The Importance of Geology

Sharon F. Diehl, USGS

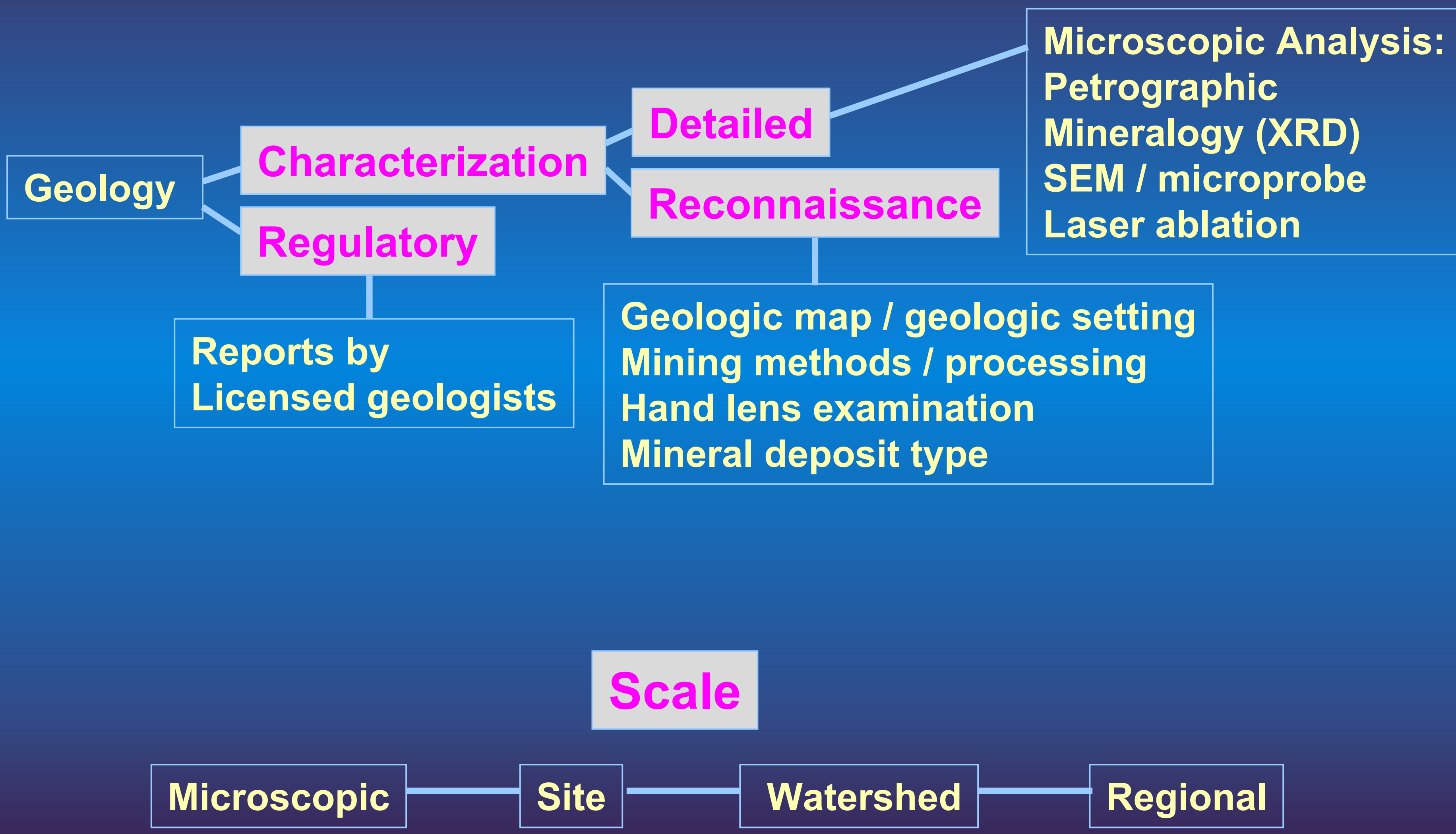
Billings Symposium / ASMR Annual Meeting

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

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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)

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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 ($MnCO_3$)

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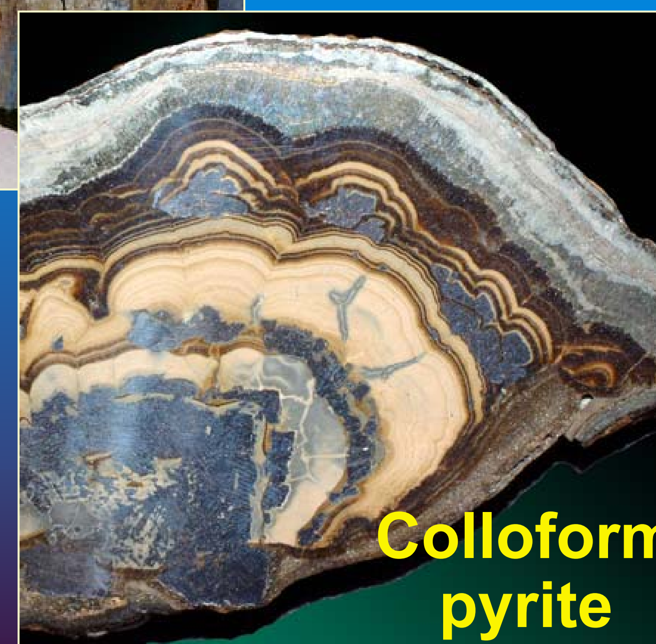
Sulfide Texture and Resistance to Weathering

Less
easily
weathered

More
easily
weathered



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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

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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, CO_2, 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)

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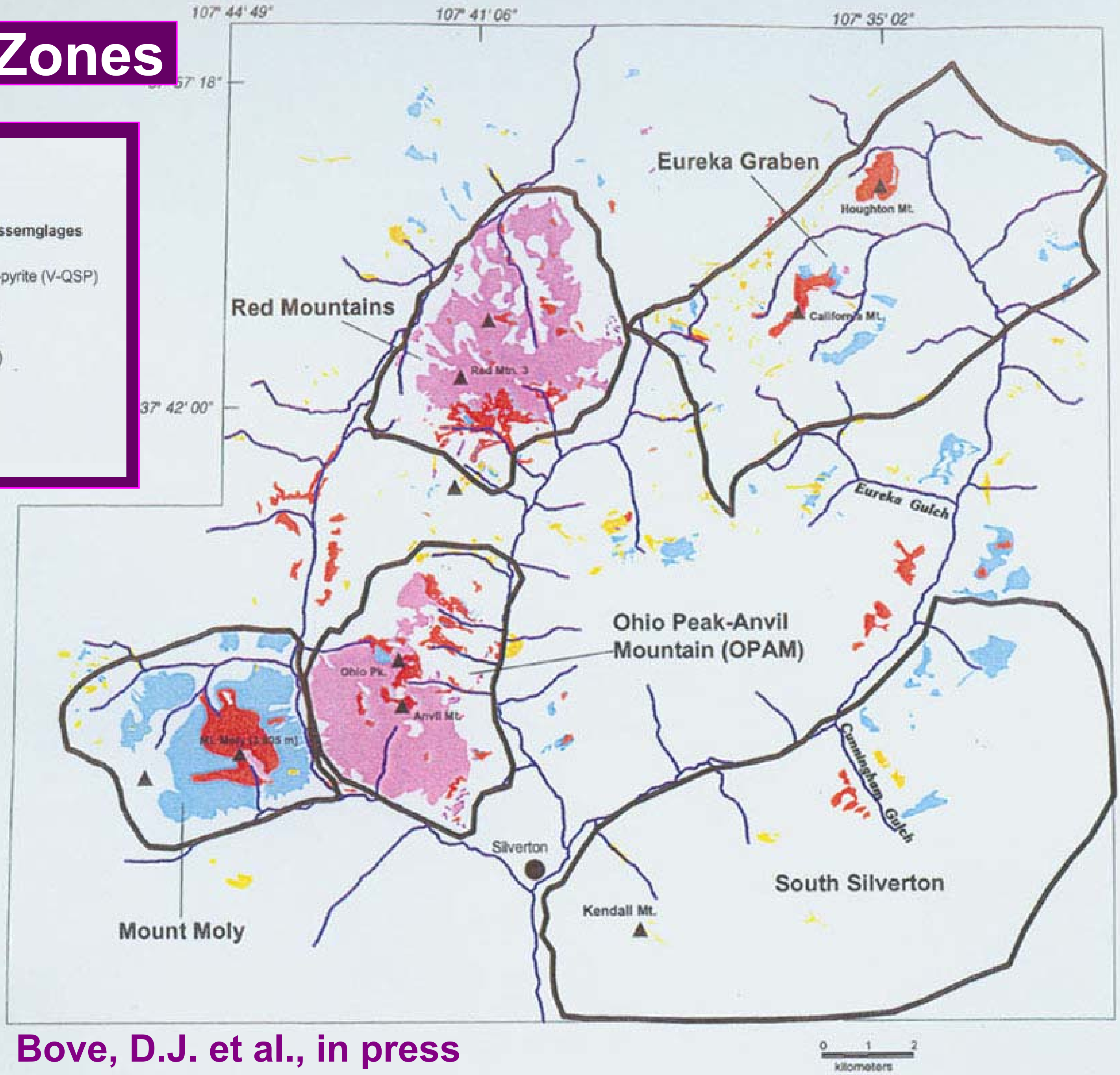
Alteration Zones

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

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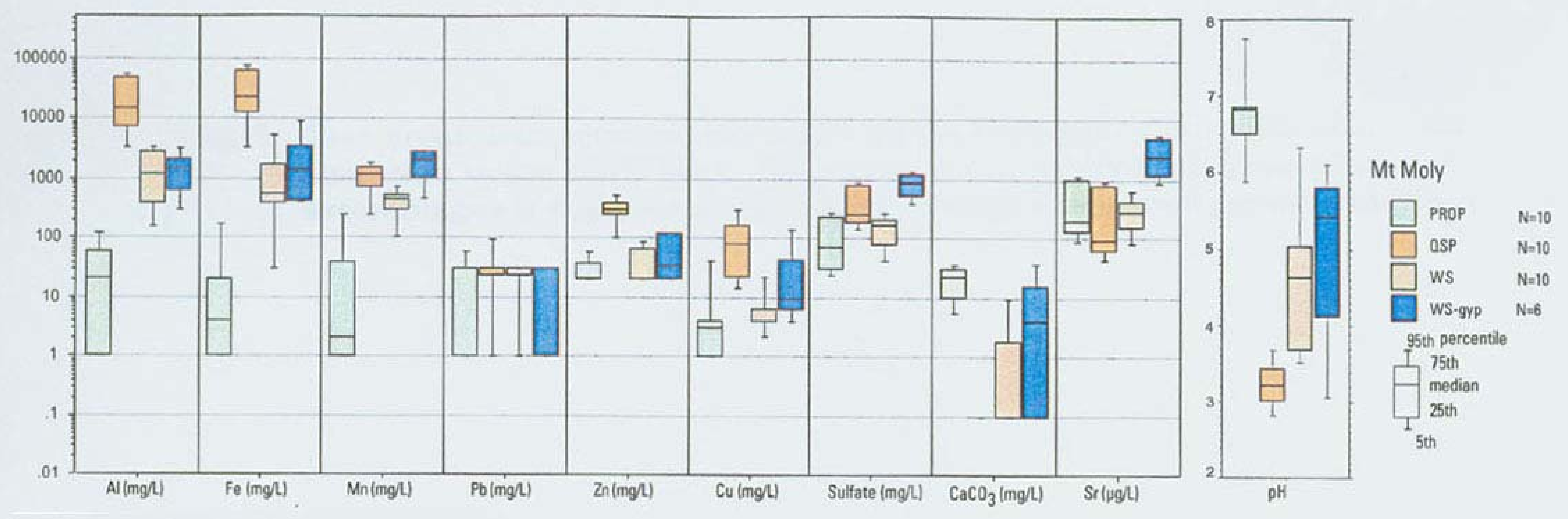
TRACE METAL ENRICHMENT IN WATERS DRAINING FROM ALTERATION ZONES



[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

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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.

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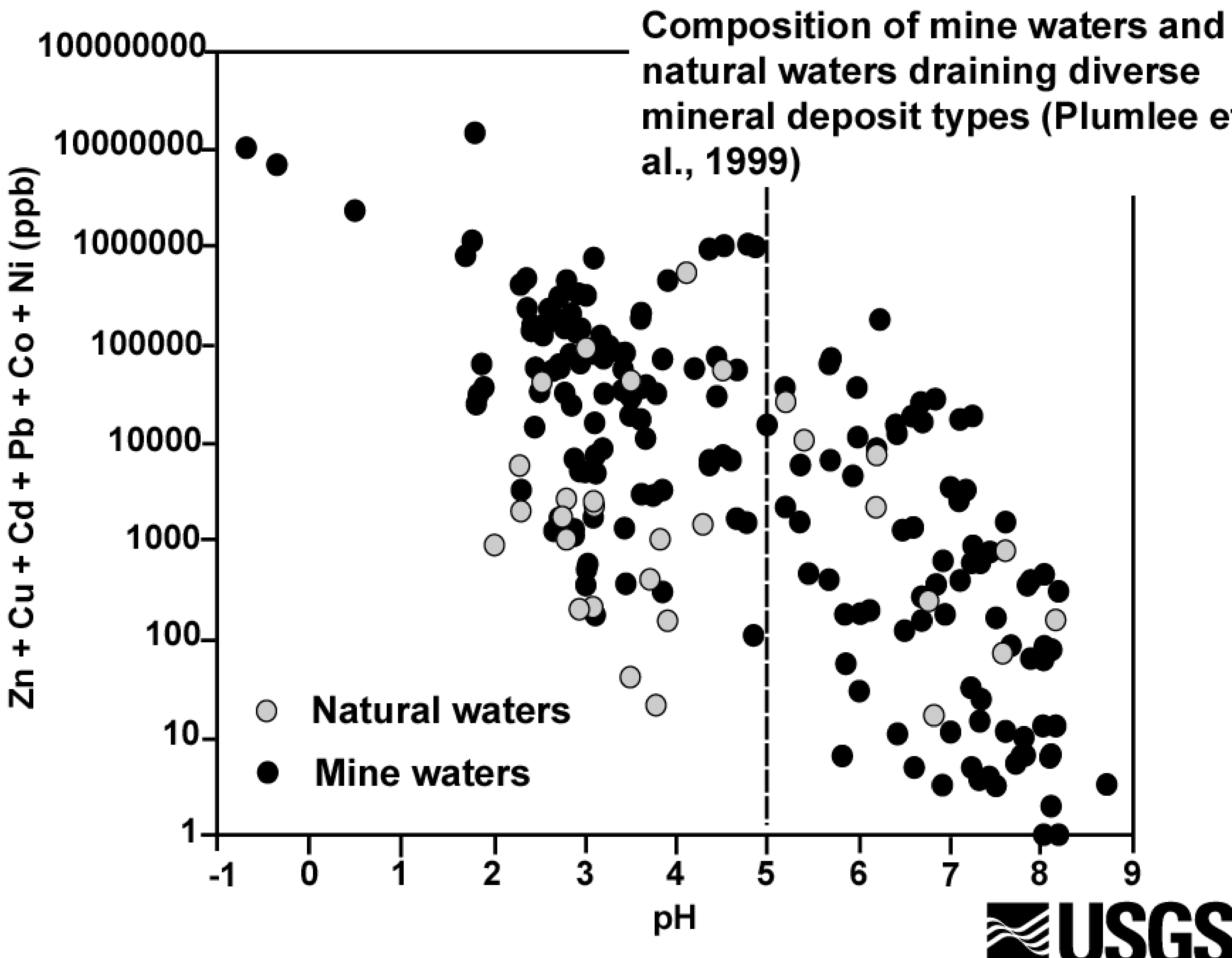

Composition of mine waters and natural waters draining diverse mineral deposit types (Plumlee et al., 1999)
Zn + Cu + Cd + Pb + Co + Ni (ppb)
100000000
10000000
1000000
100000
10000
1000
100
10
1
-1
0
1
2
3
4
5
6
7
8
9
pH
Natural waters
Mine waters
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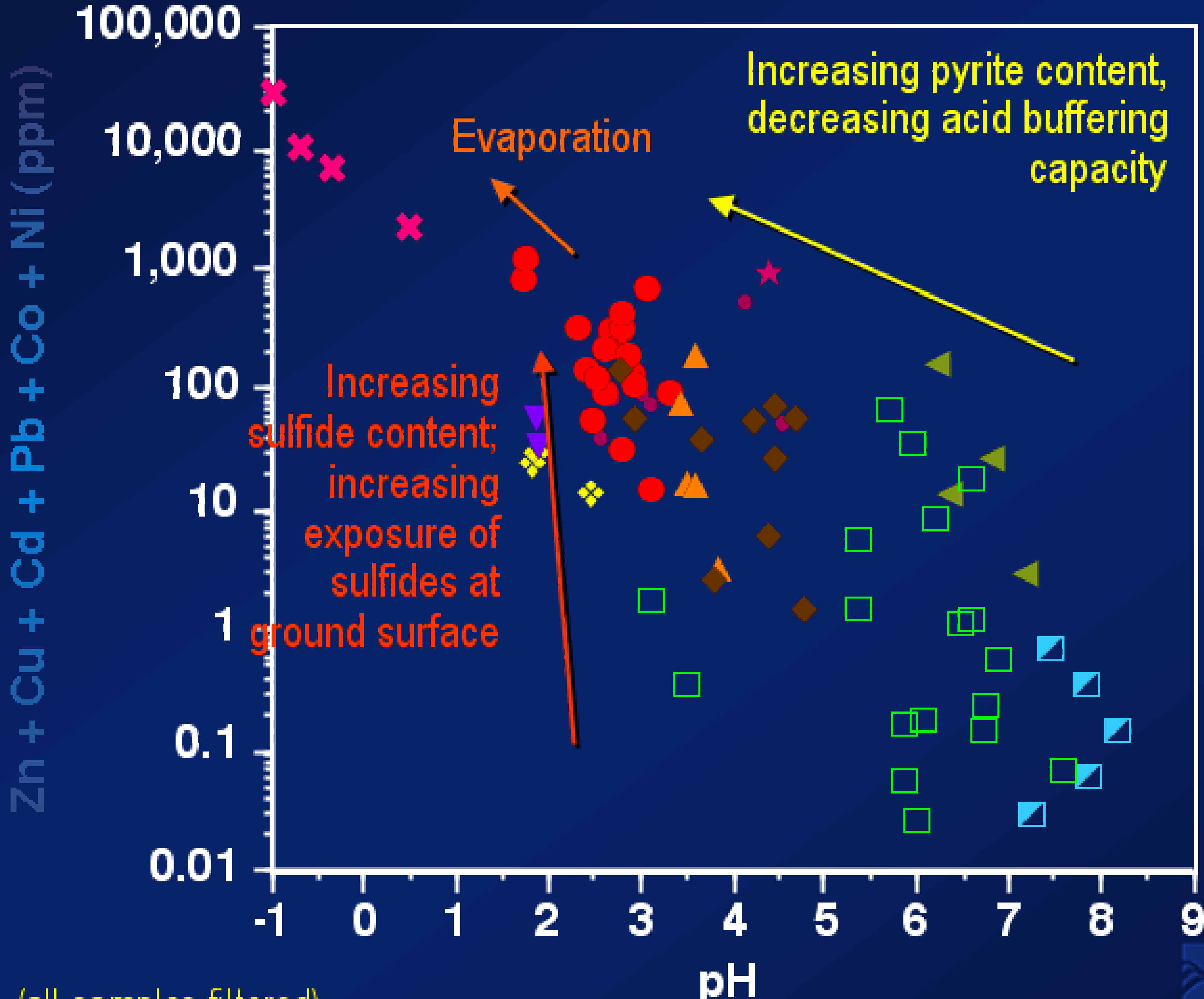
Geologic controls on mine-drainage composition



Symbols depict waters draining deposits with similar geologic character-istics

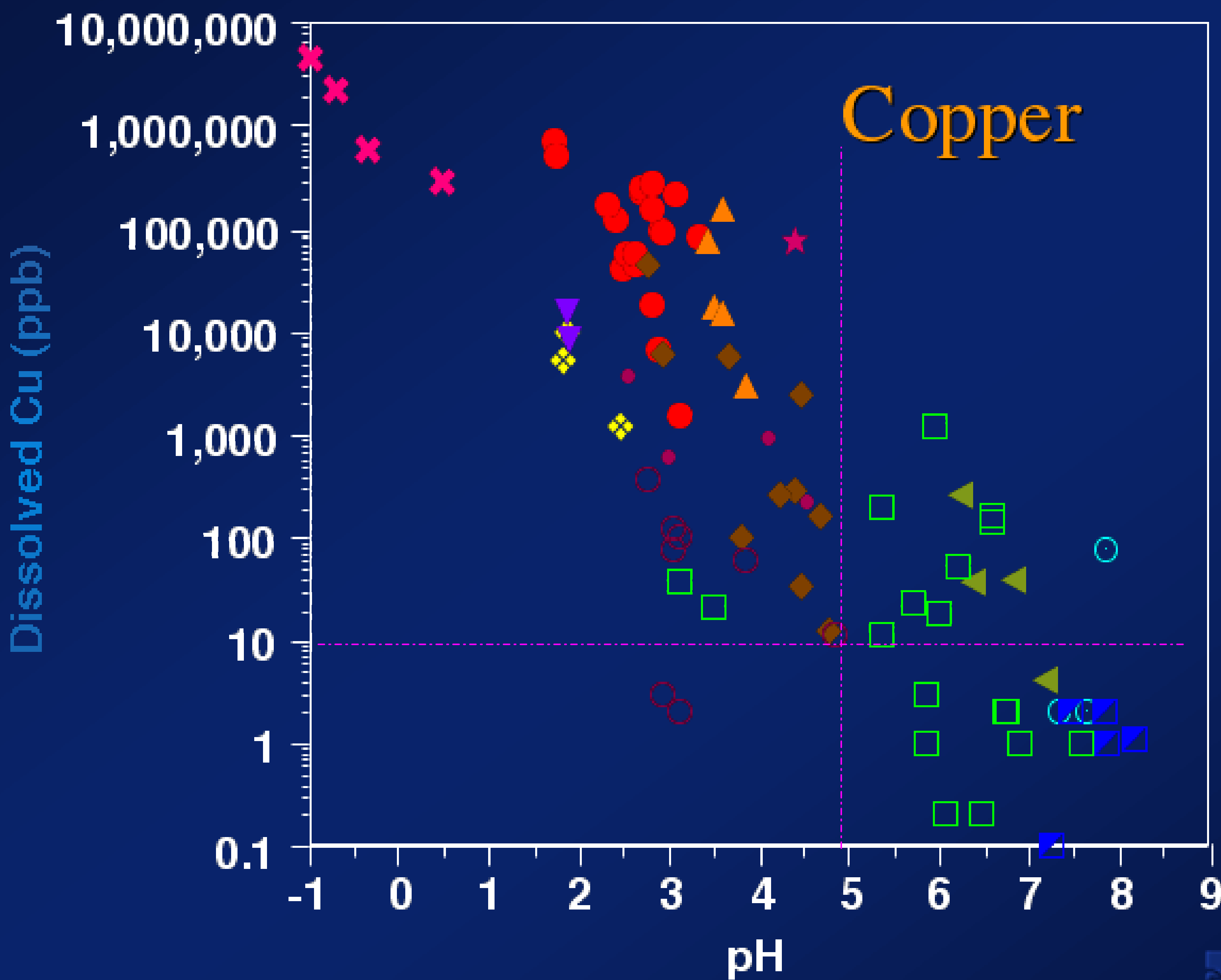
Plumlee et al., 1999

(all samples filtered)

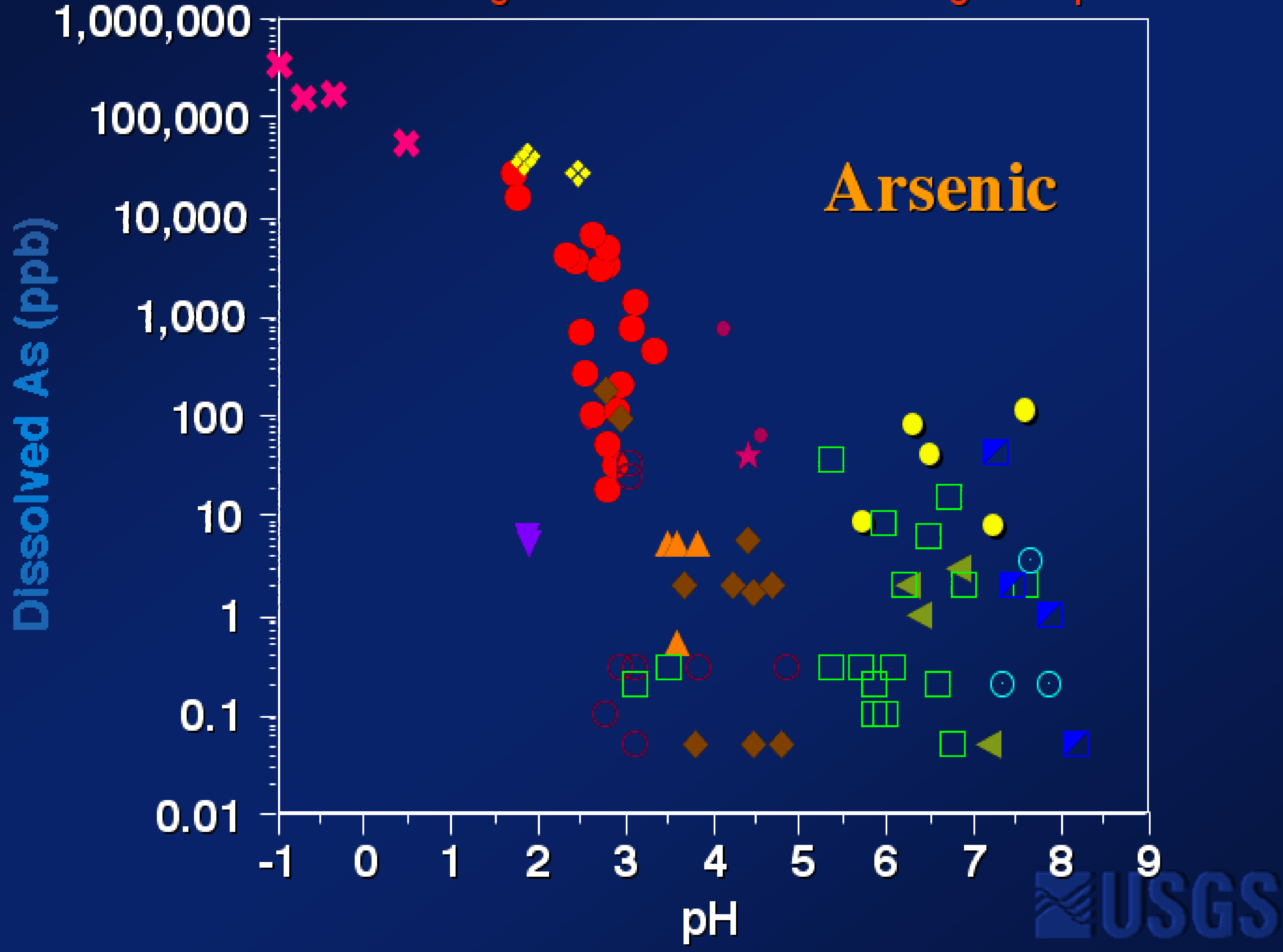
Legend

- 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

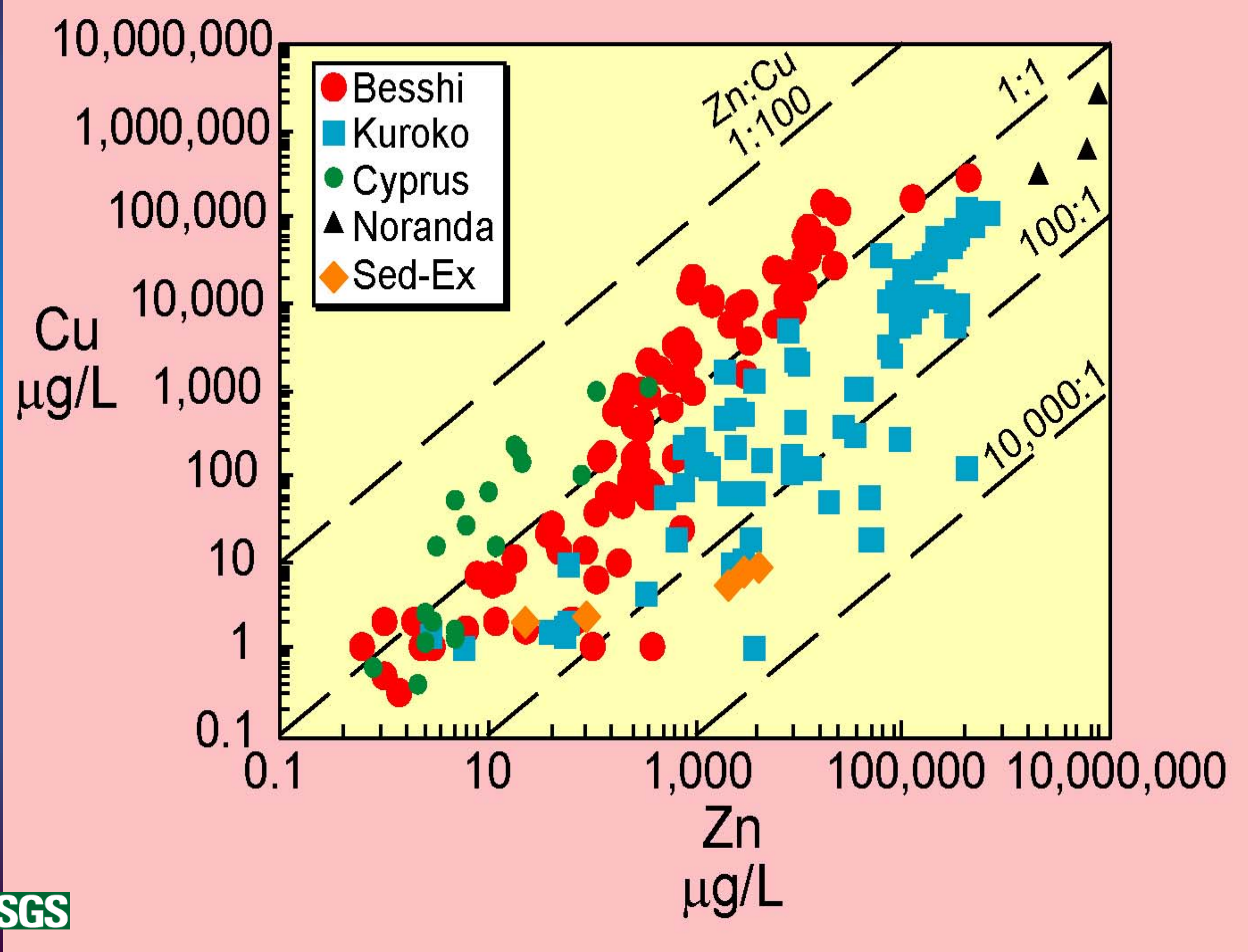


Geologic controls on mine-drainage composition



Types of Massive Sulfide Deposits

(Seal and Hammarstrom, 2003)



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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

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Volume 6B

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Part B: Case Studies and Research Topics

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

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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

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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

[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

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Case Study 1:
Bulk Mineralogy of Mine Waste Samples

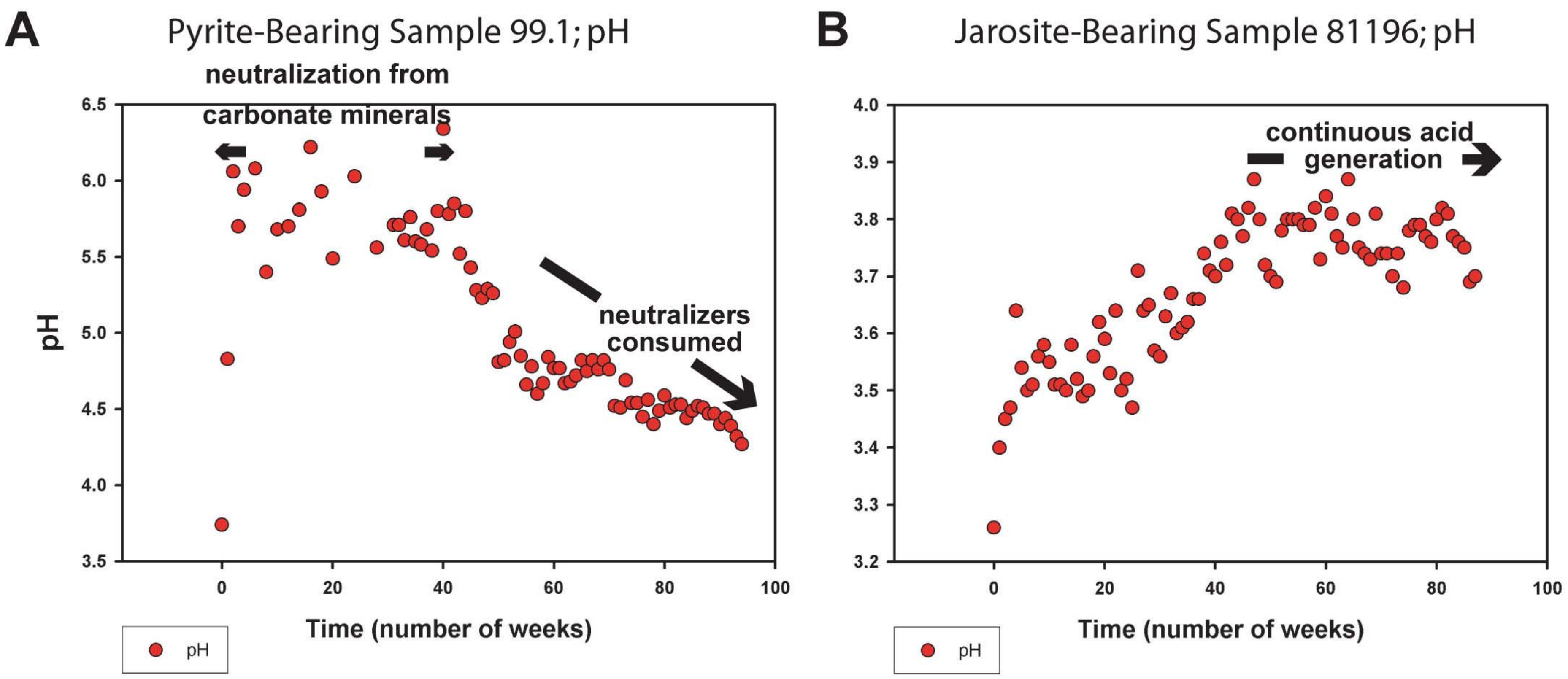
SEMI-QUANTITATIVE MINERALOGY (sample 99.1, wt. %)

	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

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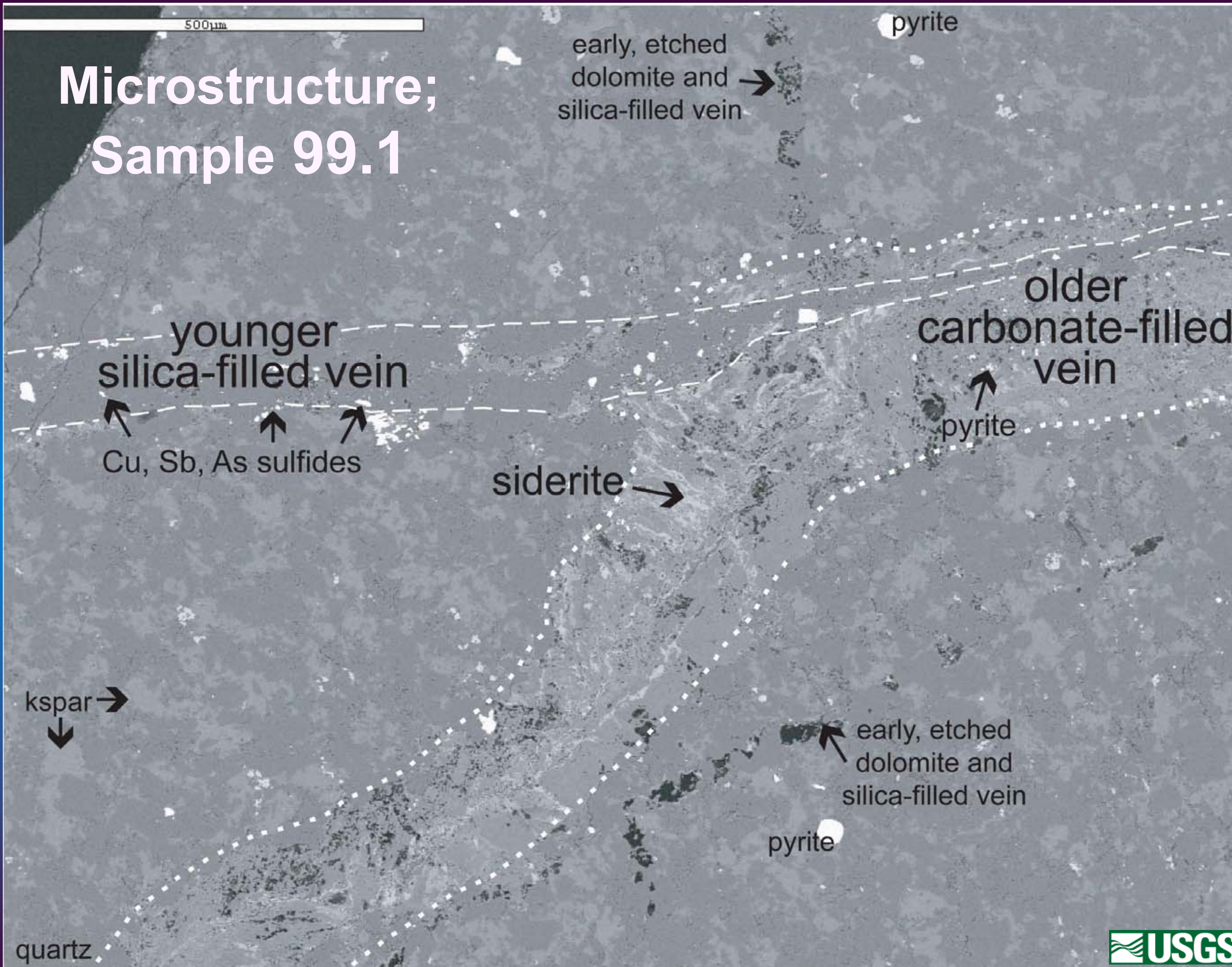
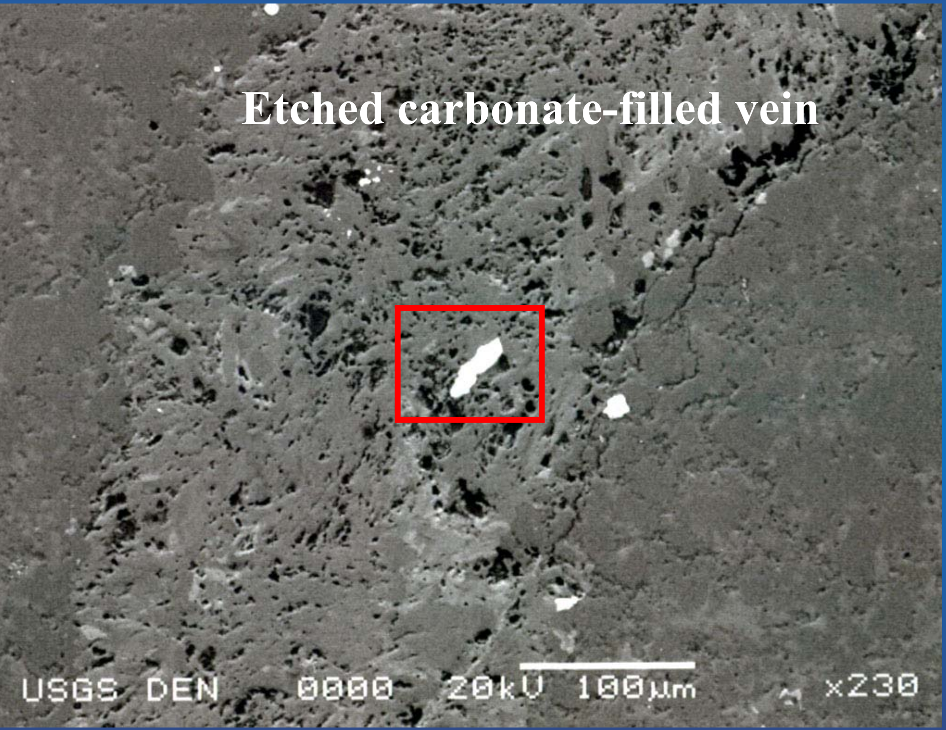
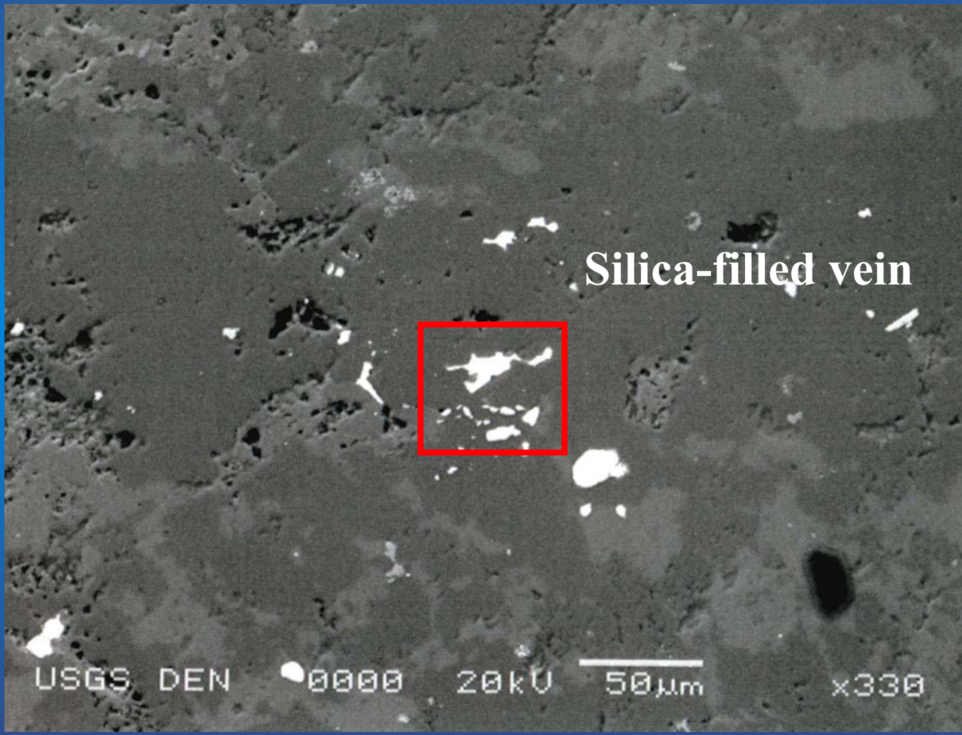
Microstructure; Sample 99.1

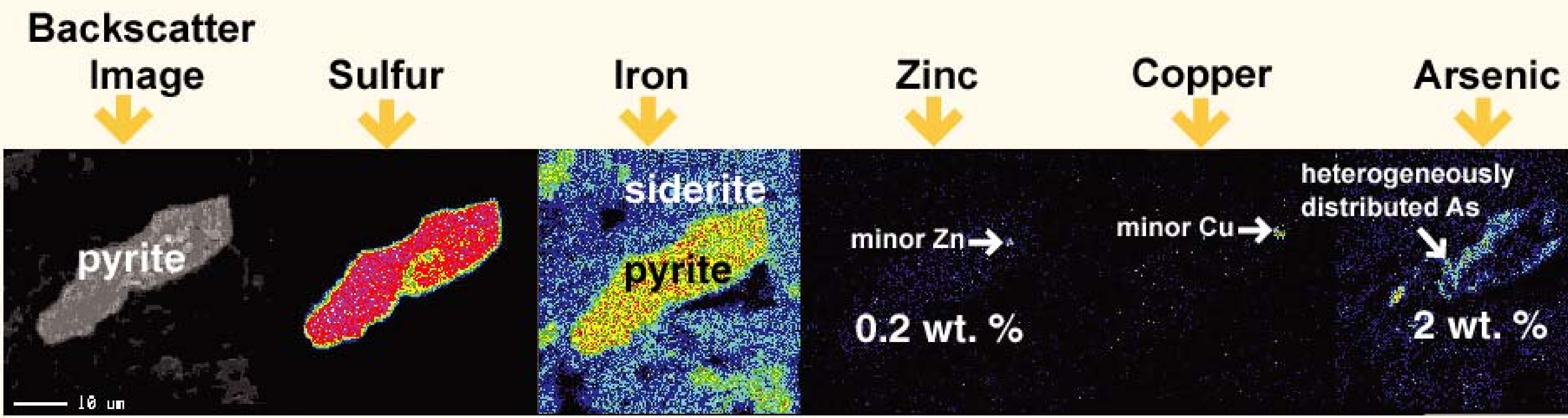


Microstructure; Sample 99.1

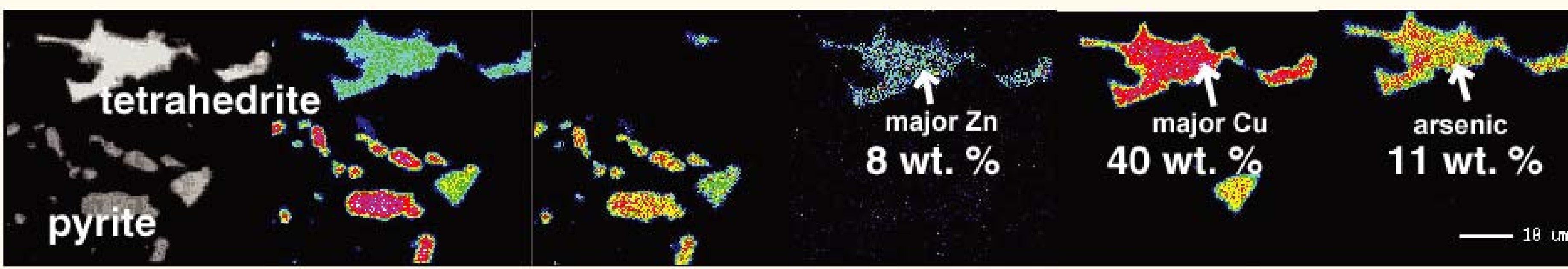




Microprobe Element Distribution Maps

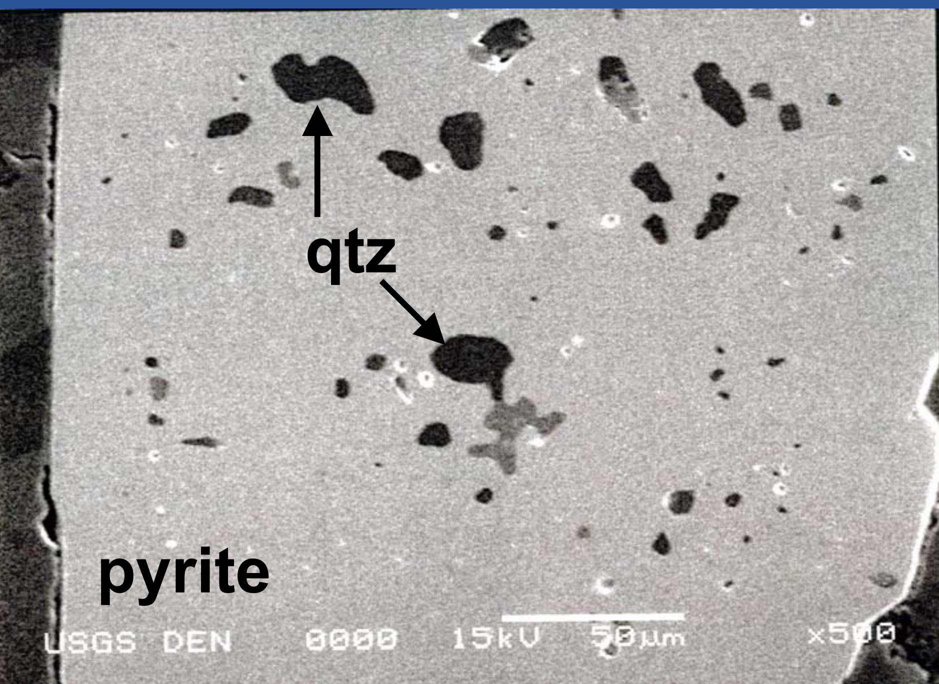


Sulfides in Carbonate-filled Vein

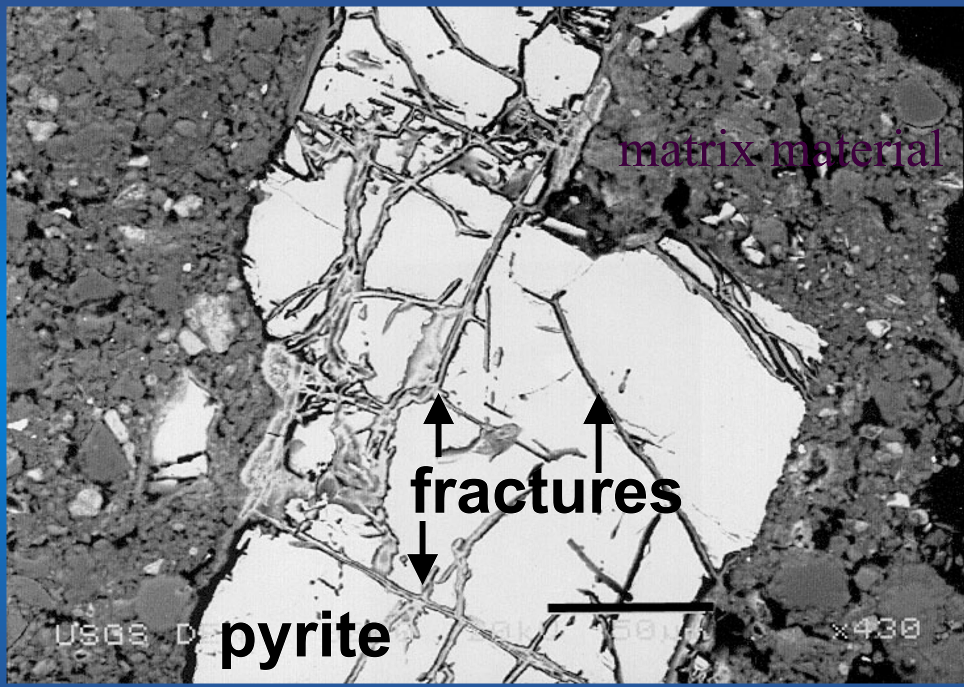


Sulfides in Silica-filled Vein

Pyrite-bearing Sample 99.1

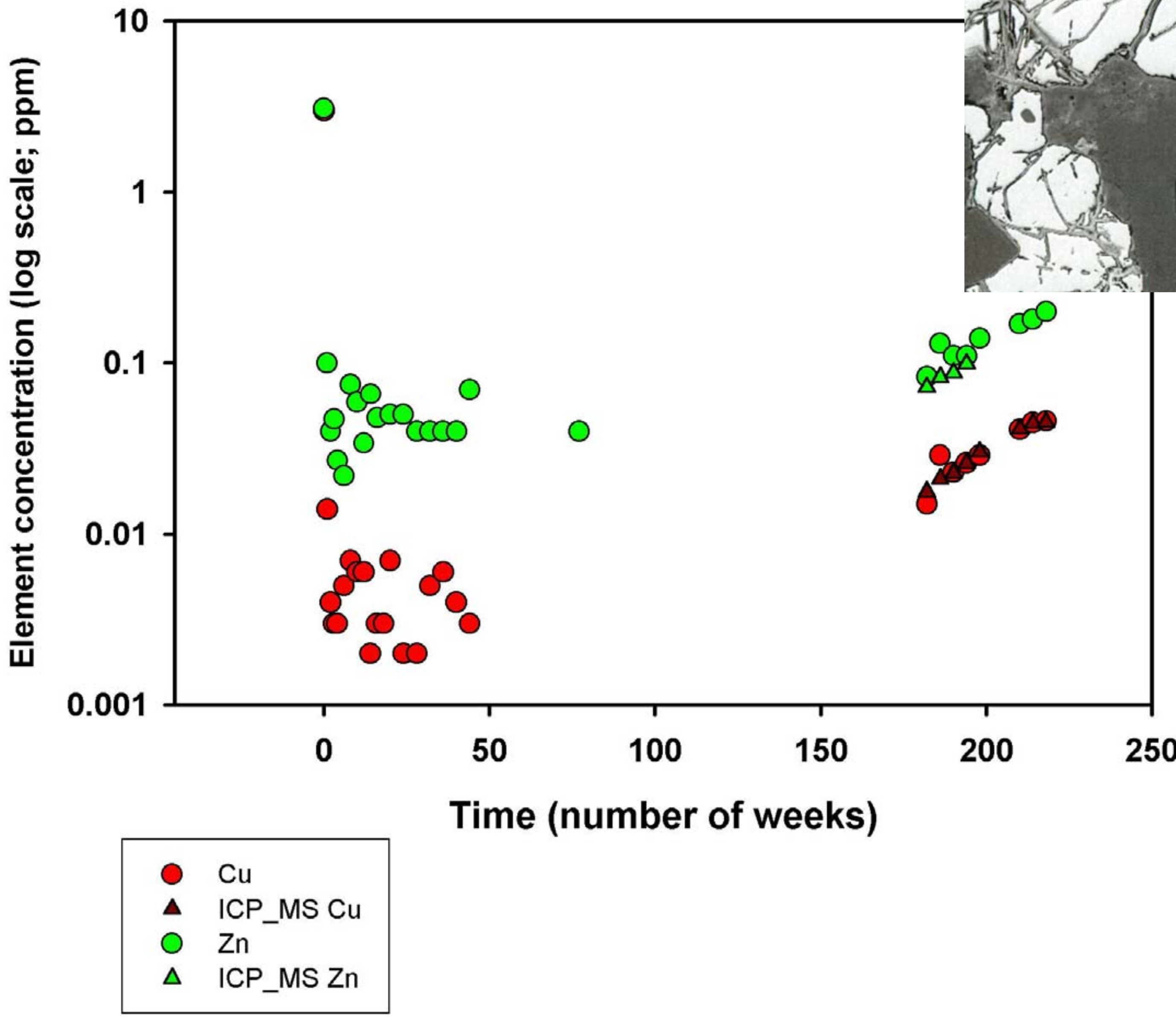


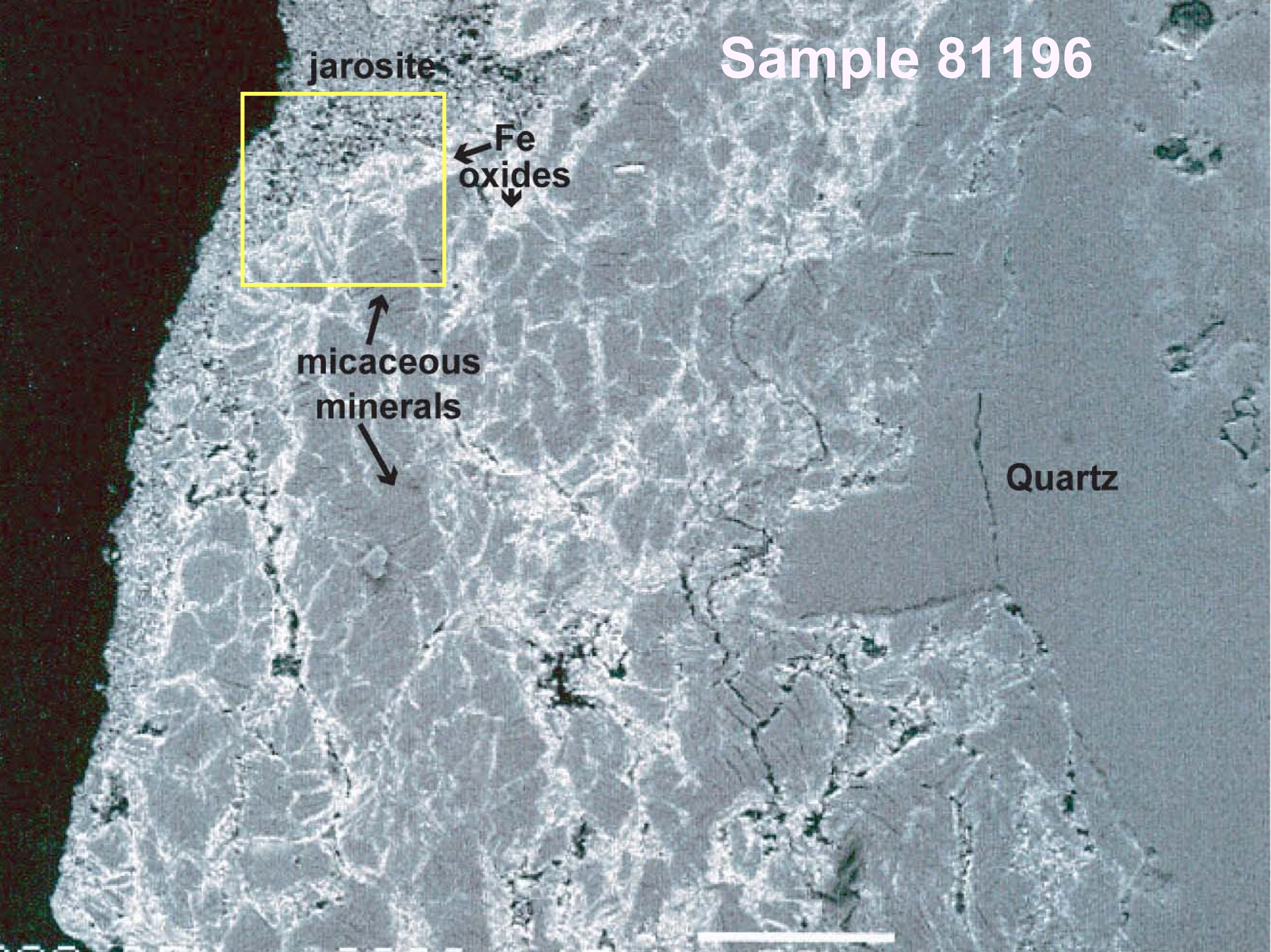
Pyrite Before Leaching



Pyrite After Leaching

Pyrite-Bearing Sample 99.1
Cu and Zn from sulfides

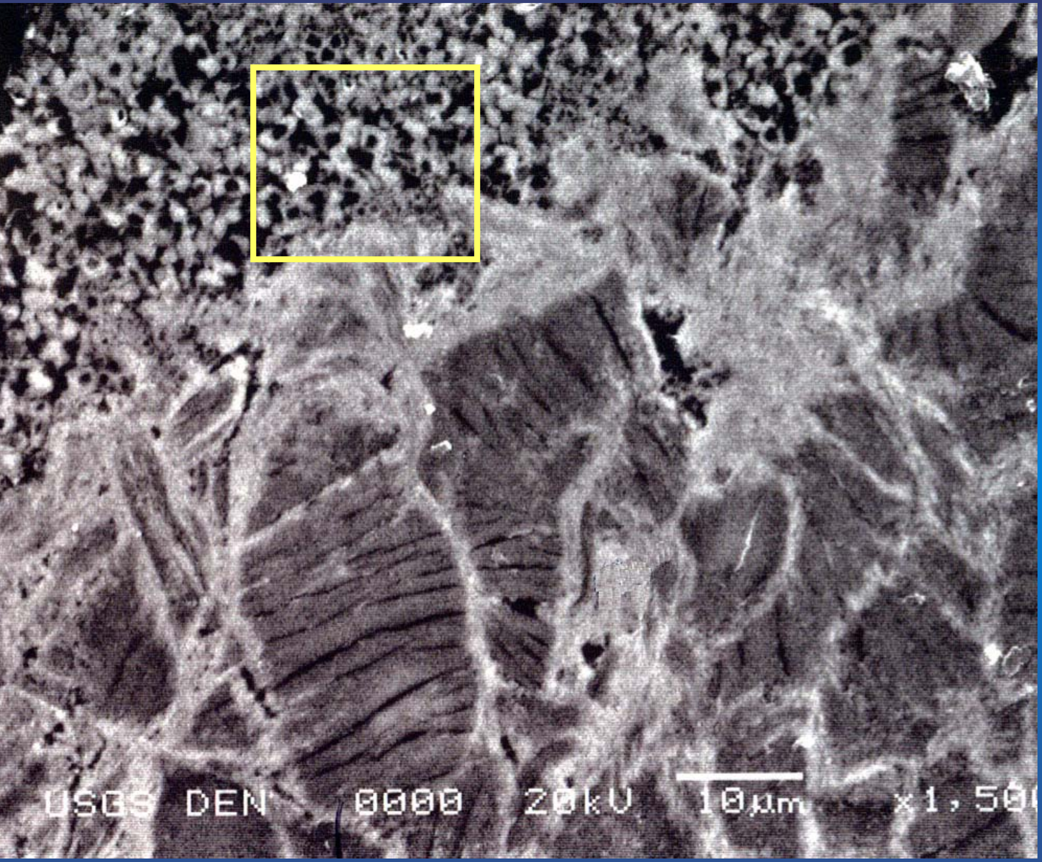




Sample 81196
jarosite
Fe
oxides
micaceous
minerals
Quartz

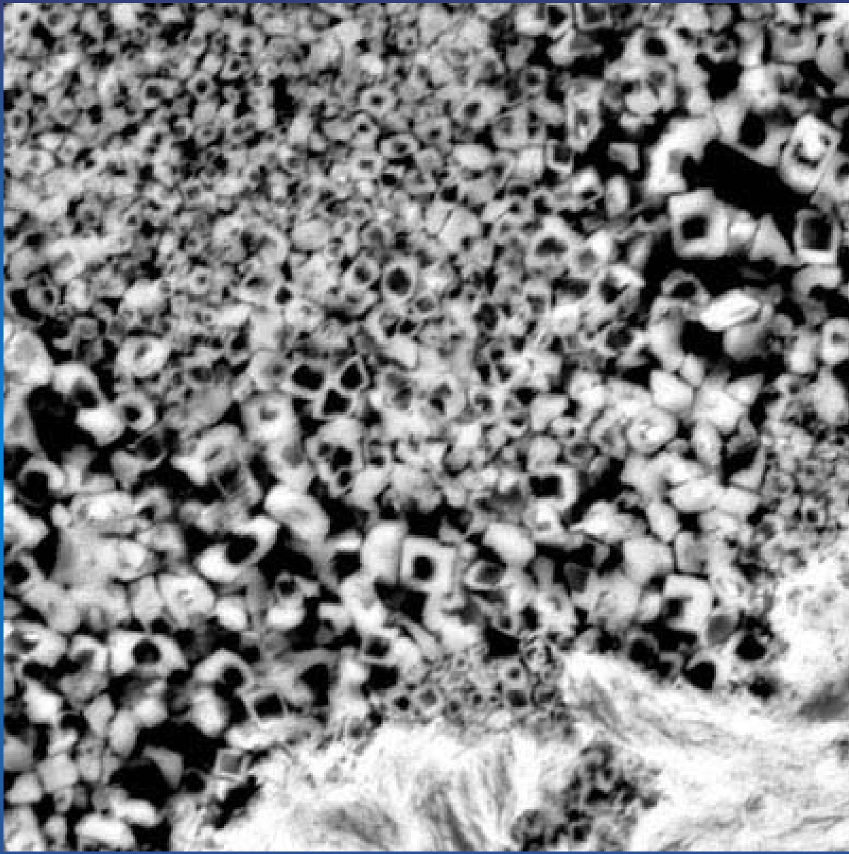
Textures

Cleavage/Shrinkage Cracking (?) in Mica



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

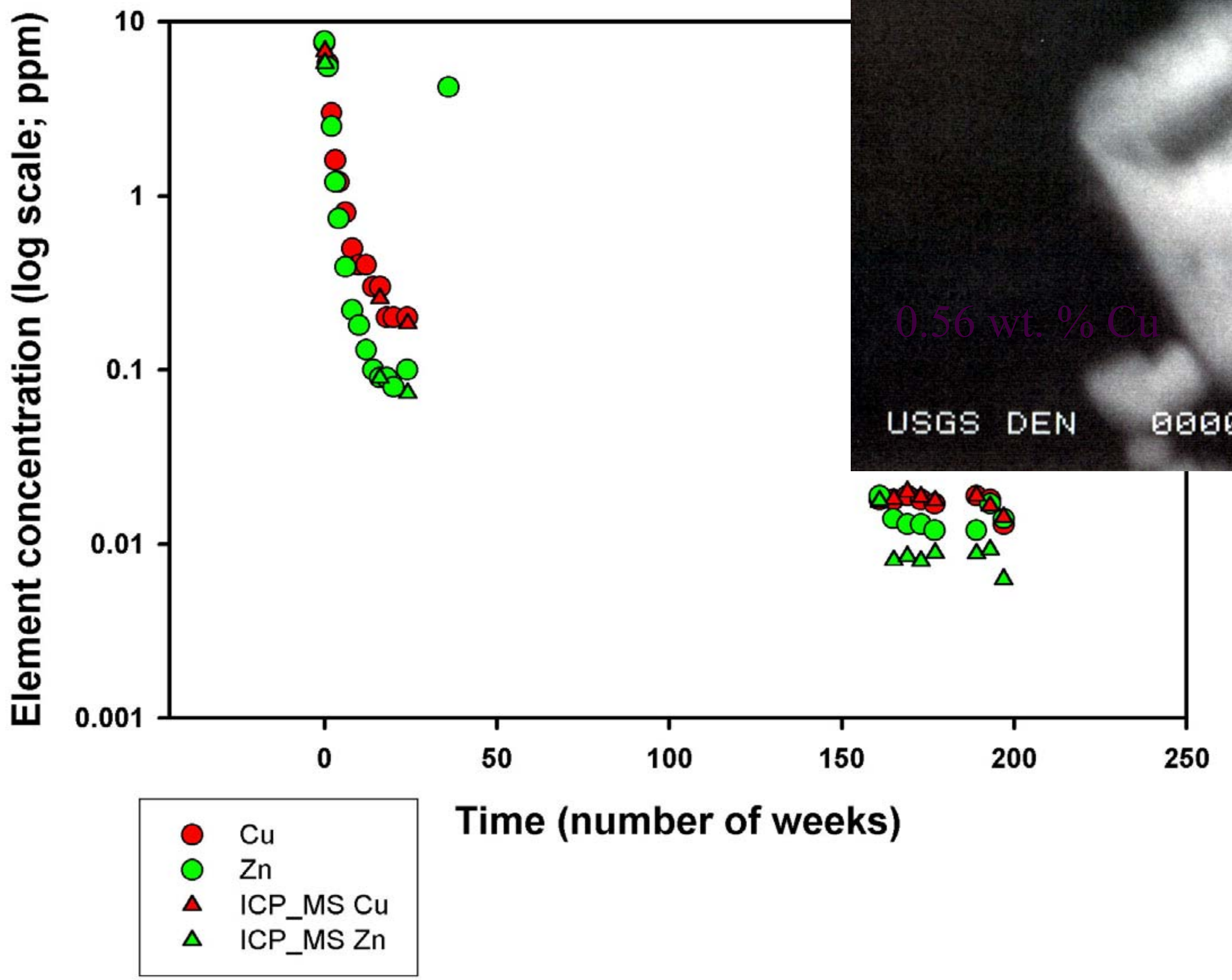
Zoned Jarosite

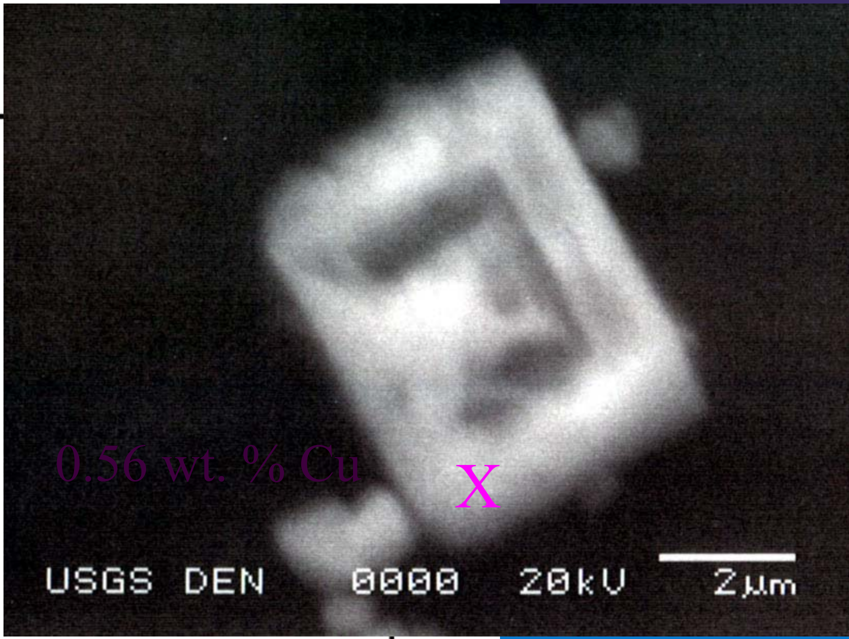


Jarosite crystals exhibit a chemical zonation evidenced by dissolution of the crystal cores.

Sample 81196; Trace Metals in Jarosite-Bearing Mine Waste

Trace elements in Jarosite





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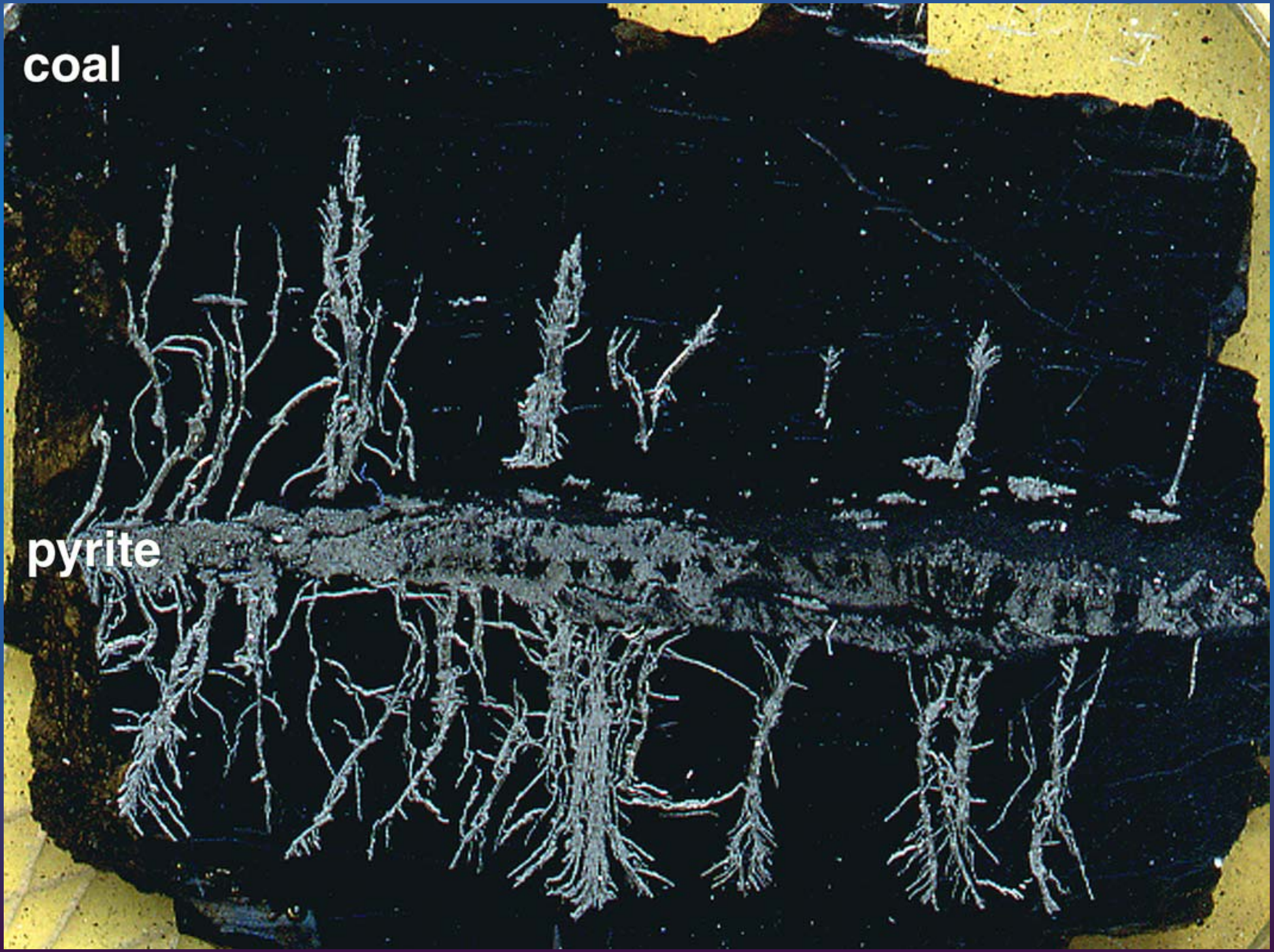
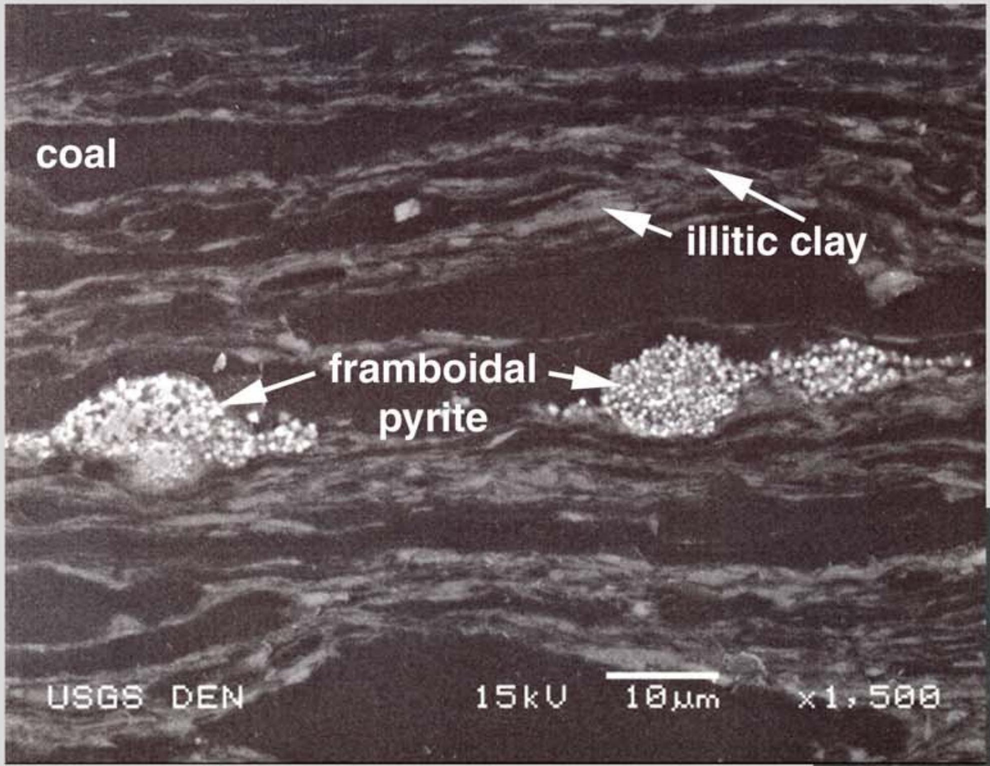
Case Study 2:

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

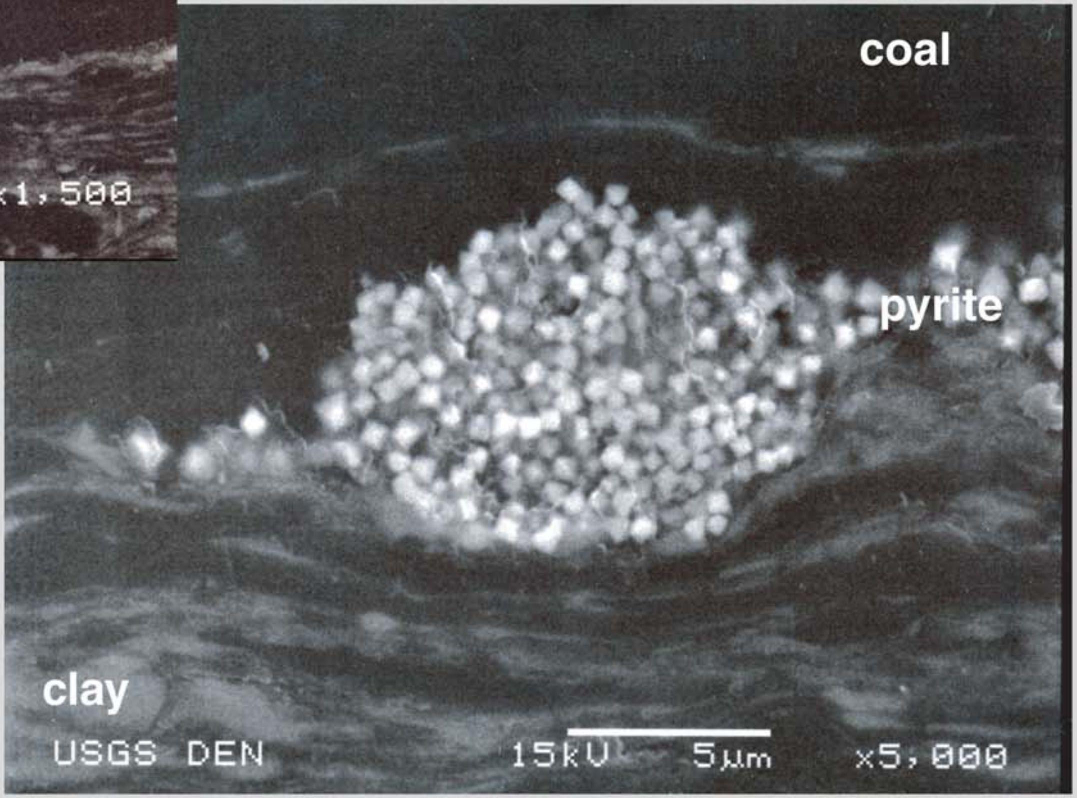


Framboidal Pyrite



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.



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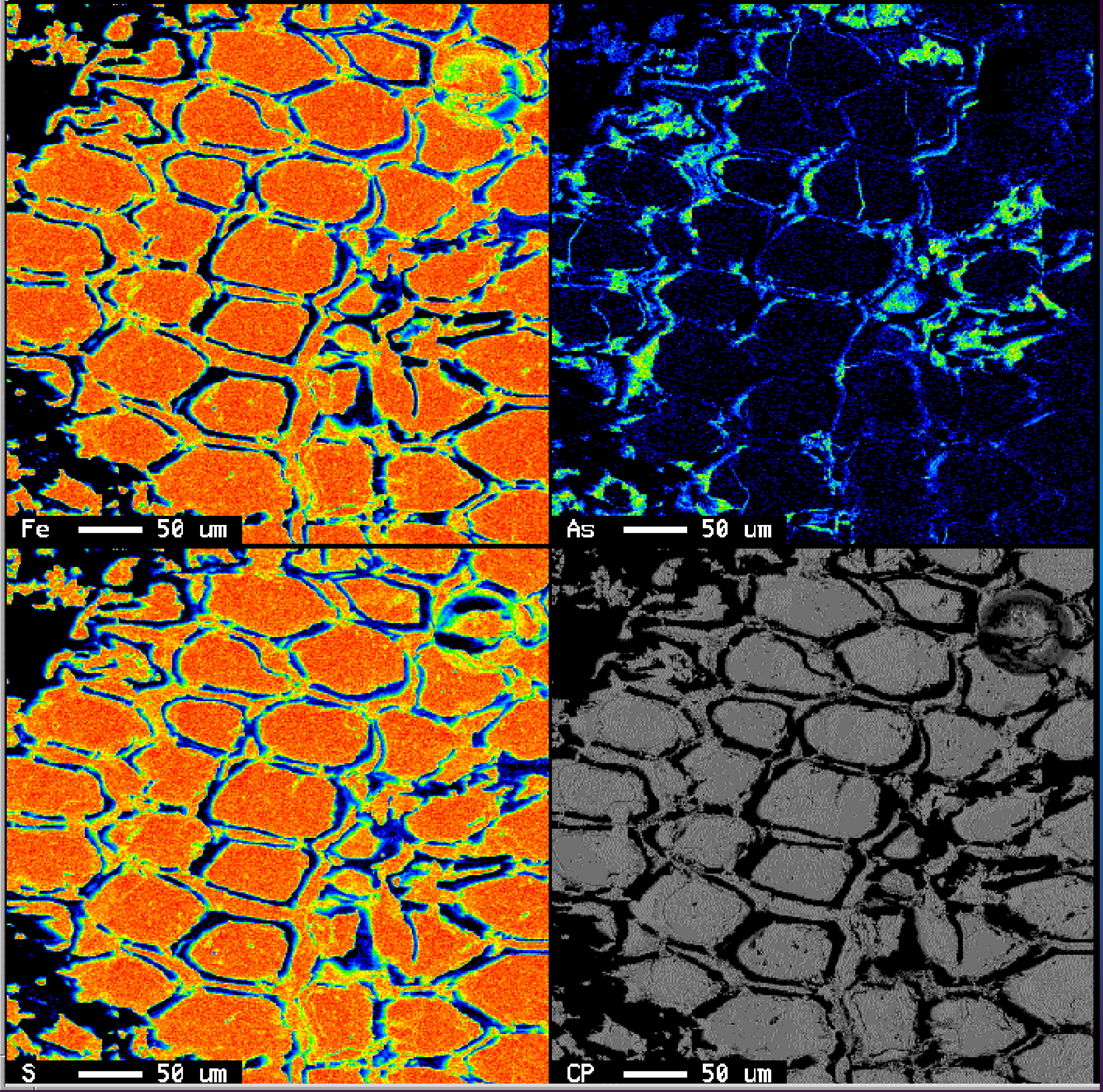
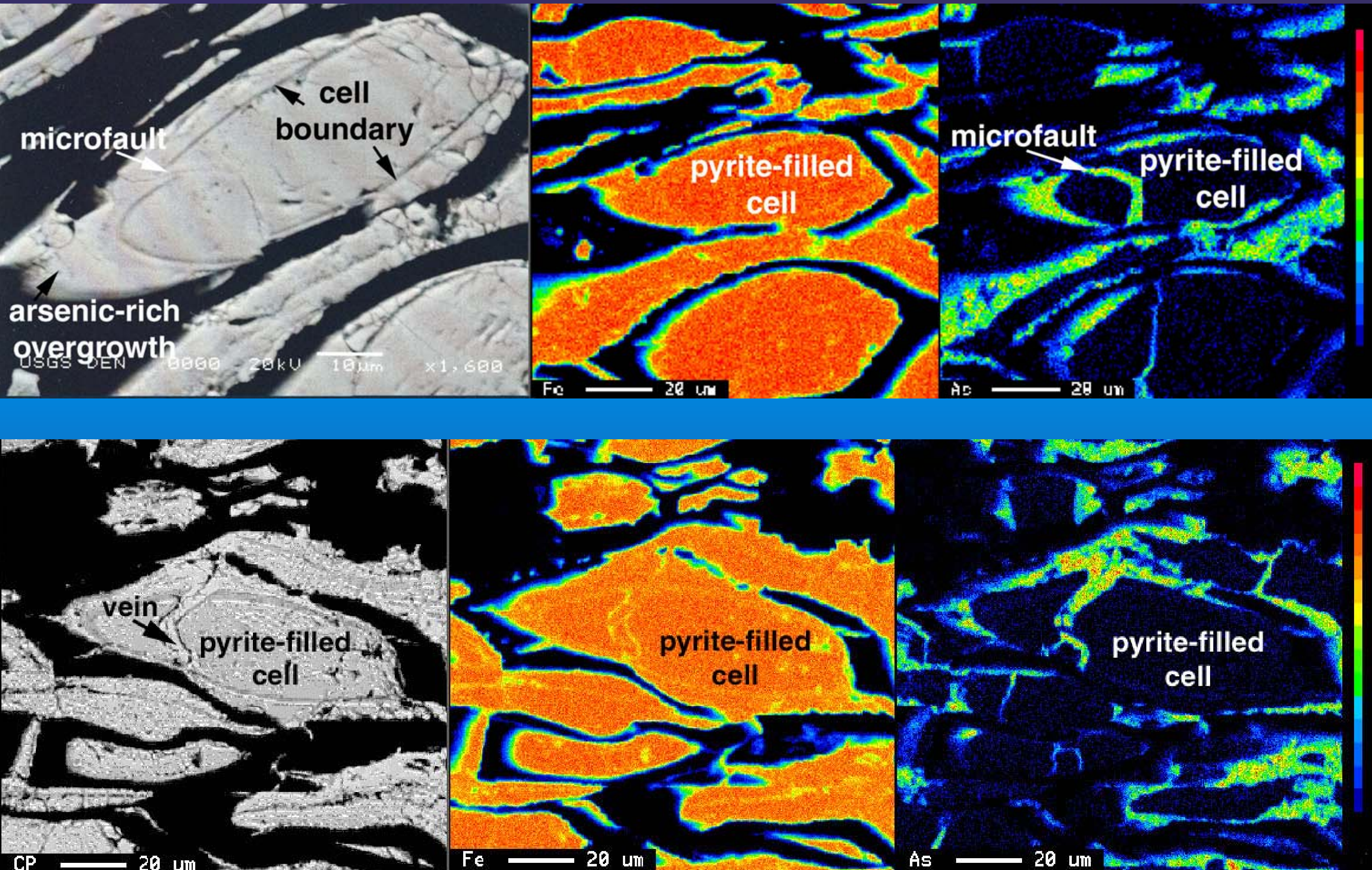


Lost Creek Mine

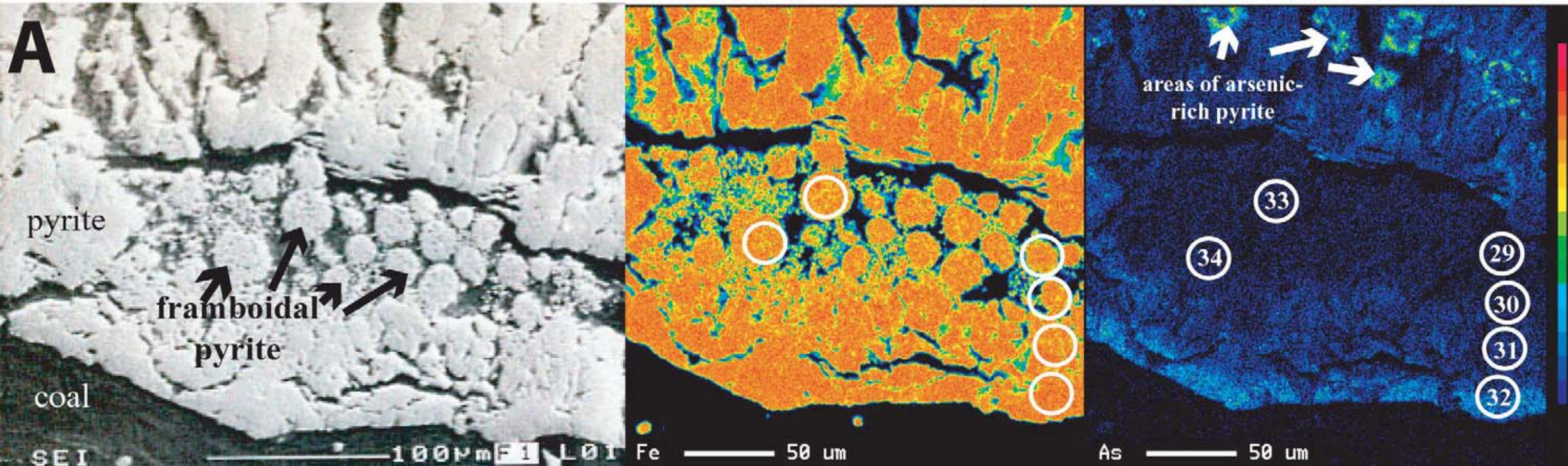
Pyrite fills woody cell structures.

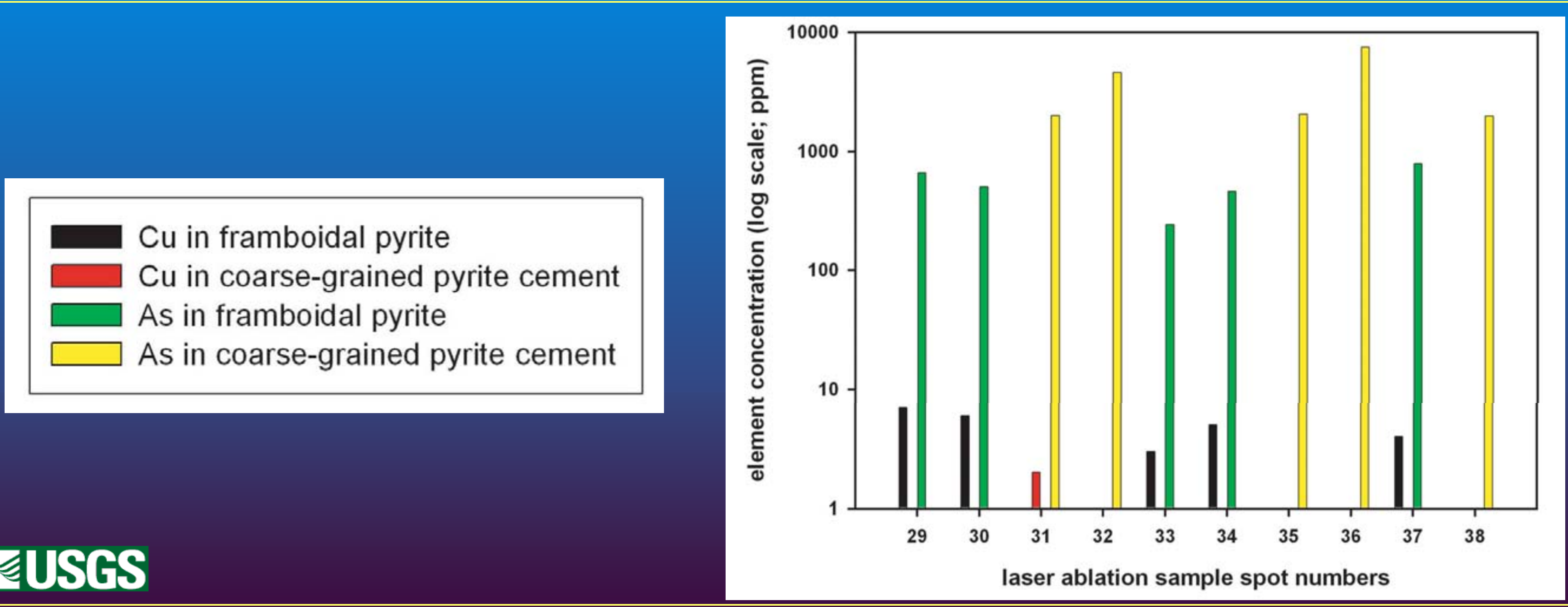
Arsenic-rich pyrite replaces early arsenic-poor pyrite in lumens, occurs as overgrowths, and along microfaults.

Element Maps of Arsenic in Microstructures



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





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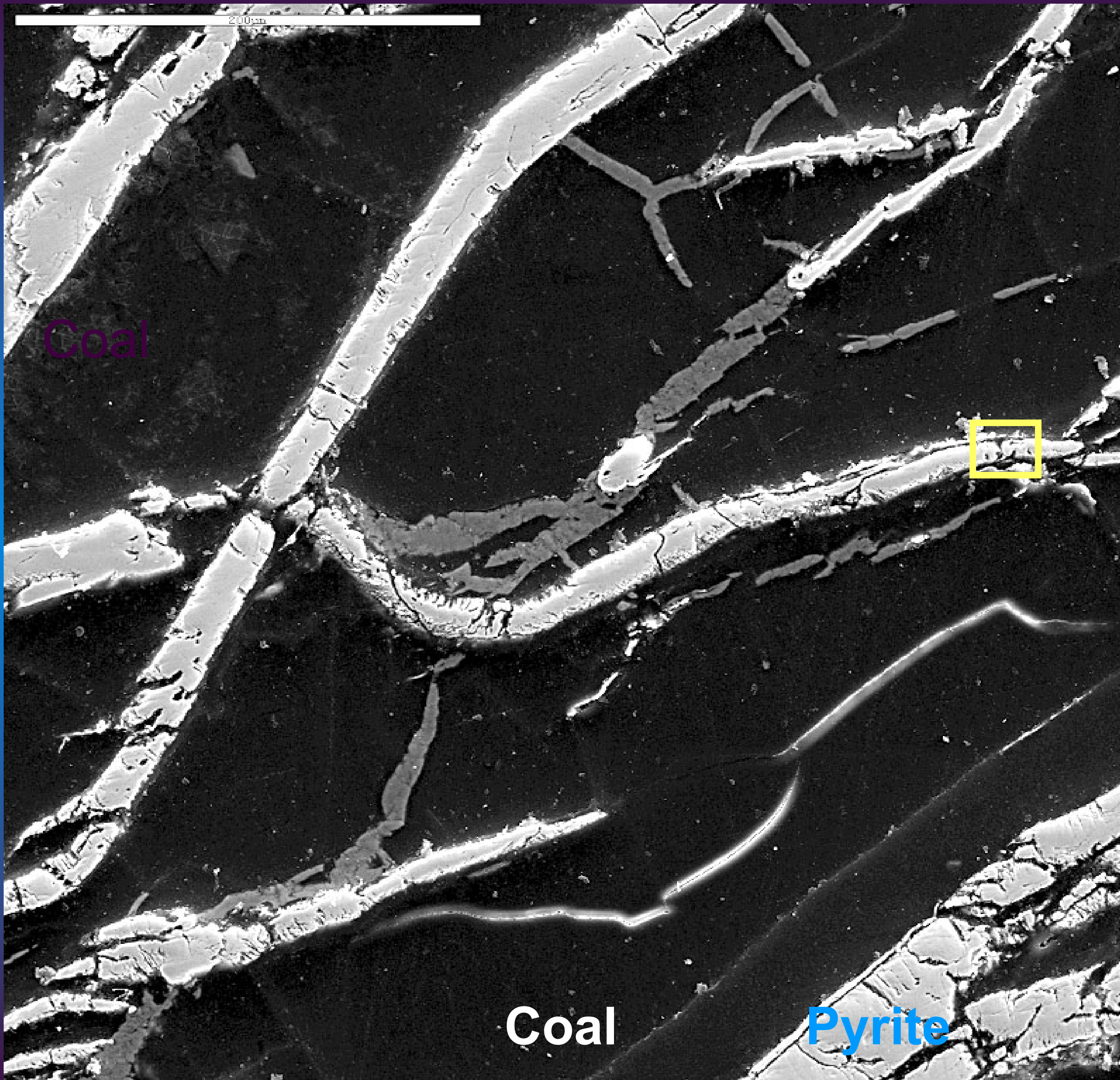
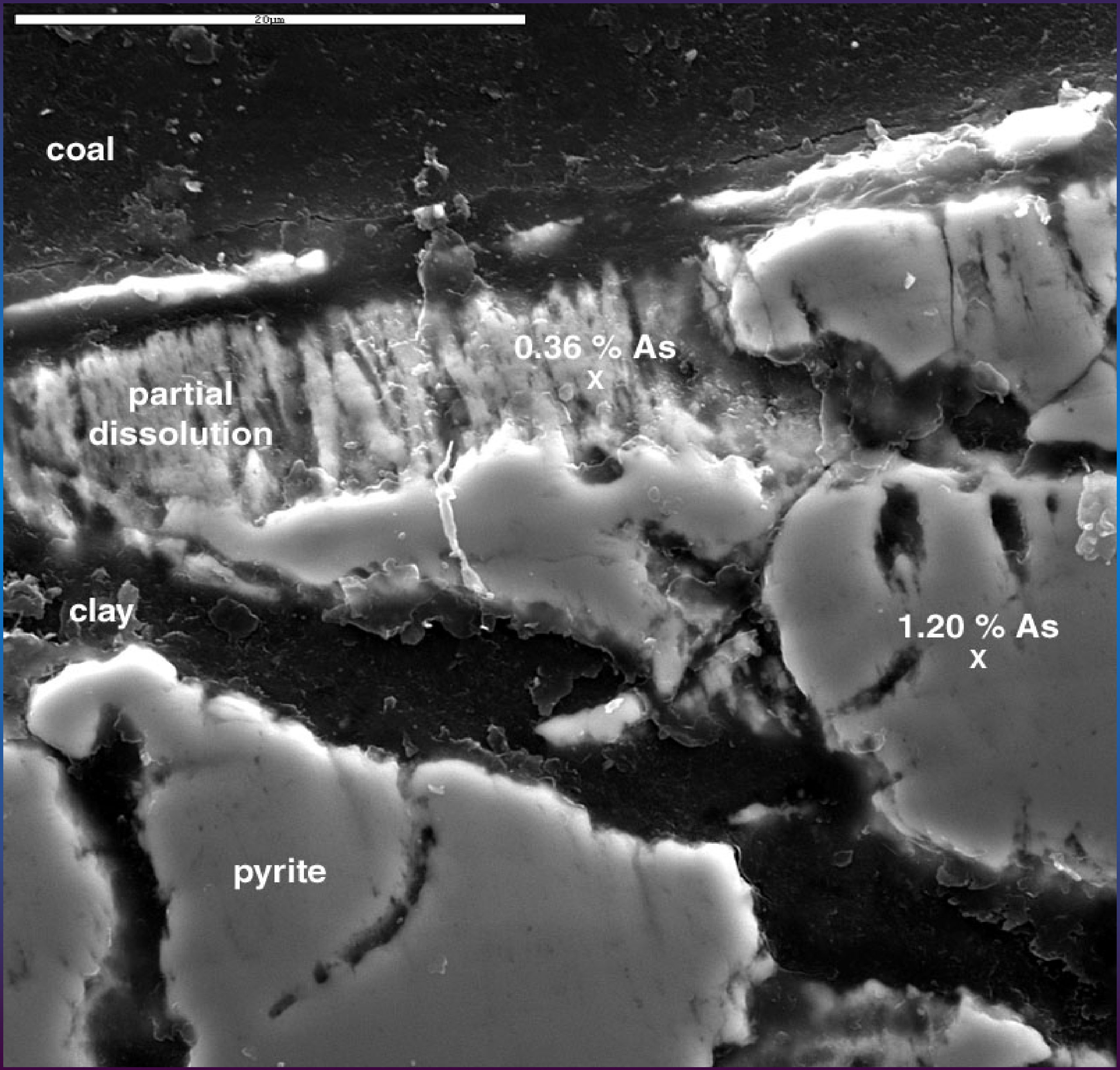
Arsenic-rich Pyrite and Clay-filled Fractures



Arsenic-rich Pyrite-filled Veins



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

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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.