Impact of gold mining on the aquatic system: a case study at Furtei (Sardinia, Italy)

Rosa Cidu, Stefania Da Pelo, Franco Frau

Dipartimento di Scienze della Terra, Università di Cagliari, via Trentino 51, 09127 Cagliari, Italy

Abstract An epithermal, high-sulphidation, gold deposit, hosted in Tertiary volcanic rocks, was exploited from 1997 to 2003 at Furtei in Sardinia (Italy). Gold and silver were recovered by cyanidation from oxidized ores, and by flotation from sulphide ores. Following bankrupt in 2008, sulphide-rich materials derived from exploitation, and processing residues were left on site. Cyanide in the tailings impoundment underwent natural degradation. In 2011, cyanide concentrations below the Italian limit for industrial effluents were observed, but concentrations of dissolved toxic components, especially ammonium, aluminum, arsenic, copper, iron and manganese, in the tailings impoundment were much above standard values. Analyses of waters draining the mining area showed that waste materials disposed on dumps, flotation tailings confined in an impoundment, and mineralized rocks exposed in open pits have a high capacity of acid drainage generation and release of contaminants. During the rainy season, the waste rock dumps produce acidic, highly contaminated drainage that flows downstream of the mine and poses a hazard to a cultivated plain. Useful data for the implementation of reclamation programs are provided.

Key Words gold mine, cyanide, mine closure, Furtei Sardinia

Introduction

In the mining industry, cyanide is primarily used for leaching gold and silver from ores. The high toxicity of cyanide in regard to the health of humans, wildlife, and aquatic life requires the development of a cyanide-management plan. Cyanide concern in the local population of mining areas has been highlighted by incidents at mine sites involving the inadvertent release of cyanide to the environment. Aside from the potential for environmental threat, such incidents broadly and negatively affect the image of the mining industry and have led to emotional and damaging political responses (Botz *et al.* 2005).

A small-scale gold mining operated near Furtei (Sardinia, Italy) from 1997 to 2003. Solutions bearing cyanide and other chemical species dissolved from the ore were disposed in a tailings impoundment. Sulphide-rich wastes were dumped on site. Following a stand-by period, cyanidation was resumed few months in 2008, then, the society underwent bankrupt in December 2008; consequently, the decommissioning plan was not undertaken. This study is aimed to investigate the impact of gold mining on the aquatic system after seven years since cessation of mining and processing.

Study area

The high-sulphidation, epithermal gold deposit at Furtei is hosted in calc-alkaline andesitic-basaltic rocks of Oligo-Miocene age. At Is Concas, Santu Miali and Su Masoni ore bodies (Fig.1), primary mineralization mainly consists of pyrite, followed by enargite, with minor amounts of luzonite, tennantite and chalcocite. Sphalerite and wurtzite are more abundant at Sa Perrima ore body. The primary mineralization was covered by an oxidized cap extending 10–50 m downward, mainly composed of Fe oxyhydroxides, gypsum, Cu–Fe–Al sulphates and arsenates (Da Pelo *et al.* 2009 and references therein). Host rocks show four alteration facies: vuggy and massive silica, advanced argillic, argillic, and propylitic (Ruggieri *et al.* 1997). Gold exploitation began by open pit mining in 1997; estimated reserves were 2150 000 metric tons with 2.82 g Au per ton.

From 1997 to 2001, gold and silver were extracted from the oxidized ore by cyanidation. From 2001 to February 2003, sulphide ores were processed by flotation for recovering copper concentrates. Tailings from ore processing were disposed in an impoundment (Fig. 1). Seeps from the impoundment were observed since 1998; they have been collected in a well and pumped back to the impoundment. Pit lakes occurred at Sa Perrima, Is Concas, Santu Miali Cima and Santu Miali Est. They were filled by rainfall, and by interception of the groundwater table. The pit lakes at Santu Miali Cima and Sa Perrima have been completely recovered in 2004 and 2007, respectively.

The long-term mean rainfall in the area is 500 ± 119 mm/y and mean annual temperature 16.5 ± 1 °C. The dry period (rain <40 mm/month) usually extends from June to September. The area hosts two important reservoirs: Sa Forada and Casa Fiume. The Sa Forada lake lies within the mine concession. It is an artificial basin fed by water from an upper reservoir via a 30-km gallery. Water in the Sa Forada lake is renewed weekly, and is drained to the lower Casa Fiume reservoir (Fig. 1). From here water is distributed over a large area in southern Sardinia, and mainly used for irrigation. The only important water course in the area is the

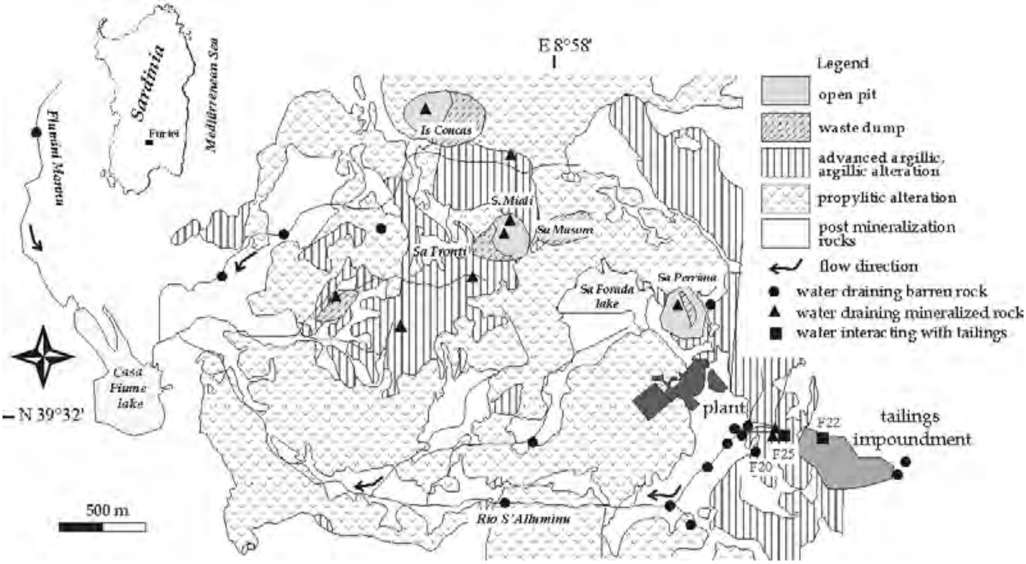

Figure 1 *Schematic map showing the gold mine area at Furtei (Sardinia, Italy), main alteration facies in Tertiary volcanic rocks and the location of water samples.*

Flumini Mannu. This river flows outside of the mining concession, but it may occasionally receive the flow of small tributaries draining the mining area. Surface drainage in the area consists of ephemeral streamlets, which flow strongly depends on rainfall. Due to the occurrence of argillic and advanced argillic alteration, groundwater circulation in the mining area has been estimated to be very low (hydraulic conductivity: 10^{-7} m/s), with flow directions mostly from East to West (Progemisa 2003). A shallow phreatic aquifer (depth: <20 m) occurs in the Quaternary alluvial sediments; the water table level may rise to surface during the rainy season and originates ephemeral springs, especially along the Rio S'Allumimu stream. A confined aquifer (depth: 20–130 m) is hosted in the volcanic sequence with intercalated lacustrine calcareous layers. This aquifer has been intercepted by prospecting drills that showed flow rates in the range of 0.02 to 0.2 L/s. Agriculture activities occur only outside of the mine property (specifically to the West and to the South-East), whereas livestock is sometimes grazing in areas within the property.

Methods

Open pit exploitation at Furtei, was preceded and accompanied by studies on the environmental impact, particularly on the aquatic system. Pre-mining baseline studies were carried out in 1994: waters interacting with mineralized rocks were acid (lowest pH: 2.3), had a dominant sulphate–chloride composition, and high levels of contaminants, up to 2000 mg/L Al, 29 mg/L Cu, 11 mg/L Zn, 4 mg/L Ni, 3 mg/L Co, and 0.4 mg/L As (Cidu *et al.* 1997).

Hydrogeochemical surveys were carried out since 1997 when gold exploitation started. Waters draining non mineralized rocks, shallow and deep groundwater interacting with mineralized rocks, and waters interacting with tailings were collected under different seasonal conditions; locations are shown in Fig. 1. At each sampling site, temperature, pH, redox potential (Eh), alkalinity, and conductivity were measured. Water samples were filtered in situ through 0.4 µm pore-size polycarbonate filters, and acidified upon filtration for metal analyses by ICP-AES and ICP-MS. Anions were determined by ion chromatography on a filtered unacidified aliquot. Readily released cyanide was determined by photometric method (Merck SQ 118, methods 30 and 31, λ 585 µm) on an unfiltered unacidified aliquot; freshly prepared standards were used for calibration; diluted aliquots were used for evaluating analytical errors. Cyanide analyses were carried out within few hours upon water collection.

Speciation calculations were carried out using the PHREEQC computer program (Parkhurst and Appelo 1999) and the minteq.dat thermodynamic database in which cyanide species are provided for several cations (Ag, Ba, Ca, Cd, Cu, Fe, Hg, K, Li, Na, NH_4, Ni, Sr, Tl, Zn).

Results

Waters in the Furtei area show a large variability in pH and dissolved components (Fig. 2). Waters draining non mineralized rocks are characterized

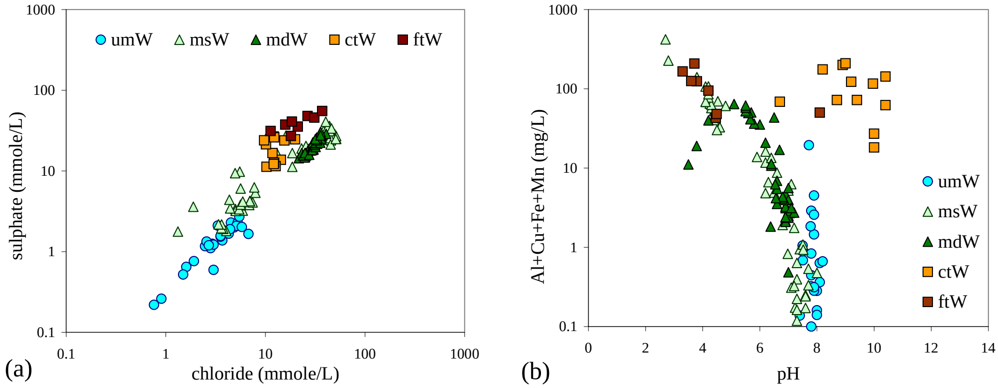

Figure 2 *Concentrations of sulphate versus chloride (a), and dissolved metals versus pH (b) in the Furtei waters; umW = water draining non mineralized rocks, msW = shallow groundwater draining mineralized rocks, mdW = deep groundwater draining mineralized rocks, ctW = water interacting with cyanidation tailings, ftW = water interacting with flotation tailings.*

by near neutral pH, relatively low total dissolved solids (up to 1.5 g/L TDS), chloride more abundant than sulphate, and low concentrations of harmful metals. The chemical composition of these waters, either under exploitation or after mine closure, did not significantly change with respect to pre-mining conditions.

Acidity, TDS, sulphate and metals significantly increase in waters interacting with the mineralized rocks. Waters interacting with tailings show alkaline pH under cyanidation, and acid pH under flotation. These waters have high concentrations of sulphate and metals.

Figure 3 shows cyanide concentrations versus time in water at the tailings impoundment (F22), at a seepage (F25) and borehole (F20) located downstream of the impoundment (see Fig. 1 for location). During the period of ore processing by cyanidation (1997 to 2002, and few months in 2008), cyanide concentration in the impoundment was in the range of 60 to 400 mg/L (Fig. 3), and pH varied from 8 to 11. In this period, the cyanide solution was pumped back to the processing plant for reusing. In 2003, under ore processing by flotation, cyanide concentration in the impoundment was in the range of 80 to 30 mg/L, and pH became acidic (about 4) due to the presence of pyrite in the flotation tailings.

Cyanide seeps immediately downstream of the impoundment were firstly observed in 1998, one year after exploitation started. The time lag between the start of mining and the arrival of the cyanide-contaminated groundwater probably reflected a combination of factors including the incremental nature of mining and processing. Cyanide concentrations in the seep rapidly in-

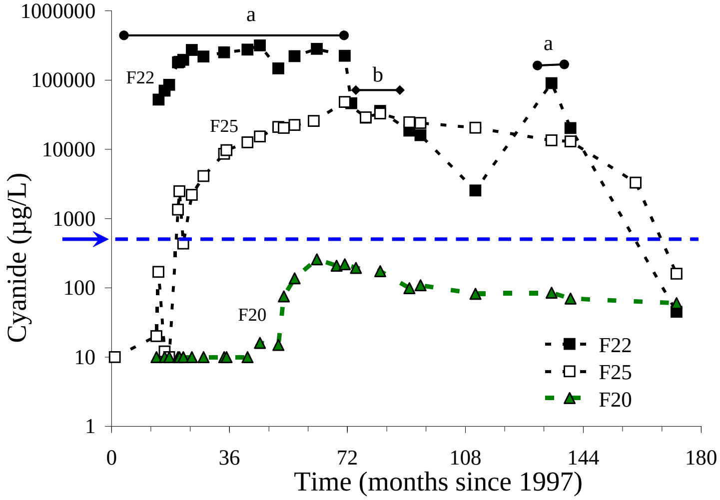

Figure 3 Concentration of cyanide in water at the tailings impoundment (F22), seepage out of impoundment (F25), and borehole (F20). The lines a and b indicate ore processing by cyanidation and flotation, respectively. The arrow and dashed line show the Italian limit for industrial effluents (500 µg/L CN^-).

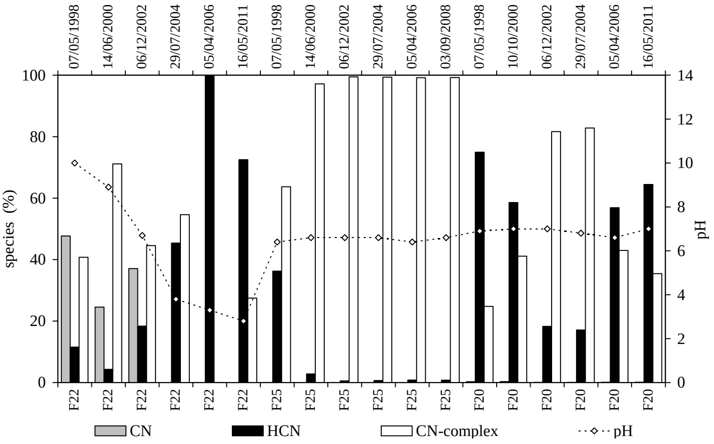

***Figure 4** Cyanide species (%) and pH values in selected water samples collected at the tailings impoundment (F22), and seepage (F25), and borehole (F20) located downstream of impoundment.*

creased above the Italian limit (500 µg/L) for industrial effluents (Fig. 3). Cyanide in the borehole water was first observed in 2001; peak values (250 µg/L cyanide) occurred in 2002, but did not exceed the Italian limit (Fig. 3).

Since 1998 to present (2011), all seeps from the impoundment have been collected in a well and pumped back to the impoundment. The collecting system avoided the downstream dispersion of the cyanide-contaminated water, as testified by two piezometer controls located about 200 m downstream in which cyanide was always found below 100 µg/L.

Figure 4 shows the relative abundance of cyanide species calculated by PHREEQC, together with pH values, in selected water samples at the tailings impoundment (F22), and at the seepage (F25) and borehole (F20) located downstream of the impoundment.

Significant amounts of the highly toxic species, free cyanide (CN^-), were only observed in water at the impoundment under elevate concentrations of cyanide (see Fig. 3) and alkaline pH conditions. The toxic species HCN dominated in the water F22 under acidic conditions, as well as in the borehole F20 at near-neutral pH and low concentration of cyanide. Less toxic, metal cyanide complexes were very abundant at any pH condition and reached 100% abundance in the seepage F25. The most abundant complexes were negatively charged, and incorporated copper, calcium, and iron, such as $[Cu(CN)_3^{-2}]$ up to $2.9*10^{-3}$ mole, $[Cu(CN)_4^{-3}]$ up to $4.2*10^{-4}$ mole, $[CaFe(CN)_6^{-2}]$ up to $1*10^{-4}$ mole, $[Fe(CN)_6^{-4}]$ up to $5.4*10^{-5}$ mole.

Main hazards to the aquatic system

In the Furtei mining area, acidic water with extreme concentrations of Al, As, Cu, Fe, Mn and Ni are at present confined in the Is Concas and Santu Miali pit lakes, and in the tailings impoundment. Despite confinement, these waters pose a serious hazard to the aquatic system. In fact, the water level in pit lakes rises dramatically in the rainy season, and might overflow under heavy rain events, especially at Is Concas. Considering that storm events are occurring more frequently in recent years, pit lakes should be urgently recovered.

Since the beginning of gold exploitation, cyanide has been the main concern for the local population. In 2011, the more reactive cyanide species initially associated with the processing residues have naturally degraded within the tailings impoundment area, likely resulting from volatilization (decrease in pH), leaching, and bacterial degradation. Cyanide degradation resulted in high concentrations of nitrogen compounds, such as nitrate and ammonium (up to 114 mg/L NH_4^+ in the sample F22). However, relatively insoluble electrically neutral cyanide compounds (e.g. CuCN) might persist in the impoundment, and the natural attenuation of cyanide in the solid portion of gold mill tailings must be verified. Leaching tests on cyanidation tailings carried out in 2006 (Da Pelo *et al.* 2009) showed leachates with variable pH (between 6.2 and 9.7, depending on sulphide content in tailings), and cyanide concentrations in the range of 110 µg/L to 3 mg/L. The relatively low cyanide in leachates might indicate that cyanide has probably disappeared from the solid phase, which is in agreement with observations at other sites (Zagury *et al.* 2004). Despite cyanide degradation, the pumping system collecting the seeps from the tailings impoundment should be maintained in operation for avoiding the dispersion of the highly contaminated water in the downstream plain.

Other hazards to the aquatic system are represented by pyrite-rich waste dumps, especially at Sa Fronti (see Fig. 1 for location). Here, rock varies in size from small particles to large boulders. During the rainy season, these materials produce highly acidic (pH 2), and extreme contaminated drainages that flow downstream to a cultivated plain. A drain system able to collect the rainwater should be engineered for minimizing runoff onto the dump that would allow reducing the oxidative dissolution of sulphides.

Conclusions

A small scale gold mine operated from 1997 to 2003 at Furtei in Sardinia. Oxidized and sulphide ores were processed by cyanidation and flotation, respectively. Mining-related wastes and processing residues were left on site. Following the society bankrupt in 2008, the Sardinia Regional Government was charged for all legacies related to the abandoned mine; at present, investigations aimed to plan remediation actions are ongoing.

The waters draining the mining area have high acidity and elevate concentrations of metals. The main sources of contamination are waste materials disposed on dumps, flotation tailings confined in an impoundment, and mineralized rocks exposed in open pits; these materials have a high capacity of acid drainage generation and release of extreme concentrations of contaminants. Results of this study can help the Sardinia Regional Government in the implementation of reclamation programs.

Acknowledgements

The authors thank financial support by the former Sardinia Gold Mining, the University of Cagliari and the Fondazione Banco di Sardegna.

References

Botz MM, Mudder TI, Akcil AU (2005) Cyanide treatment: Physical, chemical and biological processes. In: Developments in Mineral Processing, MD Adams (Editor) Vol. 15: 672—700

Cidu R, Caboi R, Fanfani L, Frau F (1997) Acid drainage from sulfides hosting gold mineralization (Furtei, Sardinia). Environmental Geology 30: 231–337

Da Pelo S, Musu E, Cidu R, Frau F, Lattanzi P (2009) Potential release of toxic elements from rocks and mine wastes at the Furtei gold mine (Sardinia, Italy). Journal Geochemical Exploration 100: 142—152

Parkhurst DL, Appelo CAJ (1999) User's guide to PHREEQC (version 2) — A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. USGS Water-Resources Investigations Report 99–4259, Denver, Colorado

Progemisa (2003) Caratterizzazione idrogeologica Permesso di Ricerca 'Costa Sa Tiria'. Report Sardinia Gold Mining SpA, vol. 28 (in Italian)

Ruggieri G, Lattanzi P, Luxoro SS, Dessì R, Benvenuti M, Tanelli G (1997) Geology, mineralogy and fluid inclusion data of the Furtei high-sulfidation gold deposit, Sardinia, Italy. Economic Geology 92: 1–19

Zagury GJ, Oudjehanib K, Deschênes L (2004) Characterization and availability of cyanide in solid mine tailings from gold extraction plants. Science of the Total Environment 320:211–224