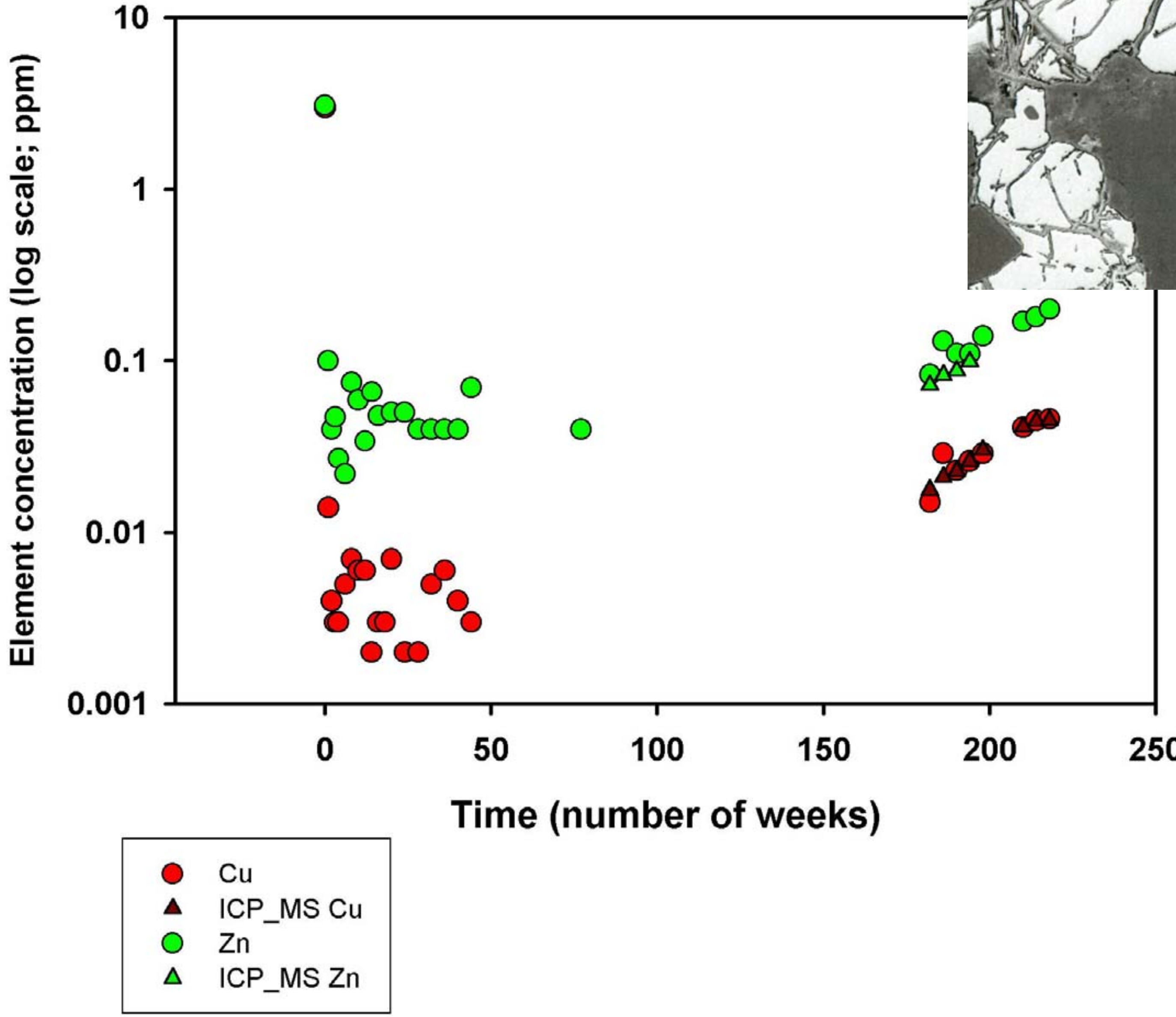


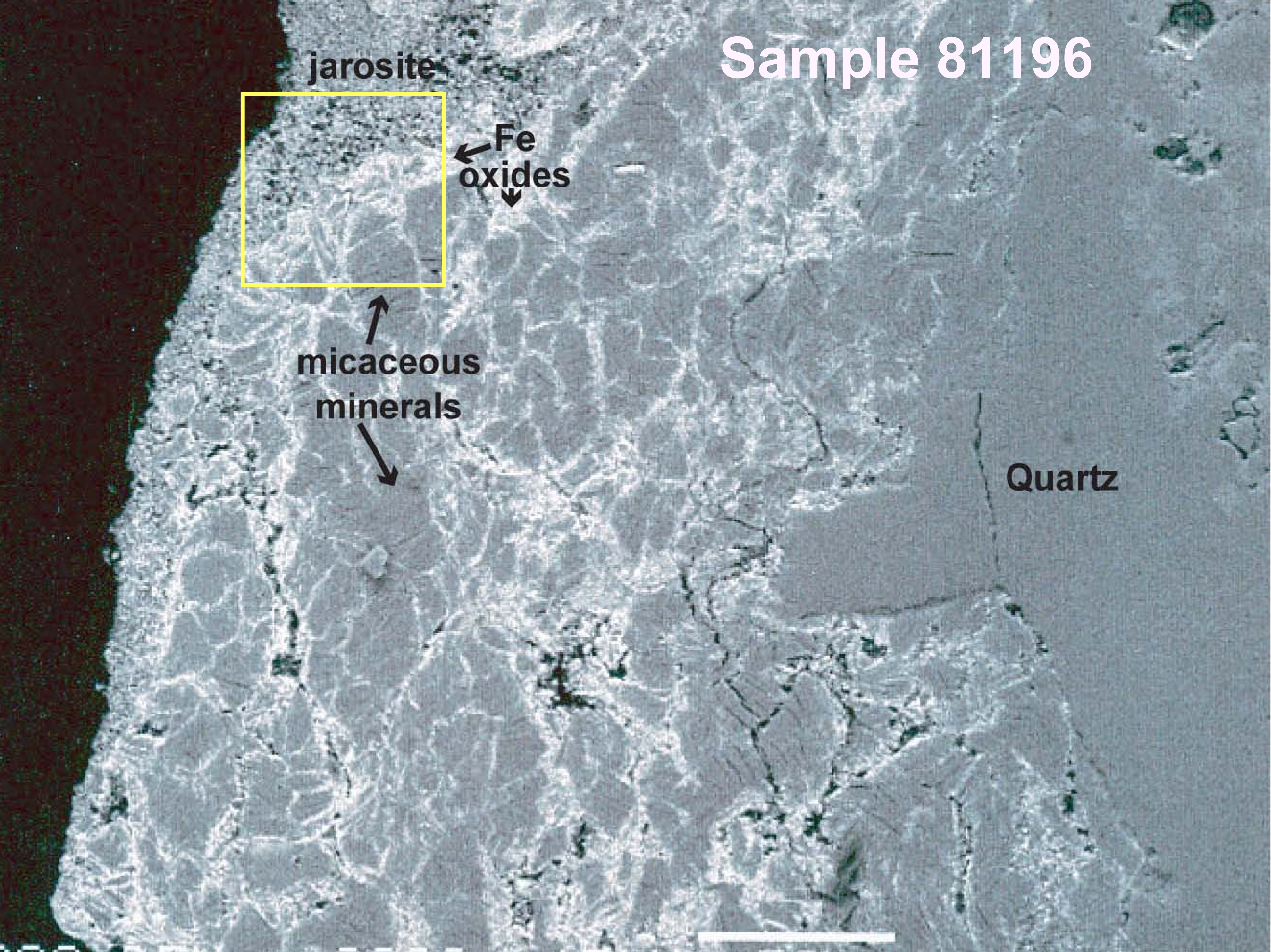
Pyrite Before Leaching



Pyrite After Leaching

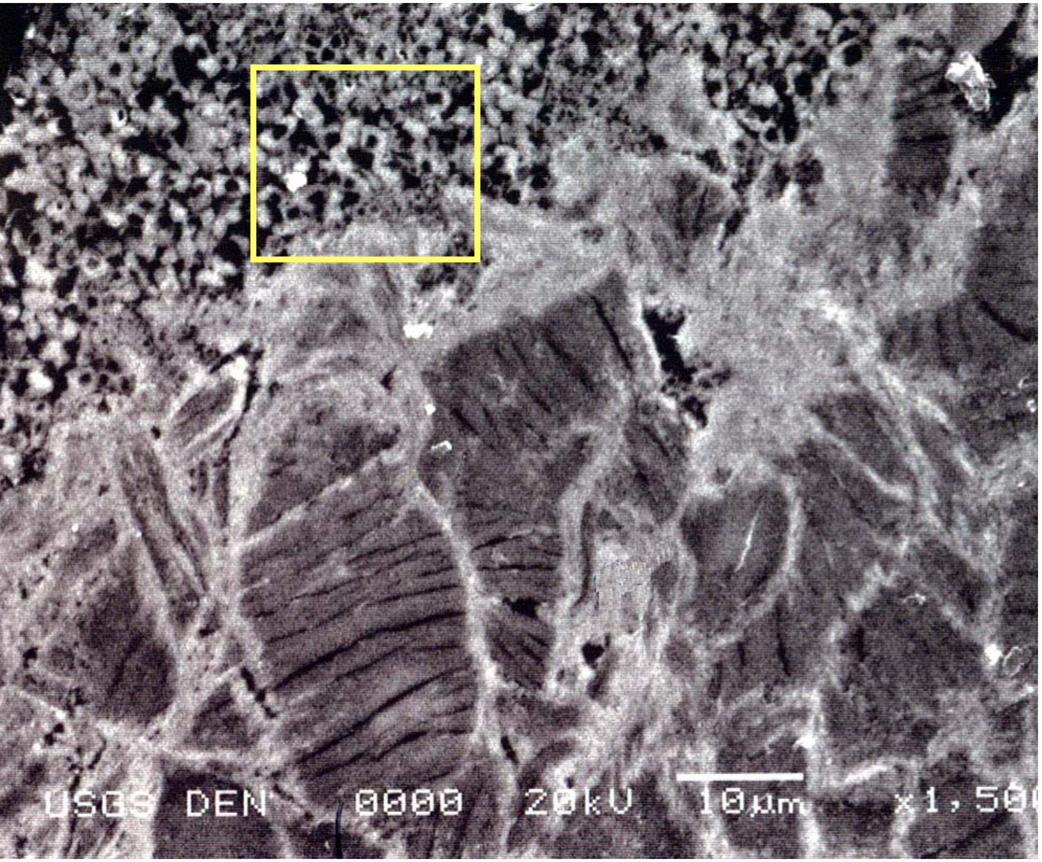
Pyrite-Bearing Sample 99.1
Cu and Zn from sulfides




Sample 81196
jarosite
Fe
oxides
micaceous
minerals
Quartz

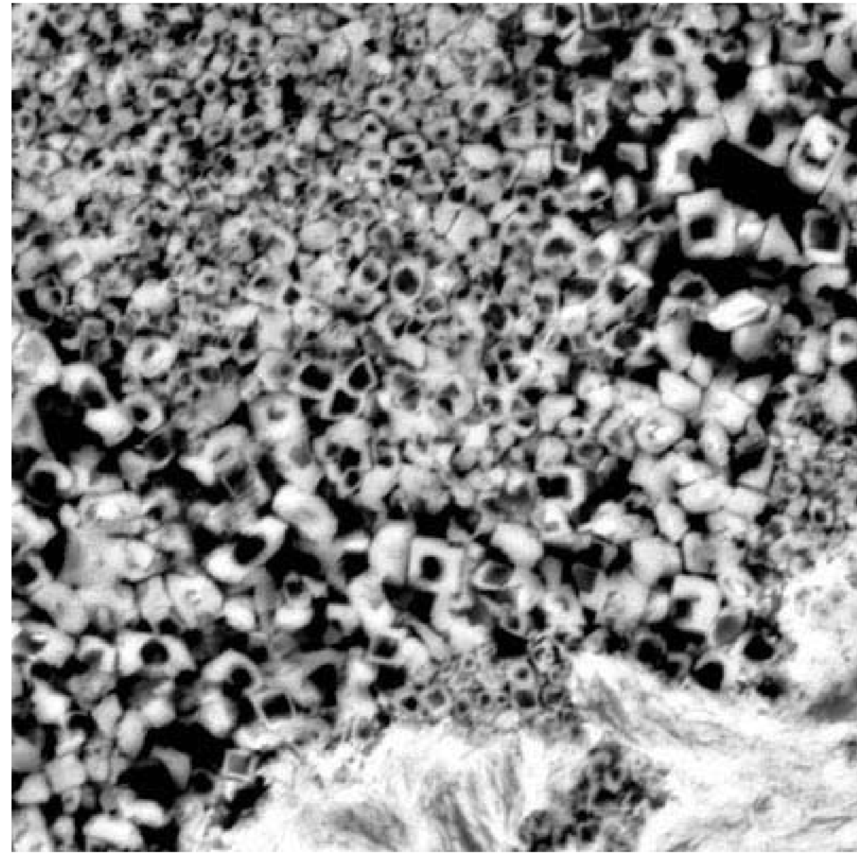
Textures

Cleavage/Shrinkage Cracking (?) in Mica



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

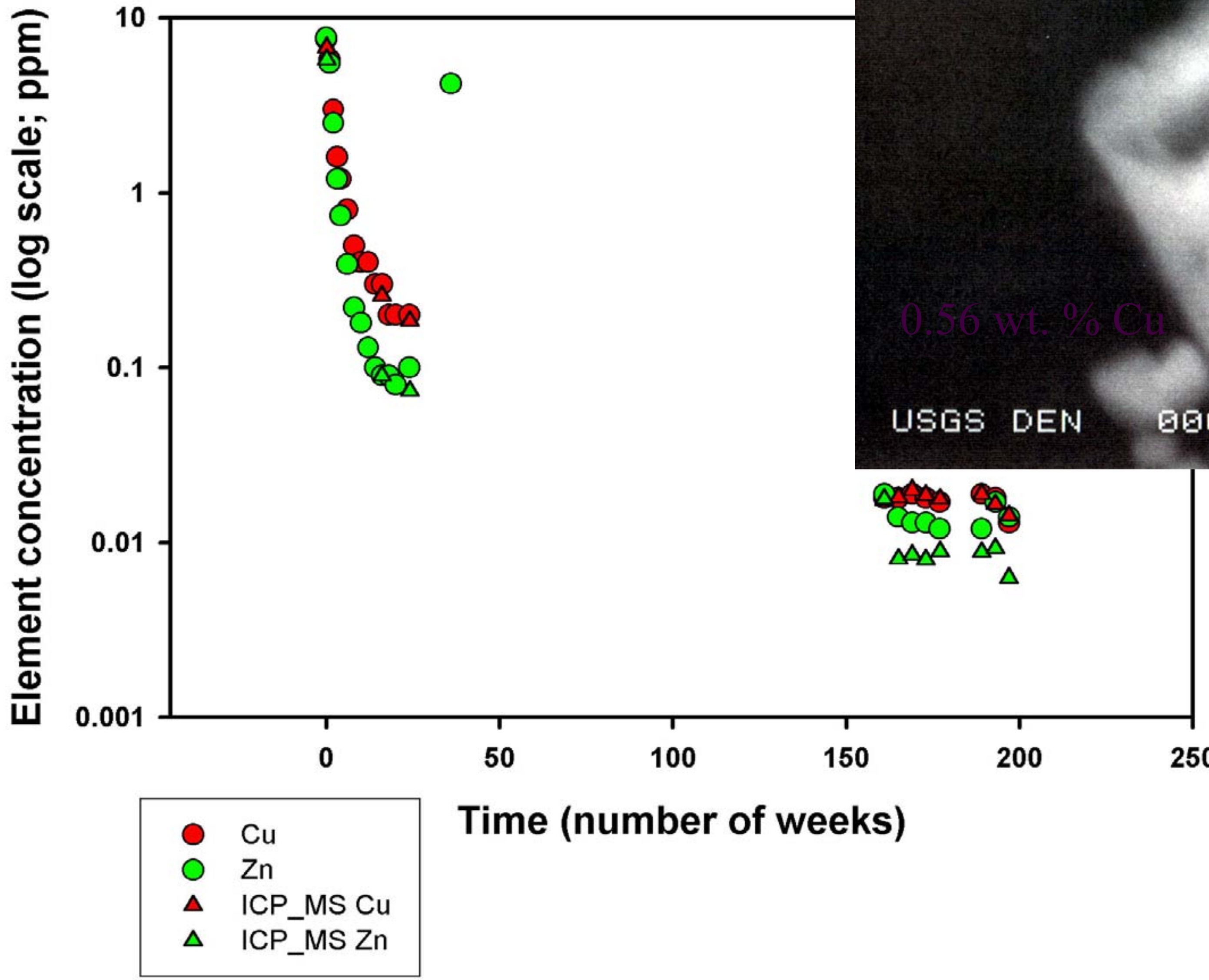
Zoned Jarosite

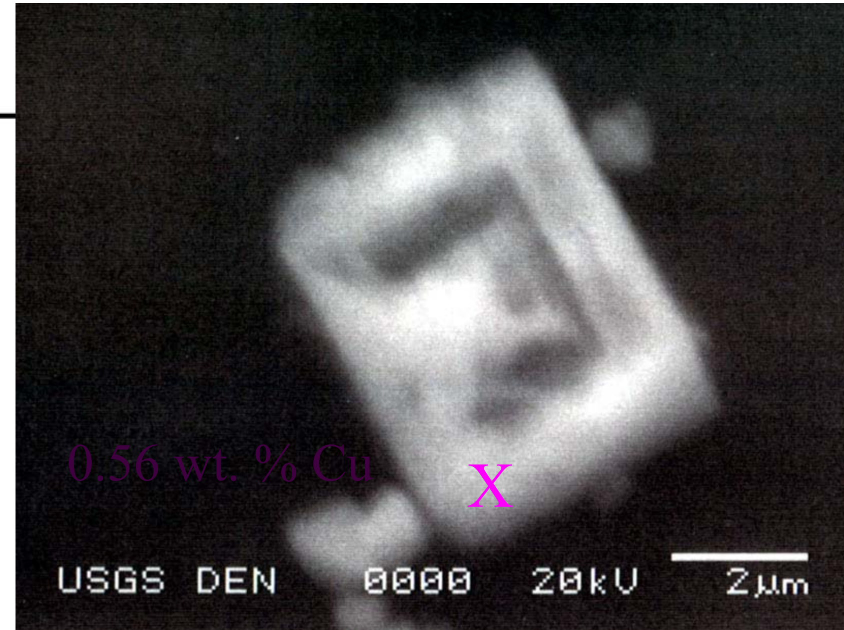


Jarosite crystals exhibit a chemical zonation evidenced by dissolution of the crystal cores.

USGS

Trace elements in Jarosite

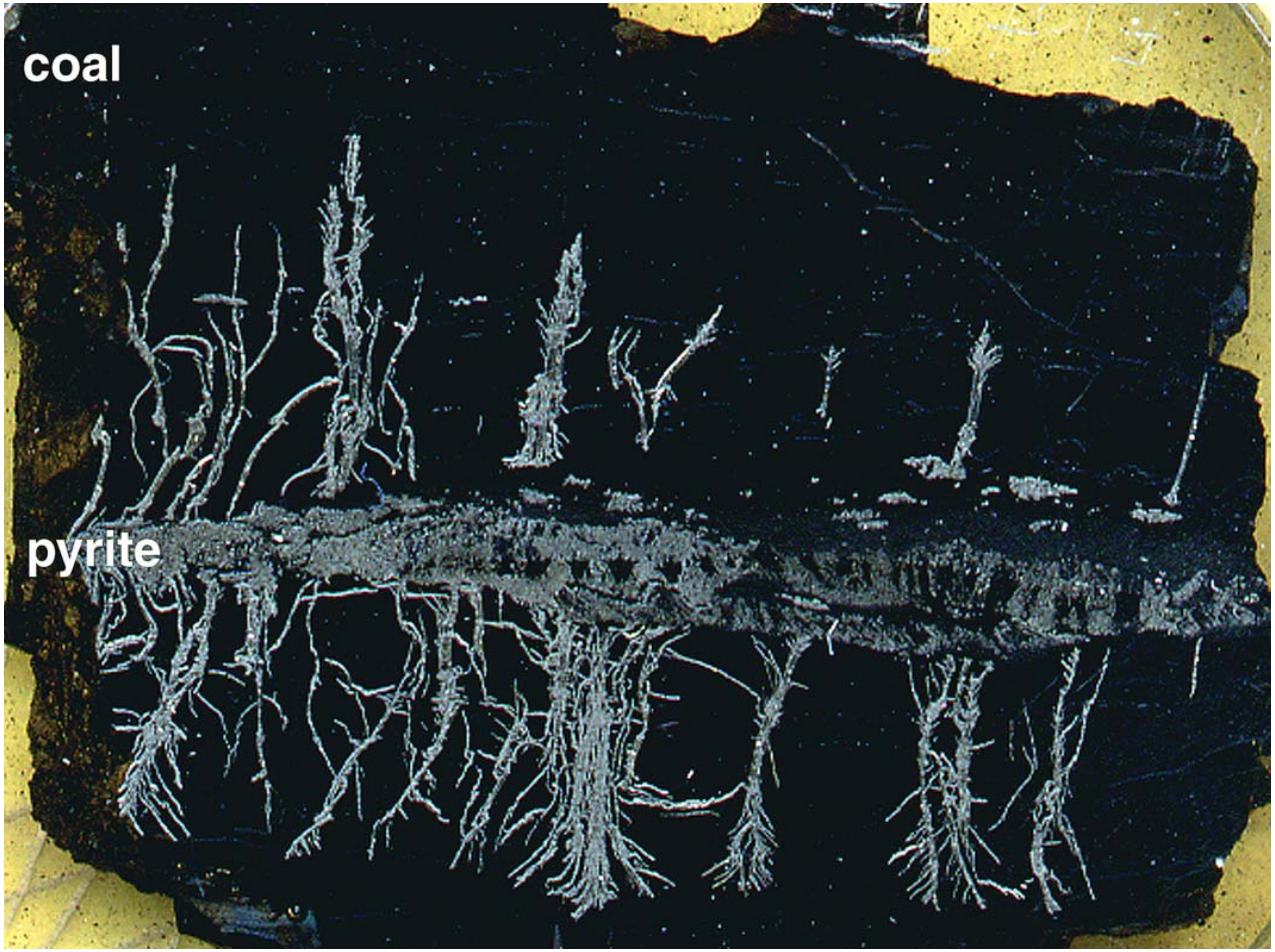




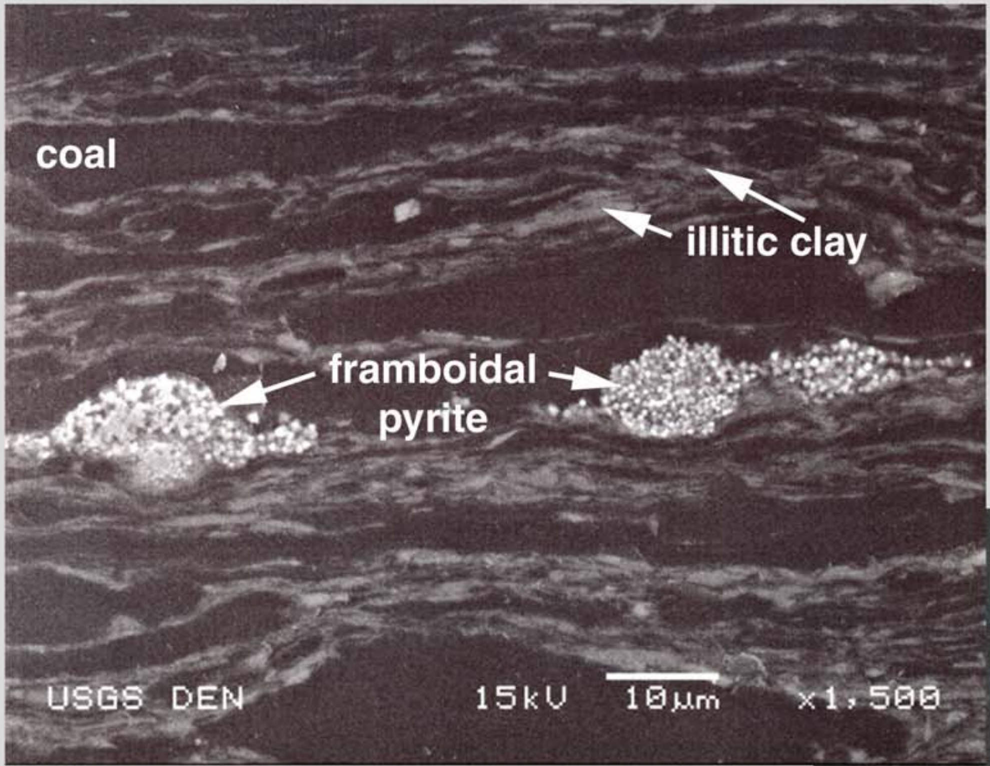
USGS

Case Study 2:

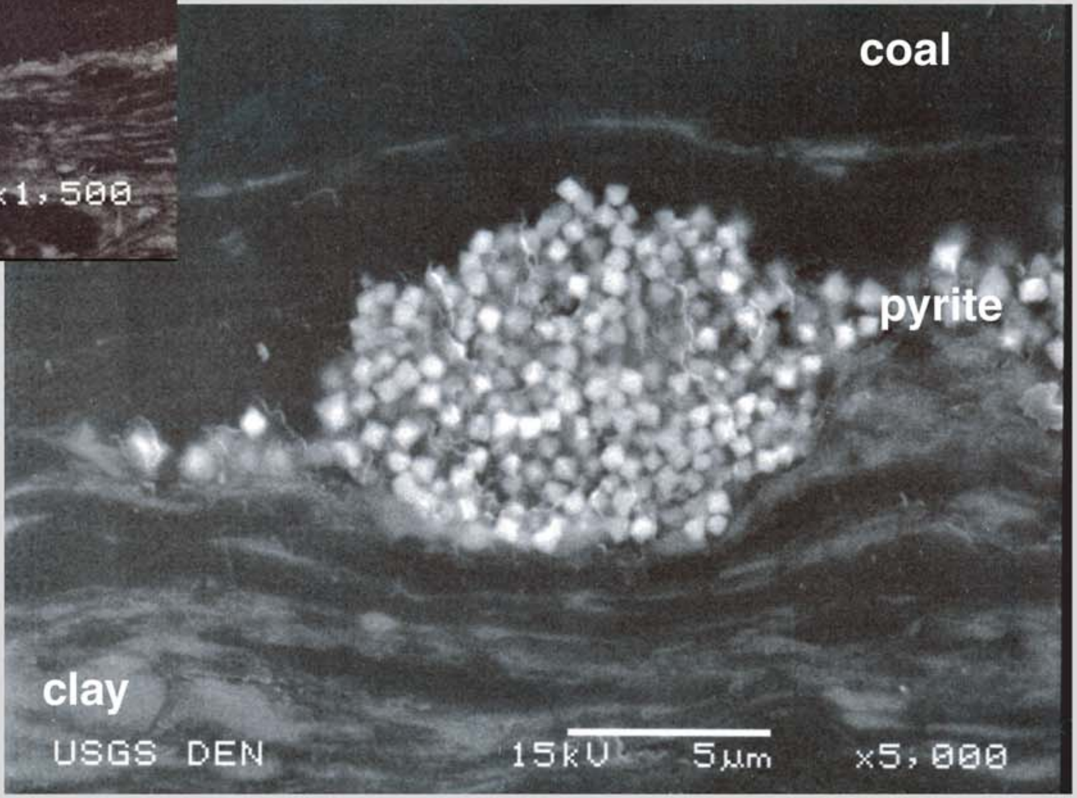
Trace Elements in Coal/Pyrite from the Lost Creek Mine, Warrior Basin, Alabama



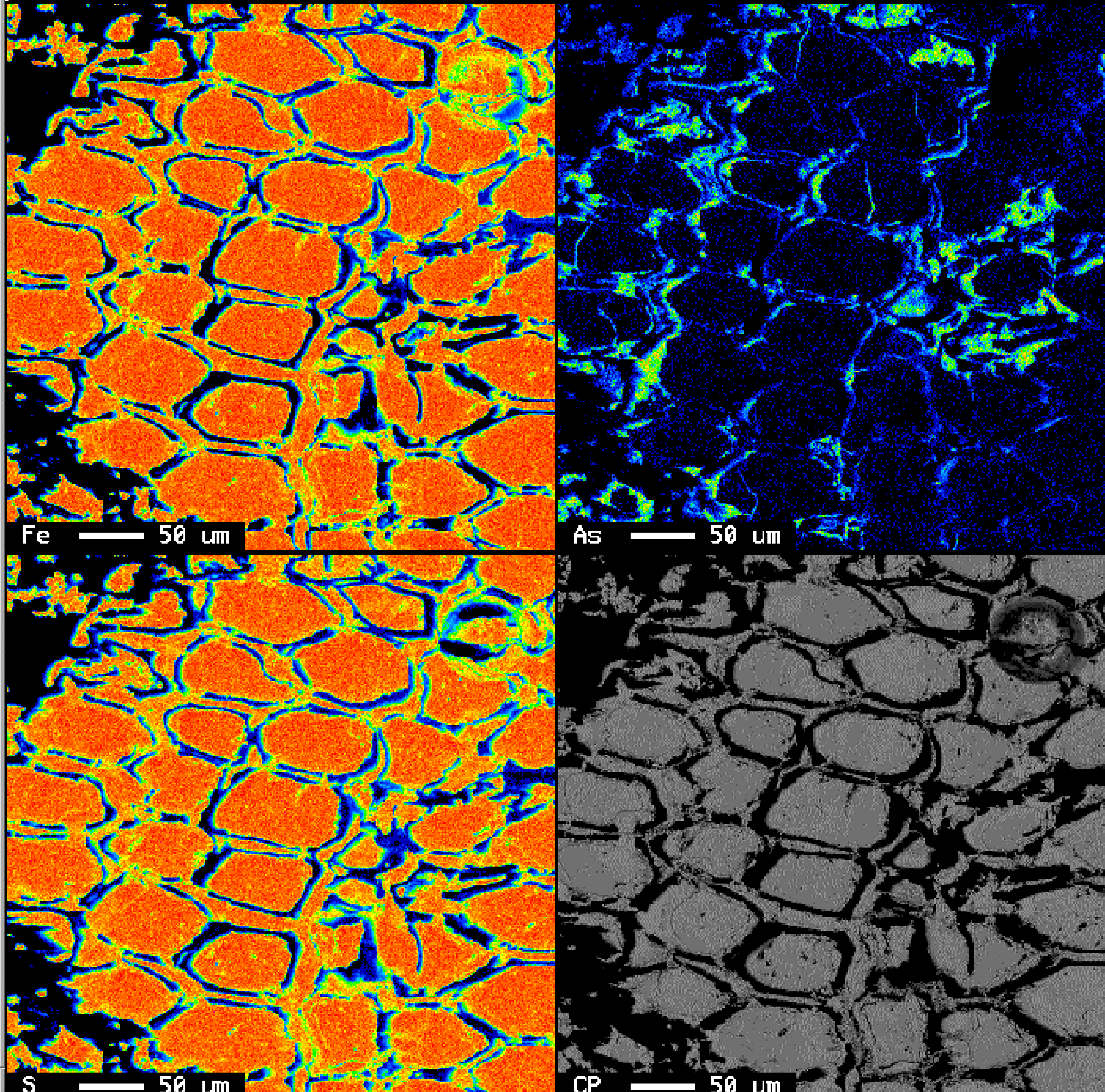
Framboidal Pyrite



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.

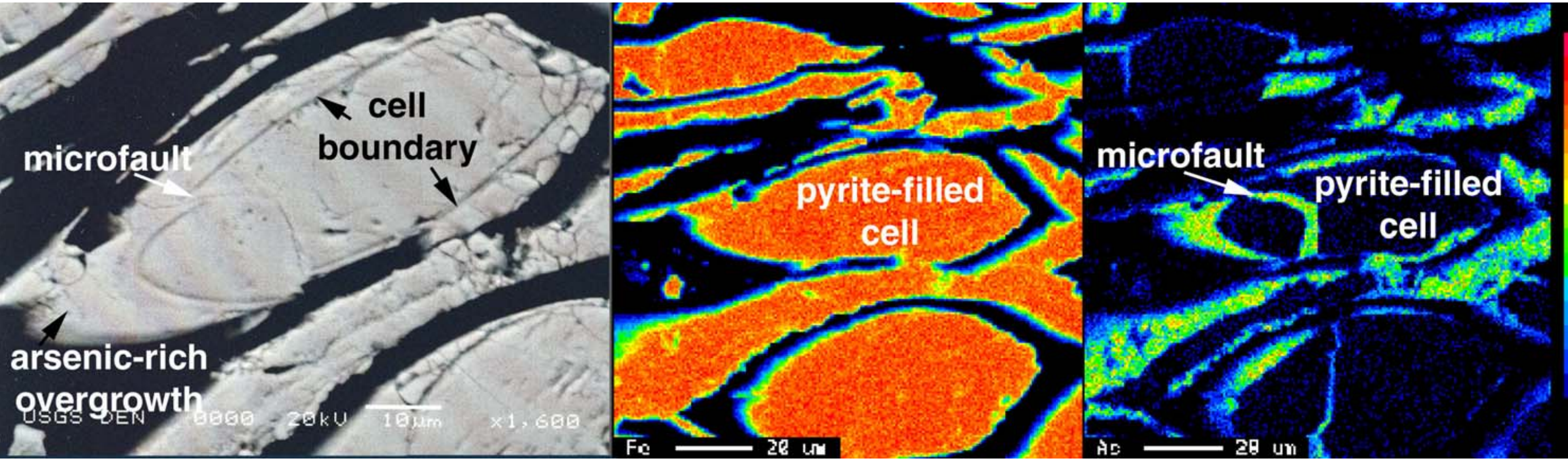


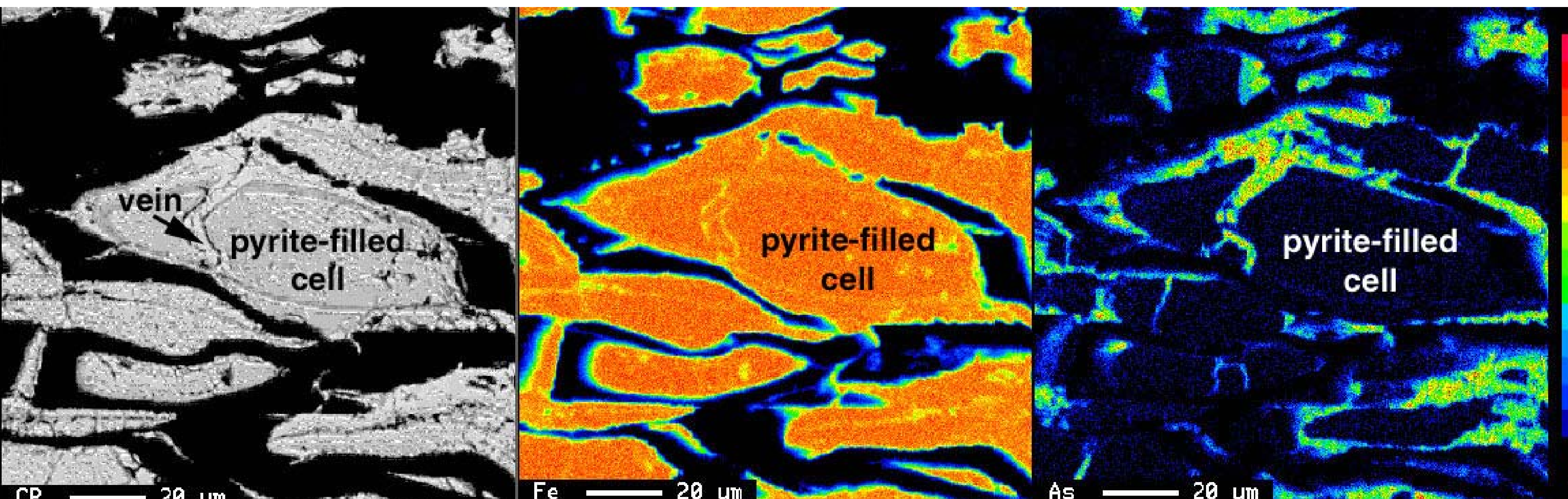
Lost Creek Mine

Pyrite fills woody cell structures.

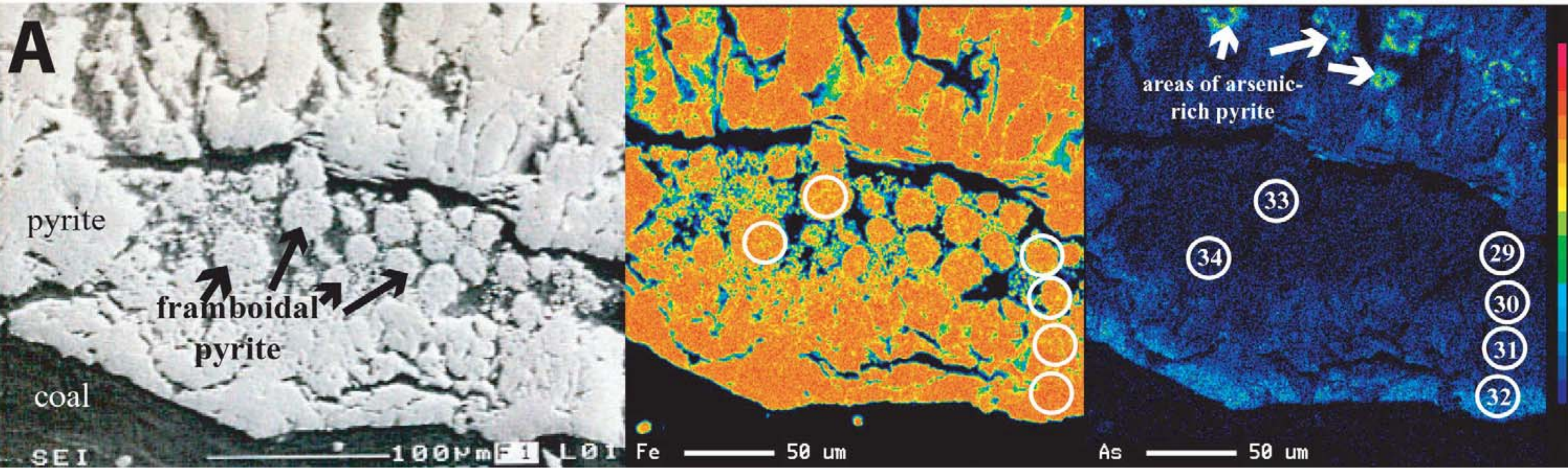
Arsenic-rich pyrite replaces early arsenic-poor pyrite in lumens, occurs as overgrowths, and along microfaults.

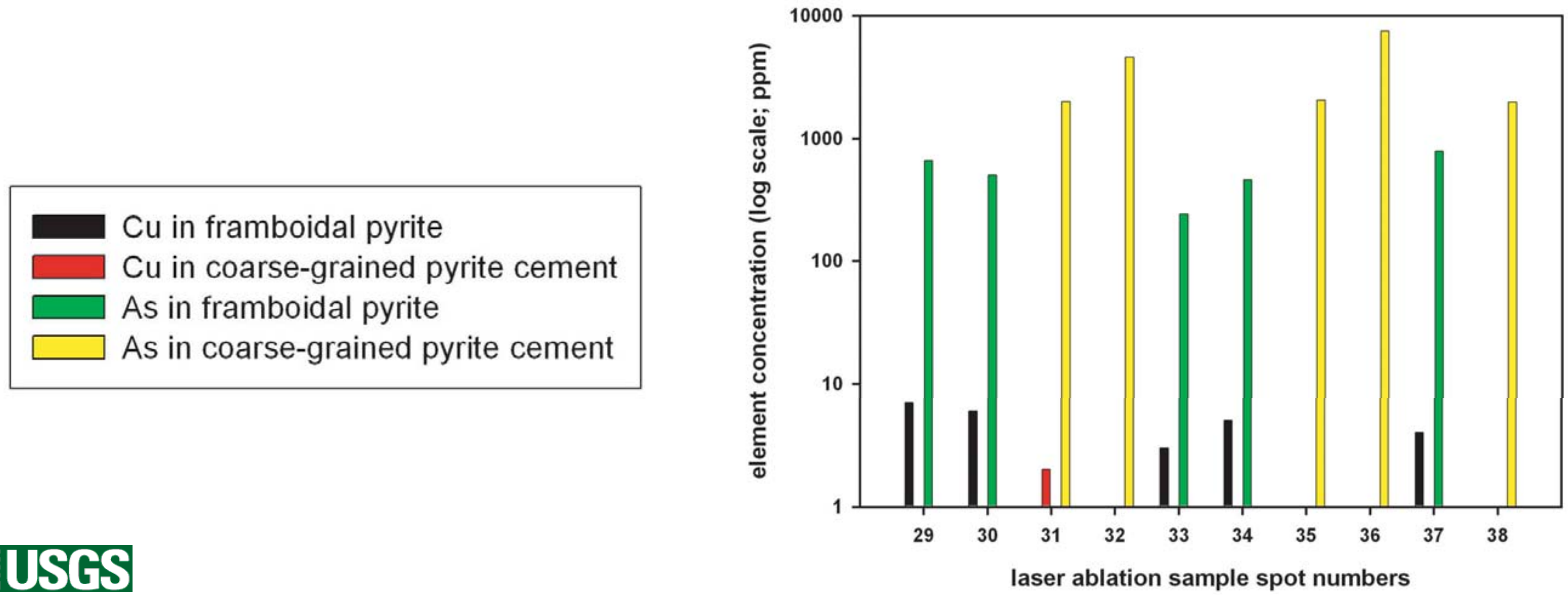
Element Maps of Arsenic in Microstructures



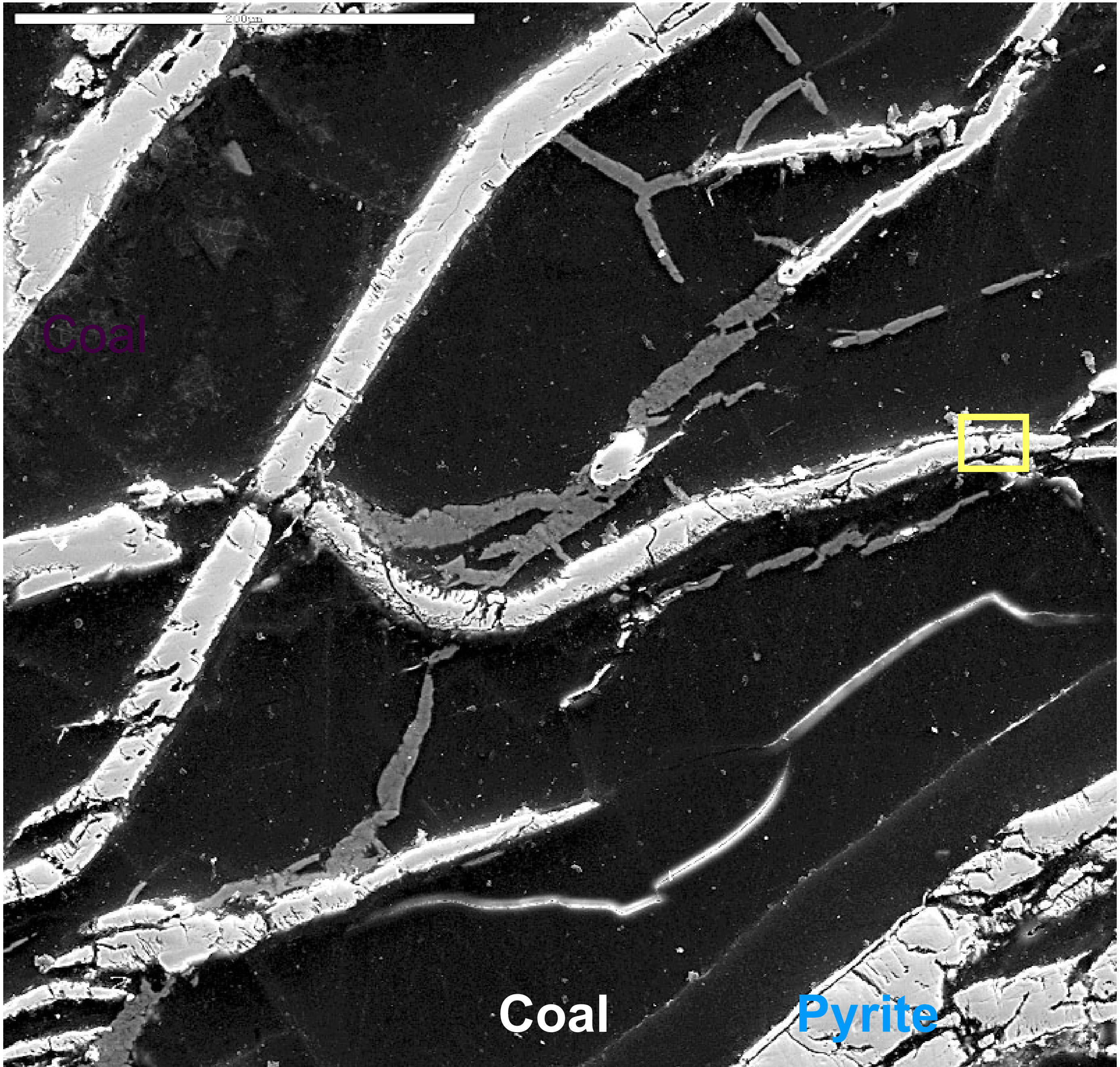


USGS


A
pyrite
framboidal pyrite
coal
SEI
100µm
Fe
50 um
areas of arsenic-rich pyrite
33
34
29
30
31
32
As
50 um

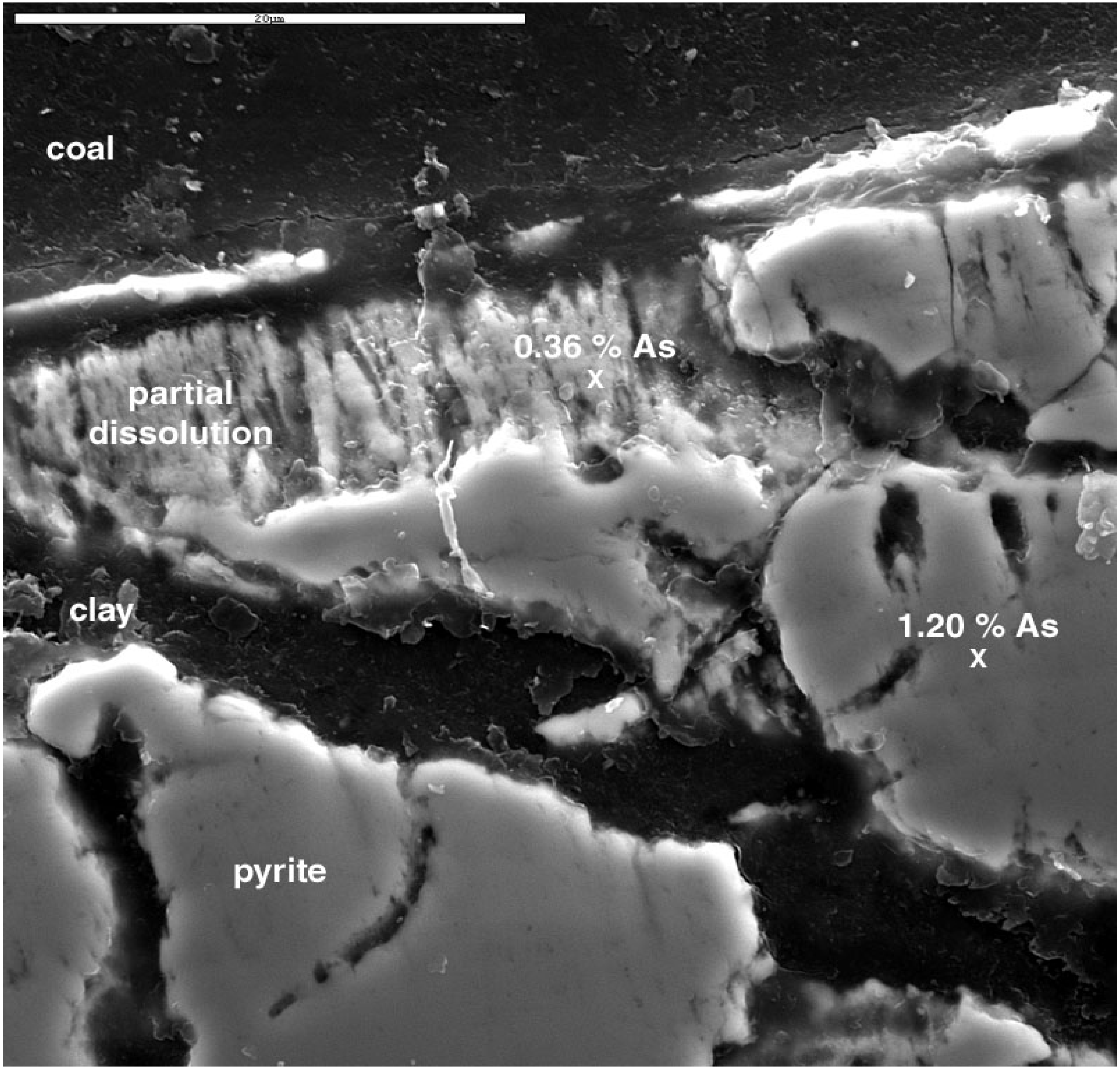

Cu in framboidal pyrite
Cu in coarse-grained pyrite cement
As in framboidal pyrite
As in coarse-grained pyrite cement
element concentration (log scale; ppm)
10000
1000
100
10
1
29
30
31
32
33
34
35
36
37
38
laser ablation sample spot numbers

USGS



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.

USGS