

WALL ROCK GEOCHEMICAL CONTRIBUTIONS TO A HIGH-ARSENIC, ALKALINE PIT LAKE AT THE JAMESTOWN MINE, CALIFORNIA

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Introduction

The Harvard ore body at the Jamestown gold mine, located along the Melones fault zone in the southern Mother Lode Gold District, California (Fig. 1A), was mined in an open pit operation from 1987-1994. Dewatering produced a hydrologic cone of depression; recovery towards the pre-mining groundwater configuration has produced a monomictic pit lake presently 90 m deep (Fig. 1B). Water sources include ground water, springs, and rain/runoff. Rainfall is seasonal in this region, with arid summers and wet winters. Filtered (0.45 μm) arsenic concentrations, measured approximately quarterly at five depths March 1998-present, have fluctuated between 700 and 1000 $\mu\text{g/L}$ and are dominated by inorganic As(V) species.

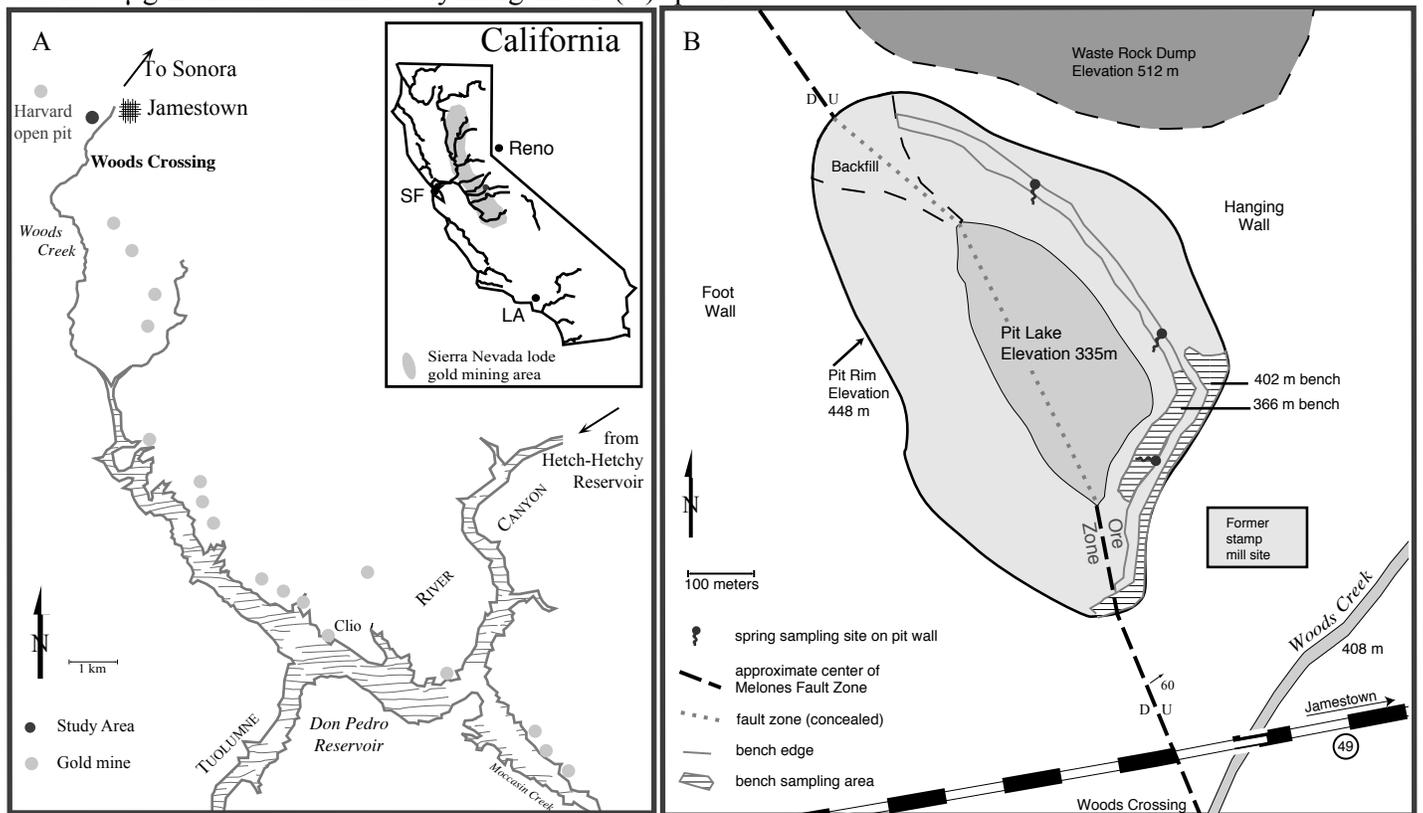


Figure 1. (A) Location of study area. (B) Site map.

Wall Rock Mineralogy and Arsenic Sources

Two major geologic units comprise the wall rocks. The hanging wall is composed of interlayered slate, metavolcanic and metavolcaniclastic rocks, and schists; the footwall rocks are chlorite-actinolite and talc-tremolite schists generated by metasomatism of greenschist facies mafic and ultramafic igneous rocks (Fig. 2). Alteration in the ore zone is characterized by intense CO_2 metasomatism and varying degrees of albitization, sericitization, and silicification associated with vein sets. The major source of arsenic is arsenian pyrite (Fig. 3); minor quantities of cobaltite, niccolite

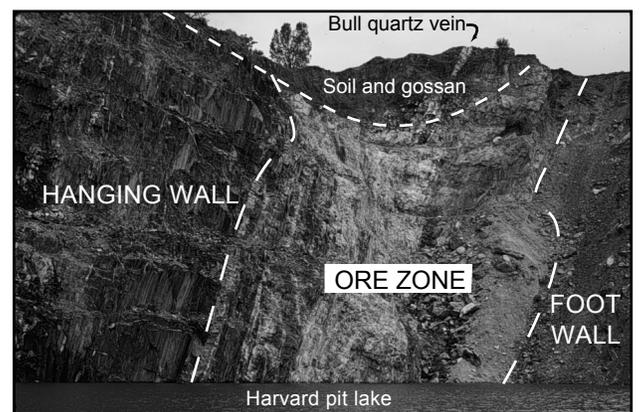


Figure 2. View to south of ore zone at the Harvard open pit.

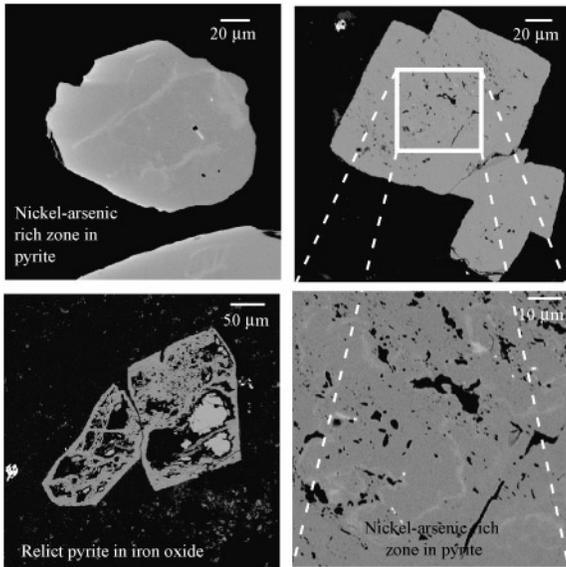


Figure 3. Backscattered electron images. Arsenic-rich areas are light irregular lines.

Water Composition

Water chemistry is dominated by Ca-Mg-sulfate-bicarbonate. Major ion concentrations and pH (nearly constant at 8.1) are controlled by equilibrium with calcite and magnesite. Sulfate concentrations continue to increase with time and currently are not limited by equilibrium with a solid phase. The lake shows monomictic stratification with respect to temperature and dissolved oxygen.

Arsenic concentrations exhibit seasonal variation; highest concentrations are associated with onset of winter storms. The influxes may be due to storm-related washoff of oxidized weathering products on the pit walls and in fractures. The arsenic is present as > 97% As(V) throughout the year at all depths. Arsenic concentrations may be limited by sorption but particulate materials, both suspended and as sediment, are sparse; pH conditions do not promote arsenate sorption.

Mass Contributions from Wall Rocks

An ARCVIEW 3d model (Fig. 5) was constructed from a partial topographic map of the site to constrain wall rock mass inputs. There is considerable (but unquantified) uncertainty in the volume and surface area calculations generated from the model (Fig. 6). Surface areas represented here are the minimum possible, since they do not incorporate any surface roughness or fracture-face area. Adding to the uncertainty in relative surface areas, the boundaries between the ore zone and the zones denoted hanging wall and foot wall are gradational, not clearly delineated.

Pyrite Oxidation Products: Temporary Sinks for Arsenic

Pyrite weathering products which accumulate on the pit walls in the ore zone during summer include jarosite, copiapite and hexahydrite, all of which incorporate arsenic at concentrations from <100 up to 1200 ppm. Arsenic concentrations are highest in fine-grained fractions of iron-rich weathering products (Fig. 4). Jarosite is present on joint surfaces and pit walls. Copiapite, a hydrated Fe-sulfate, forms efflorescences on the pit walls during summer. Areas around the copiapite efflorescences are encrusted with iron oxyhydroxides, mostly goethite.

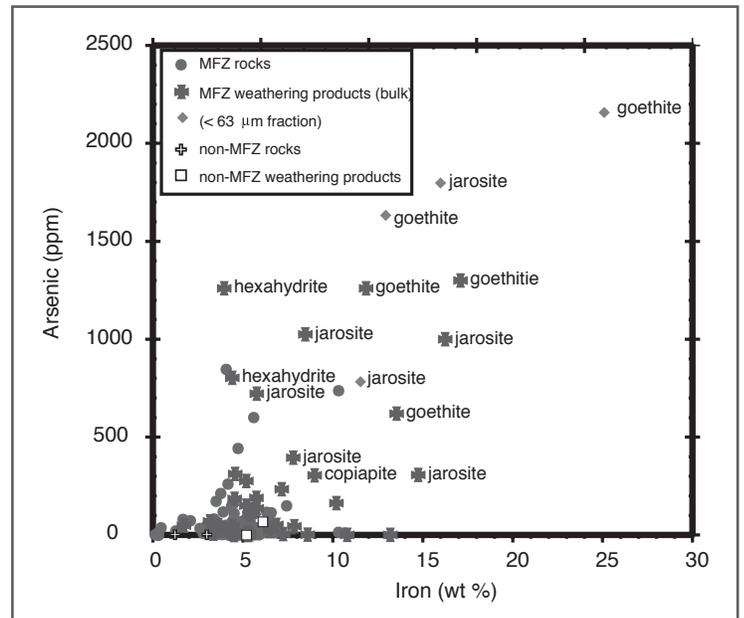


Figure 4. Association between iron and arsenic in rocks and weathering products in and near the Melones Fault Zone.

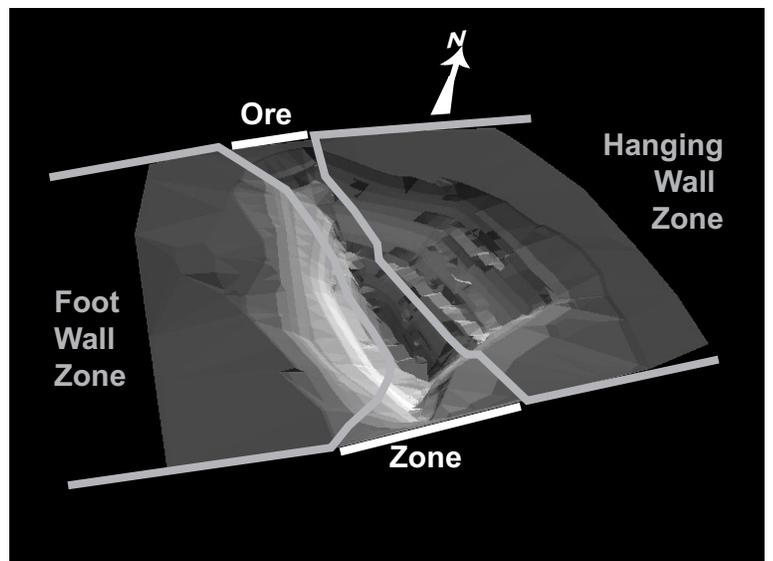


Figure 5. Surface area zones shown on image of Arcview model.

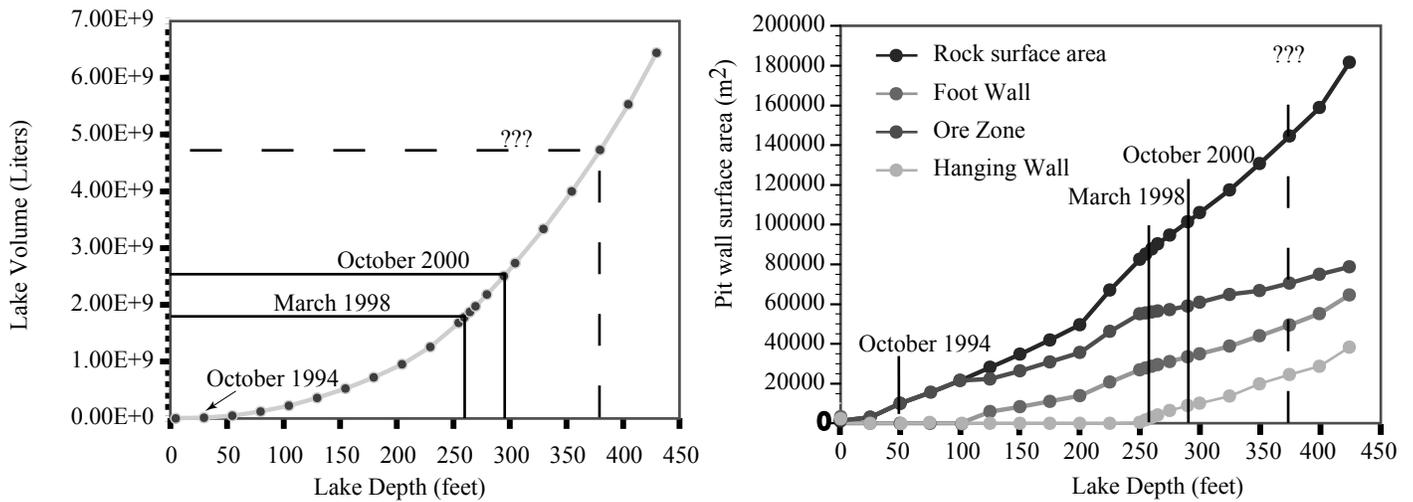


Figure 6. Pit lake volume (left) and minimum surface areas of hanging wall, foot wall and ore zone (right) as a function of lake depth, calculated with the Arcview model.

Using lake depth and unfiltered concentrations from October 2000, we calculated the total moles of arsenic, sulfate, and iron in the pit lake. From the results, we calculated how much arsenian pyrite was oxidized to produce all the arsenic in the pit lake, and how much non-arsenian pyrite was oxidized to produce the remaining sulfate assuming that all arsenic in the pit lake is from arsenian pyrite with average composition $FeS_{1.99}As_{0.01}$ (= 0.61 wt.% As), and that all sulfate in the pit lake is from arsenian pyrite or pyrite, not other sulfide phases. The mass of iron in the pit lake is deficient; most of the iron produced from pyrite oxidation is NOT dissolved or suspended in the pit lake. The masses and volumes of arsenian pyrite and pyrite represented by the dissolved and suspended arsenic and sulfate in the pit lake are shown in Table 1. We represent the "missing" iron as goethite left behind in the wall rock or precipitated into sediments.

Table 1. Quantities of arsenian pyrite and pyrite oxidized to produce masses of arsenic and sulfur in the Harvard mine pit lake

	MOLES DESTROYED	KG DESTROYED	DENSITY (kg/m ³)	CUBIC METERS DESTROYED
Arsenian pyrite	2.81E+06	3.39E+05	5000	68
Pyrite	1.03E+07	1.23E+06	4990	247
	MOLES CREATED	KG CREATED	DENSITY (kg/m ³)	CUBIC METERS CREATED
Goethite	1.31E+07	1.40E+06	4300	325

Several possible scenarios for the source(s) of pyrite to the pit lake waters were explored. Approximately 10% of the sulfate mass in the lake was introduced by springs on the hanging wall (see Fig. 1B). However, the springs have very low (<10 µg/L) arsenic concentrations. The source of the springs is a mixture of ground water and process water from elsewhere on the site, used to water the vegetation on the waste rock

pile north of the pit lake. For the remainder of the arsenic and sulfate, we considered the (minimum) surface area below the lake surface (corresponding to lake depth in October 2000) and modal abundance of pyrite and arsenian pyrite in the hanging wall, ore zone, and foot wall (Table 2). The scenario results are summarized in Table 3.

Table 2. Minimum rock surface area, and modal abundance of pyrite and arsenian pyrite in the foot wall, ore zone, and hanging wall used in mass calculations.

	Foot Wall	Ore Zone	Hanging Wall
Surface Area (m ²)	33487	59027	8953
% Pyrite	0.5	4	2
% Arsenian Pyrite	0	1	0

Table 3. Results of 4 possible scenarios for introducing arsenic to the pit lake.

<p style="text-align: center;">End-Member Case 1:</p> <p>All arsenic from arsenian pyrite in the ore zone</p> <p>Required reaction rind in ore zone: 11.5 cm thick</p> <p>contains: 68 kg arsenian pyrite 272 kg (no-As) pyrite</p> <p style="text-align: center;">Not reasonable! Too thick for short (6-year) history of pit lake filling.</p>	<p style="text-align: center;">End-Member Case 2:</p> <p>All arsenic from ground water (not including low-As springs)</p> <p>Currently not enough information is known to assess the ground water contribution, either about the water balance (rain + ground water + runoff - evaporation) or the chemical composition of ground waters entering beneath the pit lake surface.</p> <p style="text-align: center;">More data required!</p>
<p style="text-align: center;">End-Member Case 3:</p> <p>All arsenic from storm runoff which has dissolved/eroded oxidized arsenic-bearing phases</p> <p>Would require: 3350 m³ copiapite (with 300 ppm As) OR 1130 m³ jarosite (with 600 ppm As)</p> <p>Not reasonable! However, much less is required to account for seasonal concentration increases. For example, the rain of November 1998 brought in 240 kg As, which could be accounted for with 340 m³ copiapite or 130 m³ arsenian jarosite.</p>	<p style="text-align: center;">End-Member Case 4:</p> <p>All arsenic from reaction rind along fractures in the ore zone</p> <p>Assumed reaction rind along fractures: 0.2 cm thick</p> <p>3400000 square meters must be affected. This is approximately 60x the minimum surface area of the ore zone.</p> <p style="text-align: center;">Could account for much of the arsenic present in the pit lake</p>

Conclusions

Seasonal geochemical variations in the Harvard mine pit lake at the Jamestown Mine are imposed by winter rains, runoff which has interacted with the mine pit walls and fractures, and summer stratification. Early winter rains erode, partially dissolve, and transport arsenic-bearing salts derived from arsenian pyrite into the pit lake, temporarily increasing local arsenic concentrations. Additional ground water studies are required to determine the relative contributions of arsenic from wall rocks and from ground water along the mineralized zone, but enough arsenian pyrite is present along the ore zone to account for seasonal variations in pit lake arsenic concentrations.

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Acknowledgements

Technical Support:
Robert Jones, Stanford University
Chris Vandeven, Stanford University
Funding:
U.S. Geological Survey Mineral Resources Program
U.S.EPA STAR Fellowship U915154
NSF-EAR 9902859
Stanford University McGee Fund
The Lieberman family, for fellowship support