Technical and Economic Criteria for Processing Mercury-Containing Tailings

Final Report

United Nations Environment Programme
Division of Division of Technology, Industry, and Economics
Chemicals Branch

April 2010

IOMC
INTER-ORGANIZATION PROGRAMME FOR THE SOUND MANAGEMENT OF CHEMICALS
A cooperative agreement among UNEP, ILO, FAO, WHO, UNIDO, UNITAR and OECD

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1 Summary and conclusion

Tailings are a common consequence of metal ore mining. Depending on the mineralogy of the mined ore and the process employed the tailings may contain elevated concentrations of toxic pollutants among them mercury. Metal ores that frequently contain mercury as an impurity include gold, silver, copper and zinc. Here mercury in most cases may occur as a sulphide but also elemental mercury may be found. At several stages of the ore processing mercury may be mobilized and released into the environment, most notable in gaseous form during roasting, smelting and refining operations. A part of the mercury remains in the liquid and solid phases that after processing are dumped in tailings. Mercury may also be found in tailings from gold and silver amalgamation. It is estimated that the application of this method in the past 500 years released around 300,000 t mercury to tailings and other environmental media.

Tailings, if not properly designed and managed, may pose a serious risk to the environmental and human health. Mobilization of pollutants may occur via wind erosion, water erosion, leaching and by evaporation and could cause widespread contamination of soils and water systems. Several examples from different parts of the world are described that are characterized by heavy contaminations.

In the recent years rising prices for precious metals and improvements in processing technologies gave new economic incentives to consider the extraction of precious metals from low-grade tailings. If along with other metals mercury could be extracted and separated, reprocessing of tailings would enable economic profits and environmental benefits at the same time.

There is a large number of tailing reprocessing projects that has been started and often already concluded in the past decades. Some exemplary projects are described that deal or dealt with tailings from gold and silver mining. Two of these projects are going to treat mercury containing tailings: The large scale Laguna project in Mexico that intends to treat historic silver mining waste and the Singida project in Tanzania where scattered tailings from recent artisanal small scale mining are planned to be reprocessed. In Mongolia, reprocessing is proposed as one possible approach to remediate gold mining tailings.

Whether or not the reprocessing of a tailing is economically, technically and legally feasible cannot be said without a detailed evaluation. The phases of such an evaluation and its major parameters are described, providing a guideline for initial (scouting, scoping) as well as the final evaluation stages such as pre-feasibility and feasibility studies.

Finally, the report provides an exemplary description of Andacollo (Chile), a polluted mining area where mercury is occurring both as a mineral in other metal ores and as a remainder of historic gold ore processing. In Andacollo, mercury has been in use since centuries for the small scale and semi-industrial extraction of gold. A large number of tailings both from present as well as from historical mining pose a permanent threat to human health and the environment. The description provides an overview of the current situation, the available information of the tailings and discusses challenges and opportunities of their reprocessing.

Based on available information the conclusion may be drawn that reprocessing of mercury containing tailings could be a viable remediation option for certain sites. Nevertheless, a site specific analysis must be conducted to verify its technical and economical feasibility. Moreover, the mercury specific problems must be addressed in the planning of any reprocessing. Without proper control of mercury emissions during the tailing processing and possibly a removal of mercury from the waste, the environmental impact would be negative. In general, the global economic situation is actually (2010) very in favour of reprocessing projects. With gold prices hitting record high, low grade tailings become more and more interesting for mining companies and investors. Numerous examples show that even old or scattered small tailing piles from historic or recent amalgamation procedures are now getting in the focus of prospectors. This might be a unique chance to get rid at least of some part of toxic mining wastes that have accumulated in almost 500 years intensive use of mercury in gold and silver ore processing.

2 Introduction

2.1 Mercury containing tailings as a threat to human health and the environment

Tailings are a residue of raw material or waste separated out during the processing of mineral ores[1]. They are a common consequence of mining and can be found in all parts of the world where mining takes or took place. The number of abandoned mines has been estimated to be going into millions (UNEP 2001). Not all mining activities produced tailings, but the number of tailings worldwide is certainly tremendous. Unfortunately, even on national levels inventories of abandoned mines or mine tailings are mostly incomplete if existing at all, so that the full dimension of problems resulting from historic and present mining activities is not yet clear.

Fig. 1: Tailings from hydraulic mining, Shady, near Patterson, California, USA[2]

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[1] Definition according to US EPA (1997) Terms of Environment: Glossary, Abbreviations and Acronyms. http://www.epa.gov/OCEPAterms/

[2] U.S. Geological Survey. These tailings were deposited in the creek valley as an alluvial fan, and were afterward partly eroded. http://libraryphoto.cr.usgs.gov/htmlorg/lpb198/land/ggk03240.jpg Photo: Public Domain.

In the earth crust mercury is a rather rare element, but following the plate boundaries distinct ‘mercury belts” exist where the mercury content of mineral deposits is strongly enhanced. Historical and present mining of such deposits has caused and is continuously causing mobilization of mercury into the environment, including releases to air, water and soil. Tailings from mining and mineral processing in these areas may contain high mercury concentrations and could be a source of permanent secondary emissions. In addition, mercury may also occur in tailings where mercury has been used for the processing of gold and silver ores.

A recent study identified more than 1,200 sites worldwide where mercury has been mined or processed, and in addition 500 sites where gold or silver ores and 600 sites where non-ferrous metals are processed. All of these sites are potential long-term sources of mercury releases. Leaching and erosion processes could mobilize mercury to soil, water systems and air, where it could further be transported in dissolved, particulate or gaseous form. The annual release of mercury from these sites has been estimated to be in the order of about 60 t to 90 t to the atmosphere and 70 t-165 t to the hydrosphere. Since field data are very scarce, these figures are associated with large uncertainties (UNEP 2009a).

Because of its high mobility in the atmosphere, mercury from tailings does not only represent a risk to the local residents near the original source but also to the global environment. Wherever it is transported, it could be taken up by plants and microorganisms and thus enter the food chain.

Therefore, it is in the interest of countries directly affected as well as of the international community, to reduce the environmental risks that emanates from these sources.

2.2 Reprocessing of tailings – a viable approach to reduce the risk of mercury releases?

Within the scope of the UNEP "Mercury Waste Management Project“, the issue of mercury containing tailings has arrested new attention. One option to reduce the threat from mercury containing tailings is to reprocess them. In many cases, tailings still contain considerable concentrations of valuable metals from the original ore. These have not been extracted completely, because available technology did not allow higher yields at reasonable costs. In the recent years rising prices for metals like gold or copper and improvements in processing technologies gave new economic incentives to consider the extraction of precious metals from low grade tailings. If along with other metals mercury could be extracted and separated, reprocessing of tailings would enable economic profits and environmental benefits at the same time.

2.3 Objective of this study

The present study will provide guidance on how to assess the feasibility of reprocessing mercury containing tailings. While emphasis will be given to tailings from gold mining (where mercury has often been used for gold extraction or has been a minor component in the ore), the principal approach may also be applied to tailings from the mining of other metal ores like silver or copper. As an introduction to this topic an overview on global mercury deposits and occurrences of mercury as impurity in other mineral deposits will be given.

Finally, this report will be supplemented with the exemplary description of Andacollo (Chile), a polluted mining area where mercury occurs both as a mineral in other metal ores and as a remainder of historic gold ore processing. Mercury has been in use since centuries for the small scale and semi-industrial extraction of gold. In Andacollo a great number of tailings both form present as well as from historical mining pose a permanent threat to human health and the environment. The description provides an overview of the current situation, the available information about the tailings and discusses challenges and opportunities of a potential tailings reprocessing.

3 Toxicity of mercury and its compounds

3.1 Overview

Mercury is a toxic element and can cause significantly damage on the human health. In tailings, mercury may occur in three major chemicals forms: As elemental mercury Hg^0, in inorganic compounds as Hg^{2+} like in $HgCl_2$ or HgS and in organic compounds like methylmercury (Me-Hg). All of these forms are recognized as highly toxic (UNEP 2002). The degree of toxicity and the most common exposure paths are different for each species. They are discussed separately in the sections below. A more detailed overview on the toxicology of mercury might be found in: US HHS 1999; US EPA 1995; US EPA 2001; WHO 1991; WHO 2003; UNEP 2002; Grandjean 2008.

3.2 Elemental mercury (Hg^0)

A broad range of neurological and behavioural disorders may result as the consequence of an exposure to elemental mercury, including tremors, emotional liability, insomnia, memory loss, headaches, respiratory and cardiovascular effects, gastrointestinal and hepatic effects, effects on the thyroid gland, and the immune system, effects on the skin, reproductive and developmental effects as well as performance deficits (WHO 1991; WHO 2003; USEPA 1997; USHHS 1999; UNEP 2002).

An acute mercury intoxication with elemental Hg^0 via inhalation may damage preferential the lung. About 80 % of inhalated mercury is absorbed by the lung tissues, readily enters the blood system and penetrates the blood/brain barrier where it acts in the case of chronic intake as a serious neurotoxicant (UNEP 2002).

3.3 Oxidized mercury (Hg^+ and Hg^{2+})

Inorganic oxidized mercury compounds are absorbed through the gastrointestinal tract and have caused intoxications after dermal application. Their vapour pressure is low, but they can be inhaled in toxicologically significant quantities from dusts. Monovalent mercury compounds (Hg^+) are much less soluble and are less toxic than divalent forms (Hg^{2+}).

High exposures to inorganic mercury compounds may result in damage to the gastrointestinal tract, the nervous system, and the kidneys. Symptoms include skin rashes and dermatitis, mood swings, memory loss, mental disturbances and muscle weakness.

Most information on the toxicity of inorganic compounds originates from studies of mercuric chloride ($HgCl_2$). As the water solubility and bioavailability of many inorganic compounds, notably mercurial compounds, are much less than those of mercuric chloride, such compounds are likely to be clearly less toxic (WHO 1991; WHO 2003; US EPA 1995).

3.4 Methylmercury (CH_3-Hg^+)

Methyl mercury ($MeHg^+$) is far more toxic to living organism than inorganic mercury forms (Qiu et al. 2006). Several adverse health effects have been identified that could be connected with an exposure to methyl mercury. Most prominent are neurotoxicological effects particularly in developing organisms like unborn children. Epidemiological studies showed that children that were exposed to elevated methylmercury levels during pregnancy had a higher risk of developmental neuropsychological impairment (IQ < 75) than children without elevated exposure (Counter and Buchanan 2004). Other debated effects, which still need further investigation, include cardiovascular effects (higher blood pressure), sensory disturbance and accelerated aging process (US EPA 2001; Mozzafarian 2006).

Dysarthria, ataxia, deafness and constriction of the visual field were typical symptoms of methylmercury poisoning observed in Minamata Bay, Japan, during the 1950s and 1960s (Satoh 2000). The poisoning was caused by dumping methyl mercury containing waste into the bay where it was accumulated by fish, the primary nutrition of the local population.

4 Occurrence of mercury in mineral ores

4.1 Overview

The average abundance of mercury in the earth's crust is approximately 0.05 mg/kg, but the concentration is subject to significant local variations (UNEP 2002). Mercury may be found in trace concentrations in a broad range of mineral deposits, but it may be enriched in specific ores and in specific regions of the world. The following chapters depict locations of major mercury deposits and regions where mercury is frequently found as an impurity in other deposits.

4.2 Mercury ore deposits and mineral deposits enriched in mercury

4.2.1 Location

Mercury ore deposits appear worldwide in 26 mercury mineral belts (Rytuba 2003). The richest mercury ores in the world contain up to 2.5 % mercury by mass (in small spots up to 5 %) and even the low concentrated mercury deposits show at least 0.1 % Hg.

The most deposits are concentrated primarily in two large subduction related belts along present or past plate boundaries (Gray et al. 2000; Loppi 2001).These are:

- The Mediterranean-Tethyan (Variscan) belt. It extends from Europe to Asia and touches Spain, Italy, Algeria, Slovenia, Turkey, Mongolia, and China. Three of the world's largest (now abandoned) mercury mines in the world are part of this belt: Almadén (Spain), Idrija (Slovenia) and Monte Amiata (Italy).

- The Circum-Pacific belt follows the western margin of South-, Central-, and North-America extends through southern Alaska to Japan and from the Philippines to New Zealand. It includes the large mercury deposit Huancavelica in Peru, several important mining districts in the California Coast Ranges (USA) (Bailey et al. 1973; Gray 2000a) and the deposit on Palawan, Philippines.

The main mercury deposits and occurrences in the world are shown in Fig. 2

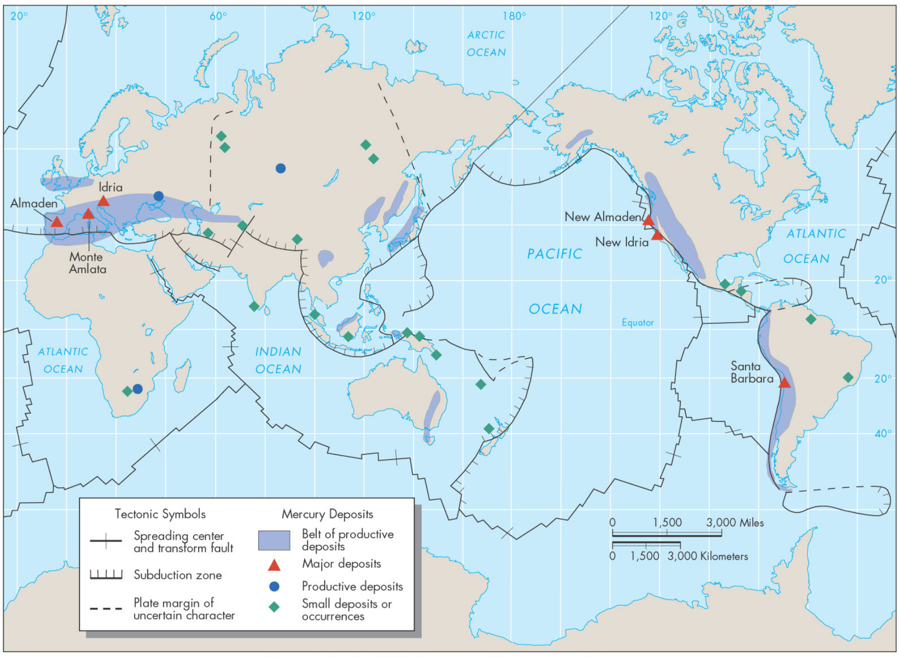

Fig. 2: **Mercury deposits. Relationship between mercury deposits and recently active subductions zones (Keller 2005)**[3]

4.2.2 Deposit types

The global mercury deposits may be classified into three types (Rytuba 2003).

- The Almadén-type deposits consist of massive cinnabar and elemental mercury replacement bodies hosted in quartzite, tuff breccias, submarine mafic to intermediate composition pyroclastic flows, mafic dikes, and organic-rich black shales. These deposits are generally large – 10 mio. t to 100 mio. t of ore containing about 2 wt% to 20 wt% Hg. Mercury, beside smaller concentrations of zinc is the only metal found in the ore. The deposits are limited to the Almadén mercury belt in Spain (Rytuba and Klein 1996).

- Silica-carbonate deposits are more widely distributed. They are associated with altered silica and carbonate minerals (serpentinite) along fault zones and are generally small (0.1 mio. t to 10 mio. t of ore containing 0.2 wt% to 0.8 wt% Hg). Formation occurred from hydrothermal fluids at low temperature (<120°C). In

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[3] Keller, Edward A.: Introduction To Environmental Geology, 3rd ed.; ©2005. Printed and electronically reproduced by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.

these deposits, mainly metals that can be transported in the vapour phase are concentrated. This concern besides mercury, e.g. antimony, nickel, chromium, tungsten and thallium, secondarily arsenic. Examples for this deposit type are New Almadén and Knoxville in California, USA (Rytuba and Kleinkopf 1996).

- Hot-spring type mercury deposits occur in most of the mineral belts. Spatially they are associated with silica-carbonate type deposits. These deposits are formed generally epithermal (250 °C) in hydrothermal systems at shallow depths. The mercury deposits in Andalusia, Spain and Monte Amiata, Italy belong to this group.

The by far most common mercury mineralization in mercury deposits is HgS (cinnabar and metacinnabar) followed by native mercury. Further Hg-minerals like $(Cu, Hg)_3SbS_{3\text{-}4}$ (Schwarzit) or Hg_2Cl_2 (Calomel) are frequent but have no importance as discrete ore mineralization (Pohl 2005).

The global production of mercury from cinnabar and other mercury containing ores during the last five centuries has been estimated to be around 1,000,000 t. Half of that mercury has been mined before 1925 (Hylander and Meili 2003). In the last years the mercury production rate has dropped enormously - from 2,820 t in 1995 to less than 1,320 t in 2008 (USGS 1997, 2010). Today the main producer of primary mercury is China with 800 t/yr Hg followed by Kyrgyzstan (250 t/yr).

The following chapters give a description of major and minor mercury deposits that were or are still important for mercury mining. More information on mercury deposits may be found in (Gray et al. 2000a; Rytuba 2003; Feng et al. 2009).

4.2.3 Major deposits

Almadén, Spain

Approximately 260,000 t of mercury (over one-third of the world's mercury) has been produced in the Almadén mercury mineral belt in central Spain in the past 2000 years - approximately one quarter of all mercury produced in human history. The Almadén mining area consists of 11 distinct mercury deposits within a small area of 10 kmx20 km. The mercury ore bodies have extremely high grades containing up to several percent mercury, mostly in the form of cinnabar, but also as elemental mercury

(Rytuba and Klein 1996). The mines were closed in 2005 due to stronger environmental requirements and the decline of the mercury prices. Until then it was the oldest mercury mine in the world – having been active since Roman times. It is still home of the world's largest reserves of cinnabar (Rytuba 2003; USGS 2010).

Idrija, Slovenia

With a total production of 107,000 t of mercury, the mining district of Idrija has been the world’s second largest mercury mine. The deposit was discovered 1490 and closed down in 1995 after a working history of five centuries (Gosar et al. 1997; Biester et al. 1999; Hines et al. 2000). During the first 20 years, only native (elemental) mercury was recovered before 1508 a rich cinnabar ore was detected (Riart et al. 2003). The average recovery rate of mercury has been estimated to 73 % (Gosar et al. 1997), thus about one quarter was left in tailings or emitted to air.

Monte Amiata, Italy

The Monte Amiata mining district in southern Tuscany (central Italy) was first exploited in 1217. Until the mines were closed at the end of the 1970s, the total amount of Hg production mounted up to 69,000 t (Loppi 2001; Riart et al. 2003). The mercury ore (cinnabar) appears in strata-bound lenses and joints and differs in its composition from 0.3 %-5 % Hg (Pohl 2005).

New Almadén, USA

The New Almadén mercury mine was the oldest and most productive Hg mine in the United States. The site was known to the Ohlone Indians for its cinnabar before a Mexican settler discovered the ores in 1845 (Riart et al. 2003). The mine has been operated intermittently after 1927, was purchased by the County (1976) and has now been developed into a nature and recreation park.

New Idria, USA

The detection of mercury (cinnabar) ore at New Idria (1854) came soon after the discovery of gold in California. The New Idria mines were America's second most productive mines. Before production started in New Idria and New Almadén, mercury was almost exclusively imported from Europe.

Huancavelica, Peru

The Huancavelica mercury mines were discovered 1563/1564 by the Indian servant of Jerónimo Luis de Cabrera. The mines became the most profitable source of mercury in Spanish America and produced app. 52,000 t of Hg until their closure in the mid-1970s (Gray et al. 2000a). Mercury from the Huancavelica mine was crucial in the production of silver in Mexico, Peru and Bolivia.

4.2.4 Minor deposits and occurrences

Almería, Spain

In Almería (Andalusia), Hg deposits are located in the Betric Ranges. This mining site was exploited in the 19th century for mercury and antimony. The Valle del Azogue mine belongs to the group of epithermal hot-spring deposits with low-sulphidation (Viladevall et al. 1999; Navarro et al. 2006, 2009).

Halıköy, Turkey

In western Turkey several abandoned Hg mines are located. One of these mines was the Halıköy mine which produced a total Hg amount of about 2,000 t from 1962 to 1986 (Gemici 2009).

Khaidarkan mine, Kyrgyzstan

The mercury deposits near Khaidarkan in Kyrgyzstan have been exploited since 1941. After the closure of the major mercury mines in Almadén, Idrija and Algeria the Khaidarkan mine is the last remaining major supplier of primary mined mercury to the global market. Until now, Khaidarkan produced around 36,000 t mercury. Two smaller, now abandoned mines in the vicinity, Chonkoy and Chauvay, produced additional 9,000 t (UNEP 2009b). In Khaidarkan alone mining and processing left approximately 13 mio. t mercury containing wastes (flotation tailings and calcines from metallurgy) at the borders of the city (Higueras et al 2009).

Tajikistan

In Tajikistan, a lot of antimony-mercury deposits as well as gold-sulphides and gold-rare metal mines exist. The largest antimony mine, the Dhizhikrut mine, still produces mercury as by product (Rytuba 2003). Two further important mining areas have been the Jijikrut and the Konchoch-Skal mine, which operated for more than 30 years and produced during this time several mio. t of mercury-antimony waste that occasionally eroded into the nearby Zeravshan river (Sznopek and Goonan 2000).

Gorlovka, Ukraine

In the Ukraine, mercury was mined primarily in the Donetsk-Makeevka and Central mining districts of the Donbas region. As an example, the Nikitovka mercury mines in Gorlovka produced about 30,000 t of mercury until it was shut down in 1994. The mercury ore consists of cinnabar, but mercury containing coal was also mined as a by-product and used by the local industry. After the closure of the mine, the area was freely accessible, so that local inhabitants collected coal for domestic use and caught fish in tailings ponds (Kolker et al. 2004).

Boliden, Sweden

In northern Sweden, mercury-rich sulphide deposits are situated in the Långsele and Skellefte ore district. Mercury appears as gold and silver amalgam and reaches concentration between 10 mg/kg and 340 mg/kg (Rytuba 2003).

Guizhou, Shaanxi, Henan and Sichuan provinces, China

Most (78 %) Chinese mercury resources are concentrated in the north-eastern district of the province Guizhou. Many large mercury mining areas are located in this region, among them Wanshan, Wuchuan, Lanmuchang, Tongren, Danzhai (Feng et al. 2009). The Wanshan district in the eastern part of the province Guizhou alone accounted for 50 % of the mercury production in China that amounted to approximately 800 t in 2008 (Zhang et al. 2004; USGS 2010). Further Hg ores are located in the Shanxi, Henan or Sichuan Province (Jiang et al. 2007).

Palawan Mine, Philippines

The Palawan mercury mine at the Philippines, southeast of Manila produced about 2,900 t of mercury from 1953 to 1976 (Feng et al. 2009). More than 2,000,000 t of mine-waste were produced that were partly dumped into the nearby Honda Bay (Gray et al. 2003a; Maramba et al. 2006).

Alaska

Although the mercury production from the Alaska belt, primarily in the Kuskokwim River basin, is small on an international scale (1,400 t) Hg has been important for the local economy. The mercury ore is predominantly cinnabar partly in combination with antimony, arsenic and gold (Gray et al. 2000a). In NW-Alaska, the Red Dog mining area is actually a zinc-lead (sphalerite) mine and is the world's largest producer of zinc concentrate with mercury as an important by-product.

British Columbia, Canada

Two mercury mines (the Pinchi Lake and Bralorne Takla mine) were active in the Pinchi fault region located in central British Columbia, Canada in the 1940s. The Pinchi Lake mine) reopened again from 1968 to 1975 (Plouffe et al. 2004).

Mc-Dermitt, USA

The Mc-Dermitt mercury mine in north-central Nevada (Humboldt County) has been operated between 1975 and 1989. During that time, it was the largest North American mercury producer (Nevgold Resource Corp 2008). The major ore minerals at the Mc-Dermitt mine are cinnabar and Corderoite ($Hg_3S_2Cl_2$) with Radtkeite (Hg_3S_2ClI) as a secondary mineral (McCormack et al. 1991).

Azzaba Mine, Algeria

The mercury ore deposit of Azzaba is located in the North East Algeria, some 400 km east of the capital Algier. Algeria has been a significant supplier of Mercury in the past but halted supplies during the second half of 2003. The production was finally stopped at the end 2004 due to technical, economic and environmental problems (UNEP 2008). During its operation time, the mine produced 200 t-300 t Hg per year (Mobbs 2002).

4.3 Mercury associated with other minerals

4.3.1 Overview

Mercury occurs as an impurity in many sulphide ores because it can substitute the elements zinc, copper, cadmium, bismuth, lead, and arsenic. In some metal ores, it also occurs as elemental mercury or as an alloy with other metals (amalgams). In some of these deposits, mercury contents were high enough to allow an aimed production of mercury as a by-product (Tab. 1). It should b noted that in some regions coal could also contain considerable amounts of mercury.

Tab. 1: Occurrences of mercury in mineral deposits (Rytuba 2003; Yudovich et al. 2005a)

Deposit type	Mercury phase	Examples
Deposits that where used for production of by-product mercury		
Volcanogenic massive sulphides	Solid solution in sphalerite (ZnS)	Skellefte (Sweden); Eskay Creek (Canada)
Sedimentary exhalative deposits	Solid solution in sphalerite (ZnS))/ cinnabar (HgS)	Balmat (New York); Red Dog (Alaska)
Polymetallic base metal	Solid solution in sphalerite (ZnS)/ cinnabar (HgS)	Cobalt (Ontario, USA)
Hot-spring gold	Cinnabar, Hg^0, corderoite ($Hg_3S_3Cl_2$)	Mc-Dermitt (Great Basin); Crofoot/Lewis (Nevada9
Comstock gold-silver	Cinnabar, corderoite	Comstock Lode (Nevada)
High sulphidation gold-silver	Cinnabar	Yanacocha, Peru
Sediment hosted gold	Cinnabar, Hg in pyrite (FeS2), arsenic-antimony sulphides	California; Great Basin; Carlin gold belt (Nevada)
Antimony-mercury	Cinnabar	Dhizhikrut (Tajikistan)
Deposits that have not been used for production of mercury		
Antimony	Solid solution in antimony sulphides, cinnabar	Tajik (Tajikistan)
Mississippi Valley type	Solid solution in sphalerite (ZnS)	Upper Mississippi Valley; Tennessee
Volcanogenic manganese	Mercury adsorbed on iron manganese oxides	Franciscan Complex (Coast Range, California)
Basaltic copper	Mercury copper amalgam	Lake Superior (Michigan)
Volcanogenic uranium	Cinnabar	Sierra Pena Blanca District, Chihuahua, Mexico
Bedded barite	Cinnabar	
Low sulphide gold-quartz vein	Mercury in sulphosalts, mercury – gold-silver amalgam	Abitibi Belt (Alaska); Bendigo/Ballarat, Victoria, (Australia)
Porphyry copper	Cinnabar	Andacollo (Chile), Dizon (Philippines’)
Coal		Donbas (Ukraine), Guizhou (China)

4.3.2 Mercury in zinc ores

Mercury is commonly found as constituent of the zinc mineral sphalerite, where it partly replaces zinc in the crystal structure (Kerfoot et al. 2004). Almost all sphalerite ores contain mercury, mostly in the lower mg/kg range, but some sphalerites may contain up to 41 % mercury (US EPA 2000). Schwartz (1997) calculated a global average of 123 mg/kg and estimated that annually zinc ore with a total content of 600 t mercury are processed. Examples for mercury containing sphalerite are the Skellefte district in Sweden, Nye County in USA and the Akoluk deposit in Turkey. The mercury content in sphalerite may vary in wide ranges. During smelting operations, mercury is released to the atmosphere if no flue gas control equipment is installed. Another part of the mercury remains in the smelter slags ("Black Sand") that are often dumped into rivers (Steele 2004), used as concrete sand (National Slag Association) or asphalt pavements (US TFHRC).

4.3.3 Mercury in copper ores

Most of the mercury associated with copper is found in massive sulphide deposits. The mercury fraction is a function of the zinc concentration and the environmental conditions during formation of the deposit (Rytuba 2000). Kerfoot et al. (2000) and Kot et al. (2009) listed mercury concentrations from copper mining areas in central Baja California (Mexico) and Michigan (USA), ranging from 0.25 mg/kg to 7 mg/kg.

There are only three porphyry copper deposits worldwide from where mercury has been reported. These are the Dizon mine (Philippines), Andacollo (Chile) and Tsagaan-Suvarga (Mongolia) (Singer et al. 1997; Rytuba et al. 2003). In Michigan (USA), mercury is found in basaltic copper deposits.

4.3.4 Mercury in gold and silver ores

Mercury is commonly associated with gold deposits although the amount of mercury in gold ore can vary widely, from less than 0.1 mg/kg to over 100 mg/kg (Jones 2005). Hot-spring type gold deposits show mercury concentrations from one to several hundred mg/kg. Mercury is especially concentrated in the upper layers of these ore bodies (Rytuba 2000).

A good overview on Au/Hg deposits including a map is given by Borisenko et al. (2004). Examples for the occurrence of mercury in Au and/or Ag mineralization can be given in a large number, e.g. the Crofoot, Lewis and Paradise Peak in Nevada (Sillitoe et al. 1994; Rytuba 2003), the Muzhievo gold-base metal deposit in the Ukraine (Shumlyanskyy et al. 2005) and the Mercury Murray Brook gold Mine in northern Canada (Shaw et al. 2006).

Another well-known gold deposit with high mercury content is located in the Yanacocha district in Peru. It is mainly an epithermal, high-sulphidation-style deposit (Bell et al. 2005). As an example, in 2000 the mine produced 120 t gold and 70 t mercury (Ban Mercury Working Group, n.y.).

4.3.5 Mercury in antimony ores

Mercury associations with antimony are more rarely than Hg-Au or Hg-Ag associations. Important antimony deposits with remarkable mercury impurities are the Dhizhikrut mine in Tajikistan (Rytuba 2003) and the Azogue mine in Spain where Hg contents up to 11 % were found in the mineralized zone (Viladevall et al. 1999).

4.3.6 Mercury in coal

The most important source of mercury releases into the atmosphere is the combustion of mercury containing coals. The average mercury content of coal is estimated to be 0.1 mg/kg±0.01 mg/kg (Yudovich et al. 2005a,b), but in some regions the mercury concentration is enriched by one to two orders of magnitude (up to 60 mg/kg), often accompanied by other toxic metals like thallium or arsenic. Notably coals with high mercury contents were found, amongst other, in the Donbas basin (Ukraine), the Appalachian basis, Texas (USA), in Siberia (Russian Federation), South Africa and China (Yudovich et al. 2005 a,b).

5 Historical and present usage of mercury in processing metal ores

5.1 Historical usage of mercury

The first use of mercury in ore processing probably dates back to the Phoenicians who used Hg from the Almadén mercury deposit in order to amalgamate precious metals (de Lacerda and Salomons 1998). In Europe, since Roman times (50 AD) the amalgamation process was in widespread use. Environmental problems caused by mercury have been reported since this time. In Spanish America, the mercury amalgamation process started with the introduction of the “Patio” amalgamation process in 1554 and went on for several centuries. In this procedure mercury is spread over a large surface, was mixed with salt brines, pyrites and elementary mercury. This mixture was allowed to stand for some days before the amalgam was separated. It is estimated that only between 1560 and 1700 more than 20,000 t of mercury were imported by the Mexican silver mines, most of it came from the Huancavelica (Peru) and Almadén (Spain) mercury deposits. In the year 1870, 70 % of the silver in Mexico was produced using the method described above. At the same time, the mercury consumption in North-America peaked because of the high gold production at diverse gold mining areas. The gold rush was not only responsible for the high mercury usage; it also was the impulse to pass this technology to other countries. For example, in South Africa around the year 1850, 48 % of the gold production was carried out using the amalgamation process (Marsden and House 2006). Since 1880, the cyanide procedure became more and more important. Because of the introduction of this new extraction technique and the simultaneous exhaustion of many silver and gold deposits, the use of mercury in the amalgamation process decreased significantly thereafter. Since then the amalgamation method was mainly restricted to small scale mining operations.

It is estimated that the application of this method in the past 500 years released around 300,000 t mercury into tailings and other environmental media (de Lacerda 1997).

5.2 Present use of mercury in small scale gold and silver ore processing

A second gold and silver rush begun in the 1970/1980s in some countries (particular developing countries in Latin America, Asia and Africa) and lead to the expansion of the comparatively cheap and easy to learn mercury amalgamation process. It is estimated that artisanal and small scale gold mining (ASGM) activities are now present in 70 countries (Telmer and Veiga 2009) giving work and income to roughly 20-30 million miners and their families (Spiegel and Veiga 2010). A large share of the ASM gold production is based on the mercury process leading to a mercury consumption of about 1,000 t/yr, 300 t of which are directly emitted into the atmosphere and 700 t discharged into tailings, soil and water (Spiegel and Veiga 2010).

UNIDO (United Nations Industrial Development Organization) estimates that in 2004 10 to 15 million people were working in small scale gold mines releasing 650 t-1,000 t of Hg annually (Veiga and Baker 2004).

Details of the amalgamation process

There are two principal routes of the amalgamation process.

1. **Amalgamation of concentrates**. After crushing and grinding, the ore is concentrated by gravity methods or flotation. Mercury is added to the concentrate and both components thoroughly mixed. Free gold particles react with mercury to form a gold amalgam that can be separated off.

2. **Whole ore amalgamation.** After crushing, the coarse material is moved to a mill and ground together with mercury. Alternatively mercury impregnated copper plates are used to extract gold from the ground mixtures. Gold forms an amalgam on the surfaced of the plates, which can be scrapped off. Another approach is to put mercury into the depressions of sluice boxes and let an ore slurry flow over it. Recovery rates of gold are rather low and very much mercury is lost to the tailings (see chapter 10.3.4.3 for a detailed description of the process as realized in Andacollo, Chile).

Details and realization may vary from place to place, but in all cases, a semisolid gold amalgam is produced. Due to its high density, it can easily be separated from other, mostly lighter minerals. To liberate gold from mercury the amalgam is heated, so that mercury evaporates. If retorts are used, most of the mercury could be recovered.

The amalgamation process generally works best on relatively coarse ore material that could be cut off easily from the gangue material. On the other hand, the ores must be ground fine enough to achieve large surfaces where mercury could react with the precious metal. If the treated gold is very fine, cyanidation is more effective. Nowadays the combination of ore/concentrate amalgamation and subsequent cyanidation of the tailings is therefore a widespread method (http://www.e-goldprospecting.com/html/gold_amalgamation.html). Unfortunately, the combination of amalgamation and cyanidation strongly enhances the mobility of mercury and the transport into the aquifer (Hylander et al. 2007).

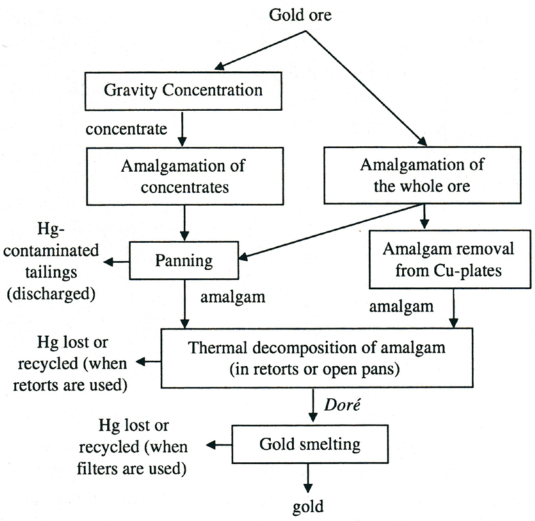

Fig. 3: Typical method for the amalgamation process used in ASM (from Veiga et al. 2006) [4]

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[4] Reprinted from Journal of Cleaner Production, Volume 14, Issues 3-4, 2006, Marcello M. Veiga, Peter A. Maxson and Lars D. Hylander, Origin and consumption of mercury in small-scale gold mining, p. 436-447., Copyright (2005), with permission from Elsevier

6 Fate of mercury during the metal ore processing

6.1 Introduction

As mentioned above mercury in environmental media may occur in different chemical forms (species). The most important are elemental mercury (Hg^0), oxidized mercury (Hg^{2+}) and methylmercury ($Me\text{-}Hg^+$). Each form has a specific mobilization and transport pattern and a set of toxicological properties. Therefore, it is important to know at which stage of ore processing which species could be released. The following discussion will concentrate on unit operations that are relevant for gold, silver, copper and zinc ores, but may in part be applicable to other minerals as well.

6.2 Speciation of mercury in metal ores

In precious metal ores mercury is typically present as cinnabar (HgS), but sometimes it may be found in other compounds or as an amalgam with like copper or silver, that contain mercury in the elemental state (van Zyl and Eurick 2000; Kerfoot et al. 2004). In massive sulphide deposits of zinc and copper ore, mercury occurs either as cinnabar or as a solid solution with other sulphides (Schwartz 1997).

6.3 Unit operations in ore processing

Generally, ore processing for the mentioned metals could consist of a combination of some of the following process steps:

- Ore extraction
- Comminution (crushing, grinding)
- Concentration
- Roasting (to oxidize sulphide)
- Metal extraction (leaching, amalgamation)
- Recovery (cementation, electrowinning, smelting)
- Refining

The amount and type of releases strongly depend on the mineralogy of the mined ore, the chosen process and its efficiency. At different stages of the process steps, different mercury species might get physically mobilized or chemically transformed.

6.4 Releases of mercury during ore extraction, crushing and grinding

During the mere mechanical treatment, there is only little risk of mercury releases, since the ore is not subjected to chemical reactions or heat (Strum 2001; van Zyl and Eurick 2000). Nevertheless, during blasting, ore transport, crushing and milling dust may evolve. If dust control measures are lacking, mercury containing particles may be transported into the surrounding area, as it has been observed for other mining areas (Loredo et al. 2003). If elemental mercury is present in the ore, it could be expected that blasting, crushing and milling leads to enhanced mercury releases from the ore simply because the specific surface of the rock material is increased by orders of magnitude.

6.5 Releases of mercury during ore concentration

Gravity concentration and flotation are the most common methods to produce an ore concentrate. All other material will be discharged into a waste or tailings dump. Since mercury is associated with the metals of interest in many cases, it cannot be separated from these during the concentration process. This is especially true for mercury in zinc ores and amalgams, where mercury is present in the same mineral like the other metals. The situation might be different with mercury in cinnabar, but information on this issue could not be found. It should be noted that in some cases the concentration step is omitted.

6.6 Releases of mercury during roasting and autoclaving

Gold ores rich in sulphide are pre-treated by roasting in order to oxidize and remove sulphur. During roasting about 80 %-90 % of the mercury are released in gaseous and particulate form that needs to be captured by suitable technical measures (van Zyl and Eurick 2000; Miller and Jones 2005). Alternatively, the milled ore is pumped into an autoclave where it is treated with sulphuric acid under elevated temperature and oxygen pressure. The sulphides are dissolved and oxidized. Mercury will be discharged with the process steam or the resulting slurry material, mostly in oxidized form (Hg^{2+}) (Strum 2001).

In zinc ore processing roasting is an essential step since zinc always occurs as zinc sulphide. Roasting converts the ore into calcines that consist mainly of zinc oxide, while mercury is released together with sulphur dioxide (Nyberg 2004).

6.7 Releases of mercury during metal extraction

In gold, silver and copper ore processing leaching with cyanide (or other lixiviantes) is now standard. The ground ore is either piled in a heap and slowly leached by a percolating cyanide solution (heap leaching) or is mixed with sufficient volume of water and cyanide and agitated (frequently for 8h). Gold is oxidized by oxygen and dissolved as a cyanide complex. Mercury, copper and silver behave similar and are also dissolved as cyanide complexes. After the end of the active leaching process, the remaining material is either left at its place or pumped into a tailings pond. Since mercury reacts slower with cyanide some mercury may still remain in the material at the time the process is stopped (because only little more gold could be mobilized, see Shaw et al. 2006 for an example in New Brunswick). Slow reaction with cyanide may later lead to a mobilization and eventual leaching of mercury from the tailings.

In order to recover the gold from the solution activated carbon is added and after it retreated with alkali to release the gold complexes from the carbon. A part of the mercury on the coal cannot be removed by this process and remains on the surface of the coal particles. These have to be regenerated at 700 °C in carbon kilns, a temperature sufficient to evaporate mercury and mercury compounds. To remove mercury from the off-gas carbon filters have to be employed (Strum 2001; Miller 2007).

Recent field investigations showed that gaseous mercury emissions could be strongly elevated during active heap leaching, but may be greatly reduced within some years after ceasing the operation (State of Nevada 2009). Similar emission is to be expected from agitated leaching, but no information could be found on this issue.

In most zinc ore mining processes the calcines from roasting is treated with sulphuric acid. Zinc oxide dissolves. It is expected that mercury (in the oxidized form Hg^{2+}), if not already removed, will be dissolved also.

6.8 Releases of mercury during recovery operations

Recovery of gold, silver and copper from cyanide solutions is achieved either by electrolysis (electrowinning) or by cementation with zinc. In both cases, mercury joins gold and silver in their reactions, so that it can be found in the resulting metal products. Emissions of gaseous elemental mercury can be significant and must be controlled by suitable measures (Strum 2001). To remove mercury from the raw gold metal (the doré) the product is treated in a vacuum chamber at 600 °C-700 °C that removes about 99 % of the mercury. The resulting gold and silver may still contain up to 8,000 mg/kg mercury. Smelting at 1,500 °C removes most of it, but the final cleaning is only achieved in a refinery.

Zinc ore is treated in a different way. One method to produce metallic zinc is to electrolyse the zinc sulphate solution that has been produced by acid dissolution of the zinc oxide from roasting. The other process works with coal. Here the zinc oxide is reduced by carbon monoxide at high temperature so that zinc is released as a gas that is condensed after it.

One typical residue of roasting and smelting zinc ore are slags, called “Black sand”. A part of the mercury remains in these resides that sometimes have been dumped into rivers (Steele 2004), used as concrete sand (National Slag Association) or as a component in asphalt pavements (US TFHRC).

7 Release of mercury from tailings

7.1 General characterization of tailings and potential release paths for mercury

Crushing and grinding, being part of most ore processing, convert ore to fine grained material with diameters from several µm up to a few mm. This material undergoes several treatment steps in the process (concentration, roasting, leaching, smelting). At each stage, a part of the material may be excluded from further processing and discharged. Wet material (mixture of mineral particles and water e.g. from flotation or tank leaching) is usually deposited as a slurry in tailings ponds, whereas more compact material is piled in tailing heaps or waste dumps. At some sites, leaching with run-of-mine ore (uncrushed ore) takes place producing heaps of much coarser material.

If mercury is present in tailings, the potential environmental risk depends primarily on its amount and speciation (chemical form). The latter property is decisive in determining the bioavailability of mercury. Mercury has a rather limited environmental impact if it is not in a readily bioavailable form and if it is not transformed into more soluble, thus bioavailable mobile species under the geochemical/ microbiological conditions found at a specific site. Such a transformation can take place in the tailing through chemical or microbiological reaction or outside the tailing after relocation of mercury contaminated material by erosion.

In summary mercury may be released from tailings through the following processes

- Evaporation of elemental mercury → risk of direct inhalation or later precipitation and subsequent transformation into other species.
- Transport and dispersion of mercury containing particles through wind erosion → risk of direct inhalation, contamination of soil, homes, water systems, food. Risk of dissolution and biotransformation into methylmercury.
- Transport and dispersion of mercury containing particle through water erosion → contamination of soil, fluvial system. Risk of dissolution and biotransformation into methylmercury

- Leaching of soluble mercury compounds including mercury cyanide complexes by possibly acidified groundwater and rainwater → contamination of groundwater, soil and adjacent fluvial systems

The following chapter attempts to classify different mercury containing tailings that may be formed during the ore processing.

7.2 Classification of tailings

7.2.1 Overview

Tailings may be generated from different ores and at different stages of ore processing. One possible concept to classify mercury containing tailings could be based on their origin:

(a) Tailings and slags from mercury ore mining

(b) Tailings from the processing of metal ores containing mercury

(c) Tailings from gold and silver ore processing based on the amalgamation method

(d) Tailings from gold and silver ore processing containing cyanide from the leaching procedure

(e) Slags from roasting and smelting of sulphidic ores containing Hg residua

Examples for each of these types are given below.

7.2.2 Tailings and slags from mercury ore mining

Tailings from mercury mining could contain discarded gangue material and unprocessed ore minerals. In general, most of these ore fragments consist of mercury sulphide (HgS) and native mercury. Due to crushing and milling the specific surface of the ore particles is strongly increased which may lead to an enhanced oxidation.

A potential problem which is associated with accelerated weathering of sulphides is the oxidation to sulphuric acid that is often observed in sulphidic rock bodies and tailings (acid mine drainage, Price 2003). The formation of sulphuric acid may lead to a dissolution and chemical transformation of mercury and therefore to an increased mobilization and discharge of this element into the aquatic system. If other sulphides than cinnabar are missing and the pH of the aqueous phase neutral to alkaline, cinnabar will likely not dissolve. In such cases, transport is observed mostly in particulate non bioavailable form (Gray et al 2000b; Gray 2003).

Another typical waste product of mercury ore processing are calcine slags. During the roasting, mercury sulphide is reduced to elemental mercury that is evaporated and recovered in a retort. The residue is a coarse slag that may contain mercury in form of mercury sulphide or elemental mercury that is adsorbed to the material. There are several examples known, where these slags have been dumped into nearby rivers or into marine systems. Mercury containing tailing material from mercury mining could be observed in a large number of sites. Examples are Idrija (Slovenia), Palawan (Philippines), mining areas in Nevada (USA) and the province Guizhou (China) and in Khaidarkan (Krygyzstan).

At the Idrija mining district, most of the roasted ore tailings were dumped into the nearby rivers Idrijca and Soca. The annual spring flood transported the tailing material over large distances into the Adriatic Sea, were sea currents further transported and distributed the sediments within the Gulf of Trieste (Biester et al. 2000). Bottom and overbank sediments from these rivers contain up to 1000 mg/kg total Hg (Biester 1999; Gosar et al. 2006). Li et al. (2008) measured a maximum value of even 2759 mg/kg of total Hg. Median mercury contents in soils near the towns of Idrija and Spodnja Idrija reach elevated total mercury contents of about 47 mg/kg (Gosar et al. 2006), while maximum values in soils for the mining area reached 87.6 mg/kg (Gosar et al. 2006).

The Palawan Mine (Philippines) was operating between 1953 and 1976. In this relatively short period, more than 2000,000 t of mine-waste calcines were produced and partly dumped into the nearby Honda Bay. These calcines contain high mercury concentration of 43 mg/kg-660 mg/kg total Hg (Feng et al. 2009); even sediment samples from the pit lake and Tagburos Ceek near the mine show concentrations of 4 mg/kg-400 mg/kg (Maramba et al. 2006). Mercury in the mine water flowing through tailing material reaches elevated concentrations ranging from 18 µg/l to 31 µg/l (Feng et al. 2009) and exceeded the WHO drinking water standard (1.0 µg/l) by several factors. The methylmercury concentration is highest in the pit lake water, ranging from 1.7 ng/l to 3.1 ng/l. This methylmercury may be transferred to seawater where it could enter the food chain by accumulating in marine fish and seafood. A food source pathway of Hg to humans is most likely in this coastal, high fish-consuming population (Gray et al. 2003).

Investigations at the Tongren district, Guizhou, China show high total Hg concentrations, ranging from 1.8 mg/kg to 900 mg/kg in mine waste samples. High concentrations of Hg were also found in the leachates of mine waste (ranging from 0.01 µg/l to 130 µg/l) and stream water samples from 92 ng/l to 2300 ng/l (Li et al. 2008). Erosion from tailings and particle bound transport was identified as a major source of contamination of stream sediments that leads to high methylmercury levels in water even far away from the original source (Feng and Qiu 2008).

The tailings pond at the Khaidarkan Mercury Mine area (Krygyzstan) is filled with fine-grained residues from milling and floatation of a complex mercury ore processes to extract fluorite, antimony and mercury from complex ore. The total mass amount of tailings is estimated to about 400,000 t with a mercury content of around 100 mg/kg or below. Over one hundred mio. t of mercury containing waste rock is deposited in a high position in the mountains north of the town of Khaidarkan, but it is likely that mercury levels are much lower in this material. Moreover, a local smelter is surrounded by slag heaps. Reprocessing of the tailings pond is considered as one option to recover fluorite from the material (Higueras et al 2009).

One of the highest mercury concentrations in sediment samples is measured at the mercury mining district at Almadén (Spain). The mercury content in soil samples show extremely high values of up to 8.889 mg/kg. Stream sediments where found to have mercury concentration up to 1.6 wt% and water samples up to 11.2 µg/l. Moreover, very high concentrations in methylmercury were detected (Higueras et al. 2006).

The calcine heaps of the Mc-Dermitt Mine, Nevada, USA have a total volume of 1,000,000 m^3 and contain ~ 1000 t Hg. Here and at other mining sites in the area erosion is able to mobilize mercury containing material. Nevertheless, since the region is characterized by a dry climate, run-off from the mines rarely happens. Drainage is observed only at two out of 14 mines, but material is transported some kilometres downstream of those mines. Mercury concentrations (total and methylmercury) in the tailings are high, but are lower by orders of magnitude in the stream due to dilution (Gray 2003).

7.2.3 Tailings from the processing of metal ores containing mercury

As described in the preceding chapters, mercury may occur as an impurity in other metal ores. As a consequence, mining residues at certain locations may also contain considerable amounts of mercury that pose a risk to the environment.

Elevated mercury levels were found in Lake Superior (Michigan, USA) sediments. The contaminations near the Keweenaw peninsula could be traced back to shoreline tailing piles that were produced by copper and silver mining. Mercury was especially present in the ‘slime clay’ fraction of stamp sands that were dumped near the shore and could easily be mobilized. (Kerfoot et al. 2000, 2004).

Mercury is also present in the copper ores of Andacollo and Punitaqui (Chile). In waste rock piles up to 720 mg/kg could be found, flotation tailings still contained up to 3.9 mg/kg (Andacollo) and 190 mg/kg (Punitaqui). Erosion might have delivered contaminated materials to streams where it is found in the sediments (Higueras et al 2004).

7.2.4 Tailings from gold and silver ore processing based on the amalgamation method

Mercury has been used for processing (amalgamating) gold and silver ores since Roman times, but especially intensive since the Spaniards started exploiting the ores of Central and South America. Based on the data provided by Lacerda (1997) and (Nriagu 1994), it might be estimated that about 100,000 t of mercury were lost to tailings, soil and sediments. Much of these tailings have been dumped into or near river systems where their toxic components are transported as sediments over long distances. Even decades after the ceasing of ore processing activities, the tailing material may continuously release mercury and other pollutants to the water systems, posing a sustaining threat to the biosphere and human health. Important paths for mercury releases are degassing of elemental mercury and leaching into adjacent aquatic systems.

In Goldenville, Nova Scotia, Canada historic gold mining left behind about 3 mio. t of mercury contaminated tailing material. Over the years (mine was operative between 1860 and 1945) erosion dispersed the tailing material over an area of 2 km^2. Continuous release of mercury and other toxic inorganic pollutants (TIP) has caused a poisoning of ecosystems downstream including the nearby Atlantic Ocean. Although mining has long been ended, releases of pollutants into river systems didn’t slow down (Wong et al. 1999). In the Carlson City mining district, over the past 100 years tailings have been transported over 100 km and formed a 1.5 km^2 fan area in the Carslon River Valley (Lacerda and Salomons 1999).

Extreme high total Hg concentrations of 500 mg/kg-4500 mg/kg are also described from other gold mining areas in Canada and USA (de Lacerda and Salomon 1998). Because the releases are diluted with Hg poor substances, the measured Hg-concentrations are frequently significantly lower (0.04 mg/kg-0.2 mg/kg (de Lacerda and Salomon 1998).

Tailings from the Au ore mining district Portovelo-Zaruma in Ecuador, where the amalgamation process has been used for many centuries, contain an average of 15 % (1.28 %-27.5 %) of the deployed mercury if whole ore processing was applied. If gravity concentrates were amalgamated, the mercury content in the tailing material decreased to 1.4 %. The total mercury concentration in the tailings shows high concentrations of 360 mg/kg to 430 mg/kg. It is estimated that 0,43 t Hg are annually released from these tailings which over the years lead to a notable amount of total mercury release to the environment (Velásquez-López et al. 2010).

In China, e.g. in the Xiaoqinling region (Tongguan County), rudimentary amalgamation techniques have been used for 900 years and still are. Investigations in this region by Dai et al. 2003 estimate that every year about 120 t of mercury are released into the environment due to gold extraction procedures, with 38.0 % released into atmosphere, 62.0 % into solid tailing material and 0.003 % directly into the river with the tailing water.

7.2.5 Tailings from gold and silver ore processing containing cyanide from the leaching procedure

As shown above, a wide range of gold deposits contain mercury as an impurity. When the gold ore is subjected to cyanide leaching, a part of the mercury will also be mobilized from the matrix and bound within soluble mercury cyanide complexes. Depending on the ore characteristics and the treatment time, a part of the mercury will remain in the ore and will be discharged to tailings. As long as cyanide is present in the tailings, mercury (and other metals) may still be mobilized and released to the groundwater or river systems whichever is present at the tailing site.

One example of high amounts of mercury and cyanide remained in the tailing material is the Murray Brook mine in New Brunswick, Canada. Between 1989 and 1992, oxidized Cu-Pb-Zn sulphides known as gossan were mined in Murray Brook by open pit mining. The ore was crushed and subjected to cyanide leaching with adjacent zinc precipitation recovery. The remnants of this process were stocked in unsaturated tailings nearby a local river. In 2002 it was estimated that, although cyanide is thermodynamically unstable, the tailings still contained about 4,700 kg cyanide, which is able to mobilize 11,000 kg Hg. Mercury in the pore water was found to be present as a mobile cyanide complex (99 %), which is continuously leached to the surrounding aquatic systems (Shaw et al. 2006).

7.2.6 Slags from roasting and smelting of sulphidic ores containing Hg residua

Slags from the roasting and smelting process of Zn or Pb sulphidic ores may contain residua of mercury and therefore constitute a potential risk for the human health and the environment. These slags (known as “Black sands”) cause environmental pollution in the vicinity of many plants nearby the deposits. Approximately 13.4 mio. t of heavy metal containing slags were dumped into the Columbia river from 1896 to 1996 from where it was carried downstream (Steele 2004).

7.3 Chemical speciation of mercury in tailings

7.3.1 Frequently occurring species

Mercury may occur in tailings in different chemical forms (species). Which of them may be found at an individual site primarily depends on the mineralogy of the mined ore and the chemical processes the material underwent during ore processing and later by weathering, oxidation, leaching etc. The following species are frequently found in tailings:

- **Mercury sulphides** (cinnabar, metacinnabar). Mercury sulphides are the principle component of mercury deposits (Pohl 2005). It may also be found in tailings of mercury ore processing, especially if the roasting process was ineffective (Biester et al. 1999). The solubility of mercury sulphides is very low, but they may be transported in colloidal form (Slowey at al. 2005). They are sometimes considered as ‘resistant to physical and chemical weathering’ (Gray 2003) but nevertheless are not resistant to chemical conversion in aqueous media or soil (Han et al. 2008; Maramba et al. 2006).

- **Solid solution of mercury in other metals sulphides**. Zinc sulphides (sphalerite) usually contain mercury as an impurity. It does not form a separate phase but replaces zinc in the crystal structure of sphalerite (Schwartz 1997). This type of compound is called a solid solution.

- **Elemental mercury** is a frequent component of mercury ores but may also be found in tailings from mercury ore processing, possibly sorbed to other minerals (Biester et al. 1999). Naturally occurring gold, silver and copper amalgams also contain elemental mercury and may therefore be expected in tailings (e.g. from gravity concentration and flotation). High concentrations of elemental mercury are found in tailings from gold and silver ore processing by amalgamation. Depending on the geochemical conditions at a specific site, by and by this mercury may be converted to more mobile (mercury oxides, sorbed mercury) or immobile (mercury sulphide) species (Slowey et al. 2005). It is also possible that elemental mercury is produced by reduction of oxidized mercury (e.g. through reaction with humic matter; Schöndorf et al. 1999).

- **Mercury cyanide complexes**. Cyanide that has not been effectively removed from heap or tank leach tailings may react with mercury that is an original component of the precious metal ore or that has been introduced for amalgamation. The products are highly mobile mercury cyanide complexes that could be leached into the surrounding water systems (Shaw et al. 2006).

- **Methylmercury** is formed by microbial processes from inorganic aqueous mercury species (Wood et al. 1968). It is found in tailings (Gray 2003), but, more critically, in adjacent and also distant water systems that have been contaminated with mercury and have active populations of sulphate-reducing bacteria (Fageneli et al. 2003; Slowey et al. 2005).

- **Mercury oxides, chlorides.** Seldom found in the original ore, these compounds may later be formed from elemental mercury through oxidation (Slowey et al.

2005). These compounds are slightly soluble in water and may be leached into adjacent aquatic systems.

- **Mercury bond to organic matter.** Mercury has a high affinity to organic matter and is often found sorbed to substances like humic acid (Guedron et al. 2009).

- **Mercury bond to inorganic matter.** In many places, mercury is especially enriched in the fine grained fraction, consisting of sand, silt and clay (Ashley et al. 2002). It should be noted that this fraction might also be transported as dust. Moreover, mercury bound to clay-size particles is bioavailable and may serve as a precursor for microbial methylation (Guedron et al. 2009).

7.3.2 Analytical determination of mercury speciation in solids

For the analytical determination of mercury speciation, different methods may be applied. Frequently used methods are

- In **pyrolytic and chemical extractions** (PCE) the sample is pyrolized and leached to determine relative percentages of volatile, ‘soluble’ and residual mercury. The results are operationally defined and specific species cannot be determined with this method.

- In **extended X-ray adsorption fine structure spectroscopy** (EXAFS), high energy synchrotron-sourced X-ray radiation is applied to identify specific species based on scattering patterns. Data analysis is undertaken to link patterns to a database of model compounds. The non destructive EXAFS is most useful for the identification of specific species - if they are already included in the model database. Mercury oxide is hardly to detect.

- **Solid-phase-Hg-thermo-desorption** (STDP) identifies Hg species by incremental heating. The thermal release patterns are compared with a database of compounds. The method allows the identification of a smaller number of specific species than EXAFS, but it is the best of the three mentioned methods for the identification of Hg^0. Since the release patterns of several species are overlapping, it is difficult to identify species like HgS and some forms of matrix-bound Hg.

Although the methods determine mercury species by different physical processes, a comparison of the results is useful to get a complete picture. More information on these methods is given by Sladek et al. (2003).

7.3.3 Examples for investigations of mercury speciation in mine tailings

Investigations to identify the speciation of mercury in tailing material at Idrija, Slovenia determined HgS as the predominant species in older tailing material. In comparison mercury oxide (HgO), unbound elemental Hg and elemental Hg (Hg^0) sorbed to matrix components (dolomite, Fe-oxyhydroxides) were identified in younger tailing material. Further research showed that the Hg concentrations and dispersion of the Hg phases depend on the distribution of different sediment grain size fractions of the sample. Accumulation of cinnabar (> 80 % of total Hg) predominantly occurs in coarse grained river sediments, where it constitutes up to 1000 mg/kg in present and past day sediments. On the other hand non cinnabar Hg was found to be enriched in areas where fine grained material was deposited - reaching 1 mg/kg-60 mg/kg in flooded soils and 1 mg/kg-18 mg/kg in sediments of the Gulf of Trieste (Biester et al 1999; Biester et al. 2000).

EXAFS speciation analysis of samples from gold mine tailings in California and Nevada, which were performed from identified mercuric sulphides (cinnabar, metacinnabar) as the most common mercury speciation. Secondarily soluble mercury chlorides were found (Kim et al. 2004).

Similar findings were made by Hojdová M. et al. (2008) who identified that >80 % of the Hg in historic mercury mines in the Czech Republic tailing material was present as HgS and only a minor amount of <14 % as mineral surface bound Hg, which might undergo methylation and thus represents a potential long-term environmental risk.

Geochemical investigations of tailing material from the gold mining district at Clear Creek (San Benito County, California) showed that the elemental Hg initially introduced during the gold mining process has partially been transformed to readily soluble species, such as mercury oxides and chlorides (3 %-4 %). The major content of the Hg (75 %-87 %) was found in the intermediately extractable phase. This phase likely includes (in)organic sorption complexes and amalgams, while the highly insoluble forms such as mercury sulphides (cinnabar and metacinnabar) account for 6 %-20 % (Slowey et al. 2005).

Navarro et al. (2006) studied the Hg mobility in contaminated soils and mine wastes of the Valle del Azogue mining area (SE Spain). In calcines and tailing material, the dominant speciation was elemental Hg, which is solved in a notable quantity into the aqueous phase (67 µg/l) and represents a long-term potential environmental risk.

Guedron et al. 2009 used sequential extractions, XDR and µXRF analytics to analyze soil samples from the former French Guiana gold mining area. The total Hg concentration in these samples could be correlated with sulphur and organic carbon, which suggest the association of Hg with sulphur-bearing functional groups.

7.4 Human exposure

Mercury may leave the tailing on different paths. Each of them is linked to a specific type of potential human exposure, which could be ordered as follows:

- **Inhalation of gaseous elemental mercury**: e.g. on or near tailings with a high content of elemental mercury. Elemental mercury has a low but significant vapour pressure so that it is emitted slowly but continuously into the gas phase Once it has left the tailing the contaminated air will probably be mixed with unaffected air masses through diffusion or advection, but the mercury concentrations in the air above tailings are nevertheless several orders of magnitude higher than the natural background level. They are comparable with the indoor levels found in chlor-alkali plants or over cinnabar deposits and may remain unchanged even more than a century after the end of mining activities (Lacerda and Salomons 1999). Living near or even on tailings[5] might lead to increased inhalation of elemental mercury.

- **Inhalation or ingestion of mercury contaminated dust or soil**: e.g. on or near tailings without protective layer against wind erosion, ingestion of mercury contaminated soil especially by playing infants. Mercury species may be bound to solid particles in the tailing material. Since many tailings are not covered, they are subject to erosion by wind, rainwater or water currents (floods) causing a contamination of land, agricultural products, homes, streets and water

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[5] Such a situation is found in Andacollo, Chile where according to Prey (2001) “Many homes are built on massive amalgamation tailings”.

systems. Depending on the grain size of the tailing material, wind-strength and -direction, distant areas from the original source may be contaminated with mercury containing particles (Schöndorf et al. 1999; Moreno Brotons et al. 2009).

- **Dietary intake of mercury species.** In aquatic media, under anoxic or suboxic as well as oxidizing conditions, inorganic mercury species could be converted through methylation to methylmercury by microorganisms (sulphate reducing bacteria, fungi and phytoplankton; Counter and Buchanan 2004; Winch et al. 2008). As a lipophilic substance, methylmercury undergoes strong bioaccumulation in the aquatic food chain (Chen et al. 2008). Fish and shellfish are most affected, with the highest levels of methylmercury found in predatory fish and sea mammals. Populations with a high proportion of fish in their diet are most frequently affected (Satoh 2000). Exposed mothers pass methylmercury to their unborn (through the placenta) and infant children (through breast milk; Counter and Buchanan 2004). Moreover, methylmercury is found in rice and other plants in heavily polluted areas (Feng et al. 2007; Li et al. 2009).

8 Reprocessing of tailings

8.1 Potential economic incentives

Tailings often contain considerable amounts of valuable metals from the original ore that were not extracted in the past. This precious metal content in the tailings is rather at the lower end of profitability since the material has already been processed before, but rising precious metal and base metal prices as well as improved processing technologies have turned once relatively less attractive waste dump sites to economically interesting projects. Because tailings consist of already mined and ground material and access to the tailings is usually easy, a reprocessing of tailing material can be achieved with comparatively small expenditure. Under certain circumstances even a non-profitable operation may be advisable, e.g. if a necessary tailing remediation would be more expensive than the reprocessing.

8.2 Environmental and social benefits

Apart from economic incentives, reprocessing of tailings offers opportunities for the improvement of the local environmental situation, public health and quality of life.

- **Safe storage**: Reprocessing of tailings always means that material is removed from its place of former deposition and will be transported to a new location after processing. That offers the chance to construct a tailings storage facility at nowadays standards that in comparison with the former situation minimizes future releases of hazardous substances and the risk of severe dam tailings failures.

- **Permanent removal of mercury**: Due to similar chemical properties, mercury may be extracted from tailing material together with precious metals - at least to a certain degree. By applying suitable and sufficient control measures the extracted mercury may be separated from the waste stream and recovered for final environmentally safe disposal

- **Rehabilitation of former tailing areas**: Quite often tailings are in the direct vicinity of villages. Sometimes they represent an obstacle to further urban or settlement development. Removal of tailings, subsequent remediation and recultivation allows the reuse of formerly covered land.

- **Improvement of public health**: Minimizing and possibly eliminating mercury releases from tailings gradually lead to a reduction of pollutants and thus to an improvement of the health situation of local residents.

- **Improvement of agriculture:** Mercury containing tailings pose a threat to agricultural use of adjacent land, especially because of wind and water erosion. Removal and safe storage of tailings will stop the pollution of agriculturally used land and water systems.

8.3 Public involvement

In order to achieve the above mentioned potential benefits local communities and public administration should be involved at an early stage. Realisation of a tailing reprocessing project could be greatly facilitated if their interests and the interests of the mining company are brought into coherence in advance. Early involvement could also help to settle potential conflicts (e.g. on ownership and land use issues).

8.4 Examples for recent, planned or proposed reprocessing projects

8.4.1 The Laguna project, Zacatecas, Mexico (silver, gold, mercury)

After the Spanish occupation, Mexico became one of the world's biggest producers of silver (Nriagu 1994). Silver like gold was successfully extracted by using the amalgamation process – but due to its inefficiency important amounts of precious metals together with vast amounts of mercury had been left in the tailings (Micon 2005)). One large scale project to reprocess tailing material is located near the city of Guadalupe in the central Mexican state Zacatecas. According to a feasibility study (MINCO 2009), there are 6.8 mio. t of tailing material with average contents of Ag (57 g/t), Au (0.31 g/t) and Hg (329 g/t !). The mercury content of these tailings alone (2200 t) is approximately twice as high as the annual output of all still operating mercury mines (950 t, USGS 2009). The recovery and sale of the mercury constitutes an integral part of the project (Minco 2005).

Tailings in the surrounding of the Zacatecas region have been reprocessed since 1920 by lixiviation with calcium thiosulphate (CaS_2O_3) recovering gold, silver and mercury as a by-product. Four plants are operating to extract Ag, Au, and Hg using CaS_2O_3 solution from surface soil that is mixed with tailing material from historic silver ore amalgamation. The metal ions extracted are cemented by scrap Cu wires. Hg is separated by evaporation from the cemented amalgam and Ag and Au are obtained from the residue. A part of the soil was separated and leached like an ore in an industrial process. It is estimated that in total 13,000 t-34,000 t of Hg had been discarded in the extraction of Ag (Ogura et al. 2003).

8.4.2 Kaltails project, Kalgoorlie, Western Australia Gold Tailing (gold)

The Kaltails project was established to reprocess and move tailings dumps from the Boulder and Lakewood areas of the city of Kalgoorlie. The operations started in 1990 and were finished in 1999. The tailings heaps were hydraulically mined, moved to a processing plant and stored in a new engineered impoundment located 10 km south east of Kalgoorlie (Whincup 2006). 60 mio. t of tailing material was processed by Carbon-in-Circuit (CIC), Carbon-in-Pulp (CIP) leach and absorption circuit’s cyanidation to give 695,000 ounces of gold (Engels and Dixon-Hardy 2010).

8.4.3 Remediation of mercury containing tailings in Mongolia (gold)

Since 1997, small scale mining activities expanded sharply in Mongolia. It is estimated that now up to 100,000 people work in this sector. In gold mining, the amalgamation process is widely employed. Since recovery is low (30 %), the resulting mercury containing tailings are further treated with cyanide to extract most of the remaining gold. In 2007 in Khongor Soum (Mongolia) wastewater containing cyanide and mercury was directly poured into a waste treatment plant that flowed over. As a consequence a contaminated pond was formed that poisoned the local well and the drinking water system. A joint UNEP/OCHA mission visited the site. In order to eliminate the risk posed by the amalgamation tailings it was recommended to treat or reprocess them. If done in an environmentally sound manner reprocessing would also provide an economic opportunity (UNEP/OCHA 2007).

8.4.4 Singida Project, Tanzania (gold)

In the 1990s, gold deposits were discovered in the region of Singida, Tanzania. Since then the deposits were continuously exploited by small scale miners using the amalgam method (VIPR 2008). They have left a large number of tailings that in part have already been reprocessed several times. According to a chemical analysis of several tailing piles, these still contain considerable concentrations of gold (1.5 g/t-

5.0 g/t). In total about 75 piles were subject to a detailed investigation. It is expected that the piles can be processed at low cost (Lake Victoria Mining Company, 2009).

8.4.5 Cobalt Camp Reclamation (Cobalt, silver, nickel)

In 1903, silver was discovered near the town Cobalt in northern Ontario, USA, leading to a mining rush similar to the Klondike gold fields. Between 1903 and 1922, over 300 million ounces of silver were produced from 100 mines of various owners and dimensions. Cobalt was a major component of the mines ore but was normally thrown away since at that time demand for cobalt was low. Approximately 18 mio. t of tailings were left in lakes, on shorelines and in open areas over a large region. They contain high levels of arsenic (trace component of the sulphidic ore) as well as mercury (up to 4 g/t), which are polluting local streams, lakes and drinking water. The company BacTech plans to build a (demonstration) bioleaching plant capable of treating 200,000 t/y of mine tailings (capacity possibly to be extended later to a 1,000,000 t/y). The plant shall effectively remove a source of arsenic pollution, along with recovering cobalt, silver, and nickel for sale to market. By utilizing a bioleaching approach, gaseous releases of arsenic and mercury are avoided that would occur if a classical smelter process was employed (BacTech 2009a, 2009b).

9 Criteria for analyzing the feasibility of processing mercury-containing tailings

9.1 Introduction

Mercury contamination in waste dumps from historical mining activities represents a potential risk to human health and the environment. A promising approach to mitigate the environmental risks could be the reprocessing of the tailings, if they contain a considerable amount of valuable metals, like gold, silver or copper. The recovery of these metals is the driving economic incentive behind any reprocessing project, but to establish a win-win situation for the executing mining company, affected communities and the environment, the operations should be planned in a way that mercury is either recovered or treated in such a manner that further releases from the waste material to the environment are avoided or below acceptable limits.

Whether or not the reprocessing of a tailing is economically, technically and legally feasible cannot be said without a detailed evaluation. The phases of such an evaluation and its major parameters are described in the following sections, providing a guideline for initial (scouting, scoping) as well as the final evaluation stages such as pre-feasibility and feasibility studies. The description may also be used as a Terms of Reference (ToR) document for a detailed feasibility study. Additional attention is given to the potential pathways of mercury releases and options for their prevention.

9.2 Remediation of mercury containing tailings as an alternative

The reprocessing of tailings is a cost intensive procedure, which should go hand in hand with the improvement of the environmental situation. It should also be noted that a remediation of mercury containing tailings according to the state of the art could be a valuable and sustainable alternative. It is not the purpose of this study to provide a detailed catalogue of remediation options but some general remarks may be allowed here.

State of the art remediation could mean, if the material displays highly elevated concentrations of mobile or (under the specific environmental conditions of the site) easily mobilized mercury species, it may be necessary to remove the material and store it in a safer location. The material could be excavated and possibly be mixed with cement slurry, which would be backfilled into secure empty spaces.

To avoid water ingress the area should be covered with an impermeable layer and topsoil followed by recultivation. A cover layer of clay, geotextiles or synthetics maybe applied.

If the mercury content in the sludge is below levels of concern, excavation could be avoided and a cover as described above would be applied directly. The capping will prevent exposure to livestock, limit water ingress, reduce dust generation and allow safe agricultural production in the area.

For more detailed information of remediation options, the reader is referred to specialized literature. The following non-conclusive list may serve as a starting point (see reference list at the end of this document for full citation):

State of Colorado (2002): Best Practices in Abandoned Mine Land Reclamation: the remediation of past mining activities.

Dybowska et al. (2006): Remediation strategies for historical mining and smelting sites.

GRS (2009): Sino-German Workshop 2008 REMCOSITE. Remediation of mercury-contaminated sites

9.3 Evaluation phases

9.3.1 Overview

A feasibility study is the appropriate basis to decide whether or not the reprocessing of a tailing is economically viable. It includes the technical, economic, legal, operational and schedule feasibility of a proposed tailings processing operation. Since a full feasibility study with its necessary testing program might be quite expensive (2 %-5 % of the project costs, McIntosh Engineering 2003), it is advisable to proceed in distinct phases. In each phase of the evaluation process the amount of necessary information and analysis is increased (and so are the process costs) and the quality of conclusions is more and more improved. After every stage, a decision can be made on whether further investigations are still worthwhile or the process can be abandoned. If the investigation should be , the results of the concluded step can be used for the next phase. The number of evaluations steps is in principle not limited, but in practice, the following steps may be found (Muir et al. 2005; McIntosh Engineering 2003):

1. Scouting: Preliminary investigation on whether a resource has any potential to be processed. May be performed by a single person and little testwork.

2. Scoping or Order of Magnitude feasibility study: Constitutes an initial financial appraisal. Accurate to ± 40 %-50 % and normally obtained by copying existing plant concepts and figures.

3. Preliminary feasibility (or pre-feasibility) study: More detailed analysis of the deposit and potential costs. Identification of information gaps. Accurate to ± 20 %-30 %.

4. Feasibility study (FS): Most detailed step. Will determine definitively whether or not to proceed with the project. Full FS provide budget figures and are the basis for capital appropriation. Accurate to ± 15 %.

9.3.2 Scouting

In a first step some raw data should gathered in order to assess whether or not a specific site could have potential of being reprocessed. The two key parameters for making a decision are the precious metal content (gold/silver) and the leachability of the ore by cyanidation.

At this stage, taking samples by grabbing from a range of equally distributed locations of the tailing is sufficient. The samples are assayed by chemical analysis for relevant metals (gold, silver, mercury) and sulphur. Metallurgical testing is performed by mixing aerated sample material with an excess of a cyanide solution in order to quantify the extractable fractions of the metals.

Scouting gives by no means any reliable information on the economic and technical feasibility of a project, but the information on the extractable metal content allows to estimate whether further analysis is justified.

Industry sources have reported that reprocessing of tailings with an average gold concentration of 0.2 g/t can be profitable at current gold prices (2010)[6] depending on the dimension, homogeneity and grain size of the tailings. This information may be taken as a rule of thumb, but of cause, site specific conditions and market price changes may alter this value upwards or downwards.

9.3.3 Scoping or Order of Magnitude feasibility study

A scoping or Order of Magnitude feasibility study constitutes a first financial appraisal. It is based on a geological report on the grade and quantity of the deposit. Thus, more extensive sampling and a quantification of the tailings volume is necessary. The calculated total metal content of the tailing is multiplied with its current market price to give a gross value of the tailing. Due to losses during the process or incomplete recovery rates, only a part of the total metal content can be transferred into the final product. Because of this, reduction factors are applied to the gross value to give a net value per ton of material. As a rule of thumb, the net value per ton material should exceed estimated process costs by a factor of two (taken from similar operations) to make the project potentially profitable.

The whole calculation is based on experienced data (process layouts, factors, costs) from similar operations at other sites. Since process costs may vary in wide ranges from site to site, the analysis only gives a rough estimate, which helps to verify whether there are good chances to establish a profitable operation at the site. A more detailed analysis in a feasibility study including site specific data is necessary to check whether this estimate is justified.

A good example for a scoping study may be found in Mutiny Gold (2009): White Well Project, Australia.

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[6] For example tailings reprocessing projects in South Africa targeted grades of 0.2 to 0.4 g/t (MEI Online, 2007)

9.3.4 Preliminary (pre-)feasibility study

Both pre-feasibility and detailed feasibility study are carried out in the same manner, but they differ in depth and extension. The purpose of the pre-feasibility study is to develop a detailed operation plan and based on this an analysis whether the expenditures for a full detailed feasibility study are warranted. Moreover, information gaps are identified (often including more extended sampling) that need to be filled before a reliable resource estimate and thus economic appraisal is possible.

According to the Canadian Institute of Mining, Metallurgy and Petroleum (CIM 2003) “A Preliminary Feasibility Study is a comprehensive study of the viability of a mineral project that has advanced to a stage where the mining method, in the case of underground mining, or the pit configuration, in the case of an open pit, has been established, and where an effective method of mineral processing has been determined. This Study must include a financial analysis based on reasonable assumptions of technical, engineering, operating, and economic factors and evaluation of other relevant factors which are sufficient for a Qualified Person acting reasonably, to determine if all or part of the Mineral Resource may be classified as a Mineral Reserve.

A pre-feasibility study typically includes the following elements (adapted to tailings, McIntosh Engineering 2003):

- Introduction and scope of work
- Summary and Conclusions
- Location and description of the project
- Map with inset and site plan
- Regional and local geology
- Description of mineralization
- Ore resource estimate
- Tailings longitudinal drawing
- Mining method(s) and sequence of extraction
- Ore transport
- Process plant
- Mill flow sheet
- Mine infrastructure and utilities
- Pre-production construction schedule

- Production schedule
- Capital cost estimate
- Operating cost estimate
- Preliminary financial evaluation

9.3.5 Detailed Feasibility study

According to Castle (1975) “the purpose of a detailed feasibility study is to clearly define a project and confirm (or deny) its economic viability”. More importantly, it is the basis for the definitive investment decision:

> CIM (2003) “Feasibility Study means a comprehensive study of a deposit in which all geological, engineering, operating, economic and other relevant factors are considered in sufficient detail that it could reasonably serve as the basis for a final decision by a financial institution to finance the development of the deposit for mineral production”.

The study thus includes all elements relevant for the planning, construction, commissioning, operating and decommissioning of a project. The detailed FS is based on the results of a pre-feasibility study and consists of an in-depth analysis of economic and practical issues, including:

- General description of the site
- Mineral Resource
- Mineral Extraction
- Surface and Groundwater Management
- Processing
- Waste Dump Management
- Infrastructure
- Social and Environmental issues
- Permitting and Land Acquisition
- Economic analysis
- Project Execution and Project management

The decision of further proceeding with the project will be based on the definition of the cut off grade (the concentration of the precious metal in the tailing material that is necessary to produce profits) and the market forecast. Costs estimations, initial investments and revenues are also considered.

More information about conducting feasibility studies may be found in[7]:

- McIntosh Engineering (2003): Hard rock miner's Handbook. 3rd Ed.
- UNIDO (1995): Manual for the Preparation of Industrial Feasibility Studies.
- Thompson (2005) Business Feasibility Study outline
- Ryan et al. (2005) Feasibility study plant design

The following examples may give useful insights

- Outokumpu (2005): Fäboliden gold project pre-feasibility study
- Banro Corporation (2009): Twangiza feasibility study (Tanzania)
- Micon (2005): Feasibility study for the La Laguna silver project Zacatecas State, Mexico

9.4 Elemental evaluation parameters

9.4.1 General description of the site

A thorough description of the site, the tailings and relevant local and regional conditions is the basis of any further decision.

Regional site conditions

- **Location**: A short description of the location and the project area should be given.

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[7] see chapter 11 (References) for more details

- **Background and site History**: The study shall also include a review of the history of the property. Especially which mining techniques and processing techniques have been used throughout the life of mine. This might be give valuable information towards the composition of the waste pile. It should also contain the different feeding points over the time which is a helpful information regarding the grain size distribution of the tailings. It should be noted whether the site has been used as disposal site for municipal or industrial waste, since removal and disposal of such foreign material causes additional costs. Moreover, the processing of the tailing material might be critically affected even to a degree that the reprocessing is no longer technically nor economically feasible.

- **Topography**: The geographical situation and access to the site should be described. A topographic map should be included.

- **Infrastructure**: The infrastructure details of the site should include accessibility to electricity, water and labour. Furthermore, areas of interest are roads, ports and railway connections for both shipping of products from site and shipping of equipment to the site.

- **Tailings site Description**: A detailed description of the dump site shall be given including shape and dimensions of the tailings. The spatial distribution of the waste material is important for transportation cost estimation. A statement shall also be given regarding the accessibility of the site.

Climate

- **Temperature**: The study should include a description of the climatic conditions with average temperatures and maximum and minimum temperatures on a monthly base.

- **Precipitation, humidity and evaporation**: Annual precipitation in the region, the rainfall pattern determined by season as well as dry periods should be included in this section. Furthermore, the humidity and evaporation should be included.

- **Wind conditions**: The orientation and characterisation of different wind patterns should be described.

Environmental Site Conditions

- **Surface Hydrology**: This section includes a description of the surface hydrology and the influence of the waste dump sites to the rivers and creeks in their vicinity.

- **Groundwater Hydrology**: The description of the groundwater hydrology should contain the groundwater regime of the region and the waste dump site.

- **Soil Resource:** A characterization of the soil and their contamination is necessary through a set of geochemical and physical tests. Current erosion levels, locations and directions have to be determined.

- **Seismicity**: The seismic potential of the region has to be listed, such as ground acceleration and interpolate movement.

Legal Environment

- **Actual political situation**: This section should contain a general description of the actual political situation and the stability of the country.

- **Ownership**: The ownership history of the property and the respective project area should be reviewed. It is important to detect if there are any pending lawsuits or claims arising from past ownership. Further an overview on the right of way and right of water in the project shall be given. Laws concerning expropriation and resettlement shall be consulted as well. Certain countries have imposed restrictions on foreign ownership, which should be pointed out. Usually full Due Diligence on the legal situation is required.

- **Uses of land and regional planning**: The details of the section should determine the land use for agricultural use, use for pasture, industrial use, others or a mixture of all together.

- **Governing authorities**: References shall be made towards the governing authorities in terms of environment, taxes, etc. for the property and concerning the enforceability of rights.

9.4.2 Mineral Resource

9.4.2.1 Exploration

Sampling of waste dumps and tailings ponds

Before any exploration works are carried out, the site history and the origin of the material should be reviewed, allowing to draw conclusions on the composition of the dump site. Older dump sites that have been active for a long period can show a higher variability in metal concentration and composition, whereas younger dump sites are in general much more homogenous. The exploration program for material heaps is different from for the tailings ponds. Both strategies will be explained in the following:

- **Waste dumps:** Any dump site needs to be thoroughly surveyed and a grid covering the site shall be generated. If possible, an essay excavation at the boundary of the dump site shall be conducted. This might show that the site is composed of different layers and therefore each layer can be sampled and strata boundaries measured. Small dumps can be easily explored using auger drilling. Since auger drilling is relatively inexpensive, the grid spacing between samples can be less than 50 m. In some cases, waste dumps have been sampled with a grid spacing of less than 5 m. For each sample, the exact location is to be recorded in a clear and understandable form. Large scale heaps are first explored with bigger grid spacing such as 50 m or 100 m using a core drill. If not stated otherwise the holes should be drilled vertical. The grid spacing can, when needed and the budget permits, be scaled down to a smaller spacing. In case of restrictions in accessibility, the sampling scheme needs to be altered to squares or triangles.
- **Tailings ponds:** The development of the tailings ponds differs from that of the waste dumps. Agglomeration of coarse grains can be found close to the inlet of the pond whereas finer grains can be found in the centre and in the direction of the outlet, if drained. In comparison to the heaps, the material in the ponds is less oxidized due to the absence of oxygen but the ponds boundaries might be oxidized due to changing water levels. The exploration program has to be

adjusted to the different distribution of material stated above. Ponds can be explored with diamond core drills but special attention shall be given to core retrieval. Sometimes it can also be feasible to drain the pond, which allows making the sample process less difficult, but most of the time drainage is not an option since the water can be highly toxic.

Sample preparation and Chemical analysis

Each incremental sample is thoroughly mixed and then a subsample being taken for further analysis. Sample should be packaged and stored in their original damp condition, as drying enhances their leachability. Samples should be analyzed within three months by which time oxidation may have altered them in way that they are no longer useful for testwork (Muir et al. 2005).

Further information on sampling procedures may be found in Holmes (2005).

The analysis of the samples shall be carried out by an accredited laboratory. Quality assurances such as having parts of a sample analyzed by a different laboratory are essential for the overall success of the project. The main parameters that should be analyzed are the concentrations of gold and mercury. The following methods could be applied:

Flame Atomic Absorption Spectroscopy (AAS)

The sample is ground and dissolved in aqua regia and evaporated in an acetylene flame. A beam of light at a wavelength matching that of gold (mercury or any other metal of interest) is passed through the flame. The gold atoms in the evaporated sample absorb the light proportionately depending on the concentration of the element in the solution. The absorption is compared to standard solutions to determine the gold concentration in the sample.

Mercury may be analysed by Flame AAS also, but cold vapour AAS is more selective. Mercury is reduced in solution using stannous chloride or sodium borohydride in a closed system. The reaction quantitatively releases mercury (from the sample solution) and is carried by a stream of air or argon through a quartz sample sell placed in the light path of an AA instrument for analysis.

Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES)

The aqueous sample is evaporated in a plasma (Argon, heated by a magnetic field to 6000 K- 10,000 K). Due to the high temperature atoms in the sample emits light at characteristic wavelengths. The intensities of the emitted light are measured and compared to those of standard solutions. A software then calculates the metal concentration in the sample.

Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)

Like in the previous method, a liquid sample is evaporated, atomized and ionized in a plasma torch. The resulting ions are sucked by vacuum pump into a mass spectrometer, where they can be separated by a magnetic field according to their atomic mass.

Gold, for examples measured at the mass of 186, as well as the signals of any potentially interfering isotopes. The intensity at 186 μ is measured and compared by software to those of standard gold-bearing solutions to determine the concentration of gold in the sample.

9.4.2.2 Collation of geological Data

Drilling of samples

There are varieties of drill mechanisms, which can be used to sink a borehole into the ground. Each has its advantages and disadvantages, in terms of the depth to which it can drill, the type of sample returned, the costs involved and penetration rates achieved. There are two basic types of drills: Drills, which produce rock chips, and drills, which produce core samples.

- **Reverse Circulation (RC) drilling** is a drilling method, where the drill cuttings are returned to surface inside the rods. The drilling mechanism is a pneumatic reciprocating piston known as a hammer driving a tungsten-steel drill bit. RC drilling utilises much larger rigs and machinery and depths of up to 500 m are routinely achieved. RC drilling ideally produces dry rock chips, as large air compressors dry the rock out ahead of the advancing drill bit. RC drilling is cheaper than diamond coring and is thus preferred for most mineral exploration work.

- **Diamond core drilling** (Exploration diamond drilling) utilises an annular diamond-impregnated drill bit attached to the end of hollow drill rods to cut a cylindrical core of solid rock. The diamonds used are fine to micro fine industrial grade diamonds. They are set within a matrix of varying hardness, from brass to high-grade steel. Matrix hardness, diamond size and dosing can be varied according to the rock, which must be cut. Holes within the bit allow water to be delivered to the cutting face. This provides three essential functions; lubrication, cooling, and removal of drill cuttings from the hole.

The collation of the data includes the following items:

- Topographic data
- Diamond drill holes
- Core size distribution
- Sampling and assaying
- Core recovery
- Reverse circulation drill holes

9.4.2.3 Database Management

An exploration database should be used to support the preparation of a deposit model. The model will be the base for the mine planning and will be used for further development of the project for the supply of a processing plant. The outcome from the resource model will be verified through the application of geostatistics. Furthermore, the consultant shall elaborate a resource classification according to UNFC[8] or JORC[9] code.

The database management includes the data organization (data collection, drill hole logging, and database checks) and the drill hole location survey.

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[8] United Nations Framework Classification for Fossil Energy and Mineral Resources http://www.unece.org/energy/se/pdfs/UNFC/UNFCemr.pdf

[9] The Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves. http://www.jorc.org/jorc_code.asp

9.4.2.4 Mineral Resource Model

Mineral Resource modeling

The data will then be imported into computer aided modeling software (CAM) such as Surpac, Datamine, Gemcom, Vulcan, Lynx, Micromine or any other software followed by the generation of a geometrically and structurally consistent geological 3D model. It is based on correlated layers intersected by drilling. This correlation considers discontinuities as well as structural complexities resulting from changes in the formation of the waste dumps. Descriptive statistics applied to all samples, shown as histograms, correlograms and ternary diagrams, will define ranges of ore quality parameters and the distribution thereof. The distribution pattern distinguishes different sample populations and points to different domains in the tailings. These domains might be indicative to variable situations during the development history of the waste dump. Furthermore, the upper cut-off grade can be defined depending on the degree of confidence and the presence of outliers (cumulated histograms). Geostatistical analysis is a trend and estimation procedure used to evaluate the orientation and range of sample values within a population. The name of the procedure is called variography. A variogram shows the change in variance of sample values with increasing distance between sample points (lag distance). Depending on orientation, they give the range of influence within the sample population. Variogram maps indicate the orientation of the maximum range for all three directions in space, producing a distribution ellipsoid (anisotropy) or sphere (isotropy).

Exploratory Raw Data Review

This section will describe in detail the sample location, spacing and orientation the sample length and the statistic assay data.

Compositing of Samples

In a further step, the composite will be determined with the sample size of composites, their length and statistics.

Generation of 3D block model

Interpolation of mineral properties will be based on geostatistical algorithms, e.g. Kriging, which is a linear algebraic interpolation, where weighting is based on a distribution ellipsoid. This method results in an interpolation with minimum estimation error. The interpolated quality values are aggregated to blocks of a defined size, which are coloured according to the average quality value. The interpolation will be done for the principal ore quality parameters and densities.

Resource estimation

The resource area will be subdivided into measured, indicated and inferred resource categories of international standard according to the data density, geostatistical analysis and field relationships. The bulk tonnage and average quality parameters for the tailings site will be calculated.

9.4.2.5 Geotechnical Management

Stability analysis determines the cohesion and the friction angle, porosity, shear strength and grain size distribution. The geotechnical investigations include a:

- Baseline investigation with field work including drilling tests as well as laboratory tests
- Lithological characterization of the waste dumps concerning geotechnical and geomechanical parameters
- Seismicity
- Geotechnical Management of the facilities (Waste dump, processing plant and tailing)
- Geotechnical monitoring during operation

Samples should also be taken from the preliminary plant site as well as from the proposed dump site for the foundation design and to identify problems that might occur. The sampling can be carried out in accord with the drilling contractor who is responsible for the geological sampling.

9.4.3 Mineral Extraction

The mineral resource model shall give a good overview on the metal content of the tailings and the contained mercury and amalgamated gold. On that basis, the extraction work within the study has to consider options for developing and operating the project. These concepts have to include:

- Definition of the reclamation (excavation and haulage) method

- Evaluation of the tailings access
- Definition of the production rates
- Definition of the necessary equipment size of the main production equipment and transport equipment;
- Initial plans and schedules for the production and ramp up phase

General Considerations and Design Criteria

This section should include a short description of the used design and optimization parameters for the tailings extraction and the definition of the criteria used for the process plant design and the mineral ore quality.

Mineable Reserves

The mineable reserves will be defined according to the actual standards. This includes the definition and description of the following factors:

- Cut off grade
- Losses and Dilution if parts of the tailings will be extracted
- Other relevant design parameters

After application of all the parameters, the final reserves will be determined and their compliance with international standards approved.

Reclamation of tailings

Principally three technical methods can be employed to reclaim tailings:

- Mechanical reclamation: Shovel and truck operation. Best suited for small or scattered deposits. Also the method of choice for sandy material that cannot safely be flushed without the danger of settling. Not as effective as hydraulic mining, but needs less capital.
- Hydraulic mining: A monitor shoots water with high pressure in order to erode the tailings in sections. The material is washed downstream where it is collected in a sump. Screenings are used to exclude unwanted coarse material. The resulting slurry is then pumped to thickeners and the underflow is reprocessed in the plant. Hydraulic mining is best suited to large tailings of slimy material.
- Dredging (underwater reclamation): Very expensive and only employed when other methods are technically not possible (e.g. flooded land, underwater

deposits). In some areas draining in a dry season and subsequent hydraulic of mechanical reclamation could be an option.

Some tailings impoundments are hydraulically mined not only to process the tailings but also to re-site them for environmental reasons. This is an effective method and can take a shorter time than mechanical excavation, depending on the density and particle sizes of the tailings. In hydraulic mining, the water demand is quite high. Recycling of water is a must since supply of fresh water is normally limited.

A detailed description and comparison of different reclamation methods is given by Muir et al. (2005).

Waste Dump Design

After processing of the tailings, the waste has to be dumped at a different site. The site location has to be determined and the waste dump designed. These parameters should be included in this section. Site selection is the most important aspect in affecting the tailings storage facility design. Different sites have different characteristics and a suitable location is sort that is most practical in terms of cost and proximity to the mining and milling operations. The tailings characteristics will have an effect on the type of storage impoundment area, and therefore the site location. In order to solve the tailings problem the site selection is dependent on the storage capacity required of the facility, the site availability, the construction, operating and closure costs, geotechnical and geological conditions, the hydrology of the area, and the ease of the day to day operations. Some secondary site selection considerations are:

Production Schedule

After design of the extraction method, the winning of the tailing material will be defined by yearly capacities in a detailed production schedule as well as in a short term planning for the initial phases on a monthly base.

Operation

The operation of the mineral extraction from the tailings will be detailed described with the following items:

- Loading and haulage requirements

- Working time of main extraction equipment
- Drilling and blasting operations (if necessary)
- Requirements for ancillary equipment
- Equipment summary

Organization

The organization of the whole process including the staffing requirements is part of this section.

9.4.4 Surface and Groundwater Management

Surface Water Management

For the further treatment of the tailings, the surface water has to be collected and pumped to a discharge system. In order to evaluate all necessary data in the course of a pre- or feasibility study, the following aspects have to be investigated, depending on the location and the availability of water.

- Hydrological baseline study (Evaluation of the existing hydrologic and hydraulic conditions and creation of a numerical model to characterize the hydraulic flow patterns)
- Surface water management concept
- Stream diversion if necessary
- Drainage and drainage control
- Development of storage ponds
- Water supply pond
- Contact water treatment plant if necessary
- Development of a site water balance
- Surface water management concept for the waste dumps
- Surface water hydrological closure plan
- Groundwater Management

For the extraction of the tailings and their rehandling groundwater base line investigations have to be considered in order to minimize the actual influence of the mercury contaminated tailings and to estimate the historical contaminations. For the groundwater analysis and handling, the following investigations might be necessary:

- Hydrogeological investigations like evaluation of the groundwater flow regime and hydraulic testing
- Numerical groundwater model
- Dewatering reinjection system if necessary

9.4.5 Processing

9.4.5.1 Metallurgical sampling

In contrast to the geological sampling, the metallurgical sampling has the aim to provide sufficient material covering a range of head grades, hardness and other parameters that are essential for processing. To quantify the variation of these parameters it is important that the sample collection covers all parts of the deposit. The collected material should represent as close as possible the anticipated feed for processing. Mixing the samples in order to derive an average grade is not acceptable and shall only be carried out if it is required due to the scale of the processing test because it can lead to false interpretation of the material properties. Dividing samples and sending one part to assays and the other for processing tests is the desired practice. It is desirable to test for bias and estimate the level of precision.

Sample types can be as follows:

- Grab samples
- Reverse circulation drill cuttings
- Diamond drill core
- Auger drill samples
- Channel samples
- Bulk samples

The selection of the sampling method depends on the properties of the waste dumps. If for example the waste dump extends to great depths and the material is highly consolidated RC drilling and core drilling are the only options. Whereas if the dump pile is shallow and not very consolidated auger drill samples, channel samples and grab samples can be easily obtained. For prefeasibility stages, samples from the exploration can be used for bench scale testing. However, pilot plant testing requires high volumes and most likely a separate sampling program.

9.4.5.2 Metallurgical testing

The metallurgical testing examines the behaviour of the material from the tailings site in a given set of chemical and physical conditions. The objective is to find the optimal technology for separation and concentration under the constraint of economic viability. In general, a bench scale test and a pilot plant test have to be carried out. The bench scale test is carried out at small throughput and shall clarify the response to different methods. Within the bench scale test a mass balance is prepared for follow up pilot plant test work. The pilot plant test confirms processing possibilities at a larger throughput. The outcome from the pilot plant test will be used for flowsheet shaping and preliminary plant design. If possible, the test work that uses water shall be carried out with water from the proposed plant site. The tests are depending on the grain size of the tailings and might impact a further crushing and grinding. For the sake of completeness comminution test are included in the below lists.

Test work Pre-feasibility Study Level

In the pre-feasibility stage bench scale testing has to be carried out covering the following tests: Crushing and grinding test, work index determination, batch flotation test, cyanidation bottle rolls and thickening and filtration test might be necessary depending on the grain size of the tailing material and to allow a better understanding of the tailing material. In detail the following test are recommended:

COMMINUTION

1. Bond work indices (rod and ball)
2. Bond abrasion indices
3. SAG power index
4. Bondwork indices (crushing)
5. MacPherson autogenous index
6. Autogenous media competency (includes 1, 2 and 7)
7. Uniaxial Compressive strength (UCS)/ Point Load Index (PLI)
8. Fracture frequency

FLOTATION

1. Preliminary reagents/pH
2. Rougher grind-grade-recovery
3. Regrind and cleaner flotation

4. Locked cycle
5. Optimization of major ore type (variability)

DEWATERING

1. Concentrate thickening
2. Concentrate filtration
3. Tailing thickening
4. Tailing filtration

HEAVY MINERALS

1. Gravity gold recovery
2. Heavy liquid separation
3. Gravity/magnetic/electrostatic separation (if applicable)

LEACHING

1. Small diameter columns
2. Intermediate diameter columns
3. Bottle rolls (variability)
4. Batch agitation leaching (Carbon-In Leach [CIL] / Carbon-In Pulp [CIP])

Test work Feasibility Study Level

For feasibility study level, testwork has to be done on both lab scale and pilot scale. The following tests shall be carried out in addition to those from the prefeasibility study (as required):

COMMINUTION

1. Bond work indices (rod and ball) 2nd facility (a measure of grindability)
2. JK tech drop weight test (a procedure for the testing of ores for certain mill types, developed by the Julius Kruttschnitt Mineral Research Centre)
3. Grinding pilot plant [10]

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[10] More information on comminution testwork may be found in the SGS Comminution Tests Handbook, that is available for from SGS: http://www.met.sgs.com/

FLOTATION

1. Ultra fine grinding
2. Pilot plant (complex material)

HEAVY MINERALS

1. Pilot plant

LEACHING

1. Large diameter column
2. Semi-continuous (CIL/CIP)

9.4.5.3 Flow sheet development

The Flow sheet shows diagrammatically the sequence of operations in the processing plant. In its simplest form it can be presented as a block diagram in which all operations of one character are grouped such as comminution, separation and product handling. It includes details of machines, flow rates and rejection parameters at each stage. The first flow sheets will be prepared after bench scale testing has been carried out. With more testing the original flowsheet will be verified and upgraded.

9.4.5.4 Unit operations in gold ore processing

Pre-treatment for the removal of mercury

In order to avoid later releases during the ore processing it would be advantageous to selectively remove the mercury before the material is further processed. This could effectively be achieved by thermal treatment of the tailing material. The need for additional facilities and energy makes this procedure quite expensive, so that he whole reprocessing project might become unprofitable.

Comminution

In many cases, tailings consist of already processed fine-grained material, so that further comminution is not necessary. If the tailings contain course materials like sands and waste rock, crushing and grinding could enhance the extractability of gold.

Concentration

Concentration of gold can be achieved through gravity separation, froth flotation and leaching. In most of the gold producing mines, a combination of the mentioned techniques is used to produce a concentrate that can be further processed through leaching. The mineralogical properties, the grain size and the chemical bond of the waste from the dump site determine its response to the various processing options. Each option has a different impact on the environment and considerable different processing costs:

Gravity Separation: Gravity separation has the least impact on the environment. It is easy to test at bench scale and has low capital cost. In order to use a gravity separator the material has to be fine ground and fluidized to processable slurry. When fed with low concentrations the resulting product often requires further treating. In gold plants, for example, a number of gravity devices, are being used to recover relatively coarse gold. Over the past few years, gravity separators that take advantage of differential specific gravities in a high-gradient centrifugal force field (e.g. Knelson and Falcon separators) have been used successfully for gold. Older devices are for instance spirals on which the centrifugal forces are lower, pinched sluices, and Reichert cones. For coarser grain sizes, jigs are commonly used as a primary stage to recover coarse liberated minerals sized 2 mm and above. Feed slurry is distributed into the hutch which consists of a moving slurry bed located above a screen and is subjected to a pulsating motion and upward hutch water flow which alternately causes dilation and compaction.

Froth Flotation: Froth flotation is widely used to separate complex ores before further processing. Within the process several different chemicals are used that act as collectors, frothers and modifiers making the froth floatation an expensive and possibly polluting process. Treatment of low grade material only using froth floatation is ineffective in terms of cost and resulting grades. Nevertheless, if considerable amounts of gold are bound to pyrite, it is advisable to separate pyrite by flotation and treats it separately (Muir et al. 2005).

It should be noted that there are many cases where reprocessing is done without a prior concentration step.

Roasting: Concentrates rich in sulphides have to be roasted in order to remove sulphur by oxidation to sulphur dioxide. Otherwise, the sulphide content leads to a high consumption of cyanide in the leaching operations and low extraction of metal. Roasting also renders gold within pyrites free and makes it available for leaching agents. During roasting approximately, 80 %-90 % of mercury is released into the gas phase, where it has to be captured by the SO_2 scrubber, and mercury specific absorption units (Miller 2007)

Leaching: Currently almost every gold processing route includes leaching. For gold dissolution most frequently a diluted cyanide solution is used, but other lixiviantes are under close investigation for further application (Aylmore 2005). The most common forms of leaching are heap or dump leaching and agitated leaching. Cyanide leaching requires rather low capital costs and returns good results but it is potentially dangerous to the environment if not managed properly.

The processing route mainly depends on the grain size of the waste as well as the size of the gold particles.

- **Heap leaching** is the sprinkling of crushed ore on a pad with the cyanide solution. The solution seeps through the heap, where by combined action of oxygen and cyanide elemental gold (and other metals like silver, copper or mercury) are dissolved as waste soluble cyanide complexes (Marsden 2006). If the material is too fine, percolation could get slow and inhomogeneous leading to low metal extraction. In such cases, prior agglomeration into coarse particles might be necessary. The gold bearing solution is collected at the base of the pad. Other lixiviantes such as thiourea, bromide and iodide solutions are also potential alternatives to cyanide leaching, but have not yet been used on industrial level (Aylmore 2005). Mercury, silver and gold show similar chemical behaviour in cyanidation leaching. All three form strong complexes with cyanide and will be transferred to the eluate. Recent field investigations showed that gaseous mercury emissions could be strongly elevated during active heap leaching, but may be greatly reduced within some years of ceasing the operation (State of Nevada 2009).
- **Agitated (tank) leaching**: For leaching by agitation, the material to be treated is brought into contact with the leaching solution and the oxidizing agent in one or more leaching tanks. The thorough mixing during a leaching period lasting several hours can take place mechanically or through aerating. However, in the latter case, problems peculiar to this technique, such as increased cyanide consumption resulting from hydrogen cyanide gassing out, can be expected.

After leaching is completed, the fluid and solid phases of the leach slurry are separated from each another by conventional separation techniques. No information could be found on gaseous mercury releases during tank leaching. Since heap leaching produces considerable amounts of gaseous elemental mercury the same process might be expected in tank leaching also.

Recovery from the solution

After separation from the ore and dissolution, gold is now dissolved in the so-called pregnant solution. Three process routes are applied to recover gold from the solution:

- **Merrill-Crowe process (zinc cementation)**: The process starts with the filtration of pregnant solution in media filters. The clarified solution is then passed through a vacuum deaeration tower where oxygen is removed from the solution. Zinc dust is added reducing and precipitating the gold in form of a metallic sludge, which is filtered off. Being the older of the two recovery methods, it is now widely replaced by the CIP/CIL process (see below). Nevertheless, it is still used for around one quarter of the global gold production, especially in cases of high silver or high mercury content of the pregnant solution. High mercury concentrations may lead to a contamination of working areas during the CIP/CIL process steps after elution. By cementation, up to 95% of the mercury cyanide complexes is removed from the solution (Walton 2005) and will be found in the raw metal product.
- **Carbon-in-pulp (CIP)/ Carbon-in-leach (CIL) processes**: Introduced on industrial scale in the 1970s. To recover the gold activated carbon is added, either to the ore/solution mixture (carbon-in-pulp process) or to the separated pregnant solution (carbon-in-leach process). The gold-cyanide complexes are absorbed to the surfaces of the carbon particles, which can be filtered off. Addition of diluted alkali releases the cyanide complexes, which the can be converted into metal by electrolysis (electrowinning process). Mercury complexes are also absorbed to activated carbon and stripped by strong alkalis. It will join gold during electrowinning and can be found in the raw product. Moreover, it is emitted from the solution during electrowinning. Precautionary measures have to be taken in order to avoid gaseous mercury emission and contamination throughout the process. Mercury might not be fully removed from the carbon, so when exchanged or it must be removed by thermal treatment.

- **Resin-in-pulp (RIP)/ Resin-in-leach (RIP)**: Instead of activated carbon, a base resin or better gold-selective ion exchange resin is employed.

The product from all process will be melted in a furnace into doré bars that contain mostly gold but also precious metals like silver and copper. Mercury can be distilled from this product and captured with retorts (additional gas cleaning required).

These bars are sent to an external refinery where the other metals are separated and the gold purified.

9.4.5.5 Plant Design Criteria

In the feasibility study stadium a plant design should be proposed that would be used for the financial evaluation. The main data that determines the plant design beside the process itself are the operating schedule and the capacity of the plant. The equipment dimensioning for the proposed plant depends on the anticipated throughput whereas the operating hours, expected reliability and maintenance schedules shape the economics of the processing plant. In general a processing plant should run as continuous as possible therefore most plants have a 24 hours per day, 365 days per year working schedule.

Steps for the processing plant design and layout are in general the following:

- Selection of the main process
- Metallurgical balance
- Equipment selection
- Operating schedule and capacity determination
- General criteria (seismicity, altitude, environmental constraints, extreme climate)
- Infrastructure for the plant
- Waste dump
- Safety policy

Instead of constructing a new processing plant, transport to an already existing processing plant in the vicinity might be a viable option. While transport costs would probably rise, capital costs could be much lower. The technical feasibility of such an option depends on the tailing material characteristics (is the process being used in the plant suitable or must it be adapted?), the capacity of the plant, operational schedule, availability of transport routes.

9.4.6 Tailings Management

Processing of tailings necessarily produces new tailings with even higher volume, because only a very small part of the material will be extracted, but water added. As the environmental situation should be improved by the project, the design and location for the waste dump should be carefully chosen.

Tailings characteristics can vary greatly and are dependent on the ore mineralogy together with the physical and chemical processes used to extract the economic product. Tailings of the same type may possess different mineralogy and therefore will have different physical and chemical characteristics. The tailings characteristics have to be determined to establish the long term behaviour of the tailings and the potential short and long term liabilities and environmental impacts. Once the likely characteristics of the tailings are determined from mineralogical examinations and pilot plant tests, the necessary design requirements can be identified to mitigate liability and impact. A certain type of tailings storage method may be preferred or certain design considerations may need to be adapted to a more realistic or suitable storage method. To help determine the design requirements of a tailings storage facility the following characteristics of the tailings will need to be established:

- Chemical composition (including changes to chemistry through mineral processing)
- Physical composition and stability
- Leaching behaviour
- Behaviour under pressure
- Erosion stability
- Settling behaviour
- Hard pan behaviour (e.g. crust formation on top of the tailings)

The engineering characteristics of tailings are in most instances influenced by the method of deposition. It is therefore essential that the physical characteristics, phenomenon and material parameters (e.g. beach slope angles, particle size segregation) that can differ because of varied deposition techniques are identified.

The following aspects are part of the dump site planning:

- Characterisation of the waste dump material with geochemical and geotechnical parameters
- Basic concept of the storage
- Design of the facility
- Embankment of the foundation for the waste dump
- Operation and waste management
- Geotechnical monitoring
- Construction sequencing
- Monitoring
- Remediation/ recultivation

During the operation phase, waste is normally produced in form of slurries that are collected in tailings ponds behind dams. Tailings ponds that consist of waste material from leaching processes often contain considerable amounts of cyanide as well as heavy metals, whose release into the environment must be avoided by sound technical measures. Failure of tailings dams is still a frequent accident that, unfortunately, could be observed continuously in places around the world. A typical trigger for dam breaches is heavy rain that leads to an overflow of the pond or a softening of the dam. Failures lead to fatal consequences as thousands (sometimes millions!) tons of slurry were abruptly released into the surrounding landscape – often killing people living or working nearby and poisoning wide areas and long stretches of river systems (WISE Uranium 2009; Rico et al. 2008).

Several countries have developed detailed guidelines and standards that are the basis for tailings management even outside their borders. Three countries (Canada, Australia, South Africa) are the main driving forces behind current international tailings management guidance. All of them are very active in mining and have a large number of tailings storage facilities. A good overview that also includes guidelines and legislation from other countries is given by Dixon-Hardy and Engels (2007). Also suggested are:

- Australian Ministry for Industry, Tourism and Resources (2007) Tailings Management.

- Mining Association of Canada (1998) A Guide to the management of tailings facilities

9.4.7 Infrastructure

The feasibility study should include a brief overview of the required infrastructure to confirm the technical feasibility and to assist in the economic assessment. This will refer to:

- Identify key structures that will be required to support the mining plan
- Estimate the costs and time required to construct the necessary structures
- List of all buildings, structures, roads, water treatment facilities and power supply
- Schedule for construction of the surface facilities
- Detailed costing for the initial construction

Water Supply

Since most mining and processing operation require considerable amounts of water supply with fresh water is an important requirement. There are numerous examples where mining operations could not take place at full scale because sufficient supply of fresh water could not be guaranteed. The amount of water required has to be calculated and compared with available resources. In addition, the system of discharge has to be planned. The following main items should be considered.

- Water supply source
- Effluent discharge requirements
- Water supply design
- Effluent discharge design
- Water reclamation

Electrical Power Supply

Plants usually require a connected load for the supply of the processing and ancillary facilities in the order of several megawatts. A power transmission line and switchyard or alternatively a generator set to supply the energy should be planned. The evaluation of the electrical supply for the project has to include the following sections:

- Regulatory requirements

- Power supply during construction
- Power supply during operation
- Description of the power line or gen set
- Description of the substation
- Development schedule
- Electricity price assumptions

Surface Facilities

The study has to describe the necessary project infrastructure concerning the surface facilities. The main compounds for the evaluation of the facilities will be as follows:

- Definition of the project area
- Main compound layout including definition of earthworks
- Buildings and facilities
- Regional and surface roads
- Project area, roads and bridges
- Water supply
- Water discharge
- Power supply
- Waste management
- Fire protection
- First aid
- Communication

9.4.8 Social and environmental aspects

Within the course of a feasibility study, a full environmental impact analysis (EIA) has to be carried out regarding several aspects of the mining operations affecting the community and the environment.

Environmental impact

The environmental impact study deals with the potential pathways of releases from the process facility to the environment. Its task is to identify direct and indirect environmental impacts as well as the nature and significance of any adverse effects on the marine and terrestrial environments during construction and during operations.

Especially the production process shall the object of closer evaluation. The following should be considered:

- Archaeology
- Noise emissions
- Dust emissions
- Gas emissions
- Surface water
- Groundwater
- Soil and sediments

Environmental monitoring plan

The ongoing assessment of the environmental effects of the project should be monitored.

Mitigation measures

The EIA shall examine and recommend suitable mitigating and abatement measures for the impacts identified. The effectiveness of the measures proposed, should be stated and impacts of significance clearly identified. Measures recommended should be practical and readily implementable. This should include a description of the measures envisaged to prevent, minimize and where possible offset any significant adverse effects on the environment of the project.

Social impact

The environmental impact assessment shall determine the social impacts both positive and negative on the immediate community and the nature of the effect including items such as local employment opportunities and nature of rehabilitation options. It shall also include a description of the settlements and land use in the vicinity of the proposed mining activities, the current sources of water and food supply, the demographic profile and current population numbers.

Project closing and restoration plan

Within the project development a closing plan should be elaborated covering land rehabilitation (if necessary), land use after mining, equipment and waste disposal and other factors that need to be addressed in order to guarantee a sustainable land integration.

The restoration plan will define the restoration objectives and evaluate alternatives. General tasks will be:

- Identification of restoration models
- Restoration measures
- Restoration and monitoring plan
- Scheduling of the restoration and closure operations

9.4.9 Permitting and Land Acquisition

Permitting

For the execution of a tailings reprocessing project the following permits are presumably needed:

- Definition of the involved authorities (municipal, regional and state)
- Investigation permit
- Extraction concession
- Permits relating to water (water supply, effluent discharge and others)
- Power lines
- Assumed pipelines
- Roads
- Environmental permits

Land Acquisition

The maximum surface area of land required for the project will consist of tailings site, the waste dump site and the site for the surface facilities. The status of the private and public land has to be determined. The project needs furthermore easements rights for water supply and discharge pipelines.

Waste dumps and tailings ponds pose great environmental hazards to the environment and the community. If the legal owner cannot be determined or has no funds/legal obligation to clean up the waste, public authorities should consider to step in and try to find a solution that respects public as well as private interests, e.g. by buying the land.

Only as a last resort after all attempts for a compromise settlements have failed the authority should check to acquire the land through expropriation.

If the public entity owns the land, it could process the waste on its own or through some kind of public private partnership. A public private partnership would allow engagement of companies who have the knowledge and technology to process the waste while on the other side the public counterpart would provide a sufficient level of legal certainty and community involvement. It is proposed that the public entity holds the land and engages through contracting or granting a concession to a company for waste processing. This is only a recommendation since legislature varies from country to country and a different structure might be more appropriate.

9.4.10 Economic analysis

The economic decision whether to proceed further with the reprocessing of the tailings or not will be answered partially in terms of technical, environmental and legal feasibility in the previous chapters. The economic decision shall be made on the basis of a financial analysis, taking all previously stated factors and their respective costs into account.

Market analysis

Market analysis includes the status of national and international current stockpiles, reviews indices that evaluate sector performance and elaborates demand and prices for the next years. The market organization (monopoly, oligopoly), market accessibility and potential competitors will be consulted as well as the price structure and quality factors that influence the commodity pricing.

Operating cost

The operating cost estimate compiles cost information that has been identified and calculated in the preceding chapters. The cost estimate has to be based on prices used in previous studies, price quotes recently obtained and reasonable/representative price estimates. The price sources shall be clearly stated within the study. The operating costs shall contain beside the costs for the extraction of the material the following items:

- Labour
- Administration
- Utilities
- Maintenance
- Licenses
- Insurance
- Depreciation
- Taxes
- Royalties

The following operating costs have been reported for tailings reprocessing projects:

- Las Lagunas, Dominican Republic (Au, Ag tailings): USD 325 per oz Au (EnviroGold 2009)
- Harmony, South Africa (Au tailings): R 80,000 per kg Au ~ USD 294 per oz. (MEI Online 2008):
- Ararat, Armenia (Au tailings): USD 180 per oz. (Global Gold Corp. 1997)

Environmental costs

In the past closures and post-closure expenditures where rather limited. Due to higher public awareness and strengthening environmental standards, decommissioning and rehabilitation are now significant cost factors that should be accounted for in a realistic dimension.

Capital Cost

The capital costs shall be based on the equipment requirements identified in the preceding technical chapters. The cost estimates have to incorporate price quotes obtained from suppliers as well as cost details from previous studies executed by third-party consultants.

A detailed description of the capital expenditure shall be given including the following items:

- Permits
- Land purchase
- Machinery
- Cost of financing
- Buildings
- Cost of consulting services

- Cost of legal advice
- Follow up investments
- Equipment replacement

Financial Structure

In accordance with the proposed legal structure, several options of financing the project have to be prepared. It is followed by an evaluation of the financial instruments.

Financial Analysis

A financial analysis shall be prepared to evaluate the projects financial viability. The most common analysis is the net present value approach (NPV). It takes the projected operational and capital expenditures (OPEX and CAPEX) as well as inflation into account to elaborate the cash flows for the life cycle of the project and discounts at a chosen discount rate. The cash flow should also include tax and royalty charges as well as depreciation. The discount rate should be appropriate for this type of business in the country. The analysis also includes a sensitivity investigation where the impact on the NPV is evaluated by changing factors such as commodity price, operating cost, capital cost, exchange rates, inflation etc.

SWOT Analysis

The SWOT (strength, weakness, opportunities and threads) analysis is carried out to determine risks and opportunities that can lead to overall project failure respectively improvement. The risks shall be categorized as financial, technical, geological, environmental and other risks such as political risks.

9.4.11 Project Execution & Project management

The consultant or contractor needs to provide a detailed time schedule including milestones and deadlines. Measures to evaluate the progress of the project such as monthly progress reports have to be installed to inform the client about the work that has been carried out and possible delays. The project manager has to show an outstanding track record of accomplished projects in order to qualify him for the job. The involved parties shall also agree on general communication principles, allowing everyone to have the same level of information. Risk sharing agreements shall be made between the client and the consultant regarding the budget, technological failure etc.

9.5 Literature

For further and more detailed information on mining and ore processing, the reader is referred to:

“SME Mining Engineering Handbook”: This comprehensive reference work distils the entire body of knowledge that characterizes mining engineering as a disciplinary field. More than 250 experts contributed to this text, which devotes attention to all branches of mining metals, coals and non metals. All locales of mining like surface, underground, and hybrid mining are mentioned.

“Surface Mining”: This SME classic is a reference book for the working engineer. This hardcover edition gives a brief history of surface mining and a general overview of the state of art surface mining today. The topics range from production and productivity to technological developments and trends in equipment.

M. D. Adams: Advances in gold ore processing: This handbook gives an in-depth overview on unit operations in gold ore processing as well as on managing feasibility studies

9.6 Concluding remarks

The success of a reprocessing project depends heavily on the size, the accessibility and the gold content of the deposit. If the dumps are situated in a very remote location and are scattered over a big area, the exploration of each deposit and their respective grades will be rather costly.

Other factors that will decide on the feasibility of the project are the grain size of the gold, which percentage is present as element and what percentage is bond to other substances.

Further important is the settlement of ownership issues, such as seen in Andacollo. As long as the ownership remains unclear or there is a dispute about sharing of potential profits a remediation project has little chance to be realized.

10 Case Study: Options for tailings reclamation in Andacollo, Chile:

10.1 Summary

Andacollo, a small mining town in north-central Chile, copes with a number of severe environmental problems due to heritage and active open-cast mining. One of these is the presence of numerous abandoned rock waste dumps (tailings, flotation ponds, span. *tranques de relaves*) within the town and along its outskirts resulting from historically largely unregulated, inefficient small scale ore processing for gold using the amalgam extraction process. Recently, studies on the effects of Hg on the population have begun to consider the waste dumps as potential sources of contaminants to the environment through deflation, mass wasting, and effluents. The remaining content of economically mineable minerals in the dumps, on the other hand, is unknown and subject to speculation.

Because at least some of the primary ore also contains Hg minerals and because the Hg used in the amalgam processing is only partially recovered, the fate of the unrecovered Hg and its mobility remains to date unresolved. Several heterogeneous and sparse data sets indicate that Hg concentrations at or near the dump surfaces are not significantly elevated; neither are Hg effects on nearby residents discernible. It is possible that much Hg evaporates from freshly dumped slurries at the surface of dry, sun-baked tailings deposits and is rapidly disseminated in the air.

The ineffectiveness of the traditional equipment used by the small processing shops (*marays, trapiches*) in removing Hg, Hg-Au amalgam, and primary ore minerals during processing is generally acknowledged. Stakeholders therefore agree that residual concentrations of ore (Cu, Au, Mo) may remain in the tailings.

Because the tailings, regardless of their metal content, are a significant dust source, pose at least a respiratory health risk, are a nuisance, and hinder town development, their re-processing, removal or cover (with the objective to ensure utmost elemental immobility) should remain a priority in local and regional environmental efforts in order to restore acceptable living conditions for the community.

A detailed cataster and a geochemical characterization of each tailing would provide critical input parameters to a more comprehensive study to estimate and rank environmental risk and remaining economic potential of individual tailings. This, in turn, would lead to a remediation strategy that also would need to consider the local historical, social and legal situation.

10.2 Introduction

10.2.1 Significance and Problem

Mercury, a potent environmental toxin, commonly occurs as a product of low-temperature ("epithermal") mineralization associated with economically but low-grade mineable ore deposits. In addition, in small scale, low-technology processing operations, liquid Mercury (Hg) is used to extract finely dispersed gold (Au) from milled or ground ore because Au dissolves in Hg ("amalgam process"). Thus, mine waste, in particular of low-efficiency or small scale mining, may still contain significant grades both of economically mineable ore (Au, Cu, Mo etc.) as well as unrecovered Hg which was introduced anthropogenically during the extraction process.

These dumps (also: tailings; span. *tranques de relaves*) pose both a problem and an opportunity: They may, when left unmanaged, pose a significant long-term risk to the local environment, including agriculture, watershed, and population, particularly if they lack an impermeable base liner and adequate cover to protect them from erosion (by water) and deflation (by wind). In their review, Renner and Dalheimer (2009) name the remediation of mining-related sites the most significant environmental issue in Chile. On the other hand, mine dumps are usually readily accessible, consist of pre-treated, milled and/or crushed rock, and may still contain economic quantities of ore. The characterization and management of mine dumps is therefore a matter of importance.

10.2.2 Objectives

This report compiles relevant information pertaining to the accumulation of heavy metals and potential remediation of inactive mining-related dumps in and near Andacollo, central Chile. It describes the environmental, political and historical circumstances of mining in the region, provides an overview over the physical state of the dumps, lists past and present efforts at addressing problems, and sketches potential remediation pathways by reprocessing.

10.2.3 Methods

The present author compiled information from published and unpublished (mostly) scientific literature, communicated with 12 key persons with relevant knowledge through telephone interviews, backed up by subsequent e-mail exchange, and augmented the knowledge base through a survey of newspaper archives etc. This report, therefore, does not include new or original data generated by the author but rather represents a compilation of existing information.

The report includes information through January 11, 2010.

10.3 Site Description

10.3.1 Geography, Climate, Access

The Coquimbo region (*IVa Region* of Chile) is characterized by a mountainous landscape and a semi-arid climate. Except for a discontinuous narrow coastal belt, the region is dominated by high-gradient, mostly E–W oriented valleys (the "*Valles Transversales*" system), which flow from the Andes (4000m to 6000m altitude) to the coast over less than 150 km. The main valleys are flanked by mountain belts with altitudes of 600 to 1000 m (**Fig. 4**)

The most detailed and site-specific climate data for Andacollo are given by Baeza and Cortés (2009) which also includes several appendices of meteorological data.

The regional climate is strongly influenced by the Pacific high-pressure cell and is transitional between that of the northern Atacama Desert and the Mediterranean climate of central Chile. The mean daily temperature on the coast is 14 °C and increases towards the interior to 16 °C. Days are commonly sunny throughout the year.

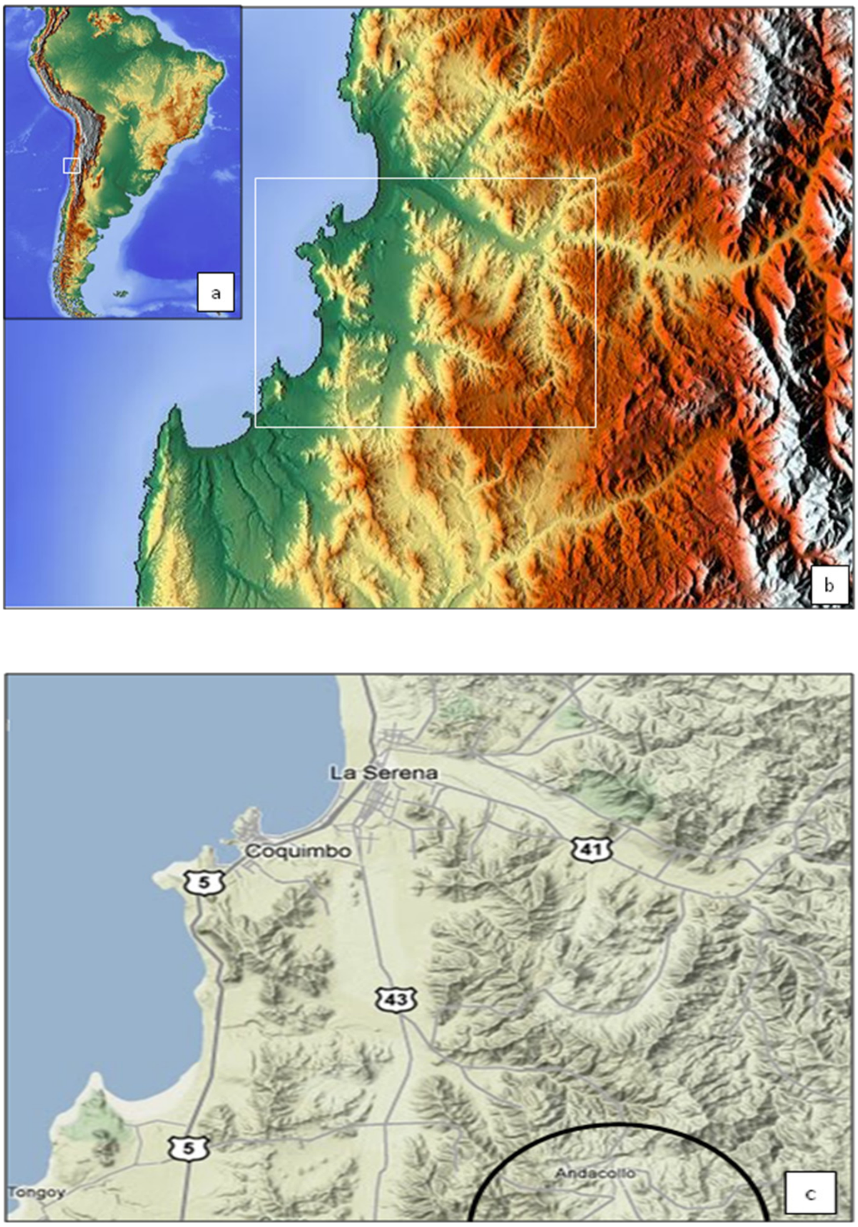

Fig. 4: Location map. Andacollo is located in the foothills of the central Andes, north-central Chile. The town (30°13'54.48"S, 71° 5'5.84"W) lays approx. 50 km se of Coquimbo, the capital of the IVa Region[11].

The average precipitation along the coast is ~126 mm/a and ~131 mm/a in the interior and rises from 50 mm in the northern sector to 220 mm in the southern sector of the region. Whereas the average precipitation (rain + snow) in the high-altitude Andes is ~180 mm (mean of past 20 years), the minimum of 11 mm in 1963 and the maximum

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[11] Source: maps-for-free.com under GNU Free Documentation license

of 740 mm in 1987 indicates that the region is characterized by strong annual variations in precipitation.

Precipitation maxima correlate with El Nino years, which bring infrequent but intense rains and subsequent flashfloods, and precipitation is seasonally concentrated during the months April-September (winter). The minor streams of the region, including those of Andacollo, have commonly an intermittent character, behaving as dry *arroyos* most of the year but turn into high-flow-volume torrents during periods of strong rain. A strong El Nino year usually has catastrophic consequences for the Coquimbo Region, such as of 1987 and 1997, when several roads and bridges were cut by debris flows, literally isolating the region (Oyarzun et al. 2006).

Andacollo is located in the Coquimbo region of Chile at 30°14’ south, 71°06’ west, 56 km southeast of La Serena, at a mean elevation of ca. 1100 m within a semi-arid hilly setting (Fig. 4). Access to the town is on a paved route (D-41) from Ovalle or La Serena and takes about 45 minutes. The route is subjected to traffic by mining trucks, taking copper concentrates and cathodes from the CMCDA mine to Coquimbo.

10.3.2 Mining History

The Coquimbo region is rich in mineral deposits and hydrothermal alteration zones of potential economic interest and therefore has a long record of mining-related environmental disturbances, primarily as a result of runoff and downstream dispersion (Oyarzun et al., 2004, 2006 a, b). Since the second-most-important economic sector in this region is agriculture, mining-related contamination is particularly important, also because mining and agriculture coexist in narrow strips of land flanked by mountains (Higueras et al. 2004).

One of the main environmental problems regarding the district occurs in the mining town of Andacollo, located ca. 30 km inland from the coast in the Andean foothills (UTM zone 19J; 30°13'54.88"S, 71° 5'5.89"W). Andacollo is home to ~10,200 inhabitants (2002 census; tendency decreasing; INE 2002; Fig. 5)

The historical, economic and political aspects of the mining history of Andacollo are best described by Danús Vásquez (2007). Krosta (1989) and Millán (2001) also provide good summaries. Mining for gold has taken place near Andacollo since prehispanic (Incaic) times. Gold production from alluvial placer deposit there is recorded as early as

1533. Even before then, Indios collected alluvial gold from depressions or other hydraulically favourable locations during and after inundations and paid gold as tribute to the Inca occupiers (Miers 1826).

Hard-rock mining for Au, even though initially of minor importance, may have begun before the end of the 16th century (Oyarzun et al. 2006). Andacollo saw a virtual explosion in its population as a consequence of a rise in the gold price in 1932, swelling its inhabitants from 500 to >20000. In the 1930s, when Andacollo had its heydays, alluvial gold mining still employed ~16,000 miners, produced ~43 % of Chile's alluvial gold and consumed the lion's share of the water supply. In 1933, 16000 miners worked the alluvial deposits, producing approx. 6 kg Au per day. Krosta (1989) estimates that 1,500 of the ca. 12,000 inhabitants of Andacollo worked (approx. 1987) in mining-related jobs.

Hard-rock mining for the gold veins (Krosta estimates approx. 50 to 60 of them) near Andacollo occurred, at least until the recent past, with little planning and system. Miners simply rented temporarily small plots from local landowners for a monthly fee and abandoned these spaces when the yield decreased. This system of small scale subsurface mining reached its peak in the 1950s. Ore is transported to the processing facilities ("*plantas*") in town by truck where it is mechanically ground by marays and trapiches and extracted principally using the amalgamation process (mechanism and history of these traditional ore grinders is described in chapter 10.3.4.2).

In the 1950s, owners of small processing shops added flotation cells and formed small associations, offering the miners to upgrade their fine-ground sulphidic copper ore for subsequent sale of the concentrate (Duarte, 2008b). At that time, there existed approximately 50 small mines, delivering ore to approximately 70 small processing plants using trapiches, all located in or very near the urban centre (Fig. 8). Krosta (1989) estimates 200 working trapiches in approximately 50 processing centers in Andacollo, yearly processing approx. 40,000 truck loads and using 10 t of Mercury to produce 3,5 t Au.

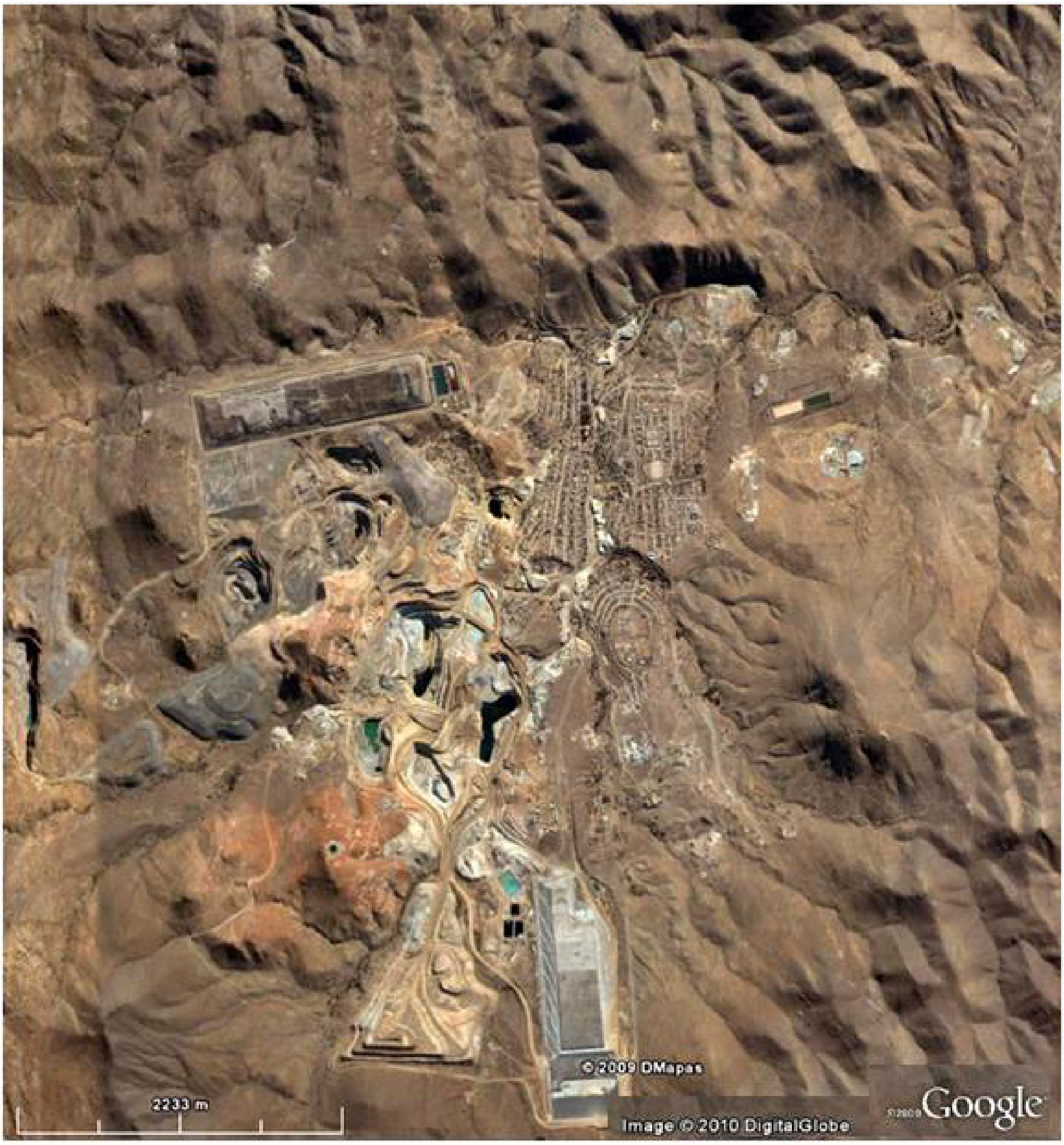

Fig. 5: **Satellite image of Andacollo and surroundings. The town of Andacollo is oriented north-south in the valley of the Andacollo Basin. Quebrada Los Negritos drains the basin along its northern end towards the northwest. Pits and dumps by the two large open-cast mines (Dayton, top left; Carmen de Andacollo, below) dominate the western margin of the town (*GOOGLE EARTH 2010*).**

In 1557, Bartolomé Medina introduced the practice of mercury amalgamation into Mexico. From there it spread south, and the use of this liquid metal to capture gold came into widespread use (Duarte 2008b). Miers 1826-pp. 393 ff. plastically describes the process by which finely ground gold-bearing ore is mixed with elemental liquid Mercury (Hg), forming amalgam (see also Krosta 1989) or other audiovisual sources.

The path of mercury in the Andacollo environment is described in chapter 10.5.

Andacollo is, as described below, not only a gold deposit but also of copper. Even though its occurrence was also known from pre-Incaic time and the intense colours of the oxidation zone are apparent in the landscape (Fig. 5), industrial copper mining began only at the beginning of the 20th century. Danús Vásquez (2007) writes that “even though Au brought Andacollo fame and richness for many years, it is copper which extended its life as a mining town, beginning at the middle of the 20th century” (translation by CH).

The lack of regulatory oversight during the first half of the last century and of a coherent town or regional development plan still forms a heavy burden on Andacollo. Not only are the hills around Andacollo laced through with abandoned and open mine shafts, unsecured waste rock heaps, and broken mining equipment, but also all neighbourhoods of the town either have one or several of these now abandoned tailing dumps or are built on them. Danús Vásquez (2007) writes of chaotic exploration and a complete absence of planning, leading to the loss of approximately half the reserves. These problems were well recognized in the 1960s already (Millán 2001). Efforts by ENAMI in the 1960s to consolidate the family-run operations and plan a more efficient open-cast mine were stiffly opposed by local and regional representatives (Danús Vásquez 2007; Duarte 2008a).

Fig. 6: Satellite image of Andacollo town. Numerous abandoned flotation ponds and tailing dumps from small scale mining (pale colours) stretch along the principal drainages (N-S: Qda. Culebrón; E-W: Quebrada Los Negritos) and dot the town (*GOOGLE EARTH 2010*).

10.3.3 Geology and Mineralogy

Andacollo is a geologically complex district, including porphyry Cu, epithermal stratabound Au, Cu vein and Hg vein deposits (Oyarzun et al. 1996; Guzmán et al. 2000; Higueras et al. 2004; Emparan and Pineda 2006; Moreno and Gibbins 2007). These metals are mined from porphyry copper and epithermal stratabound (span. *manto*) and vein gold deposits, respectively (Fig. 7). The rocks are affected by NNW-orientated, syn- and post-mineralization faults. Hydrothermal alteration affects both the volcanic and the intrusive rocks and displays a general zonal pattern that includes a core of potassic alteration and an outer halo of phyllic alteration. In this halo, mineralization occurs disseminated and as veinlets ("stockwork").

The mineral paragenesis includes as primary minerals major pyrite, chalcopyrite, hematite and magnetite and minor bornite, pyrrhotite, arsenopyrite and molybdenite. Supergene processes (i.e. surface-related alteration due to oxygenated or CO_2-saturated waters) led to formation of copper oxides (cuprite, tenorite, malachite, chrysocolla, atacamite and chenevixite), native copper, chalcocite and covellite. Other minerals of the supergene zone include montmorillonite, kaolinite, goethite, jarosite and amorphous silica. The porphyry body underwent a late enrichment in gold from a distal source, i.e. the gold-rich epithermal system (Higueras et al. 2004).

Although Hg is generally rare in porphyry Cu deposits because these are generated at temperatures high enough to keep the Hg phase gaseous, Andacollo is one of the three porphyry copper deposits worldwide from where Hg has been reported (the other two include Dizon, Philippines, and Tsagaan-Suvarga, Mongolia; Singer et al. 1997; Rytuba 2003). In the porphyry copper deposit (Minera Carmen de Andacollo), Hg was presumably more enriched in the upper, low-temperature oxidized parts of the deposit, which has now been largely removed by mining. A similar assumption can be made for the epithermal Au deposit (Dayton Mine).

The Au epithermal deposit consists of Au-bearing pyrite and native Au, with minor chalcopyrite, sphalerite (ZnS), galena (PbS), and cinnabar (HgS). The Hg-bearing veins contain schwazite, Hg tetrahedrite ($(Cu,Hg)_{12}Sb_4S_{13}$), pyrite, chalcopyrite, bornite (Cu_5FeS_4), and galena. The Cu veins that occupy a marginal position within the district consist of pyrite, chalcopyrite and bornite.

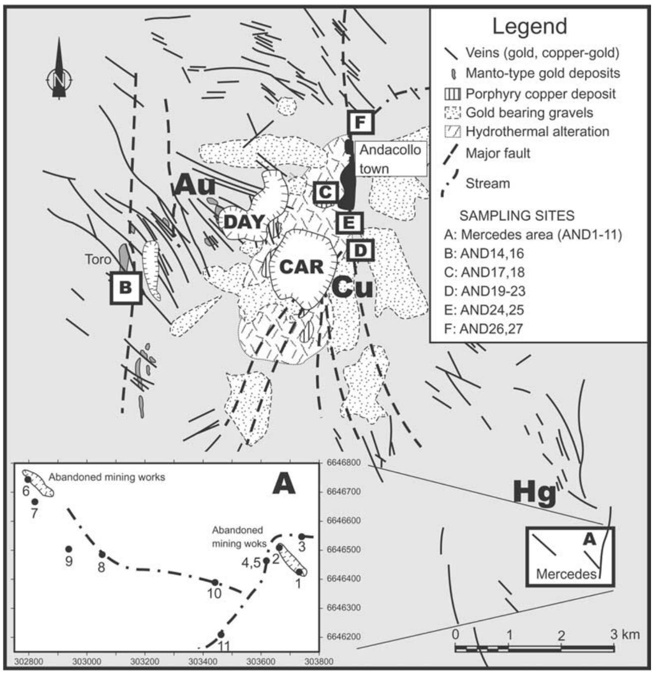

Fig. 7: **Sketch geologic map of the Andacollo district, showing location of the main geologic and metallogenic features, mining operations, and sampling sites (Higueras et al., 2004). CAR, Carmen open pit; DAY, Dayton open pit. Sites C–F represent regions of geochemical sampling in and near Andacollo by Higueras et al. (2004)[12].**

10.3.4 Present activities

10.3.4.1 Large scale mining

After a long period of economic depression through the 1980s, two modern, medium-sized open-pit mining operations started at Andacollo in 1996–1997:

- Carmen de Andacollo ("CDA"; then a joint venture of Aur Resources Inc., Companía Minera del Pacıfico and Empresa Nacional de Minería - ENAMI), exploiting the porphyry Cu deposit, and

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[12] Reprinted from Applied Geochemistry, Vol 19, Volume 19, Issue 11, November 2004, Pablo Higueras, Roberto Oyarzun, Jorge Oyarzún, Hugo Maturana, Javier Lillo, Diego Morata: Environmental assessment of copper–gold–mercury mining in the Andacollo and Punitaqui districts, northern Chile, p. 1855-1864., Copyright (2004), with permission from Elsevier.

- Compania Minera Dayton (“Dayton”), then a subsidiary of Vancouver-based Dayton Mining Corporation that focused on the exploitation of epithermal Au deposits.

Both mines are modern and fully mechanized and leach piled ores. In contrast to many of the small artisanal mining operations, these two mines operate within the legal framework including the environmental regulations.

(1) Aur Resources gradually increased its interest in the Carmen de Andacollo Mine to 90 % by 2006, but was taken over by Teck Cominco, a major Canada-based mining company, which began a major extension of the mine, accessing the lower-grade but much larger hypogene zone of the deposit. According to the Teck website (access Jan. 11, 2010), Carmen de Andacollo employs 429, many of which are from Andacollo, and therefore exerts major influence on the economic and social well-being of the town.

Teck has currently a 90 % interest in the mine, with ENAMI, a Chilean government entity, holding the remaining 10 % interest.

The Carmen de Andacollo Mine is an open-pit truck-and-shovel operation, employing standard drilling and blasting techniques. The Andacollo ore processing facilities produce LME Grade A copper cathode by utilizing sequential crushing, agglomeration, heap leaching, dump leaching and solvent extraction/electro-winning (SX-EW) processes. Aur evaluated bacterial leaching technology in 2000 prior to selling the property.

The (now largely mined out) supergene zone of the Andacollo porphyry contained approx. 33 mio. t of recoverable ore at 0.76 % Cu within a roughly north–south elongated body of 1800 m x 1200 m.

The Andacollo hypogene deposit, slated for start-up in 2010, directly underlies the currently producing but soon depleted Andacollo supergene deposit, with a projected mine life to 2029. The hypogene deposit has mineral reserves of ~423 mio. t at an average grade of 0.38 % copper and 0.13 g/t gold. The mine plan assumes conventional open-pit mining on 10-m benches at a waste-to-ore strip ratio of 0.22:1. An average of 26.7 mio. t/y of rock will be mined, of which 20 mio. t/y (55,000 t/d) will be ore. The processing plant will produce about 254,000 t/yr of concentrate with a grade of 27 % copper and 6 g/t gold. Concentrates will be trucked 59 km to the port of

Coquimbo for shipment to smelters. The hypogene development is expected to produce 81,000 t of copper and 66,000 ounces of gold in concentrate annually over the first 10 years of the project. Cathode copper production from the supergene deposit is scheduled to continue until 2012.

The mine expansion was opposed by part of the local population because dumps would approach the settled neighbourhoods to within 200 m and have exposed residents to noxious sulphuric acid fumes (Franks 2009). Recently, the expansion plans have also run into problems because its water project (necessary for flotation), taking water from high Andean aquifers (Pan de Azucar), were rejected (Teck 2009).

(2) Open-pit mining of the Dayton mine produced over 90,000 t per day of waste and ore. Heap-leaching was used to extract Au in solution. Infill drilling and refinement of the mine plan through exploration efforts in 1995 and 1996 allowed the mine to begin commercial production in January, 1996.

Despite increasing record production and a positive audit in 1998, the mine had to adjust its economically mineable deposits by -30.8 % in March, 1999, forcing it into bankruptcy soon thereafter. Dayton thus suspended mining at the site in September 2000 after only four years of operations, blaming weak gold prices and below par output, and layed off 260 employees. The operation, including the residual leaching, was closed in December 2000; management advertised the sale of the mining fleet, the crushing plant and the conveying/stacking system but reserved the sale of the gold recovery plant, which was planned to be marketed after the cessation of gold recovery through active leaching through 2001 and possible subsequent passive leaching. Final closure was planned for 2003 (Danús 2000; Millán 2001).

Soon after it ceased operating, Dayton Mining was taken over by Canada's Pacific Rim Mining. After unsuccessful negotiations with various potential purchasers in 2004 and 2005, Trend Mining acquired the mine for US$ 5.4 mio. and sold the property to a group of private investors soon thereafter (September, 2005) which put day-to-day management in the hands of Chilean professionals. The dismantling of the equipment was halted and the mine reopened in 2006.

The rise in the price of gold increased the reserves and extended the projected mine life to 350,000 oz Au and 5 years, respectively. Gold production from heap leaching using sodium cyanide commenced in April, 2006. COREMA approved the mine’s 2007-

2010 mining plan, including the extension of the mine (Las Loas Project) in October, 2008, thus extending the mine life to 2011. The mine currently employs about 110 and another 200 contractors.

10.3.4.2 Small scale mining in Andacollo

Small scale mining in Andacollo is rooted in strong traditions and is of subsistence type. Activities in artisanal mining therefore strongly depend on the fluctuations of the gold price. It seems that almost all mining for Au has now migrated from the alluvial gravels to the epithermal vein deposits. Mining is done in small operations consisting between three and 15 miners (*pirquineros*). Cordy et al. (2009) wrote: “Miners manually pulverize a part of the ore, pan it in a small *batea* and visually estimate the concentration of gold in the vein to be mined. The grades usually range from 30 g to 60 g Au/t. The extraction process is very artisanal and it is estimated that a miner extracts on average 120 kg/day of ore. It was estimated (in 2008) that the ASM in Andacollo produce between 0.3 t/a to 0.6 t/a of gold, but this has likely increased recently. “

Danús Vásquez (2007) describes the complex and gradual development of mining and its political and economic framework from largely unregulated artisanal small scale mining to open-cast industrial mining over the past 50 years.

10.3.4.3 Ore processing by small scale mining

The Spanish invaders introduced water-powered ‘‘trapiches’’ which are rock crushers similar to those used for wheat grinding and had been used in Europe. A trapiche consists of two large millstones mounted vertically and opposing each other on a horizontal axle, which is turned on top of a circular stone (see Miers 1826 for a historic description or Pray 2001, for a well-written review of present-day trapiches; Krosta, 1989, or other audiovisual sources for their operation[13]). An electrically powered

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[13] Two other videos about ore processing in Andacollo:
Trapiches de Andacollo (“Planta Salitre”), Movie (2min 54 sec); available at
http://www.viajeinformado.com/index.php/Videos/Trapiches-de-Andacollo.html

version is presently used by the small scale mining operations in the Andacollo district. These crush ore up to 10 cm in diameter and leave a residue of 65 % <200 mesh (approx. 74 µ).

Fig. 8: A trapiche in Andacollo (photo: Katja Radon, GNU license)

Marays are more primitive and consist of a cylindrical block or rock situated in a bowl-shaped base made of concrete. A horizontal wooden beam mounted at its top is used to manually rock the cylindrical block back-and–forth and to grind crushed ore in the bowl. The slurry is then taken manually from the maray and filled in a bucket.

The trapiches are used for two purposes: (1) to crush ore fine enough to allow subsequent flotation of the Cu sulphides; and (2) to recover fine-grained Au directly from the slurry by amalgamation with Hg. The latter process is executed in two variations: Either Hg is added in small quantities (determined by operator's experience) to the slurry within the trapiche; alternatively, Cu plates covered with a thin film of Hg are immersed in the slurry (Pray 2001; Higueras et al. 2004; Oyarzun et al. 2006). Au will then form an amalgam with Hg. The liquid Hg and the solid Hg-Au amalgam are then collected from the trapiche or are shaved from the copper plate, respectively.

Proceso de Oro, Movie (1 min 32 sec.), http://www.youtube.com/watch?v=onpCGeHv4lU

They are then filtered and shaped to form a marble-sized nugget of ca. 60% Au. Both processes (the addition of liquid Hg and the amalgamation on Cu plates) lead to Hg losses remaining in the slurry (estimated below). At some installations, the trapiche slurry is sent through a flotation system if the miner can afford to pay the trapiche operator for the flotation-circuit rental time and if he believes his ore still contains sufficient fines to warrant this second processing step. Both trapiche and flotation slurry waste are dried in the sun in shallow ponds that layer up into the tortas. (P. Cordy, pers. comm.)

10.3.5 Concessions, Properties

Property rights to the waste dumps in Andacollo are disputed, lie close to the core of the remediation issue, and are presently a significant obstacle to any solution. Efforts by the city administration to tackle the presence of the abandoned tailings in the town (Fig. 9; Appendix[14]) have been underway for several years but have to date fallen short of their intention due to problems to conclusively identify the legal property owners (Duarte 2007; V. Rakela, pers. comm.). This situation is commonly debated in local news media and is also a theme among the experts interviewed for this report.

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[14] An ever better view on the tailings withing the city limits is available here http://www.fotolog.com/andacoxo_city/28416736:

Fig. 9: **Tailing piles in the town of Andacollo (Photo: Katja Radon, GNU Licence)**

10.3.6 Institutional oversight

Chile participates in UNEP projects and has undertaken a number of studies and initiatives to reduce Hg in the environment. A national inventory and risk management plan (CONAMA 2008) was presented in April, 2008 (abridged English version: CONAMA 2007). It identifies a large number of potentially Hg-contaminated sites; two of the three sites visited in Andacollo ("*Planta Whittle*", "*Entrada localidad de Chepiquilla*") reach very high points of environmental risk and rank among the top five sites of the 29 identified potential Hg-contaminated sites in the country (CONAMA, 2008, p. 184). This document also gives a comprehensive overview of all relevant laws and regulations pertaining to the emission and handling of Hg in Chile and suggests concrete methods to diminish Hg in the environment in all sectors, including the small scale mining and amalgam processing sector (CONAMA 2008, p. 238-239).

A 65 km^2 large polygonal area, including the town of Andacollo, was declared "*zona saturada*" in Sept. 2008 by CONAMA because the air quality monitoring stations had shown that the particulate matter index (PM10) had exceeded its limit of 150 µg / m^3 in 2007 more than eight times during a period of 24 hours. An environmental alert was thus automatically triggered (seven exceedances are the limit). The declaration of "*zona saturada*" mandates the drawing-up of a prevention and decontamination plan by the local authority, CONAMA in Coquimbo (http://www.conama.cl/portal/1301/article-

45440.html). The regional director of COREMA, Marcelo Gamboa, indicated that such a decontamination plan would be undertaken as soon as the declaration of “zona saturadas” had been approved by the cabinet (*consejo de ministros*).

SERNAGEOMIN and CONAMA are actively pursuing a number of projects assessing abandoned tailings (*Faena Mineras Abandonada y/o Paralizada*, FMA/P) and managing environmental risks from inactive mining sites (*pasivos ambiental mineros*, PAM). A significant number of training reunions have been held, and the relevant government agencies appear internationally well connected (see, e.g., CONAMA mercury webpage, http://www.conama.cl/portal/1301/article-39723.html). Recently, a South-African developed processing technology is being introduced in Andacollo by CONAMA, along with awareness and training sessions.

The Andacollo town administration (*Municipalidad de Andacollo*) presented a new long-range development plan (*Plano Regulador*) to COREMA (*Comisión Regional del Medioambiente*) in Sept. 2008, which defined greens and cultural heritage zones and also plans a bypass for heavy traffic. Plans for the tailings were not mentioned in that press release (http://www.gorecoquimbo.cl/gore_news02.php?sc=2&id=2182).

10.4 Hg in the Environment at Andacollo

All sources agree that the major introduction of Hg in the environment at Andacollo begins by ore mill operators using elemental mercury in the grinding process. It thus appears warranted to describe this process in order to trace the flux of Hg in this region.

10.4.1 Amalgamation in the Trapiche

The process of amalgamation in trapiches was pictured by Pray (2001). On the inside walls of the cylindrical trapiches amalgamated copper plates are attached that are submerged in the slurry. Golf particles that are physically released from the rock matrix by grinding are captured by the mercury on the surface of the plates. From time to time, the gold loaded amalgam is s rubbed off and replaced by new mercury. During the grinding sulphides like pyrite might poison the copper amalgam surface. Ammonia has to be added to refresh them – sometimes it is just the urine of the operator.

The gold amalgam that has been scraped from the copper plates is now squeezed in a wet cloth in order to remove excess mercury. The product is a silvery ball consisting of 30 % gold and 70 % mercury.

Only a certain part of the gold can be extracted (around 50 %). The rest joined by mercury particles is discharged to tailings. The amalgam scraped from the plates

10.4.1.1 Estimates of Hg loss in trapiche operations

- Krosta (1989) estimate that a single trapiche processes approximately 7 t of ore per day and requires 30 g Hg/t of ore - 50 g Hg/t of ore of which 10 g/t are not recovered. If 200 trapiches processing 5 tons of ore daily during 300 working days per year, approx. 3 tons of Hg per year are lost to the environment, largely by being introduced with the spent slurry on the tailings.
- Higueras et al. (2004) estimate that no more than 70% of the metallic Hg used in Au amalgamation at Andacollo is ever recovered, amounting to ca. 2,5 t-4,5 t of Hg annually or approximately 0.4 kg/Hg-0.8 kg/Hg per trapiche per day.
- Cordy et al. (2009) quotes miners as estimating that”they lose 1 part of mercury per part of gold produced, but this is probably too conservative: The ratio of Hg_{lost}: Au produced is at least 3 times higher. Losses of 25 % of the mercury added were reported by the miners.” (…) Considering the typical Hg_{lost}:$Au_{produced}$ ratio of 3 for operations like this, and considering the gold production between 0.3 t/yr and 0.6 t/yr, the mercury consumed and released in Andacollo might be around 1-2 t/yr. This is a preliminary estimate and a detailed investigation is under way to evaluate the mercury emissions and the population exposed.”
- Higueras et al (2005) have reported mercury losses of 30 % to 50 % of the mercury introduced in the (ore processing) process.
- Valenzuela (pers. comm.) communicated similar values.

10.4.2 Old tailings

The Hg content of the tailings has been barely investigated. A compilation and discussion of known and estimated values is discussed in chapter 10.5.2.

10.4.3 Gold shops

The degree of Hg recovery is also strongly dependent on the recycling mechanism employed during amalgam roasting in the gold shops (some roasting also takes place at the trapiche installations). Miners bring the amalgam nugget to local gold shops where it is roasted in order to upgrade it from ca. 30 %-50 % Au to 99 % by removing Hg by roasting and removing other metal impurities using nitric acid. Cordy et al. (2009) stated that this procedure results in an increasing exposure risk for the local population because many gold shops are located in residential areas. Two gold shops are located in the neighbourhood of the elementary school. Furthermore, large industrial open pit mines are a constant source of airborne particulates that could be actively recruiting mercury from the air. This dust is settling in residential houses, providing a constant source of low-level exposure that could also lead to mercurialism in residents who are not directly involved in the gold trade.

The gold shop operators are aware of the dangers of mercury inhalation, but previously seemed unaware that there are harmful quantities of mercury in the gold that they purchase from miners. Sometimes large quantities of amalgam, for which recovery of mercury is economically significant, are burned by miners or gold shop workers using retorts, but in most cases shop workers burn the amalgam directly under fume hoods that have no fans. The atmospheric mercury either escapes the chimney into the urban air or stays in the enclosed burning rooms, where mercury concentrations exceed the detection limit of the used Lumex Vapour Analyzer (>50 000 ng/m^3 at 3 metres from the amalgam burning)."

10.4.4 Modern heap-leach operations

Detailed data from the ore samples from the two operating modern mines are not available. Higueras et al. (2005) and Cordy (unpublished, pers. comm.) measured atmospheric Hg concentrations through and near the Dayton mine, respectively, which were not to moderately elevated. Higueras et al. (2005) state: "Dayton (Au) open pit did not show high levels of mercury, except for a few data from the Natalia pit in the order of 20 ng/m^3-30 ng/m^3 Hg." These authors interpret the nearly consistently low concentrations of atmospheric Hg in their profiles through the pits of Carmen and Dayton as indicating low levels or possibly even a depletion of Hg from the presently mined lower levels of the Carmen deposit, possibly also applicable to Dayton. The upper, lower-temperature and possibly Hg-enriched levels of both deposits have largely been mined.

However, the current extension of the Carmen de Andacollo deposit to exploit its very-low-grade hypogene zone of the porphyry copper deposit (ca 400 mio. t of ca. 0,4 % Cu) is generating a very large tailing deposit south of the deep open pit, due south of Andacollo (Fig. 5). Oyarzun et al. (2008) express concern about contamination by particulate material in the future, considering the prevailing winds in the Andacollo Basin. Proper management of these heap-leach dumps will be a matter of priority.

10.4.5 Stream sediments

Samples from Andacollo stream sediments (Higueras et al. 2004) show highly elevated values of 75 µg/g-2,200 µg/g Cu) and 0.2 µg/g-3.8 µg/g Hg (their Table 2). Also, among the 36 samples analyzed by Baeza and Cortés (2009), one of the two samples from the Andacollo stream showed the highest value (3.3 µg/g) of the entire dataset. Hg was and probably still is introduced to the stream via metallurgical activities and subsequent runoff from the nearby flotation tailings and leaching piles, which are easily eroded when not or inadequately maintained.

10.4.6 Soils

Soils near Andacollo have generally elevated Hg concentrations. The highest values are found at Mercedes, a site ca. 8 km sw of Andacollo, where Hg-minerals are mined (Fig. 7; samples AND3-11 of Higueras et al. 2004, with concentrations ranging from 0.2 µg/g-2.6 µg/g.)

10.4.7 Air Quality near the tailings

Sensitive and high-resolution air quality measurements taken under standardized conditions (wind speed, solar irradiation flux, temperature, soil texture etc.) or calibrated to known flux curves would indicate whether the tailings dumps are a source of airborne Hg to the environment. Such a conclusion, however, would also have to entail identification of all other relevant Hg sources to the air in order to extract any underlying signal from the tailings. Some of these sources (gold processing shops, amalgam burning) are readily identifiable and high-intensity point sources; others (such as airborne emissions from modern mining) are non-point sources of unknown magnitude and difficult to constrain.

The air quality is a major and multi-layered concern in Andacollo whose adequate treatment would exceed the scope of this study. Controversy exists over the appropriate number and locations of measuring stations (since 2001; there are four), their maintenance and administration by specialists contracted to the CDA mine rather than to an independent organization, and the access to and use of past years' data. Health statistics of 2004 show that the inhabitants of Andacollo have double the rate of deadly pulmonary diseases compared to the national average. Prof. D. Moraga (Coquimbo) was able to obtain air quality data from the CDA mine for only 2 out of 7 years of sampling; those showed no exceedances.

The study of Higueras et al. (2005) does, unfortunately, not allow the identification of specific measuring sites in Andacollo.

The best – and to date only – topographically referenced survey of airborne Hg was undertaken by P. Cordy (Univ. of British Columbia, Canada) as part of his Ph.D. project. Field work was completed in 2007. Cordy (pers. comm., preliminary findings) largely surveyed the residential neighbourhoods, not the tailings, but did not find elevated Hg concentrations related to tailings dumps in Andacollo. This may be due to the long-term cumulative effects of high daytime evaporation rates from the surface of the tortas and efficient removal and dilution of Hg vapour by turbulent daytime air currents (see also discussion below). Gustin and others (1996) showed that Hg concentrations decline exponentially with height above Hg-emitting sources.

As part of their 2007-2010 development plan, Minera Dayton agreed to install additional methods to reduce dust emissions, in particular near the feeder for the primary crusher. (http://www.davidnoticias.cl/?p=854)

10.5 Technical description of mine tailings

10.5.1 Siting and dimensions

A comprehensive and detailed geotechnical description of Andacollo mine tailings is given by INGENIERIA Y GEOTECNICA LTDA. (1990a, 1990b), performed for

SERNAGEOMIN. In this report, 64 individual Andacollo mine tailings as of March 20, 1990, are described over two volumes of >230 pages each.

In these volumes, each tailing dump is documented in the following categories based on inspection and evaluations:

1. *Información General*
2. *Numero y ubicacion de los tranques de relaves*
3. *Datos administrativos generales*
4. *Caracteristicas de los relaves*
5. *Caracteristicas de los tranques de relaves*
    - *5.1 Geologia de la zona*
    - *5.2 Caracteristicas de los muros*
    - *5.3 Caracteristicas de los reservorio o cubetas de depositacion de relaves*
    - *5.4 Condiciones de estabilidad estatica*
    - *5.5 Condiciones de estabilidad sismica*
6. *Fenomenos no sismicos que podrian afectar a los tranques de relaves de la Planta X.*
7. *Efecto de un colapso de los tranques de relaves de la Planta X*
8. *Efectos de una falla parcial del muro*
9. *Filtraciones no controladas*
10. *Instrumentos para la operacion, auscultacion y control de los tranques de relaves de la Planta X*
11. *Evaluacion de la situacion global actual de los tranques de relaves de la Planta X*
12. *Comentarios adicionales*

This report provides an excellent geotechnical base for future evaluations but is not digital and contains no geochemical or mineralogical data. In addition, even though the report identifies and names the tailings and associated ore processing centers (*plantas*), it does not contain an index map, which would allow relating these names to locations. (Table 3 in the appendix lists the names of the tailings dumps identified by name in this report.) With little local help, the names in Table 3 could be readily correlated to the site descriptions obtained from modern remote-sensing data, e.g., Google Earth (Fig. 10 in the appendix).

Baeza and Cortés (2009) outlined some tailings dumps in Andacollo but did not characterize individual tailings. FundacionChile (2009) characterized the prominent “Planta Whittle” site geochemically.

The *Conservador de Bienes Raíces* Andacollo of the Andacollo town administration and the corresponding office in Coquimbo have additional property data.

10.5.2 Composition of tailings

10.5.2.1 General

The textural and mineralogical composition of the abandoned mine tailings (chapter 12.4 in the appendix) is unknown in detail. They appear to mostly consist of silty material (2 µ-62 µ mean grain size) with a significant sandy (62 µ-2000 µ) and shaly (<2 µ) component. Trapiche*s* grind ore up to 10 cm in diameter and leave a residue of 65 % to 80 % <200 mesh (which corresponds to ~74 µ minimum grain diameter; Rickard (quoted in Pray 2001); Higueras et al. 2004). The degree of rock alteration (argillic vs. unaltered), the details of trapiche processing, and any additional processing of the coarse residue in a flotation device will further modify grain size, sorting, and size-dependent mineralogical composition.

Spent slurries from the *trapiches* are routed short distances from the trapiche installations to the tailings dump. INGENIERIA Y GEOTECNICA LTDA. (1990a, 1990b) estimate grain size proportions for each tranque de relave. For example, the proportion of silt-and-finer grains at the sites *Planta de Andacollo*, *Ema* and *Miraflores* are uniformly given as 50 %-80 %.

Because both small scale mining and trapiche operations are subsistence enterprises with very short-term financial horizons (days to months), the composition of the tailings depends on the ore processed. This, in turn is subject to the market conditions for Cu or Au ore, which may fluctuate significantly. In addition, milling time at trapiche installations is rented to paying clients from different mines. All these conditions combine to make a straightforward and reliable classification of Andacollo tailings dumps impossible.

10.5.2.2 Site-specific data

To date, there appear to exist five mostly minor or incomplete data sets on the major and trace elemental composition of Andacollo tailings (Table 2 in the appendix).

- *Data published in Higueras et a. (2004) and Higueras et al. (2005)*

Higueras et al. (2004) conducted a baseline survey of Hg, As, Cu and Zn in the Punitaqui and Andacollo districts and collected samples from a variety of environments, including some samples from waste rock piles and flotation pilings in Andacollo (their Table 2): 7 samples from flotation pilings (from trapiche operations ?) show values ranging between 0.7 µg Hg/g mine Water and 3.9 µg Hg/g mine water from a trapiche operation (sample AND19) shows <1 µg Hg/l.

Higueras et al. (2005) added to the previous study a survey of atmospheric Hg emissions along six profiles, four of which (P2, P3, P5, P6) either cross or begin/end in Andacollo. In these profiles, values of atmospheric Hg near trapiches are extremely high, as also shown by Cordy et al. (2008).

Interpretation and critique: The original copious data of Higueras et al. (2005) are published as a topographic profile, unfortunately with the x-axis in seconds (not as topographic coordinates). This does, at least in its present form, not allow the identification of specific sites. Of interest would have been differences between, e.g., streets, tailing surfaces, and parks. The data would probably complement nicely those of Cordy et al. (2008).

- *Data collected by Baeza and Cortés (2009), two students of Dr. D. Moraga (UCN Coquimbo)*

Baeza and Cortés (2009), in the first publicly available attempt to rigorously relate ambient Hg-exposure to dosis and health effects in various population groups of Andacollo, took samples near points of a topographic grid (375 x 300 m cell dimensions) projected on the map of Andacollo. Locations as close as possible to a total of 36 grid intersections were sampled. 10 of these 36 sites fell on abandoned mine dumps. CP values ("*coeficiente de peligro*") from these 10 tailings sites ("*suelos relaves*"; their Fig. 18) do not show statistically significant different values from those 26 samples not considered to represent tailings ("*suelos sin relaves*"; their Table IX; see also their Figs. 17 and 18).

Absolute values (mg Hg/kg = ppm) range from 0,025 mg Hg/kg (their Annexo 3: Sample 30, Mirador de la Mina Hermosa) to 3,220 (Quebrada de Andacollo; two orders of magnitude difference). A subset of 18 soil samples (it is not clear what defines this subset; their table V, p. 52) yields a mean of 0,66 mg/kg (not, as erroneously stated, 0,711 mg/kg). A mean calculated from all 36 soil samples (Annexo 3), however, yields the mean of 0,711 mg/kg mentioned in the text.

Interpretation and critique:

1. It is uncertain whether values in this data set are comparable because the sampling technique may have introduced artefacts: Samples from the neighbourhood (e.g., paved substrate such as streets, sidewalks, culverts etc.) may not be comparable with values from samples taken from loose or poorly consolidated bulk material (e.g., the quebrada or from a tailings surface).
2. The author of this report found it impossible to relate the stated sample coordinates to the named locations. Because coordinates (their Anexo 3) are given in the UTM-grid (zone 19J ?), they have to be recalculated to geographic coordinates prior to projecting them on Google Earth maps. In doing so, the data points showed nonlinear random mismatches to identifiable locations, which could not be resolved.
3. The maximum value of the data set comes from the drainage and suggests that drainages are concentrating Hg.
4. Original Hg content of all samples may be affected to different degree by evaporation (see below), depending on irradiation, age of deposit, exposure etc.)
5. Overall values roughly agree with the values found by FundacionChile (2009) (below).

- *Data recently collected in the framework of this UNEP project by FundacionChile (2009).*

Analytical work by FundacionChile (2009) includes sampling and geochemical analysis for trace elements of one prominent tailings dump within the town centre (S30 13.831 W71 05.032, so-called “Planta Whittle”, “Sitio 1”). A total of 31 samples from this site (plus two control samples outside the area) were taken in a systematic fashion. Overall results show a low concentration of Hg (mean 0,32 mg/kg) and a maximum of 1,1 mg/kg but high concentrations of several other metals.

A detailed description of the sampling results and their interpretation is given in the original report and will not be duplicated here.

Interpretation and critique: This is the first detailed survey of a single tailings dump. The low Hg concentrations are surprising and give rise to considerations (see Discussion section below).

- *Exploratory data taken by Minera Dayton:*

  Minera Dayton had taken some surface samples from very few abandoned tailings in town (P. Valenzuela, pers. comm.). They showed significant but not outstanding residual ore concentrations and variable but generally low Hg concentrations. (Sr. Valenzuela agrees with the numbers of Higueras et al. (2004), estimating a weekly Hg loss of 0.5 kg-0.8 kg per trapiche operation, but does not know the fate of the unrecovered Hg).

- *Soil samples taken by Dr. Katja Radon, Epidemiologist, University Munich (LMU München):*

  In the frame of her studies of Hg in Andacollo, school children, Dr. Radon also took a small number of randomly collected “soil samples” in Andacollo: Values from these samples, taken in front of homes, in backyards (patios) etc. range between 0,25 µg/g and 76 µg/g Hg. One sample identified as “torta de relave, ca. 50 years old” yielded 0,38 µg/g Hg. Mo and Cu values, however, are unusually elevated in most samples.

  Interpretation and critique: The low number of soil samples by Dr. Radon and their near-random location obviously does not permit to use them in a rigorous evaluation of a possible Hg contribution from the tailings; however, the range of the values is consistent with those from all other sources.

10.5.3 Exposure

Satellite images and ground photos clearly show that most tortas are subject to intense degradation by water (erosion) and wind (deflation); those located on slopes are at risk to fail due to mass wasting; those next to intermittently active stream beds are subject to failure by basal erosion (Figs. 8, 9). The cataster of INGENIERIA Y GEOTECNICA LTDA. (1990a, 1990b) provides the most detailed data; see also Fig. 10. Oyarzún et al. (2008) place the hydrology of the Elqui basin and human demands on it in a larger perspective and predict that its hydrology will be strongly affected by climate change.

Flash floods pose a particular high threat to the stability of the tailings dumps. Many retaining walls for flotation ponds were initially quickly built (“starter walls”) and then covered when operations scaled up, leaving the heap with a weak basal perimeter. An intensive flash flood occurred in 1987 in the Andacollo Basin, damaging or destroying many tailings dumps. The cataster (INGENIERIA Y GEOTECNICA LTDA. 1990a, 1990b) provides a risk assessment for each tailing dump.

10.5.4 Other metals in mining-related heaps (besides Hg)

Primary ore entering the artisanal processing facilities derives either from the oxidized zone of the porphyry copper deposit or from the mining of epithermal Au-veins. It is principally enriched in Cu, Au, Pb, Zn, As, Hg, Ag, and Mo (Guzman et al. 2000 and references therein; Higueras et al. 2004).

Marays and trapiches are acknowledged to be inefficient devices that leave economic minerals (those not attracted to the Hg “traps”) in the slurry. Where this ore slurry is processed through subsequent flotation tanks, fine-grained sulphides such as pyrite, arsenopyrite, or galena and the Au associated with these minerals accumulate in the froth and are recovered; the remaining slurry, still containing some sulphides, the oxides, and some amalgam enters the dump.

Higueras et al. (2004) listed highly elevated values of Zn and, in particular, Cu in flotation tailings and waste rock piles (up to 21,000 mg/kg Cu; sample AND6; their Table 2). The best available local data to date describe the *torta de relave* of *Planta Whittle* and note high concentrations of Cu, Mo, and Pb (FundacionChile, 2009). Measurements of individual surface samples from tailings by Minera Dayton (P. Valenzuelas, pers. comm.) and Radon (pers. comm.) confirm this assessment. In a popular-science article, Pray (2001) states that “not one” of the many relaves he investigated contained >5 g Au/t on average and most assay at ~2 g Au/t.

The owners of the *plantas* are well aware of the residual ore content of the sediment deposited in the flotation ponds or routed to the waste heaps. In the 1990s, truck loads of this material were occasionally sold to the Dayton mine.

Because each heap has its own individual history and its composition reflects geologic, economic and social factors, content and concentrations of the above-named minerals in the heaps are likely to be highly variable both among the heaps as well as internally.

10.6 Societal Aspects

Andacollo is torn between the major tasks of generating and maintaining long-term economic prospects, currently offered only through the two operating open-cast pits, and maintaining a long-term healthy and liveable environment. A recurrent theme in public discussions, common in similar situations worldwide, is that the mineral wealth of the region has not left the town richer but rather settled with a plethora of environmental problems; the wealth has largely bypassed the locality and been exported. Because the two mining operations are by far the dominant employer, there is justified concern that the town will be left with a seriously affected environment once the resources are depleted and mines are closed, as had been the case once before in the 1960-1990s. Even as of 2006, 26,7 % of the population lived below the poverty line (MIDEPLAN 2006).

The unsightly and potentially environmentally risky waste dumps are only one of the numerous environmental problems of Andacollo. A review of newspaper clippings (El Observatodo, Andacollo Estrella, La Nación) allows recognizing the following mining-related grievances:

- Poorly defined environmental contamination expressed by increased mortality, respiratory and nervous health problems, and seriously affecting livestock and agriculture;
- Heavy traffic through the town, causing excessive transient loads on the main road to the mines, dust, and noise;
- General high dust load from the several artificial sources, including the open-cast mines and the abandoned waste piles in town;

- Dust load from the regular bank blasts of the open-cast mines, aggravated when the wind drives the dust into town;
- Erosion, mass wasting and effluents from the waste dumps;
- Distrust against the company-sponsored air quality monitoring stations.

Communication with several people knowing Andacollo first-hand indicate that many inhabitants of Andacollo possess an ambivalent attitude to the waste dumps: When the discussion centers about their possible commercial value due to remaining Au or Cu content, claims to ownerships abound. When the discussion tends towards the sites as sources of contamination (and resulting financial responsibility), claims to ownership diminish greatly. I assume that this problem permeates into written records and affects the efforts by the city administration to have dumps removed.

A corollary effect of having two large scale mining operations operating next to and affecting a low-resource town is that potential conflicts are not resolved at equal eye-height. City administration and individuals have little leverage against the economic power of the mines, can be compromised by threats of layoffs, and are tempted to regulate conflicts through short-term solutions or individual settlements rather than jointly attempting to search a long-term solution for all valley users.

There are also regional economic arguments exerting pressure on environmental emissions and urging to reach solutions on legacy environmental issues such as heavy-metal laden mining dumps. These include the national efforts of Chile to position itself as a global supplier of high-quality agricultural products, the strong agricultural sector in the IVa region (Coquimbo) requiring stable and high-quality water supply, the increasing quality demands of North American and agricultural European customers, and the negative effects of climate change on the Elqui Basin (Oyarzún et al. 2008). Thus, the environmental threat by the Andacollo tailings to be eroded by flash floods is less and less acceptable to regional authorities and agriculture at large.

There is also a growing awareness of environmental issues in the Andacollo basin, manifesting itself in several local activist groups, in websites, blogs and the increasing use of participatory tools in regional regulation, recently summarized in detail by Lostarnau (2008). This author also describes the differing degrees of community participation in which the two large mining enterprises (Dayton and Carmen de Andacollo) are engaged.

10.7 Discussion

10.7.1 Hg pathways in the environment

Given that the primary ore processed by major and small scale mining in Andacollo contains low but uncertain concentrations of Hg, that – more importantly – large quantities of Hg are introduced during low-efficiency processing, and that the preliminary analysis of Hg content in the waste dumps indicates that their Hg content may be low, the question arises where all the Hg remains. These are significant quantities under discussion: The authors listed above each estimate 3 t-10 t of Hg to be yearly emitted during the artisanal ore processing in Andacollo.

10.7.2 Hg-content of Andacollo tailings

Whether none, some or all of the dumps contain significant amounts of Hg is not yet established due to several reasons:

1. There are insufficient data.
2. Primary dump material comes from various sources and is piled for various reasons (flotation waste, milling waste from trapiches and marays, stock piles, sterile dumps) which may contain primary Hg as cinnabar, schwazite, amalgam or in metallic form).
3. Artisanal processing through the centuries was and still is highly variable in its Hg recovery efficiency. Depending on local circumstances, highly variable proportions of Hg may thus have become mixed with milled ore and have ended up on the waste dumps.
4. Exposure to dry air, daily warming of the tailings surface due to high solar irradiation, and periodic strong winds may facilitate the surface evaporation of Hg from the top of the tailings. (This hypothesis will be expanded below) Variable but possible high evaporation rates must be multiplied with variable supply rates: Times of dump inactivity may allow evaporation to deplete the surface Hg content, times of intense processing, slurry dumping and tailings buildup may trap Hg in the tailings.

Apparently, there are of no quantitative investigations of the efficiency of trapiches used in Andacollo; however, any future documentation of elevated concentrations of residual Hg and other metals in the tailings would be consistent with findings from other locations where waste products of ore amalgamation have been analyzed (Cordy, pers. comm.). It thus is likely that the tailings resulting from simple trapiche and maray processing contain the highest anthropogenic Hg concentrations, those with added flotation (which recover the fines) less, and simple ore rock piles even less.

Cordy (pers. comm.) did not note any discrete elevated levels of mercury in the vicinity of tailings piles. However, he noted very high anthropogenic concentrations of Hg ranging from >500 ng/m^3 up to 50,000 ng/m^3 in air in processing facilities and gold sale shops nearby, possibly swamping any subtle signals from nearby dumps. P. Cordy estimates that passive mercury emissions do not exceed 500 ng/m^3 at a few m distances from the tailings; however, he did not focus on this aspect, and his analysis is still pending.

10.7.3 The case for Hg evaporation

There is only incidental evidence of significant Hg evaporation in Andacollo. The best data are from Cordy (pers. comm.) based on his field work in 2008 measuring Hg concentrations in the air (see also Cordy et al. 2008). His data show a rapid decrease of Hg concentrations within a few m distance even from very significant point sources of Hg; repeat measurements at the site of an amalgam burn show that Hg concentrations disappear rapidly. Cordy (pers. comm.) interprets these high gradients as possible evidence of strong turbulent dilution and transport removal of Hg-contaminated air. Once Hg evaporates, high daytime surface temperature gradients along with turbulent eddies efficiently remove Hg vapour, maintaining conditions at the ground surface that are thermodynamically favourable towards more evaporation. It is plausible that this process, over time, could deplete Hg in tailings to a depth of at least several cm.

Higueras et al. (2003) suggested for the Almadén District (Spain) the following pathway which he suspected also applies to Andacollo: Hg gas emitted by the sources (e.g. from trapiches, marays) is initially deposited in the surrounding soils as Hg^{2+}, either from direct deposition of emitted Hg^{2+}, or from conversion of emitted Hg gas to Hg in the aqueous phase.

Because solar irradiation is high, the reflectivity of the milled rock powder is low, and exposure times at the waste dump surfaces are irregular but often high, evaporation may be a significant process by which Hg can be returned to the atmosphere. Photolysis of inorganic Hg^{2+} to Hg^0 at the soil surface may also contribute significantly to the re-emission of Hg gas to the atmosphere.

The observations of Cordy (pers. comm.) and Higueras et al. (2003) are supported by numerous studies of atmospheric mercury emissions from mine wastes, which demonstrate that the Hg0-flux from mine dumps to the atmosphere can be high, and is also highly sensitive to a number of environmental parameters such as temperature, incident solar energy, substrate texture and humidity, and precipitation. Fluxes can range between 30 ng/m^2/h and several 1,000s of ng/m^2/h (see, e.g., Sexauer Gustin et al. 2001 for a summary). Emissions may change fivefold within a few hours (Lindberg and others 1999) as a response to a change in an environmental parameter and respond to the specific activation energy of a Hg phase. Indeed, several studies show that at the New Idria, Ivanhoe and Sulphur Bank sites (all USA) emissions to the atmosphere are the primary mechanism by which Hg is released to the environment (Sexauer Gustin et al. 2001). This may be the typical case in semi-arid to arid climates where transport by fluvial and groundwater systems is reduced.

In the absence of specific Andacollo data, all estimates of Hg-content and fluxes of the tailings dumps must remain speculative. The current state of knowledge, however, allows the possibility that some or most of Andacollos tailings dumps have Hg concentrations not much different from regional background values due to intense evaporation.

10.8 Outline of Technical Options

10.8.1 Remediation options

Generally, remediation will likely choose between relocating the waste rock or in-situ remediation. Both options will require thorough environmental studies. The former option must find a suitable and environmentally safe site for the old piles, certified by an "*estudio de impacto ambiental*" and ensure that dust generation during the removal is minimized.

The latter involves reshaping, capping and vegetating as well as capturing and treating the drainage from the piles. Both principal remediation options should weigh rehabilitation costs, acceptable risks and socio-economic impact on the area for each pile.

Minera Dayton committed itself in their 2007-2010 operations plan to remove one or several of the piles from the city limits once the plan had been approved. Plans had been to remove at least one of the piles by the end of 2008 (El Observa Todo, July 20, 2007). COREMA, the *Comisión Regional de Medio Ambiente*, approved the mine operations plan on Nov. 10, 2008; however, as to the date of this report, no action has taken place yet. The former environmental manager of Minera Dayton, Snra. Liliana Pasten, is quoted in newspaper articles citing problems in drawing up legal contracts between the town administration and the private owners of the dumps (El Observa Todo, Jan. 31, 2008). Sr. Pedro Valenzuela, her successor, confirmed the continued commitment. In order to test the planned removal actions, Minera Dayton removed in 2009 several small old tailings within their own property. In doing so, they confirmed that this removal poses no technical problem, in particular when mixing the fine-grained material with coarser-grained ore and keeping the tailings slightly moist or covering the material with tarps when transporting in order to avoid major dust emanations.

Minera Dayton continues to work with the *Municipalidad*; the planned project, however, encountered the problems similar to those described in the press clippings: Proprietors did not want to give up the tailings voluntarily but only wanted to sell them. Negotiations thus stopped. Minera Dayton hopes that the state of "*zona saturada*", declared in February 2008, will give the authorities major legal powers so that removal proceedings can eventually begin.

Mr. Venturini, general manager of Minera Carmen de Andacollo (pers. comm.) stated that the tailings remediation in Andacollo is not that much of a technical but more of a complex political problem because there is a significant problem of determining legal ownership owing to the antiquity of the mining in Andacollo. The mine is prepared and technically well equipped to contribute to a removal of the tailings in town but would understandably have legal problems and generate huge negative publicity if the legal owner of a given tailings dump had not been a priori been established with absolute certainty and had not agreed to transfer the material. Understandably, the mine cannot do much to influence the process of legal determination but hopes that the decontamination process associated with the declaration of "*zona saturada*" may give the authorities more power to determine or declare ownership. Certainly, the mine is very much interested in social responsibility and sustainability.

The upgrading of the CDA mine (*proyecto hipogeno*) and the installation of a new concentration plant has made it possible to readily process the tailing material (which would have been more problematic in using the leaching process). In addition, CDA has budgeted funds for 2010 to characterize the tailings.

10.8.2 Other Measures of reducing Hg in Andacollo

Hg-related contamination in Andacollo is multiply sourced. Most importantly, aside from possible sources in the old tailings dumps, Hg is introduced by handling Hg in trapiches installations and, in particular, during amalgam burning. The modern heap-leach operations may be another possible source of Hg. CONAMA has recently started a local program with the goal to encourage trapiche operators and miners to switch to the iGoli-process, a mercury-free South African method of ore processing (http://www.conama.cl/portal/1301/article-46849.html, http://www.universia.cl/portada/actualidad/noticia_actualidad.jsp?noticia=151616).

10.9 Conclusions

The present data situation pertaining to the mineral content and concentration of Hg in the former flotation ponds and tailing dumps of Andacollo is unsatisfactory. The discussion of the mine-related dumps is therefore inconclusive because the few existing data sets are heterogeneous and sparse.

The ineffectiveness of the traditional equipment used by the small processing shops (marays, trapiches, flotation) is generally acknowledged. Stakeholders agree that residual concentrations of ore may remain in the tailings and that Hg was likely introduced in significant quantities anthropogenically. However, it is uncertain whether significant amount of Hg remains in the tailings due to high natural evaporation rates; the concentrations of economically recoverable metals (Au, Ag, Cu, Mo) are unknown as well.

10.10 Recommendations

A satisfactory geochemical characterization of each tailing would provide a critical input parameter in a more comprehensive study to estimate risk and remaining economic potential of individual tailings. This, in turn, would lead to a remediation strategy (which also needs to consider the local historical, social and legal situation).

Steps towards remediation of abandoned tailings in Andacollo should therefore include:

- Developing remediation goals in close cooperation with local stakeholders (Andacollo inhabitants, miners, trapiche operators, land owners, public health experts, community representatives etc.)Constructing a detailed tailings cataster that included data on location, dimensions, composition, internal structure, composition etc. (possibly based on and expanding SERNAGEOMINs Project FOCIGAM or building upon the INGENIERIA Y GEOTECNICA LTDA., 1990a, 1990b, cataster). It may be convenient to compile a cataster of abandoned shafts, adits etc. at the same time.

- Drilling or augering the tailings, taking bulk samples and examining them geochemically for economically recoverable metal content. A correlation of metal concentration with depth, age, grain size and sorting, mineralogy etc. at some historically well-known dumps may facilitate to reach generalizations with respect to the distribution of metal species and minerals within other tailings dumps. Such a characterization could eventually develop in a remediation plan.

- Measuring experimentally site-specific evaporation rates of Hg using a field flux chamber (including control sites, blank sites etc.) to assess likely percentages of remaining Hg in the tailings dumps.

- Conducting a hydrological and stream survey to examine the role of effluents and effects of flash flooding.

- Updating the INGENIERIA Y GEOTECNICA LTDA., 1990a, 1990b report with the goal to quickly reduce the risk of spreading heavy metals, including Hg, into the hydrologically stressed Elqui Basin during flash floods.

- Identification of remediation/ processing options

- Development of a tailings remediation/ processing strategy based on the remediation goals and the findings of the analytical work and taking into account the needs and interests of stakeholders

There is excellent technical knowledge, mostly residing at local universities, available to tackle these tasks. Partial financing may become available from the two local mines.

Chilean government agencies at all levels are well staffed to provide the necessary framework.

This report should have also made clear, that there are – beyond the tailings – other and likely more significant point sources of Hg in the Andacollo region, in particular any facility where liquid mercury or amalgam is roasted, handled and stored. The use of Hg in ore processing at Andacollo is widespread and historically established; an economically and socially acceptable resolution of this problem would represent a true step forward for Andacollo.

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12 Appendix

12.1 Personal communications

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12.2 Additional information

Table 2: Elemental concentration in Andacollo mining dumps

Compiled from literature; January, 2010

Location		Coordinates	Coordinates	Hg	Zn	Cu	As	Cd	Source
				µg/g	µg/g	µg/g	µg/g	µg/g	
Stream Sediments									
AN-03-F	Estero Pral, aguas arriba de las minas	30° 17' 47.28" S	71° 2' 26.7" W	0,74	88	142	<10	<10	1
AN-03-I	Estero Pral, aguas arriba de las minas			0,43	74	108	<10	<10	1
AN-05-F	Estero Pral, aguas abajo de las minas	30° 17' 49.98" S	71° 2' 30.84" W	2,57	101	148	<10	<10	1
AN-05-I	Estero Pral, aguas abajo de las minas			1,09	81	109	<10	<10	1
AN-08-F	Qda. que baja de Mina Fe	30° 17' 48.36" S	71° 2' 54.3" W	0,77	63	122	<10	<10	1
AN-08-I	Qda. que baja de Mina Fe			0,22	48	75	<10	<10	1
AN-10-F	Qda. que baja de Mina Fe	30° 17' 52.32" S	71° 2' 37.74" W	0,20	90	128	<10	<10	1
AN-10-I	Qda. que baja de Mina Fe			0,15	82	104	<10	<10	1
AN-11-F	Estero Pral, aguas abajo de las minas	30° 17' 58.14" S	71° 2' 37.2" W	0,47	81	148	<10	<10	1
AN-11-I	Estero Pral, aguas abajo de las minas			0,36	77	127	<10	<10	1
AN-14-F	Qda. en la zona Toro	30° 15' 14.88" S	71° 7' 10.14"W	1,86	428	102	<10	<10	1
AN-14-I	Qda. en la zona Toro			3,79	481	176	<10	<10	1
AN-16-F	Qda. en la zona Toro	30° 15' 44.4" S	71° 6' 42.3" W	1,53	356	102	<10	<10	1
AN-16-I	Qda. en la zona Toro			0,68	288	119	<10	<10	1
AN-24-F	Qda. de And. aguas arriba del pueblo	30° 14' 30.18" S	71° 5' 24.6" W	5,52	140	2220	16	<10	1
AN-24-I	Qda. de And. aguas arriba del pueblo			6,31	136	2228	<10	<10	1
AN-26-I	Qda. de And. aguas abajo del pueblo	30° 13' 28.74" S	71° 4' 51" W	1,38	110	965	<10	<10	1
Soil Samples									
AN-07-F	Cerca de las labores de An-6	30° 17' 42.42" S	71° 3' 0.12" W	3,40	127	64	25	<10	1
AN-07-I	Cerca de las labores de An-7			2,52	99	48	29	<10	1
AN-09-F	Junto a un horno de metalurgia primitivo	30° 17' 42.42" S	71° 3' 0.12" W	47,00	85	51	45	<10	1
AN-09-I	Junto a un horno de metalurgia primitivo			20,00	66	23	24	<10	1
AN-23-F	Junto a una instalación de trapiches	30° 15' 7.5" S	71° 4' 46.14" W	7,38	137	-10	<10	<10	1
AN-23-I	Junto a una instalación de trapiches			2,35	89	-10	<10	<10	1
Flotation tailings									
AND20A	Cuatro muestras a profundidades crecientes	30° 15' 4.62" S	71° 4' 50.22" W	2,00	35	570	<10	<10	1
AND20B		30° 15' 4.62" S	71° 4' 50.22" W	2,90	93	970	<10	<10	1
AND20C		30° 15' 4.62" S	71° 4' 50.22" W	3,90	44	4000	<10	<10	1
AND20D		30° 15' 4.62" S	71° 4' 50.22" W	2,00	47	690	<10	<10	1
AND21	Muestra de un corte del dique de estériles, e	*no location*	*no location*	1,40	38	5500	<10	<10	1
AND22	Muestra de toda la longitud del tomamuestras	*no location*	*no location*	0,70	26	1500	<10	<10	1
AND25	Desmuestre en vertical de un dique de estéril	30° 14' 31.08" S	71° 5' 9.18" W	1,40	230	4400	<10	<10	1
Waste Rock Piles									
AND1	Muestra de escombrera de labores superficia	30° 17' 51.18" S	71° 2' 26.76" W	620,00	32	3000	170	<10	1
AND2	Similar a la anterior, pero aquí la mineralizaci	30° 17' 48.6" S	71° 2' 29.28" W	720,00	47	4000	290	<10	1
AND6	Mina La Fe, muy parecida a la de la mina Co	30° 17' 40.56" S	71° 3' 1.38" W	330,00	15	21	1400	18	1

Location		UTM E	UTM S								2
1	Caletones 1	299738	6654901		1,27						2
2	Caletones 2	300159	6654689		0,28						2
3	Las Catanas	300174	6654524		1,39						2
4	Av. La Feria (25 de Octubre)	300125	6654320		0,25						2
5	Plaza Balmaceda (Corazón de Maria)	300134	6654320		0,34						2
6	Casuto (Simón	300142	6653948		0,80						2
7	Casuto Oriente	300134	6653347		0,44						2
8	Subida Casuto	300137	6653345		0,39						2
9	Av. Sixto Valdivia	300128	6652774		0,20						2
10	Nueva Churrumata	300064	6652512		0,11						2
11	Camino a Nueva Churrumata	299762	6652626		0,13						2
12	Frente al Parque Oasis	299768	6652627		0,03						2
13	Punta Arenas	299791	6652867		2,24						2
14	Qda. de Andacollo	299623	6653442		0,04						2
15	Barrio Martínez	299695	6653711		0,03						2
16	Barrio Bella Vista Sur	299694	6653711		1,96						2
17	Barrio Bella Vista Norte	299728	6653990		0,52						2
18	Qda. de Andacollo	299750	6654322		3,22						2
19	El Polvorín	299701	6654608		0,10						2
20	El Curque	300518	6652801		0,21						2
21	El Curque Alto	300873	6652396		1,24						2
22	El Gallo	300657	6651922		0,26						2
23	Cerro El Calvario	300821	6651767		0,97						2
24	Caupolican Sur	299363	6654849		1,14						2
25	Caupolican Norte	299394	6654617		1,51						2
26	Cancha la Catolica	299320	6654560		1,16						2
27	Matadero	299336	6653649		1,16						2
28	Calle Nueva	299357	6653409		0,19						2
29	Subida Mina Hermosa (Subida)	299390	6653139		1,21						2
30	Mirador de Mina Hermosa	299154	6652686		0,03						2
31	La Coipa 1	298850	6653160		0,90						2
32	Matadero	298995	6653392		0,88						2
33	La Coipa 2	298996	6653752		0,04						2
34	Mirador Barrio Norte	299002	6653728		0,36						2
35	Frente Dayton	298994	6654302		0,05						2
36	El Salitre	299009	6654707		0,57						2
Torta de relave					0,38						3

					Hg	Zn	Cu	As	Cd		4
MPA 01 Lado A	all samples from torta de Planta Whipple	30°13' 50.40 S	71°05' 02.87 O		0,14	2,66	$4,18\cdot 10^{2}$	< 2,33	$< 6,40\cdot 10^{-2}$		4
MPA 02 Lado A					0,30	12,6	$1,05\cdot 10^{3}$	< 2,33	$< 6,40\cdot 10^{-2}$		4
MPA 03 Lado A					0,35	32,3	$1,94\cdot 10^{3}$	< 2,33	$< 6,40\cdot 10^{-2}$		4
MPA 04 Lado A					0,20	24,8	$1,29\cdot 10^{3}$	< 2,33	$< 6,40\cdot 10^{-2}$		4
MPA 01 Lado B		30°13' 49.22 S	71°05' 03.03 O		0,21	25,5	$1,52\cdot 10^{3}$	< 2,33	$< 6,40\cdot 10^{-2}$		4
MPA 02 Lado B					0,90	2,5	$1,57\cdot 10^{2}$	< 2,33	$< 6,40\cdot 10^{-2}$		4
MPA 03 Lado B					0,33	15,9	$9,76\cdot 10^{2}$	< 2,33	$< 6,40\cdot 10^{-2}$		4
MPA 04 Lado B					0,22	21,6	$1,63\cdot 10^{3}$	< 2,33	$< 6,40\cdot 10^{-2}$		4
MPA 05 Lado B					0,43	19,7	$1,78\cdot 10^{3}$	< 2,33	$< 6,40\cdot 10^{-2}$		4
MPA 01 Lado C		30°13' 48.33 S	71°05' 03 O		0,19	23,7	$1,17\cdot 10^{3}$	< 2,33	$< 6,40\cdot 10^{-2}$		4
MPA 02 Lado C					0,20	28,4	$1,67\cdot 10^{3}$	< 2,33	$3,50\cdot 10^{-1}$		4
MPA 03 Lado C					0,63	29,5	$9,46\cdot 10^{2}$	< 2,33	$5,02\cdot 10^{-1}$		4
MPA 04 Lado C					0,23	26,5	$1,17\cdot 10^{3}$	< 2,33	$4,23\cdot 10^{-1}$		4
MPA 05 Lado C					0,79	66,7	$3,92\cdot 10^{3}$	< 2,33	$4,56\cdot 10^{-1}$		4
MPA 01 Lado D		30°13' 47.62 S	71°05' 02.11 O		0,34	13,1	$1,87\cdot 10^{3}$	< 2,33	$4,47\cdot 10^{-1}$		4
MPA 02 Lado D					0,28	18,8	$1,25\cdot 10^{3}$	< 2,33	$3,37\cdot 10^{-1}$		4
MPA 03 Lado D					0,24	34,3	$3,61\cdot 10^{3}$	< 2,33	$4,35\cdot 10^{-1}$		4
MPA 04 Lado D					0,20	30,8	$4,42\cdot 10^{3}$	< 2,33	$1,78\cdot 10^{-1}$		4
MPA 05 Lado D					0,25	35,9	$5,75\cdot 10^{3}$	< 2,33	$1,60\cdot 10^{-1}$		4
MPA 01 Lado E		30°13' 48.17 S	71°05' 1.32 O		0,15	27,8	$8,28\cdot 10^{2}$	< 2,33	$4,09\cdot 10^{-1}$		4
MPA 02 Lado E					0,22	16,4	$8,46\cdot 10^{2}$	< 2,33	$3,79\cdot 10^{-1}$		4
MPA 03 Lado E					0,22	13,7	$9,84\cdot 10^{2}$	< 2,33	$3,58\cdot 10^{-1}$		4
MPA 04 Lado E					0,27	27,8	$2,83\cdot 10^{3}$	< 2,33	$4,10\cdot 10^{-1}$		4
MSA 01		30°13' 48.44 S	71°05' 02.18 O		0,28	30	$1,76\cdot 10^{3}$	< 2,33	$3,07\cdot 10^{-1}$		4
MSA 02		30°13' 48.67 S	71°05' 01.69 O		0,79	36,9	$4,67\cdot 10^{3}$	< 2,33	$1,58\cdot 10^{-1}$		4
MSA 03		30°13' 48.95 S	71°05' 01.94 O		0,29	26,6	$1,64\cdot 10^{3}$	< 2,33	$3,43\cdot 10^{-1}$		4
MSA 04		30°13' 49.33 S	71°05' 02.23 O		0,23	22,1	$1,23\cdot 10^{3}$	< 2,33	$3,37\cdot 10^{-1}$		4
MSA 05		30°13' 49.45 S	71°05' 01.75 O		0,34	21,9	$1,38\cdot 10^{3}$	< 2,33	$2,66\cdot 10^{-1}$		4
MSA 06		30°13' 49.57 S	71°05' 01.31 O		1,11	54,7	$5,41\cdot 10^{3}$	< 2,33	$3,83\cdot 10^{-1}$		4
MSA 07		30°13' 49.92 S	71°05' 01.63 O		0,33	17,9	$2,19\cdot 10^{3}$	< 2,33	$2,65\cdot 10^{-1}$		4
MSA 08		30°13' 50.41 S	71°05' 01.8 O		0,38	8,24	$8,93\cdot 10^{2}$	< 2,33	$2,73\cdot 10^{-1}$		4
Control 1		30° 14' 978 S	71° 03' 782 O		0,04	32,1	7,5	< 2,33	$7,65\cdot 10^{-1}$		4
Control 2		30° 15' 764 S	71° 02' 913 O		0,09	25,4	7,76	< 2,33	$4,03\cdot 10^{-1}$		4

Sources:
(1) Higueras et al., 2004
(2) Baeza and Cortés, 2009. Please note: Their UTM coordinates do not correctly plot in Lat/Long. According to the text, 10 of the 36 samples come from tailings
(3) Radon (unpublished, pers. comm.)
(4) FundacionChile (2009)

Table 3: Tailings dumps of Andacollo

List of names from INGENIERIA Y GEOTECNICA LTDA., 1990a, 1990b

Name	**Location (S)**	**Location (W)**
	WGS 84	WGS 84
Planta Andacollo	30°13'37.50"	71° 3'54.31"
Planta Arenillas		
Planta Arizona		
Plantas Azulina, Nueva Esperanza y Renacimiento		
Planta Barrera		
Planta Bellavista		
Planta Búfalo		
Planto Cacho de Cabra		
Planta Canales-García		
Planta Carlos V		
Depositos de Residuos Mineros de la Planta Chevron		
Planta Churrumata		
Planta Concepción		
Planta Cuevas		
Planta El Gomero		
Planta El Volcán		
Planta Ema	30°14'37.15"	71° 5'11.78"
Planta Emanuela		
Planta Erika		
Planta Flora		
Planta Florida		
Planta Gálvez		
Planta González		
Planta Indey		
Planta Irene		
Planta Jeraldo		
Planta Jeraldo 1		
Planta Jeraldo 2		
Planta Jeraldo Tapia		
Planta John Kennedy		
Planta La Caldera		
Planta La Exotica		
Planta Lorena		
Planta Los Leones		
Planta Los Litres		
Planta Los Valientes II		
Planta Manuel Rojas		
Planta María		
Planta Martinez		
Planta Mary		
Planta Militza		
Planta Miraflores	30°14'26.07"	71° 5'22.01"
Planta Miranda		
Planta Miranda abandonado		
Planta Monreal I (sic!)		
Planta Palmira		
Planta Pedro Pablo		
Planta Ponce		
Planta Princesa y Andrónica		
Planta Punta Caletones		
Planta Rodríguez		
Planta Rosario		
Planta Rubilán		
Planta Ruiz		
Planta San Antonia		
Planta San Juan		
Planta Santa Teresita		
Planta Sauce II		
Planta Silva		
Planta Tapia		
Planta Urquieta		
Planta Victoria		
Planta Whittle	30°13'49.33"S	71° 5'1.87"W
Planta Zepeda		

12.3 Coordinates and approximate sizes of mining-related heaps in and near Andacollo

Site No.	Coordinates		Estimated area (m^2)		Comment	Name
1	30°13'31.03"S	71° 4'55.07"W	12720		high but heavily eroded by cutbank of Quebrada Negrito	
2	30°13'30.00"S	71° 4'42.98"W	10120		flat, active	
3	30°13'24.50"S	71° 4'32.73"W	13190		flat, active, topographically highest in complex	
4	30°13'23.42"S	71° 4'28.17"W	10360		flat, abandoned, deeply incised gully to the east	
5	71° 4'28.17"W	71° 4'32.48"W	5149		flat, abandoned, breached, with bush vegetation	
6	30°13'22.25"S	71° 4'24.69"W	6771		may not be a *torta* but a deeply covered point bar in Qdra. Negritos	
7	30°13'32.12"S	71° 4'14.07"W	9644		western half may be active, eastern part abd but flat; low vegetation	
8	30°13'36.11"S	71° 4'16.27"W	5249		western half may be active, eastern part abd but flat; low vegetation	
9	30°13'42.86"S	71° 4'20.75"W	10680		multiple tortas; one of them quite high	
10						
11	30°13'38.96"S	71° 3'55.27"W	18790		large abd. complex; several walls breached	
12	30°13'59.77"S	71° 4'1.22"W	43530		large active complex with at least one active dump	Planta Andacollo
13	30°13'35.19"S	71° 4'34.46"W	1983		old and abandoned dump, barely recognizable; gravel and soil covered	
14	30°13'30.33"S	71° 4'30.63"W	3103		small abd. and heavily degraded platform	
15	30°13'36.71"S	71° 5'0.94"W	8098		large high and fresh heap next to road; has material here ben excavated	
16	30°13'33.23"S	71° 5'14.45"W	4004		heavily eroded abd. dump by Quebrada Los Negritos; Calle El Salitre	
17	30°13'49.58"S	71° 5'1.97"W	4660		high, steep and moderately eroded dump across from Plaza	Planta Whittle
18	30°13'59.85"S	71° 4'25.63"W	21740		accumulation of individual piles; not necessarily a flotation pond	
19	30°14'11.92"S	71° 4'23.76"W	5472		accumulation of individual piles; not necessarily a flotation pond	
20	30°14'9.70"S	71° 5'3.51"W	5784		deeply eroded high and steep pile next to Qda.; northernmost of three	
21	30°14'13.07"S	71° 5'2.58"W	4210		deeply eroded high and steep pile next to Qda.; central of three	
22	30°14'17.45"S	71° 5'1.19"W	18570		deeply eroded high and steep pile next to Qda.; southernmost of three	
23	30°14'2.80"S	71° 5'17.07"W	11510		high and deeply eroded pile in Barrio Churrumata	
24	30°14'4.88"S	71° 5'20.92"W	10930		next to 23; has a small pond; deeply eroded	
25	30°14'9.46"S	71° 5'37.47"W	17580		of ~17 small ponds between pit and heap pile	
26	30°14'18.03"S	71° 5'40.98"W	18870		complex of ~8 tranques; maybe one of them active	
27	30°14'17.53"S	71° 5'32.71"W	12750		complex of tranues; some of them active	
28	30°14'21.17"S	71° 5'31.83"W	15420		complex of tranques south of no. 27; all abondeoned and degraded	
29	30°14'26.05"S	71° 5'21.97"W	30850		complex of six smalle to large tranques in various states	Planta Miraflores
30	30°14'26.37"S	71° 5'7.00"W	12040		steep, high, prominent abandoned large dump on the entrada to Chepiquilla	
31	30°14'31.92"S	71° 5'6.09"W	5525		smaller abd. dump just to the s of No. 30	
32	30°14'29.46"S	71° 5'11.36"W	7947		largely overgrown, heavily eroded dump	
33	30°14'36.98"S	71° 5'11.44"W	10840		chain of 3 N-S-dumps in good shape, along road	Planta Ema
34	30°14'41.31"S	71° 5'8.59"W	23620		complex of abandoned, degraded and partly overgrown dumps divided by paved road to CDA	
35	30°14'45.75"S	71° 5'14.91"W	24210		complex of abandoned, degraded and partly overgrown dumps contiguous with no. 36	
36	30°14'51.54"S	71° 5'17.76"W	21580		complex of poorly defined and heavily degraded abandoned dumps contiuguous with 35	
37	30°15'0.84"S	71° 5'17.06"W	9590		complex of dumps just w of road to CDA; a small pond still in operation ?	
38	30°15'0.96"S	71° 5'6.02"W	12820		complex of ~8 abandoned dumps draining into Qda.	
39	30°15'3.87"S	71° 4'52.64"W	33710		complex of ca. 5 large dumps; some still active	
40	30°15'5.09"S	71° 4'41.24"W	19220		complex of ca. 5 dumps; at leas one active	

Fig. 10: Location of identified tailings in Andacollo. (*GOOGLE EARTH 2010)*

12.4 Andacollo photo guide

The following list refers to photos that give valuable information about tailings in Andacollo. Due to uncertain copyrights these photos cannot be reprinted here.

a) Oblique air photo viewing eastward. Heap-leach dump and pits of active Dayton Mine in foreground. Photo by Ricardo Martini, Google Earth ID 4088045.

b) View from Cerro de Calvario south along the Andacollo Basin, with Basilica in foreground right. Heap of Planta Whittle, across from the wooded Plaza, in center foreground. Segment of Andacollo Panorama at http://www.ingservtur.cl

c) View from Barrio Matadero towards the southwest to Cerro Colorado (background) and Churrumata (middleground).www.flickr.com/photos/suelosanto/2652179392

d) Canalized bed of the principal stream in downtown Andacollo, subject to flash flooding. Source: www.flickr.com/photos/suelosanto/2562736707.

e) Tailing dumps in southern Andacollo. View from Av. Chepiqilla towards the WNW. Source: www.flickr.com/photos/suelosanto/2652179392/

f) Mine dumps along the main street in southern Andacollo. Source: www.flickr.com/photos/suelosanto/2562722593/

g) Dump along the main street in southern Andacollo. Source: El Observa Todo, 2008-01-30.

h) Residences in front of the tailings dumps of Planta Whittle, next to Andacollo Basilica. Source: www.flickr.com/photos/suelosanto/2562449594/

Fig. 11: **Erosion of abandoned or poorly maintained flotation ponds and tailings dumps in Andacollo (*GOOGLE EARTH 2010)*.**

a) Two large tailings dumps in northern Andacollo. Cutbank erosion by the (here dry) stream has clearly eroded a major part of the northern dump.

b) Largely abandoned tailings dumps of *Planta Andacollo* (~2 km wnw from the town center, 30°13'37.50"S, 71° 3'54.31"W) are eroded due to breaching of poorly maintained retaining walls. At this site, INGENIERIA Y GEOTECNICA LTDA. (1990a, 1990b) documented major damage during the 1987 rain storms.

c) Planta Miraflores (group of 5 heaps; 30°14'26.07"S, 71° 5'22.01"W). Two small heaps in the SW are abandoned and severely degraded; the two large dumps to the E appear to be inactive but show partially breached retaining walls. Quebrada Culebrón drains to the east.

d) Group of three large and severely eroded tailings dumps in southern Andacollo. The principal drainage of Andacollo, Qda. El Culebrón, flows northward along the western, steep slopes of the dumps. Numerous erosional gullies are visible.