Prediction of environmental impacts from orogenic gold deposits

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Abstract

Environmental effects of mining of orogenic gold deposits are predictable and manageable. The principal environmental effects result from the presence of metalloid-bearing accessory minerals, mining and processing methods used, and climatic conditions in which the mines are set. The environmental impacts can be broadly divided into chemically altered mine drainage, physically altered mine drainage, and solid wastes. Arsenic and antimony are the two important accessory metalloids in neutral mine drainage. The anthropogenically-induced metalloid concentrations are typically <5 mg/L but in some unmanaged historical cases they reach >50 mg/L As. Metalloid ratios are linked to the relative arsenopyrite and stibnite contents of the mined ore. Underground mines typically focus on As-rich gold ore, whereas open cut mines can expose a broader range of rock types, including zones of disseminated stibnite. Metalloids can be immobilised in solid mine wastes because of the formation of secondary minerals, adsorption onto iron (oxy)hydroxides, and the presence of localised sustained acidic conditions (pH <5). However, roasting of ore can yield the soluble mineral arsenolite. Mine water quality can also be affected by physical mining-related changes, in particular the increased total suspended sediment (TSS) contents and the related turbidity levels. The negative effects are not limited to visual/aesthetic changes, and can also include potentially significant impacts on aquatic fauna. Control of suspended solids is an important component of mine site management.

Keywords: gold, orogenic, environmental impact, arsenic, antimony.

Introduction

The ability to predict potential future environmental issues associated with mining is crucial for the responsible running of modern operations. Mining-related environmental impacts are usually predictable, and therefore preventable or manageable. The compilation of empirical data including information on deposit type, host rock, primary and secondary mineralogy, deposit trace element geochemistry as well as other information such as mining and ore processing methods, hydrology, topography and climate contribute to the development of so-called geoenvironmental models of mineral deposits (Seal et al., 2002). Geoenvironmental models are particularly useful in providing information assisting with the prediction and mitigation of potential mining-related environmental issues but they can also be applied in the baseline characterisation of a future mine site as well as in the assessment of abandoned mine sites and their remediation requirements.

Mining-related environmental and geology-based research worldwide contributes to the development of geoenvironmental models. This paper, which concentrates specifically on the New Zealand-based examples of mined deposits and the known environmental issues associated with them, aims to contribute a New Zealand perspective to the existing orogenic gold deposit models (see: Goldfarb et al., 1995a; Ashley, 2002). The paper presents a compilation of findings from the existing published literature as well as from authors' unpublished research concerning modern and historic mines.

Orogenic deposits

Orogenic (mesothermal) deposits are associated with deformed metamorphic terranes, in particular greenschist facies rocks, and a large proportion of them are located within orogenic belts around the Pacific plate margin (Berger, 1986; Groves et al., 1998; Goldfarb et al., 2005). Known world-class deposits of this type include those from Australia (e.g. Ballarat, Bendigo, Hillgrove, Kalgoorlie, Gympie deposits), Russian Far East and NE China (e.g. Chukotka Belt, Yana-Kolyma Belt) and North American Cordillera (e.g. Bralorne-Pioneer, Klondike, Bridge River, Mother Lode, Juneau Gold Belt, Abitibi Belt) (e.g. Boyle, 1979; Goldfarb et al., 1998; Groves et al., 1998; Bierlein et al., 2004; Goldfarb et al., 2005).

Mineralisation within the orogenic deposits is commonly associated with regional shear zones and apart from quartz lodes it can be present in disseminated form. Orogenic Au deposits typically contain between 2 and 5 % of sulphide minerals, the most common of which include pyrite and arsenopyrite, and variable but lesser stibnite, chalcopyrite, pyrrhotite, sphalerite, galena, and tetrahedrite may also be present (Plumlee et al., 1999). Carbonate minerals can be abundant, typically up to 15%, and varying enrichments in elements such as arsenic (As), antimony (Sb), mercury (Hg) and tungsten (W) are often present (Fig. 1) (Goldfarb et al., 1995a; Groves et al., 1998).
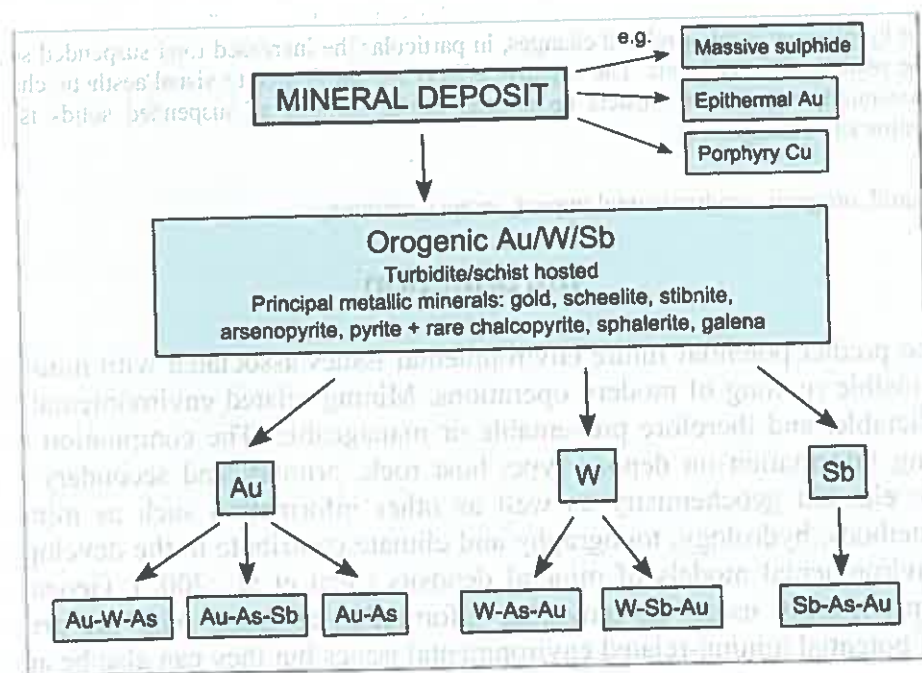

Figure 1. Geochemical categorisation of orogenic mineral deposits of the South Island of New Zealand.

The flowchart in Fig. 1 presents the categorisation of (mined) orogenic deposits of the South Island of New Zealand. These deposits have been subdivided according to their varying Au, W, As and Sb contents. With respect to the economic value of the resource, gold mineralisation is by far dominant. As gold is the most common commodity mined from orogenic deposits, it is predominantly gold deposits that are given attention in this work. Scheelite ($CaWO_4$, source of tungsten) and/or stibnite (Sb_2S_3, source of antimony) are commonly associated with gold in many localities and in some cases these minerals comprised a primary resource locally, with gold present only as a minor component. No separate As ore category has been created, since, even if mined, arsenic has never been the primary resource at any of the mined deposits. Instead, arsenic has only been a by-product of

gold production (e.g. Blackwater mine, Haffert and Craw, 2008). The locations of some of the known mined orogenic deposits are presented in Fig. 2.
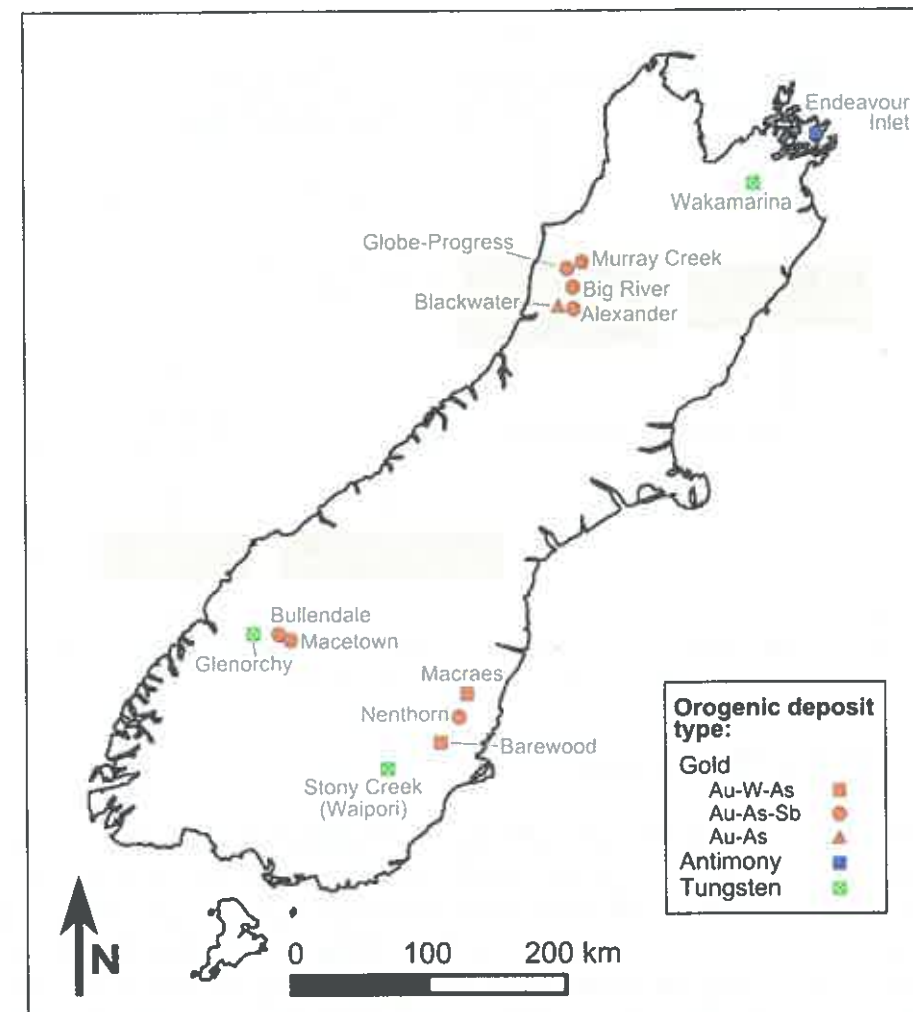

Figure 2. Examples of mines developed in orogenic deposits of the South Island of New Zealand (Sources: Williams, 1974; Pirajno, 1979; McKeag and Craw, 1989; Christie and Brathwaite 2003; MacKenzie et al., 2007).

Environmental impacts arising from the mining of orogenic gold deposits: NZ perspective

Mining-related environmental impacts are closely related to the geological setting and geochemical characteristics of deposits (Ashley, 2002). As mentioned earlier, additional factors, such as mining and processing methods used during extraction are also important and are considered in this work. Apart from the visually obvious land disturbance, environmental impacts arising from the mining of orogenic type deposits can be broadly divided into chemically altered mine drainage, physically altered mine drainage, and solid wastes (Fig. 3).
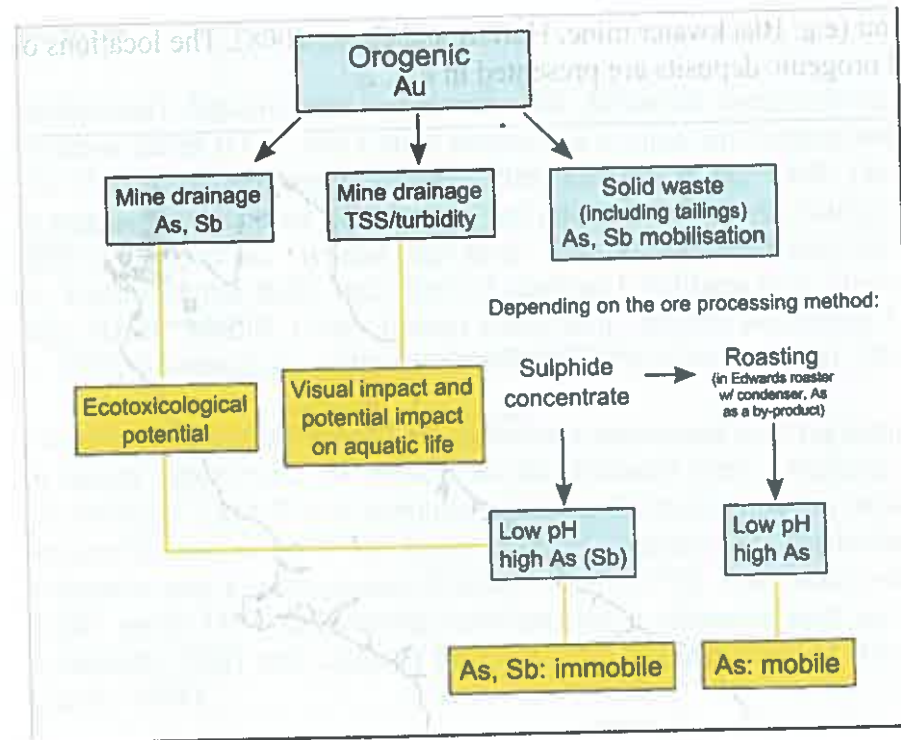
Figure 3. Flow chart showing a range of environmental impacts resulting from the mining of orogenic gold deposits.

Chemically altered mine drainage

Arsenic and antimony are the principal elements of environmental concern associated with the mining of orogenic gold deposits. Both metalloids are potentially toxic at low dissolved concentrations in water (< 0.01 mg/L) and their mobilisation is facilitated by circum-neutral pH of surface waters (Vink, 1996; Ashley et al., 2003; Craw et al., 2004). The development of near-neutral pH levels (so-called neutral mine drainage) during the mining of orogenic gold deposits is linked to the typically high carbonate mineral contents of the mineralised quartz lodes and/or host rocks, which ensure that any acidity generated from the dissolution of sulphides is buffered (Goldfarb et al., 1995b; Craw, 2001; Filella et al., 2009). Enrichment in As and Sb is the main mine water chemistry characteristic associated with the mining of orogenic Au deposits.

The anthropogenically-induced elevated metalloid concentrations are typically < 5 mg/L in New Zealand mine waters (e.g. Bullendale, Big River, Globe Progress and Macraes mines; Fig. 4) (Craw et al., 2000; 2004; Haffert and Craw, 2010; Druzbicka and Craw, 2013), although in some rare cases extreme concentrations of tens of mg/L were recorded (e.g. 50 mg/L As at the historic Globe Progress mine adits and 77 mg/L As in the wetland at the Prohibition Mill site of the Blackwater mine) (Hewlett et al., 2005; Craw et al., 2007; Haffert and Craw, 2008).

The influence of mining methods on mine water composition has recently been studied at the Globe Progress mine (Fig. 2) (Druzbicka and Craw, 2013). It was found that a change from underground to open cast mining resulted in a shift in the metalloid signature of mine drainage waters. Prior to the opening of the modern Globe Progress mine in 2007, arsenic was the dominant metalloid in mine waters (typically < 0.1 mg/L) and the Sb/As tended to not exceed 0.4 (Druzbicka and Craw, 2013). At that time mine waters drained historic

underground tunnels and historic mining targeted arsenopyrite-dominated quartz veins. A gradual evolution of mine water composition was observed since the opening of the modern open cast mine with antimony to arsenic ratios reaching consistent results of > 1 (up to > 30, Druzbicka and Craw, 2013) (Fig. 4). The main reason for this transformation was a change in the type of ore mined which now included later-stage cataclasite characterised by abundant stibnite (see Globe Progress mine ore composition in Fig. 4).

The Sb/As signatures of the rest of the mine waters associated with the mining of the predominantly arsenopyrite-rich gold deposits and presented in graph in Fig. 4 are <1, with an exception of some Macraes pit water compositions. Slightly Sb-enriched waters occur at the Macraes mine despite stibnite being absent from the mineralised rocks (see above, Macraes is an Au-W-As type deposit). These results are due to elevated antimony concentrations present principally in solid solution in arsenopyrite (Fig. 4; Craw, 2002; Craw et al., 2004).
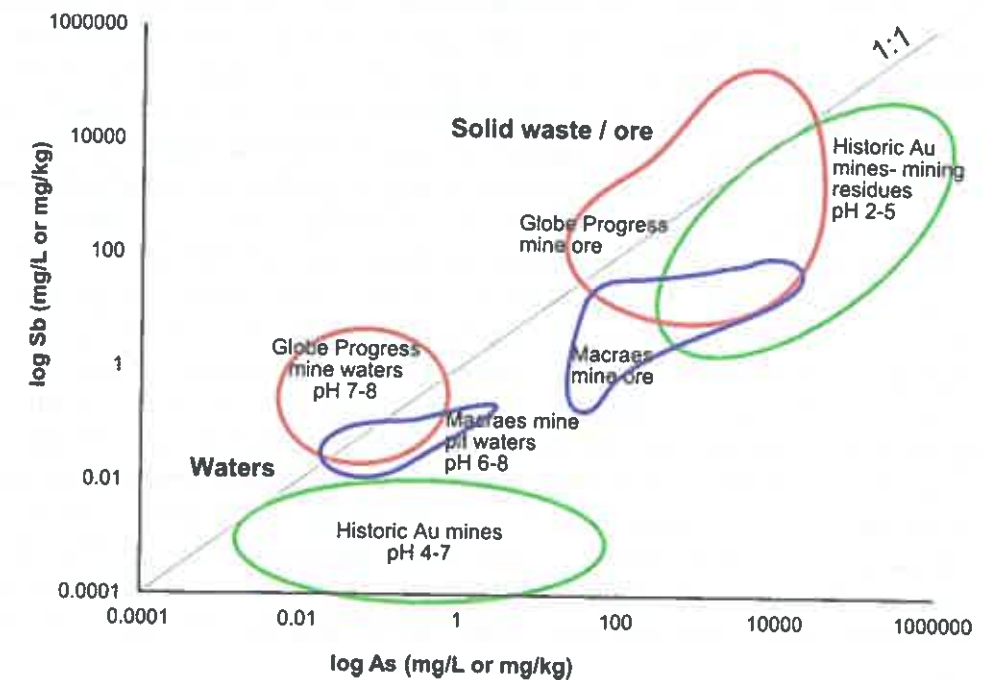

Figure 4. Generalised arsenic and antimony compositions of mining residues/ore and waters associated with historic and active orogenic gold mines in New Zealand. Solid line represents 1:1 relationship. Based on data from Craw et al. (2004), Haffert and Craw (2008), Haffert and Craw (2010), Druzbicka and Craw (2013) and authors' unpublished data.

Physically altered mine drainage

Even though the increased total suspended solids (TSS) and the related turbidity levels are well-known natural and anthropogenically-induced phenomena, not many examples of scientific studies exist on the topic. Suspended solids in water may be associated with various types of mining activities and in the case of orogenic gold deposits these would be most likely related to physical earth and rock-moving (excavation) as well as ore processing. Druzbicka and Craw (2013) reported that release of untreated turbid pit waters occurred periodically at the modern Globe Progress mine but no published data on the TSS levels and potential associated environmental impacts exist to date.

The negative effects of elevated TSS levels in mine waters are not limited to visual/aesthetic changes but can also include potentially significant impacts on aquatic fauna though, amongst

others, habitat alteration and various direct impacts such as interference with organisms' ability to find food and shelter, and gill abrasion and clogging in fish (Fig. 3) (Ryan, 1991; Davies-Colley et al., 1992).

From the chemical perspective, it is important to mention that discharge of turbid processing waters or tailings into the environment may result in the introduction of particulate metalloids and fragmented sulphide minerals into mine waters, and it may also contribute to an increase in metalloid contents of stream sediments (Salomons, 1995).

Solid wastes

The main environmentally-sensitive feature of solid wastes (waste rocks, processing residues, mine soils) associated with the mining of orogenic gold deposits is, as in the case of mine waters, their enrichment in arsenic and antimony (Fig. 3, 4). The relative metalloid content and the level of metalloid mobility at mine sites are dependent on the original deposit type and its composition (above). In the case of active mines, the final composition may be additionally affected by active treatment (Druzbicka and Craw, 2013). At historic sites, the type of processing methods used during mining was also found to be important and this refers specifically to the use of roasting as an intermediate step in gold extraction at processing sites (Fig. 3). The reason for this distinction is the fact that roasting results in the release of arsenic from the sulphide-rich ore which, if allowed to precipitate, results in the formation of arsenolite as a by-product of gold extraction (Haffert and Craw, 2008). The presence of this mineral was found to be the diagnostic feature between sites which did or did not include roasting, particularly in Edwards roasters equipped with a condenser, as part of their ore processing activities. The best examples of mine processing sites in which arsenic-rich ores were subjected to roasting in Edwards roasters include the Prohibition Mill site and the Snowy Battery site (Blackwater mine, Haffert and Craw, 2008). The Prohibition Mill site in particular is characterised by extremely high As contents (up to 40 wt%), high mobility of arsenic (as arsenolite) as well as acidic character of the processing residues (Fig. 3) (Craw et al., 2007; Haffert and Craw, 2008; Haffert et al., 2010). The acidic character of the site is the result of arsenolite dissolution and the oxidation of arsenite oxyanions (Haffert and Craw, 2008).

In contrast, historic mine sites at which roasting did take place but on a comparatively smaller scale and with no arsenolite recovery systems in place, are represented by the Premier mine's processing site (Macetown mining area). The site contains arsenic levels of up to 8 wt% locally (source: author's unpublished data).

Historic mines in which ore was concentrated but no roasting has been undertaken are represented by the Phoenix Battery site (Bullendale mining area) as well as Big River and Barewood mines (Craw et al., 2000; Haffert and Craw, 2010). These sites also tend to be characterised by acidic pH (~2-5, Fig. 4) which results from the oxidation of remnant sulphide minerals (Haffert and Craw, 2010). Significant amounts of arsenic and antimony are immobilised at these sites thanks to the formation of secondary minerals (scorodite, arsenical ferrihydrite, iron arsenate, kankite, zykaite, bukovskyite) as well as through the adsorption onto iron (oxy)hydroxides (Fig. 5) (Walker et al., 2009; Haffert et al., 2010; DeSisto et al., 2011). Provided that the pH and oxidation/reduction conditions at these sites remain unchanged, the sites are thought to remain stable with metalloid mobilisation occurring on a minor scale only.
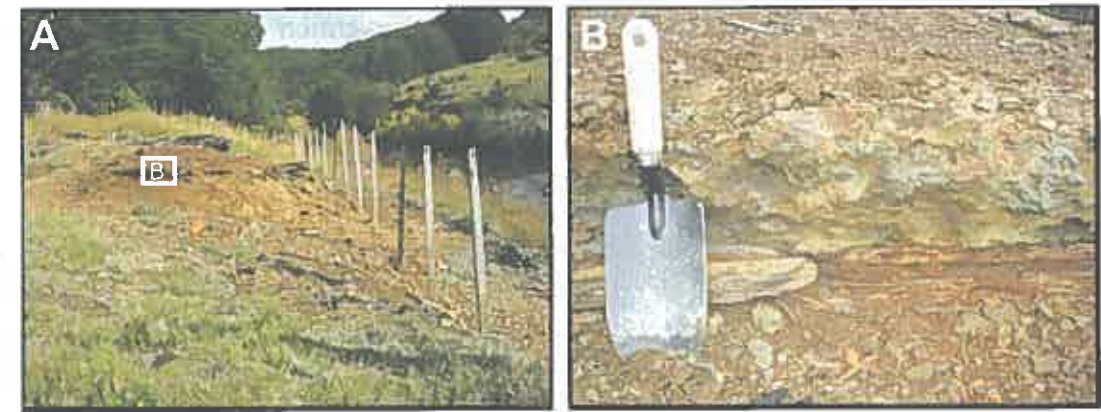
Figure 5. A- View of the Big River battery site showing the extent of unvegetated processing residues. White rectangle shows the location of the deposit pictured in B. B-Orange and green-coloured hard pan consisting of remnant primary sulphide minerals (arsenopyrite, stibnite) as well as secondary phases (scorodite, Fe(oxy)hydroxide). Source: authors' unpublished data.

Historic mine sites are characterised by the variable arsenic and antimony concentrations, ranging from 10s of mg/kg to wt% values. The highest arsenic concentrations recorded to date in New Zealand include 40 wt% at Prohibition Mill site, 40 wt% at Bullendale mine, ~25 wt% at Snowy Battery and Big River mine, and ~10 wt% at Golden Point battery sites (the latter is a processing site of an historic Macraes mine; Fig. 4) (Mains and Craw, 2005; Haffert and Craw, 2008; 2010). Antimony concentrations are usually lower than arsenic as stibnite tends to be present in much smaller quantities in these mineralised zones than arsenopyrite (Fig. 2). The highest concentrations recorded to date at an historic orogenic gold mine reached 3.5 wt% at the Big River processing site (authors' unpublished data).

At active mines exploiting orogenic gold deposits in New Zealand, the presence of vast quantities of arsenic and antimony-bearing waste materials provides a potential for large scale metalloid mobilisation, especially from the voluminous tailings which are stored in direct contact with water. Metalloid mobilisation is also possible from mineralised waste rocks if the water-rock interaction is not prevented in the waste piles. An example of such waste materials are waste rocks categorised as potentially arsenic generating (PAG) at the Globe Progress mine which were shown to contain up to 2.4 wt% As and 10.8 wt% Sb (Druzbicka et al., 2010).

Conclusions

The knowledge and understanding of geological and geochemical factors associated with a particular deposit is crucial in ensuring the prevention and/or minimisation of the environmental impacts of mining operations. Such knowledge, including that gained from research on un-rehabilitated historic sites, is essential for the responsible environmental planning and management of modern mines.

This paper presented a New Zealand perspective on some of the environmental impacts that can be expected from the mining of orogenic gold deposits, contributing knowledge to the existing geoenvironmental models. Findings from recent environmentally-focussed studies highlighted the important role metalloids play in orogenic mineralised systems and the impact mining and processing methods can have on environmental issues arising from the mining of these deposits. The geochemical knowledge of the deposits and the observation geochemical processes taking place during and post-mining can be useful in the design of treatment and

remediation technologies, therefore contributing to the prevention and/or minimisation of some of the possible negative environmental impacts associated with mining.

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