Pre-Mining Characterization and Prediction

Bob Seal
US Geological Survey
Reston, Virginia, USA
rseal@usgs.gov

September 14, 2011

USGS
science for a changing world

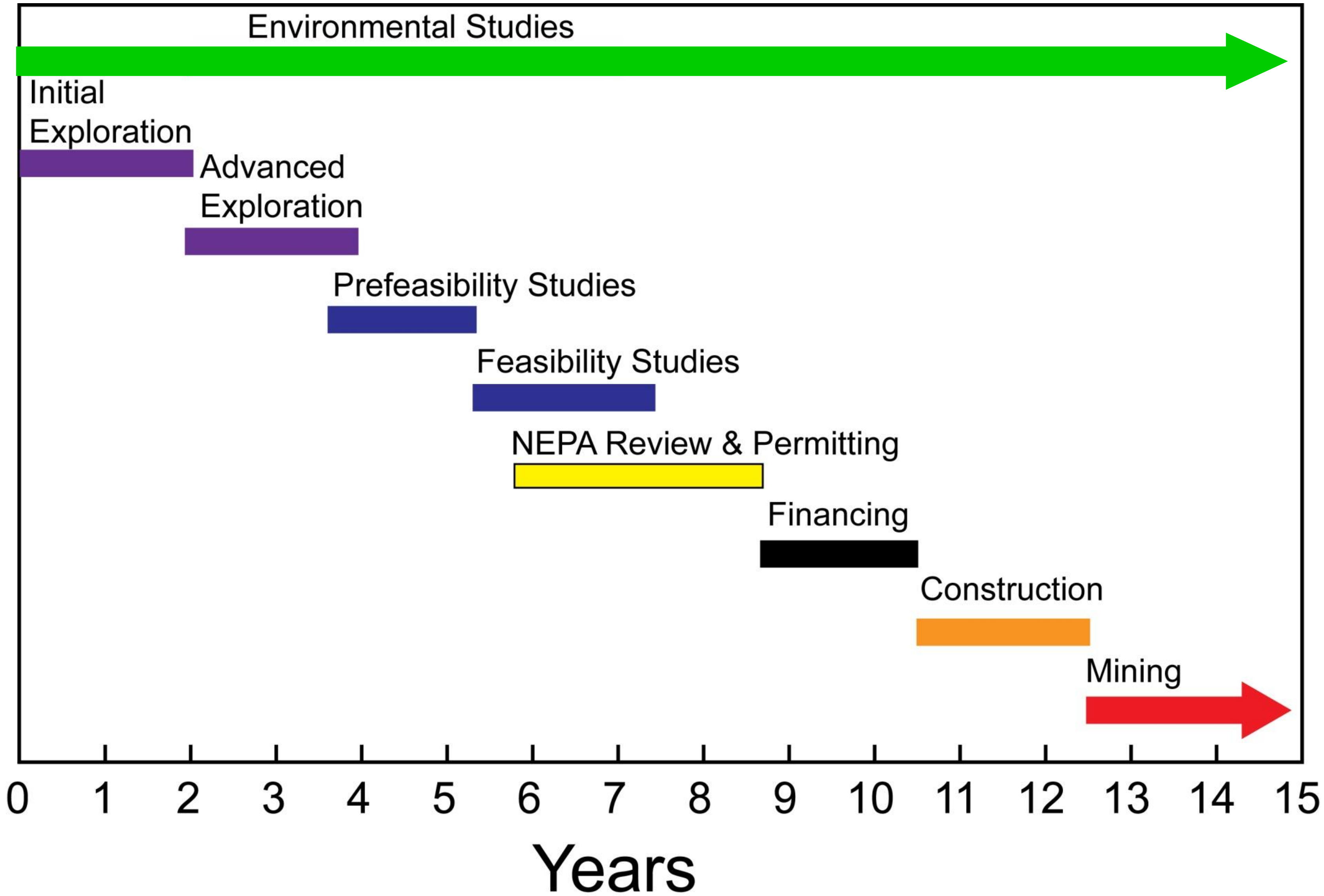
Environmental Geochemistry & Mining

How does it fit in?

What is important?

What do you look for?

"Typical" Time Frame for Mine Project Start Up



Modified from USEPA (2011)
http://www.epa.gov/region10/pdf/bristolbay/mining_session_presentation_part1.pdf

Two Main Goals of Environmental Geochemistry

- Characterization of baseline (pre-mining) conditions
  - Establishes monitoring sites.
  - Forms basis of environmental goals for closure.
  - Provides crucial information for design.
- Prediction of behavior of mine wastes
  - Needed to design mitigation and remediation during production and for closure.

Importance of Geochemical Baseline Characterization

- Ore deposits are geochemical anomalies that express themselves in all media:
  - Surface water, groundwater, sediment, soil, biota
- Natural pre-mining geochemical conditions commonly exceed various environmental criteria for surface and ground water, soils, and sediments.
- Difficult to determine pre-mining conditions once mining has started.
- Needs geology as a guide.
- Needs to be done in an up to date regulatory context.
- Provides useful insights for mine planning.
  - Water mass balance.
  - Ground-water chemistry that may need to be pumped during mining.

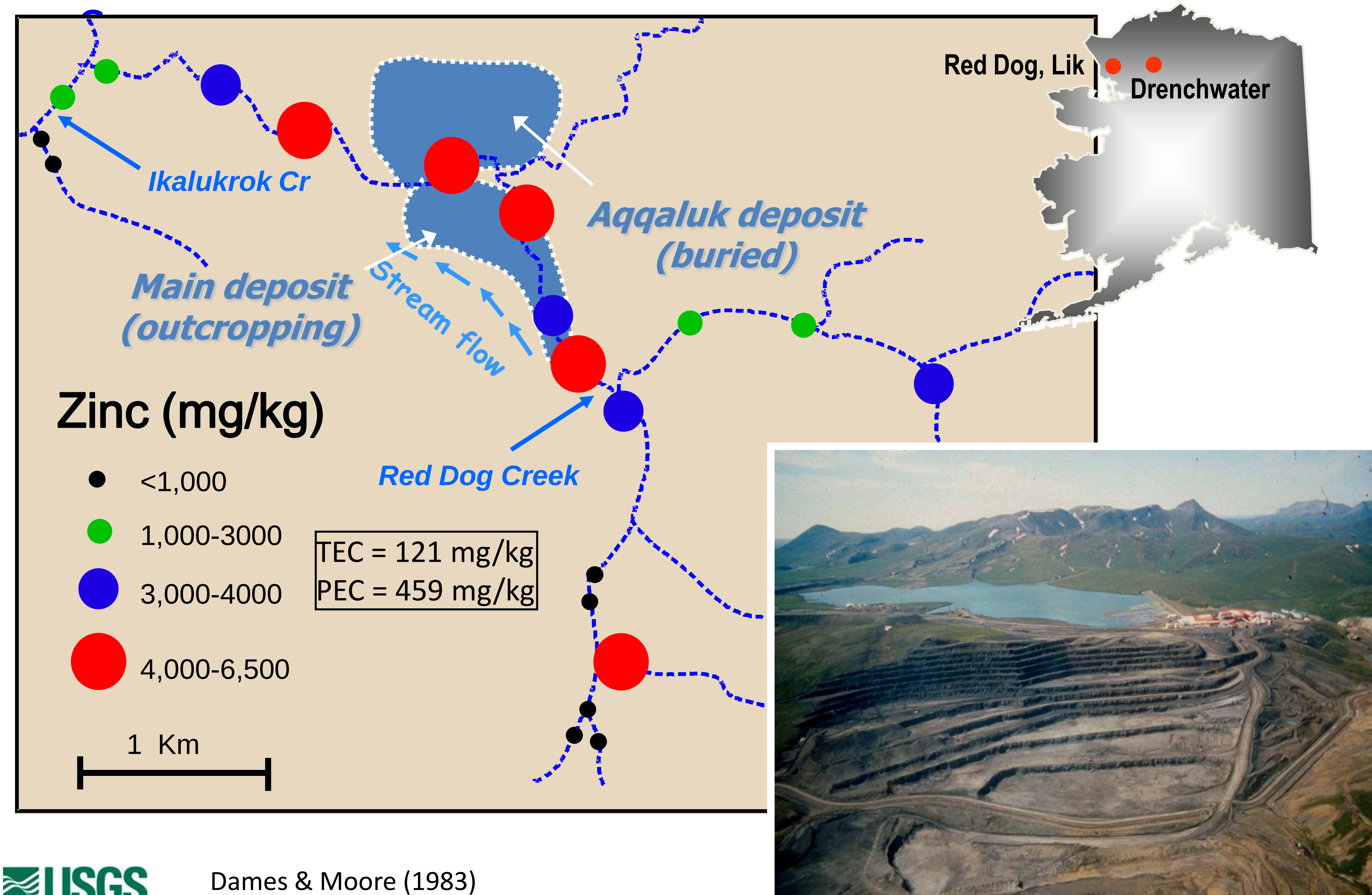
USGS
science for a changing world

Minor & Trace Elements in Average Rocks

Element	Ultramafic Rocks	Basalt	High-Ca Granite	Low-Ca Granite	Shale	Sandstone	Carbonate Rocks	Residential Soil	Sediment TEC
Al wt %	1.2	**8.28**	**8.2**	7.2	**8**	2.5	0.42	**7.7**	
Cr mg/kg	**1,800**	**185**	22	4.1	**90**	35	11		**43.4**
Mn mg/kg	1,560	1,750	540	390	850		1100	**1,800**	
Fe wt %	**9.64**	**8.6**	2.96	1.42	4.72	0.98	0.33	**5.5**	
Co mg/kg	**175**	**47**	7	1	19	0.3	0.1	**23**	
Ni mg/kg	**2,000**	**145**	15	4.5	**68**	2	20	**1,500**	**22.7**
Cu mg/kg	15	**94**	30	10	**45**		4	**3,100**	**31.6**
Zn mg/kg	40	118	60	39	95	16	20	**23,000**	**121**
As mg/kg	0.8	2.2	1.9	1.5	13	1	1	**22**	**9.79**
Se mg/kg	0.05	0.05	0.05	0.05	0.6	0.05	0.08	**390**	
Cd mg/kg	0.05	0.21	0.13	0.13	0.3		0.035	**70**	**0.99**
Hg mg/kg	0.01	0.09	0.08	0.08	0.4	0.03	0.04	**5.6**	**0.18**
Pb mg/kg	0.5	7	15	19	20	7	9	**400**	**35.8**
U mg/kg	0.002	0.75	3	3	3.7	0.45	2.2	**230**	

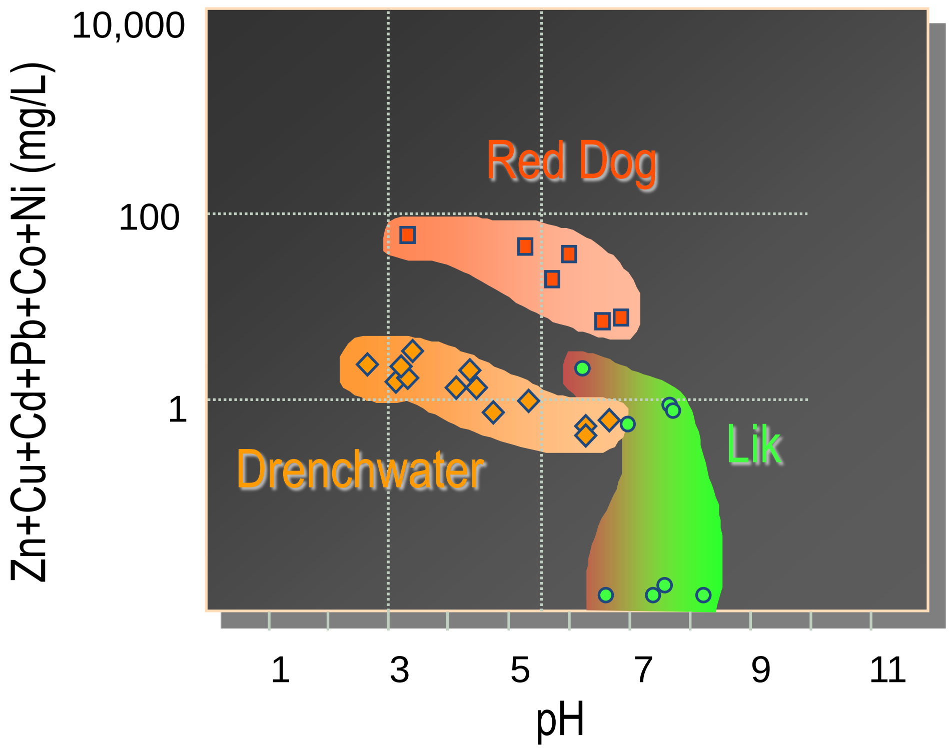
USGS science for a changing world

Red Dog, Alaska, Pre-Mining Stream Sediment



Dames & Moore (1983)

Why pre-mining baseline characterization is important: Red Dog, Alaska

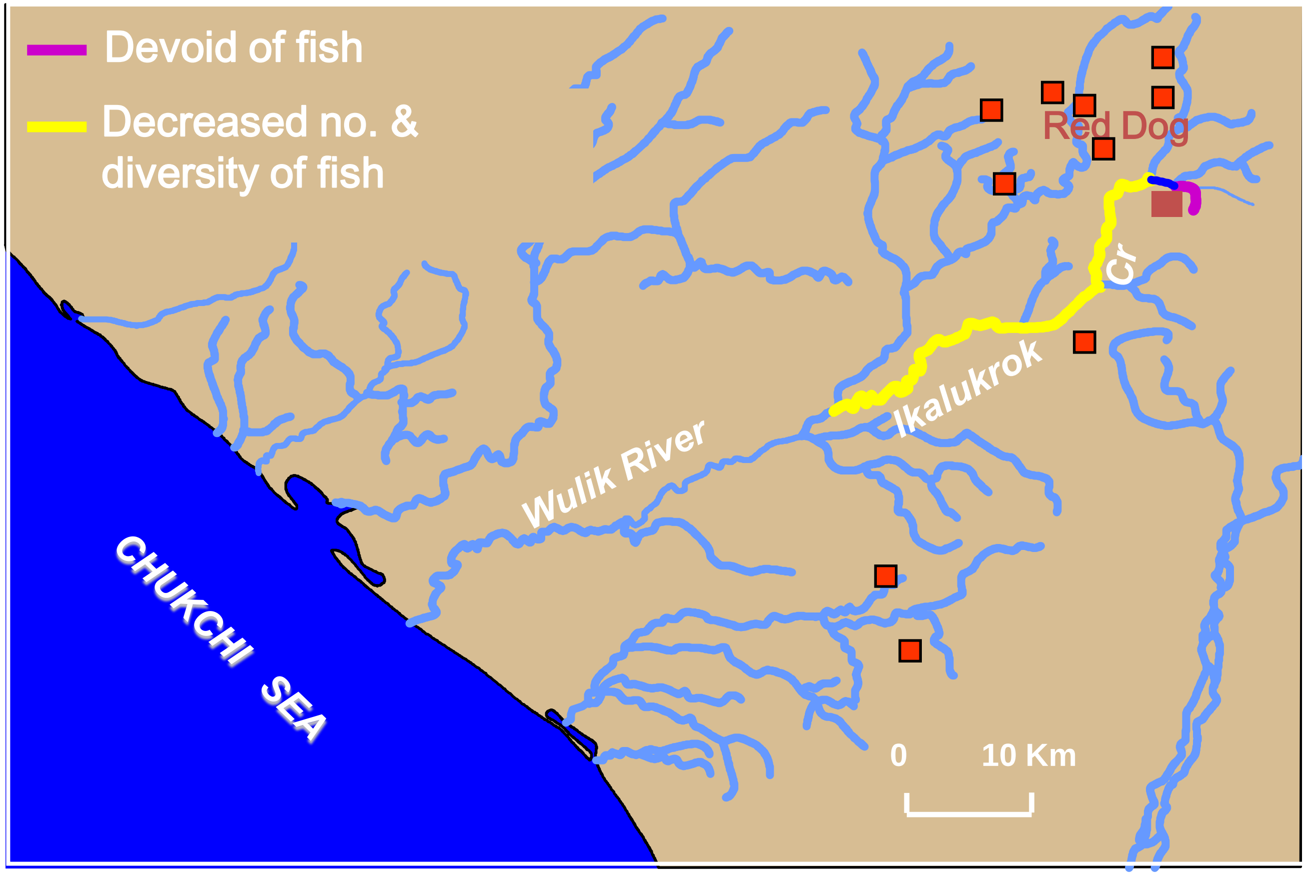


- Sedimentary-Exhalative massive sulfide deposit (Zn, Pb, Ag)
- Exposed at surface prior to mining

USGS science for a changing world

Dames & Moore (1983); Kelley & Taylor (1997)

Pre-Mining Ecology & Water Chemistry



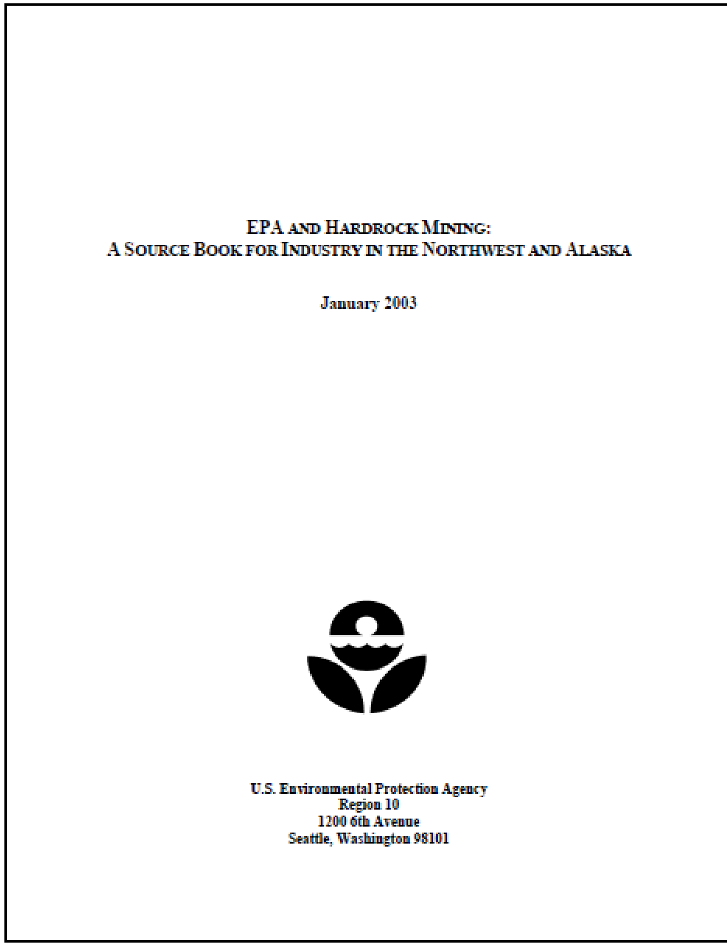
- Water pH of 2.5-2.8
- High dissolved concentrations of Zn, Cd, Pb, As, Fe, and SO_4

USGS science for a changing world

Dames & Moore (1983); Kelley & Taylor (1997)

Expectations for Mining Impact Assessment (Section 6)

- Impacts to surface and ground water hydrology
  - Surface water hydrology
  - Ground water hydrology
- Impacts to water quality
  - Background and existing water quality
  - Regional hydrology and hydrogeology
  - Hydrology of mines and waste facilities
  - Solid wastes and materials characterization and management
  - Waste water quality and management
  - Post-closure mine and waste facility water quality
  - Closure and reclamation effects
- Impacts to aquatic resources
- Impacts to wetlands


EPA AND HARDROCK MINING:
A SOURCE BOOK FOR INDUSTRY IN THE NORTHWEST AND ALASKA

January 2003

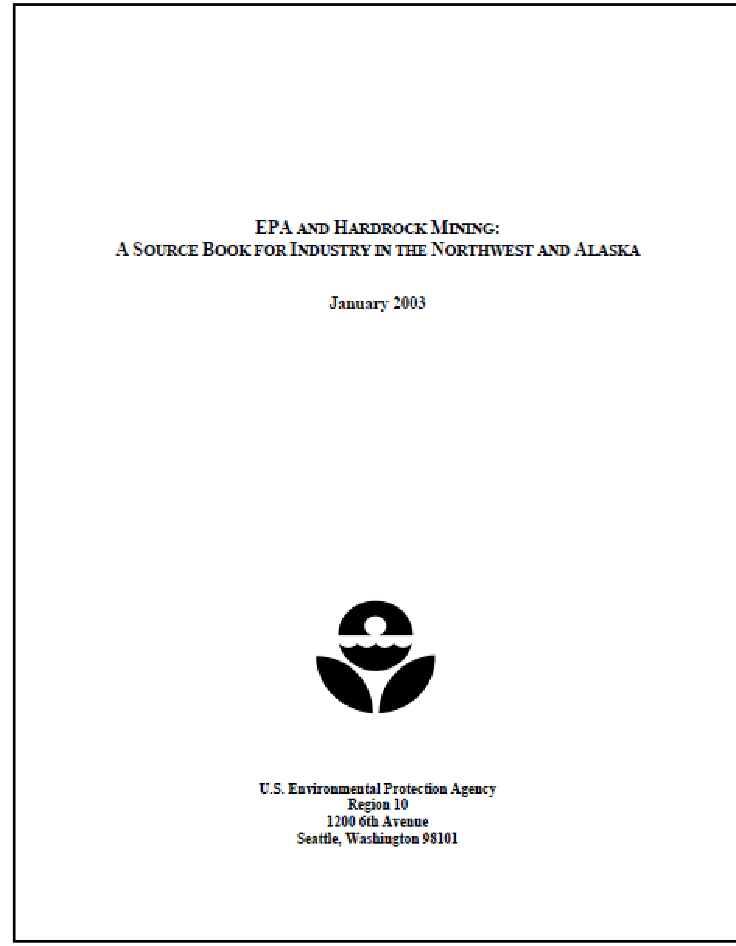
U.S. Environmental Protection Agency
Region 10
1200 6th Avenue
Seattle, Washington 98101

USGS science for a changing world

http://yosemite.epa.gov/R10/WATER.NSF/Sole+Source+Aquifers/hardrockmining

Additional Information (Appendices)

- Hydrology
- Receiving Waters
- Characterization of Ore, Waste Rock and Tailings
- Effluent Quality
- Wastewater Management
- Solid Waste Management
- Aquatic Resources
- Erosion and Sedimentation
- Wetlands



EPA AND HARDROCK MINING:
A SOURCE BOOK FOR INDUSTRY IN THE NORTHWEST AND ALASKA

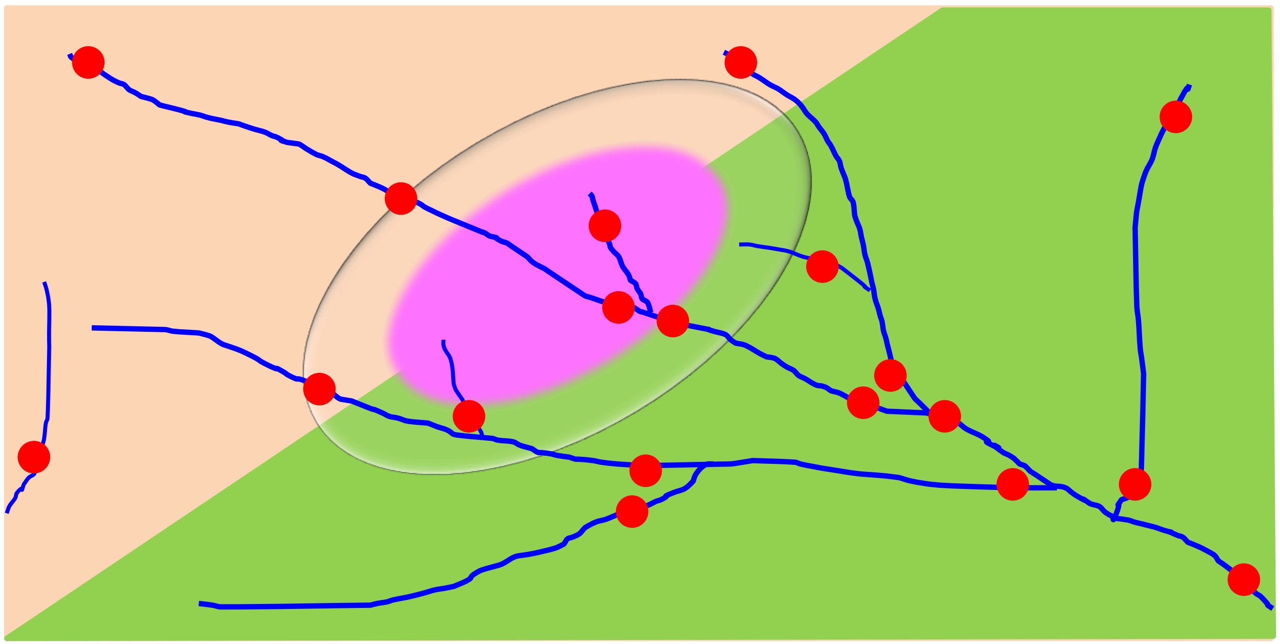
January 2003

U.S. Environmental Protection Agency
Region 10
1200 6th Avenue
Seattle, Washington 98101

http://yosemite.epa.gov/R10/WATER.NSF/Sole+Source+Aquifers/hardrockmining

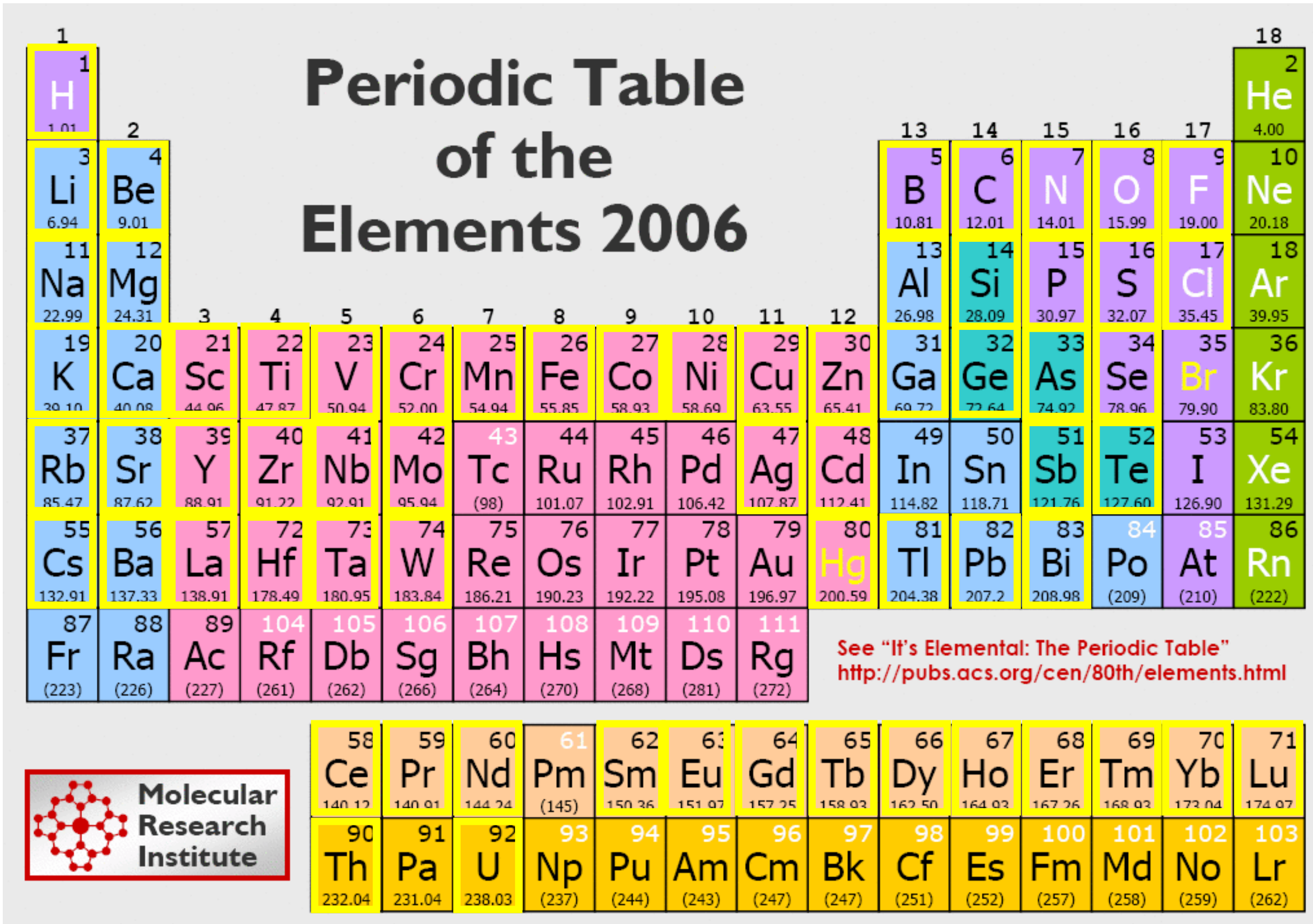
Goals of Baseline Characterization

- Establish sites to monitor environmental performance during mining – away from footprint of the mine.
- Establish closure goals for after mining – within footprint of the mine.



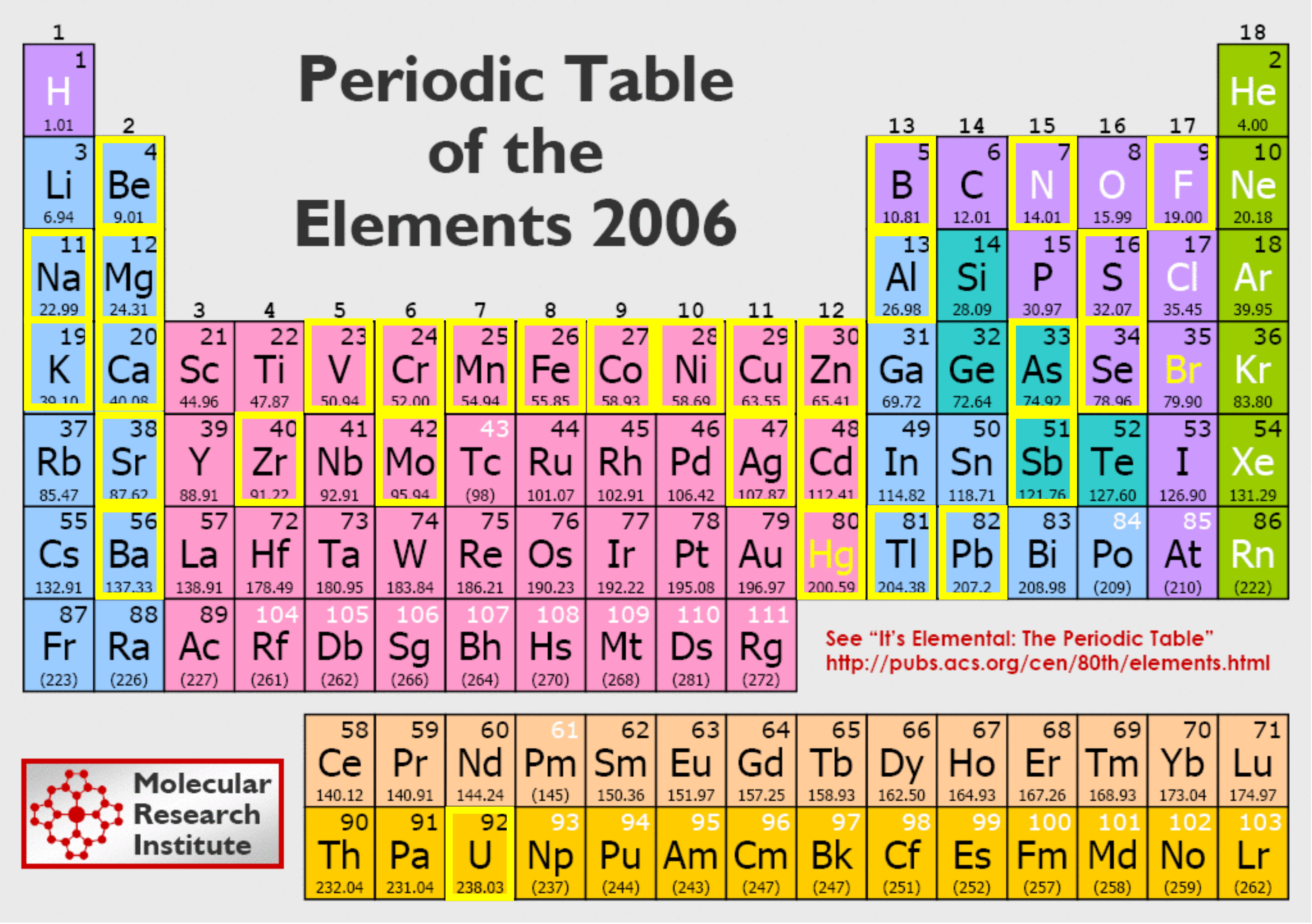
- Design of baseline characterization needs to include geologic and hydrologic context.

Routine Analytical Accessibility



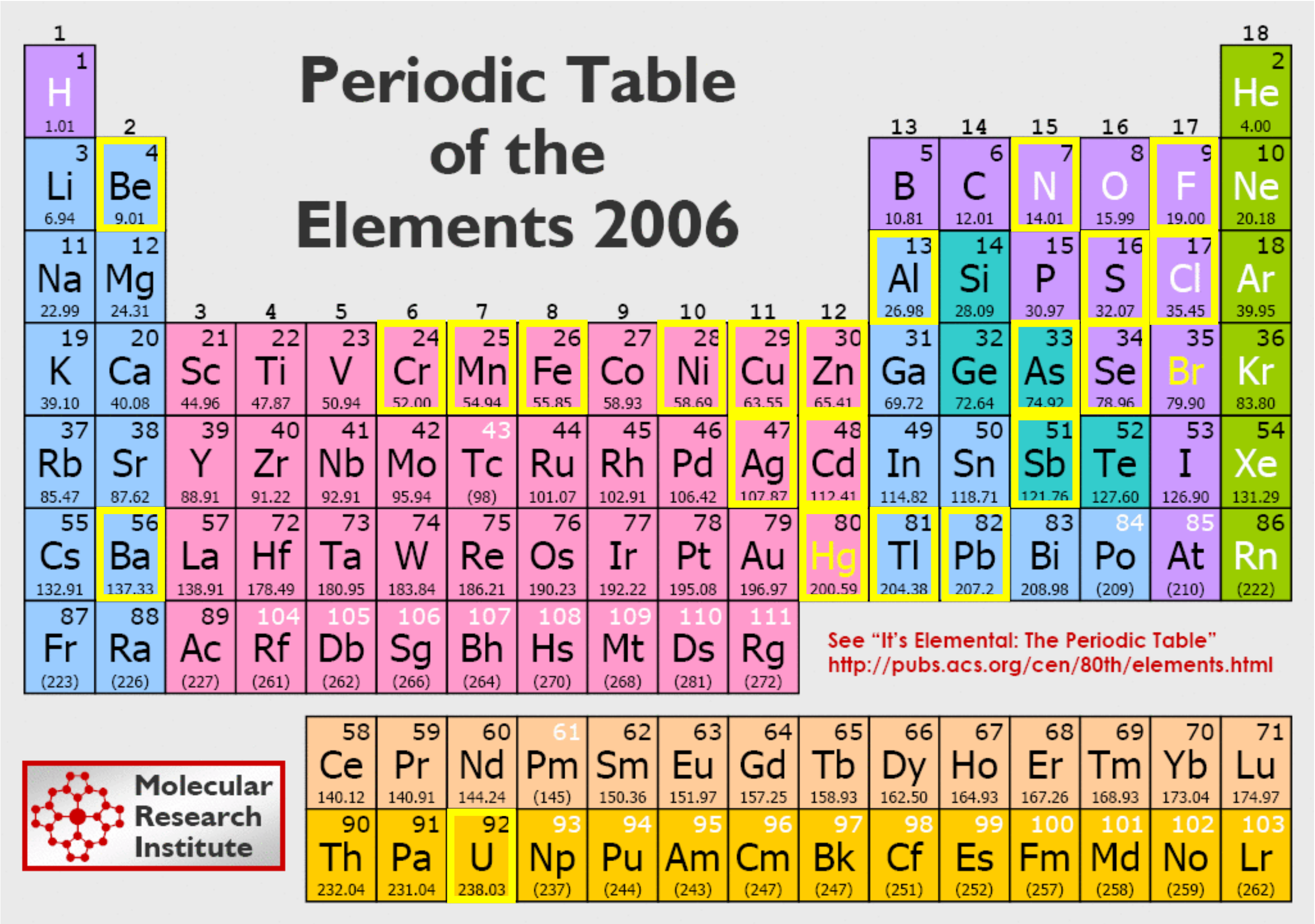
- Inductively coupled plasma-atomic emission spectroscopy (ICP-AES), EPA Method 6010A: Cations
- Inductively coupled plasma-mass spectrometry (ICP-MS), EPA Method 6020: Cations
- Ion Chromatography (IC), EPA Method 300: Anions
- Cold Vapor Atomic Fluorescence Spectroscopy (CVAFS): Mercury

Aquatic Risk Assessment Benchmarks



Suter, G.W., II, 1996, Toxicological benchmarks for screening contaminants of potential concern for effects on freshwater biota: Environmental Toxicology and Chemistry, v. 15, p. 1232-1241.

Water Quality Criteria (Aquatic or Human Health)



Suter, G.W., II, 1996, Toxicological benchmarks for screening contaminants of potential concern for effects on freshwater biota: Environmental Toxicology and Chemistry, v. 15, p. 1232-1241.

USEPA Environmental Criteria

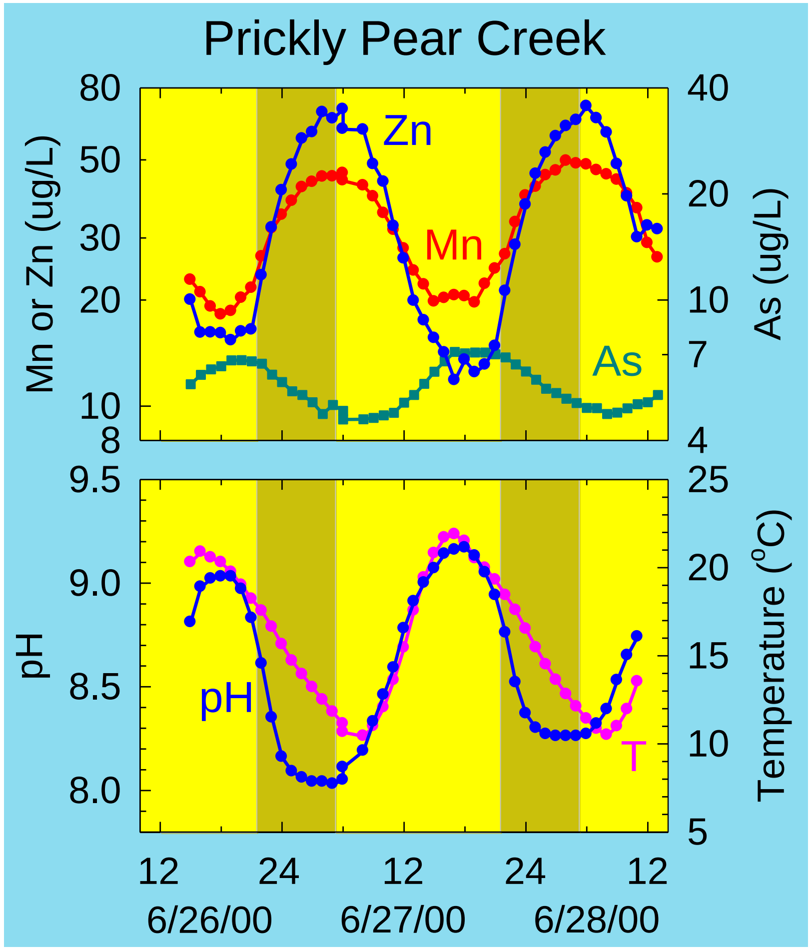
Element	Human	Health	Aquatic	Ecosystem
Media	Residential Soil	Drinking Water	Acute Surface Water Toxicity	Sediment PEC
Units	mg/kg	µg/L	µg/L	mg/kg
Al	77,000	200	750	
As	23	10	340	33.0
Cd	70	5	2*	4.98
Cr	280	100	570	111
Cu	3,100	1,300	13*	149
Fe	55,000	300		
Hg	6.7	2	1.4	1.06
Mn	1,800	50		
Mo	390			
Ni	1,600		470*	4.86
Pb	400	15	65*	128
Se	390	50		
U	230	30		
V	78			
Zn	23,000	5,000	120*	459

*Aquatic criteria in **green** vary with water hardness

USGS
science for a changing world

Baseline Characterization for Monitoring (and Closure)

- Needs to capture the range of natural geochemical variations.
- Needs to use geology as a guide.
- Needs to use hydrology as a guide.
- Diurnal (diel) variations in surface-water chemistry are not uncommon.
- Needs to be done in a *current* regulatory context.



Nimick et al. (2010)

USGS science for a changing world

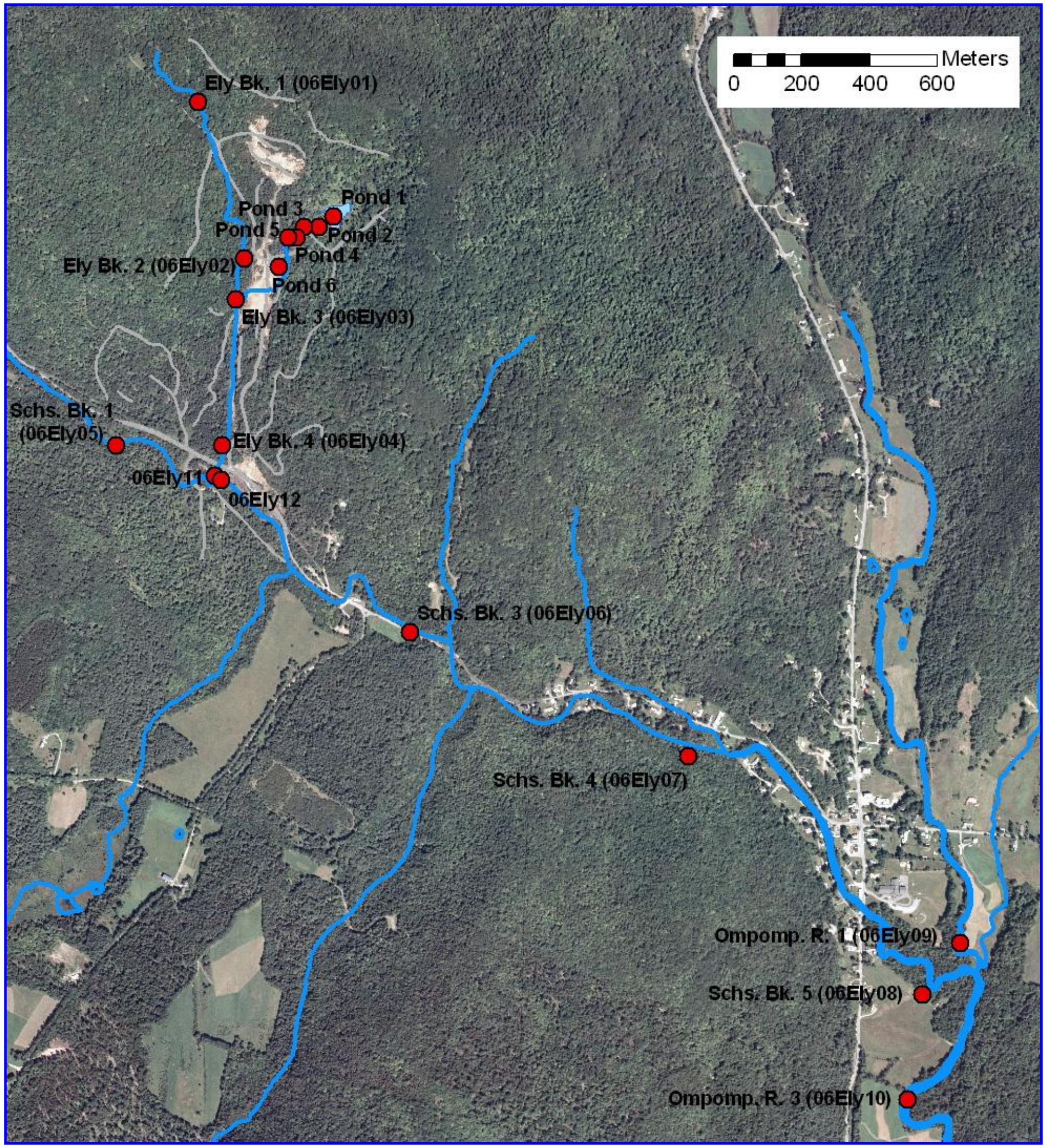
Quality Assurance/Quality Control (QA/QC)

- Procedures to assess the quality of your data
- Water chemistry
  - Blanks (analyzing distilled, deionized water) 1:20
  - Duplicates 1:20
  - Reference waters vs. spiked samples
  - (Charge balance)
- Soils and Sediments
  - ~~Blanks~~
  - Duplicates 1:20
  - Reference materials

USGS
science for a changing world

Ely Mine Superfund Site, Vermont, USA

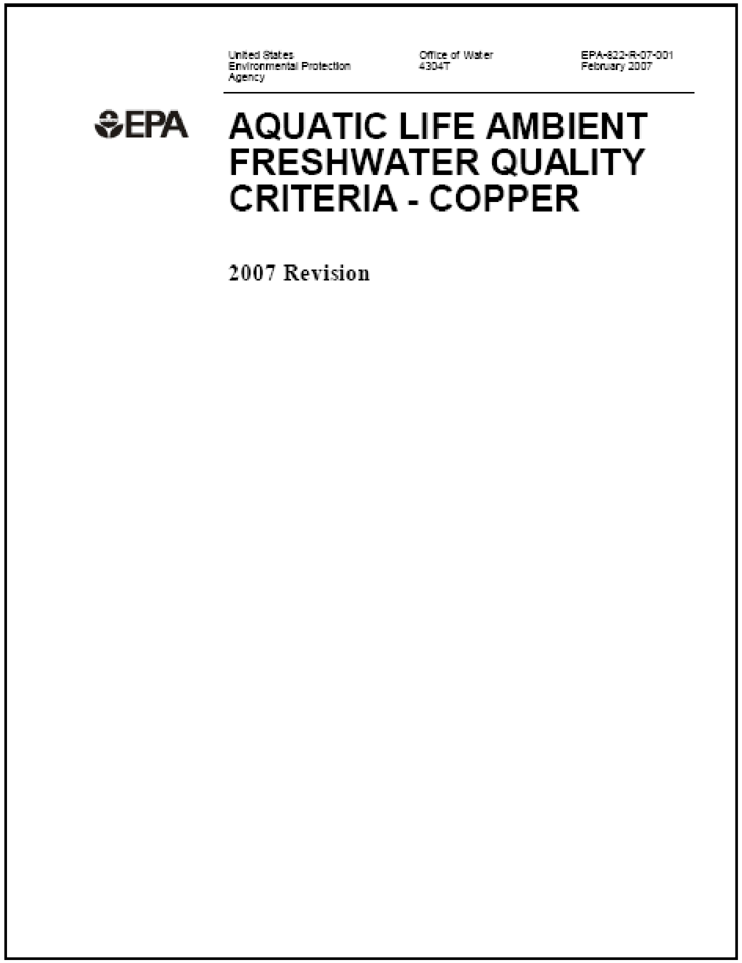
- Today's problem: metal-rich AMD.
- Acid in Ely Brook is rapidly neutralized by Schoolhouse Brook.
- Metals persist downstream.



USGS science for a changing world

Surface-Water Environmental Criteria

- USEPA and the world community are changing from hardness based criteria to "Biotic Ligand Model" (BLM) criteria.
- At present, BLM is only adopted in USA for Cu.


United States Environmental Protection Agency | Office of Water 4304T | EPA-822-R-07-001 February 2007

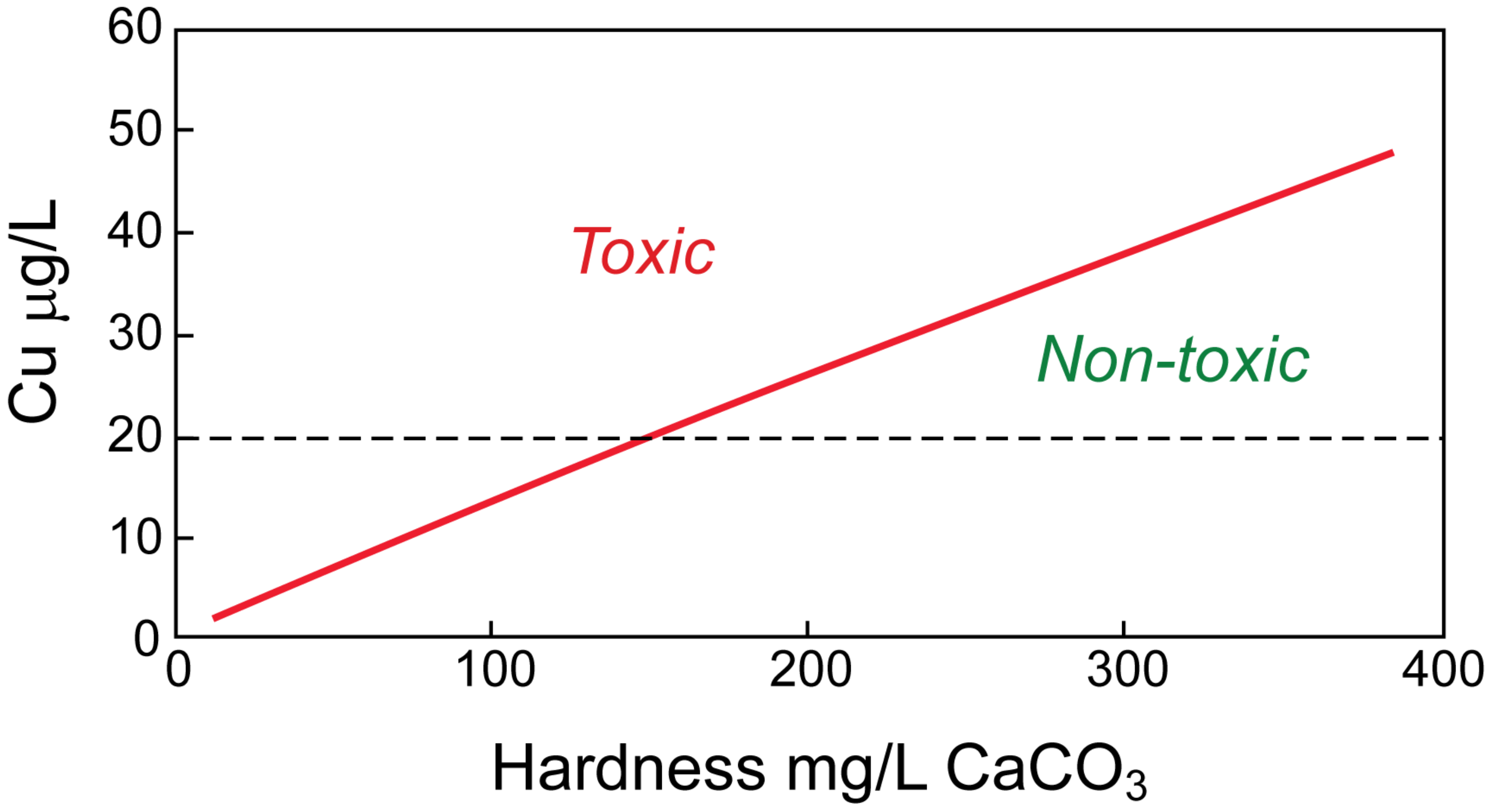
EPA

AQUATIC LIFE AMBIENT FRESHWATER QUALITY CRITERIA - COPPER

2007 Revision

http://water.epa.gov/scitech/swguidance/waterquality/standards/current/upload/2009_04_27_criteria_copper_2007_criteria-full.pdf

Surface Water Ecosystems: Acute Copper Toxicity



Hardness (mg/L $CaCO_3$) = 2.5 Ca (mg/L) + 4.1 Mg (mg/L)

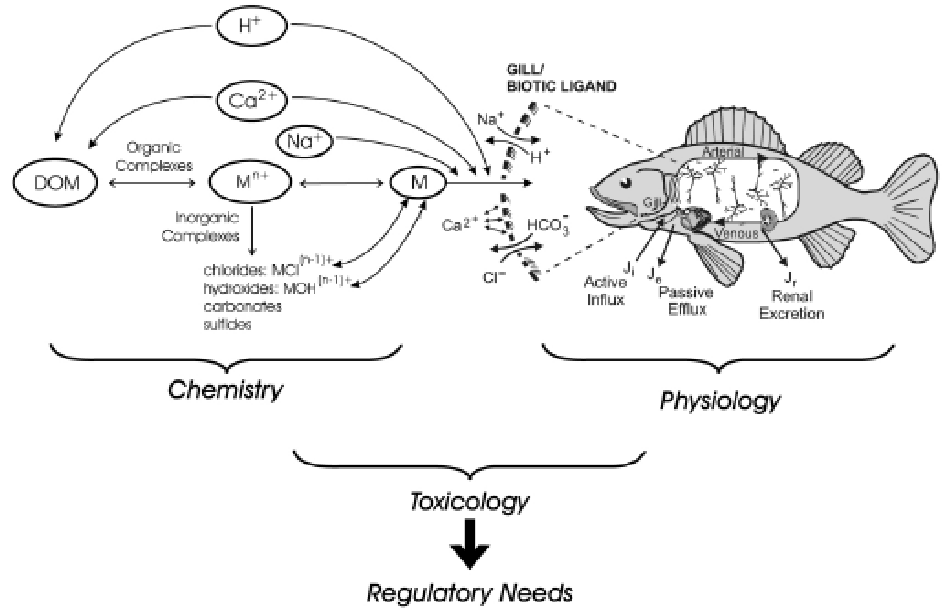
Cadmium (Cd), Chromium (Cr), Copper (Cu), Lead (Pb), Nickel (Ni) , Silver (Ag), Zinc (Zn)

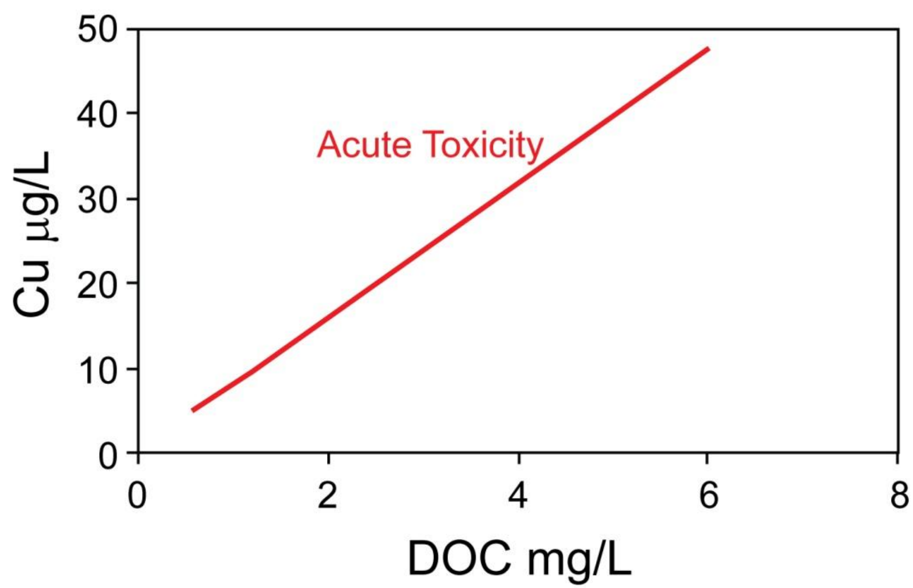
http://water.epa.gov/scitech/swguidance/standards/current/

USGS science for a changing world

Surface Water: Biotic Ligand Model Data Requirements

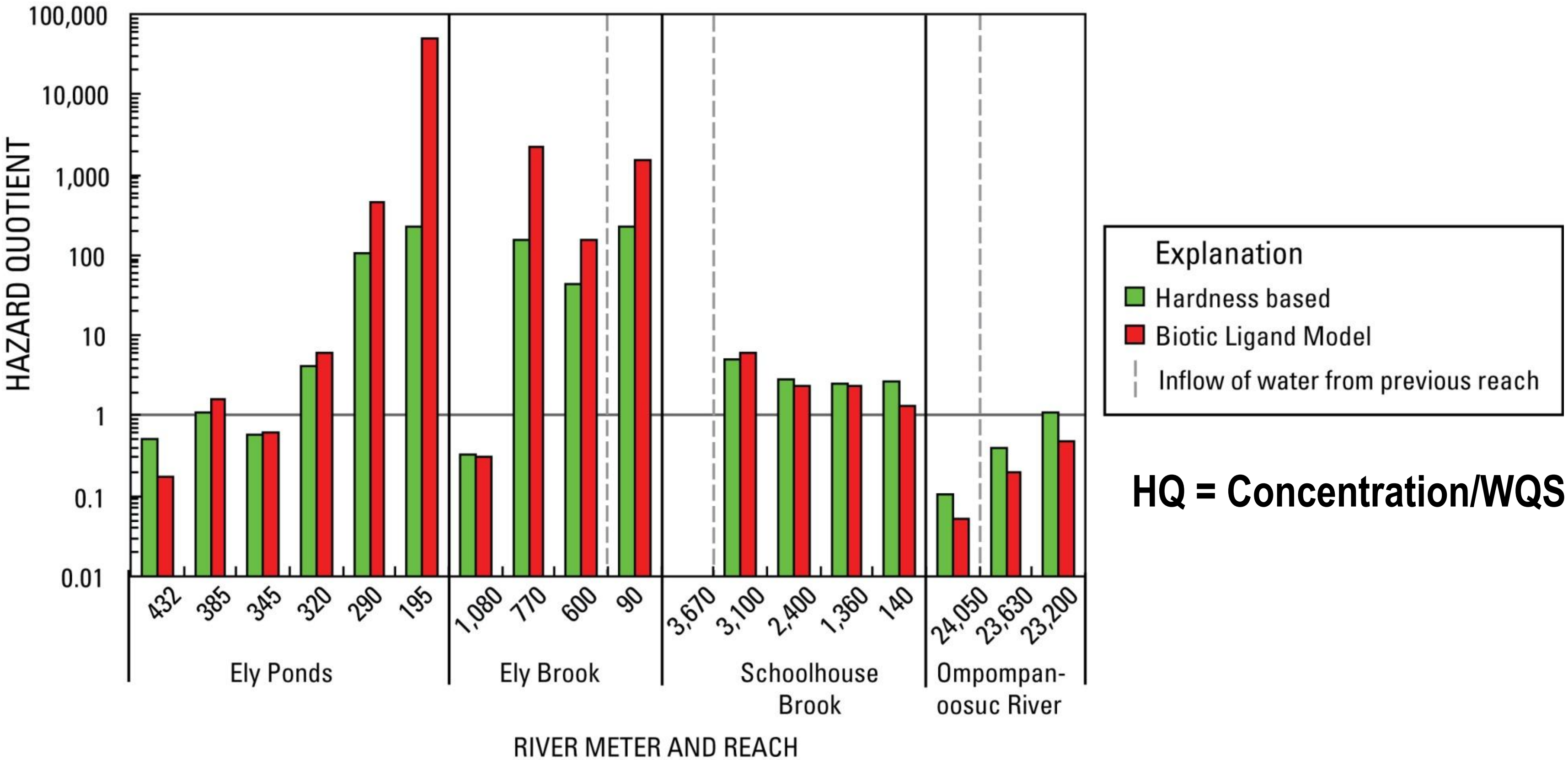
- pH
- Na
- K
- **Ca**
- **Mg**
- Chloride
- Sulfate
- Alkalinity
- **Dissolved Organic Carbon (DOC)**





USGS
science for a changing world

Ely Mine Superfund Site, Vermont, USA

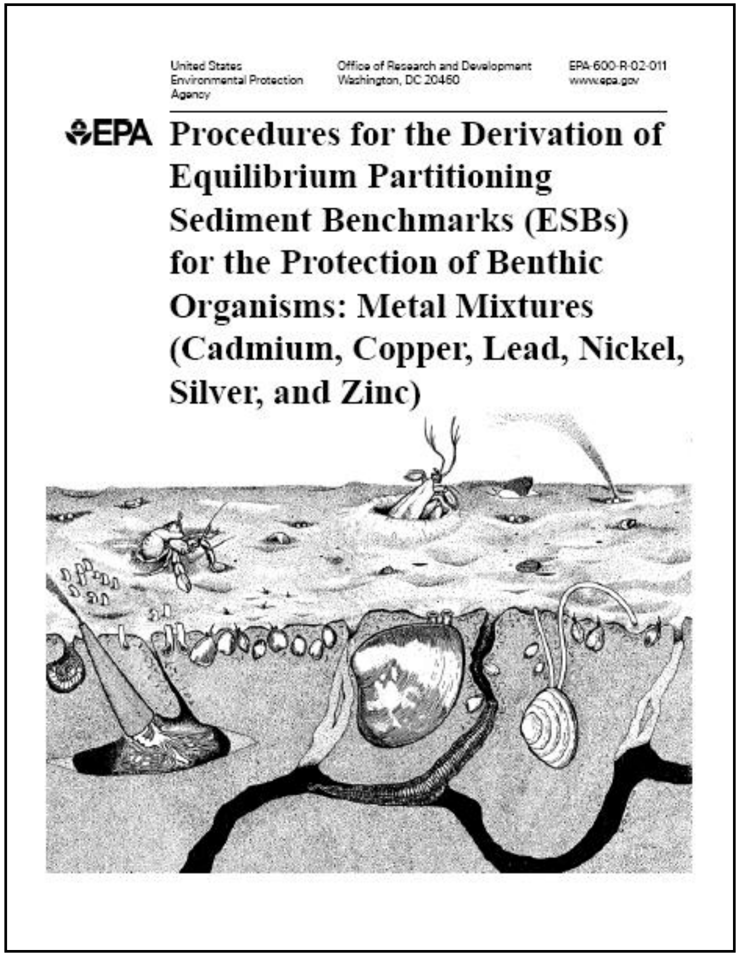


HQ = Concentration/WQS

- Hardness-based and biotic ligand-based approaches yield grossly similar results.
- Some reaches the hardness-based criteria are more restrictive; in other the BLM criteria are more restrictive.

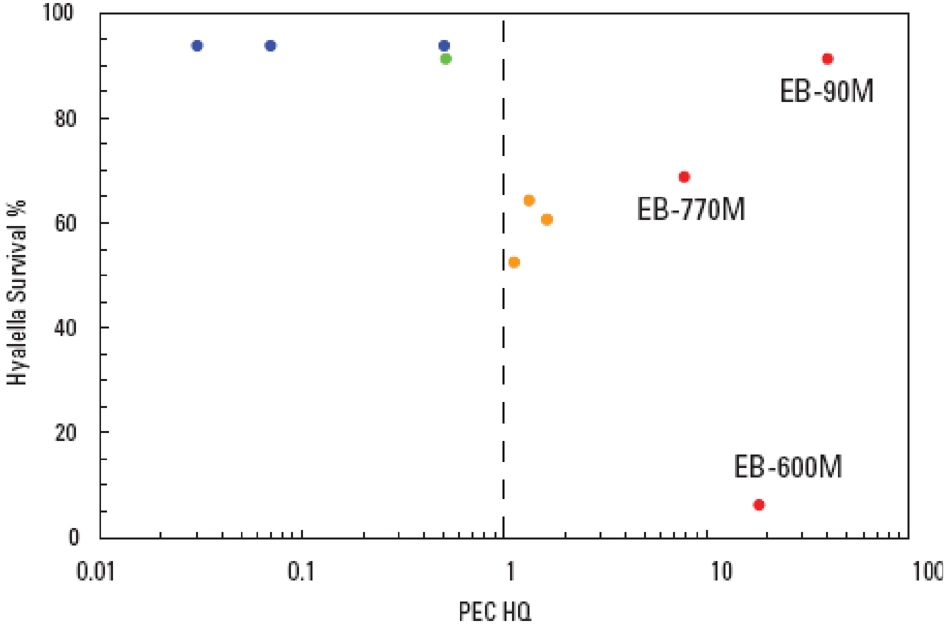
Equilibrium Partitioning Sediment Benchmarks

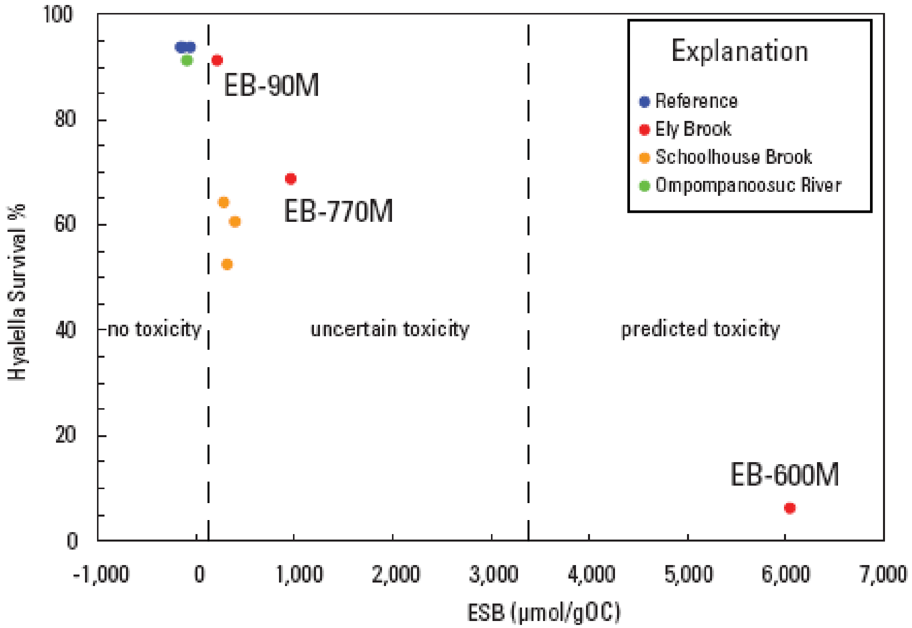
- Criteria are called "Equilibrium Partitioning Sediment Benchmarks" (ESBs)
- Use measurements of:
  - Acid volatile sulfur (AVS)
  - Simultaneously extractable metals (SEM)
  - Organic carbon (OC)
- ESB = (ΣSEM-AVS) $/f_{OC}$



http://www.epa.gov/nheerl/publications/files/metalsESB_022405.pdf

Probable Effects Concentrations vs. Equilibrium Partitioning Sediment Benchmarks





- At the Ely abandoned mine, ESB approach better explains laboratory bioassay results than PEC approach.
- ESB requires more extensive analytical suite (SEM, AVS, f_{OC})

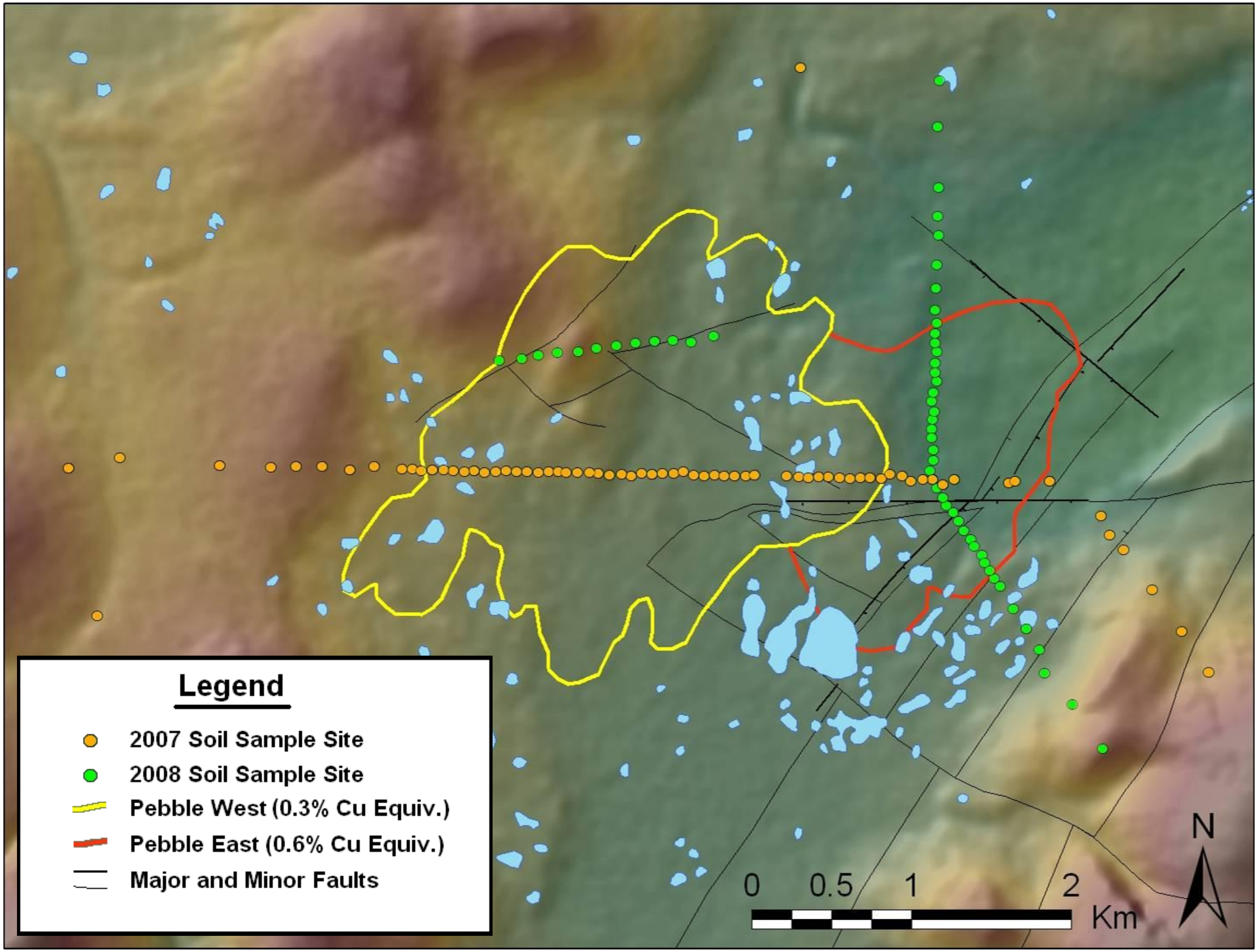
USGS
science for a changing world

Baseline Characterization for Closure

- Insights from exploration geologists will improve process and product.
- Ore deposits are geochemical anomalies that can commonly and naturally exceed environmental criteria.
- They express themselves in all media:
  - Groundwater
  - Surface water
  - Sediment
  - Soil
- Needs to include up-gradient and down-gradient of deposit (streams, groundwater, glaciers, etc.)

USGS
science for a changing world

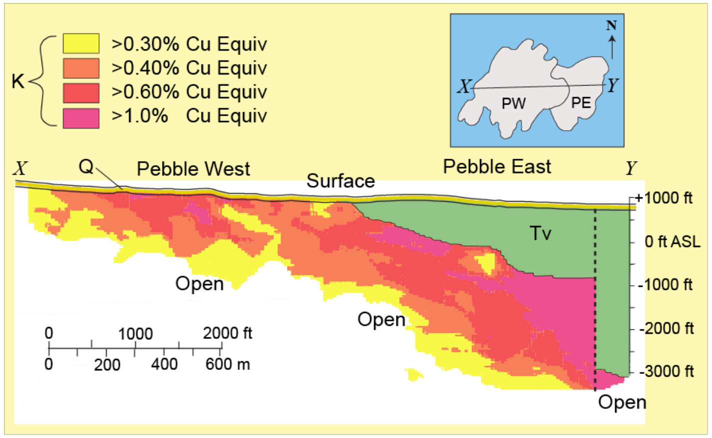
Pebble Deposit (SW Alaska): Soil Traverses

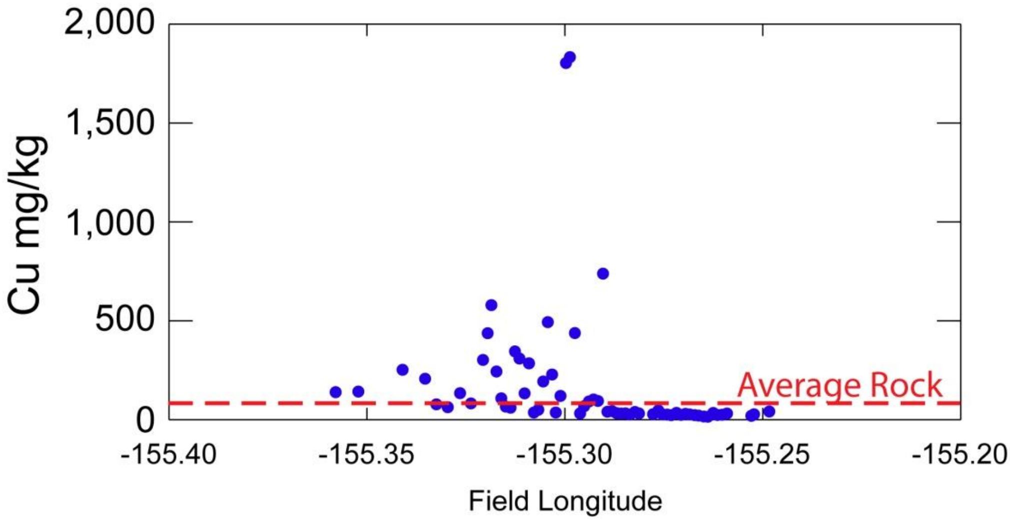


USGS
science for a changing world

Soil Characterization

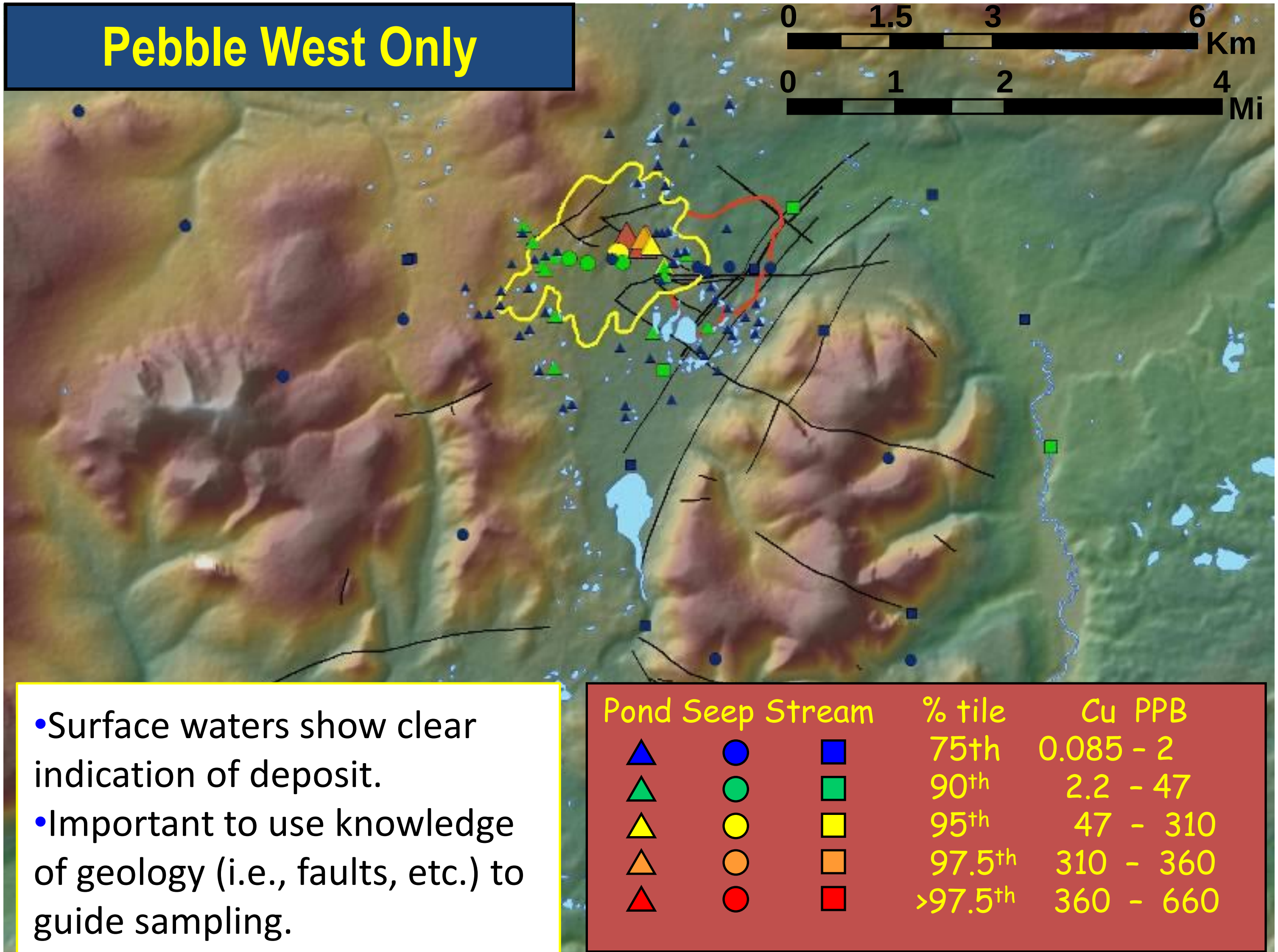
- Porphyry copper deposit
  - Very large (10 billion tonnes)
  - Copper, gold, molybdenum
- Goal is to characterize natural variations
  - Both highs and lows.
- Exploration department will likely have soil survey maps
  - Samples may not have been analyzed as extensively as needed.
  - Maps can serve as guide for effective baseline survey.
- Requires statistically significant data sets for both mineralized areas and unmineralized areas.





USGS
science for a changing world

Waters: Cu by HR-ICPMS



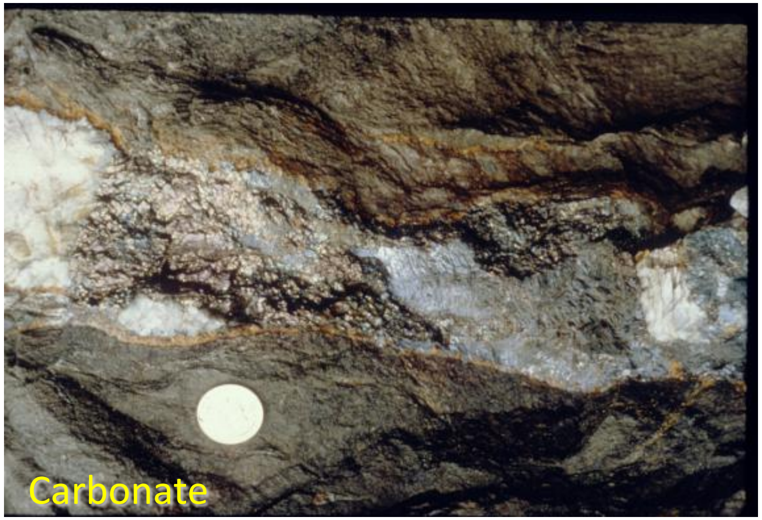
- Surface waters show clear indication of deposit.
- Important to use knowledge of geology (i.e., faults, etc.) to guide sampling.

Pond	Seep	Stream	% tile	Cu PPB
▲ (blue)	● (blue)	■ (blue)	75th	0.085 – 2
▲ (green)	● (green)	■ (green)	90th	2.2 – 47
▲ (yellow)	● (yellow)	■ (yellow)	95th	47 – 310
▲ (orange)	● (orange)	■ (orange)	97.5th	310 – 360
▲ (red)	● (red)	■ (red)	>97.5th	360 – 660

Prediction

Ore & Alteration Characterization

- Mineralogy
  - Trace element hosts
- Geochemistry
- Acid-Base Accounting
  - Sulfide Minerals
  - Carbonate Minerals



USGS
science for a changing world

Static Tests:
Acid-Base Accounting: Pyrite vs. Calcite (sort of…)

$$FeS_2 + 3.75\ O_2 + 3.5\ H_2O = Fe(OH)_3 + 2\ SO_4^{2-} + 4\ H^+$$
$$2\ CaCO_3 + 4\ H^+ = 2\ Ca^{2+} + 2\ H_2O + 2\ CO_2$$

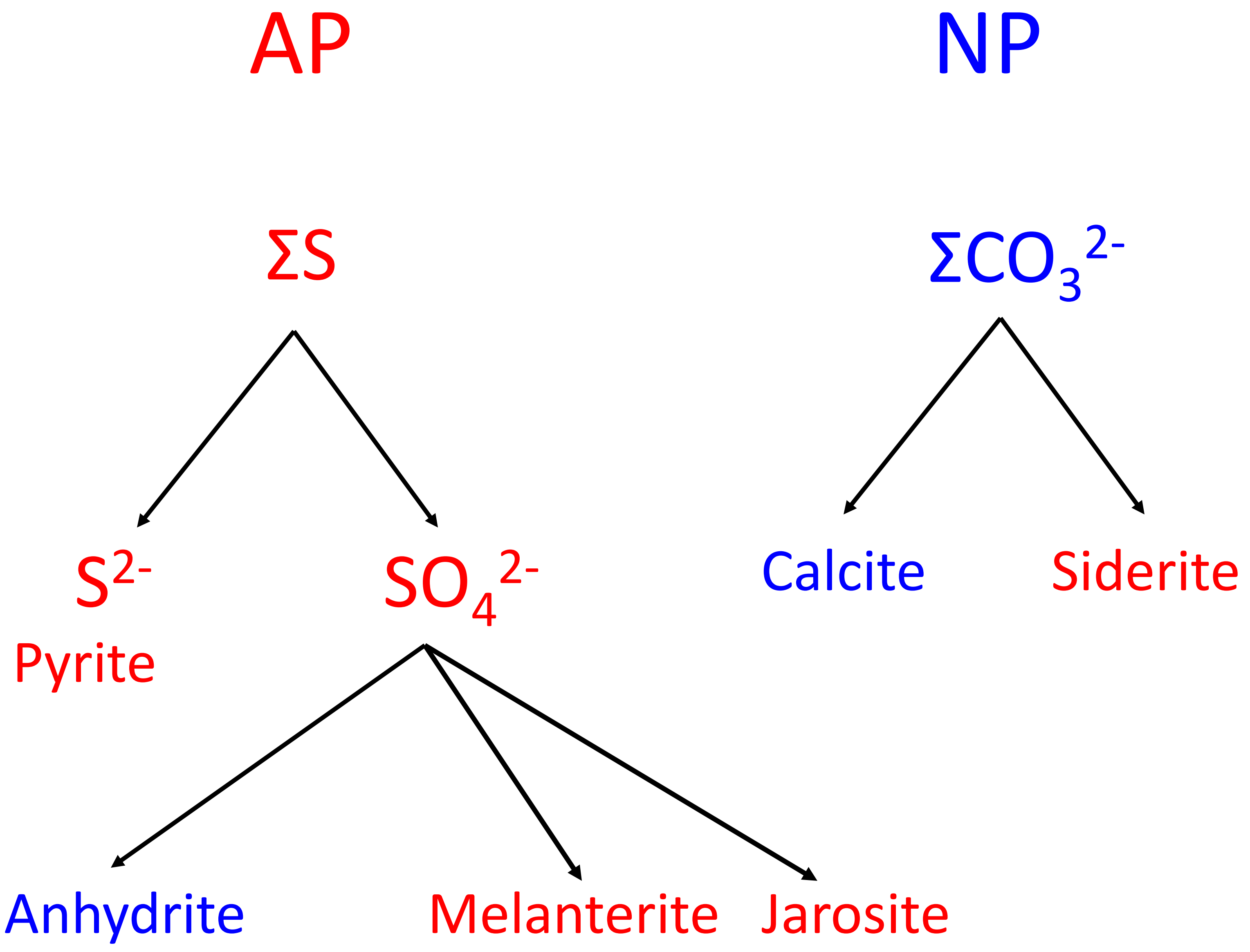
$$FeS_2 + 2CaCO_3 + 3.75O_2 + 1.5H_2O = Fe(OH)_3 + 2SO_4^{2-} + 2Ca^{2+} + 2CO_2$$

NNP = NP – AP

NP/AP

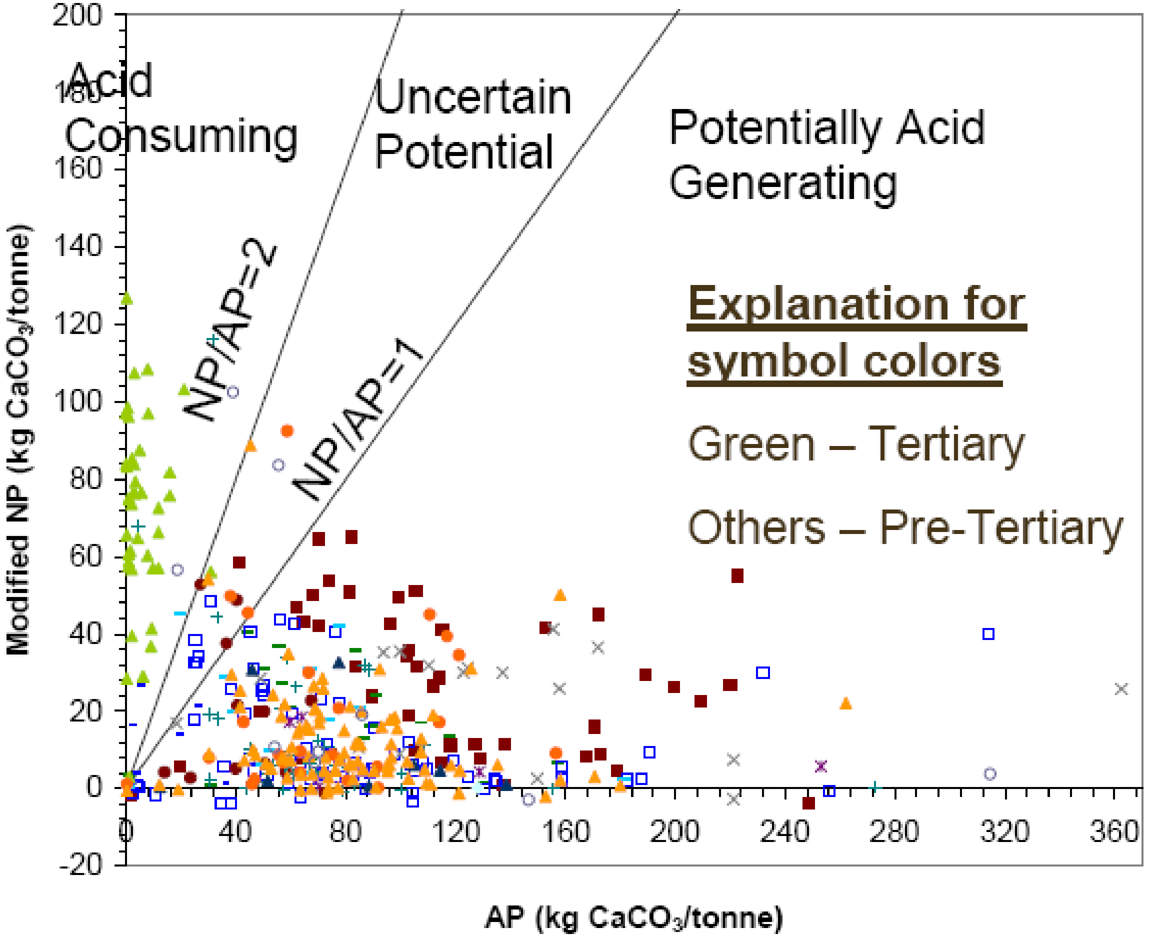
AP: Acid-producing potential
NP: Acid-neutralizing potential
NNP: Net neutralizing potential

USGS science for a changing world


AP
NP
ΣS
ΣCO_3^{2-}
S^{2-}
Pyrite
SO_4^{2-}
Calcite
Siderite
Anhydrite
Melanterite
Jarosite

Acid-Base Accounting

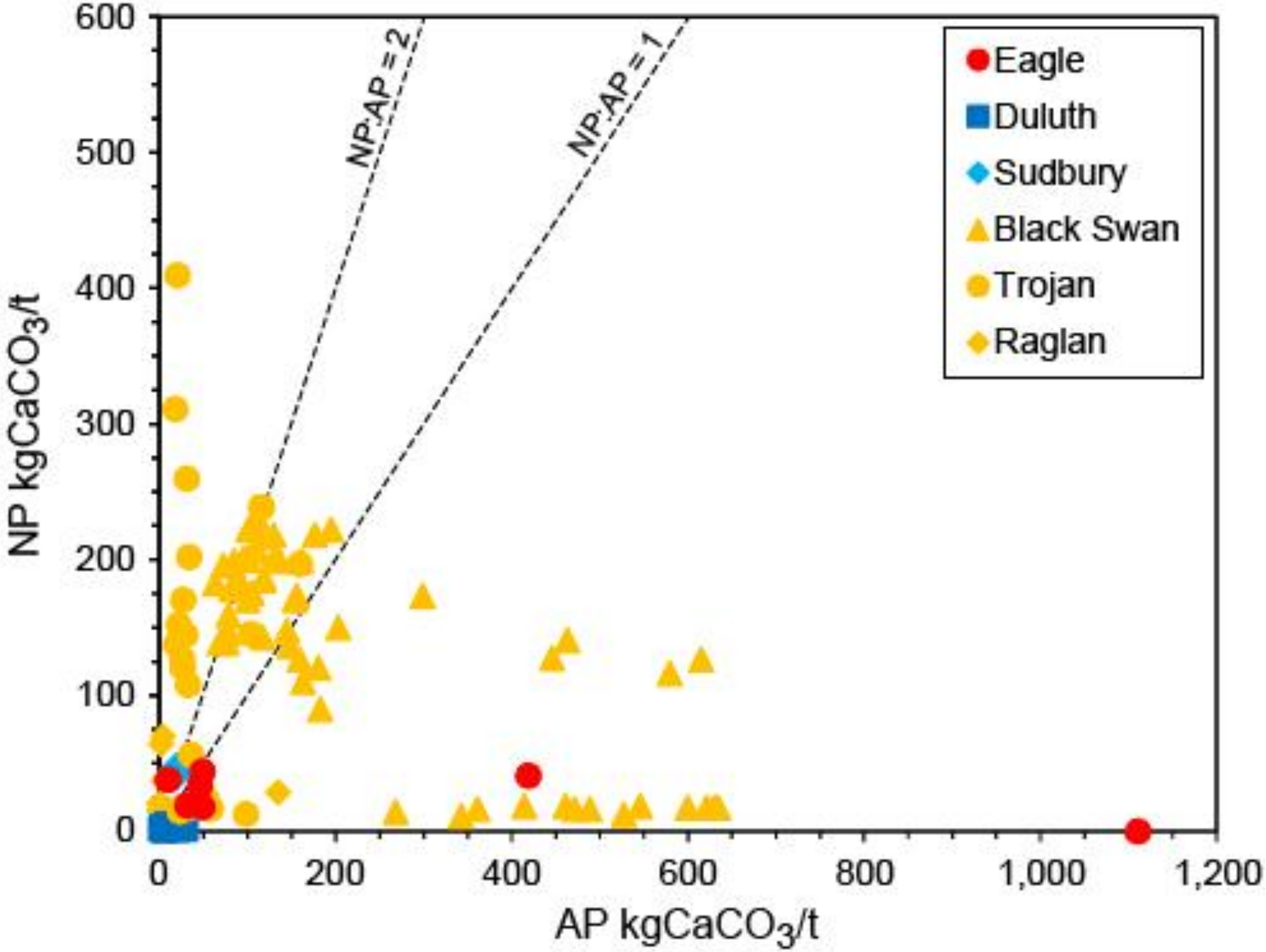
- Goal is to determine which material needs special handling and which does not.
- NP/AP < 1: PAG
- 2 > NP/AP > 1: Uncertain
- NP/AP > 2: Acid Consuming



Pebble Porphyry Cu-Mo-Au deposit, AK
http://www.pebblepartnership.com

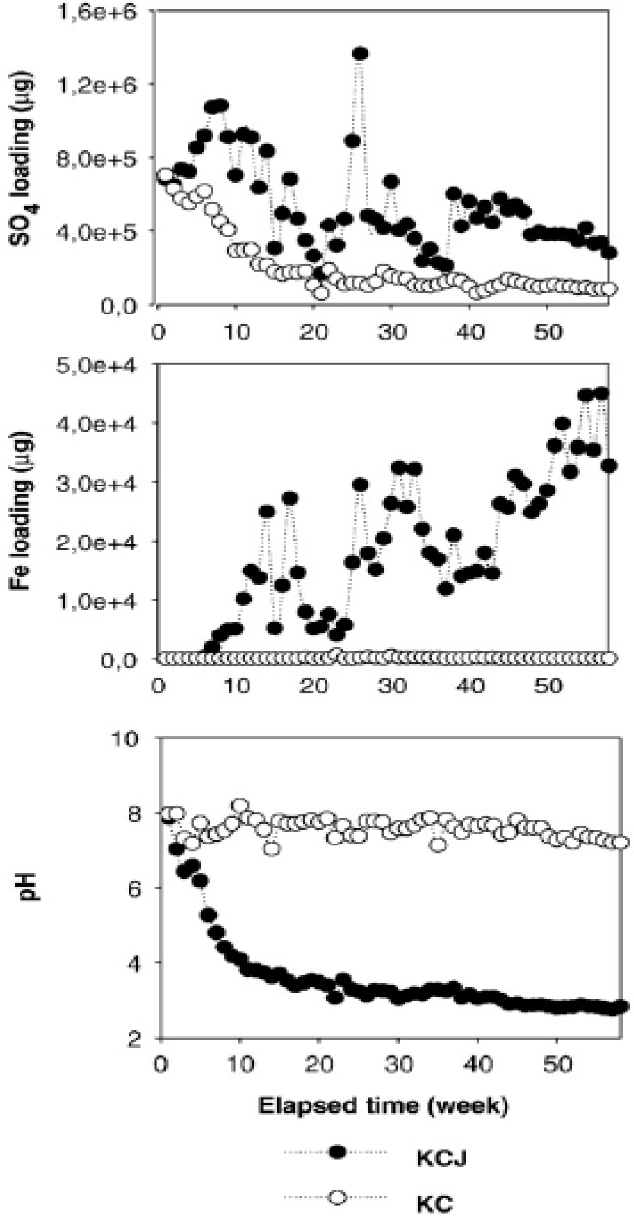
USGS science for a changing world

ABA: Ni-Cu(-PGM) Deposits



USGS
science for a changing world

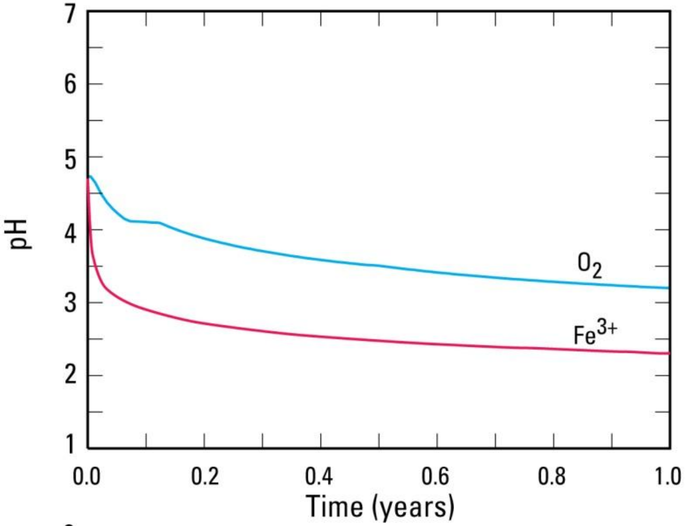
Humidity-Cell (Kinetic) Tests



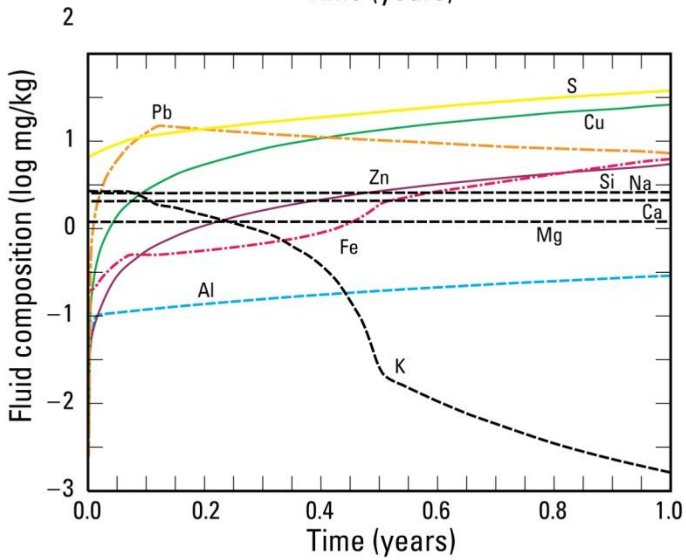
From: Ardau et al. (2009)

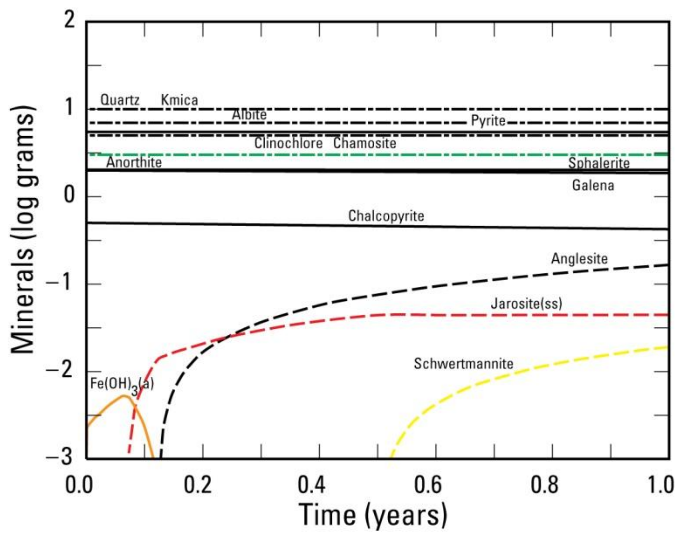
- Long-term behavior
- 1 kg sample
- 7-day cycle: 3 days dry air, 3 days humid air, 1 day leach (0.5 L)

Modeling



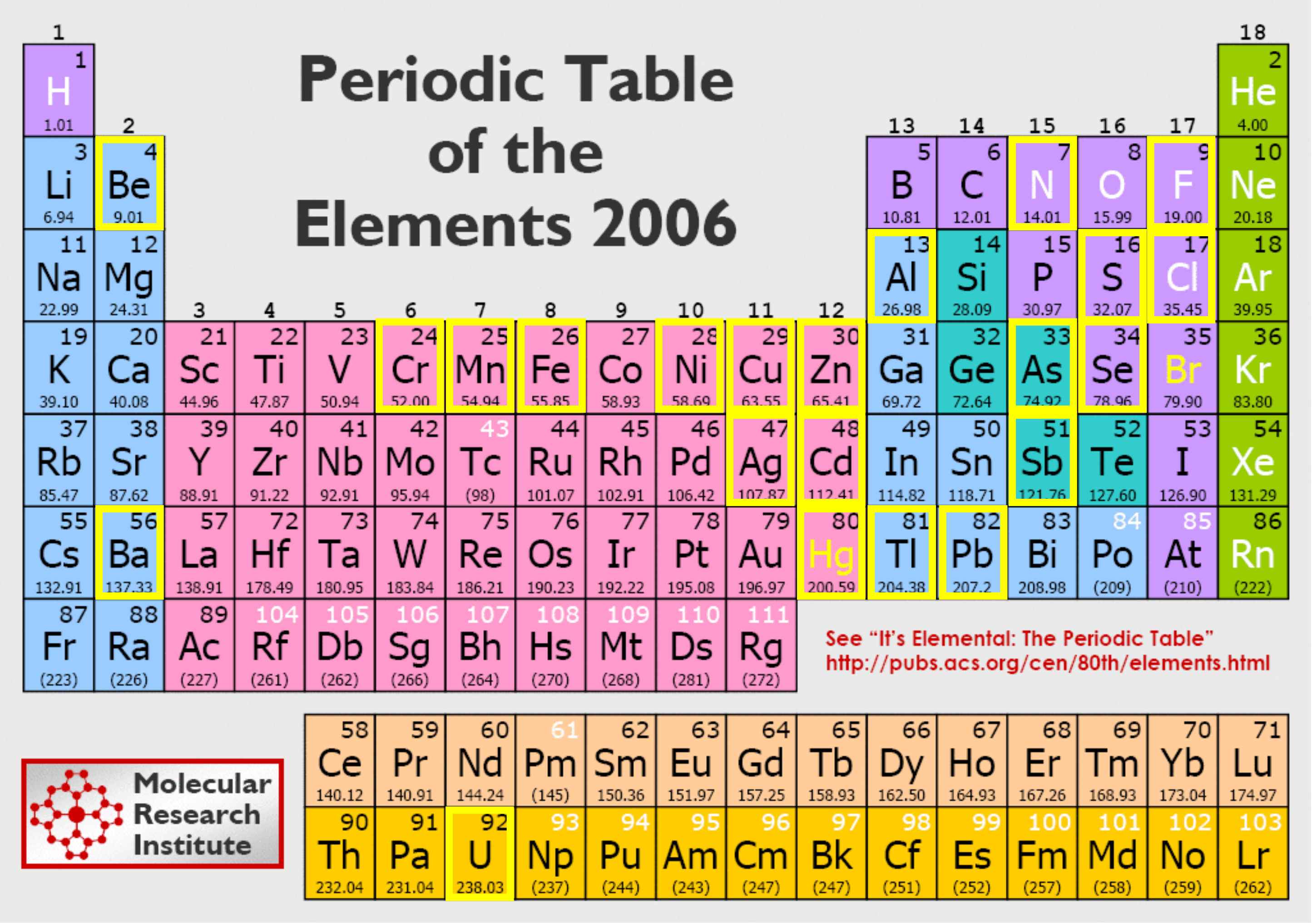
- Chemical interactions in solution
- Rates of dissolution of various minerals
- Equilibrium state of system
- Combines several “models”





USGS
science for a changing world

Water Quality Criteria or Drinking Water Standards



Suter, G.W., II, 1996, Toxicological benchmarks for screening contaminants of potential concern for effects on freshwater biota: Environmental Toxicology and Chemistry, v. 15, p. 1232-1241.

Mine Waste Characterization

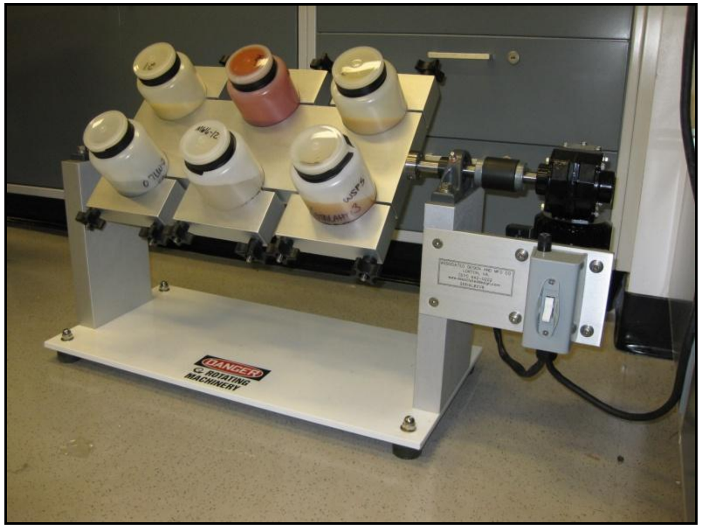
Bulk Chemistry of Solids: Compare to:

- Soil guidelines (human health)
- Sediment guidelines (aquatic health)

Leachate Chemistry: Compare to:

- Drinking water guidelines (human health)
- Surface water guidelines (aquatic health)

- NOT an answer to a questions.
- A tool for asking intelligent questions
- NOT a replacement for site specific studies.



USGS
science for a changing world

Rating Table

Deposit	*VMS*				*Orogenic Gold*				*Taconite*			
Target	Human Health		Ecosystem Health		Human Health		Ecosystem Health		Human Health		Ecosystem Health	
Pathway	Soil	Drinking Water	Sediment	Surface Water	Soil	Drinking Water	Sediment	Surface Water	Soil	Drinking Water	Sediment	Surface Water
Ag	1	1		1	1	1		1	1	1		1
Al	1	3		5	1	1		1	1	1		1
As	3	1	5	1	5	5	5	5	5	5	3	1
Cd	1	5	5	5	1	1	3	1	1	1	1	1
Cr	1	1	1	1	1	1	3	1	1	1	3	1
Cu	1	1	5	5	1	1	3	1	1	1	3	1
Fe	3	3		3	1	1		1	3	3		1
Ni	1	1	1	1	1	1	3	1	1	1	1	1
Pb	5	5	5	3	1	1	3	1	1	1	1	1
Zn	1	1	5	5	1	1	1	1	1	1	1	1
AP/pH	5	5		5	1	1		1	1	1		1

Rating Table

Deposit	*Magmatic Ni-Cu MS*				*Low Sulfide PGM*			
Target	Human Health		Ecosystem Health		Human Health		Ecosystem Health	
Pathway	Soil	Drinking Water	Sediment	Surface Water	Soil	Drinking Water	Sediment	Surface Water
Ag	1	1		1	1	1		1
Al	1	3		5	3	1		3
As	1	1	1	1	1	5	1	1
Cd	1	5	5	5	1	1	1	1
Cr	3	1	5	3	1	1	5	1
Cu	1	3	5	5	1	1	5	1
Fe	5	3		3	1	1		1
Ni	3	1	5	5	1	1	5	1
Pb	1	1	5	1	1	1	3	1
Zn	1	1	3	5	1	1	3	1
AP/pH	5	5		5	1	1		1

USGS
science for a changing world

Summary

- Goals need to include establishment of monitoring sites for use prior, during, and after mining.

- Goals also need to include documentation of pre-mining geochemical landscape within the footprint of the proposed mine, especially in all regulated media (groundwater, surface water, sediment, soil).

- Insights from exploration geologists will be invaluable because of their knowledge of geologic and geochemical features of the deposit.

USGS
science for a changing world