ENVIRONMENTAL OCCURRENCE AND IMPACTS OF ARSENIC AT GOLD MINING SITES IN THE WESTERN UNITED STATES

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ABSTRACT

Arsenic is a common element in the natural environment and is frequently a significant component in gold deposits of the western United States. Such deposits contain various forms of arsenic: arsenides, sulfides, and sulfosalts. Upon weathering such minerals routinely lower the pH of nearby waters, mobilizing arsenic and other metals. Arsenic may also be mobilized in aqueous environments where cyanide has been used to leach gold ores, resulting in high water pH. Incorrect construction of monitoring wells can result in contamination by cement/grout, which may raise pH causing arsenic concentrations to appear inordinately elevated.

Concentrations of arsenic toxic to humans and aquatic life have resulted from mining activities in some instances. Hence, regulatory agencies in the U.S. are requiring gold mining companies to comply with very restrictive arsenic standards.

The authors of this paper have been involved on many mining projects, mostly in the Western United States, where elevated arsenic content impacted the development of mineral deposits, or created a potential for environmental problems. Several case histories of the pre-mining arsenic content in surface and ground water on gold mining projects throughout western United States and Alaska are presented. The technical aspects of an elevated arsenic content in surface and ground water, mined areas, and waste disposals are discussed. Potential for arsenic contamination of water resources during and after gold mining operations with cyanide heap leach or other gold recovery methods are also presented. Several recommendations for mine operations of how to deal with the problem of elevated arsenic content in pyritic environments are offered.

Introduction

Arsenic is quite common in the natural environment, and ranks twentieth among the elements in abundance in the earth's crust. In particular, arsenic is found in high concentrations in sulfide deposits, where it is present as a native element or alloy. Over two hundred minerals are known to contain some form of arsenic. Out of these two hundred minerals, arsenopyrite is by far the most common.

Mining activities in sulfide ore deposits can accelerate the oxidation of minerals containing arsenic. As a result, typically acidic waters with elevated arsenic and other heavy metals concentrations can be related to many open pit or underground metal mines. This process is more severe in ore deposits with little or no carbonate rocks or soils present. Discharge of waters with high metal concentrations from abandoned mines into surface streams or percolation of waste rock or spent ore leachates into ground water systems can cause considerable environmental problems.

Environmental scrutiny and regulation of mining sites has escalated greatly worldwide in the last ten years. During the 1980's in the United States, regulatory agencies began to treat some mining wastes in ways similar to other industrial hazardous wastes, leading to litigation and cleanup costs that are often tens of millions of dollars. Arsenic is of particular interest because: **1)** it is a commonly encountered component of gold ores; **2)** it may be mobile under both highly acidic and highly basic conditions; and, **3)** it has a "notorious" reputation in the popular press and literature as a poison.

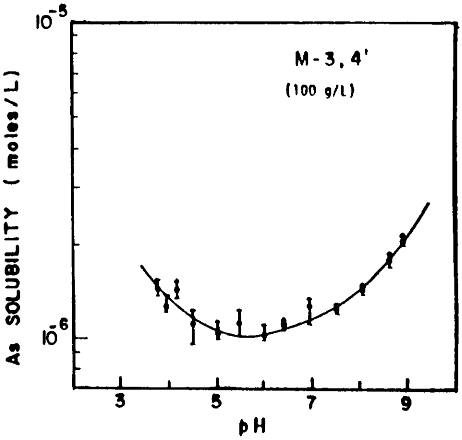
An arsenic value in excess of 0.05 mg/l in drinking water is considered a hazard to human health. Both the World Health Organization (WHO) and the U.S. Environmental Protection Agency (EPA) have adopted this value as a standard. Although arsenic poisoning is very rare, several cases of arsenic intoxication from water wells in mining areas have been reported in Nova Scotia, Canada (Grantham and Jones, 1977), Silesia, and Chile (U.S. Environmental Protection Agency, 1976).

Natural Occurrence of Arsenic

Arsenic commonly occurs in most rock types but only in the range of a few milligrams per kilogram (Boyle, 1974). Rose, et al. (1979) list median arsenic concentrations for most unmineralized igneous and sedimentary rock types as being between 1.0 and 2.1 mg/kg; shales have 12.0 mg/kg. Arsenic shows an especially strong coherence with gold in many deposits of the western United States. Most arsenic is present in sulfides, particularly pyrite, arsenopyrite, and as arsenides and sulfosalts. The arsenic content of gold ores may range from traces to a value greater than 5000 mg/kg.

The chemistry of arsenic in water is complex, involving chemical, biochemical, and geochemical reactions that together control the concentration, oxidation state, and form of soluble species. This paper deals only with practical generalizations regarding arsenic in mine waters. Detailed discussions can be found in Braman (1983), Irgolic (1982), Cherry et al. (1986), and Welch el. al. (1988). Stable forms of arsenic in solution are arsenate (As^{+5}) or arsenite (As^{+3}) oxyanions (Hem, 1985). The dominant aqueous species, under varying pH and redox conditions at equilibrium are shown in Figure 1 from Welch et al., (1988).

FIGURE 1



"Average" surface waters contain only about 2 micrograms per liter (ug/l) dissolved arsenic (Rose, et al. 1979). Even in mineralized areas prior to mining dissolved arsenic concentrations of surface waters are usually less than 20 ug/l. Adsorption by hydrous iron and aluminum oxides, or combination with sulfide in reduced environments appear to be the major inorganic factors that maintain arsenic concentrations at low levels in most waters.

Arsenic in Acid Environments

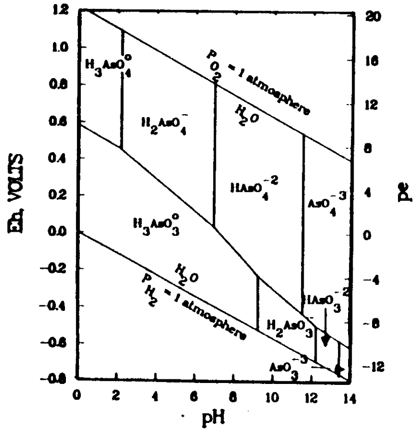
Weathering of gold, sulfide ores, is widely known to result in the generation of free acidity (low pH), and the liberation of trace metals, including arsenic, especially in noncarbonate terrains. Nordstrom and Ball (1985), for example, report pH values as low as 0.5 and arsenic concentrations above 30.0 mg/l in oxidizing mine waters from a northern California site.

In such waters, a small increase in pH results in a marked decrease in dissolved arsenic concentration. Most of the arsenic will rapidly adsorb onto ferric oxyhydroxide particles and settle to the bottom of the adit, stream, or settling pond. Some fraction of the arsenic may still be mobile in surface waters, adsorbed on colloid sized particles of the iron oxyhydroxides. Thus, bottom sediments of streams, ponds and reservoirs are the sinks where insoluble arsenic accumulates. For similar geochemical reasons, dissolved arsenic concentrated in smelter wastes and tailings tends not to migrate long distances in surface waters.

Arsenic in Non-Acid Environments Cyanide-Related

Arsenic is also soluble in some high pH environments along with manganese, zinc, chromium, nickel, selenium, vanadium, and uranium. Such environments are common at cyanide-leach gold sites, where leachates from spent ores often have a pH above 9.0. The partitioning of arsenic between the soluble and solid phases is partially controlled by pH, as is shown in Figure 2 (Cherry, et al., 1986) for gold tailings from South Dakota.

FIGURE 2



Arsenic in/near Reduced Ores

Welch et al. (1988) have summarized arsenic concentrations in ground waters of the western United States. They report the following:

Ground Water Sources	Range of Maximum Arsenic Concentrations (mg/l)
Mining Areas	0.13 - 48.00
Basin - Fill Deposits	0.05 - 2.75
Volcanic Areas	0.17 - 3.40
Geothermal Areas	0.08 - 15.00

The referenced study does not report pH measurements or analyses for other constituents, so it is not possible to determine the redox conditions of these mine-related waters. Several are from tailings in gold districts, thus it is assumed the high concentrations result from the oxidation of sulfides. Other ground waters may be associated with the relatively reducing geochemical conditions of sulfide-rich ore bodies that are largely isolated from surficial weathering. Boreholes and wells yielding water from sulfide-rich zones of unmined and unoxidized ore often exhibit pH values between 6.0 and 8.5, low total dissolved solids (TDS) and sulfate concentrations, and high arsenic concentrations, between 0.05 and 1.0 mg/l (east-central Idaho). Once such an ore is exposed, the entire geochemical environment changes, oxidation begins, and net acid generation can develop. Such drastic changes between pre-mining and post-mining geochemical environment may be especially pronounced in non-carbonate, hard rock areas where the local geologic materials and waters provide little buffering capacity. In these situations, water quality data from monitoring wells in or near the surface ore may give no indication of future oxidation and acid generation.

Environmental Regulations

U.S. regulations setting acceptable concentrations of arsenic and other metals in mining related waters have become incredibly complex, but usually relate to the concentrations deemed acceptable in drinking water supplies and in surface waters containing aquatic life.

	U.S. Drinking Water Standard	U.S. EPA Aquatic Life Standards Fresh Water	
	mg/l	Acute mg/l	Chronic mg/l
Arsenic	0.05	0.36	0.19

This paper does not discuss the complexities of the regulations, such as determination of arsenic species, sample collection, and preservation procedures, etc., but these details can become quite important in determining the arsenic concentrations that are biologically available. In the western United States, most modern gold mines are being developed in rural areas, on government-managed land, away from large populations. As such, the surface and ground waters are often not to be used for drinking purposes. Thus the aquatic life standards would often be the most restrictive.

Arsenic Occurrence at Gold Mining Projects in the Western United States

Elevated arsenic content in surface and ground water is found in most gold mining projects in the western United States. Here, the process of acquiring a permit to open a new mine or to expand an existing mine requires an extensive hydrologic study of the background concentrations of trace metals in the surface and ground waters of the mine sites. Hydrologic studies must also address the environmental consequences of the proposed project. Great attention usually concentrates on the potential impacts of spent ore and waste rock disposal on the surface and ground water quality, many years after cessation of the mining operation.

The authors of this paper have been involved on numerous mining projects, mostly in the western United States, where elevated arsenic content created environmental problems for the mining operation. Discussion of several examples from open pit or underground mining operations follows. The case histories presented here do not identify the owner and name of the project due to the terms of our consulting agreements.

Study of background hydrologic conditions at seven gold mining projects in the western United States indicates that elevated content of heavy metals and arsenic, in particular, are present in surface and ground water prior to the mining operation (see following Table).

TABLE 1

Arsenic Concentrations in Surface and Ground Water at Gold Mining Projects in Western United States

Location	Maximal Arsenic Concentration in Pre-Mining Conditions			
	Surface Water (mg/l)		Ground Water (mg/l)	
	As	pH	As	pH
South Dakota	0.446	4.8	0.263	7.5
Central Nevada	No perennial streams		0.85	8.7
Central Idaho	0.031	5.6	1.4	6.8
Northeast Idaho	0.029	6.9	2.7(1)	>11.0
			1.0	6.5
Central Colorado	26.0	3.2	19.0	4.3
South Alaska	0.011	7.9	0.47	8.2
North-Central Washington	0.02	8.1	0.012	8.1

(1) Well contaminated by cement as discussed in this paper

In Colorado, where extensive gold and silver mining occurred at the end of the 1800's, there are many abandoned mine sites with acid mine drainage. Most of these mines discharge water with low pH due to the oxidation of the sulfides within the mine workings. At some mine sites, tailings from the ore processing were disposed into local water drainages. One example is the Yak Tunnel, near Leadville, Colorado. The Yak Tunnel is 5.8 km long and was completed as a drainage gallery in 1912. Since then, 1,600 to 3,800 m^3/day of acid water (pH 3.5) with a high trace metal content has discharged into the upper reaches of the Arkansas River. The elevated arsenic content (approximately 0.44 mg/l) is of great concern to the regulatory agencies. A permanent treatment plant for the discharged water is being considered.

The Minnesota Mine near Empire, Colorado discharges only about 800 m^3/day of acid water (pH 4.5) from the extensive underground workings. However, due to the disposal of gold mill tailings in the local drainage, the surface water is highly acidic (pH 2.8), with arsenic content up to 26 mg/l, during low flow. Recently, a minable gold ore deposit was discovered in the area of the Minnesota Mine. The mining company interested in developing an open pit gold mine in this area, was held responsible for the clean up of the past mining disturbance.

Many recently proposed gold projects involve open pit mining. There is considerable experience with abandoned underground gold mines discharging poor quality water, but experience with abandoned and water-filled open pits in the western United States is largely lacking. This lack of historical data together with environmental pressures have encouraged regulatory agencies and mining companies to make predictions of future water quality, including future arsenic concentrations. At one open pit gold site in north-eastern Idaho, it is proposed that the pit will not be backfilled with waste rock, and thus will fill via surface water runoff, precipitation, and ground water inflow. The arsenic content of this ore ranges between 600 to 3000 mg/kg. Although the pre-mining surface and ground water quality are well known, prediction of water quality in the abandoned open pit is difficult. Using pre-mining surface and ground water quality and quantity data, simple mass balance calculations have been developed to predict water quality during and after pit filling. These calculations have assumed that pit water quality during and after mining will be similar to pre-mining inputs, which is probably incorrect. Such mass-balance calculations are not capable of yielding accurate predictions of arsenic concentration because they do not consider the impacts of oxidation-reduction reactions, absorption processes, or the role of microorganisms.

Potential Solutions for the Mining Industry

There are several possible approaches to reducing arsenic concentrations in mine water, usually considered either passive or active.

Passive Approaches

Many natural soils and man-made clay liners have the capacity to attenuate arsenic and other trace metals from mine discharges and/or from leachates percolating through waste rock or spent ore. These materials attenuate potential contaminants via cation and anion exchange, sorption, precipitation, and biodegradation.

Study of the potential for surface and ground water contamination by arsenic at the Sunbeam Gold Mine in central Idaho (Straskraba et al., 1988) demonstrated that the geochemical characteristics of the site would prevent arsenic migration from the spent ore into local ground waters. Laboratory testing with an application of two different methods confirmed that arsenic in the alkaline spent ore leachate would be removed by attenuation on acidic illite clays and by the presence of hydrous iron-oxide impurities.

Similar studies have been performed for mining sites in Nevada (Rouse and Pyrih, 1985) and South Dakota (Cherry et al., 1986). An extensive study on attenuation of pollutants by clay minerals in municipal landfill leachate, applicable to mining sites, was published by Griffin and Shimp (1978). Their study indicated that heavy metals were strongly attenuated by even small amounts of clay in laboratory column tests. They concluded that montmorillonite clays have the highest attenuation capability, followed by illite and then kaolinite. The cation exchange capacity of the clay minerals is considered to be the dominant attenuation mechanism responsible for removal of heavy metals from the leachate.

Marshy areas or wetlands can also remove metals from mine discharges (Kleinman, 1985; Holm and Jones, 1985). Allowing acid mine discharges to percolate through either natural or man-made wetlands seems to be effective at removing redox-sensitive constituents such as iron thus it should be useful at lowering arsenic concentrations. Use of wetlands may be limited where: insufficient flat surface area is available; soils development is inadequate; and, growing seasons are short.

Active Approaches

Several methods of active water treatment for arsenic removal are potentially available to the mining industry. Such methods involve chemical precipitation, sorption, and reverse osmosis. Arsenic removal by chemical precipitation with Fe^{2+} and Fe^{3+} is considered as most effective and commonly used (Rosehart and Lee, 1972). Removal of the arsenic from mine effluents by chemical precipitation ranges from 94 to 98 percent effective.

Arsenic removal from mine waste waters by sorption was tested and reported by Gupta and Chen (1978), and Lee and Rosehart

(1972). Both groups concluded that activated carbon adsorption is a feasible method. This method is, however, more expensive than chemical precipitation, and may not be cost effective. Reverse osmosis is not considered as cost effective for the large volumes of water treated in typical mining projects. The reverse osmosis method may be suitable for treating drinking water supplies for mining towns.

Another method of acid mine water control which has been successfully applied in several coal mines in the eastern United States is a combination of spray liquids and controlled release pellets. These are based on a blend of polymers, bacteria-inhibiting agents, and other chemicals, usually formulated for a site specific treatment. By inhibiting iron-oxidizing bacteria, these commercial products retard new acid generation. Experiments with the method were reported by Kleinman et al. (1981). To our knowledge these acid generation retardants have not been used in any metal mines in the western United States.

Active treatment approaches are invariably more expensive than passive approaches, but are sometimes favored by regulatory agencies in the United States where the political/environmental factors are sensitive. In addition, the efficiency of active water treatment is easier to predict and verify than the results of passive approaches.

Conclusions

The authors of this paper believe that more attention and research should be concentrated on the use of passive approaches for attenuation of arsenic and other trace metals. Such approaches can be quite effective in removing heavy metals from mine effluents in certain situations, and their effectiveness should be evaluated prior to choosing the more expensive active treatment options.

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