A MULTIPLE TRACER / GEOCHEMICAL APPROACH TO CHARACTERIZING WATER AND CONTAMINANT MOVEMENT THROUGH ABANDONED MINE WORKINGS NEAR RICO, COLORADO

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Thanks to Jan Christner
RICO MINING DISTRICT

Southwest Colorado

San Juan Mountains

Rico

Delores River

Colorado mineral belt

Utah

New Mexico

Delores River

San Juan Mountains

Rico

Colorado mineral belt

Utah

New Mexico
Rico mining district

MINING HISTORY

- 1869 - 1977 – Active silver, zinc, lead mining district
- 1930-31 - St. Louis tunnel driven to explore for deep ore bodies
- 1955 - Sulfuric acid production plant (from pyrite)
- 1956 – 1979 - Series of ponds constructed for sulfuric acid production and tailings disposal
- 1971 – Rico Argentine Mining Co ceased mining operations and deeper workings allowed to flood
- 1973-1975 – Heap leach NW of St. Louis tunnel adjacent to Delores River
- 1976-1977 – Mining activities ended
- 1879 - 1968 – production - 83,000 ounces of gold, 14,500,000 ounces of silver, 5600 tons copper, 84,000 tons lead, 83,000 tons zinc.
GEOLOGY

- Domal uplift PC monzonite -6000 ft.
- Dome bounded by numerous near vertical faults
- NE_SW Blackhawk fault bounds east side of dome – numerous associated reverse& normal faults sub-paralell to BH Fault
- Pennsylvania age Hermosa Fm was intruded by dome – widespread in outcrop /subcrop –dips away from dome -2800 ft thick
- Comprised of interbedded sandstones, limestones, shale, conglomerate, arkose – extensively faulted
ORE BODIES

- Mineralization due to hydrothermal fluids moving along faults and limestone bedding planes in the downdip direction.
- Significant mineralization can occur 400 - 500 feet from the major faults.
- The primary ore deposits are:
  - massive sulfide replacement deposits in the limestones of the middle and upper members of the Hermosa Formation,
  - metamorphic deposits of sulphides in limestones of the Ouray, Leadville and Hermosa formations and as
  - veins on fractures and small faults in Hermosa sandstones and arkoses. The
  - ores were mined primarily by stoping limestone blocks that contain target metals at a high enough grade. The limestone beds were stoped in a downdip direction, which resulted in a lot of connection between levels of mine workings.
ENVIRONMENTAL ISSUES

• Discharge from St. Louis tunnel contains high concentrations of heavy metals – NPDES permit lapsed - June 2010 – Zn - 3900 ug/l - Portal discharge to ponds which discharge to Delores River

• Unlined ponds - adjacent to Delores River – ponds contain sludge / tailings - 64,000 yd³
  – Zn – 18,000 – 38,000 ppm
  – Cd – 51 - 190 ppm
  – Cu – 650 - 2400 ppm
  – Pb – 200 – 1000 ppm

• Discharge of AMD (pH -2-3) from Blaine workings – ore bodies have high sulphide content

• TMDL on Silver Creek – dissolved Cd & Zn
Treatment ponds

Mill Tailings
NOTES:
1. SILVER CREEK, ALL MINE WORKINGS AND BRIDGES TRACED FROM "comp_Plan.tif", EXCEPT THE FOLLOWING
   A. ARGENTINE SHAFT TUNNEL PER "scan02.tif"
      ("ARGENTINE MINE AND ST. LOUIS TUNNEL," DRAWN 5-21-55, P.L.J.)
   B. 517 SHAFT LOCATED PER "scan06.tif"
      ("USGS/NIKIGHT PROFESSIONAL PAPER 723, PLATE 3")
   C. BUILDING FOOTPRINTS AT ARGENTINE TAILINGS PER "iso area proposed drilling site.tif"
      ("PROPOSED DRILLING HOLES, SILVER CREEK NO TARGET PLAN", NOV. 1980)
   D. ST. LOUIS SOUTHEAST CROSS CUT PER "001211006022020157.PDF"
      ("ST. LOUIS LEVEL, SHEET 2", DEC. 1958 - R.T.)
2. ALL LOCATIONS/DIMENSIONS/ELEVATIONS APPROXIMATE ONLY; ELEVATIONS MAY BE ON DIFFERENT VERTICAL DATUMS
3. ALL MINE LEVELS SHOWN AT SINGLE ELEVATION SEPERATED BY 100-FEET FOR CLARITY.
   FURTHER REFINEMENT, IF NECESSARY IS DEPENDENT UPON ABILITY TO VERIFY ELEVATIONS.
4. NO EVIDENCE FOUND TO DATE ON HISTORIC MINE MAPS OF 517 SHAFT EXTENDING TO GROUND SURFACE.

LEGEND:
- BLAINE LEVEL
- 200 LEVEL
- 300 LEVEL
- 400 LEVEL
- ST. LOUIS/500 LEVEL
- 600 LEVEL
- 700 LEVEL
PROJECT GOALS

- Characterize stream /groundwater/mine hydrology
- Evaluate feasibility of hydraulic controls to reduce volume of discharge and /or contaminant load from St. Louis tunnel
  a) Reduce flow of water into / through mine workings
  b) Reduce mobilization of contaminants within the mine workings
  c) Isolate high-concentration contaminant source for limited small scale treatment
Hydrologic investigation

- Determine if significant volume of surface water from Silver creek enters mine workings
- Identify sources of AMD
- Characterize mine water flowpaths – contribution to St. Louis tunnel
- Determine flow and chemistry of Silver creek and mine water

• Chemical / isotopic analysis
• Stream Tracer studies
• Mine workings tracer studies
WATER CHEMISTRY / METALS LOADING

- St. Louis tunnel portal discharge
- Silver Creek
  - Time series at SC-493
  - Synoptic along entire study reach (SC-106- SC-1131)
- Underground – mine waters
  - 517 Shaft
  - Pipe discharge to 517 shaft access tunnel
  - Blaine tunnel pool and discharge from a raise from above Blaine level
  - Argentine tunnel – above Blaine level
- Argentine tails seep
St. Louis Tunnel

Portal discharge chemistry (DR-3)

<table>
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<tr>
<th>Parameter (dissolved) (ug/l)</th>
<th>June 2011</th>
<th>October 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.7</td>
<td>7.4</td>
</tr>
<tr>
<td>Cd</td>
<td>52</td>
<td>17.5</td>
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<tr>
<td>Cu</td>
<td>55.2</td>
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</tr>
<tr>
<td>Fe</td>
<td>445</td>
<td>1090</td>
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<tr>
<td>Pb</td>
<td>1.0 U</td>
<td>1.0 U</td>
</tr>
<tr>
<td>Zn</td>
<td>10,200</td>
<td>3810</td>
</tr>
</tbody>
</table>

Portal discharge vs. Delores River flow

DR-G - Delores River
DR-6 – Pond outfall
suspected loss reach below SC-106

Approx location of Argentine seep

Water chemistry – Silver Creek
Figure 33
Silver Creek Sulfate (SO$_4^{2-}$) Concentrations
June and October

[Graph showing SO$_4^{2-}$ concentration along Distance downstream (m) from 0 to 1200 m. Two lines represent October 7, 2011 and June 23, 2011 concentrations.]
**MINE WATER CHEMISTRY**

**Argentine tunnel (µg/l)**
- Cu - 349,000
- Zn - 2,460,000
- Mn - 294,000
- Pb - 239,000
- Cd - 12,000
- pH - 2 - 2.5

**517 TUNNEL PIPE - BEDROCK GW??**
- Cu - 0.5
- Zn - 10.8
- Mn - 1.0
- Pb - 0.14
- Cd - 0.1
- pH - 2 - 2.5
# Argentine seep chemistry

<table>
<thead>
<tr>
<th>Parameter (dissolved) (ug/l)</th>
<th>June 2011</th>
<th>October 2011</th>
</tr>
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<tbody>
<tr>
<td>pH</td>
<td>7.8</td>
<td>7.8</td>
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<tr>
<td>Cu</td>
<td>5.00 U</td>
<td>2.50 U</td>
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<tr>
<td>Cd</td>
<td>1.00 U</td>
<td>1.00 U</td>
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<tr>
<td>Pb</td>
<td>1.00 U</td>
<td>1.18 J</td>
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<tr>
<td>Fe</td>
<td>1000 U</td>
<td>1000 U</td>
</tr>
<tr>
<td>Zn</td>
<td>3780 ug/l</td>
<td>3810 ug/l</td>
</tr>
</tbody>
</table>

**FIGURE 27**
Argentine Tailings Seep Discharge

![Discharge Graph](image)
Stable Water Isotope Data

SW & mine waters are a mixture of snow & rain

δD per mil vs. δ^{18}O per mil
Seasonal Water Isotopes

- St. Louis tunnel – well mixed gw source
- Minewaters more depleted in Oct. suggests gw baseflow is from snowmelt
- June SC sample – snow dominated
- 517, Blaine & seep similar to Silver Creek - indicates similar source of water

δD per mil

δ18O per mil
- Relatively new water
- No bomb spike water
- No old water
- Residence time in gw / mine water flow system is few years
Silver Creek - Stream tracing
( evaluate loss to mine workings)

- Stage-discharge relationships at 2 locations – time series of flow
- Slug additions to develop point flow estimates above & below suspected loss reach
- Continuous additions to measure discharge above & below suspected loss reach
suspected loss reach below SC-106

Approx location of Argentine seep
Silver Creek – Stage discharge relationship
High flow – June 2011

- Rating curves developed @ SC-68 & SC-493 by correlating data from pressure transducers with flow measurements made w/ Marsh – McBirney flow meter

- Pressure transducer recorded stage every 15 minutes

- Used to help adjust slug results

- Results conflict with slug tests & continuous tracer results

Data from Runkel, 2012
Silver Creek – Slug additions
High flow – June 2011

• Slug tests – dissolve NaCl in stream water – add as a slug to Silver Creek
• Cl – SC relationship established at SC-636 – convert SC to Cl concentration
• Chloride profiles integrated to estimate streamflow
  – $Q = \frac{\text{mass Cl added}}{\text{integrated area under Cl curve}} \times \text{unit_conversion_factor}$
• Slug results corrected due to unsteady streamflow & fact that slug additions not performed at same time every day
FIGURE 12
Slug Results (Adjusted), Silver Creek, June 21 - 24, 2011

Data from Runkel, 2012
Silver Creek – Continuous injection tracer dilution method

• Sodium Bromide injected on 6/23 from 8:00 -19:40 – plateau concentration reached in Silver Creek

• Flow at SC-68 & SC-106 estimated by $Q_x = Q_1 \frac{C_1}{C_x}$
  – $Q_1$ = injection rate; $C_1$ = injection concentration; $C_x$ = average concentration @ SC-68 & SC-106

• Slug tests suggest a loss downstream of SC-106

• Flow from SC-106 to SC-636 - $Q_d = Q_u - (MLR \times \delta X)$
  – $Q_u$ = streamflow @ upstream site; MLR = median loss rate from slug test; $\delta X$ = distance between 2 sites
Results of continuous injection

Gaining stream – tracer dilution w/ distance = increase in flow
Losing stream – exhibit steady concentration w/ distance

Flow loss estimated to be 5.3% to 9% - within margin of error?

Synoptic sweep # 1 affected by pump outage
Synoptic sweep # 2 more representative

Data from Runkel, 2012
Mine workings tracing

- Objective – verify flowpaths & determine travel times in workings
- Tracers injected into 517 shaft, Blaine tunnel and Silver Creek
- Sample locations – 517 shaft; St. Louis tunnel portal; Silver Creek @ SC-493; Argentine tailings seep
Silver Creek tracer investigation

- **Objective** – to help determine if Silver Creek loses water to mine workings or Argentine seep

- **Rhodamine WT & bromide injected continuously** for approx. 71 hours (10/5 @ 11:02 to 10/8 @ 9:38)

No rhodamine or bromide found in 517 shaft or Argentine seep above background concentrations
517 Shaft trace

- 50 gallon slug containing 3.22 lbs of lithium & 22.65 lbs of fluorescein – mixed with pH 2.7 water
- Chased with approx. 50,000 gallons of water from Silver Creek
- DTW in shaft 450 ft
- TD shaft – 600 ft?
- **Fluorescein**
  - first arrival at St. Louis tunnel: 15 hours – velocity 567 ft/hr
  - Peak @ 37 hours - velocity 230 ft/hr

- **Lithium**
  - first arrival at St. Louis tunnel: 15 hours – velocity 567 ft/hr
  - Peak @ 21 hours - velocity 405 ft/hr

- **Mass recovery** - 1100 hrs after injection
  - Lithium – 74%
  - Fluorescein – 58%
Findings
Fast transport by advection w/ help from chasing water

SE x-cut is open – few obstructions

Significant portion of fluorescein remains in storage - mixed with water in shaft?
residence time in pool behind collapsed portion of St. Louis tunnel?

Fluorscein / Li only found at St. Louis tunnel discharge
**Blaine workings tracing investigation**

- Objective – help evaluate potential connections between Blaine & associated workings & 517 shaft – St. Louis tunnel

- Slug injection - 5.9 lbs of fluoride – Dissolved 13.2 lbs of NaF powder in 8 gallons of Blaine mine water

 Slug poured into pool of water behind coffer dam & pumped over blockage towards Morris Cook Incline (6000 – 9000 gallons of pool water)
Blaine workings tracing investigation

- Samples collected in 517 shaft, Argentine seep & Silver Creek
- 517 Shaft
  - 10 hours – 1rst arrival of F @ 517 shaft - ave. velocity – 66 ft/hr
  - Peak @ 68 hours –ave. velocity 10 ft/hr
    - (Based on estimated distance to 517 of 660 feet)
- No detection of F in Silver Creek or Argentine seep
Conclusions

- Possible loss from Silver Creek to workings – though not certain
  - 5-9 % @ high flow  22-23 % at low flow
- The x-cut that connects the 517 shaft to the St. Louis tunnel is open
  and rapidly transports water
- Fairly open connections between Blaine workings and 517 shaft
- Primary sources of AMD / heavy metals - water in Blaine & associated workings
- Water in 517 shaft has some residence time
- Argentine seep not recharged by mine workings or gw
- Residence time in GW flow systems which discharge to mine workings is 5-15 years
- Discharge from St. Louis tunnel is primarily bedrock groundwater with seasonally varying inputs from workings along Silver Creek – Blaine, 517 shaft