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
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

Acid consumption:
- Host rock
- Wallrock alteration
- Gangue mineralogy

Trace element release:
- Abundance (deposit, host rocks)
- Access of weathering agents
- Susceptibility of source mineral phases to weathering

Many sulfides (not all) generate acid when oxidized

Minerals and weathering products may consume or generate acid

Often results in a characteristic geochemical signature (depending upon type of mineral deposit)
# Acid-Generating Minerals

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyrite (FeS$_2$)</td>
<td></td>
</tr>
<tr>
<td>Marcasite (FeS$_2$)</td>
<td></td>
</tr>
<tr>
<td>Pyrrhotite (Fe$_{1-x}$S)</td>
<td>Arsenopyrite (FeAsS)</td>
</tr>
<tr>
<td>Enargite (Cu$_3$AsS$_4$)</td>
<td>Tennantite (Cu$_{12}$As$<em>4$S$</em>{13}$)</td>
</tr>
<tr>
<td>Realgar (As$_2$S$_3$)</td>
<td>Orpiment (AsS)</td>
</tr>
<tr>
<td>Others</td>
<td></td>
</tr>
</tbody>
</table>

If ferric iron is oxidant, above minerals plus:

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chalcopyrite (CuFeS$_2$)</td>
<td></td>
</tr>
<tr>
<td>Covellite (CuS)</td>
<td>Sphalerite (ZnS)</td>
</tr>
<tr>
<td>Chalcocite (Cu$_2$S)</td>
<td>Acanthite (Ag$_2$S)</td>
</tr>
<tr>
<td></td>
<td>Galena (PbS)</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siderite (FeCO$_3$)</td>
<td></td>
</tr>
<tr>
<td>Rhodochrosite (MnCO$_3$)</td>
<td></td>
</tr>
</tbody>
</table>
Sulfide Texture and Resistance to Weathering

- **Euhedral pyrite**: Less easily weathered
- **Massive pyrite**: More easily weathered
- **Colloform pyrite**: More easily weathered

Images provided by USGS.
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
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)
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

- Increasing pyrite content, decreasing acid buffering capacity
- Increasing sulfide content; increasing exposure of sulfides at ground surface
- Evaporation

Symbols depict waters draining deposits with similar geologic characteristics

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

Arsenic

Dissolved As (ppb)

pH
Types of Massive Sulfide Deposits
(Seal and Hammarstrom, 2003)
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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Kathleen S. Smith and Holly L.O. Hawk

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Volume 6A

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USE OF LEAD ISOTOPES AS NATURAL TRACERS OF METAL CONTAMINATION—A CASE STUDY OF THE PÉSS NATURAL RESERVOIR, CALIFORNIA

L.H. Fickett, T.J. VanWagoner, C.S.E. Papp, and J. Curry
C.J. Coggins, D.W. Bliesner, W.D. Robertson, and J.L. Jambor
B.A. Kimbrell
R.H. Lambeth
W.R. Miller, R.L. Bassett, J.R. McHugh, and W.H. Ficketl
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E.R. Lando
J.A. Brierley
L.H. Filippek

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# Microscopic Analytical Methods

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Method</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineralogy</td>
<td>Petrographic Microscope, Scanning Electron Microscope</td>
<td>Mineral Species; acid or non-acid generating; Mineral Textures; particle size, cleavage Structure</td>
</tr>
<tr>
<td>Trace Metals</td>
<td>Microprobe Laser Ablation Mass Spectrometry</td>
<td>Exact Residence of trace metals; Spatial Distribution of trace metals; Quantitative data</td>
</tr>
</tbody>
</table>
Case Studies

   (Lapakko, 1999; Lapakko and White, 2000; White and Lapakko, 2000)

2. Pyrite-Rich Coal Samples
**Mineralogical Characterization**

### Elemental Residence Phases

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jarosite</td>
<td>$KFe_3(\text{SO}_4)_2(\text{OH})_6$</td>
<td>Pb, Ag, Cu, Bi</td>
</tr>
<tr>
<td>Pyrite</td>
<td>FeS$_2$</td>
<td>Cu, Bi, Ag, As</td>
</tr>
<tr>
<td>Sphalerite</td>
<td>ZnS</td>
<td>Cd, Cu, Mn, Ag</td>
</tr>
<tr>
<td>Galena</td>
<td>PbS</td>
<td>Ag, Bi</td>
</tr>
<tr>
<td>Anglesite</td>
<td>PbSO$_4$</td>
<td>Zn, Cd, Bi, Cu</td>
</tr>
<tr>
<td>Tennantite-Tetrahedrite</td>
<td>$(\text{Ag, Cu, Fe})_{12} (\text{Sb, As})<em>4 \text{S}</em>{13}$</td>
<td>Cu, Zn, Sb, As</td>
</tr>
</tbody>
</table>
## Case Study 1: Bulk Mineralogy of Mine Waste Samples

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

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Before Leaching</th>
<th>After Leaching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>32</td>
<td>30</td>
</tr>
<tr>
<td>Amorphous</td>
<td>23</td>
<td>28</td>
</tr>
<tr>
<td>Potassium</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>Feldspar</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Muscovite</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>7</td>
<td>--</td>
</tr>
<tr>
<td>Siderite</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Pyrite</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Before Leaching</th>
<th>After Leaching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>33</td>
<td>32</td>
</tr>
<tr>
<td>Amorphous</td>
<td>33</td>
<td>34</td>
</tr>
<tr>
<td>Jarosite</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>Potassium</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Feldspar</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Muscovite</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Gypsum</td>
<td>1</td>
<td>--</td>
</tr>
</tbody>
</table>

---

*USGS*
Microstructure; Sample 99.1

Etched carbonate-filled vein

Silica-filled vein
Pyrite-bearing Sample 99.1

Pyrite Before Leaching

Pyrite After Leaching
Pyrite-Bearing Sample 99.1
Cu and Zn from sulfides
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.

Zoned Jarosite

Textures
Trace elements in Jarosite-Bearing Mine Waste

Sample 81196; Trace Metals in Jarosite

Element concentration (log scale; ppm)

Time (number of weeks)

Cu
Zn
ICP_MS Cu
ICP_MS Zn

0.56 wt.% Cu
X

USGS DEN 0000 20kV 2µm
Case Study 2:

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

A

pyrite

framboidal pyrite

ccoal

areas of arsenic-rich pyrite

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)

laser ablation sample spot numbers
Coal

Pyrite

Arsenic-rich Pyrite and Clay-filled Fractures
Arsenic-rich Pyrite-filled Veins

Arсенічно-багате пиритове напилення

Порожність пириту з багатим арсенієм виходить в розчин більш легко, ніж порожність пириту з більш низьким арсенієм.

coal

partial dissolution

clay

pyrite

0.36 % As

1.20 % As

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