

The environmental legacy of historic gold processing in the Reefton Goldfield

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Abstract

Historic gold processing sites are places of significant toxicity as the methods used to extract the gold were less efficient than today's methods, and regulations were not in place. These sites were abandoned after the mines closed, with no site remediation. Elevated metals and metalloids on these sites are the result of the geology of the deposits (As, Sb) and the metals added (Pb, Zn and Hg) to aid in the recovery of the gold. This study examines three historic gold processing sites in the Reefton Goldfield, New Zealand, that are used as case studies to understand the geochemical processes that occur on abandoned sites with high metalloid and metal contents. The sites were processing similar ore, so any differences in tailings mineralogy and geochemistry are the result of different processing techniques used.

The highest As value at the sites has resulted from ore roasting used to extract refractory gold from sulphides. Roasting has produced toxic and bioavailable As(III) and calcium arsenates. Vapours released during roasting have been absorbed by the roaster structure forming crystalline efflorescences. Roasting has also concentrated other metals. High As levels also result from the ageing and weathering of sulphide concentrates that have formed amorphous hydrous iron arsenate-hydrous iron oxides (HFA-HFO). Secondary minerals that have formed in the processing residues attenuate metals on site and there are no elevated dissolved metals leaving the site with all dissolved metals below the New Zealand drinking water guidelines.

Keywords: Alexander processing complex, arsenic, gold, Golden Lead, historic gold processing, Reefton Goldfield.

Introduction

Orogenic gold deposits are a source of arsenic (As) and antimony (Sb) metalloids that can be concentrated to toxic percentage levels during the recovery of the gold (Goldfarb et al., 1995; Christie et al., 2000; Craw et al., 2015). As well as As and Sb, other metals (zinc (Zn), lead (Pb) and mercury (Hg) and chemicals that are added to aid in gold recovery can also be concentrated, causing contamination of a site. Knowledge of the geology of a deposit and the processing techniques can be used to determine the possible environmental issues that a site might face (Goldfarb et al., 1995; Craw et al., 2015).

Historic processing sites are acknowledged as being places of significant toxicity (Haffert, 2009; Desisto et al., 2011; Druzbecka, 2013; Jamieson, 2014). The processing methods were less efficient than today's methods and were not controlled by strict environmental legislation. Previous environmental investigations of the Reefton Goldfield have identified elevated As and Sb in the wastes and waterways at the Prohibition and Snowy River processing sites at Waiuta and the Big River site (Haffert, 2009; Druzbecka, 2013).

This study investigates three historic processing sites in the Reefton Goldfield, the Alexander battery site, the Alexander roaster site and the Golden Lead site, and uses these as case studies

to understand the geochemical processes that occur at these abandoned sites. Since the geology of the ore that was processed was similar on the three sites, the differences in the mineralogy and geochemistry of the tailings at each site are largely the result of the processing techniques used (Fig. 1). The differences in ore processing are reflected in the concentration of metals present and the mineralogy of the mine tailings. This paper is a summary of work done as part of a MSc project at the University of Otago.

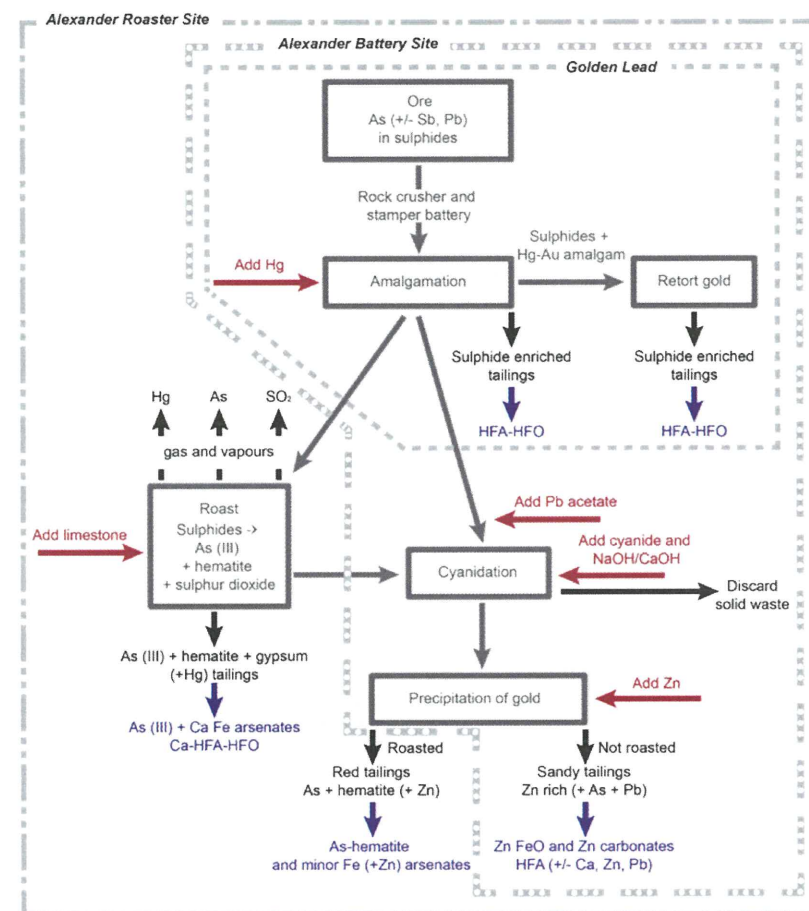


Figure 1. Simplified flow chart showing historic gold processing at the Alexander roaster and battery sites and at Golden Lead. Grey arrows represent processes, red arrows added metals and chemicals to the process, black arrows are the tailings and gas/vapours generated and blue arrows are the products of weathering.

General setting and geology

The Alexander and the Golden Lead mines are part of the Reefton Goldfield group of mines that were worked prior to 1950s. The mines are located in the Victoria Forest Park and are under the management of the Department of Conservation (DOC) (Fig. 2). Both the Alexander and Golden Lead sites, located in heavily forested mountain valleys, are remote and accessible by foot only. The Alexander mine was an underground operation located 740 m a.s.l. on the mountain above the processing complex which is situated on the true left bank of the Alexander River. The processing complex consists of two separate sites: 1) 'the battery site' consisting of the remains of the battery and Wilfley table foundations, cyanide tanks and zinc boxes, and; 2) the roaster site, consisting of the concrete foundations of an Edwards roaster, and three red tailings piles. The Golden Lead site is located at the confluence of the Golden Lead and Deep Creeks, and consists of a DOC restored 5-stamp battery with the mine on the northern hillside above the processing site (Staton, 2009) (Fig. 2).

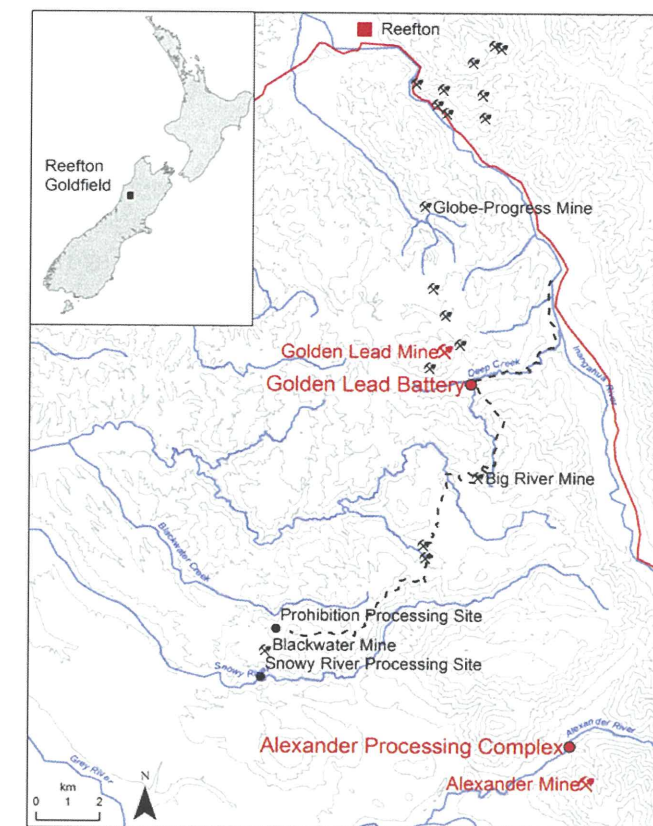


Figure 2. Location map showing the Alexander processing complex and mine and the Golden Lead battery site and mine within the Reefton Goldfield. The dashed black line is the Inangahua-Big River walking track. Topographic contours are from LINZ topographic maps.

The deposits consist of Palaeozoic orogenic gold-bearing quartz veins in a belt of north-trending intense shearing and folding (Gage, 1948; Christie et al., 2010). Disseminated gold and sulphides also occur in the hydrothermally altered wallrocks, comprised of secondary sericite, chlorite and carbonate, hosting the veins (Christie et al., 2000). The Alexander Reefs differ from other reefs in the Reefton Goldfield, being hosted in a roof pendant of the Greenland Group (Gage, 1948; Hazeldene, 1993). At Alexander, disseminated mineralisation occurs as a halo surrounding Au-bearing quartz veins that can sometimes be higher in gold than the quartz veins (Hazeldene, 1993). Gold mineralisation at Golden Lead occurs as quartz stockwork veins, with leader and stringer veins mostly thin and anastomosing and cut by later faults.

Methodology

FP-XRF (field portable x-ray fluorescence) was used to delineate high metal distribution on the three sites for As, Zn, Pb, Sb, and Hg. Field samples were collected for laboratory XRF analysis in order to calibrate the data for moisture content, particle size and sample preparation, factors that are known to affect FP-XRF results (Kalnicky and Singhvi, 2001). Field samples were also analysed by XRD, SEM and paste pH for the major tailings types, to identify their mineralogy. Twelve water samples were collected in the Alexander River catchment to assess the attenuation of As and other metalloids and metals around the processing complex.

Alexander processing complex

Gold processing

Ore was initially recovered by Hg amalgamation with later installation of a cyanidation plant. Concentrated sulphide fines were shipped to Australia for further processing, although this was an expensive endeavour and the decision was made to process fines onsite. An Edwards roaster was built on the Alexander roaster site, 300 m away from the battery site, to process the fines, reducing processing costs. The roaster operated for less than 2 years before it was abandoned due to processing complications and poor gold recoveries. During its time of operation, gold recovery on the roaster site was kept separate from the battery site (Fig. 1). Zinc, Pb, Hg, cyanide and lime were all added during processing to aid in gold recovery (Fig. 1). The mine closed in 1943 and the processing site was abandoned.

Metal distribution and processing residues

Alexander roaster site

New Zealand guidelines for metals in soil are exceeded for As, Zn and Sb on the roaster site, with As over 4,400 times higher than the guideline value of 80 mg/kg. The highest As on the three sites is within the flue of the Edwards roaster where As exceeds 35 wt% (Fig. 3a). Roasting has also concentrated Sb (2,700 mg/kg) and Hg (up to 1,360 mg/kg) to high levels in the wastes inside the Edwards roaster. The three red tailings piles southeast of the roaster, have As contents up to 2 wt% and high Zn up to 2,300 mg/kg.

The intact concrete foundations of the Edwards roaster house the remains of roasted ore as well as crystalline efflorescences on the walls and roof of the flue and chimney. Arsenic is present as Ca-Fe arsenates (yukonite and Ca-HFA (hydrous ferric arsenate) alteration) and arsenolite (As(III)) in the waste and as Ca arsenate (pharmacolite), arsenolite and As-bearing gypsum in the crystalline efflorescences (Fig. 4a, b).

The red piles, to the south of the roaster, are completely oxidised and consist of quartz and iron oxides (Fig. 4c, d). There were no sulphide minerals identified in the red tailings. The iron oxides are large (> 100 µm) and have a spongy, porous texture. XRD analysis identified hematite as the major iron oxide (Fig. 4c). The Fe/As molar ratio of the iron oxides ranged from 0.5 to 225 with the lower ratio (< 1.5 Fe/As) suggesting an iron arsenate mineral, likely scorodite, is also present, however, scorodite was not detected by XRD (Paktunc et al., 2003).

The paste pH of the residues is acidic to circum-neutral, with over half of the samples having a pH > 6.0. The red piles pH ranged from 5.37 to 6.92, and the flue wastes ranged from 4.93 to 7.1.

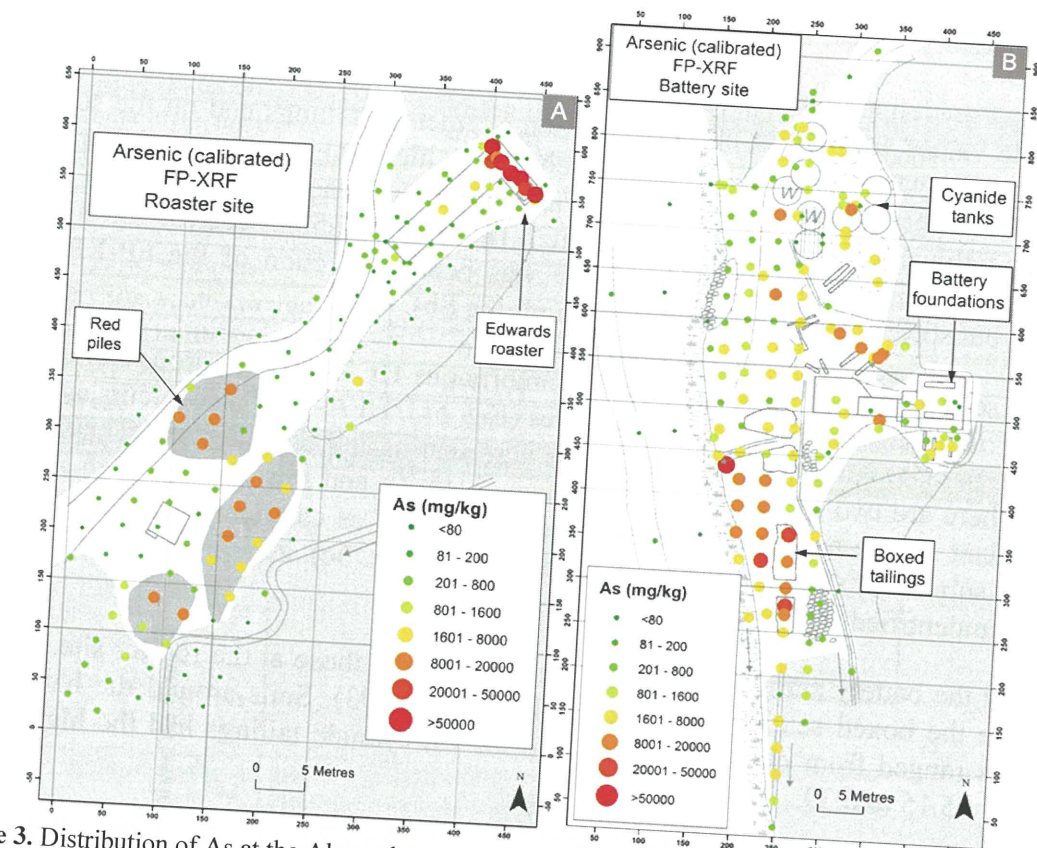


Figure 3. Distribution of As at the Alexander processing complex based on site FP-XRF analyses calibrated for sample preparation and moisture content. A. Roaster site and B. Battery site.

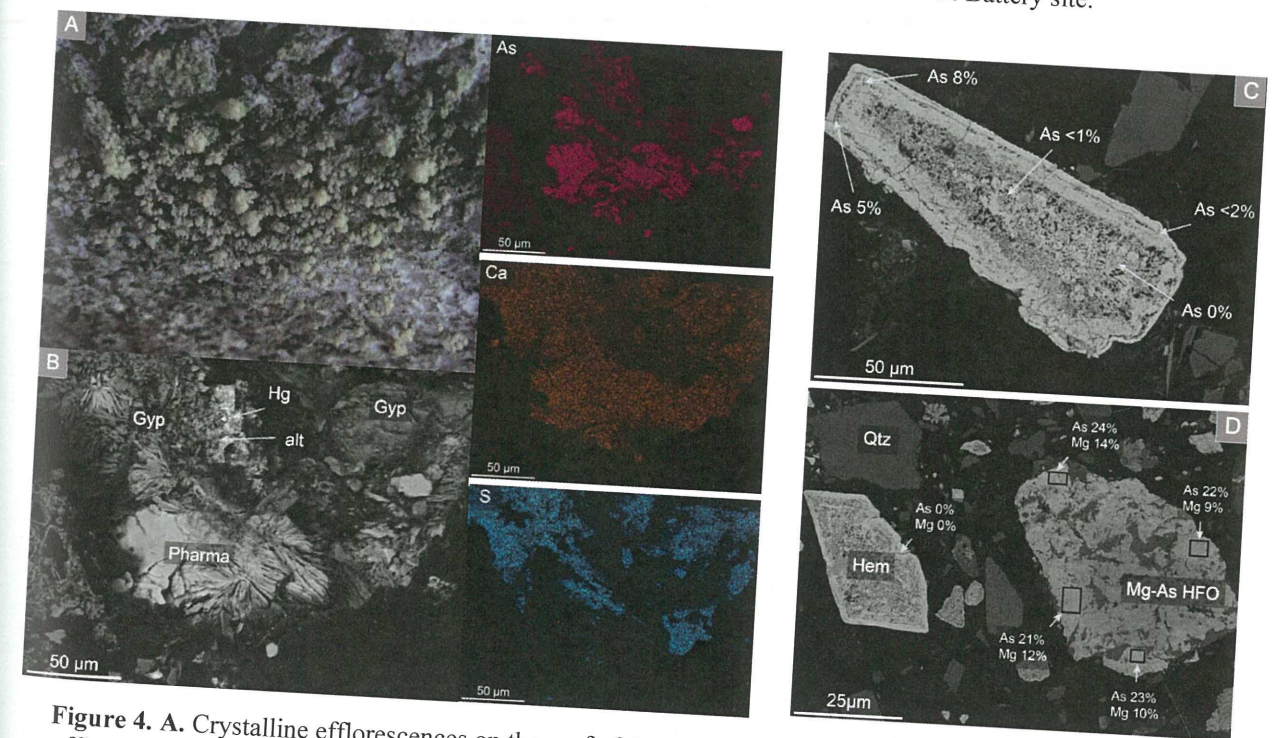


Figure 4. A. Crystalline efflorescences on the roof of the Edwards roaster. B. SEM image of the crystalline efflorescences (gyp – gypsum, pharma – pharmacolite, alt – HFA-HFO alteration, Hg – mercury material). Element maps of the SEM image for As, Ca, S. C. Porous hematite in the red piles D. Quartz (qtz) and iron oxides are the dominate minerals in the red piles (Hem – hematite, Mg-As HFO - unidentified Mg-As mineral aggregate).

Alexander battery site

New Zealand guidelines for metals in soil are exceeded for As, Zn, Pb and Sb on the battery site. Arsenic values are highest in the boxed semi-cemented tailings and on the surrounding ground (up to 8.6 wt% As) (Fig. 3b). Zinc reached very high levels (> 4 wt% Zn) and in some areas Zn levels were higher than As in the cyanide tailings. Lead values were also highest in the cyanide tailings (4,000 mg/kg Pb). Although Hg-amalgamation occurred on this site, Hg levels are low (up to 220 mg/kg). Antimony was below detection of the FP-XRF (< 100 mg/kg Sb), but still above the guidelines (> 25 mg/kg Sb).

The boxed semi-cemented tailings consist of amorphous HFA-HFO (hydrous ferric arsenate-hydrous ferric oxide) that cements soil particles (Fig. 5a). HFA-HFO also occurs as alteration around weathered sulphides (Fig. 5b) in soils surrounding the battery plant foundations and ore bins. There are two types of cyanide tailings, high Zn and low Zn. The high Zn tailings have abundant calcite and Zn carbonate minerals, as well as calcium in the HFA alteration around the sulphides, which also contains Pb and Zn (Fig. 5c). Zinc is also associated with iron in an unidentified zinc iron mineral.

Residues at the battery site were slightly more acidic than those at the roaster site. The most acidic were the boxed semi-cement clays (pH 3.08 to 4.93). Soils around the battery plant foundations ranged from pH 4.25 to 4.87 and the Zn cyanide tailings had the highest paste pH, between 5.15 to 6.39.

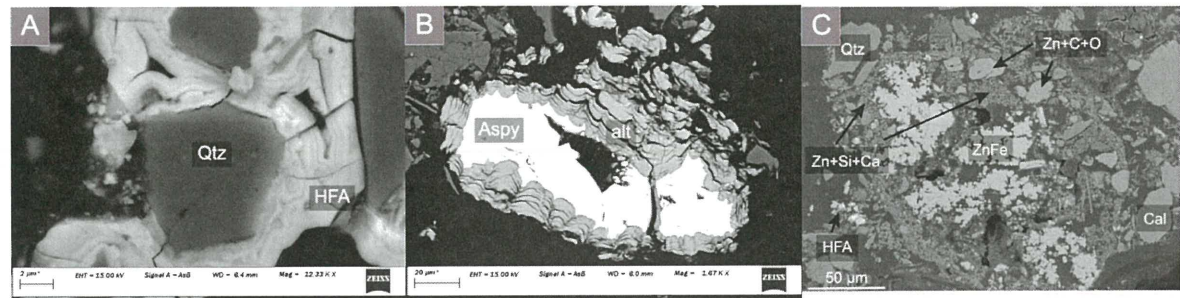


Figure 5. A. Colloform texture of the HFA cementing quartz (Qtz) grains. B. The cusate texture of the arsenopyrite (Aspy) is mirrored by the desiccation cracks in the surrounding HFO alteration (alt). C. High zinc cyanide tailings, with a dendritic mass of a zinc iron oxide mineral (ZnFe), aggregates of zinc carbonate and quartz (Zn+Si+Ca) and larger anhedral zinc carbonate (Zn+C+O) with quartz (Qtz) and calcite (Cal) the dominate minerals.

Water quality

The Alexander River is a tributary of the Grey River, which is a water source for the township of Greymouth. The size of the catchment is approximately 45 km², and water was sampled in an area less than 1 km around the Alexander processing complex. Of all the natural waterways tested, one of the creeks draining the mine adits on the hillside had the highest As (0.0084 mg/L As for the Bull Creek) (Table 1). The creek draining the battery site had low dissolved As (0.0022 mg/L) and the creek on the roaster site had As, Pb and Hg all below detection limits and only dissolved Zn increased slightly downstream. Compared to the other river catchments, the water upstream and downstream of the Alexander processing complex is below New Zealand drinking water guidelines for As, whereas As is elevated above the guidelines downstream of other Reefton Goldfield processing sites (Fig. 6).

Table 1. Results from water samples taken in the Alexander River catchment around the Alexander processing complex.

Location	As (mg/L)	Zn (mg/L)	Pb (mg/L)	Hg (mg/L)	pH
Alexander River, upstream	<0.0010	0.0054	0.00032	<0.00008	7.91
Alexander River, downstream	<0.0010	0.0066	<0.00010	<0.00008	7.59
Roaster site, creek upstream	<0.0010	0.0033	<0.00010	<0.00008	8.07
Roaster site, creek downstream	<0.0010	0.0112	<0.00010	<0.00008	8.54
Battery site, wetlands	0.0022	0.0101	<0.00010	<0.00008	8.22
Battery site, south cyanide tank	0.0097	4.1	0.0012	<0.00008	9.11
Battery site, north cyanide tank	0.007	0.88	0.0002	<0.00008	7.82
Mullocky Creek	0.0017	0.0053	<0.00010	<0.00008	8.26
Bull Creek	0.0084	0.0051	<0.00010	<0.00008	7.42
NZ Drinking Water Standards	0.01	1.5	0.01	0.007	

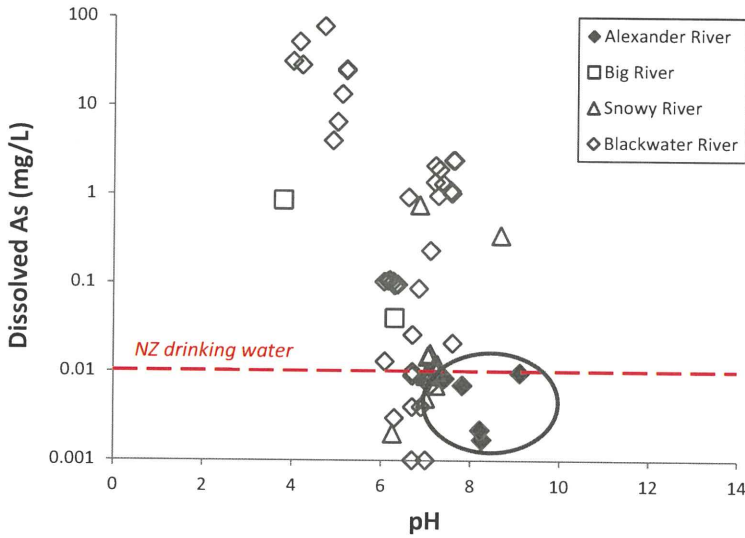


Figure 6. A comparison of As and pH of river catchments with historic gold processing sites in the Reefton Goldfield. Samples returning dissolved As below detection limits are not shown. The Alexander River catchment has the lowest dissolved As (circled), all below the New Zealand drinking water standard, and the highest pH. Big River data taken from Druzicka (2013), Snowy River and Blackwater River data from Haffert (2009).

Golden Lead

Gold processing

Gold processing on the Golden Lead site was by crushing and Hg-amalgamation. The plant operated for eight years during the 1890s. There was no roaster or cyanidation plant. The stamper battery was restored on site by DOC in 2008 (Staton, 2009).

Metal distribution and processing residues

High metal levels were confined to the centre of the site, in a moss covered hardpan and to the west and south of the hardpan (Fig. 7a). As, Pb and Hg values exceed New Zealand guidelines in the centre of the site, with As reaching extremely high concentrations (up to 12 wt% As) that are over 2,000 times the guideline value. Three auger holes into the hardpan show that

these high levels continue below the surface, although the thickness of this high metal processing residue is thin at < 20 cm, above the alluvial gravels (Fig. 7b).

The broken indurated hardpan on the surface is no more than 2 cm thick and consists of mostly amorphous HFA with colloform texture and desiccation cracks (Fig. 8a). Crystalline iron arsenate minerals were not detected by XRD. Fe/As ratios were low (< 1.5) and there was minimal sulphur present, except for some sulphide-rich rims. The processing residues below the hardpan were also comprised of amorphous HFA-HFO. Fe/As molar ratios and sulphur with depth, forming As-jarosite near the bottom of the residue pile. Rare lead containing plumbojarosite was also identified. There were no primary sulphides identified. The residues were also enriched in heavy minerals such as zircon (Fig. 8b), metal oxides and mercury-rich material. Vegetation in the residues is preserved and replaced by HFA (Fig. 8c).

The paste pH of the processing residues were all acidic, ranging from pH 2.62 to 4.23, with increasing acidity with depth.

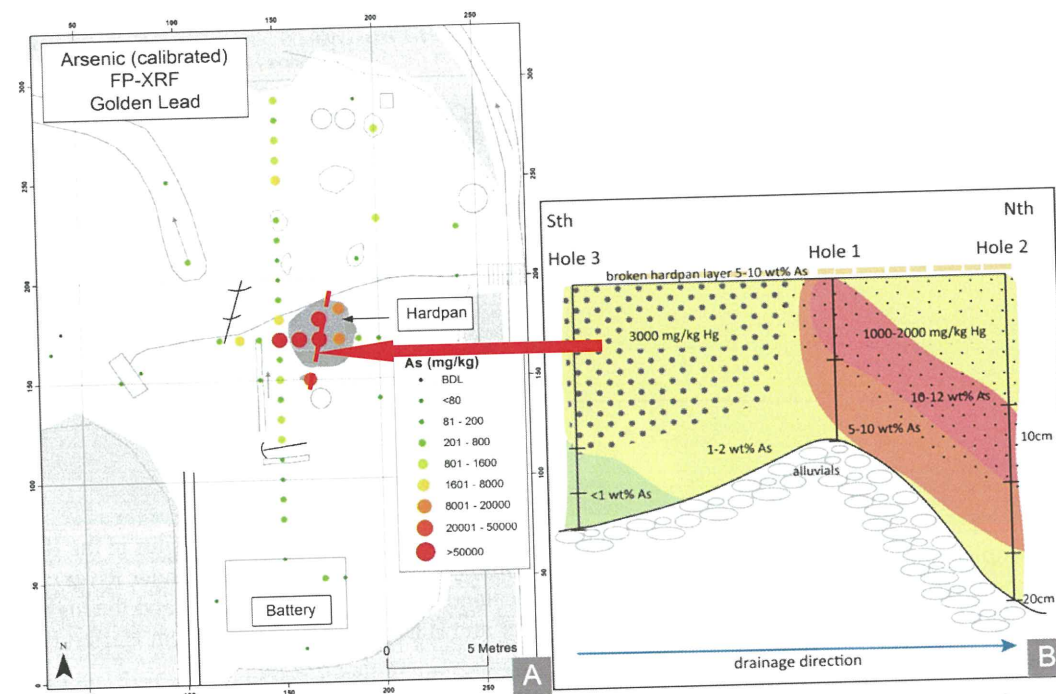


Figure 7. A. Distribution of As at the Golden Lead based on site FP-XRF analyses calibrated for sample preparation and moisture content. B. cross section through the hardpan (dashed red line on A.) shows the distribution of As and Hg (the highest metals on site) with depth.

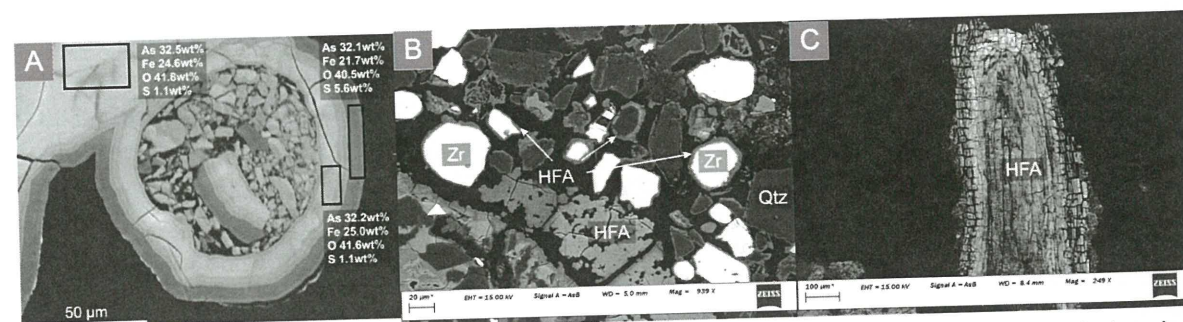


Figure 8. Golden Lead processing residues. A. Amorphous HFA hardpan with colloform texture, desiccation cracks and sulphur-enriched rims. B. HFA in the processing residues at depth cement soil particles that are enriched in zircon (Zr). C. HFA replaces vegetation.

Discussion

The extreme As levels at Alexander (in excess of 35 wt% As) are the result of ore roasting and these extreme levels are seen at other historic processing sites where the ore was roasted (Haffert, 2009; Jamieson, 2014). Roasting the ore eliminates the sulphides through rapid oxidation converting them to hematite and results in a porous and fractured calcine that is more amenable to the cyanide solutions (Dunn et al. 1995; Paktunc et al., 2006). The roasting process also produces toxic arsenolite (As(III)). Lime added to the roaster to mitigate sulphide dioxide gas release has resulted in the formation of calcium (+/- iron) arsenates in the flue wastes and As-bearing gypsum crystalline efflorescences. Calcium arsenates and arsenolite are the most soluble and chemically bioavailable of the arsenic minerals, posing a serious health risk (Meunier et al., 2010). Vapours released during roasting were also adsorbed by the porous concrete flue and are an As source for continued growth of the crystalline efflorescences.

The three red piles south of the Edwards roaster are residues that have undergone roasting and cyanidation. Zinc levels on the Alexander roaster site are highest in the piles resulting from the cyanidation/zinc precipitation process (Fig. 1). Arsenic levels are high (up to 2 wt% As) but are largely attenuated by the hematite produced during roasting. There is no dissolved As in the creek next to the red piles that drains the roaster site (Table 1).

Formation of the indurated HFA hardpan and semi-cemented clay at Golden Lead is the same process as the semi-cemented (boxed) tailings at the Alexander battery site. Both were originally comprised of concentrated sulphides that have oxidised, weathering to amorphous HFA-HFO, with high levels of As of up to 12 wt%. Oxidation of the sulphides has led to a reduction of the pH of the residues. Sulphides were concentrated from overspill from Hg-amalgamating berdans and concentrating tables (Golden Lead) or as a result of sands produced from crushing, amalgamation and concentrating which were stored for shipment (Alexander battery site). The formation of the HFA-HFO, as well as As-bearing jarosite at Golden Lead, attenuates As and Pb on site and should remain geochemically stable at current site conditions (oxidising, acidic pH). At Golden Lead, Hg is highest in the surficial processing residues (up to 3,000 mg/kg) with low Hg in the residues with depth (< 300 mg/kg), indicating low mobility of Hg (Fig. 7b).

High metal levels are largely sequestered on site at Alexander and Golden Lead by the formation of secondary iron oxide and arsenate minerals and any dissolved metals that leave the site are diluted by the high rainfall. The weathering of sulphides has resulted in the localised production of acid but lime added during ore processing, as well as carbonates in the Greenland Group host rocks, neutralise this acid so there is no acid mine drainage (AMD) leaving the site. Unlike other Reefion goldfield processing sites (Snowy, Prohibition and Big River), there was no significant increase in dissolved metals in the Alexander River downstream from the Alexander processing complex, with most metals below detection limits and all metals well below the New Zealand drinking water standards (Fig. 6).

Conclusion

High metals on the Alexander roaster site, Alexander battery site and Golden Lead site are the result of the geology of the deposits (As and Sb) and metals added during ore processing to aid gold recovery (Zn, Pb and Hg). The differences in mineralogy of the tailings on the three sites are the result of the methods of processing used which depend on what technologies

were available at the time of operation. Ore processing has concentrated both natural and added metals at the Alexander and Golden Lead sites. New Zealand guidelines for metals in the soil are exceeded on all three sites. Extreme As levels at Alexander (in excess of 35 wt% As) are the result of ore roasting, with toxic As(III) generated. High As (5-12 wt%) at the other sites is the result of weathering and ageing of fine sulphides concentrated during processing. Sulphide and arsenolite oxidation has resulted in localised acid generation but water testing has indicated that there is no AMD and dissolved metals are below New Zealand drinking water standards.

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