Effects of Mining on the Environment — A National Overview

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April 25, 2007

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

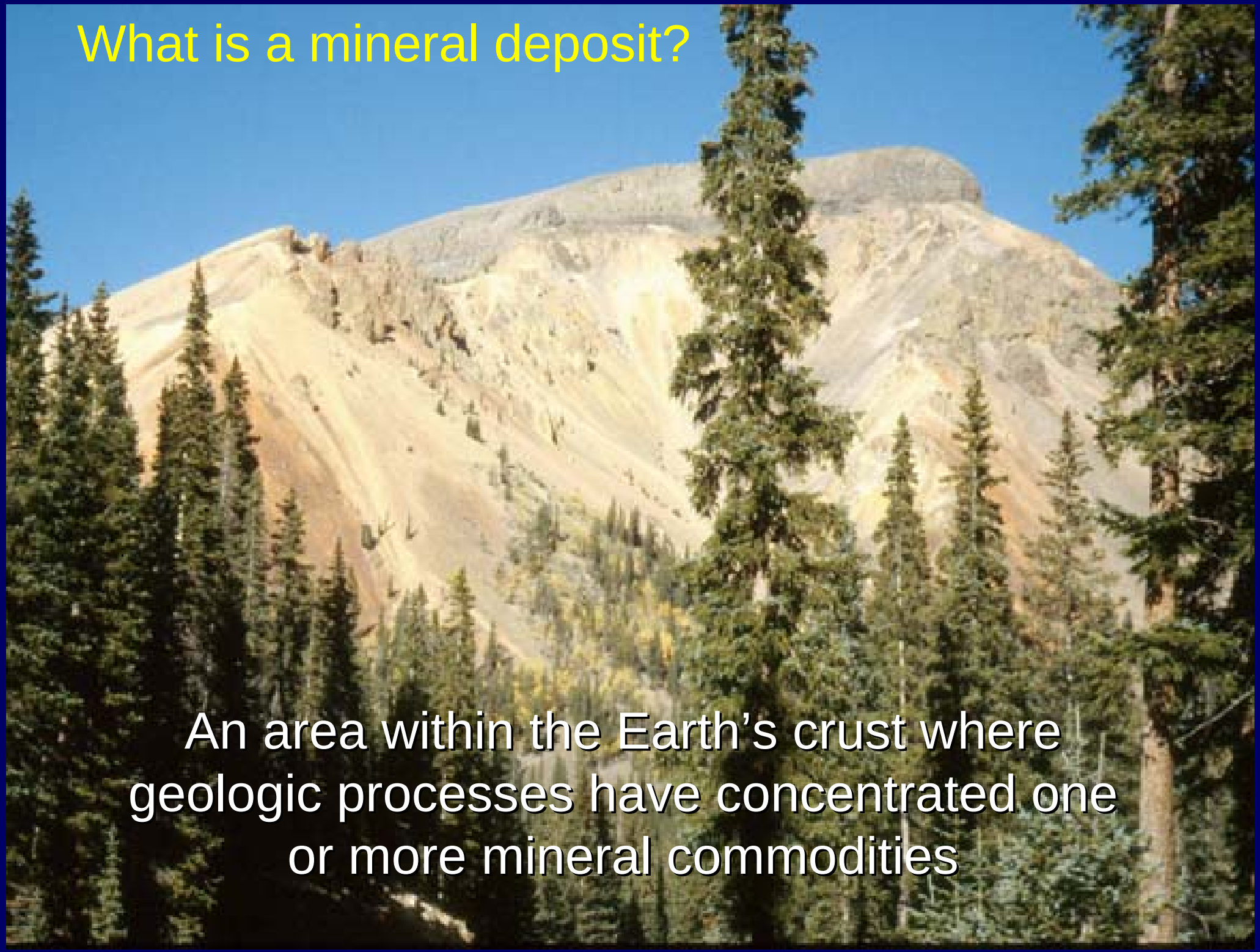
Two of the most important points of this talk are:

- Knowing the geology of the mine site is critical to understanding the environmental impact of mining at any given site

- Hydrothermal alteration associated with the mineral deposit has a major effect on the premining geochemical background as well as on the postmining environmental impact on the watershed

USGS

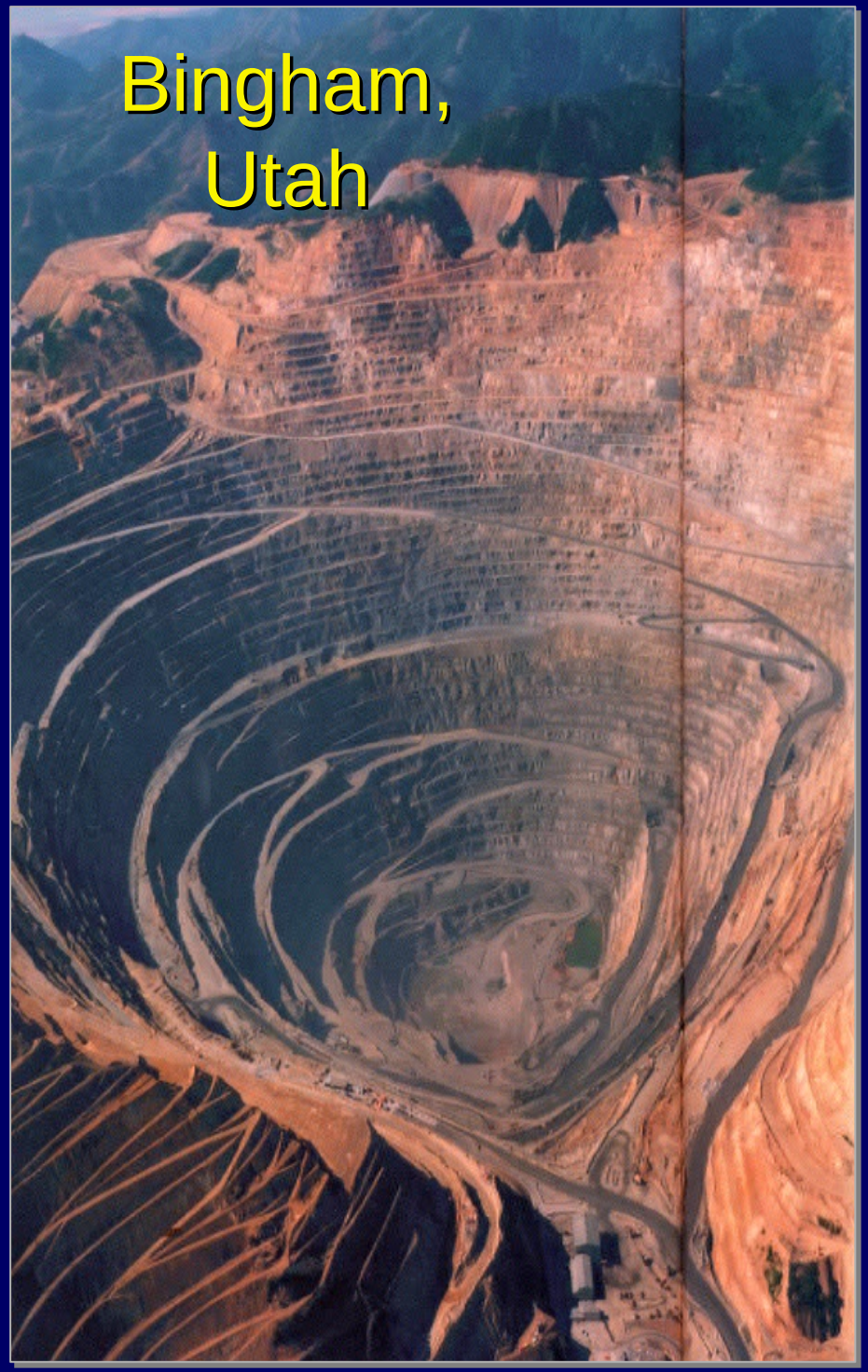
What is a mineral deposit?



An area within the Earth’s crust where geologic processes have concentrated one or more mineral commodities

What is an ore deposit?

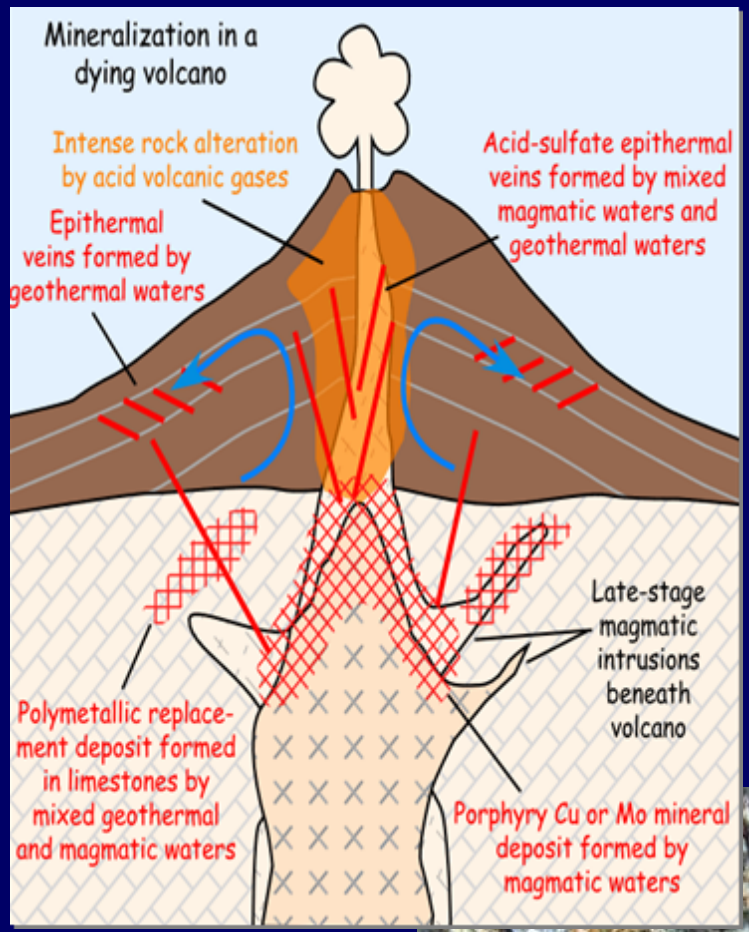
A mineral deposit in which the commodities (i.e., metals) are present in sufficient concentration (grade) and amount (tonnage) that they can (ideally) be extracted economically

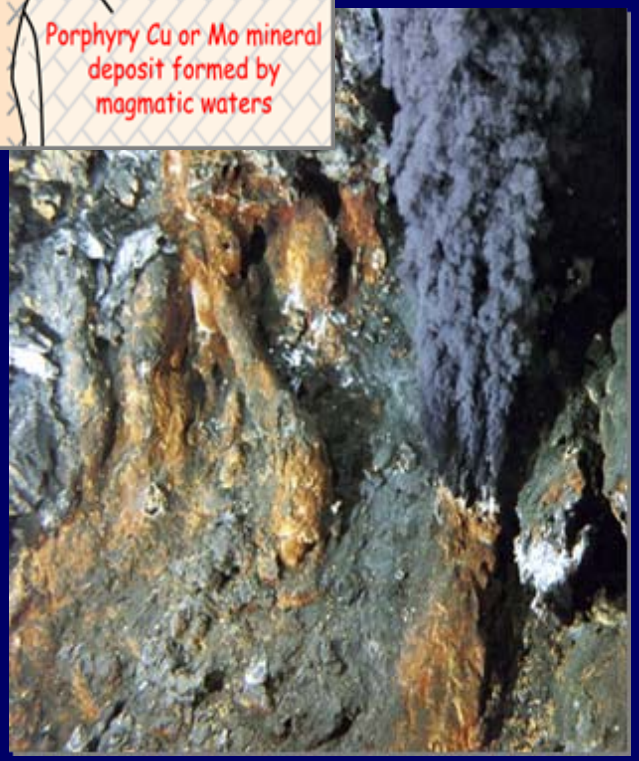


USGS

Metallic mineral deposits

- Concentrations of metallic elements and minerals in the Earth's crust
- Form by:
  - Crystallization of magmas
  - Cooling, boiling, mixing of hydrothermal fluids in the Earth's crust
  - Chemical precipitation of minerals on the sea floor or in sediment
  - Chemical reaction of two or more different fluids
  - Chemical reaction of a hydrothermal fluid with a rock





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Mineral deposit models

- Mineral deposits classified by geologic characteristics and geologic environment of formation
- Mineral deposit models developed for more than 40 deposit types
- Components:
  - Descriptive (general geologic characteristics)
  - Genetic (how they form)
  - Grade and tonnage
  - Hydrothermal alteration

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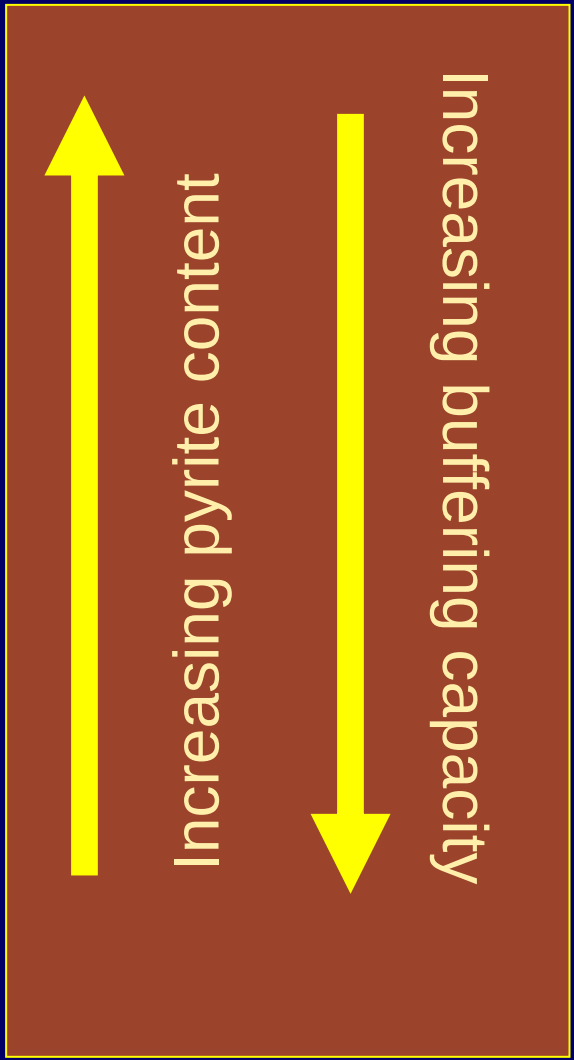
Hydrothermal alteration

- Acid-sulfate alteration
- Potassic alteration (ore zone)
- Quartz-sericite-pyrite (QSP)
- Argillic (clay minerals)
- Propylitic



USGS

Geoenvironmental mineral deposit models

- Use geologic characteristics of mineral deposits
  - Sulfide mineralogy
  - Hydrothermal alteration
  - Ore-deposit mineralogy

- Time frame of historical mining activity
  - Metal mobility from mine-waste dumps
  - Water chemistry
  - Smelter signatures in soils
  - Sediment geochemistry in surface streams

USGS

Take-home message

- A mineral deposit may not be an ore deposit. The term “ore” is an economic descriptor
- Physical processes of formation of the deposit are the primary drivers controlling the impact of the mined site on the environment
- Hydrothermal alteration controls the distribution of pyrite in many mineral deposits

USGS

Potential environmental and health impacts of mining

A complex but predictable function of:

- Mineral deposit geology
  - Environmental signatures, physical footprint
- The mining and mineral processing methods used
  - Typically mandated by the deposit geology
- Geochemical and biogeochemical processes
  - Bacterial activity can increase reaction rates by a million times
- The effect of climate on rates of weathering

Effective prediction, mitigation, and remediation strategies are also dependent upon characteristics of the surrounding watersheds

- Geology, size, topography, ecology
- Number and footprint of other environmental stressors

USGS

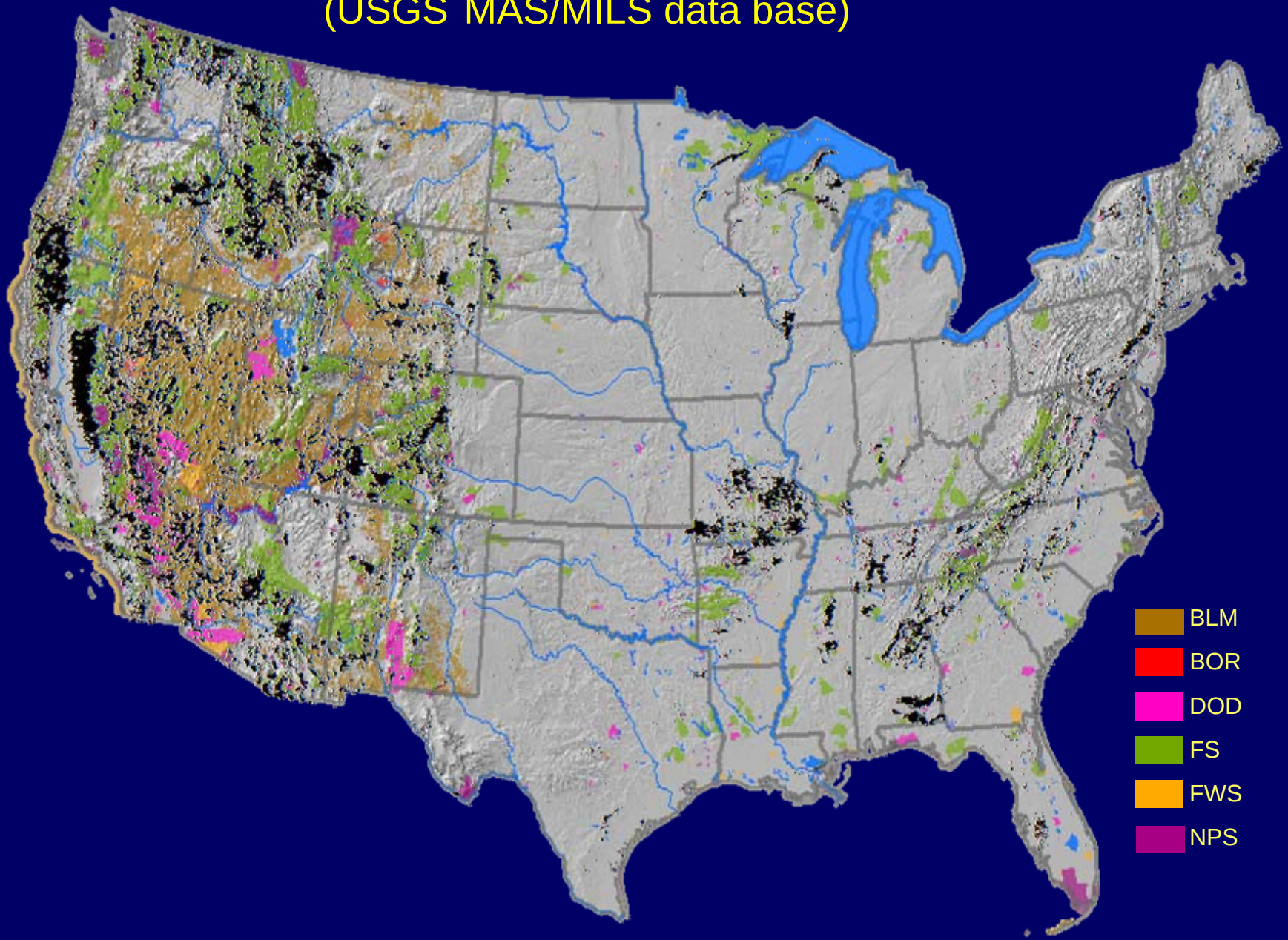
What data are available to indicate the extent of land disturbance throughout the Nation?

- USGS database of historical mines provides a representative look at disturbance by mining

USGS

Mines, prospects, and occurrences

(USGS MAS/MILS data base)



USGS

What data are in the USGS MAS/MILS databases?

- Four types of data that show the extent of land disturbance
  - Mines
    - Active or
    - Inactive
      - These data are current as of the time of data entry
  - Prospects—minimal ground disturbance
  - Occurrences—no ground disturbance

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Significant mineral deposits

- Cu, Pb, Zn, Au, Ag (Long et al., 2002)
  - Defined about 1,000 major ore deposits by deposit type
  - Upper 10 % of producers by commodity (Singer, 1995)
- Uranium
- Phosphate
- Iron
- Molybdenum
- Mercury

USGS

Significant gold deposits

Placer gold

Mercury deposits

Carlin gold deposits

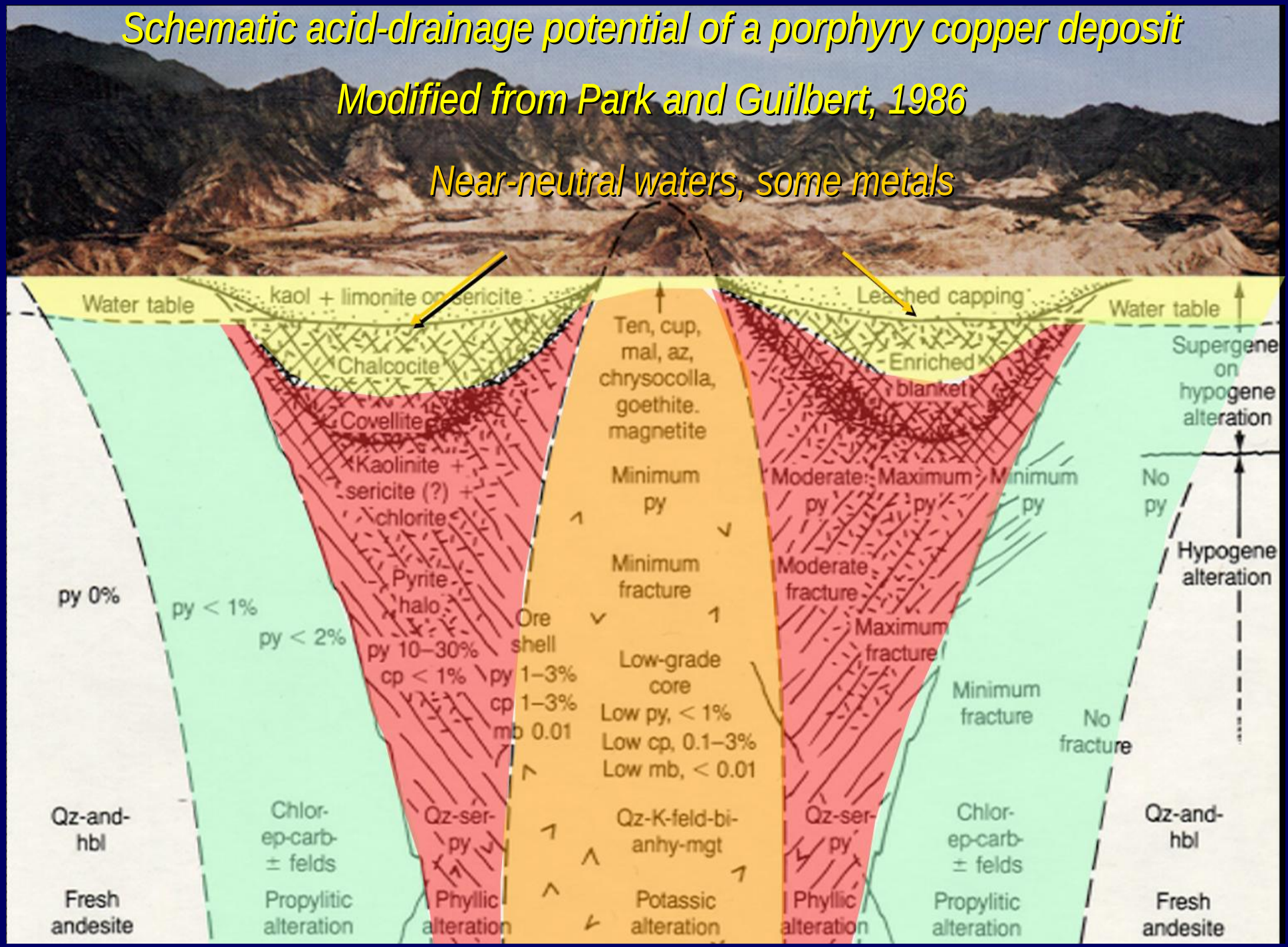
USGS

Porphyry copper and molybdenum deposits

Schematic acid-drainage potential of a porphyry copper deposit

Modified from Park and Guilbert, 1986

Near-neutral waters, some metals



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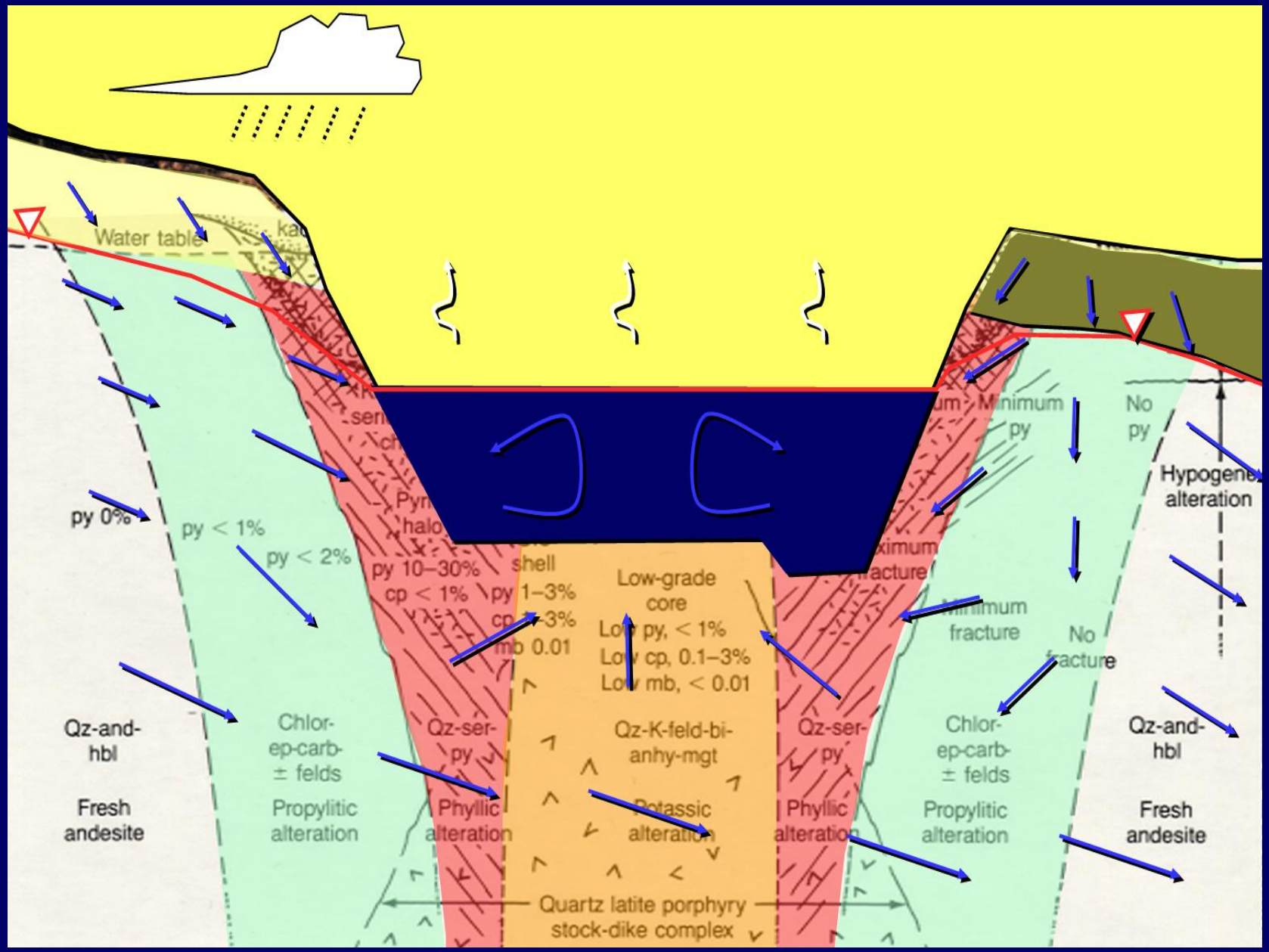
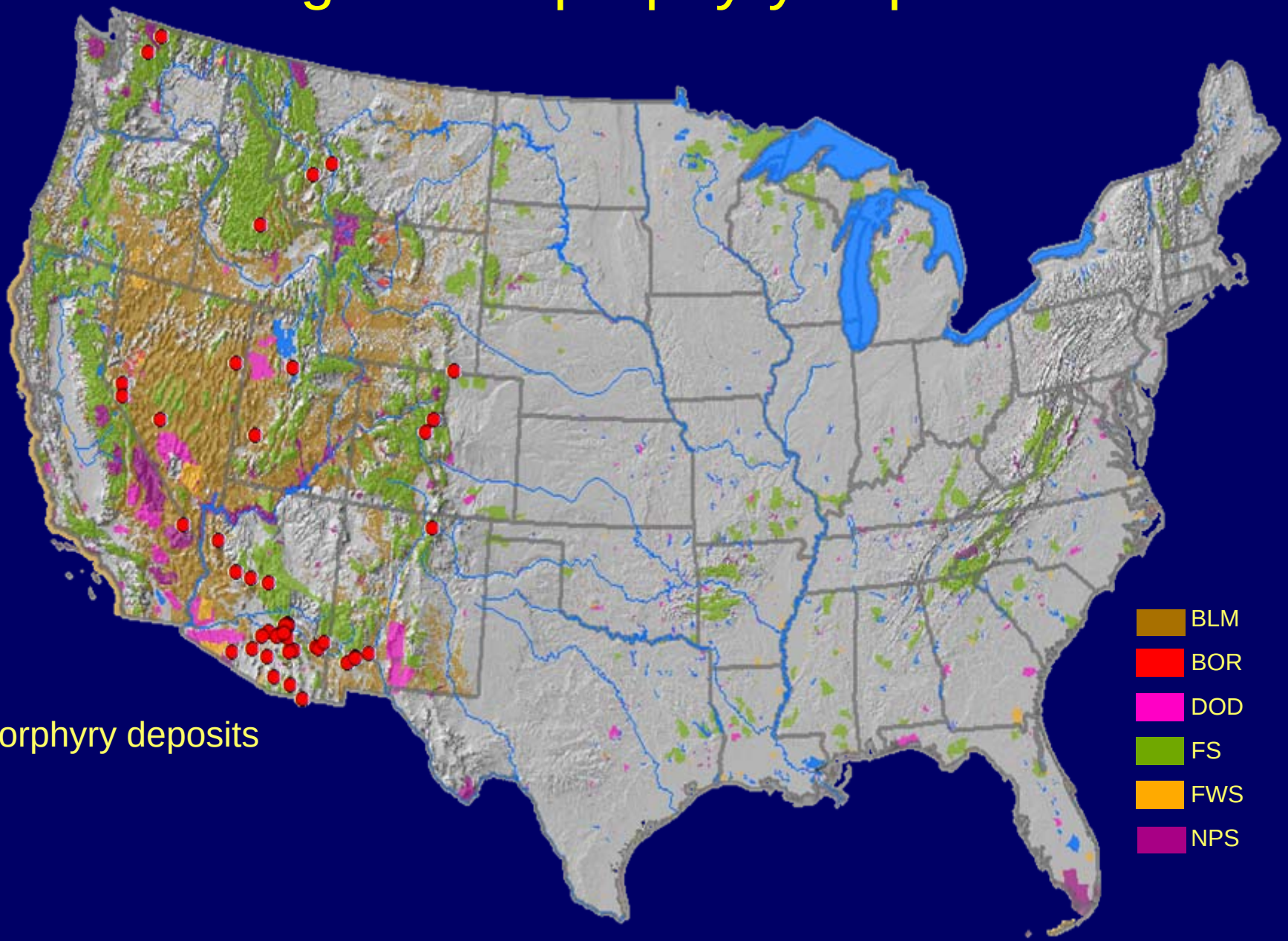
Development of pit lakes

- Fracture flow hydrology, pit wall geology, lake limnology, climate are key parameters



USGS

Significant porphyry deposits



Porphyry deposits

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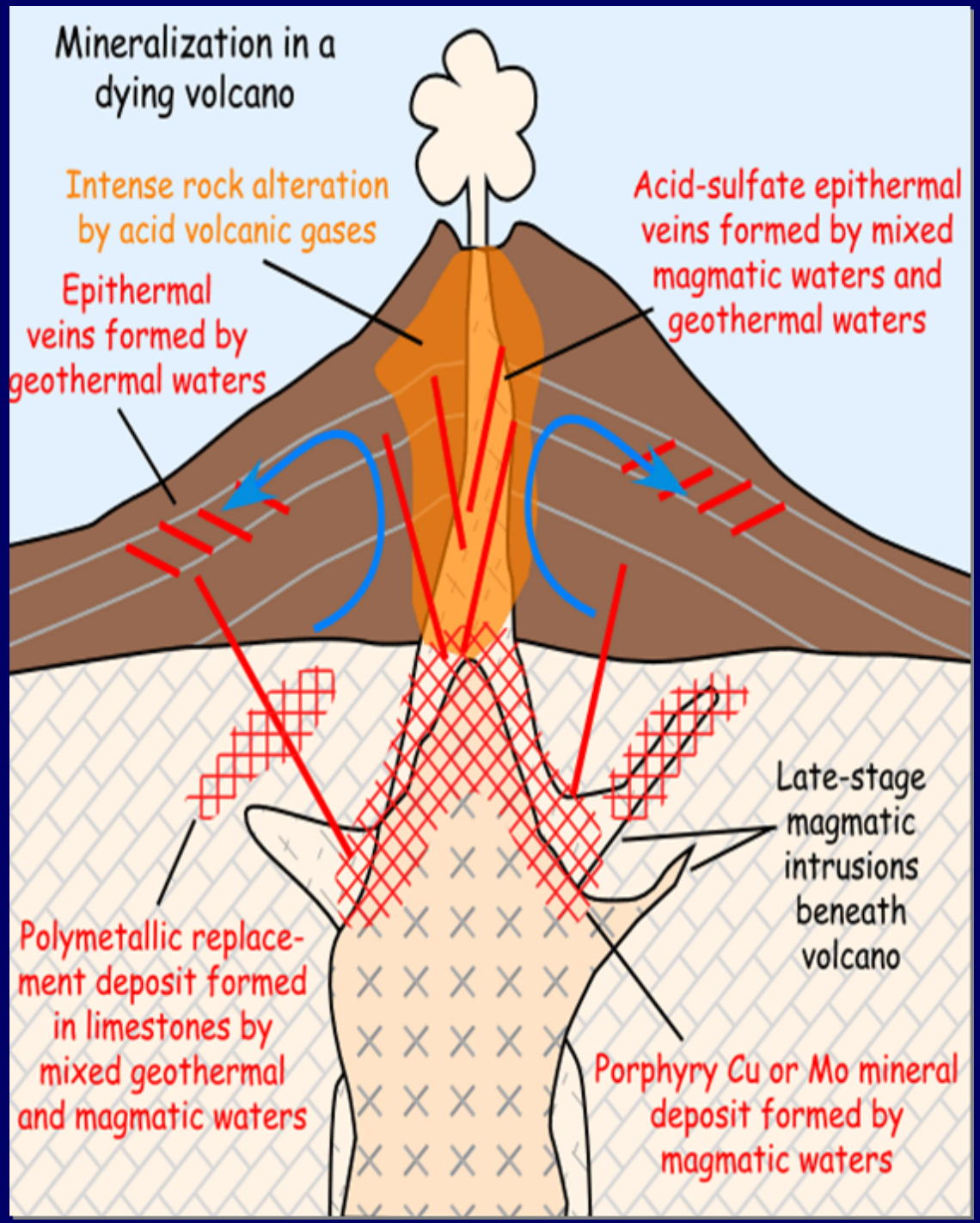
Porphyry deposits represent the biggest environmental challenge that Federal Land Management Agencies face in terms of acid mine drainage (AMD)

- Many porphyry deposits are still being mined
- Most porphyry deposits occur in arid regions and are on private land
- Most deposits that have been mined out continue to be held by mining companies and are listed as inactive mines
- In the future these will be the major AMD issues FLMA will face

USGS

Epithermal vein and

Polymetallic vein deposits



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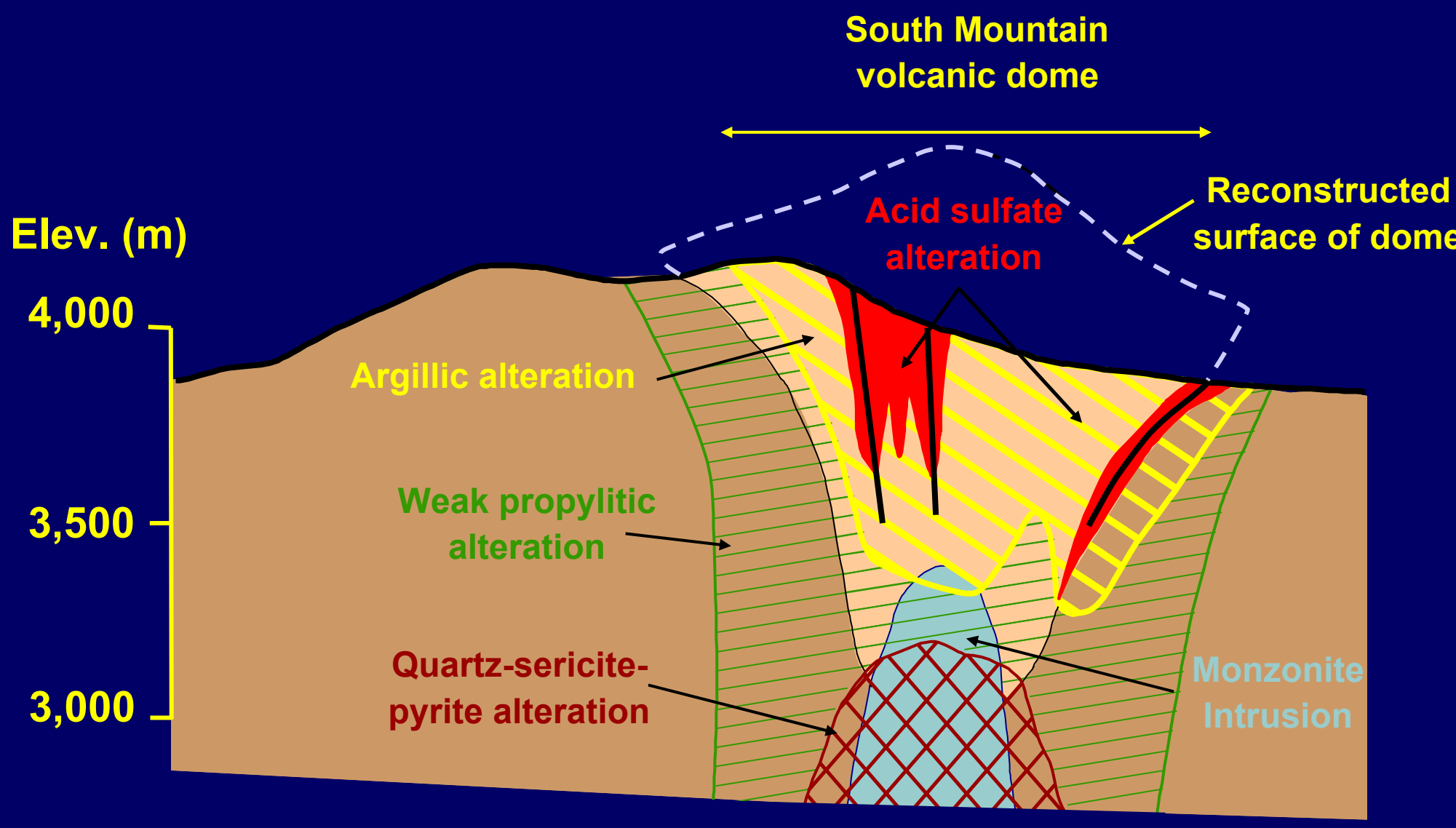
Significant vein deposits

Epithermal veins

Polymetallic veins

USGS


South Mountain
volcanic dome
Reconstructed
surface of dome
Acid sulfate
alteration
Elev. (m)
4,000
3,500
3,000
Argillic alteration
Weak propylitic
alteration
Quartz-sericite-
pyrite alteration
Monzonite
Intrusion

USGS

Red Mountains, Silverton, Colo.

Footprint of hydrothermal alteration

Animas River watershed study area

http://amli.usgs.gov

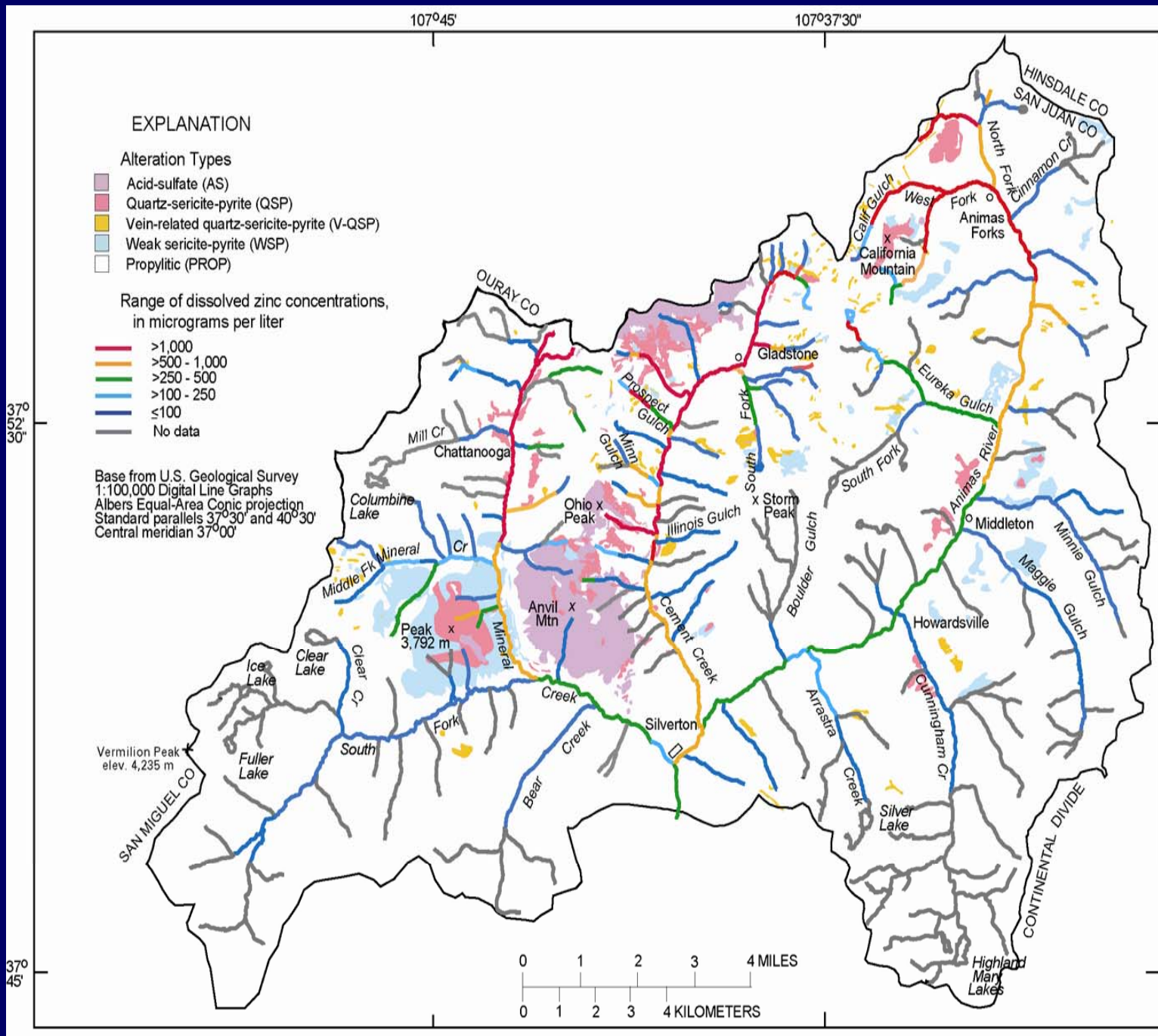


Figure 8.

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Formation of Al sulfate precipitates

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VMS deposits

- Form on the sea floor
- Very pyritic
- Little alteration
- Buried by fresh volcanic rock or by sediment to be preserved
- Very large acid generators

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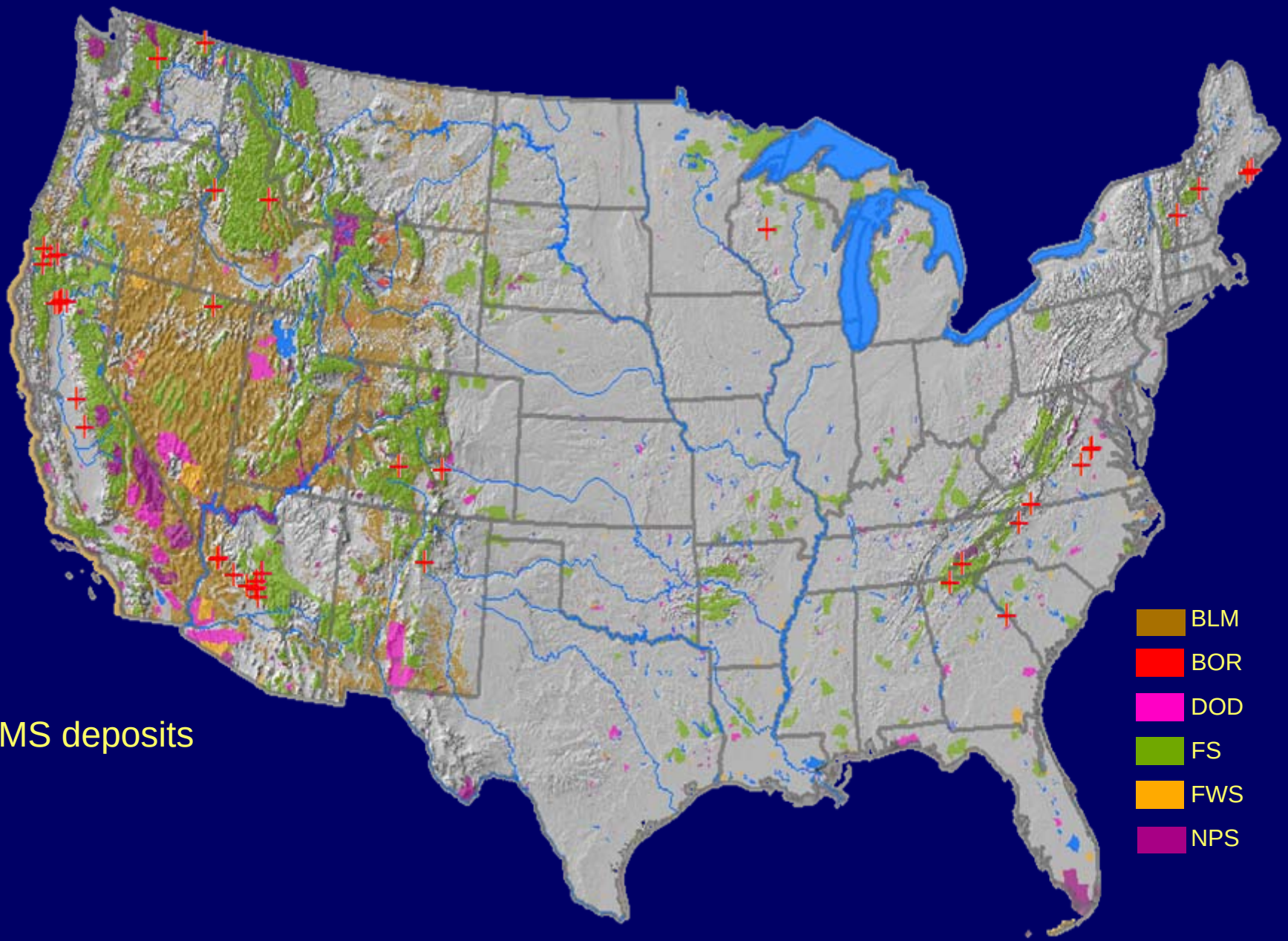
Significant volcanogenic massive sulfide deposits



+ VMS deposits

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What controls water chemistry in AMD?

- The amount of acid-generating minerals
  - Pyrite isn't the only one!
- The amount and type of hydrothermal alteration
- The acid-neutralization potential in the watershed
- The amount of water available for dilution of AMD
- Climate

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Acid-generating minerals

PYRITE (FeS_2):

- By oxygen:

a) $FeS_2 + 3.5O_2 + H_2O \Rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$

b) $Fe^{2+} + 0.5O_2 + H^+$ (+ bacteria) $\Rightarrow Fe^{3+} + 0.5H_2O$

- By ferric iron:

$FeS_2 + 14Fe^{3+} + 8H_2O \Rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$

- Bacteria speed up the key acid-drainage formation reaction (b) by 1 million times
- Dissolved ferric iron is a corrosive oxidant

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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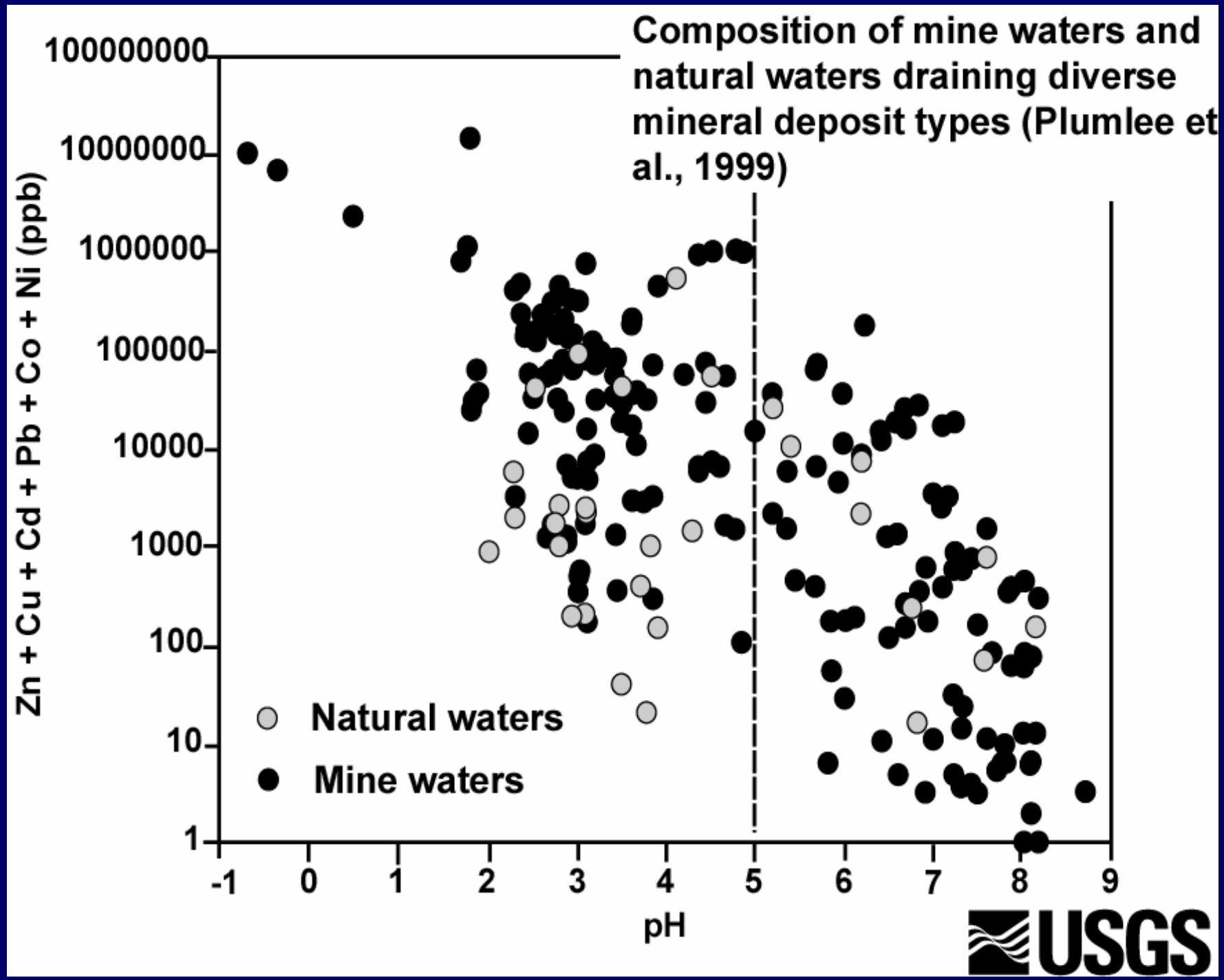
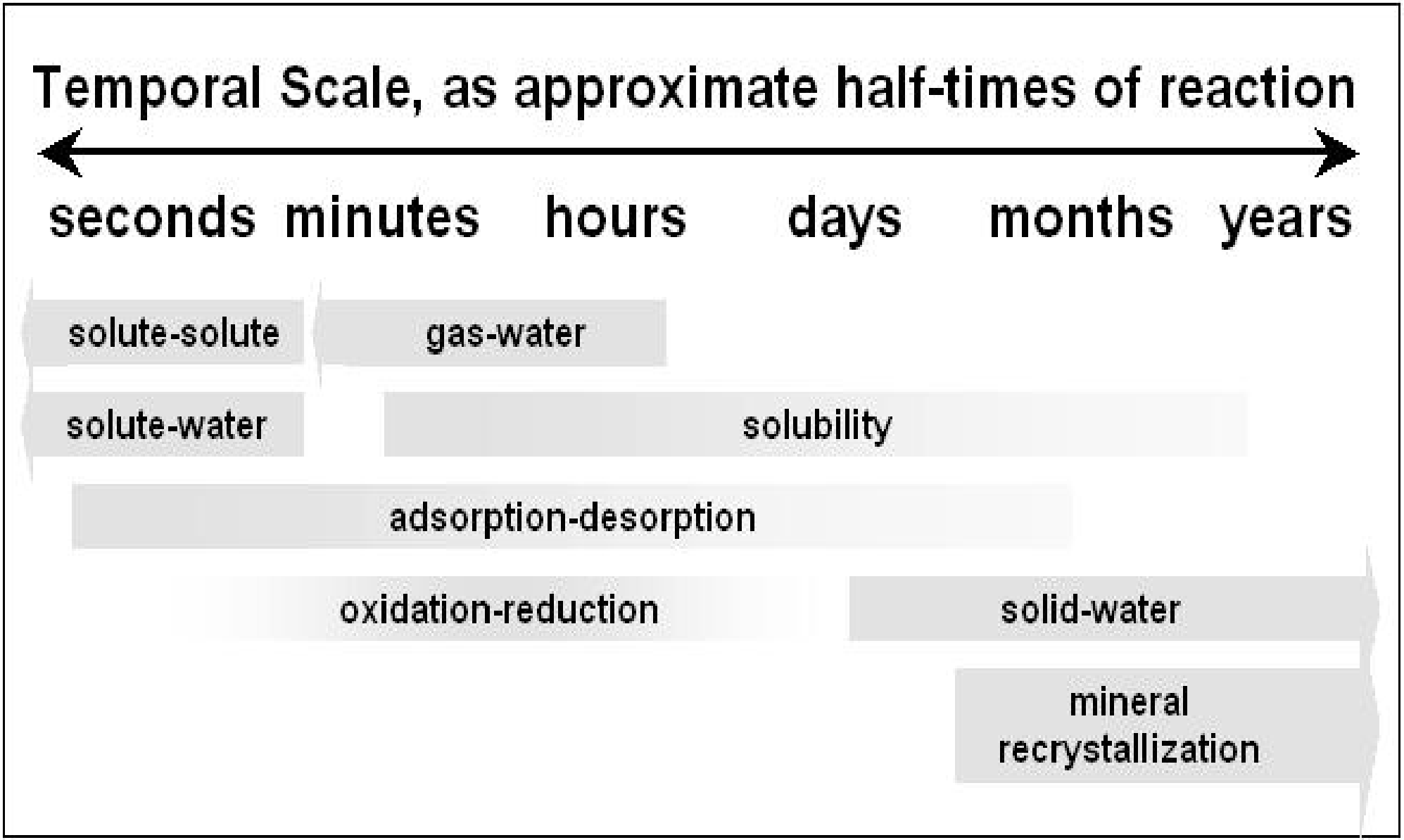
Comparison of water chemistry from “natural” and AMD sites



Differences in rate of some types of reactions that influence metal mobility



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Precipitation of iron minerals

Pyrite weathering

pH = 2.3 - 2.8 Jarosite

pH = 3 - 5 Schwertmannite

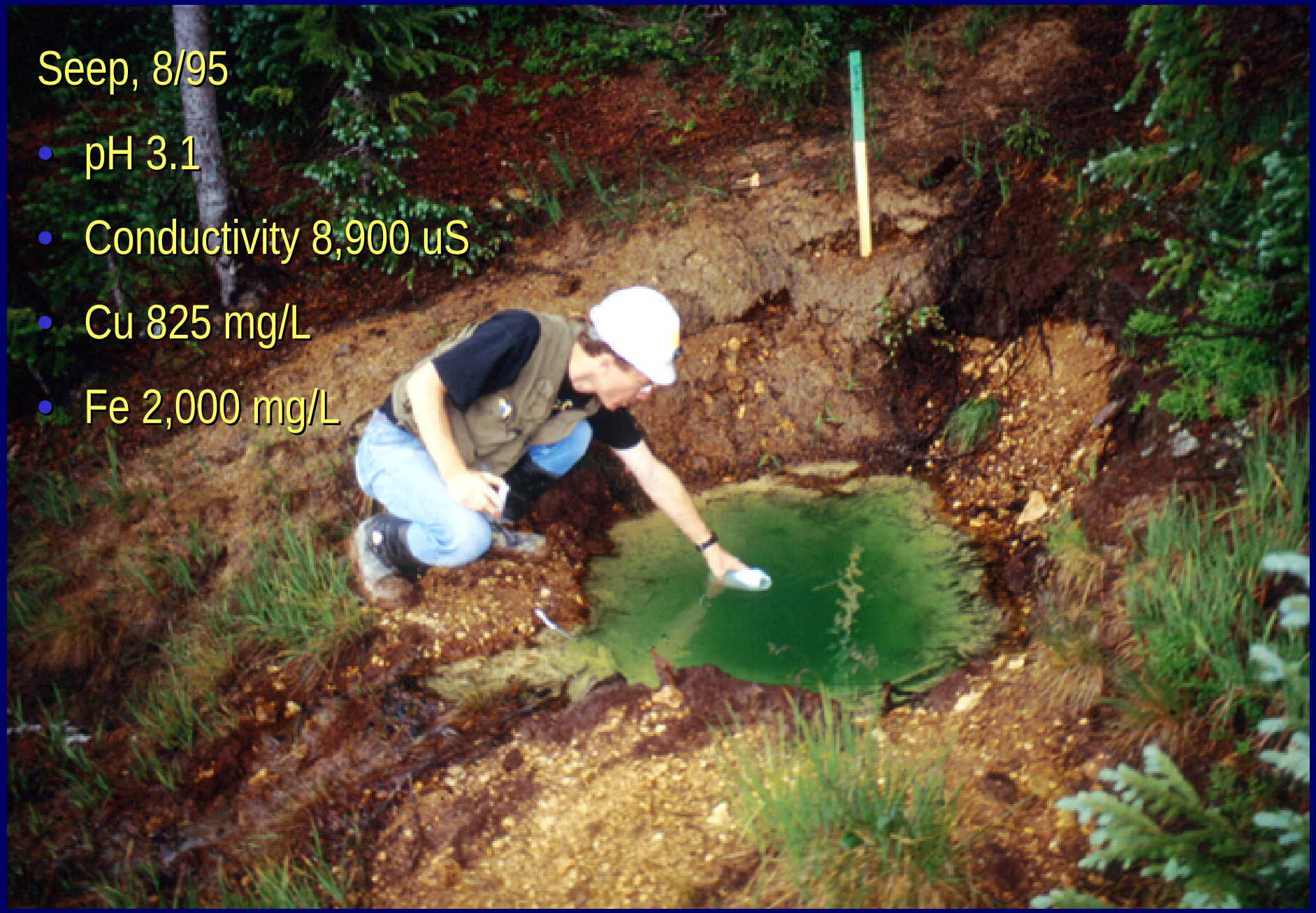
pH = 4.5+ Ferrihydrite

pH = 7+ Goethite

USGS

Geological and geochemical controls on mine- and natural-drainage water compositions

Sampling water from the Reynolds adit



Seep, 8/95

- pH 3.1
- Conductivity 8,900 uS
- Cu 825 mg/L
- Fe 2,000 mg/L

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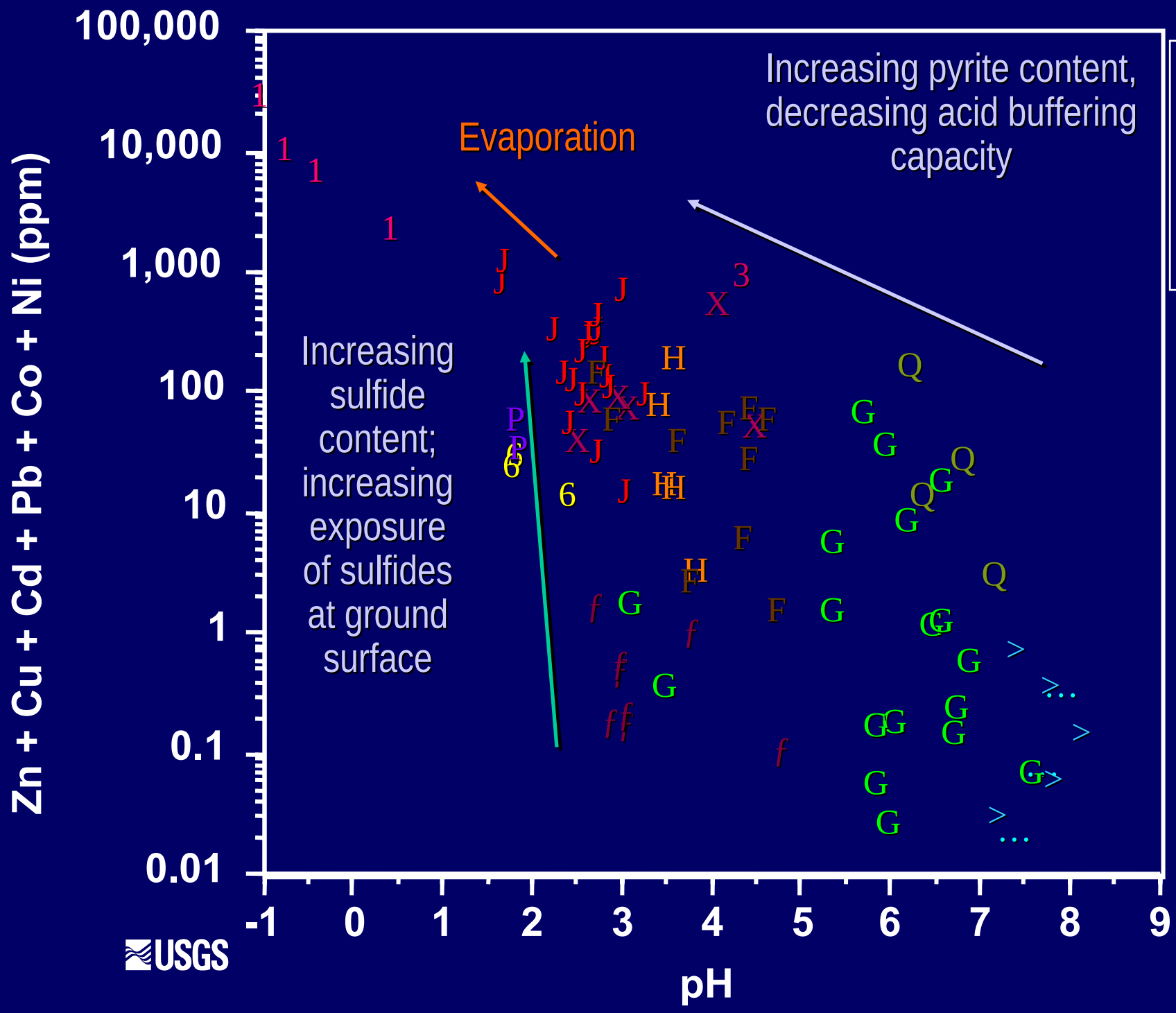
Geologic controls on mine-drainage composition



Symbols depict waters from deposits with similar geologic characteristics

Plumlee et al., 1999, (all samples filtered)

Colloidal Fe in the stream

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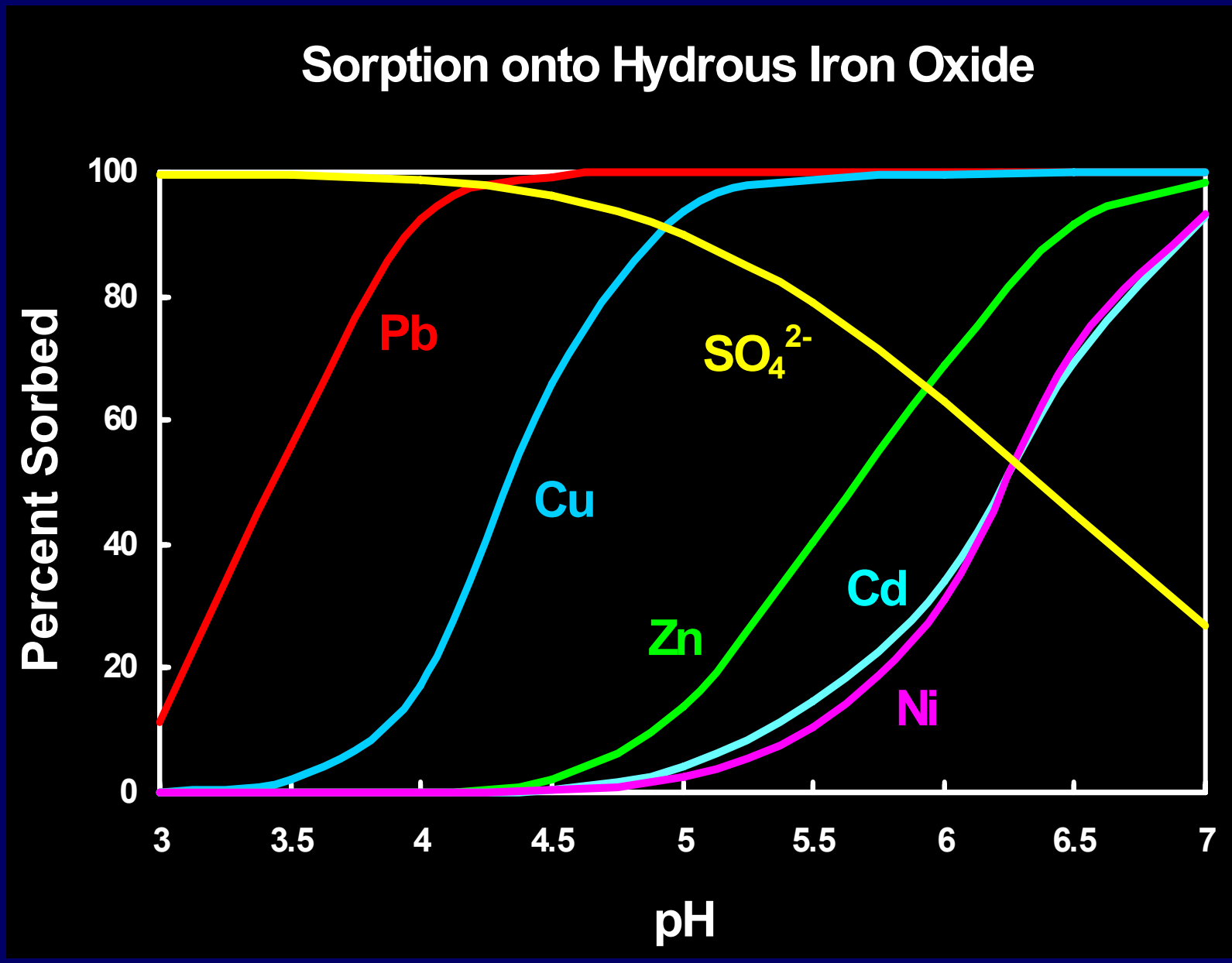
The effect of iron on trace-element concentrations in water

Preferentially removing iron from a system may result in increased dissolved concentrations of other metals



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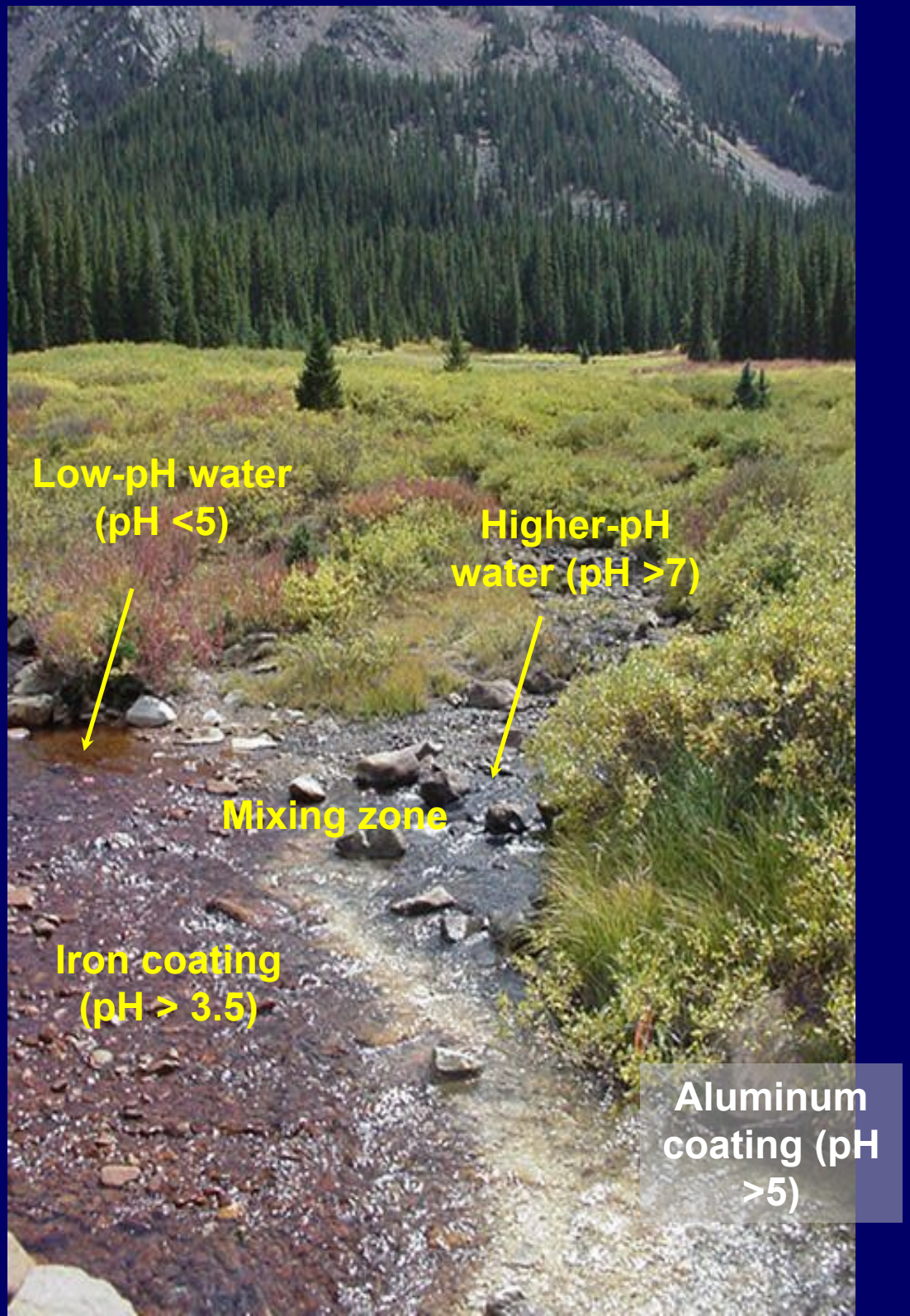
modified from Smith (1999)

Mixing zone, Snake River drainage, Colo.

Example of changes in precipitation of colloids as a function of pH in a mixing zone downstream of the confluence of an acidic stream (undisturbed by historical mining) and a neutral stream



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Acid-neutralizing minerals

- Carbonate minerals and some other minerals (some silicates, volcanic glasses) in mineral deposits, their host rocks, and watershed rocks:
  - Can react with and help consume acid generated by sulfide oxidation
  - Can also generate alkalinity in ground and surface waters, thereby increasing the waters' ability to buffer acid

Limestone

http://www.sirendesigns.com/elora_resources/gallery_1/pages/limestone_cliff_gif.htm

Calcite on pyrite, Silesia, Poland

What geochemical data are available that would show where potentially toxic mine sites might be?

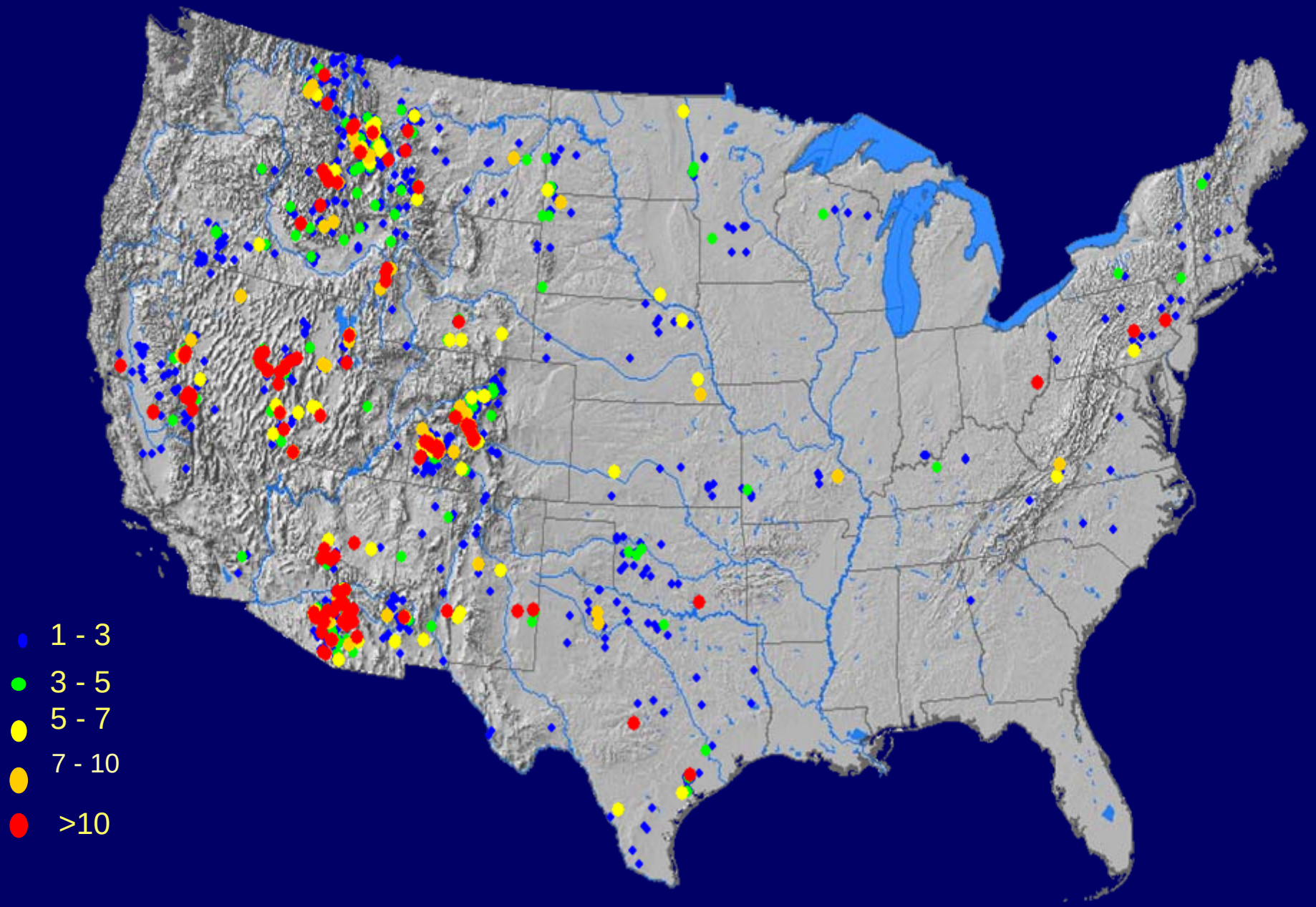
- In the conterminous U.S.
  - 330,000 analyzed NURE sediments
  - 150,000 analyzed USGS sediments
- In Alaska
  - 65,000 analyzed NURE sediments
  - 25,000 analyzed USGS sediments

USGS

Abandoned Mines (MAS/MILS)

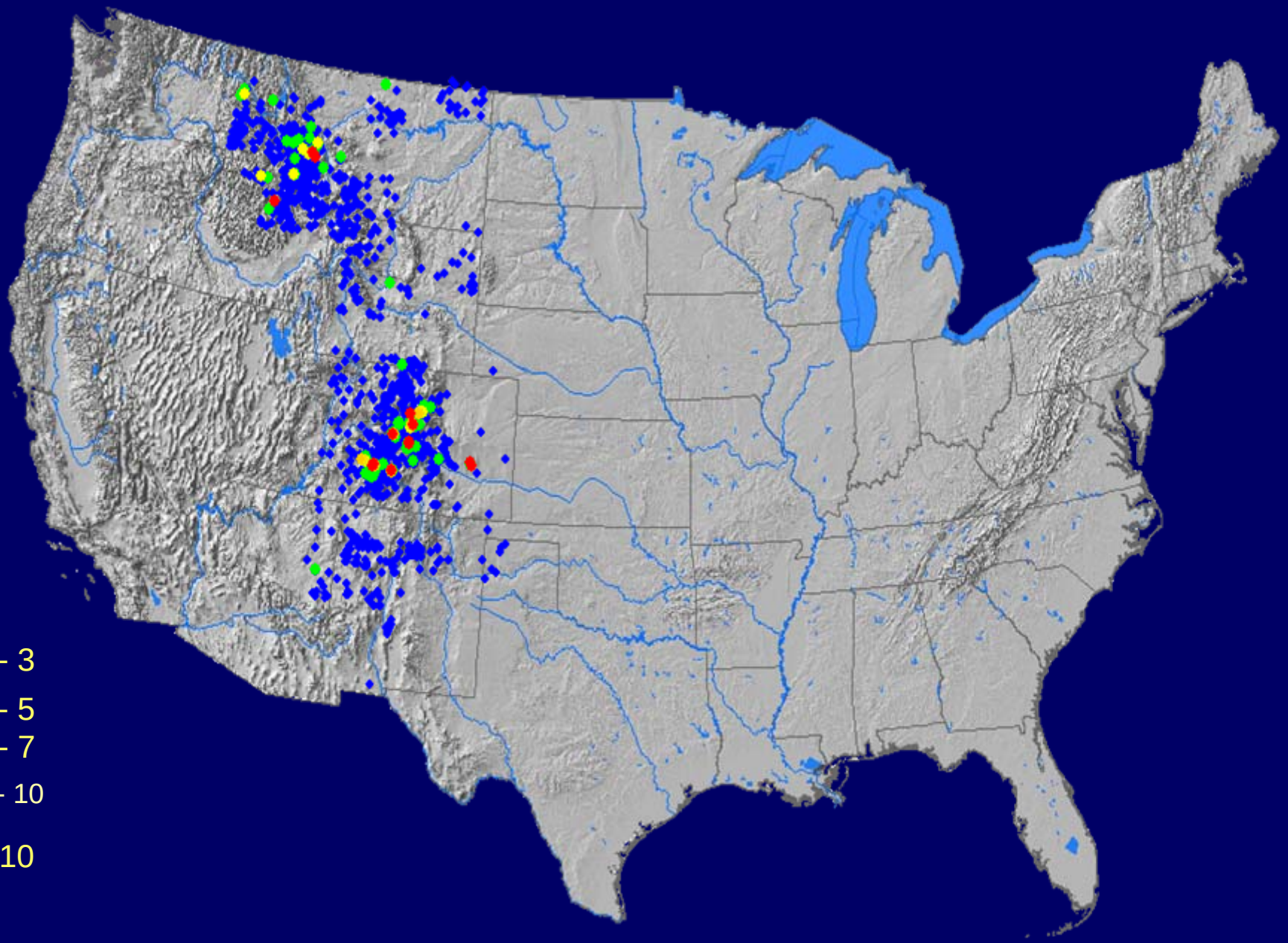
USGS

Hazard quotient Copper – Obs. Conc. / PEC 149 ppm)



USGS

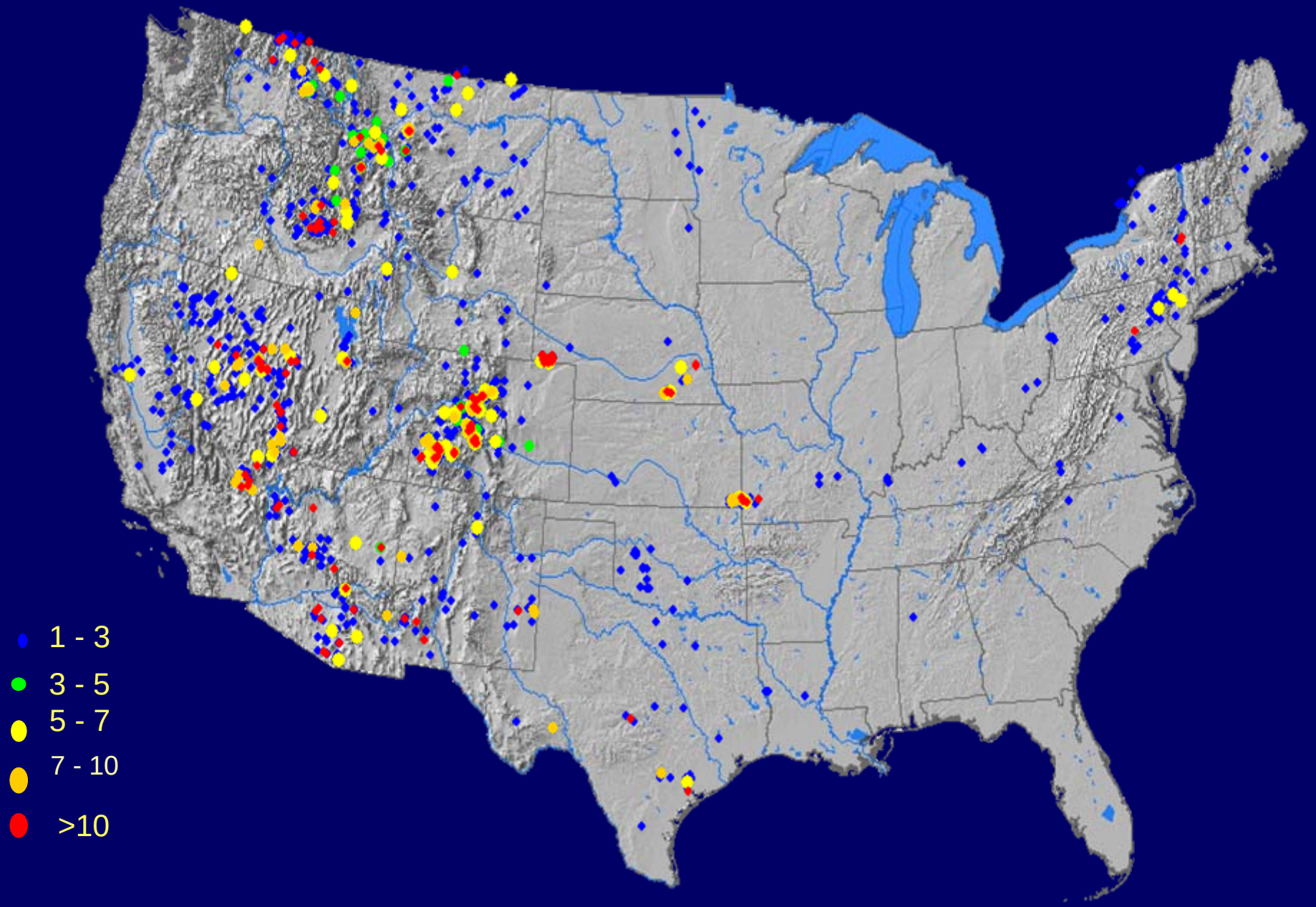
Hazard quotient – Cadmium (Obs. Conc. / PEC 4.98 ppm)



- 1 - 3
- 3 - 5
- 5 - 7
- 7 - 10
- >10

USGS

Hazard quotient – Zinc (Obs. Conc. / PEC 459 ppm)



USGS

USGS Mineral Resources Data - Windows Internet Explorer

http://mrdata.usgs.gov/website/MRData-US/viewer.htm

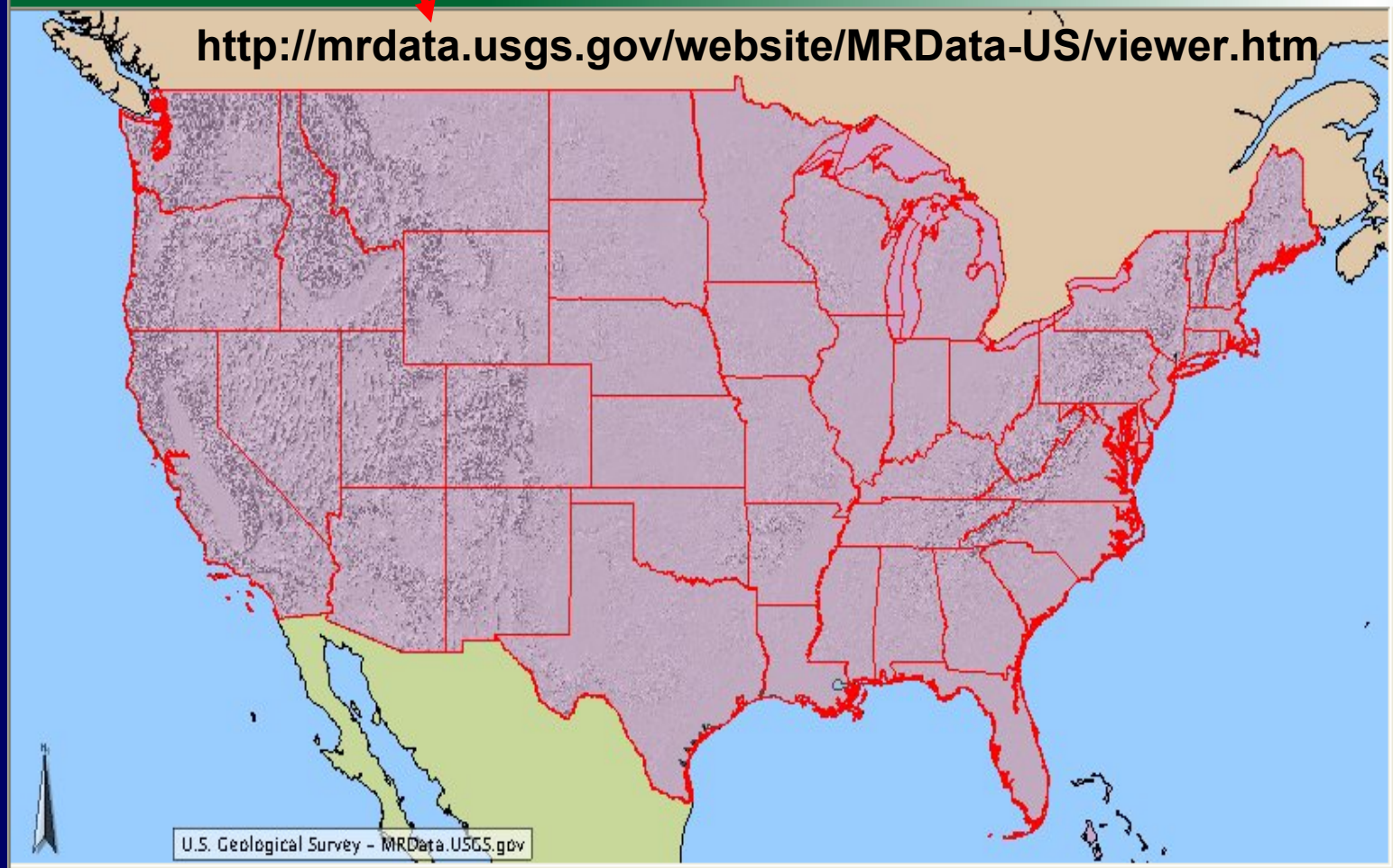
File Edit View Favorites Tools Help

USGS Mineral Resources Data

Page Tools

USGS Mineral Resources Spatial Data

http://mrdata.usgs.gov/website/MRData-US/viewer.htm



Refresh Map

Map Layers

Mineral Resources

Visible Active

- MRDS, producers
- MRDS, all
- Active Mines and Plants
- Mine claim activity 1976-2004

Geochemistry

Visible Active

- US Geochemical Survey
- Igneous Rock, Pluto
- Sediment, Pluto
- Sediment, RASS
- Soil, Pluto
- Soil, RASS
- Soil, Shacklette

Geophysics

Geology

Hydrology

Boundaries

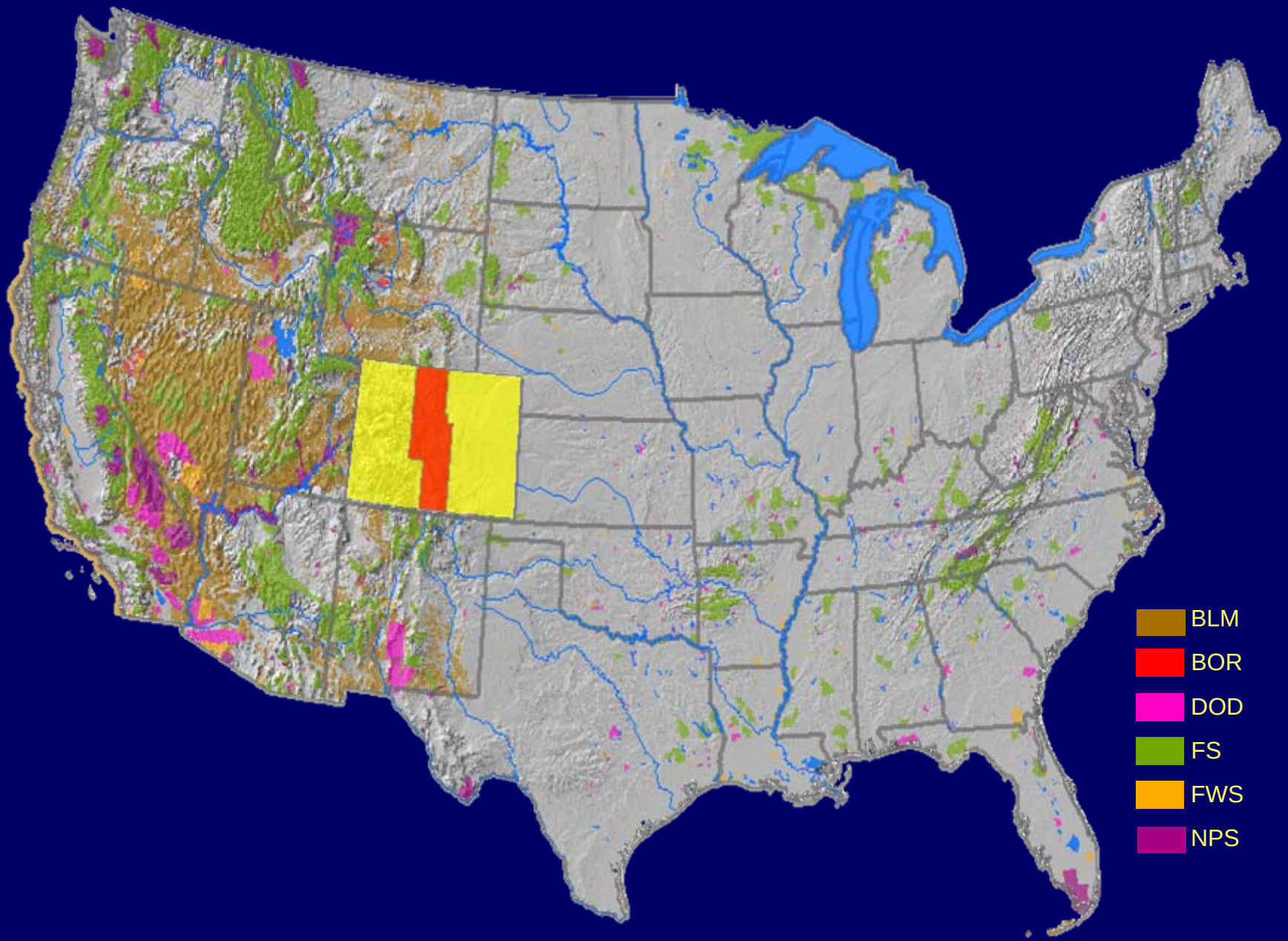
Visible Active

Active Mines and Plants

Rec	Commodity	Name	Owner/Operator	State	County	Latitude	Longitude	Mine or Plant
1	Sand and Gravel	Huber Sand Pit #2	Huber Sand Co.	Kansas	Finney	37.94776	-100.8446	M/P
2	Sand and Gravel	Pit #2	Smith Sand Co., Inc.	Kansas	Finney	37.96383	-100.9057	M/P
3	Sand and Gravel	Site #3 - Holcomb	Klotz Sand Co., Inc.	Kansas	Finney	37.97828	-100.9971	M/P
4	Sand and Gravel	Kendall #1	Klotz Sand Co., Inc.	Kansas	Finney	37.9434	-100.7715	M/P

Done Internet 100%

Central Colorado Assessment Project



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Central Colorado Assessment Project

- Provide an environmental assessment of the central 1/3 of the State of Colorado
- Develop geochemical and biological baseline data
  - Sampled watersheds underlain by single geologic units to provide a geologic signature
  - Sampled watersheds underlain by hydrothermally altered rock
  - Sampled watersheds in which historical mining had occurred

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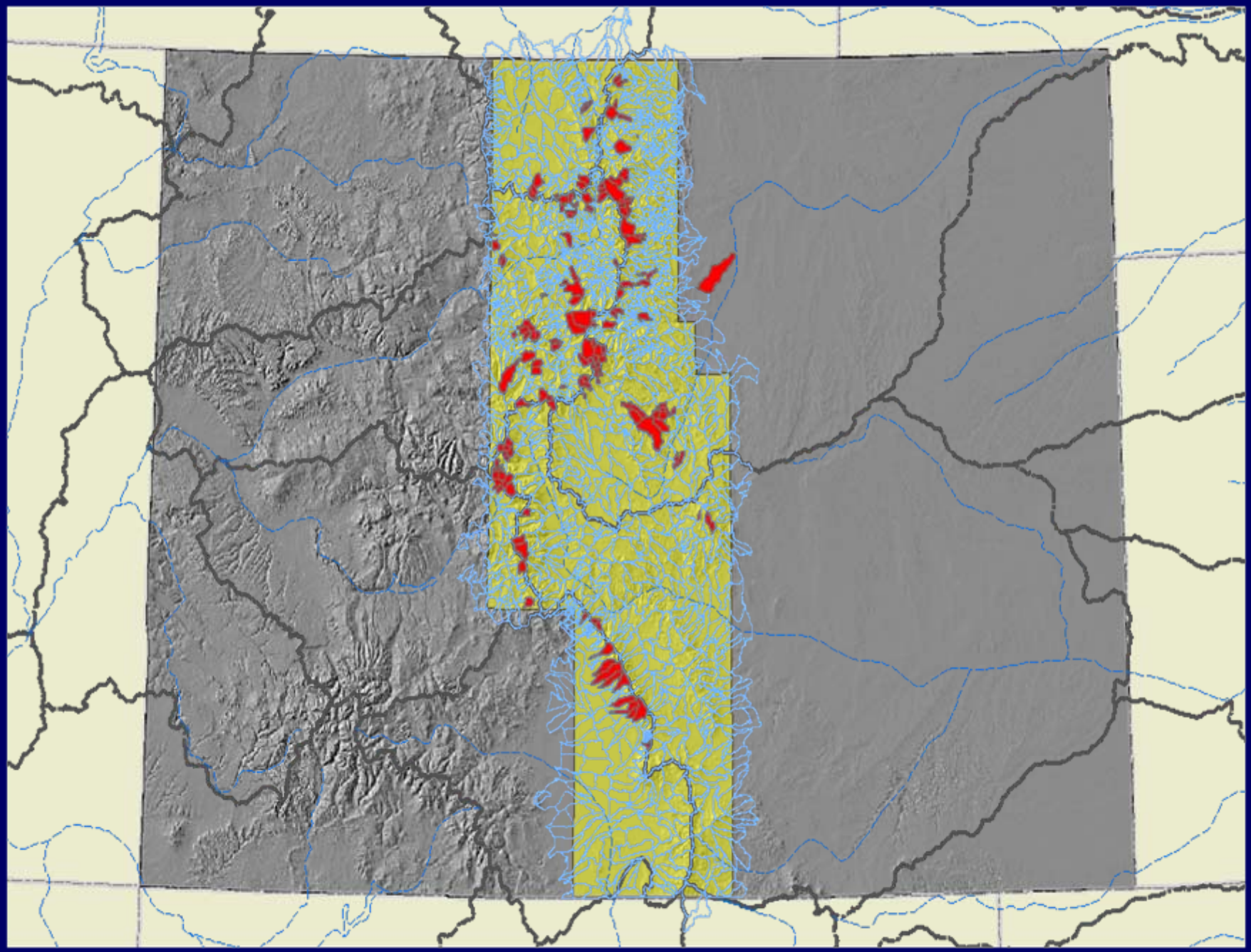
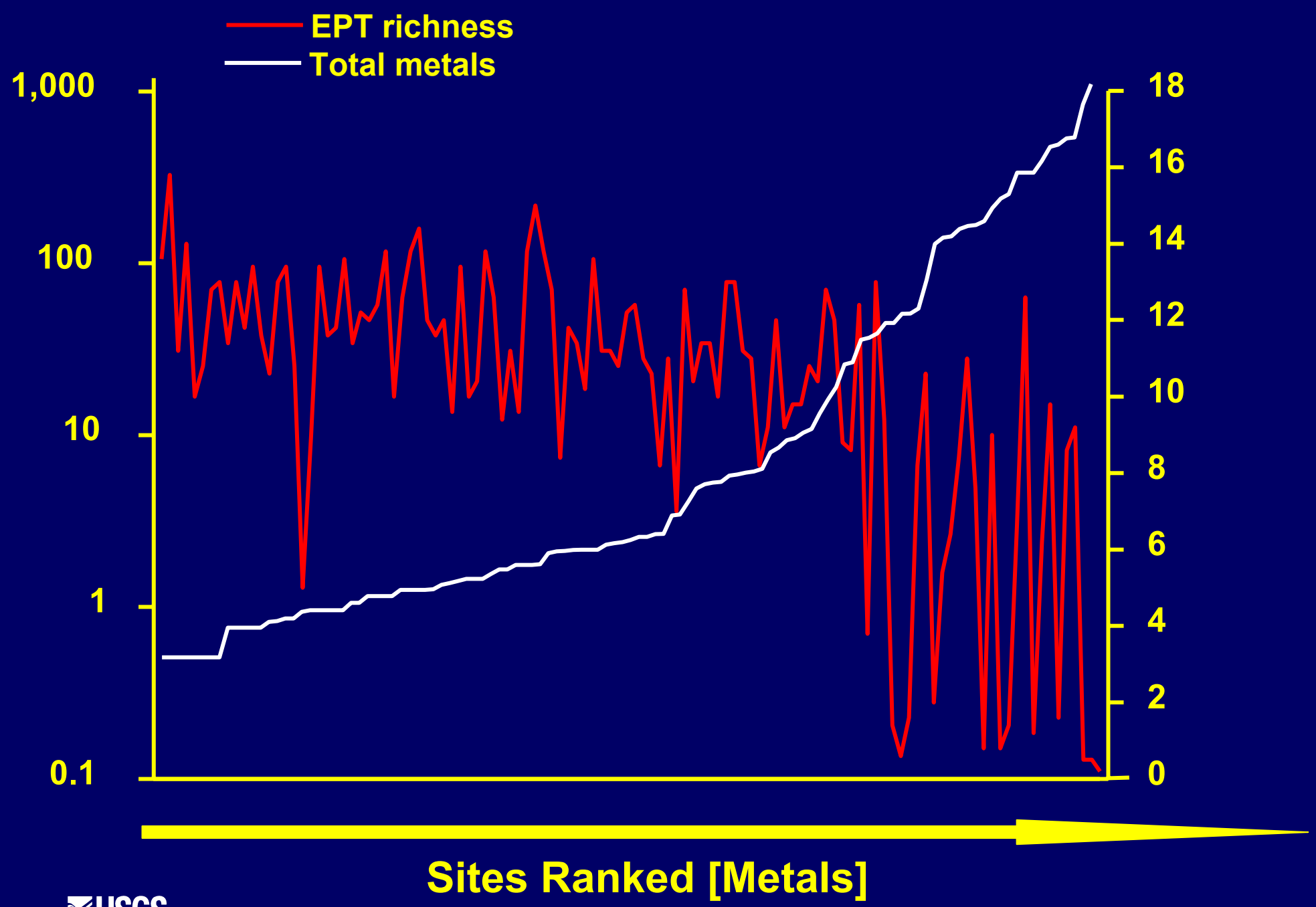
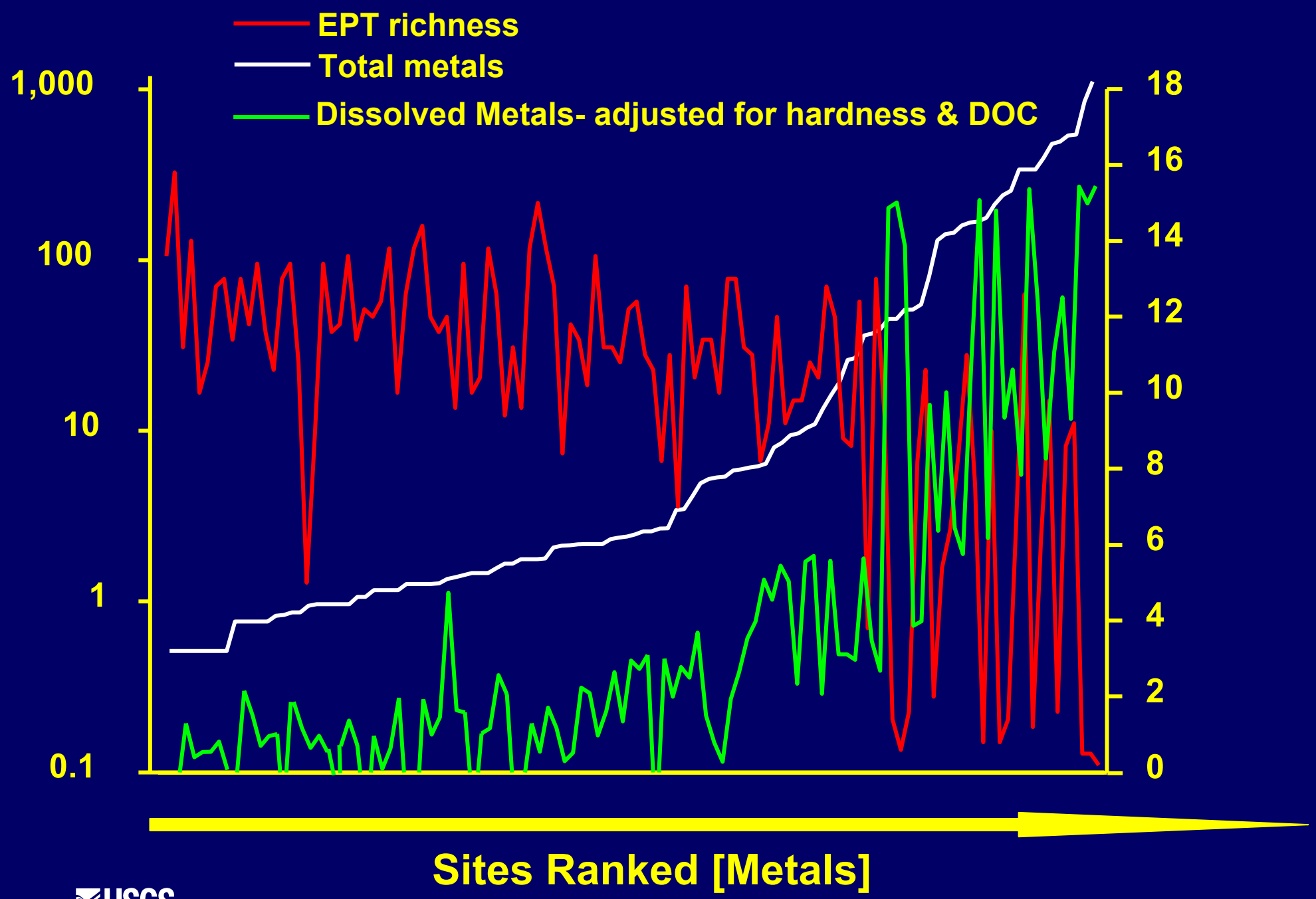


USGS

[Trace Metals]
Diversity and Abundance
Ephemeroptera
dmason@zebu.uorgeon.edu
www.tolweb.org
Plecoptera
www.tolweb.org
Trichoptera
www.tolweb,org


EPT richness
Total metals
1,000
100
10
1
0.1
18
16
14
12
10
8
6
4
2
0
Sites Ranked [Metals]

USGS


EPT richness
Total metals
Dissolved Metals- adjusted for hardness & DOC
1,000
100
10
1
0.1
18
16
14
12
10
8
6
4
2
0
Sites Ranked [Metals]

USGS

Chronic Criterion Accumulation Ratio (CCAR)

$$\sum \frac{\text{Site-specific [gill-metal]}}{\text{US EPA standard water [gill-metal] @ CCC}}$$

- New model derived from Toxic Unit Model
  - BLM derived

    (Sprague, 1970; Playle, 2004)

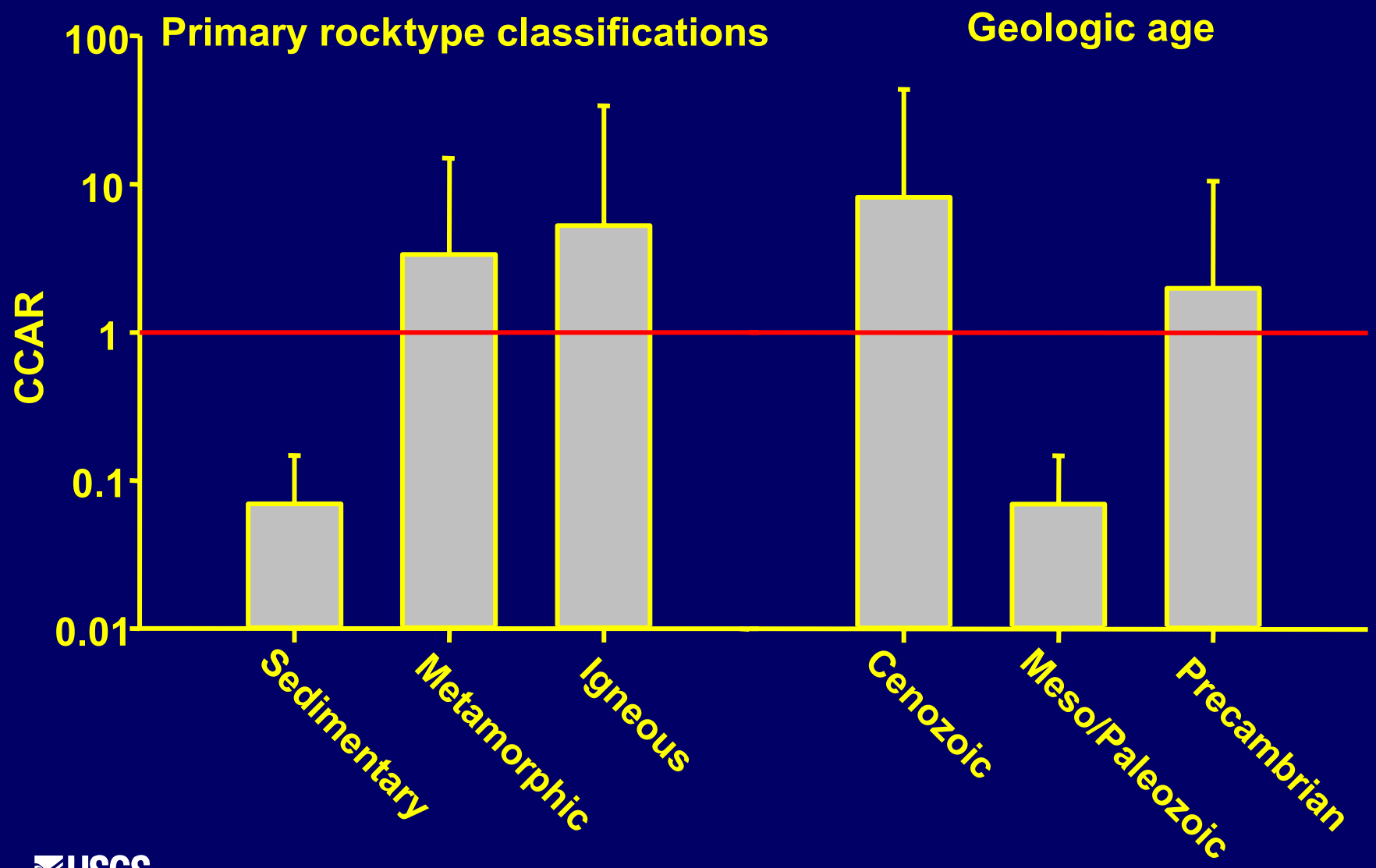
USGS

Development of biological baselines

- Develop a model of bioavailability
  - Determine that lithologic classes can differentiate bioavailability
  - Validate that model can predict indigenous taxa responses
    - Also develop bio-indicator species for assessment purposes
    - Infer adverse effect concentrations

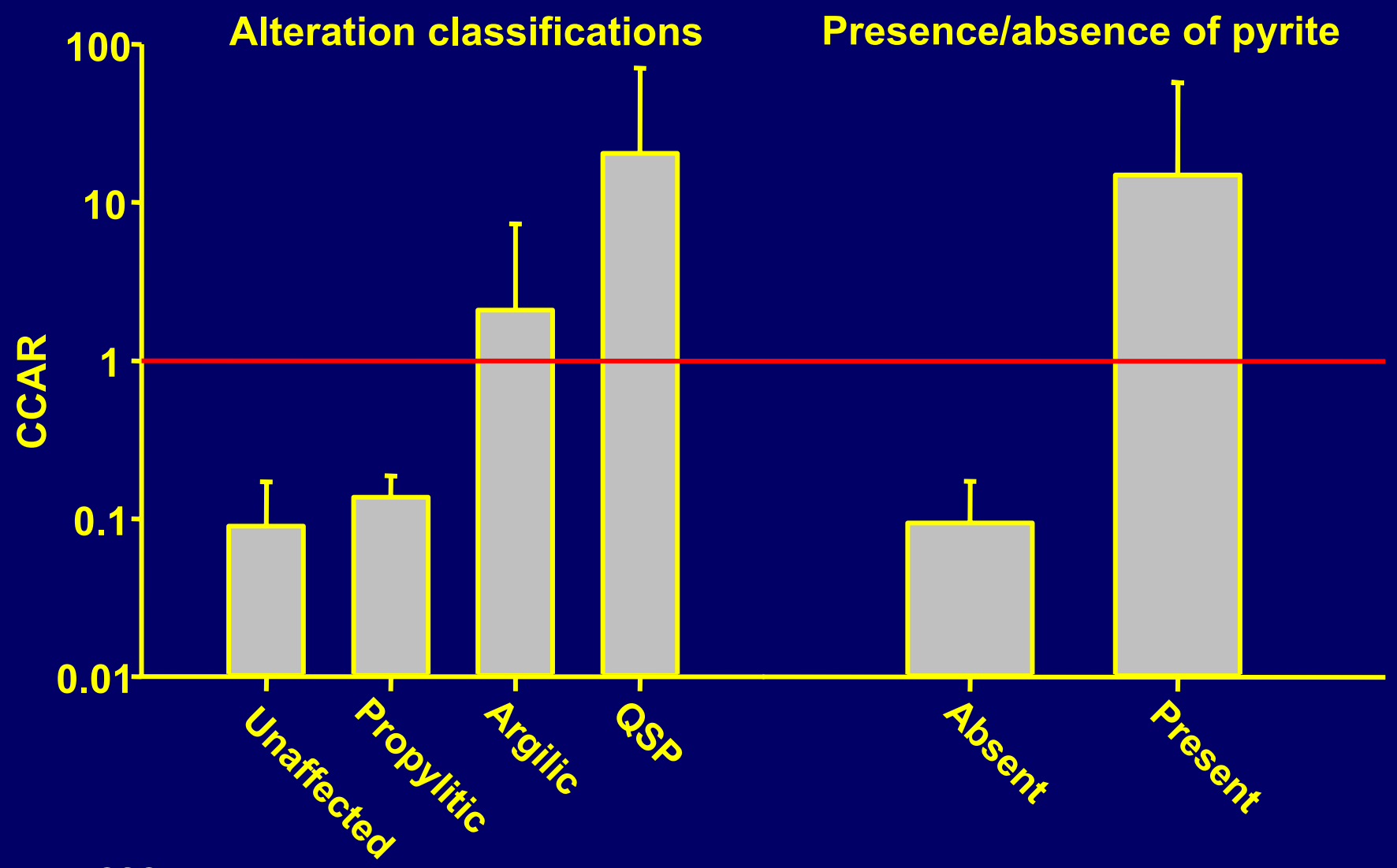
USGS

Can lithologic classes differentiate bioavailability?

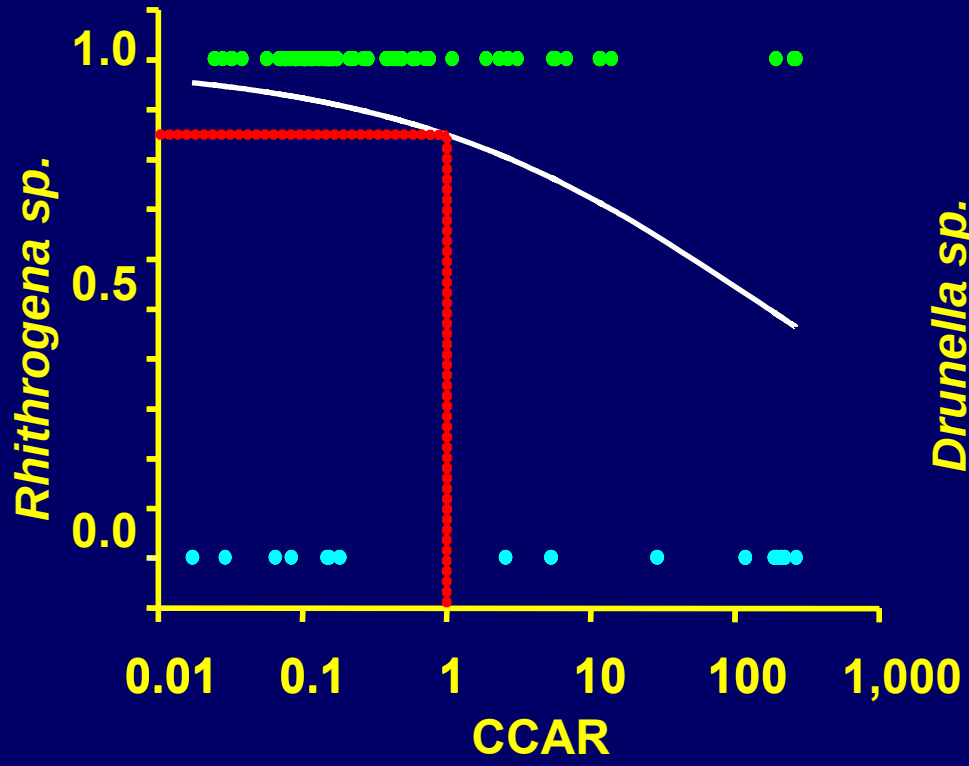


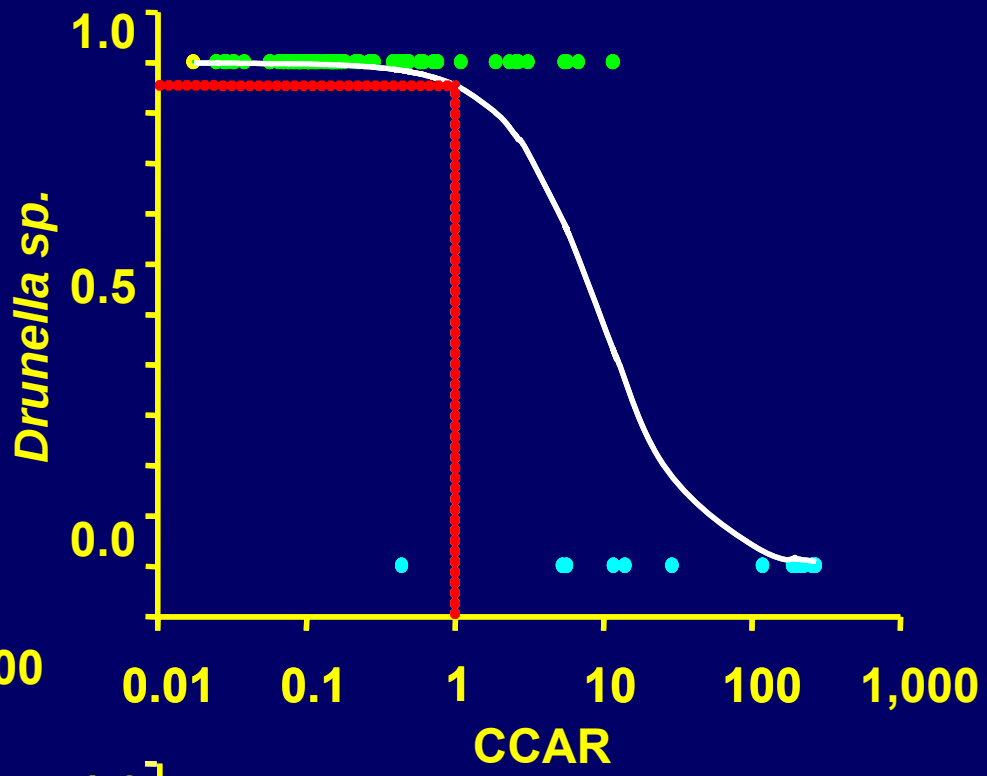
USGS

Can hydrothermal alteration differentiate bioavailability?

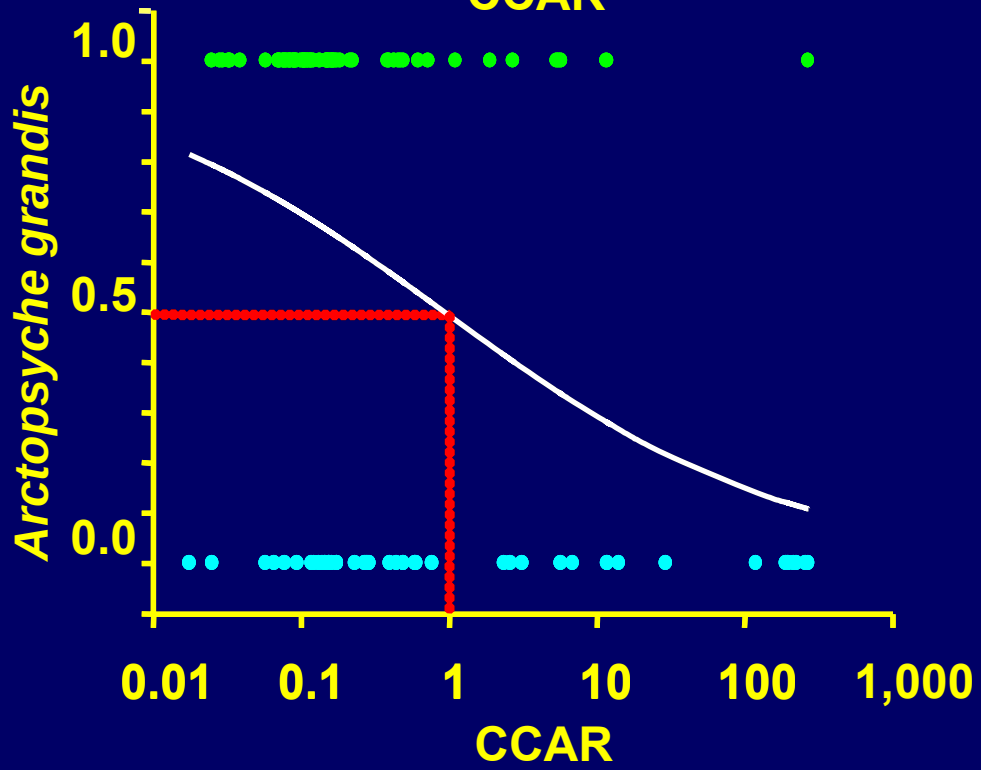


USGS

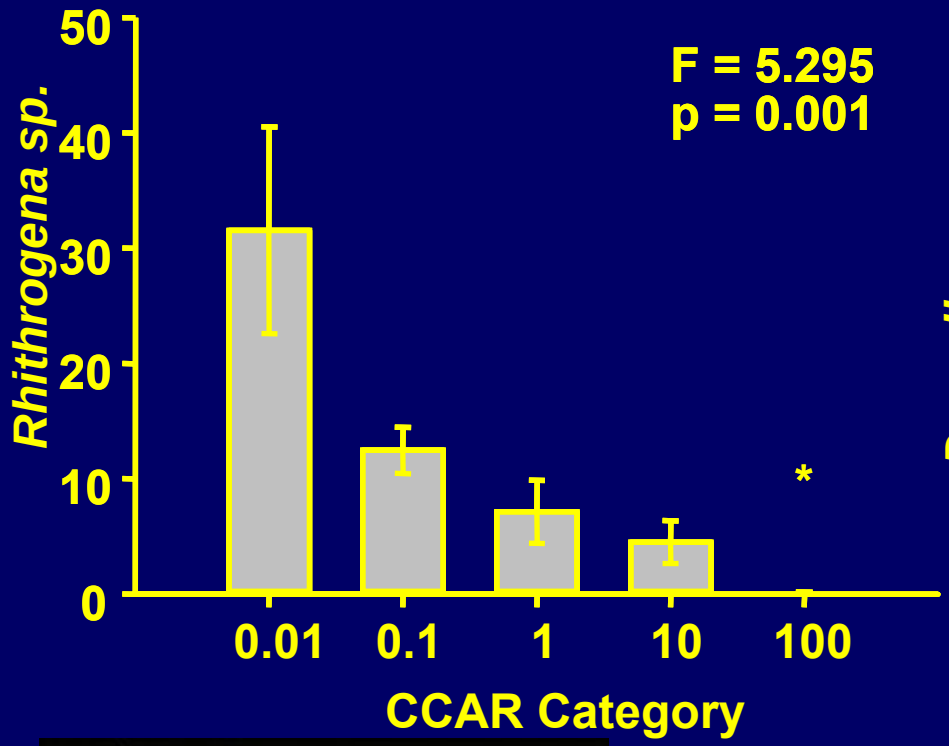

Rhithrogena sp.
1.0
0.5
0.0
0.01
0.1
1
10
100
1,000
CCAR

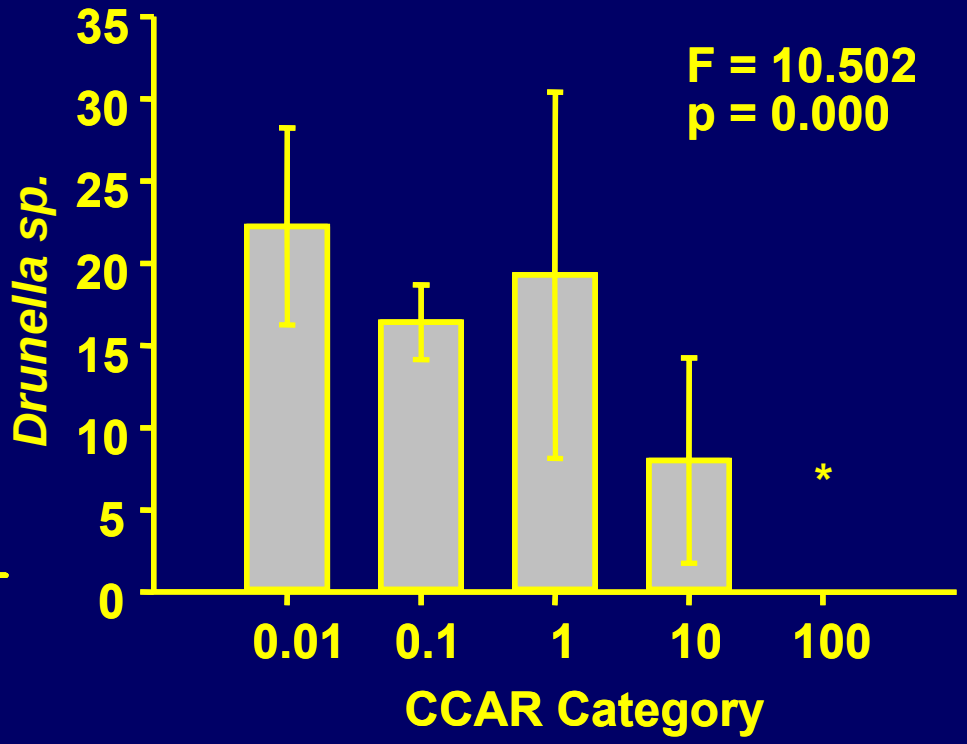

Drunella sp.
1.0
0.5
0.0
0.01
0.1
1
10
100
1,000
CCAR

FI-102
© 2002 Jeremy Monroe
Retreat-building caddisfly larva
Arctopsyche grandis (Trichoptera: Hydropsychidae)
Colorado River, Grand Co., Colorado, USA
photo by Jeremy Monroe
jeremy@freshwatersillustrated.org
Archive: FI-102 www.freshwatersillustrated.org

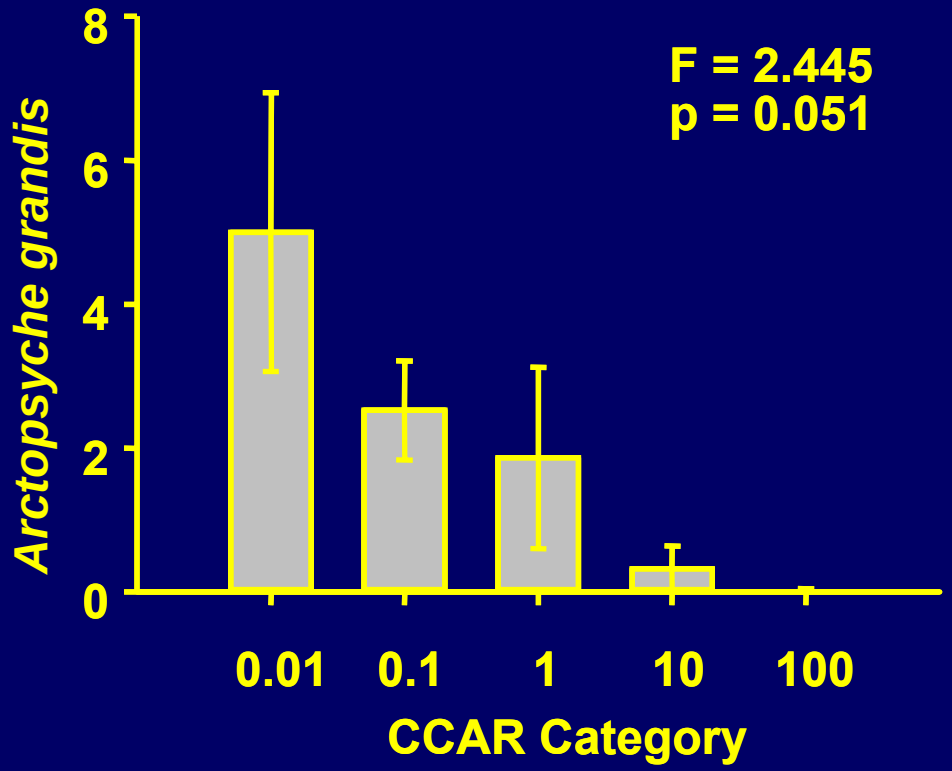

Arctopsyche grandis
1.0
0.5
0.0
0.01
0.1
1
10
100
1,000
CCAR

USGS

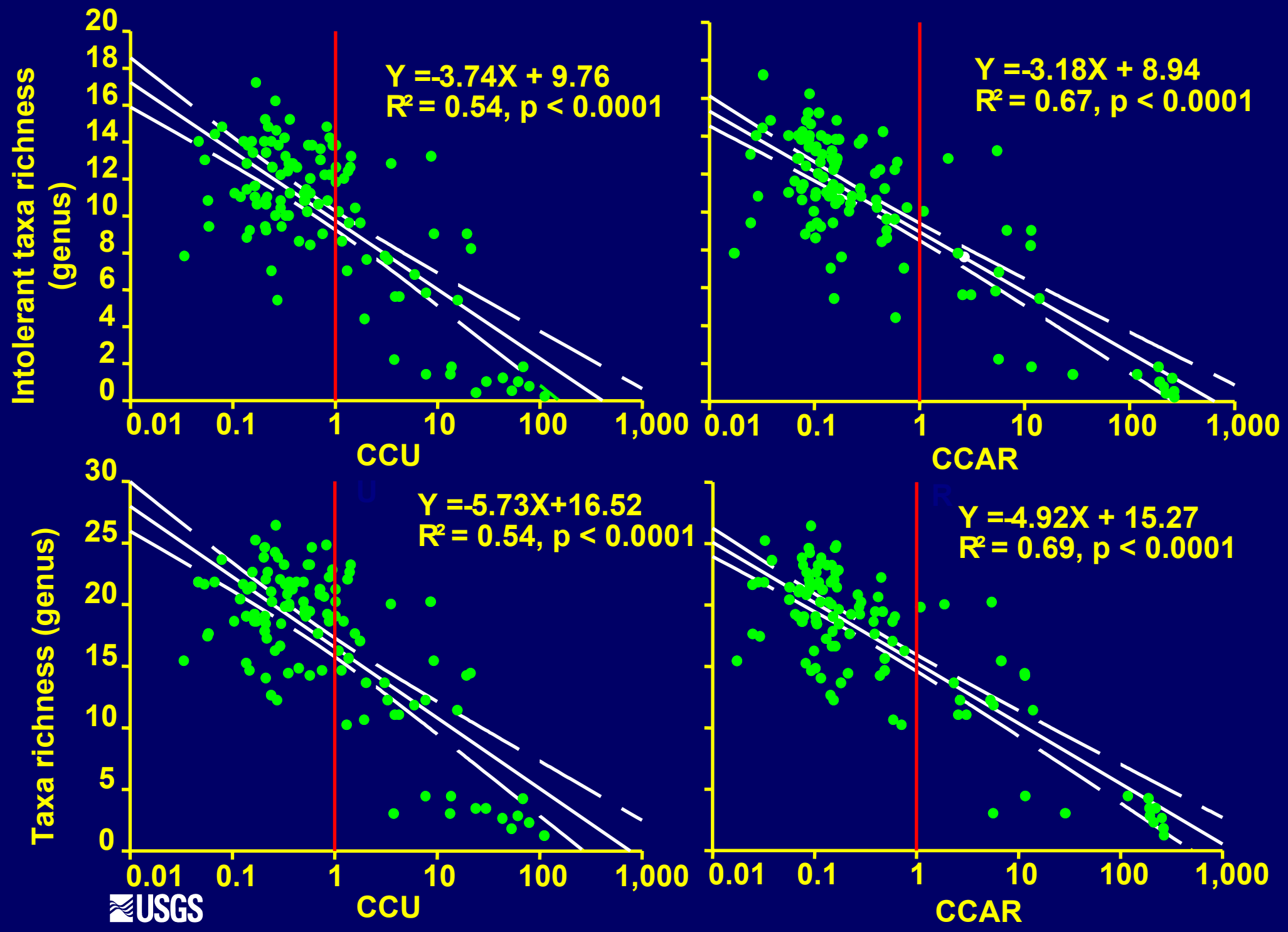

Rhithrogena sp.
F = 5.295
p = 0.001
50
40
30
20
10
0
*
0.01
0.1
1
10
100
CCAR Category


Drunella sp.
F = 10.502
p = 0.000
35
30
25
20
15
10
5
0
*
0.01
0.1
1
10
100
CCAR Category

FI-102
© 2002 Jeremy Monroe
Retreat-building caddisfly larva
Arctopsyche grandis (Trichoptera: Hydropsychidae)
Colorado River, Grand Co., Colorado, USA
photo by Jeremy Monroe
jeremy@freshwatersillustrated.org
Archive: FI-102 www.freshwatersillustrated.org

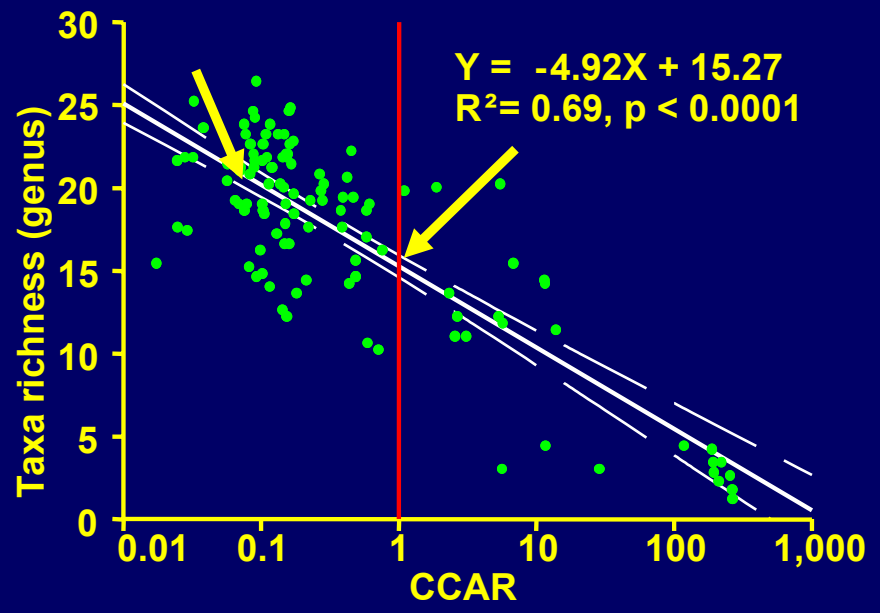

Arctopsyche grandis
F = 2.445
p = 0.051
8
6
4
2
0
0.01
0.1
1
10
100
CCAR Category

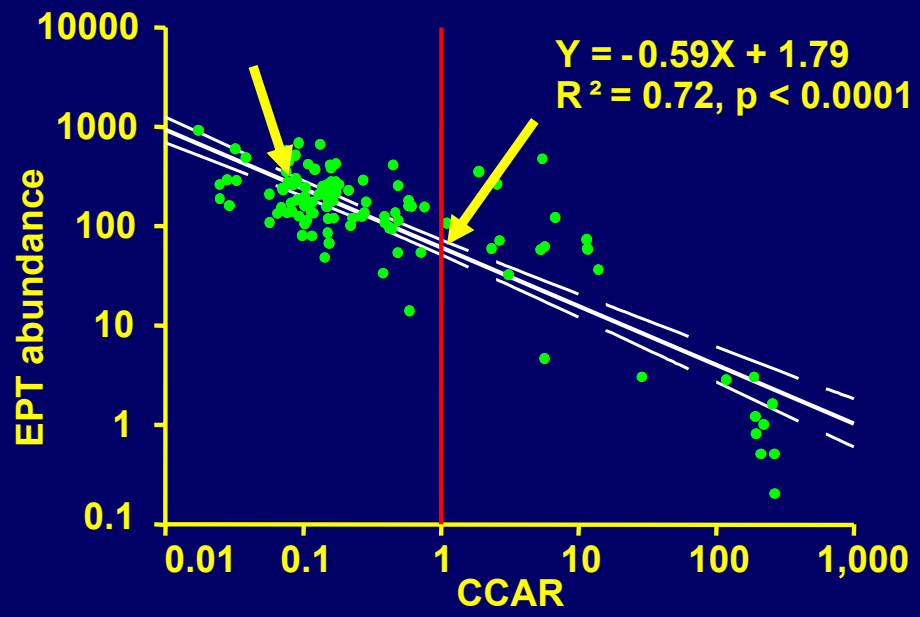
USGS


Intolerant taxa richness (genus)
Y =-3.74X + 9.76
R² = 0.54, p < 0.0001
CCU
Y =-3.18X + 8.94
R² = 0.67, p < 0.0001
CCAR
Taxa richness (genus)
Y =-5.73X+16.52
R² = 0.54, p < 0.0001
CCU
Y =-4.92X + 15.27
R² = 0.69, p < 0.0001
CCAR
USGS

Are water-quality criteria protective?

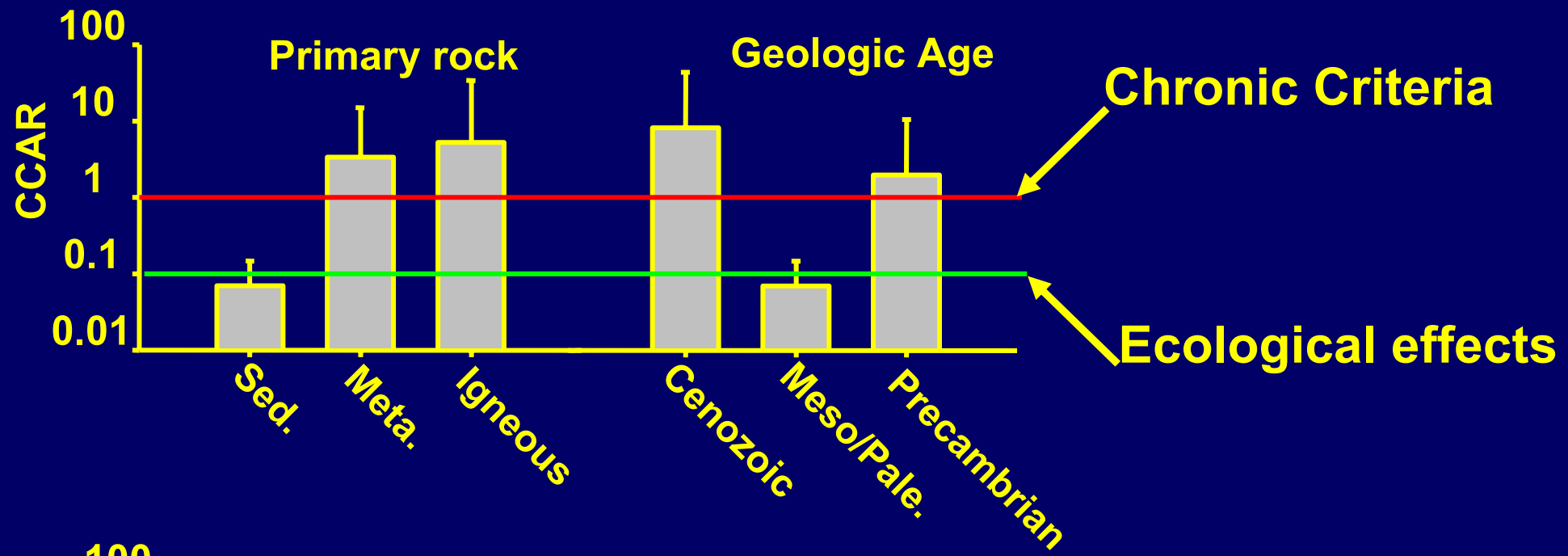
- Water Quality Criteria
  - Protect 95% of all taxa
  - Genus-level mean responses
- 30% loss in richness
- 70% loss in abundance

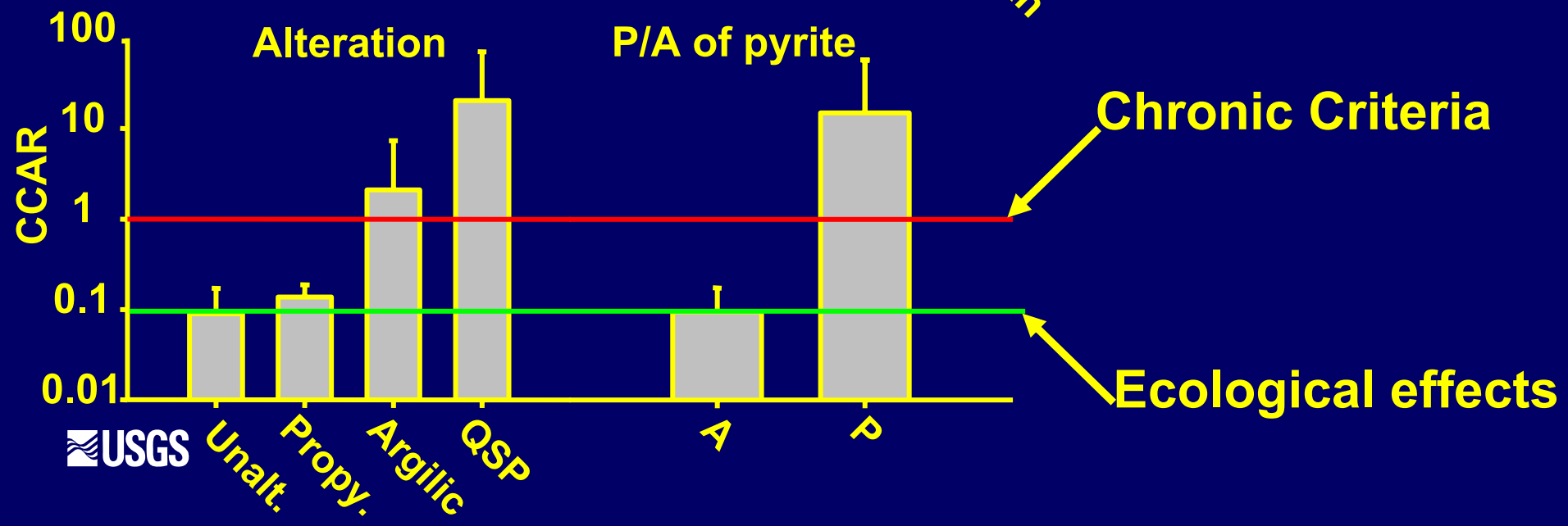




USGS

Appropriate conservative benchmarks are not applicable for all lithologies





USGS

Summary

- Lithology and hydrothermal alteration control bioavailability of metals
- Not all BMI endpoints are appropriate
- CCAR is more descriptive than CCU
- Are Water Quality Criteria protective endpoint?
- Are remedial actions based on conservative benchmark concentrations appropriate?

USGS

Colloidal Fe in the stream

USGS