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Nature and Extent of Contamination at the Abandoned Wheal Ellen Mine and Implications for Rehabilitation

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The visible effects of Wheal Ellen Mine; acid scouring, devegetation and erosion.

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ABSTRACT

The Wheal Ellen Mine, South Australia, was mined sporadically between 1860 and 1911 for Pb, Ag, Au and pyrite. The mining process exposed sulphidic material to oxygen and water, with the inevitable creation of acid mine drainage (AMD), and a resultant increase in the mobility of potentially toxic heavy metals. Since closure of the mine, AMD has continued unchecked, causing acid scouring, devegetation and erosion on the surrounding hillslopes, with fears of manifestations in the nearby Rodwell Creek, a tributary of the agriculturally important Bremer River. Following complaints, a MESA inspection in late 1995 identified Wheal Ellen as an environmental threat and safety hazard requiring rehabilitative action. Preliminary work saw the abandoned mine shafts infilled with surface dumped mine wastes, and "clean" clay dumped in readiness for spreading over the mine area as topsoil. The need for further work is acknowledged, but no plans are confirmed.

Investigations show that whole rock sulphidic wastes (up to about 98% sulphide content) constitute major acid producing potential at the mine. Tailings, containing highly reactive fine-grained sulphides also comprise a potential for acid production, even though total sulphide content (about 2%) is significantly lower. The abundant secondary mineral jarosite, formed from dissolution products of sulphides and aluminosilicates, generates acid during precipitation and again on dissolution. The background water-extracted pH of soils is approximately neutral compared to 2.5-4.0 in soil surrounding the mine. This enhanced acidity would primarily result from the downslope transportation of acid-producing materials (sulphide grains and/or jarosite) from the mine area.

Mine-related heavy metal contamination in soil surrounding the mine, particularly in major erosion features, is substantial for Pb, Zn, and Cu with minor increases in As levels. Rodwell Creek appears to be receiving groundwaters of mine origin, but current environmental impact is negligible through dilution, neutralisation by carbonates and possible natural filtering in a wetland system.

In retrospect, the relatively small volume of mine wastes involved may have best been treated by physical removal and relocation at a more appropriate treatment site. This option is no longer viable however, as surface remediation has already commenced (shaft infilling and clay dumping). MESA now needs to address the resultant potential threat to groundwater, and consequently Rodwell Creek, as well as the problems associated with surface contamination. An impermeable shaft capping (e.g. concrete) would minimise water infiltration into the shafts, although the potential for shaft subsidence may create complications. Compacted clay should create an adequate semi-impermeable cover for remaining surface wastes. Water diversion techniques (surface contouring and channel creation) would further reduce water infiltration and therefore AMD generation and transportation. Finally, importation of further clay as a topsoil cover is required, after which, rehabilitation of degraded surface soils ought to be satisfactorily addressed by MESA's revegetation plans. Monitoring of Rodwell Creek water quality and the evaluation of long-term revegetation success will need to be an integral part of rehabilitation.

INTRODUCTION

Acid mine drainage (AMD), caused by the oxidation of sulphidic minewastes, constitutes one of the most significant mining related environmental issues (Taylor, 1996). Extensive research in recent decades has provided a detailed knowledge of the processes and variables involved in acid generation and the ensuing enhancement of heavy metal mobility (e.g. MEND, 1993, Jambour & Blowes, 1994). With this knowledge, developers of new mines aim to prevent or at least minimise AMD generation. Clearly, prevention is not an option for older mines with established AMD and such sites generally require extensive rehabilitation. A number of diverse rehabilitation options exist, although rehabilitative work is seldom fully effective within realistic budget constraints.

The abandoned Wheal Ellen (or Commonwealth) base metal sulphide mine exemplifies such concerns. The past 140 years since mining commenced have seen sulphidic minewastes brought to the surface and exposed to the action of water and oxygen. AMD is now extensive, with starkly visible acid scouring on areas downslope of the mine, destruction of vegetation and enhanced erosion (Frontispiece). The increased mobility of heavy trace metal ions has no doubt contributed to the high levels in surrounding soils. Possible contamination of the adjacent Rodwell Creek, a tributary of the agriculturally important Bremer River, is a further concern.

Following complaints from the local land-owner and environmental groups the Mines and Energy Department of South Australia (MESA) conducted a preliminary investigation of the area and confirmed a need for rehabilitative action (Puccini & Mattiazzo, 1995). In the past, little work has been done on the mine and its surrounds (excepting occasional unsuccessful exploratory surveys) so detailed geological or geochemical information on the area is minimal, and information regarding environmental impacts is non-existent. Without such information, effective rehabilitation is a difficult task, as the environmental impact of AMD and heavy metal transport varies with the type and amount of sulphidic material and host rocks, hydrological regime, environmental sensitivity, ecological setting, local climate, topography and amount of waste material exposed, thus detailed site specific examinations are often required to assess environmental threat. This project aimed to select the most appropriate rehabilitation methods for Wheal Ellen, through (1) mine waste characterisation with respect to acid producing potential and/or significant heavy metal release, and (2) examination of surrounding soil and water to determine the extent of mine-related contamination.

MESA commenced rehabilitation in late 1995 by infilling shafts with surface wastes and importing topsoil. While undoubtedly removing the immediate danger presented by unprotected open shafts and reducing the level of surface contamination, infilling with sulphidic material may increase the impact AMD has on groundwaters, and ultimately Rodwell Creek. The possible implications of their actions are examined, along with a discussion of proposed further work and recommendations based on the results of this study.

Chapter 1
WHEAL ELLEN MINE

1.1 Location and Setting

Wheal Ellen Mine is located at 139°09'E, 34°53'S, South Australia, approximately 50km SE of Adelaide and 8km N of Strathalbyn (Figure 1.1).

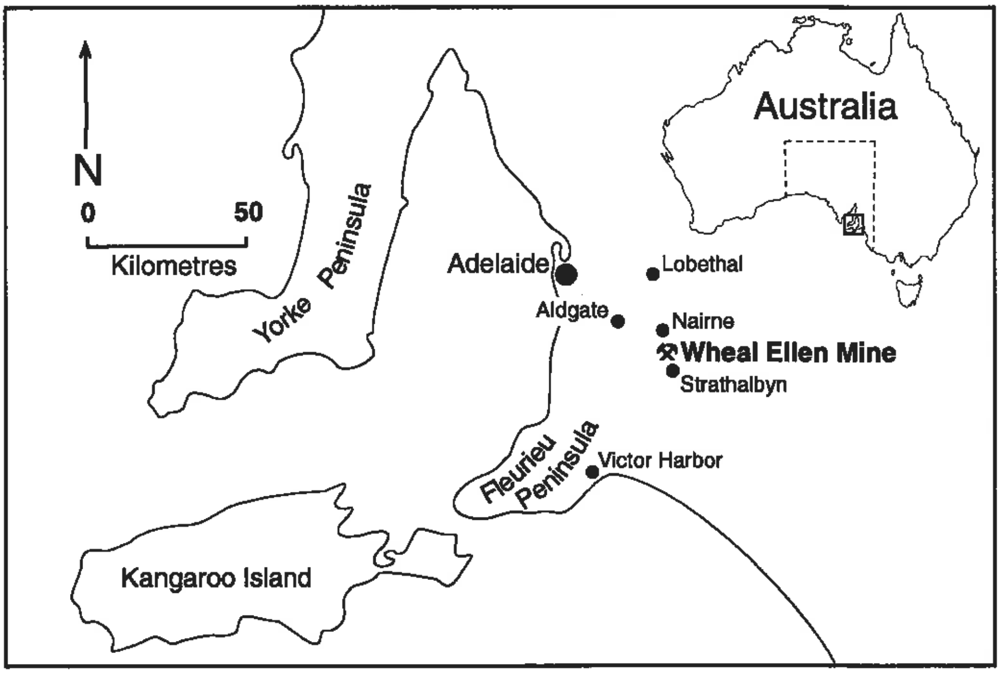


Figure 1.1 **Location map for Wheal Ellen Mine**

The mine workings lie along an exposed ridgetop surrounded by grass covered-hills with minimal tree cover and numerous rock outcrops and erosion gullies. Pasture lands (supporting sheep or cattle) dominate, excepting in the immediate vicinity of the mine where native grasses (e.g. Kangaroo, Wallaby and Spear Grasses) comprise the minimal cover. During mining, virtually all trees were removed. The subsequent development of AMD has prevented any significant natural regrowth, although recent planting of River Red Gums by the current property owners has had some success. Scattered examples of naturally regrown native and introduced vegetation can be found around the site, including (common names), Golden Wattle, Ghost Gum, Cotton/Swan Bush, Tom Thumb and Sticky Hop Bush (S. Gerrard, pers. comm., 1996).

Red, yellow and grey duplex soils, with lateritic remnants as derived from the underlying Kanmantoo sandstones and schists typify the regional soil types (Fitzpatrick *et al.*, 1995), although soil at the mine itself and downslope is skeletal and of insufficient depth (<80cm) to have developed a profile.

Climate at Wheal Ellen (as determined by Strathalbyn data) is classified as Mediterranean, type 'Csa' (Mason, 1957). Average temperatures range from 12°C (min) to 27°C (max) over summer compared with 5°C to 15°C in winter (Bureau of Meteorology, 1996). Average total annual rainfall is 495mm, with around 20-40mm each month during the summer period and increasing up to 45-65mm through winter (Bureau of Meteorology, 1996). Estimated monthly evaporation rates range from 60mm (winter) to 250mm (summer maximum). Total estimated annual evaporation is approximately 1750mm (Bureau of Meteorology, 1996).

Despite the apparently dry climate, the area surrounding Wheal Ellen forms part of an extensive surface drainage channel system (Laut *et al.*, 1977). Surface runoff from the mine (approximately 195m above sea level) collects in several gullies, the most significant leading SW into Rodwell Creek (approximately 65-70m below the mine).

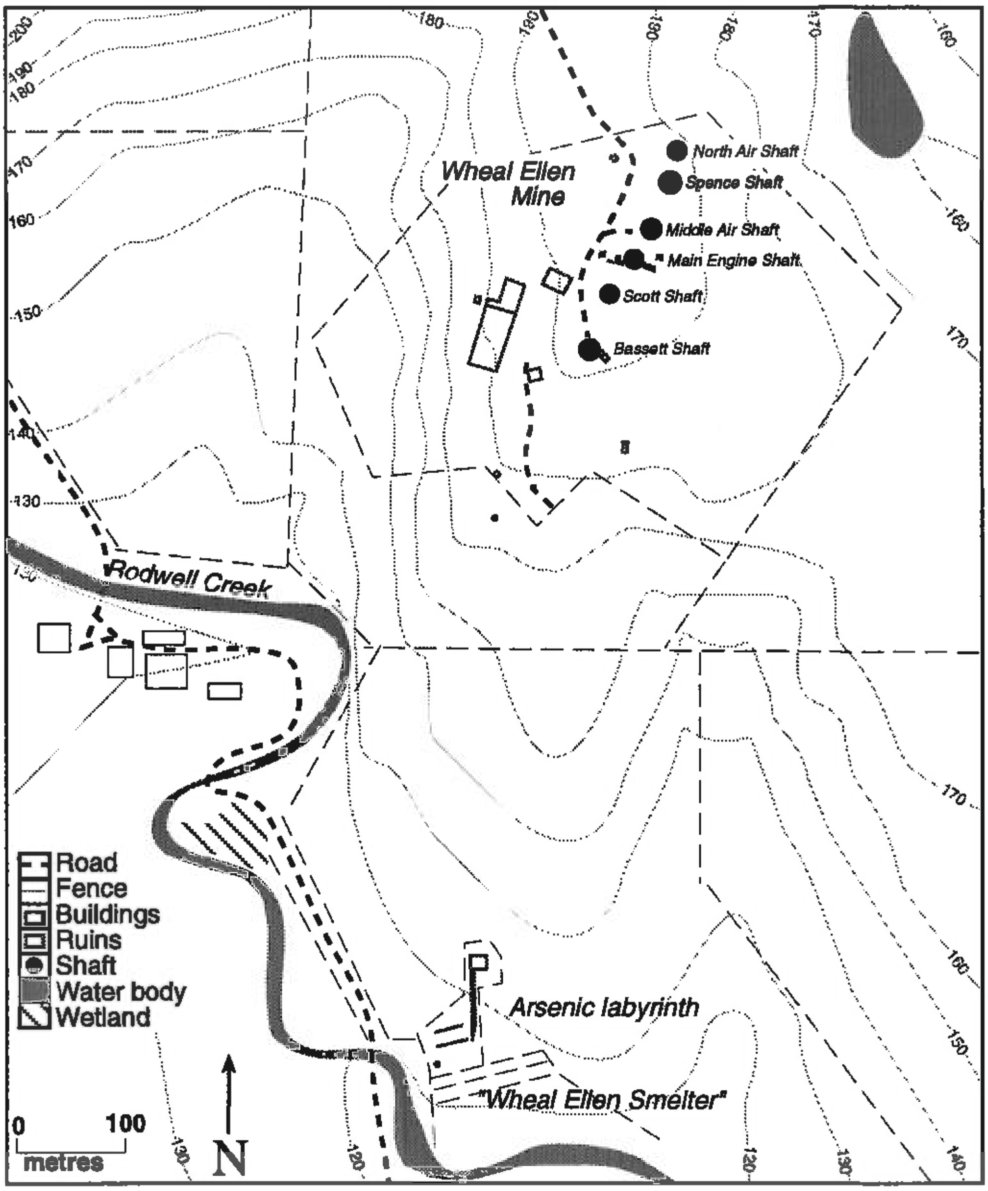


Figure 1.2 **Basic layout and topography of the mine and surrounds**

(Courtesy of MESA, 1996)

Rodwell Creek drains an extensive area, initiating in the Bugle Ranges and emptying into the Bremer River, an important water source for irrigation downstream. Flooding of the creek is not uncommon during the increased rainfall of winter months. Examples of river terraces are common on the edges of Rodwell Creek, suggesting enhanced creek sediment deposition in the past. Groundwater resources in the area exist predominantly in fractured rocks. The high salt content, derived from sea spray, tends to limit this resource to use by livestock (Laut *et al.*, 1977).

1.2 Geological Setting

Regional Geology

Wheal Ellen Mine lies within the Kanmantoo Trough, an early Cambrian fault-controlled basin stretching along the eastern and southern zones of the Mount Lofty Ranges and extending S to Kangaroo Island (Figure 1.3), a total distance of approximately 300km (Both, 1990). Kanmantoo Group rocks consist essentially of metasandstones, metasiltstones, phyllites, schists and quartzites (some micaceous), with 'greywacke' a common all-encompassing descriptive term (Sprigg & Campana, 1953).

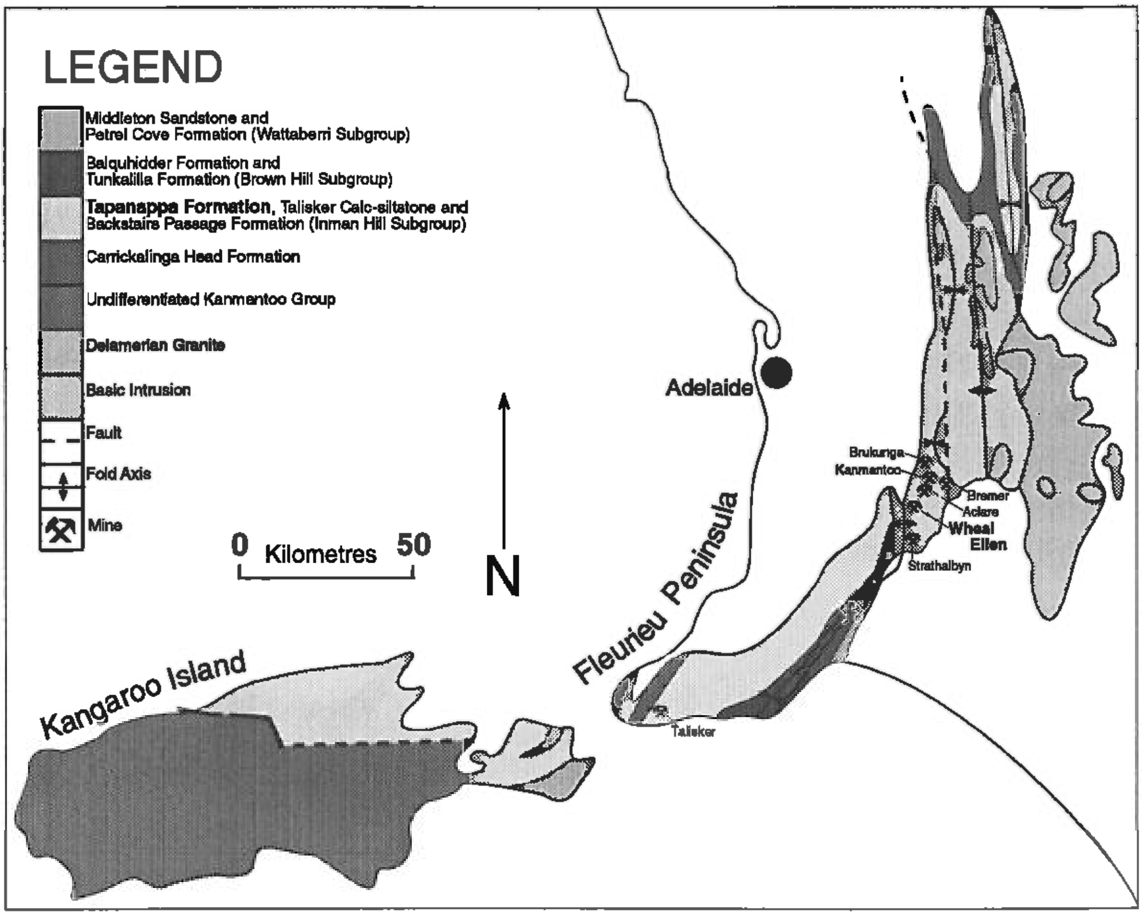


Figure 1.3 **Regional geology of the Kanmantoo Group and mine locations**

(adapted from Both, 1990)

During the Ordovician Delamerian Orogeny, the thick succession (15km) of marine "clastic flyschoids" (Sprigg & Campana, 1953) constituting the Kanmantoo Group sediments, experienced ductile deformation, metamorphism and granite intrusions (Both, 1990). Large scale (10km) upright folding and subsequent mesoscopic folding and crenulations formed during this period. Wheal Ellen occurs on the eastern limb of one of these large scale folds; a flat, south pitching regional anticline (Figure 1.3). Both (1990) documents a further three subsequent deformation events in the Kanmantoo Series.

Stratigraphically, the Kanmantoo Group is divided into several subgroups, which are each further divided into formations. Rocks hosting the Wheal Ellen Mine comprise part of the Tapanappa Formation, in the Inman Subgroup (Figure 1.3), described as "dark coloured and dirty metasandstones with thin phyllite interbeds and occasional iron sulphide rich siltstones" (Daily & Milnes, 1972).

The Kanmantoo Group metasediments host many significant mineral deposits; primarily copper (e.g. Kanmantoo) or lead-silver-zinc-arsenic (present at Wheal Ellen as well as Strathalbyn, Aclare and Talisker mines). Pyrite-pyrrhotite mineralisation (e.g. Brukunga) is also common (Both, 1990) (Figure 1.3).

Local Geology

At Wheal Ellen, micaceous sandstones dominate with lesser sandstone and quartzite. Wall rocks to the ore are predominantly mica schists (Wade & Cochrane, 1954). Various references report rutile, garnet (Wade & Cochrane, 1954), apatite, sphene, zircon (Whittle, 1969), chlorite and andalusite (Seccombe *et al.*, 1985) within the host rocks, and cerussite (Mining Review, 1909), malachite and azurite on the surface (Wade & Cochrane, 1954).

Bedding is fairly uniform (10-30° strike and 75°E dip in the N shafts to only 55°E towards the S). The whole system gently pitches S (Wade & Cochrane, 1954).

The single sheeted/tabular ore body (the "Wheal Ellen Lode") is a large pyritic Pb-Zn lode displaying high geochemical anomalies for Cu, Ag and Au in addition to Pb and Zn (Bridge Minerals, 1971). The two identified forms of mineralisation are; (1) massive coarsely-crystallised pyrite, sphalerite and galena, confined to biotite schists and (2) quartz vein hosted pyrite and chalcopyrite. Lesser amounts of pyrrhotite, magnetite, tetrahedrite, marcasite, boulangerite, arsenopyrite, and galenobismutite are also present (Spry, 1976, Askins, 1968). The first 40m depth comprises a zone of oxidation with Fe, Cu and Pb oxides. Below this is the sulphidic zone with Fe, Pb and Zn sulphides. Gold and Ag mineralisation is found throughout (Wade & Cochrane, 1954).

As far as can be ascertained through more recent work, the orebody does continue past the extent of the existing mine workings (both N and S), however, there is a sharp reduction of lode width and grade (Wade & Cochrane, 1954).

Gangue is predominantly bedding-parallel veined quartz, and mica (muscovite and biotite) as evidenced by the high dumped waste content, with lesser levels of dark green gahnite (Wade & Cochrane, 1954).

1.3 Mining History

Information pertaining to the mining history of Wheal Ellen is sparse, with no known complete record of the mining processes and production. Austin (1863), Harvey (1890) and selected *Mining Review* articles constitute the historical record, as summarised by Wade & Cochrane (1954), Drexel (1982) and Gemmell (1985).

Discovered in 1856, mining of the Wheal Ellen deposit commenced in 1857 for Pb, Ag and Au. Around 100 men were employed in peak production periods and large amounts of money were spent on mine development and treatment works. Increased ore complexity at depth rendered the unsophisticated extraction techniques insufficient to cover costs, forcing closure in 1866. At this stage, problems were already manifesting with several of the then five shafts reported as "unsafe" and the land described as "being permanently scarred by the works, metal and pyrite" (Mining Review, 1908b, Figure 1.4).

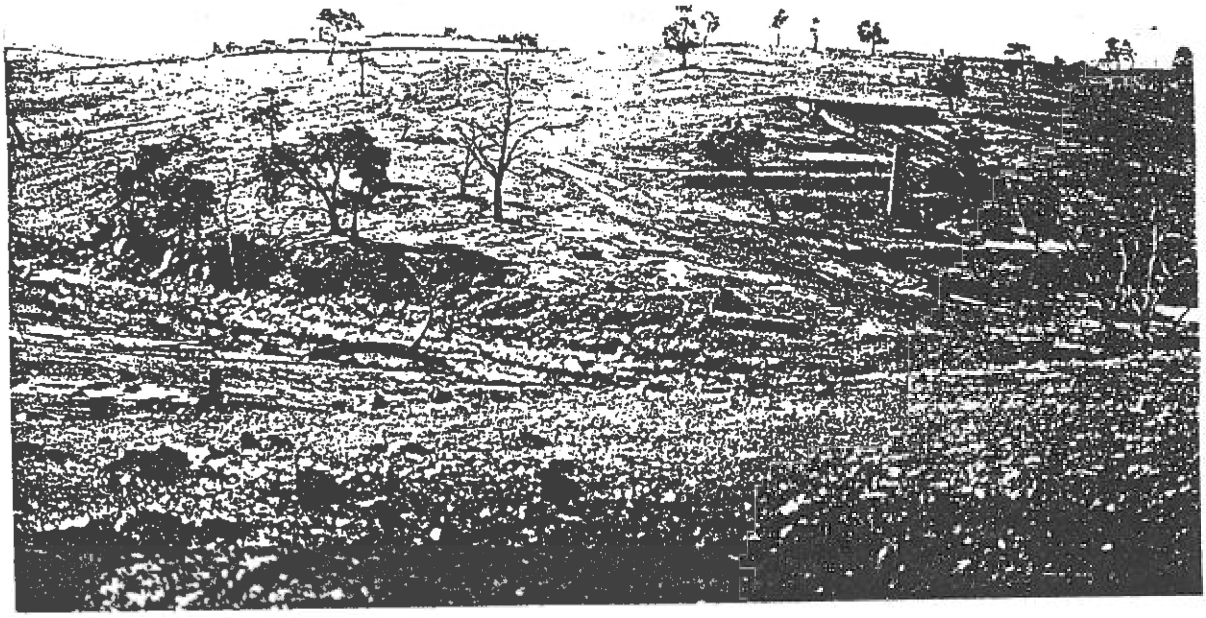


Figure 1.4 **Wheal Ellen Mine (1908); eroded western hillside (same view as Frontispiece)**

(Mining Review, 1908b)

Following identification of an untouched ore block in the southernmost shaft, mining recommenced for Pb, Ag and Au (1906-1908) and pyrite (1908-1911) under ownership of the Commonwealth Silver-Lead Company. A battery, concentrating table and pump were purchased in an unsuccessful attempt to increase mine profitability. Following company liquidation and mine closure in 1911, the mine was stripped of recoverable underground and surface equipment, while sulphidic waste rock, tailings, gossan and overburden dumps were left on the surface. Mineral separation techniques were ineffective at the time of operation and the waste rock and tailings had a high base metal sulphide concentration compared with current day standards (Smith, 1953). Total production of the area is not known exactly, but is estimated at 5.5 tonnes Ag, 2,100t Pb, 12.5kg Au and 5,000t pyrite (Wade & Cochrane, 1954).

Mine development was restricted to the one continuous lode with the mining activities covering a strike length of approximately 230m, a maximum depth of 110m and widths up to almost 4.5 m (Wade & Cochrane, 1954). The six shafts, from N to S, are (Figure 1.5);
(1) North Air Shaft (40/50(?)m depth) - ventilation
(2) Spence Shaft (55m) - haulage
(3) Middle Air Shaft (40m) - ventilation
(4) Main Engine/Main Haulage Shaft (110m) - haulage
(5) Scott/Air Shaft (80m) - ventilation
(6) Bassett/Old Main/Old Lead (110m) - haulage

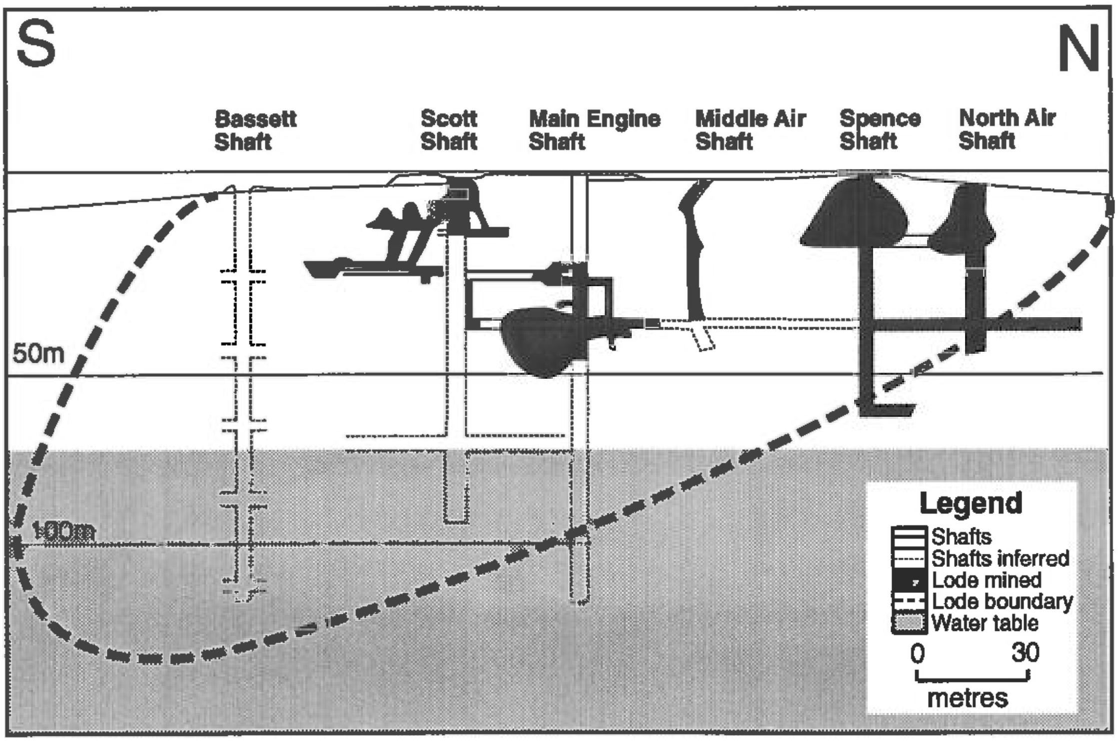


Figure 1.5 **Longitudinal-vertical projection of the Wheal Ellen shafts**

(adapted from Wade & Cochrane, 1954)

The visible effects of Wheal Ellen Mine; acid scouring, devegetation and erosion.

Several companies have since explored the area using geophysical procedures and drill holes, but the area has not been considered viable for further mining e.g. Wade & Cochrane (1954), Mining Review (1956) and Bridge Minerals (1971).

The remains of a number of stone buildings and chimneys are found at the site (see Figure 1.2). On the adjacent southern property, are the remains of the "Wheal Ellen Smelter", with a well preserved chimney and slag pile. It is assumed that the ore was smelted to maximise Pb and Ag recovery. Nearby lies a structure known locally as the "Arsenic Labyrinth" consisting of a stone flue leading up to the labyrinth through which hot gases from the smelter rose to allow As sublimation upon cooling. Approximately 50m away on the bank of Rodwell Creek lies the remnants of a sulphide waste dump with recently formed white efflorescence on the surface.

1.4 Mine Related Issues

AMD has created visible devastation of the area surrounding Wheal Ellen in the past (Mining Review, 1908b, Figure 1.4) and has continued on into the present (see Frontispiece). The most prominent effect is grass cover and native vegetation die-back on the hillslopes, with resultant erosion and water course siltation. General background information on the processes involved in AMD generation and heavy metal transportation can be found in Appendix A1.

Since closure of the mine and up until late 1995, when action was taken, the shafts posed a safety threat, being deep, uncovered and in many instances with unstable and collapsed edges.

Chapter 2
METHODS

To achieve a detailed knowledge of the nature and extent of contamination in the Wheal Ellen Mine area, various methods of sampling and analysis of both surface material and water samples from the area were utilised. This chapter outlines the procedures and purpose of the various techniques, with detailed descriptions of the sampling, preparatory and analytical techniques provided in Appendix A2.

2.1 Sampling

Various potential contaminating materials cover the surface of the mine area (Figure 2.1), which can be categorised as follows;

Sulphidic waste rock - Waste ore material, found both as whole rock fragments and as individual grains. This material has been clay covered in places, with the sulphides intermixed with the clay in many instances.
Waste country rock - Micaceous schist wall rock, often partially weathered and intermixed with secondary sulphates.
Gossan - Only accessible as two small piles, although a large dump (now clay covered) is reportedly to the S of the Bassett Shaft (Puccini, 1996), and significant amounts were infilled into shafts.
Slag - Dumped in two piles and as a small flow down an erosion gully.
Fe-rich waste rock - Mixed Fe-rich wastes, found dumped in various piles and used in the construction of the old mine road.
Secondary minerals - Secondary sulphates were found both as isolated examples of 'purer' secondary mineralisation and intermixed with other materials such as dumped country rock and soil.
Imported clays - 'Clean' clays brought to the site by MESA.
Soil - Gully soils.

Once these categories of mine materials were identified, sampling was undertaken so as to collect representatives of each form (Figure 2.1). To determine the extent of mechanical and hydromorphic dispersion of the mine waste, further sampling was conducted down the main erosion channels (Figure 2.1).

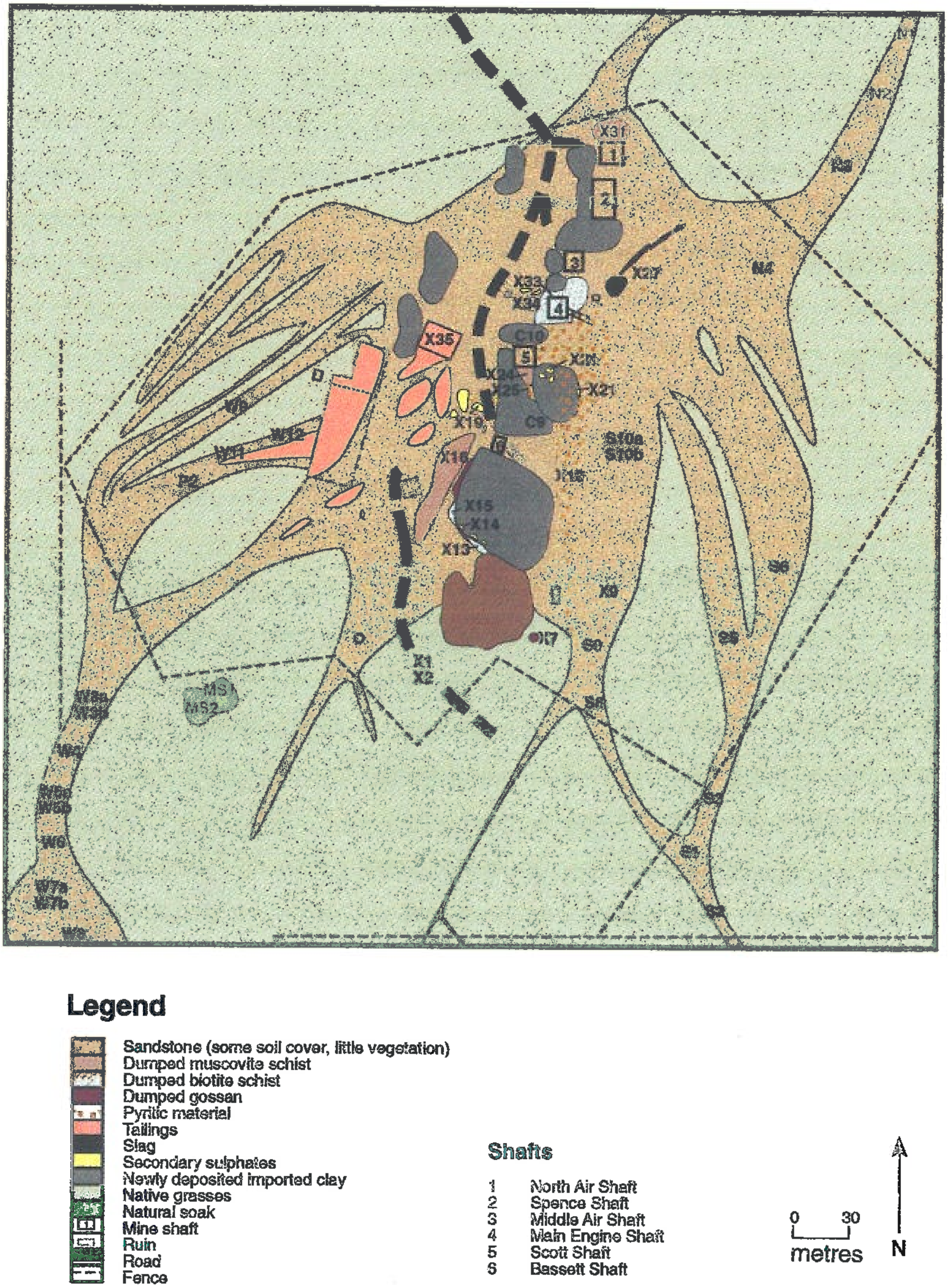


Figure 2.1 **Surface mine materials with sample sites to determine location and form of contaminants as well as the nature and extent of contamination of the surrounds**

Background values for the soils were determined through sampling away from the mine, including sites believed to be along strike of the ore-body (see Appendix A3 for details).

The small wetland and mound spring area adjacent to Rodwell Creek (Figure 1.2), was sampled by collection of surface materials ('MS' samples) together with two cores ('O' samples) (Figure 2.2). Sampling was conducted in an attempt to determine whether mine originatinated water feeds the springs, and if the wetland is acting as a natural filter, as may be indicated by elevated contaminant concentrations.

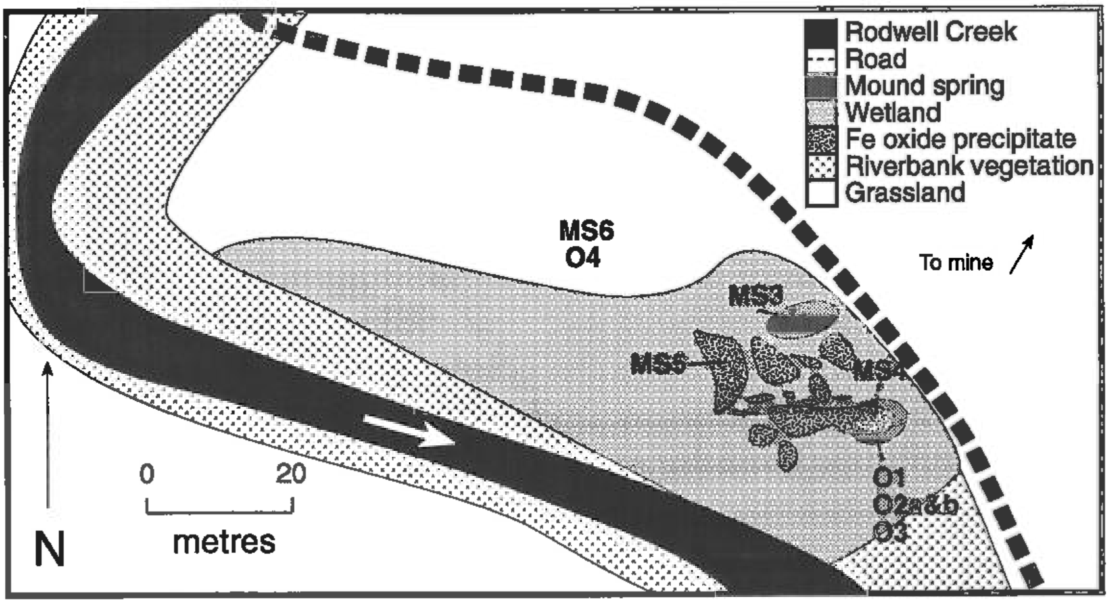


Figure 2.2 **Sampling sites at the wetland area, SW of the mine**

Water in Rodwell Creek was sampled at various locations from about 1km upstream to several kilometres downstream from the mine. Groundwater compositions were determined on water collected from bores and other water sources in the vicinity of the mine (see Appendix A3 for details).

A full list of sample sites and descriptions can be found in Appendix A3. Various constraints limited analysis to a representative sample suite (those marked on Figure 2.1) as opposed to all samples collected (Figure A3.1).

2.2 Analysis

Mineralogy

Preliminary examinations were made with a reflecting light microscope to gain a rough idea of the mineralogy, texture and degree of weathering of the samples. X-ray diffraction (XRD) was then used as a more accurate method of mineralogical determination. This method is non-quantitative, although proportions can be estimated by combining optical microscopy, the scanning electron microscope (SEM) fitted with an energy dispersive X-ray spectrometer (EDS), the electron microprobe (EMP) and X-ray fluorescence spectrometry (XRF) analysis, as outlined in the text where appropriate.

Geochemistry

Solid samples were analysed using XRF. This method provides accurate quantitative results of the level of the concentration of all major elements and any trace elements of interest (those with the potential to contaminate). An additional analysis was run to measure Cd, As and Sb which were suspected contaminants. XRF was selected over inductively coupled plasma atomic emission spectrometry (ICP-AES) or inductively coupled plasma mass spectrometry (ICP-MS), both of which require dissolution of the sample - a time consuming, hazardous and often ineffective technique.

Each sample analysed by XRF was also subjected to a standard "shake with water" test (see Appendix A2) to extract the water soluble constituents which are potential contaminants of surface and groundwater. The water solutions were tested for pH as an estimate of the potential water acidity, electrical conductivity (EC) as an indication of the solute content of the sample and ICP-AES, for elemental concentrations, to indicate the potential hydromorphic dispersion of elements, and hence their contamination potential. The same analytical techniques were used to determine the geochemistry of water samples.

The SEM-EDS were utilised to locate the presence of heavy metals within different minerals in selected samples. Once identified, heavy metal concentrations were quantified on the EMP.

Sulphur isotope ratios were also determined for some sulphides and sulphates at the mine and in water samples from Rodwell Creek, the mound spring and a bore. A comparison of the results ought to indicate whether the mine contributes to the sulphate content of local waters.

Chapter 3
CHARACTERISATION of POTENTIAL CONTAMINANTS

Assessment of the environmental threat posed by a contaminated site is difficult (Langley, 1996). 'Contamination' is subjective and often poorly defined. In the context of this study, an element or substance is classed as a contaminant when found in the environment at levels detrimental to living organisms. This chapter examines the waste materials created by mining and mineral processing, identifying those deemed to have potential to generate contamination through (1) acid generation (AMD), and/or (2) potentially toxic heavy metals. It is important to note that this potential is dependant on the surrounding environment and the nature of the potential contaminant, thus even if potential contaminants are present, if they are not being released in a form available to organisms, environmental impact is minimal (Påhlsson, 1989).

3.1 Potential Acid Producers

Any sulphide-containing material constitutes a potential acid producer. Potential will be realised if the sulphide is exposed to water and oxygen (Equation 1). Pyrite is the most prominent and well understood acid producing sulphide. Acid production occurs in several steps (outlined in Appendix A1), as summarised by;

$$\mathbf{2FeS_{2(s)} + 15/2O_{2(aq)} + 7H_2O_{(l)} \rightarrow 2Fe(OH)_{3(s)} + 4SO_4{}^{2-}{}_{(aq)} + 4H^+{}_{(aq)}} \qquad (1)$$

The secondary mineral jarosite (formed from dissolution products of pyrite and aluminosilicates) releases acid both on precipitation (Equation 2) and through hydrolysis on dissolution (Equation 3), (see Appendix A1 for details);

$$\mathbf{3Fe^{3+}{}_{(aq)} + K^+{}_{(aq)} + SO_4{}^{2-}{}_{(aq)} + 6H_2O_{(l)} \rightarrow KFe(III)_3(SO_4)_2(OH)_{6(s)} + 6H^+{}_{(aq)}} \qquad (2)$$

$$\mathbf{KFe_3(SO_4)_2(OH)_{6(s)} + 3H_2O_{(l)} \rightarrow 3H^+{}_{(aq)} + 2SO_4{}^{2-}{}_{(aq)} + 3Fe(OH)_{3(s)} + K^+{}_{(aq)}} \qquad (3)$$

Identification of Potential Acid Producers

Through XRD, the forms of waste material containing sulphides could be identified; sulphidic waste rock, tailings, slag and some secondary minerals. In addition, optical microscopy and/or SEM revealed the presence of sulphides (mostly as isolated pyrite grains) in most samples, but at levels lower than that detectable by XRD (about 0.5% (Phillips, 1989)). Results are tabulated in Appendix A6, Table A6.1.

Jarosite, through XRD analysis, was identified in partially weathered micaceous schists, some partially weathered sulphidic waste rocks, gossan, tailings, Fe-rich waste rocks as well as isolated lumps or in conjunction with other secondary mineralisation (Table A6.1).

Characterisation of Potential Acid Producers

Characteristics controlling potential acid production level include the type, concentration and grain size of the acid producer. Those samples with levels of sulphides and/or jarosite present at concentrations less than that detectable by XRD will be considered negligible in relation to acid production and will not be further discussed.

Pyritic Waste Rock

Sample **X42**, *exposed fragment of highly sulphidic rock*, contains approximately 80% pyrite, 10% sphalerite (present intermixed with other sulphides and as occasional lustrous black veins), 6% galena and occasional chalcopyrite (<1%) (Plate 3.1a) as determined by SEM combined with XRF data (Appendix A3). With around 97% sulphide concentration and pyrite predominating, acid producing potential is very high. This sample, being whole rock, has a small surface area compared to its volume, minimising contact with air and water. Although the material has a high acid-producing potential, the rate will be relatively slow (Pugh *et al.*, 1982). The sulphides are already physically degrading (Plate 3.1b) and the presence of secondary Fe sulphate (Plate 3.1c) and anglesite (XRD analysis) within the sample confirm oxidation is currently occurring. No jarosite was identified.

Sample **X25**, *sulphide grains beneath a thin imported clay layer,* contains partially weathered single sulphide grains (approximately 1mm grain size), comprising approximately 60% of the total volume. Pyrite forms the bulk with minor sphalerite and galena (0.05% Zn and 0.2%Pb). The sulphide surface area compared with that of the whole rock is great, increasing contact with air/water and hence acid production rate. Some jarosite was detected by XRD, further contributing to acid production. Water extracted pH is 2.71 - the lowest of any material measured from the mine, suggesting the material is currently producing significant acid.

Sample **X10**, *erosion gully sediments*, contained visible pyrite cubes (approximately 1mm grain size), eroded from waste piles and water transported downslope. Through optical microscopy, the sulphide content (predominantly pyrite) is estimated at 10-15% of the total volume. Although the sulphide content is considerably lower than that of 'whole rock' samples (such as X42), the potential acid production is significant as the pyrite, being individual grains, has an extensive surface area. Jarosite is detectable by XRD, which when combined with optical microscopy and XRF data allows an estimation of 10% - significant in terms of acid production. The water-extractable pH is 3.32; slightly higher than the mineralogically and texturally similar Sample X25, as sulphide concentration is significantly reduced. The position (in an erosion gully) allows for ready transportation of any acid produced.

Tailings

Sample **X35** and Profile **P1**, *tailings trapped by ruins walls,* consist of homogeneous pink fine-grained material. with sulphide concentrations up to 2%, predominantly pyrite. The fine-grained nature of the pyrite (<50μm, Plate 3.1d) renders it extremely reactive. XRD identified pyrite and jarosite in all tailings samples. SEM examination of Sample X35 failed to detect jarosite, suggesting low concentrations. Although 'Profile' samples (P1a-P1e) were not examined by SEM, similar XRF and XRD results (Appendix A3), indicate mineralogy and geochemistry is consistent with X35. Water-extracted pHs range from 3.5 to 4.3, indicating that despite the low total S content, tailings are contributing acidic material to the environment.

Slag

The pyrite content (up to 2% - XRF) of Sample **X27**, *slag flow,* would undoubtedly exist as clasts incorporated into the glass structure during smelting, with minimal acid producing potential. A water extracted pH of 4.9 confirms this, being the highest value for mine wastes.

Secondary Minerals

Sample **X19**, *secondary mineralisation at the base of shaft 'mounds',* contains sulphidic material (up to about 3% total) dispersed through the sample (Plates 3.2e & f) presumably transported hydraulically from dumps upslope. Sulphide weathering is occuring in situ, as exemplified by an anglesite rimmed galena grain (Plate 3.2g). Jarosite, is also present (Plate 3.3b). The low water-extracted pH of 2.9 indicates these materials are currently capable of producing acid.

Sample **X22**, *newly deposited sulphates atop imported clay layer covering sulphidic waste,* contains a small but significant pyrite content, believed to have been mixed in to the clay from the underlying sulphidic waste dump, during the clay's deposition. A small amount of jarosite has precipitated. Similarly to Sample X19, water-extracted pH is low (2.71), indicating acid producing potential is significant.

Sample **X21**, *newly deposited white efflourescence atop imported clay layer covering sulphidic waste.* The XRD detectable pyrite and jarosite are incorporated into the clay rather than the secondary sulphate (as evidenced by SEM analysis).

Sample **X24**, *clay/country rock/sulphate mix,* contains both pyrite and jarosite (water-extracted pH of 3.08). Similarly, Sample **X33**, *country rock/sulphate mix,* contains jarosite, and water-extracted pH is 2.93.

Samples **X38**, **X44** and **X46**, *jarosite lumps within minesite soil,* contain negligible sulphides, thus the water-extracted pH's of approximately 3 are primarily a result of jarosite dissolution.

3.2 Potential Heavy Metal Contaminants

Mine wastes containing significant levels of potentially harmful elements (Pb, Zn, Cd, As, Cu, Sb, Co, Cr, and Ni (ANZECC, 1992)), as determined by XRF, have potential to contribute heavy metal contamination. Where determinable (by combining XRD, SEM and/or EMP) the form of each of these heavy metals and their relative solubilities in water (water extractable ICP-AES results) will be discussed to ascertain the probability of mobilisation and therefore contamination of the surrounds.

Identification of Potential Heavy Metal Contaminants

The thresholds for such a definition are not clearly defined and vary with site specific factors. The ANZECC/NHMRC (1992) sets out ‘investigation levels’ for soil heavy metal concentrations with respect to environmental health. These values will be used as a basic guideline.

Table 3.1 outlines those elements deemed toxic in excess, with typical background levels, ANZECC/NHMRC (1992) investigation levels. Those elements found at concentrations significantly greater than these levels have been classified as potential contaminants at Wheal Ellen; namely Pb, Zn, Cu, Cd and Sb. Raw XRF data is tabulated in Appendix A4, Table A4.2.

The concentrations of these potential contaminants are represented diagrammatically in Figure 3.1. Comparisons with the 'clean clays' helps to illustrate the enhancement of the heavy metals in the mine materials, particularly in the case of Pb, Cu and Zn.

Figure 3.1

Geochemical maps displaying heavy metal concentrations within various mine wastes.

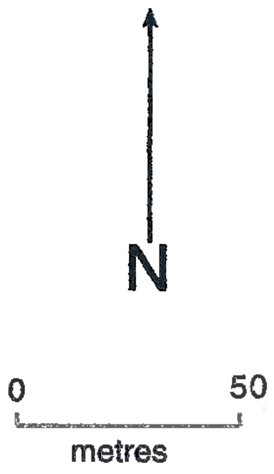
Legend

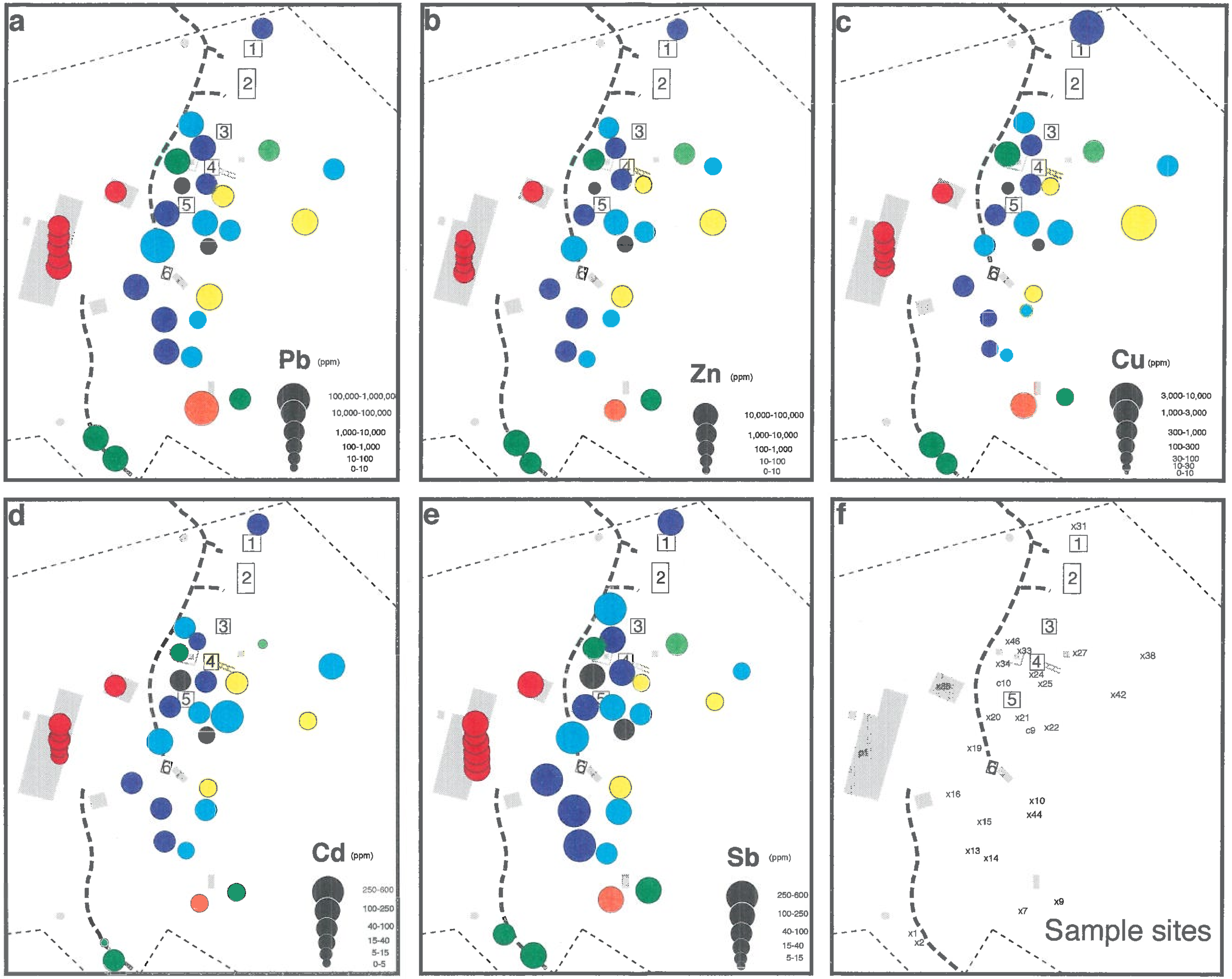
🟡 Sulphidic waste
🔴 Tailings
🟠 Gossan
🟢 Slag
● Fe-rich waste rock
🔵 Secondary minerals
🔵 Dumped micaceous schist
⚫ 'Clean' imported clays

☐ Mine shaft
▨ Ruin
■ ■ Road
- - - - Fence

Shafts

1	North Air Shaft
2	Spence Shaft
3	Middle Air Shaft
4	Main Engine Shaft
5	Scott Shaft
6	Bassett Shaft




a
1
2
3
4
5
6
Pb (ppm)
100,000-1,000,00
10,000-100,000
1,000-10,000
100-1,000
10-100
0-10
b
1
2
3
4
5
6
Zn (ppm)
10,000-100,000
1,000-10,000
100-1,000
10-100
0-10
c
1
2
3
4
5
6
Cu (ppm)
3,000-10,000
1,000-3,000
300-1,000
100-300
30-100
10-30
0-10
d
1
2
3
4
5
6
Cd (ppm)
250-600
100-250
40-100
15-40
5-15
0-5
e
1
2
3
4
5
6
Sb (ppm)
250-600
100-250
40-100
15-40
5-15
f
x31
1
2
3
x46
x33
x27
x38
x34
4
x24
x35
c10
x25
x42
5
x20
x21
c9
x22
x19
6
x16
x10
x44
x15
x13
x14
x9
x7
x1
x2
Sample sites

Heavy Metal	Average Bk. gmd.*	Inves. Levels*	Mine materials exceeding investigation levels	Potential Cont. ?	Figure No.
As	0.2-30 ppm	50 ppm	Data on As concentrations in mine materials minimal but classed as a potential contaminant	√	N/A
Ba	20-200 ppm	N/A	Elevated in secondary minerals	?	-
Cd	0.04-2 ppm	5 ppm	High in all mine samples (up to a thousand ppm)	√	3.1d
Co	2-170 ppm	N/A	Only high in sulphidic waste rock and some secondary minerals	?	-
Cr	0.5-110 ppm	160 ppm	Low in all mine materials	-	-
Cu	1-190 ppm	250 ppm	High in all mine samples (up to several thousand ppm) excepting weathered schist & weathered sulphidic waste	√	3.1c
Ni	2-400 ppm	450 ppm	Low in all mine materials	-	-
Pb	2-200 ppm	500 ppm	Very high in all mine materials (min. 3,000ppm) Up to 14% in secondary minerals	√	3.1a
Sb	4-44 ppm	60 ppm	High in all mine materials excepting some sulphidic wastes and secondary minerals	√	3.1e
Zn	2-180 ppm	350 ppm	High in all mine materials Up to almost 4%	√	3.1b

* Figures outlined in ANZECC/NHRMC (1992)

Table 3.1 **Evaluation of potential contaminants at Wheal Ellen**

Characterisation of Contaminants

Many factors determine whether elements will have a detrimental effect on living organisms. Of prime importance in mine wastes is the mineralogy, texture and solubility of primary and secondary minerals. The purpose of these investigations was to characterise all potential contaminants.

Mineralogy and percentage composition were determined by XRD, XRF, EMP and SEM. The potential for solute release was determined by "shake with water" tests and geochemical analysis of the resultant solution (Appendix A2.2). Although this test is standard, the results are arbitrary and no guidelines exist to what is 'safe'. A useful indicator of the amount being released by contaminated samples is to compare them with the relatively 'clean' clays brought in by MESA. Significant results are outlined where appropriate. All raw data is in Appendix A4.

It is assumed that there is some degree of adsorption of heavy metals onto surfaces of phyllosilicates etc as well as oxides of Fe and Al and which are not detectable by SEM or EMP. However, compared to some of the heavy metal concentrations found at the mine, these levels would be minimal.

All plate references correlate to a set of EMP data (Appendix A5; numbering corresponds to that of the plates i.e. Plates 3.1, 3.2 and 3.3).

Sulphidic Waste Rock

Sulphide mineral ratio of pyrite:sphalerite:galena:chalcopyrite varies from 8:1:0.5:0.1 (X42) to virtually pure pyrite (X25 and X10). Depending on the sample, the sulphide is mixed with varying amounts of other minerals - primary rock forming minerals (quartz, mica, feldspar) and secondary minerals (primarily jarosite and/or anglesite).

SEM analysis was conducted on sample **X42**, *exposed fragment of highly sulphidic rock*, to locate the 2.1% Pb and 3.8% Zn (Plate 3.1a). Percentage compositions are estimated at;

Pyrite	80%
Sphalerite	10
Galena	6
Chalcopyrite	<1
Quartz	2
Oxides (inc. gahnite)	2

The only detectable Pb content was in the form of galena. Zinc occurs with Fe in sphalerite and incorporated into the oxide (gahnite). These heavy metal forms are relatively insoluble (compared to say secondary minerals), and the 'whole rock' nature of the sample minimises surface area, minimising the environmental impact from such samples.

Apart from the sulphide and soil content in sample **X10**, *erosion gully sediments*, there is a small level (up to about 5%) of various secondary minerals (primarily jarosite and anglesite ($PbSO_4$)). The major potential contaminant is the 1.4% Pb component, which may be found as galena or anglesite. Judging from the low galena component of the sulphides in general and the weathered state of the material, XRD shows that the bulk of this lead would probably be anglesite. The level is almost 30 times the recommended health standards although anglesite (and galena) are fairly insoluble. Extracted solute concentrations for Pb is 5.2mg/L , Zn is 7.2mg/L. The forms of the Pb at least are fairly insoluble in neutral conditions, so the high solubilities are a result of the acidity of the extracted water (pH=3.3).

X25, *buried beneath a thin imported clay layer*, in contrast to the other sulphides analysed (and most mine samples) contained low heavy metal contents. This sample was examined under SEM, but the form of the 0.3% Pb (the highest heavy metal concentration) could not be located. This suggests the form of Pb is galena or anglesite (the same as X10). Lead levels dissolved into water are less than X10, undoubtedly due to the lesser concentration in the sample, however Zn is substantial at 22.1mg/L.

All sulphide samples had high Co levels (unlike any other sample except the secondary minerals derived from sample X25), although concentrations were too low for the mineral form to be identified.

Wade & Cochrane (1954), analysed several sulphide samples, both from underground and surface dumps. Results vary wildly, and while there is no apparent major difference in heavy metals contents in the underground and surface sulphides, there does seem to be a decline between current (my samples) and past (Wade & Cochrane, 1954) surface samples - perhaps resulting from leaching? (See Appendix A4, Table A4.9).

Tailings

Estimated percentage compositions;

Quartz	60%
Muscovite	15%
Jarosite	10% (could not be located by SEM/EMP)
Hematite	8%
Feldspar (albite, anorthite)	5%
Pyrite	2%
Rutile	<1%

An average of the five profile samples contains elemental levels comparable to that of sample **X35** and are discussed as one. XRD results indicate a mineralogical composition very similar to that of topsoil (quartz, muscovite, albite) with the added presence of jarosite (5%) and minor pyrite levels. Sample **X35** was examined on the SEM. The 1%Pb occurs as galena. Although there is only 0.1%Zn content in the whole sample, there was a small presence in the iron oxides - most likely coprecipitated. Some ICP levels border on being too high. As is common with the mine samples, Pb is high, with 1.7mg/L and Zn is 7.0mg/L.

Wade & Cochrane, (1954) assayed a tailings sample (Table A4.9), with a resultant 9.9%Pb, 1.1%Zn and 0.8%Cu. Clearly levels are significantly higher than the 1%, 0.1% and 0.05% respectively found today. Again this may be indicative of removal rate - i.e. the material is getting into the environment, however this conclusion is based on the assumption that tailings are spatially and temporally uniform which realistically may not be the case.

Gossan

Estimated percentage compositions;

Hematite	70%
Anglesite	15%
Muscovite	2%
Quartz	5%

Jarosite	5%
Ferrihydrite	2%
Other oxides (Al)	2%

The only accessible gossan sample came from 2 small (1m scale) dump piles. The 10.4%Pb content occurs in the significant anglesite component. Examination showed that not all the anglesite was pure, with significant coprecipitation (Plate 3.1h). Apart from this, some of the 0.6%Zn content was located as gahnite (Plate 3.1h). ICP-AES data shows the level of dissolved Pb as 4.46mg/L and Zn as 123.1mg/L (a massive 2,500X that dissolved from 'clean' material).

Wade & Cochrane (1954), conducted assays on several gossan samples (both surface and underground in the shafts). The heavy metal contents varied widely as for the sulphides rendering comparisons with results from this study difficult (Table A4.9).

Slag

Estimated percentage composition;

Quartz	Major
Muscovite	Trace
Albite	Trace
Hematite	Trace
Pyrite	Trace

Slag is predominantly composed of glass. The inclusion of separate minerals may be as individual clasts within this glass.

The heavy metal content in sample **X27**, *slag flow,* (0.5%Pb, 0.2%Zn and 0.1%Cu) is no doubt incorporated into the structure during the smelting process. Apart from the fact that most of the metals would be locked into the structure, as displayed by the relatively low levels in water extraction, the amount of slag at the site is minimal, and any effect is not a serious potential hazard.

Wade & Cochrane (1954) conducted assays on a slag sample from the "dump" (Table A4.9). Their results of 0.6%Cu and 0.8%Pb are marginally higher than that for this study and 1.8% Zn is significantly greater. This is undoubtedly partly attributed to natural sampling variation, whilst the ICP-AES data shows that some of the Zn and Cu can be dissolved. Over the 40 years since Wade & Cochrane conducted their study, this difference in heavy metal content could be explainable by leaching into the surrounds. Even though slag is generally inert to ordinary weathering, over an extended period heavy metals may be removed.

Fe-Rich Waste Rocks

This Fe-rich dumped material, featured primarily in the old mine road, contained a range of different clasts, compositionally including;

Quartz
Goethite/Hematite
Muscovite
Albite/Anorthite
Clinochlore
Jarosite
Anglesite
Tremolite
Sulphide (inc. galena)
(Percentages massively variable)

Sample **X1**, *old mine road gravel,* on examination by SEM was found to contain goethite (Plate 3.2a), a quartz rich sulphate mass (Plates 3.2a&b) and a gossan (similar to Plate 3.1f), among other materials, making it difficult to assign the heavy metal contents.

Hand specimen, optical microscopy and XRD suggest a similar makeup for the other waste rock samples (**X2**, *fine grained old mine road material;* **X9**, *coarse grained dumped material;* and **X34**, *coarse grained, muscovite rich, dumped material*), although specific mineral concentrations vary.

Dumped Country Rock

BIOTITE SCHIST

Quartz	45%
Mica (bt & mu)	25%
Albite	15%
Kaolinite	10%
Jarosite	5%

Sample **X13**, *dumped, partially weathered wall rock,* under SEM showed jarosite with and without Pb (Plate 3.3h). The heavy metal content (1%Pb), while significant is predominantly secondary deposits - i.e. the original wall rock contained minimal heavy metal levels compared with that coprecipitated in jarosite. As outlined below, the secondary minerals have contamination potential as shown by the water soluble contents of Pb and Zn released (5.8 and 18.5 mg/L respectively). The fine particulate nature of the secondary minerals is a possible contributor to this enhanced solubility.

MUSCOVITE SCHIST

Quartz	50%
Muscovite	25%
Kaolinite	10%
Jarosite	5%
Hematite	5%
Anglesite	5%

Sample **X16**, *dumped, partially weathered wall rock,* has its 2% Pb bound as anglesite (Plate 3.3f). Similarly to above, the muscovite schist appears to have minimal contamination potential in itself, but may contribute to contamination via the heavy metals bound in its secondary minerals precipitated through acid degraded aluminosilicates. Similar to above, the ICP levels compared with other contributors with greater total concentrations are not insignificant (165X greater than 'clean' clays) and almost (200X) for Pb and Zn respectively.

Ideally, a sample of fresh micaceous schist should be analysed to determine the natural background concentrations but the recently imported clay has covered all fresh rock.

Secondary Material

JAROSITE

Sample **X46**, *jarosite lump within minesite soil,* consisting of predominantly jarosite (50%) with quartz and muscovite, (Plate 3.3e) was examined under SEM, but no mineral was found which would account for the 2% Pb. ICP-AES data shows a very low level of Pb (0.1mg/L) being dissolved whereas the Zn is high. This suggests the Pb occurred as an insoluble mineral which was not detected during the SEM scan.

Samples **X38** and **X44** also contained a high jarosite content. Both samples were briefly examined by SEM, but no heavy metal containing secondary minerals were detected. The ICP-AES data for sample X44 is quite high at 7.9mg/L of Pb, compared with lower than detection limits for sample X38 whereas Zn levels were comparable.

ANGLESITE

Sample **X19**, *secondary mineralisation at the base of shaft 'mounds',* under the SEM had sphalerite and galena (Plates 3.2e&f). There is a significant sulphate content occurring as anglesite (Plate 3.3g) and Fe sulphate with Pb substitutions (Plate 3.3h). It seems fairly certain that sample X19 is being created from sample sulphidic waste rock (e.g. sample X25), as indicated by similarities in low Sb and low Ba levels.

IRON SULPHATE

Sample **X22** *newly deposited sulphates atop imported clay layer covering sulphidic waste,* was also investigated under the SEM, with heavy metals existing in several forms. This is one of the samples with a very high EC on water extracted material. Although Pb values (1.49mg/L) are not high, the Zn - 3020mg/L, is extremely high. Most other element contents were also high and in most cases, the highest of all samples analysed - 28.4mg/LCd, 83.5mg/LCo and 631.1mg/LCu. These values are extremely high considering most values for these elements are below detection limits, or at least very low. This material is by far the most soluble of any characterised. The 2%Zn was found in many instances coprecipitated with Fe sulphate (Plate 3.3c) and halotrichite ($FeAl(SO_4)_4.22H_20$), (Plate 3.3d). No heavy metals were found in the Fe oxide or jarosite.

GYPSUM

Sample **X21**, *newly deposited white efflorescence atop imported clay layer covering sulphidic waste.* was examined with SEM, however the approximately 1% each of Pb and Zn was not located. This could be due to the fragile nature of the newly formed crystals most of which were visibly damaged in the block mounting process.

There is a correlation of low Ba and Co in the sulphidic sample X25 and the secondary minerals above (mainly X22 and to a lesser extent X21). The fact that these secondary minerals formed within months of spreading the imported clay and are so concentrated in heavy metals and are so soluble is an alarming indication that; (1) the current clay layer is not sufficiently thick or impermeable, (2) the sulphidic material is contributing significant amounts to the surrounds and (3) at times these secondary minerals are extremely soluble - releasing their heavy metal contents.

Plate 3.1

Photomicrographs taken on the scanning electron microscope (SEM) in back scattered electron mode (BSE).

a

Partially weathered whole rock sulphidic waste (Sample X42);
Mass of partially weathered sulphidic rock displaying variations in sulphide type; pyrite (p), sphalerite(s) and galena (g), with no visible chalcopyrite, and grain size (mm-µm). Note the virtual absence of any rock forming minerals which contribute only approximately 2% to the total rock composition.

b

Partially weathered whole rock sulphidic waste (Sample X42);
Physical break up of a sphalerite grain surface (s). Newly created smaller particles have an increased surface area when compared with the initial sulphide, allowing an enhanced rate of chemical reactivity.

c

Partially weathered whole rock sulphidic waste (Sample X42);
A minimal amount (<1%) of secondary mineralisation has developed in situ within the partially weathered sulphidic rock. In this case, Fe-sulphate, with coprecipitated As, Zn, Pb and Cu (r) has deposited around quartz (q). Pyrite (p) is also present.

d

Fine-grained, pink tailings (Sample X35);
Siliceous tailings mass (dark grey). Commonly heavy metal content is negligible, although areas with up to 0.5%Pb were found. Heavy minerals, including various sulphides (s) and hematite with varying heavy metal contents (h) are visible. Average sulphide grain size is <50µm.

e

Gossan (Sample X7);
Anglesite (a) coating hematite (h) boxwork structure. The hematite had significant concentrations of Pb, Zn, As and Cu. The anglesite had no coprecipitated elements.

f

Gossan (Sample X7);
Hematitic boxwork structure (grey) with minimal anglesite (bright white). Such boxworks, with varying hematite/anglesite ratios, constitute approximately 80% of the gossan sampled.

g

Gossan (Sample X7);
Hematite/anglesite boxwork with compositional variations in the hematite as indicated by colour change. Anglesite (a) is again bright white with hematite (h) showing gradations from light to dark grey correlating with decreasing Pb content.

h

Gossan (Sample X7);
Hematite (h) deposited around gahnite (g) grain. Elevated Zn levels were detected in the anglesite (a) bordering the gahnite.

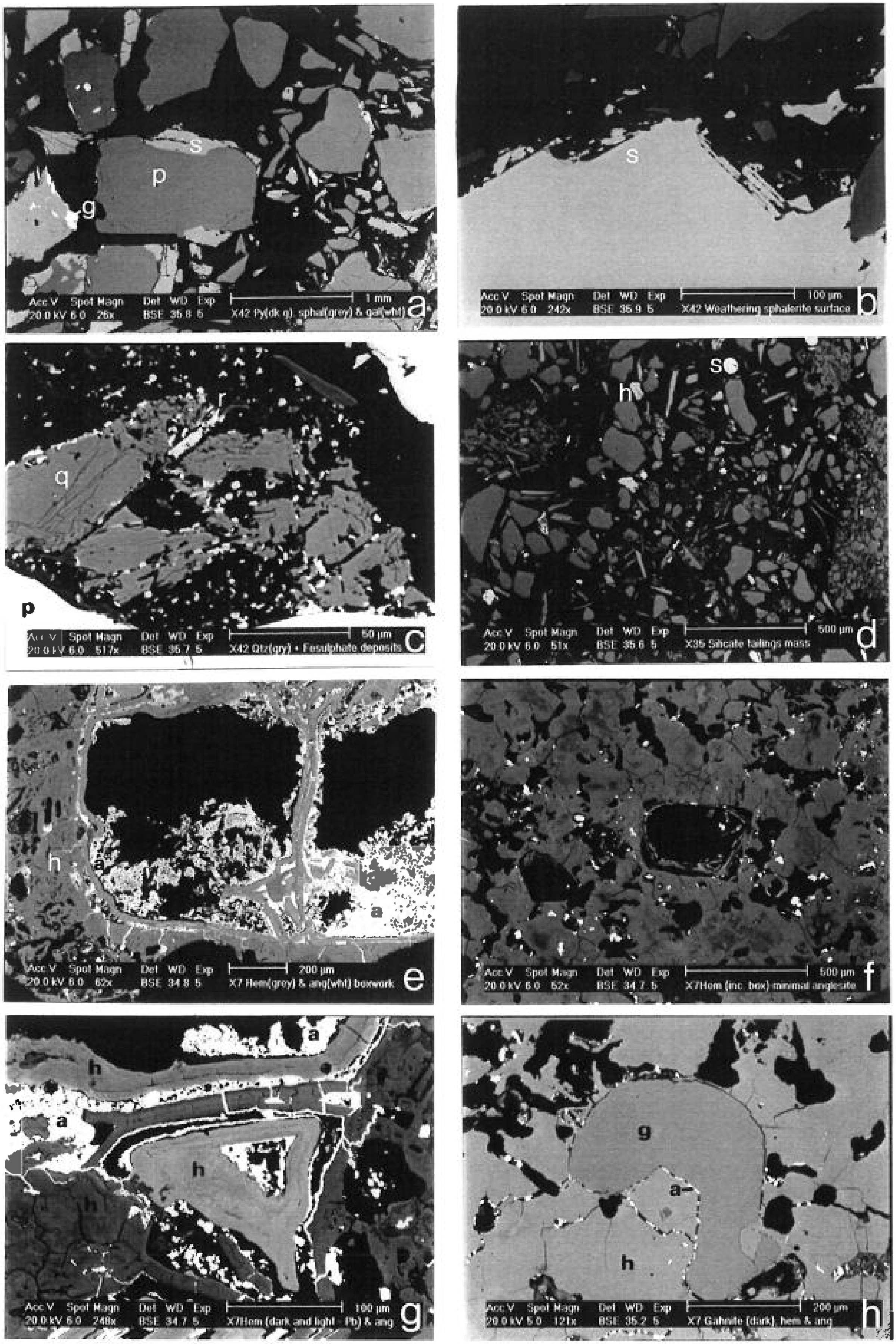

s
p
g
Acc V Spot Magn Det WD Exp
20.0 kV 6.0 26x BSE 35.8 5
1 mm
X42 Py(dk g), sphal(grey) & gal(wht)
a
s
Acc V Spot Magn Det WD Exp
20.0 kV 6.0 242x BSE 35.9 5
100 µm
X42 Weathering sphalerite surface
b
r
q
p
Acc V Spot Magn Det WD Exp
20.0 kV 6.0 517x BSE 35.7 5
50 µm
X42 Qtz(gry) + Fesulphate deposits
c
s
h
Acc V Spot Magn Det WD Exp
20.0 kV 6.0 51x BSE 35.6 5
500 µm
X35 Silicate tailings mass
d
h
a
Acc V Spot Magn Det WD Exp
20.0 kV 6.0 62x BSE 34.8 5
200 µm
X7 Hem(grey) & ang(wht) boxwork
e
Acc V Spot Magn Det WD Exp
20.0 kV 6.0 62x BSE 34.7 5
500 µm
X7Hem (inc. box)-minimal anglesite
f
a
h
a
h
h
Acc V Spot Magn Det WD Exp
20.0 kV 6.0 248x BSE 34.7 5
100 µm
X7Hem (dark and light - Pb) & ang
g
g
a
h
Acc V Spot Magn Det WD Exp
20.0 kV 5.0 121x BSE 35.2 5
200 µm
X7 Gahnite (dark), hem & ang
h

Plate 3.2

Photomicrographs taken on the scanning electron microscope (SEM) in back scattered electron mode (BSE).

a

Fe-rich waste rock (Sample X1);
Main mineral (g) is goethite with over 2% Zn content. Negligible differences in heavy metal concentrations exist between the main body of the goethite and the darker bands. Also seen are various sulphide grains (s) and gahnite (G).

b

Fe-rich waste rock (Sample X1);
Quartz (q), hematite (h) and anglesite (a) surrounding large gahnite grain (g) with no heavy metal content itself but with Pb & Zn rich surface deposits (x; minute white specks). The quartz (q) has a 0.1% Zn content; most probably adsorbed onto the surface, and the hematite (h) contains up to 3% Zn.

c

Fe-rich waste rock (Sample X1);
Jarosite, with varying levels of Pb coprecipitation as represented by colour differences (minor levels in dark grey material through to 10% Pb in white areas).

d

Fe-rich waste rock (Sample X1);
Fine grained galena (bright white specks) within siliceous matrix (dark grey) containing significant Pb (5.7%), Zn (3.0%) and minor Cu (0.8%) concentrations.

e

Secondary sulphate - predominantly anglesite (Sample X19);
Sulphide component of sample, existing in this case as a large mass, with pyrite (p), sphalerite (s) and galena (g). Light grey area is a small example of secondary mineralisation within the sulphide (anglesite - a) - indicative of the entrance of oxidants (air and water) into the material.

f

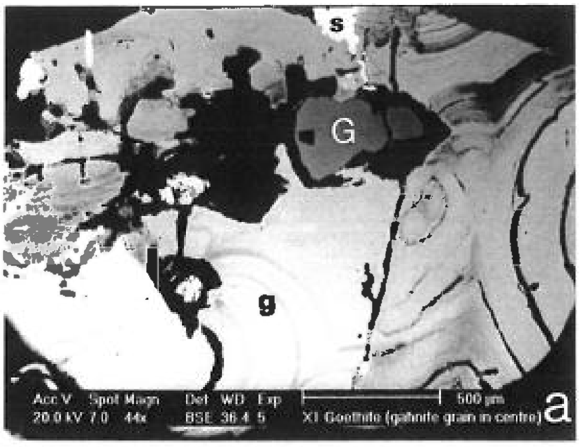
Secondary sulphate - predominantly anglesite (Sample X19);
Break up (to <100μm grain size) of essentially solid sulphide mass (s) , and dispersion into surrounding material (silicates and secondary sulphates).

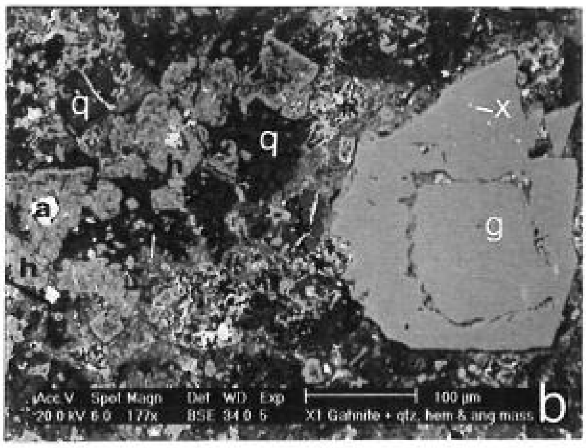
g

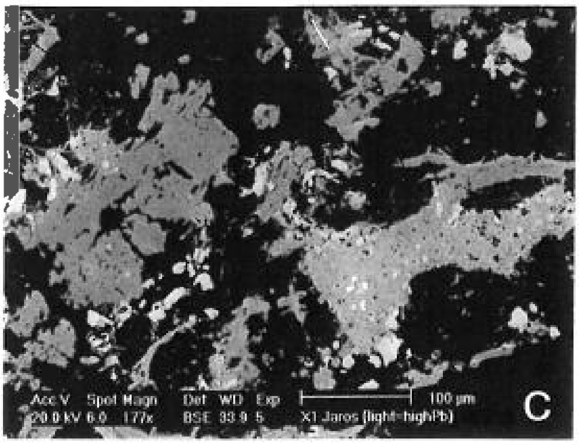
Secondary sulphate - predominantly anglesite (Sample X19);
Galena (g) with an anglesite weathering rim (a) indicating in situ sulphide ocidation and secondary mineral precipitation.

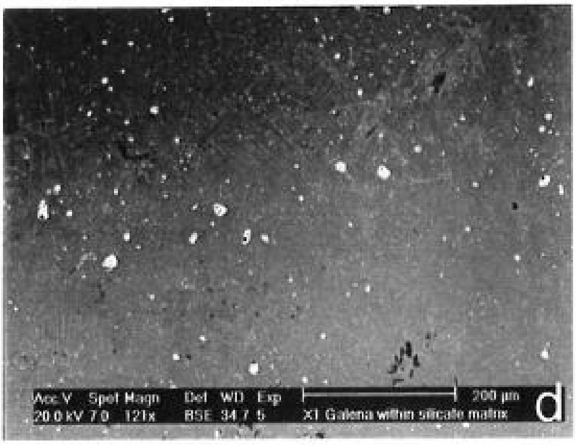
h

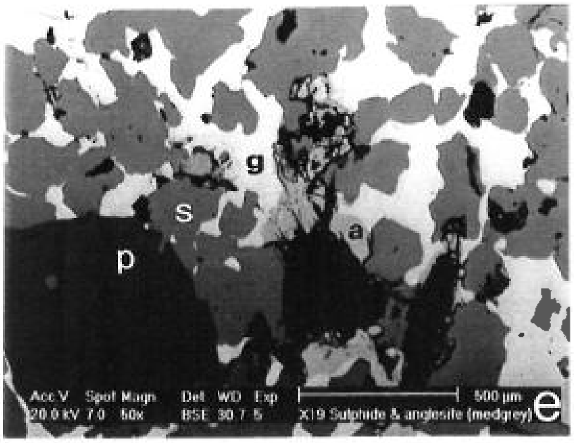
Secondary sulphate - predominantly anglesite (Sample X19);
Fe-sulphate (r) with major Pb coprecipitation (17.4%) deposited around quartz grains (q).

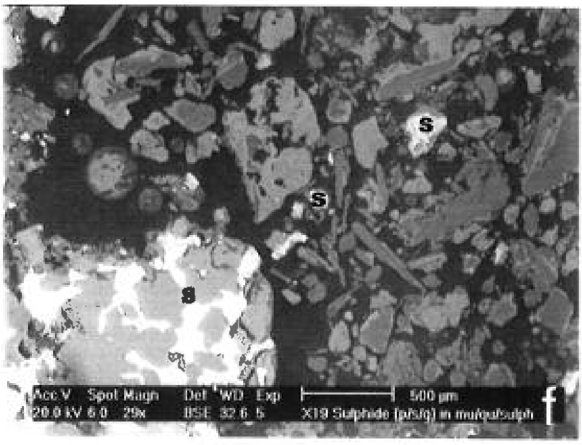

s
G
g
Acc.V Spot Magn Det WD Exp
20.0 kV 7.0 44x BSE 36.4 5
500 µm
X1 Goethite (gahnite grain in centre)
a

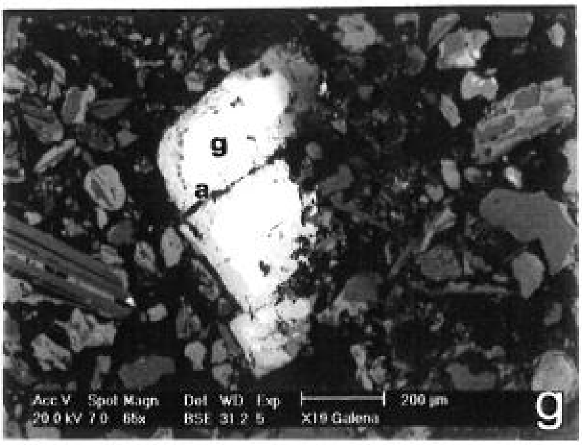

q
q
x
a
h
g
Acc.V Spot Magn Det WD Exp
20.0 kV 6.0 177x BSE 34.0 6
100 µm
X1 Gahnite + qtz, hem & ang mass
b


Acc.V Spot Magn Det WD Exp
20.0 kV 6.0 177x BSE 33.9 5
100 µm
X1 Jaros (light=highPb)
c


Acc.V Spot Magn Det WD Exp
20.0 kV 7.0 121x BSE 34.7 5
200 µm
X1 Galena within silicate matrix
d


g
s
a
p
Acc.V Spot Magn Det WD Exp
20.0 kV 7.0 50x BSE 30.7 5
500 µm
X19 Sulphide & anglesite (medgrey)
e


s
s
s
Acc.V Spot Magn Det WD Exp
20.0 kV 6.0 29x BSE 32.6 5
500 µm
X19 Sulphide (p/s/g) in mu/qu/sulph
f


g
a
Acc.V Spot Magn Det WD Exp
20.0 kV 7.0 66x BSE 31.2 5
200 µm
X19 Galena
g

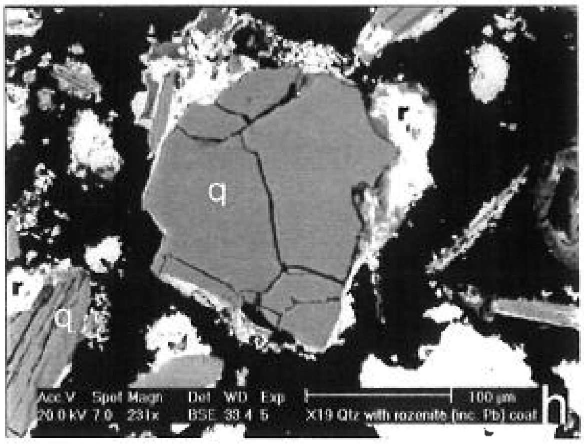

r
q
r
q
Acc.V Spot Magn Det WD Exp
20.0 kV 7.0 231x BSE 33.4 5
100 µm
X19 Qtz with rozenite (inc. Pb) coat
h

Plate 3.3

Photomicrographs taken on the scanning electron microscope (SEM) in back scattered electron mode (BSE).

a

Secondary sulphate - predominantly anglesite (Sample X19);
Degraded muscovite flakes (m) and galena grains (g) embedded in coprecipitated Fe/Pb-sulphate (r).

b

Secondary sulphate - predominantly anglesite (Sample X19);
Quartz (q) with Pb (7.5%) & Zn (1.9%) coprecipitated jarosite (j), and Zn (5.8%) and Cu (1.2%) coprecipitated Fe-sulphate (r).

c

Secondary sulphate - predominantly Fe sulphate (Sample X22);
Muscovite (m) with Pb (1.8%) coprecipitated jarosite edgings (j) embedded in an Fe-sulphate with Zn (2.9%) coprecipitation (r).

d

Secondary sulphate - predominantly Fe sulphate (Sample X22);
Halotrichite (H) with Zn (4.5%) coprecipitation bordered by Fe-oxide (h) with negligible heavy metal content.

e

Secondary sulphate - predominantly jarosite (Sample X46);
Quartz grains (q) and muscovite flakes (m) embedded in jarosite (j). Heavy metal concentrations in all minerals present are negligible.

f

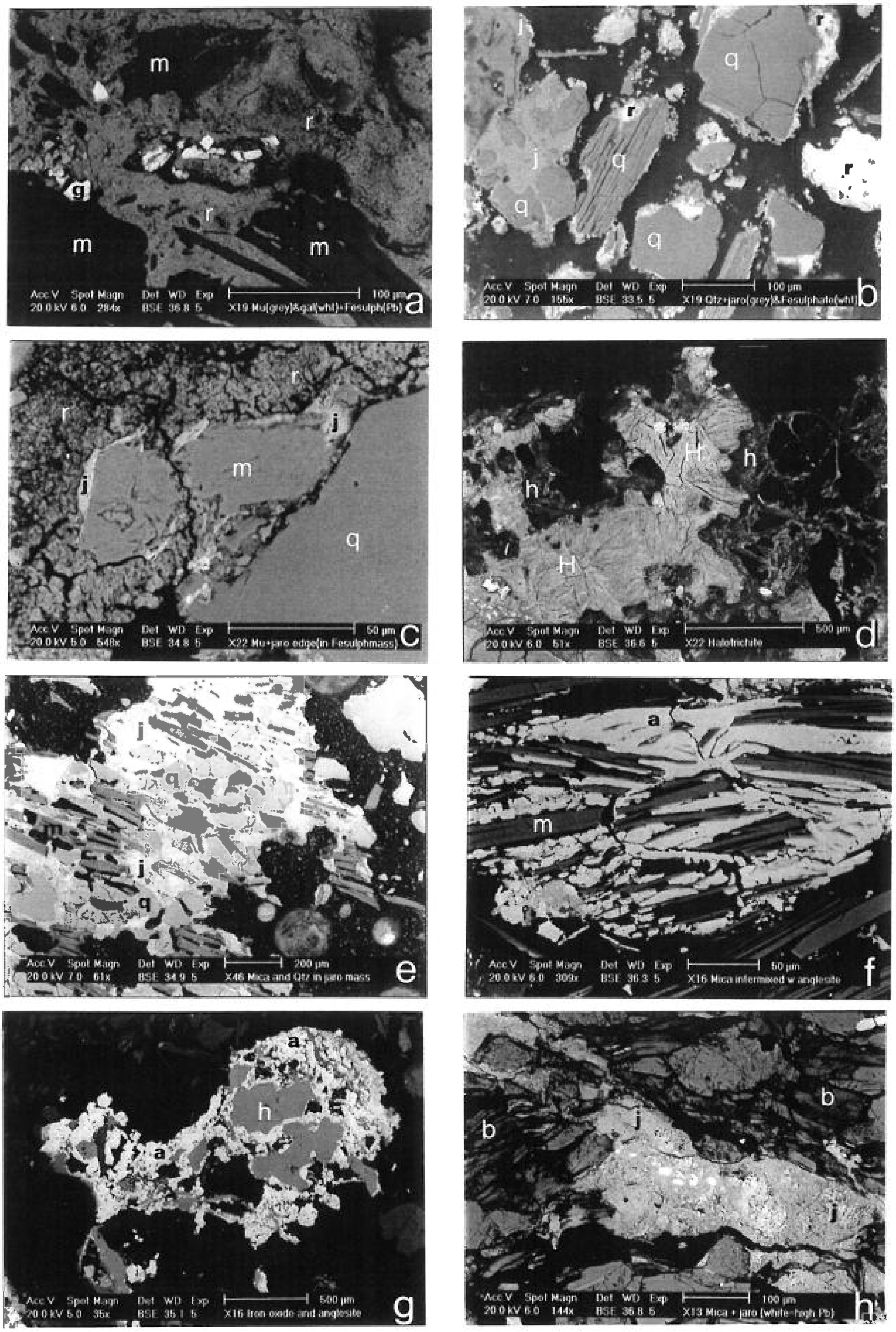
Partially weathered muscovite schist (Sample X16);
Muscovite flakes (m) intermixed with anglesite (a).

g

Partially weathered muscovite schist (Sample X16);
Fe-oxide (h) with significant As content (up to 0.2%) and varying Pb & Zn levels, surrounded by anglesite (a).

h

Partially weathered biotite schist (Sample X13);
Biotite (b) with jarosite deposits (j). White components in jarosite have an enhanced Pb concentration compared with the main body of jarosite (5.3% and 1.0% respectively).



m
r
g
m
r
m
Acc.V Spot Magn Det WD Exp 100 µm
20.0 kV 6.0 284x BSE 36.8 5 X19 Mu(grey)&gal(wht)+Fesulph(Pb)
a
j
q
r
r
j
q
q
q
r
Acc.V Spot Magn Det WD Exp 100 µm
20.0 kV 7.0 156x BSE 33.5 5 X19 Qtz+jaro(grey)&Fesulphate(wht)
b
r
r
j
m
j
q
Acc.V Spot Magn Det WD Exp 50 µm
20.0 kV 5.0 548x BSE 34.8 5 X22 Mu+jaro edge(in Fesulphmass)
c
H
h
h
H
Acc.V Spot Magn Det WD Exp 500 µm
20.0 kV 6.0 51x BSE 36.6 5 X22 Halotrichite
d
j
q
m
j
q
Acc.V Spot Magn Det WD Exp 200 µm
20.0 kV 7.0 61x BSE 34.9 5 X46 Mica and Qtz in jaro mass
e
a
m
Acc.V Spot Magn Det WD Exp 50 µm
20.0 kV 6.0 309x BSE 36.3 5 X16 Mica intermixed w anglesite
f
a
h
a
Acc.V Spot Magn Det WD Exp 500 µm
20.0 kV 5.0 35x BSE 35.1 5 X16 Iron oxide and anglesite
g
b
j
b
j
Acc.V Spot Magn Det WD Exp 100 µm
20.0 kV 6.0 144x BSE 36.8 5 X13 Mica + jaro (white-high Pb)
h

Chapter 4
NATURE and EXTENT of CONTAMINATION

The potential contaminants characterised in the previous chapter occur mainly in the vicinity of the mine. The effects of these waste materials lie in the acid they generate and/or the heavy metals they release into the surrounding environment. At Wheal Ellen this includes the soil downslope of the mine, groundwater and the sediments of Rodwell Creek. This chapter addresses the effects of over 100 years of mining activities on the environment.

The contained sulphides prior to mining produced minimal contamination as the levels of dissolved oxygen and water infiltration through the rock were minimal. It is only after the sulphidic material was broken up and brought to the surface that the acid producing potential has been realised and heavy elements, which were initially locked in the structure of sulphides or other minerals, released. In an environment with a neutral or alkaline pH, these heavy metals remain relatively immobile - adsorbed onto or coprecipitated with secondary minerals formed by the oxidation of sulphides or form their own secondary minerals. At lower pH, the solubility of these metals increases, and they are transported in ionic form by groundwater or surface water into surrounding materials (rock, soil or water). A subsequent increase in pH will cause the solutes to precipitate either onto existing minerals such as clays and Fe oxyhydroxides or form new secondary minerals. It is the nature of these minerals which will determine the bioavailability of the heavy elements and thus their impact on the floral growth and uptake by animals and humans.

4.1 Background Values of Acidity and Heavy Elements

Background can be defined as the "levels of substances or chemicals that are commonly found in the local environment" (ANZECC, 1992). In order to identify environmental contamination, elemental concentrations need to be viewed above this normal range (Tiller, 1991).

Background Soil

Several soil samples (B, C1, C2, C11, C12, C13) were taken from local sites deemed unaffected by the mine. This is not entirely satisfactory because it is quite possible that the Wheal Ellen deposit had some effect prior to mining (e.g. elemental dispersion during gossan formation), albeit a much lesser one than that following mining. Additionally, the number of samples was small and variation high. Nonetheless, a basic indication of which materials are elevated in the soil can be gained.

Water Extracted pH

With the exception of sample C2 (pH 3.6), all of the above samples have a pH greater than 6.5 (i.e. essentially neutral). Sample C2 lies along strike from the orebody and only about 200m away from the mine workings. Wade and Cochrane's (1954) survey, identified ore beyond the extent of the workings, but at an amount and grade much lower. It appears this site contains some acid forming material (most probably sulphide) but without further analysis this cannot be confirmed.

Heavy Metal Concentrations

The range and average of background levels for elements in soils from around the Wheal Ellen site are given in Table 4.1 (all data is presented in Appendix A4.4);

Element	Min (ppm)	Max (ppm)	Average (ppm)	Guideline (ppm)*
As	21	38	31	20
Ba	322	533	400	N/A
Cd	16	49	35	3
Co	12	28	18	N/A
Cr	18	36	26	50
Cu	26	387	121	250
Ni	8	12	<9	60
Pb	54	1431	358	300
Sb	164	299	223	20
Zn	29	1940	438	200

* Figures from ANZECC/NHRMC, 1992

Table 4.1 **Background values of heavy metals at Wheal Ellen.**

Despite the abnormally acidic nature of sample C2, the heavy metal concentrations lie within the ranges outlined above. Nonetheless, the values have not been included.

Background Water

Background pH and heavy metal concentrations were found by sampling Rodwell Creek water upstream of the mine and groundwater in surrounding bores/springs.

All Rodwell Creek water samples ('R' Samples) had a pH between 8.3 and 9.1 (Table A4.8) and concentrations of potentially toxic heavy metals (Pb, Zn, Cu, Cd, Co, Cr, Ni) below detection limits. Similar geochemical properties were found in the dam to the NE of the mine (Sample GD) and a spring about 1km S of the mine area (Sample JS) (Table A4.6). A bore to the NW of the mine (Sample BB), had a slightly lower pH (6.6) although heavy element concentrations are still negligible.

4.2 Nature of Contamination

Soil

Acidity

The pH of water extracted material down the erosion gullies of the mine hillslopes compared with the background levels (approximately neutral) indicate the spread of acid generating material from the mine. pH values range from about 2.5 to 3.5 on all slopes. There seems to be no significant trend with distance from the mine. Hydraulically transported sulphide grains or most likely, jarosite carried in solution, would explain this.

Sample **W4**, *western erosion gully soil,* was examined by SEM and EMP. This sample was selected as it contained the greatest heavy metal concentrations, thus the forms would be the easiest to detect. It can be broadly assumed that the forms of heavy metals will be similar in other soils samples, even though the concentrations are reduced. Sample W4 was found to have a significant secondary sulphate content, including jarosite, but no significant sulphides (Plates 4.1a & b).

Heavy Metals

In comparison with the background levels, only the levels for Pb, Zn and Cu appear to significantly increase. This increase can be seen in all the three gullies (W, SE and NE). Of the remaining elements As, show minor increases while Cd and Sb seem to be around the same levels as the background. Even though they occur in concentrations greater than recommended in the guidelines, they are 'natural contamination' due to primary Geochemical haloes associated with the mineralising process. Barium, Co, Cr and Ni are not at levels high enough to class them as contaminants in either mine gully soil or background soil (Table 4.2).

Heavy Metal	Ave. Back-ground (ppm)	Ave. Gully Soil (ppm)	Comment
Pb	358	6,800	Substantial mine related contaminant
Zn	438	1,500	Substantial mine related contaminant
Cu	121	400	Substantial mine related contaminant
As	38	60	Minor mine related contaminant
Sb	223	180	Natural contamination (minimal mine effect)
Cd	35	25	Natural contamination (minimal mine effect)
Ba	400	500	Not a contaminant
Co	18	36	Not a contaminant
Cr	26	35	Not a contaminant (level below guideline)
Ni	<9	10	Not a contaminant (level below guideline)

Table 4.2 **Determination of mine related heavy metal contaminants**

Generalised soil mineralogy;

Quartz	40-60%
Mica (muscovite/phlogopite)	10-30%
Kaolinite	5-15%
Feldspar (albite/microcline)	2-10%
Clinochlore	2-5%
Iron oxide	5-15%
Secondary sulphates (jarosite, anglesite)	2-10%
Other (eg rutile)	<1%

Under SEM examination (Plates 4.1a, b & c) the presence of Pb was detected in anglesite, jarosite and Fe oxide.

Water

All water and mound spring samples have essentially neutral pHs, suggesting that at this stage there is minimal impact from the mine on Rodwell Creek, and the dam to the N-W of the mine. A plot of pH values for samples taken from Rodwell Creek (Figure 4.3a) reveals a very small drop at the site where mine water is believed to enter ('Rg'). Although this minor trend towards acidity is much too small to be of any threat, it does act as a possible indication that mine water is getting into the Creek within a short distance of the mine. The site of main surface runoff entry ('Re') shows no detectable change in pH.

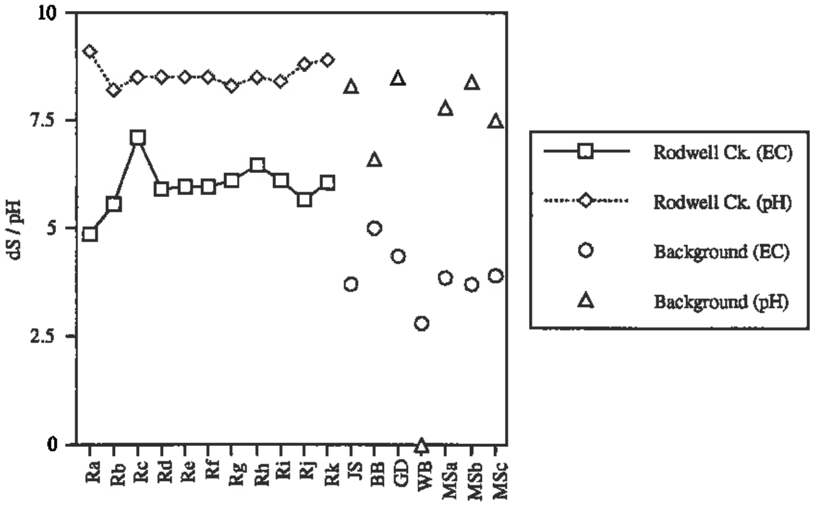


Figure 4.2 pH and EC values for water samples

EC values are all low and lie within the values of natural waters (0.05 - 10dSm^{-1}, at 25 °C). To be considered for domestic use, the water should be <1.5 dSm^{-1}, however, stock can in extreme circumstances take up to 15dSm^{-1} (Rayment and Higginson, 1992).

It is important to note that this study did not take seasonality into account, and it is possible that mine effects on Rodwell Creek could differ throughout the year.

4.3 Extent of Contamination

Soil

Water extracted pH's are consistently less than 4.5 (with a few exceptions as noted below) and down to values as low as 2.5 in some areas. Acid production is evident in all samples down to the base of the surrounding gullies, with the exceptions of the two samples closest to Rodwell Creek (W7b and W8). Either acid producing material has not been carried to these furthermost sites, or any acid produced is neutralised by the carbonaceous creek environment.

Figures 4.1a-e diagrammatically display heavy metal concentrations (Pb, Zn, Cu, Cd and Sb) of soil samples surrounding the mine. The levels are consistently high across the area, indicating that surface contamination extends at least 100m from the mine source to the base of the drainage channels surrounding the mine ridge.

Water

The lowering of pH within surface water is manifest in Rodwell Creek adjacent to the mound springs. To determine if this change in pH is related to the mine input, some sulphur isotope analyses were conducted on water samples as well as sulphides and secondary sulphates at the mine (Table 4.3).

No.	δS^{34}‰	Sample Type
X42	3.7	Sulphide (predominantly pyrite) from mine surface
X22	5.5	Newly formed Fe sulphate/halotrichite/jarosite mix on clay surface
X46	4.7	Jarosite in soil adjacent to shaft area
WB	19	Bore water, several kms N of mine
Ra	23.5	Rodwell Creek - upstream from mine
Re	14.2	Rodwell Creek - at entry point of mine surface runoff
Rg	11.9	Rodwell Creek - adjacent to mound spring
MS	6.5	Water from mound spring

Table 4.3 **Sulphur Isotope values for selected sulphide, sulphate and water samples**

Despite the minimal number of sulphur isotope results, a clear trend is evident. The sulphide sample (X42) has a δS^{34} value of 3.7‰ which falls within the range of 0-6 for Wheal Ellen as reported by Seccombe *et al* ., (1985). The two secondary sulphates (X22 and X46) are within this range also, concordant with the fact that no discernible sulphur fractionation should occur between sulphide dissolution and resultant sulphate precipitation (Taylor and Wheeler, 1994).

Figure 4.1

Geochemical maps displaying heavy metal concentrations within mine contaminated soils

Legend

🔴 Soils

⚫ 'Clean' imported clays

☐ Mine shaft

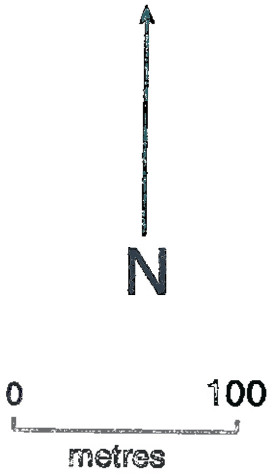
▨ Ruin

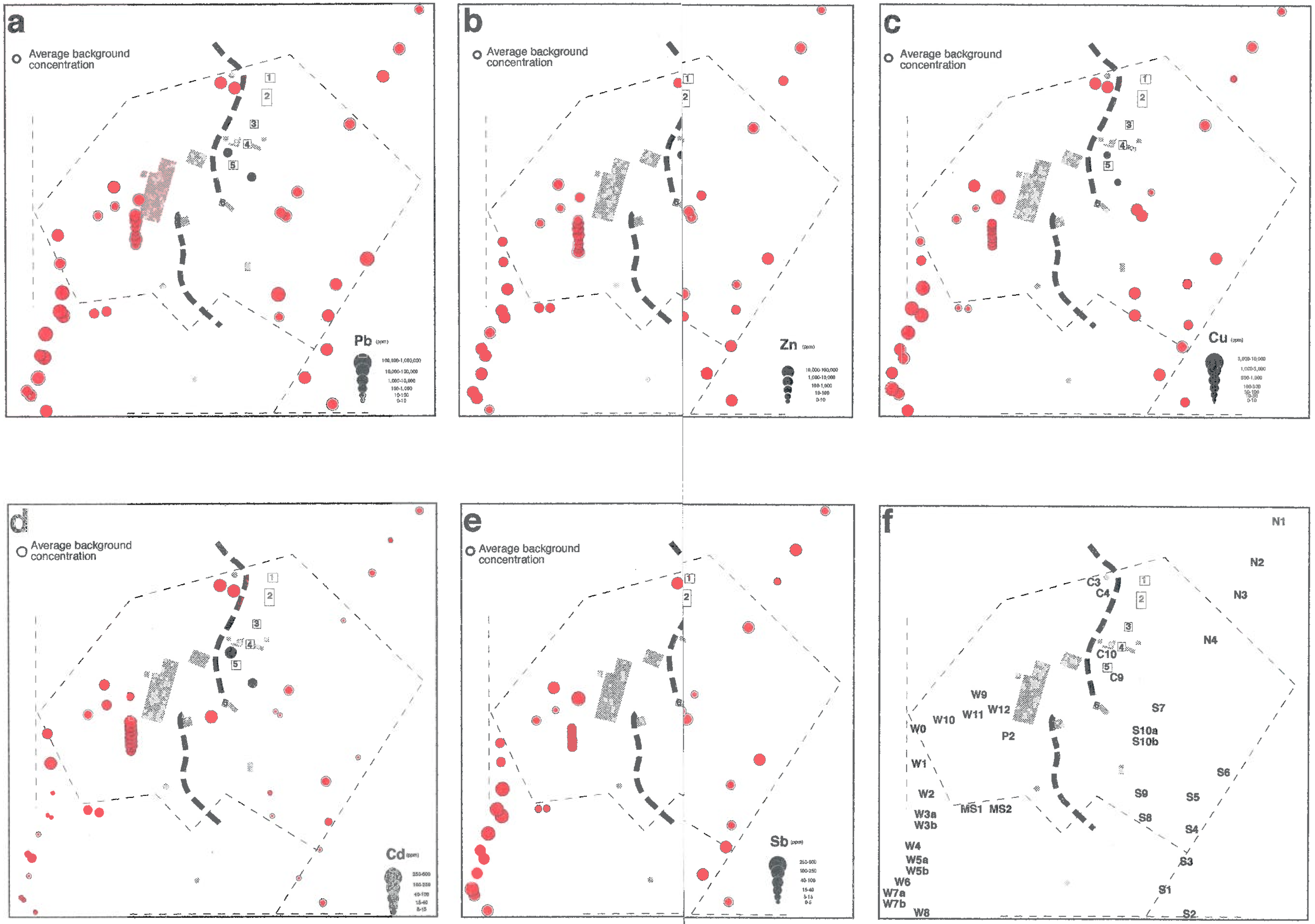
■ ■ Road

┄┄ Fence

Shafts

1	North Air Shaft
2	Spence Shaft
3	Middle Air Shaft
4	Main Engine Shaft
5	Scott Shaft
6	Bassett Shaft



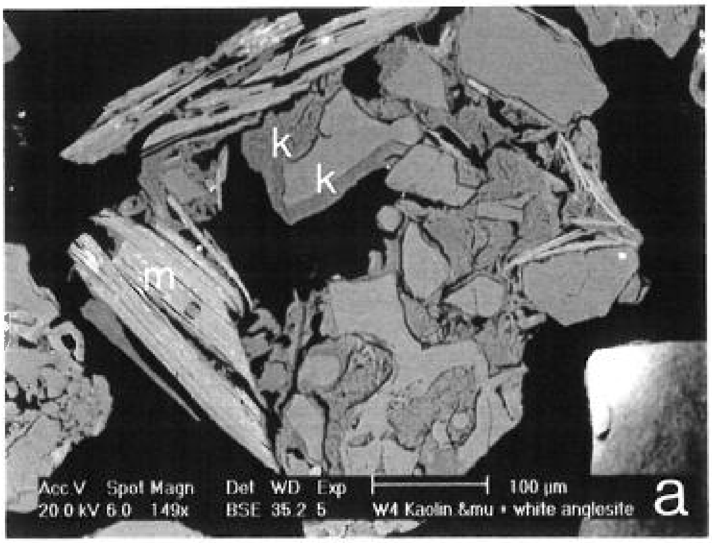

a
Average background concentration
1
2
3
4
5
Pb (ppm)
100,000-1,000,000
10,000-100,000
1,000-10,000
100-1,000
10-100
0-10
b
Average background concentration
1
2
Zn (ppm)
10,000-100,000
1,000-10,000
100-1,000
10-100
0-10
c
Average background concentration
1
2
3
4
5
Cu (ppm)
3,000-10,000
1,000-3,000
300-1,000
100-300
30-100
10-30
0-10
d
Average background concentration
1
2
3
4
5
Cd (ppm)
250-600
100-250
40-100
15-40
8-15
e
Average background concentration
1
2
Sb (ppm)
250-600
100-250
40-100
15-40
5-15
0-5
f
N1
N2
N3
N4
C3
C4
1
2
3
4
C10
5
C9
W9
W10
W11
W12
W0
P2
S7
S10a
S10b
W1
S6
W2
S9
S5
MS1
MS2
S8
W3a
W3b
S4
W4
W5a
W5b
S3
W6
S1
W7a
W7b
W8
S2

The borewater sample is slightly lower than that of the upstream water (Ra) indicative of mild sulphide input into the groundwater. Giblin *et al* ., (1994) reported the likely presence of numerous small, unidentified, sulphidic lodes in the region, and minor incorporation into groundwater is not unrealistic. The bore samples from around the general Kanmantoo area are concordant with this result, ranging from about 13‰-26‰ (Giblin *et al.*, 1994). The result for the creek water upstream of the mine (23.5‰) is not dissimilar to that expected of sulphur with seawater origins (Drever, 1982); most likely due to sea spray. As the creek water moves past the junction of mine surface water input, the ratio shows a decline, suggesting sulphate from the mine is entering the creek. The sample taken from the mound spring area shows a ratio similar to that of sulphate samples from the mine, and the water in Rodwell Creek, adjacent to this area, is similarly lowered from that further upstream. A similar isotopic halo has been identified in the waters from the Kanmantoo deposit (Giblin *et al.*, 1994) and Brukunga Pyrite Mine (Jensen & Whittle, 1969; Giblin *et al.*, 1994). Although the number of samples analysed is minimal and additional analyses are required to confirm these conclusions, the results do suggest that mine originating waters are entering Rodwell Creek, primarily through groundwater. The agreement of the results of this study, with other studies in the area further validates these conclusions.

Any extent of current heavy metal contamination of Rodwell Creek is so minimal as to be undetectable.

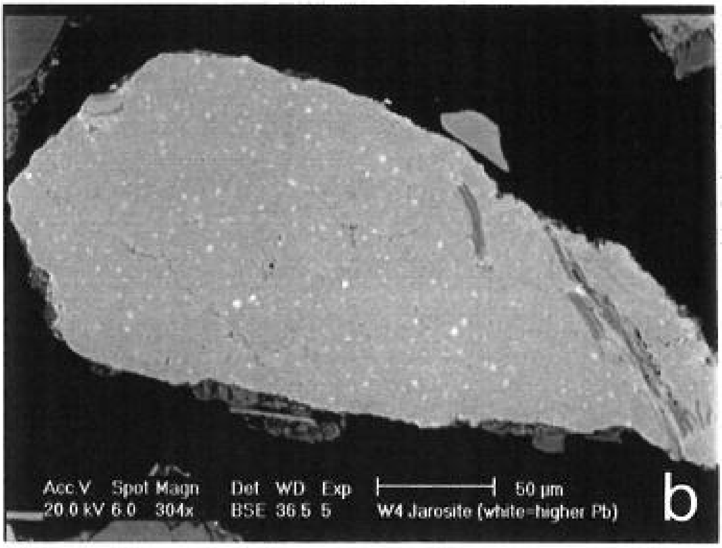
Plate 4.1

Photomicrographs taken on the scanning electron microscope (SEM) in back scattered electron mode (BSE).



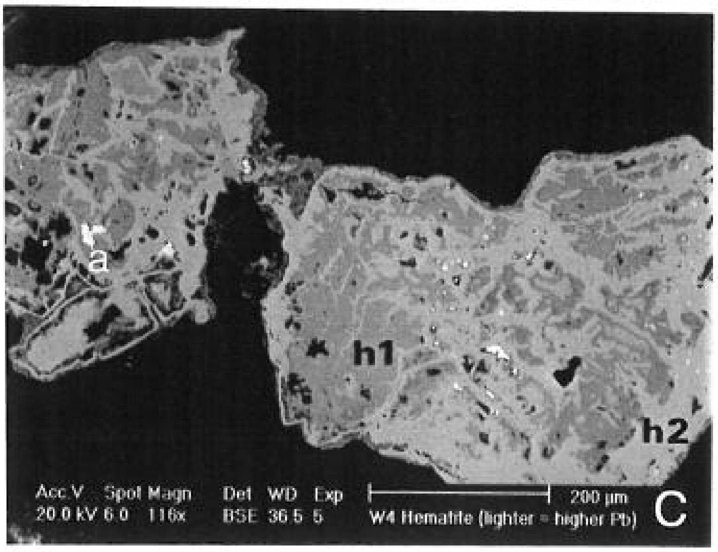
a

Western hillslope gully soil (Sample W4); Kaolinite (k) with degraded mica flakes (m). Bright white specks on the mica surface are anglesite.



b

Western hillslope gully soil (Sample W4); Jarosite, with negligable heavy metal content (grey) and jarosite with Pb and minor Cu coprecipitation (white specks).



c

Western hillslope gully soil (Sample W4); Hematite with varying heavy metal concentrations; dark grey areas (h1) contain negligable concentrations compared with approximately 1-2% each of Pb & Zn in light grey areas (h2). Bright white (a) represents anglesite deposits.

Chapter 5
REMEDIATION

5.1 The Need for Rehabilitation

The results as outlined in the previous two chapters, indicate that:
(1) acid is being produced by mine wastes containing sulphides and/or jarosite
(2) there are mine wastes (sulphides, gossan, tailings, slag) with high concentrations of potentially toxic heavy metals (primarily Pb, Zn, Cu, Cd and Sb)
(3) these heavy metals are/have been mobilised and incorporated into secondary minerals (namely jarosite, Fe-sulphate, anglesite and halotrichite)
(4) commonly these secondary minerals have a high potential for breakdown (depending on their form)
(5) contamination (acid producing materials and heavy metals) has extended at least to the base of the mine's ridge
(6) although mine waters appear to be entering Rodwell Creek, current impact is negligible

These processes have been occurring over the past 100 years since mining commenced, and undoubtedly the clearly visible environmental impacts primarily result from mine-related contamination. The conclusion of the late 1995 MESA site inspection - that rehabilitation and improvement of safety was required (Puccini & Mattiazzo, 1995) - was justified.

5.2 MESA's Rehabilitative Work

Initial Remediation of Wheal Ellen

MESA commenced work in late 1995, aiming to (Puccini, 1995);
(1) Improve mine site safety
(2) Prevent/control acid water runoff on the hillslopes (thus reducing further erosion and contamination)
(3) Rehabilitate already affected areas (namely the eroded downslopes of the mine ridge)

No mention was made in the inspection report or rehabilitation proposals of the possible presence of toxic heavy metals or past/future effects on groundwater.

With these aims in mind, the open shafts were infilled with "all rainwater pollutants" (Puccini, 1995) - several thousand tonnes of surface dumped sulphidic waste rock, tailings, gossan and country rock (Plates 5.1a (before)& b (after)). Once infilled, each of the six shafts were individually fenced off and posted with warning signs. The area was recontoured (approximate 1:3 ratio) to encourage maximum water runoff while minimising erosion. Over 2,000t of uncompacted, benign clay were imported from Mt Barker to serve as topsoil. Five hundred tonnes were placed over the main gossan dump S of the Bassett Shaft (Plate 5.1c) with the remainder being dumped around the site in readiness for future spreading. A second quantity of Mt Barker clay (6,000t) was imported in May, 1996, and similarly dumped. During this second operation, a clay covered sulphide dump* was re-exposed and intermixed with the newly spread clay (Plates 5.1d & e).

Further Rehabilitation Proposals

Various tentative proposals for further remediating Wheal Ellen Mine include (O. Puccini, pers. comm., 1996);
- The addition of a neutralising agent to the shafts and surface areas (possibly through intermixing with clay already at the site),
- Bund creation along the W hillslope, to channel any rain water to a holding pond with subsequent piping to a sump which will be sunk in the main valley to the W of the mine,
- Silt trap placement to complement the above mentioned sump,
- "Cross control ripping" of hillsides to minimise further erosion,

and
- Revegetation encouragement; including the "hand sown and raked" method of grass reseeding during an appropriate season (May), tree planting, application of "Soilguard" (a new spray-on surface soil stabiliser (Soilguard, 1996)) and prevention of use by stock.

5.3 Discussion of MESA'S Rehabilitation and Proposals

The safety measures now in place can be considered adequate. Shafts are both visible and essentially inaccessible, minimising danger to humans, stock and native wildlife.

Shaft backfilling was primarily undertaken to physically remove rainwater pollutants from the mine area surface. This action failed in two respects: (1) significant volumes of potential contaminants remain on the surface (Plate 5.1b), thus surface impacts (acid scouring etc) may continue, and (2) contaminating materials, and resultant environmental impacts have merely been relocated rather than being removed from the system. The shafts are capped only with uncompacted clay, creating a conduit for rainfall straight to the groundwater system, especially in the Main Engine, Scott and Bassett Shafts which terminate in the water table

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* Similar morphologically and compositionally to Sample **X25** *clay covered, concentrated mass of individual pyrite grains* and Sample **X42** *highly pyritic rock fragments.*

(Wade & Cochrane, 1954). The placement of an uncompacted mass of various acid producing and/or heavy metal rich materials down these water-channelling shafts constitutes enormous potential for groundwater contamination - a problem with further reaching effects and increased remediation difficulties than existed prior to 'rehabilitation'. Compounding the problem, is significant subsidence over the Main Engine (Plate 5.1g) and Spence Shafts allowing water to collect at the top of the shaft, increasing infiltration volume.

Imported clay, being intended as topsoil was left uncompacted on the surface. Consequently, solutes from the underlying sulphides have already been able to rise through capillary action with subsequent secondary minerals precipitation at the surface (Plates 5.1e & d). As mentioned above, sulphides were also intermixed with the clay during proceedings, with similar effects. As outlined in Chapter 3, the most common secondary mineralisation in this situation at the mine is Fe sulphate. Being both highly soluble and often coprecipitated with other heavy metals, Fe sulphate has a high potential for further contaminating the surrounds. As a final point, weeds, which are already sprouting profusely, have been imported with the clays.

Recontouring of the hillslope so far appears to have been effective. Despite rain over the winter months, there has been limited erosion of the dumped clay piles.

Surface application of a neutralising agent to shafts and the general mine surface area may have an initial amelioration effect. Long term benefits are limited however, as the neutraliser will have limited contact with the acid producing materials at depth. Intermixing a neutraliser with the clay already onsite may increase effectiveness, however the long term result will no doubt still be less than satisfactory.

Finally, the rehabilitation procedures obliterated historic remnants of a small wooden rail track, the original stone assay table and parts of Cornish mine buildings, contravening the original aim of "not disturbing" all historic relics (Puccini, 1995).

5.4 Natural Abatement at Wheal Ellen

Neutralisation by Country Rocks

Soil

Mineralogical analyses (XRD, optical microscopy and SEM) failed to detect any natural carbonate rocks at the mine although carbonates have been documented in the past (e.g. Mining Review, 1908b). These have almost certainly been neutralised during the past period

Plate 5.1

a

Looking N towards the surface of Wheal Ellen Mine prior to any rehabilitative work (pre December, 1995). Open and unprotected shafts are surrounded by various dumps of sulphidic waste rock, gossan and country rock (micaceous schists). To the W of the shafts lies the dumped fine-grained pink tailings.

b

Looking N towards Wheal Ellen following infilling of surface wastes into the shafts, and prior to the inbringing of foreign clay (December 1995). Although the majority of the surface material was removed, a significant surface cover of sulphidic waste rock, gossan, tailings and dumped country rock remains.

c

Immediately S of the Bassett Shaft; clay covered gossan dump (not infilled into shafts) following clay importation in May, 1996. Although the clay was partially compacted through the action of heavy earth moving machinery, the layer is far from impermeable and still allows water infiltration through to the underlying gossan. Imported weeds have readily sprouted in the piled clay while native revegetation is minimal.

d

Thin semi-compacted clay layer intermixed with surface sulphides, found extensively to the E of the Middle Air, Main Engine and Scott Shafts. This sulphidic material was re-exposed at the site during the dumping of clay in May, 1996.

e

Newly formed white efflourescence (Sample X21) covering the semi-compacted clay/sulphide mix of Plate 5.1d. This efflourescence is similarly found on the surface of tailings not infilled into shafts (Sample X35).

f

Secondary mineralisation (Fe sulphate, halotrichite and jarosite (Sample X22)) found on thin (<150mm) dumped clay layer covering sulphidic waste rock not infilled into shafts (Sample X25).

g

Main Engine Shaft having undergone significant subsidence in the 12 month period since rehabilitation commenced. Such movement creates a 'funnel', channelling rainwater directly into the sulphidic waste/tailings/gossan mix within the shafts. A similar situation exists at the Spence Shaft.

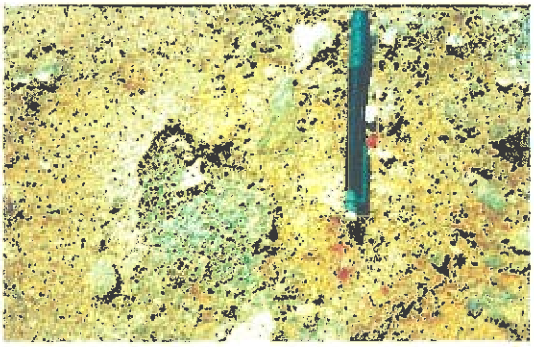
h

The wetland area to the SW of the mine, adjacent to Rodwell Creek. The system contains two moundsprings, one of which is believed to receive water containing mine originating materials which may be naturally filtered in the area before entering Rodwell Creek.

a

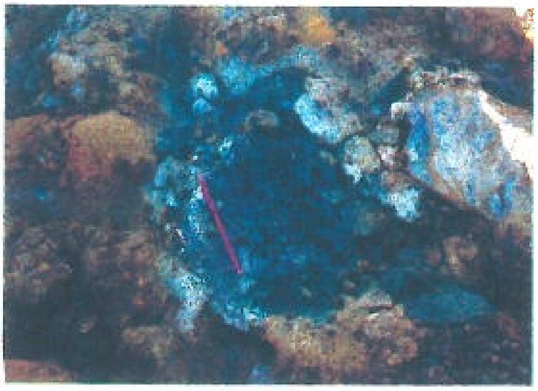
b

c



d

e



f

g

h

of acid generation, thus current neutralisation by carbonates would be negligible to non-existent.

Other minerals (primarily silicates) are capable of acid neutralisation. The abundance of these materials at the mine would reduce the effects of AMD to some degree (Fanning & Fanning, 1989).

Water

The water in Rodwell Creek has a high pH (around 7-8) as testimony to carbonate lithologies in the creek catchment area and carbonate lenses in the Kanmantoo Group displayed as calcrete along the creek's bank.

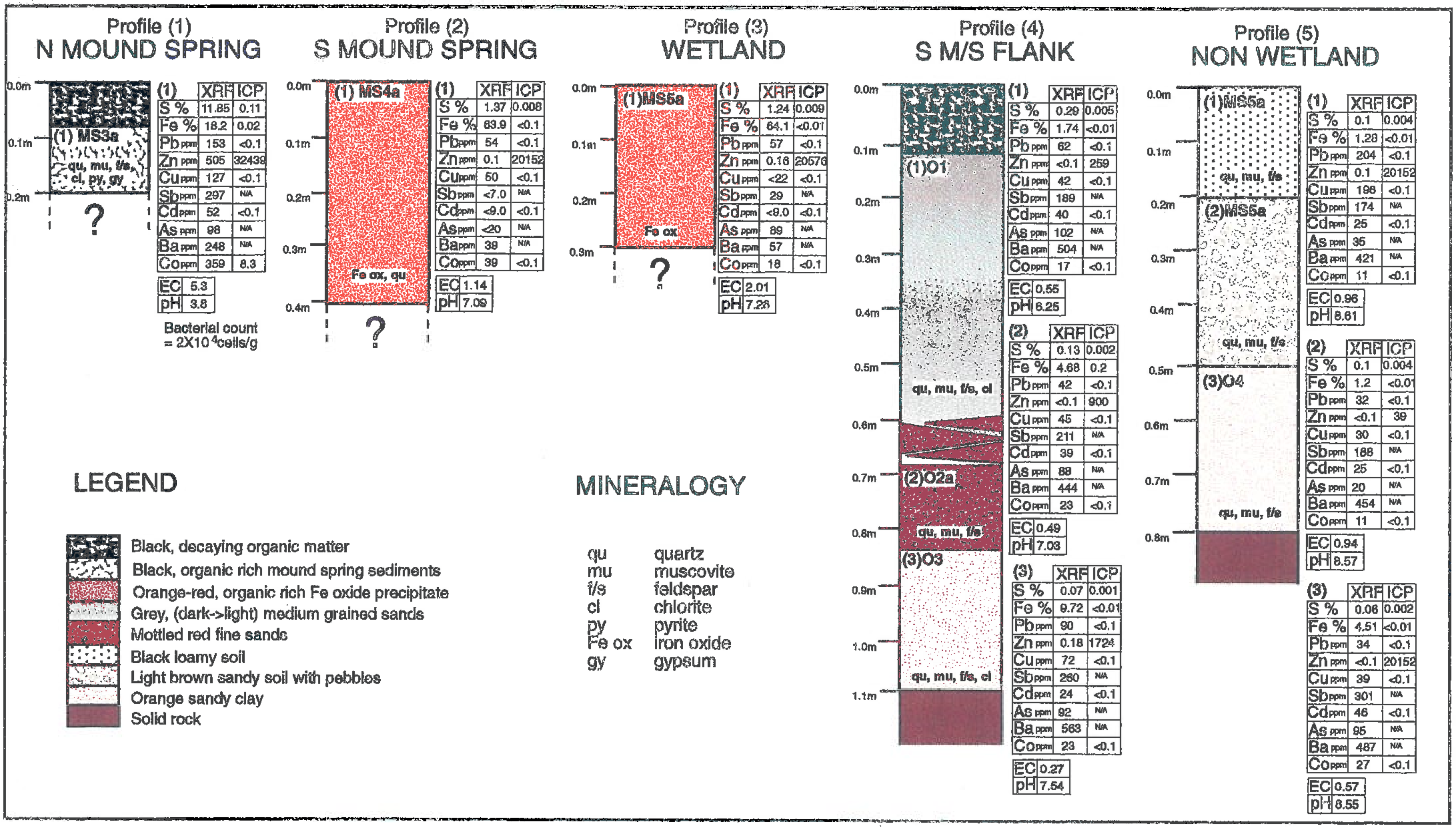
Natural Wetland System

The small natural wetland system and mound springs present at the base of the mine ridge, adjacent to Rodwell Creek (Plate 5.1h). It is suspected this area receives mine originating waters and possibly acts as a natural contaminant filter. Details of sampling and analysis in the area are outlined in Chapter 2. Various profiles of the area and relevant geochemical and mineralogical data are displayed in Figure 5.1. Information regarding processes involved in wetland filtering is detailed in Appendix A1.3.

Similarities at depth between the two core profiles (Profiles 4 & 5, Figure 5.1) suggest the area was once all fluviatile sediments. With the initiation of groundwater upwelling, possibly due to mining activities, mound springs were formed, resulting in expansion to an entire wetland area.

The two mounds (at the point of water upwelling) differ significantly in appearance, mineralogy and geochemistry. The N mound (Profile 1), being black and primarily composed of rock forming minerals contrasts significantly with the red-orange Fe oxide precipitate of the S mound (Profile 2). This same deposit variously spreads across areas of the wetland (Profile 3). Such a difference in the mound springs suggests a difference in sources. Considering the close proximity of the springs (10m), this would seem unlikely, however, the strata in the area are virtually vertical, and run along strike from the mine to the mound spring, and so could act as a barrier separating the two water sources.

The N mound spring is clearly distinctive from the other profiles - pH is much lower, EC is much higher and heavy metal levels are enhanced. Bacterial tests revealed a concentration of approximately $2x10^4$ cells/gram, indicative of sulphate reducing bacteria influence (S. Raguso, pers. comm., 1996), and their presence is tentatively confirmed by the presence of pyrite. By combining these results, it can be hypothesised that the N mound spring, at least, is



Profile (1)
N MOUND SPRING

(1)	XRF	ICP
S %	11.85	0.11
Fe %	18.2	0.02
Pb ppm	153	<0.1
Zn ppm	505	32439
Cu ppm	127	<0.1
Sb ppm	297	N/A
Cd ppm	52	<0.1
As ppm	98	N/A
Ba ppm	248	N/A
Co ppm	359	8.3

EC	5.3
pH	3.8

Bacterial count = $2X10^4$cells/g

Profile (2)
S MOUND SPRING

(1)	XRF	ICP
S %	1.37	0.008
Fe %	63.9	<0.1
Pb ppm	54	<0.1
Zn ppm	0.1	20152
Cu ppm	50	<0.1
Sb ppm	<7.0	N/A
Cd ppm	<9.0	<0.1
As ppm	<20	N/A
Ba ppm	39	N/A
Co ppm	39	<0.1

EC	1.14
pH	7.09

Profile (3)
WETLAND

(1)	XRF	ICP
S %	1.24	0.009
Fe %	64.1	<0.01
Pb ppm	57	<0.1
Zn ppm	0.16	20576
Cu ppm	<22	<0.1
Sb ppm	29	N/A
Cd ppm	<8.0	<0.1
As ppm	89	N/A
Ba ppm	57	N/A
Co ppm	18	<0.1

EC	2.01
pH	7.26

Profile (4)
S M/S FLANK

(1)	XRF	ICP
S %	0.29	0.005
Fe %	1.74	<0.01
Pb ppm	62	<0.1
Zn ppm	<0.1	259
Cu ppm	42	<0.1
Sb ppm	189	N/A
Cd ppm	40	<0.1
As ppm	102	N/A
Ba ppm	504	N/A
Co ppm	17	<0.1

EC	0.55
pH	6.25

(2)	XRF	ICP
S %	0.13	0.002
Fe %	4.68	0.2
Pb ppm	42	<0.1
Zn ppm	<0.1	900
Cu ppm	45	<0.1
Sb ppm	211	N/A
Cd ppm	39	<0.1
As ppm	88	N/A
Ba ppm	444	N/A
Co ppm	23	<0.1

EC	0.49
pH	7.03

(3)	XRF	ICP
S %	0.07	0.001
Fe %	9.72	<0.01
Pb ppm	90	<0.1
Zn ppm	0.18	1724
Cu ppm	72	<0.1
Sb ppm	260	N/A
Cd ppm	24	<0.1
As ppm	92	N/A
Ba ppm	563	N/A
Co ppm	23	<0.1

EC	0.27
pH	7.54

Profile (5)
NON WETLAND

(1)	XRF	ICP
S %	0.1	0.004
Fe %	1.28	<0.01
Pb ppm	204	<0.1
Zn ppm	0.1	20152
Cu ppm	198	<0.1
Sb ppm	174	N/A
Cd ppm	25	<0.1
As ppm	35	N/A
Ba ppm	421	N/A
Co ppm	11	<0.1

EC	0.96
pH	8.61

(2)	XRF	ICP
S %	0.1	0.004
Fe %	1.2	<0.01
Pb ppm	32	<0.1
Zn ppm	<0.1	39
Cu ppm	30	<0.1
Sb ppm	188	N/A
Cd ppm	25	<0.1
As ppm	20	N/A
Ba ppm	454	N/A
Co ppm	11	<0.1

EC	0.94
pH	8.57

(3)	XRF	ICP
S %	0.06	0.002
Fe %	4.51	<0.01
Pb ppm	34	<0.1
Zn ppm	<0.1	20152
Cu ppm	39	<0.1
Sb ppm	301	N/A
Cd ppm	46	<0.1
As ppm	95	N/A
Ba ppm	487	N/A
Co ppm	27	<0.1

EC	0.57
pH	8.55

LEGEND

- Black, decaying organic matter
- Black, organic rich mound spring sediments
- Orange-red, organic rich Fe oxide precipitate
- Grey, (dark->light) medium grained sands
- Mottled red fine sands
- Black loamy soil
- Light brown sandy soil with pebbles
- Orange sandy clay
- Solid rock

MINERALOGY

qu	quartz
mu	muscovite
f/s	feldspar
cl	chlorite
py	pyrite
Fe ox	iron oxide
gy	gypsum

Figure 5.1 Various wetland area profiles with selected geochemical details and mineralogy

receiving mine originating waters and may be quite significant with respect to immobilising mine contaminants.

The water in the wetland and water extracted from solid samples (Profiles 2, 3 & 4) has an approximately neutral pH, probably resulting from a combination of neutralisation by carbonate rich waters and physical dilution by the large volume of creek water compared with mine water influence. The neutral pH would rapidly precipitate out any Fe(II) ions within mine contaminated waters as Fe oxides. The S mound spring (Profile 2), consists predominantly of such deposits indicating an Fe rich source, although the origin can not be confirmed without further testing.

5.5 Recommendations Based on this Study

In retrospect, contaminant removal and relocation may have constituted the most effective and financially viable rehabilitation option. Appropriate dumping sites include the abandoned Brukunga Pyrite Mine (20km from Wheal Ellen) or Kanmantoo open pit (10km). Although the Wheal Ellen waste materials would still contaminate at an alternative location, the volume (estimated in the order of 10,000t) is insignificant compared with that at larger sites (eg Brukunga contains 3.5Mt of tailings and 10Mt waste rock (Agnew, 1994)). The advancement of rehabilitative action and resultant waste inaccessibility renders this option no longer practical.

Considering the work already undertaken, the primary issue to address is the threat of potential groundwater contamination. An impermeable cover over the infilled shafts would serve two purposes; minimising contact of shaft material with oxygen and water, and reducing transportation of contaminants. Concrete (or similar) may constitute the simplest and cheapest option, however complications may arise as the underlying material subsides. There has been considerable subsidence in the past 12 months (Plate 5.1g) and although no information is available concerning the extent to which the shafts are filled, it would not be unreasonable to expect future subsidence. Such movement could cause cracking of a rigid substance such as concrete. Additional fill may help to counteract current and potential subsidence. Alternatively, a flexible capping (geotextile type blanket), which would allow movement while retaining integrity may be more appropriate. These materials are costly in comparison to concrete, and cost effectiveness would need to be examined before a decision could be made. Considering the shafts are now fenced, shaft access is limited, causing further difficulties and most probably expense.

Similarly, surface wastes require an impermeable layer to reduce rain water influx, oxygen contact and capillary rise. A machine compacted clay layer of approximately 150mm depth should suffice. Using current clay on site and spreading it over the required area, will only result in about 100mm of uncompacted clay and clearly the level will reduce on compaction.

$$\text{volume} = \text{mass/density}$$
$$\text{area x depth} = \text{mass/density}$$
$$250\text{m x } 150\text{m x depth} = 8{,}500{,}000\text{kg}/2{,}000\text{kg/m}^3$$
$$\text{depth} = 0.1\text{m}$$

Importation of further clay to be compacted is required to produce a depth of 150mm

Care will need to be taken to minimise further damage to historical features, possibly compromising the effect of the barrier to a small degree.

Further clay is then required for topsoil. Depth is important; 150 mm would be a minimum, however the thicker the better - preferably up to 500mm. If topsoil is too thin vegetation may penetrate through to the compacted clay, allowing both water and oxygen to enter enhancing AMD generation and deleteriously affecting vegetation. Shallow rooted plants would be preferable to reduce the threat of penetration of the impermeable barriers by roots.

Revegetation, once the above steps are complete will be a prime concern. Eroded landscapes require the addition of topsoil. Variations aimed at improving the nutrient levels in depleted soils include the use of sewage, mulch and organic material to fertilise new plants and assist in surface stabilisation prior to the addition of seeds or seedlings (Ryan & Joyce, 1992). In conjunction with aesthetic improvement and erosion control, these measures in themselves may control acid generation in the short term (Morin *et al,*. 1991).

Installation of bores to monitor groundwater has been suggested, although this appears unlikely owing to financial constraints. Considering the newly created threat to groundwater quality, such monitoring is desirable.

Finally, it is important to realise that the land immediately surrounding Wheal Ellen Mine has been the receiver of contaminants for over a century. While rehabilitation measures as outlined above should improve the area visually as well as prevent further contamination, the land still contains soils with acid producing materials (pyrite grains and jarosite) and heavy metals (predominantly as anglesite, or coprecipitation with jarosite and Fe-sulphate), so rehabilitation attempts may not be completely effective.

SUMMARY and CONCLUSIONS

This project sought to gain an understanding of the effects of mining the Wheal Ellen deposit on its surrounds and accordingly determine the most appropriate rehabilitation methods to utilise in remediating the area.

During the operation of the mine and following final closure in 1911, the area had been variously reported as both a safety hazard and environmentally degraded (Mining Review, 1908a; Wade & Cochrane; 1954, Puccini, 1995). MESA's preliminary rehabilitation measures have adequately (albeit unattractively) resolved the safety issue (the shafts are now filled and protected), however, the environmental aspect has been less satisfactorily addressed.

Sulphidic wastes and tailings have been identified as the mine's prime acid producers. In the past, this material existed as surface dumps. Acid produced was leached from these dumps and transported downslope by rainwater, causing vegetation destruction and consequent erosion. Water extractable material from soils deemed affected by mine runoff has a pH of between 2.5-4, significantly less than the approximately neutral background values. A significant content of acid producing materials transported from the mine (minute sulphide grains and/or jarosite), would primarily explain this. In contrast to surface runoff, the effect of the mine on groundwater, suspected to be entering nearby Rodwell Creek through a wetland system, has been less dramatic. Although the pH drops slightly in creek water adjacent to the wetland, the effect is minimal as Rodwell Creek's waters are carbonate rich and volumetrically dominant.

Concentrations of Pb, Zn, Cu, Sb and Cd (all being toxic in excess) were high in most mine waste materials analysed (sulphide wastes, tailings, gossan and slag), constituting significant contamination potential. Secondary minerals, namely anglesite, jarosite, Fe sulphate and halotrichite have formed in abundance in the area. Incorporated into these minerals are enhanced concentrations of heavy metals. On contact with water, these secondary minerals (in particular Fe-sulphate) have greater solubility than their sulphidic and siliceous counterparts, allowing enhanced heavy metal release, primarily for Zn, and to a lesser extent Cu and Pb.

Although background soils are naturally high in heavy metals, soil studied downslope from the mine shows significantly increased Pb and Zn concentrations, while Cu and As levels are slightly elevated. Both background and mine soil concentrations of Cd and Sb are similarly high, thus mine impact with respect to these elements is minimal. Surrounding soils showed significantly higher than background levels of extractable heavy metals for Pb and Zn and minor Cu increases, suggesting high bioavailability of these potentially toxic elements (Helmke

& Naidu, 1996). Rodwell Creek heavy metal levels are virtually always below detection limits, indicating minimal mine impact at present.

The contamination of surrounding soils is a result of surface wastes. While MESA has reduced the level of surface waste, the shafts have been infilled with the highly acidic and/or heavy metal concentrated materials which have been further broken up (increased surface area), with a minimal and uncompacted clay cover allowing easy infiltration of water and circulation of oxygen. The shafts could act as channels for water - the Scott and Main Engine shafts have already subsided significantly, further magnifying this. This situation has the potential for massive AMD production with contaminants being directed straight in to the groundwater. If, as predicted, AMD production is enhanced and contaminates groundwater, Rodwell Creek (the closest significant water body) may be affected in years to come. Although it appears that mine originating groundwaters are entering Rodwell Creek via the a natural wetland causing heavy metal filtration, the capabilities of the wetland are not known, and an increase in contaminants could exceed the natural amelioration capacities.

Further rehabilitative work is needed to fulfil the following aims;
(1) Protect groundwater
(2) Control further acid production and heavy metal contamination by surface wastes
(3) Prevent further erosion downslope of the mine
(4) Rehabilitate areas damaged in the past (namely hillslopes around mine)

In retrospect, physical removal of all sulphidic waste, tailings and gossans and transportation to another site (e.g. Kanmantoo or Brukunga) may have been the most effective and economically viable option. This would have virtually halted acid production, and consequently prevented further heavy metal release. Considering work has commenced, however, the above options are no longer viable. The most pressing issue is now that of possible groundwater contamination from the shaft infill. An impermeable capping would best combat this threat. Secondly, although the level of surface acid producers and contaminating materials have been reduced through shaft infilling, enough remains on the surface to continue contaminating the surrounds, warranting the compaction of clay already at the site to minimise water infiltration. Contouring of the clay to encourage runoff (accompanied by channelling to remove water with minimal clay erosion) will further reduce infiltration. A layer of topsoil covering the compacted clay, coupled with techniques to encourage revegetation (eg "Soilguard" and tree planting) should be adequate measures for ecosystem establishment. Finally, monitoring of Rodwell Creek and the mine area are essential to ensure environmental sustainability of the rehabilitation.

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The University of Adelaide
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Nature and Extent of Contamination at the Abandoned Wheal Ellen Mine and Implications for Rehabilitation

KATE TRELOAR

APPENDICES

This thesis is submitted as partial fulfilment for the
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Appendix A1
SULPHIDE MINE WASTE GEOCHEMISTRY

A1.1 Acid Mine Drainage (AMD)

In any situation involving exposure of sulphides to oxygen and water, there is potential for acid generation and the subsequent release and dispersion of cations in solution. Although a natural part of the global sulphur cycle, enhanced acid production and contamination of soil and water are common side effects of both mining and mineral processing operations. Classic examples include Summitville, Colorado (Posey *et al.*, 1995), Captains Flat, N.S.W. (Dames & Moore, 1993), Mt Lyell, Tasmania (Miedecke *et al.*, 1996), Mt Morgan, Queensland (Trevis, 1980) and more locally, Brukunga, S.A. (Agnew, 1994).

The processes involved in sulphide oxidation are well known and documented (e.g. Nordstrom, 1982; Fanning & Fanning, 1989; Thornber & Taylor, 1992; Ritchie, 1994). Briefly, the acid produced through sulphide oxidation reacts with surrounding ore, country rock and gangue minerals (eg other sulphides, carbonates and silicates) whose dissolution products may be dispersed or concentrated (e.g. evapotranspiration) before either reacting further to create more acid and/or being precipitated creating secondary minerals such as sulphates (jarosite, alunite, gypsum), iron oxides (goethite, hematite, ferrihydrite) and possibly silicates (smectite) as dictated by the pH, Eh and concentration (Carson *et al.*, 1982).

Mine wastes may contain neutralising gangue minerals (e.g. minor levels of carbonate or to a lesser extent aluminosilicates) so AMD may not appear to be a problem early in the mine's history (Ritchie, 1992, 1994). Once all neutralising minerals are used, AMD becomes apparent and environmental problems are generated. Without neutralisation, AMD development does not cease until all sulphides are completely oxidised - a process which can take up to 1000 years.

Sulphide Oxidation

The main mineral involved is pyrite (although other sulphides do contribute), because Fe component after being released into solution as Fe^{2+}, oxidises to ferric ions which further acts as an oxidant to pyrite. At Wheal Ellen, pyrite is also volumetrically dominant, so its reactions only will be discussed.

On exposure to air, FeS_2 (pyrite or marcasite) oxidises, releasing ferrous ions and creating sulphate and hydrogen ions (commonly combining to form sulphuric acid) (Equation 1), being available for transportation by surface or ground water;

$$FeS_{2(s)} + 7/2O_{2(g)} + H_2O_{(l)} \rightarrow Fe^{2+}_{(aq)} + 2SO_4^{2-}{}_{(aq)} + 3H^+_{(aq)} \qquad (1)$$

If desiccation conditions exist (as may be found at the surface), the iron (II) and sulphate ions may form a variety of highly soluble $FeSO_4$ minerals - commonly melanterite ($FeSO_4.7H_2O$), with alternatives including ferrohexahydrite ($6H_2O$), siderotil ($5H_2O$), rozenite ($4H_2O$) or szomolnokite (H_2O) depending on variations in humidity (Alpers *et al.*, 1994).

Alternatively, ferrous iron will undergo direct oxidation and hydrolysis, forming iron oxides ($Fe(OH)_3$) and further acid (Equation 2). This reaction commonly occurs in streams, down to pH levels of 5, triggered by the water's higher pH. The formula $Fe(OH)_3$ does not actually belong to any known mineral, but rather describes the precipitation of very insoluble, poorly crystalline iron 'oxide' minerals (the red precipitate so characteristic of AMD discharge). In this case, other base metals are not able to bind with the Fe hydroxides (Fanning & Fanning (1989) and remain in solution.

$$Fe^{2+}_{(aq)} + O_{2(aq)} + 10H_2O_{(l)} \rightarrow Fe(OH)_{3(s)} + 8H^+_{(aq)} \qquad (2)$$

Alternatively, in more acidic conditions, ferrous iron can oxidise to ferric iron;

$$2Fe^{2+}_{(aq)} + 2H^+_{(aq)} + 1/2O_{2(g/aq)} \rightarrow 2Fe^{3+}_{(aq)} + H_2O_{(l)} \qquad (3)$$

Reactions (2) and (3) do not need to be in the presence of the pyrite in order to take place. Material often is transported long distances before the complete oxidation and hydrolysis occurs. Reaction (3) is often accelerated (factors $10\text{-}10^5$) by iron oxidising bacteria (Ivarson *et al.*, 1982; Nordstrom, 1982).

Ferric iron can take one of several pathways. In a desiccating environment, highly soluble Fe sulphates (commonly copiapite ($Fe^{II}Fe^{III}{}_4(SO4)_6(OH)_2.20H_2O$), may precipitate out (Alpers et al, 1994). Alternatively, in the presence of free water, an at pH's less than 5, the ions remain in solution and can oxidise pyrite. Again it is the sulphide which is oxidised and further Fe(II) is released (Equation 4).

$$FeS_{2(s)} + 14Fe^{3+}_{(aq)} + 8H_2O_{(l)} \rightarrow 15Fe^{2+}_{(aq)} + 2SO_4^{2-}{}_{(aq)} + 16H^+_{(aq)} \qquad (4)$$

The ferric iron is the dominant and fastest oxidant of pyrite (Nordstrom, 1982). The Fe(III) also depends on the pH of the system because that is what governs the solubility of ferric oxyhydroxides (see equation (5)).

If pH is greater than about 5, Fe(III) precipitates out as an oxide;

$$Fe^{3+}{}_{(aq)} + 3H_2O_{(l)} \rightarrow Fe(OH)_{3(s)} + 3H^+{}_{(aq)} \qquad (5)$$

The overall final equation combines pyrite oxidation, Fe(II) hydrolysis and Fe(III) -> iron hydroxide;

$$2FeS_{2(s)} + 15/2O_{2(aq)} + 7H_2O_{(l)} \rightarrow 2Fe(OH)_{3(s)} + 4SO_4{}^{2-}{}_{(aq)} + 4H^+{}_{(aq)} \qquad (6)$$

This overall equation for pyrite is basically applicable to all sulphide minerals, although research on these are much less extensive (Ritchie, 1994).

Rate Affecting Factors

Although the chemical processes described above are constant, various properties will affect the intensity of acid formation including sulphide surface area, pH, temperature, oxygen concentration, Fe(III) chemical activity and permeability of water and oxygen (Pugh *et al.*, 1982; Lowson, 1982; Milne, 1995).

Secondly, biological factors significantly affect the rate of acid production; the oxidation reactions (of pyrite and ferrous ions) may be a slow process were it not for the catalytic behaviour of certain acidophilic, aerobic bacteria (Pugh *et al.*, 1982). The influence of catalytic oxidising bacteria is apparent at most sulphide minesites, however the relative importance of the inorganic versus bacterial influences vary at each site.

$$2Fe^{2+}{}_{(aq)} + 1/2O_{2(aq)} + 2H^+{}_{(aq)} + \textit{T. ferrooxidans} \rightarrow 2Fe^{3+}{}_{(aq)} + H_2O_{(l)} \qquad (7)$$

The best known example is *Thiobacillus ferrooxidans* believed to increase the rate of ferrous (Fe^{2+}) ion oxidation (Colmer & Hinkle, 1947, cited in Ritchie, 1992) and more recently was discovered to also act as an accelerant in pyrite oxidation (Morin *et al.*, 1991). Other known examples of pyrite oxidising catalysts include; *Ferrobacillus ferrooxidans*, *F. thiooxidans*, *Thiobacillus thiooxidans* (Lowson, 1982) and the recently identified *Leptospirillum ferrooxidans* (Norris *et al.*, 1988, cited in Ritchie, 1992).

Acid within the soil destroys vegetation, often leaving soil bare and open to erosion. Additionally, the acid attacks plant pathogens, decreases soil microbe levels and creates a deficiency in plant base materials (Ca, Mg and K) or nutrient availability (especially P) (White, 1995). A lowered pH of surface and groundwaters has adverse effects on aquatic biota and other living organisms (White, 1995). When acid waters with high Fe^{2+} content mix with surface streams, ferric hydroxide precipitates as the pH increases creating a characteristic reddish brown discoloration and increased turbidity (Ritchie, 1992, 1994).

A1.2 Heavy Metal Contamination

Perhaps the biggest problem associated with AMD is not the acid itself, but rather that at lowered pH the solubility of trace and heavy metals increases (Thornber, 1992; Ritchie, 1994), increasing concentration in leaching waters by several orders of magnitude (Ritchie, 1992). Thus, AMD will leach out any heavy metals contained within the sulphides themselves or soil or dumped rock, commonly Cu, Pb, Zn, Cd, Ag, Au, Sb and Bi (Taylor, 1996), which are toxic to both aquatic and land fauna and flora in excess (Ritchie, 1994; Fergusson, 1991).

The mobilisation of heavy metals, released from minerals is primarily dependent on pH of solution, however concentration, Eh and other ions in solution are contributing controls (Thornber, 1992), making a full description of the likely chemical mobility of an element very complex (Evans, 1989).

Heavy elements may be
(a) solid; held within the crystal lattice of a mineral (primary or secondary mineral)
(b) loosely bound in a layer charging potential field layer at the solid/solution interface (either adsorbtion or ionic exchange)
(c) mobile in solution (solvated by the water molecules, complexed with at least one other soluble ion or complexed with colloidal particles)

The heavy metals will remain in solution until pH increases again when they will drop out of solution. There are various ways this can happen, as outlined below, the constraints of which are complicated and not fully understood. The mere presence of a high level of a heavy metal as determined by XRF does not in itself constitute an immediate environmental threat. The form of the metal has to be taken into account. In ionic form, the metal is available to organisms in the soil or water which in turn may be consumed by animals or humans. The following outlines the effects of metals on the environment as dependent on their form. With enough time, all heavy metals have the potential to be released into the environment where they may be taken up by vegetation and eventually animals or enter the water systems.

Sulphides

Within a sulphide there may be a high level of Fe (pyrite, pyrrhotite, marcasite), Pb (galena), Zn (sphalerite) or Cu (chalcopyrite), to name the materials relevant to this project. In the case of an isolated grain of any of these material, on oxidation, the metals may be released in ionic form to oxidising waters. If this water is of sufficient volume, the metal ion will be transported and only then may be considered a threat. Alternatively, if the sulphide oxidation creates a gossan (the surface expression of sulphide weathering) individual grains may leave a void. The ions in solution may be carried away if water is available (and hence pose and environmental threat) or be deposited around the rim of the box work as an oxide (see below for effects). The final alternative is that when a sulphide is in the ore, or in a waste dump, it occurs in fragments, only the surface will be oxidised and only those heavy metals will be released. These may be redeposited fairly rapidly as conditions change. If there is sufficient water, the ions will be carried away. In ionic form they are a threat unless incorporated into some other material. Considering AMD continues until all sulphides are oxidised, these materials are a threat only on an extended timescale (in the next 1000 years).

Precipitation

Precipitation of secondary minerals occurs on increase in pH, or a change in Eh. Depending on the form of secondary mineral, solubilities and hence the potential for incorporated heavy metals to be released into the environmnet, differs. Highly soluble minerals primarily include iron sulphates (melanterite, rozenite, halotrichite), compared with less soluble minerals such as the alunite-jarosite series (includes plumbojarosite), anglesite and gypsum (Davis *et al.*, 1993; Alpers *et al.*, 1994). Even these so called insoluble minerals do have the potential to eventually break down (Saether *et al.*, 1988), especially in an environment with a high through flow of running water. If a heavy metal is coprecipitated into a secondary mineral, it too will be released on dissolution (Alpers *et al.*, 1994).

Many silicates and other minerals are decomposed to some extent by the sulphuric acid and new minerals form from reaction products, but often in a different location (e.g. jarosite precipitates in structural partings where Eh is high enough for Fe(III) to be stable

Hydrolysis of ferric ion in the presence of potassium and sulphate ions and at a low pH creates one of the most common AMD associated secondary minerals, jarosite (Dutrizac & Kaiman, 1976);

$$3Fe^{3+}{}_{(aq)} + K^{+}{}_{(aq)} + SO_4{}^{2-}{}_{(aq)} + 6H_2O_{(l)} \rightarrow KFe(III)_3(SO_4)_2(OH)_{6(s)} + 6H^{+}{}_{(aq)} \qquad (8)$$

The K or Na (in natrojarosite) can arise from the acid sulphate weathering of silicates (e.g. micas or feldspars). The jarosite minerals are quite insoluble under Eh conditions where Fe(II) is stable. Once the jarosite is formed, it may remain for long time periods.

Summary reaction of jarosite formation;

$$FeS_{2(s)} + 15/4O_{2(g)} + 5/2H_2O_{(l)} + K^{+}{}_{(aq)} \rightarrow 1/3KFe_3(SO_4)_2(OH)_{6(s)} + 4/3H_2SO_{4(aq)} \qquad (9)$$

Jarosite precipitates and removes Fe and sulphate as well as metal ions from solution. This reaction can be carried out in a strongly acidic environment (Dutrizac & Kaiman, 1976). At increased pH's, jarosite hydrolyses, releasing acid and any heavy minerals incorporated into the structure;

$$\mathbf{KFe_3(SO_4)_2(OH)_{6(s)} + 3H_2O_{(l)} \rightarrow 3H^+_{(aq)} + 2SO_4{}^{2-}{}_{(aq)} + 3Fe(OH)_{3(s)} + K^+_{(aq)}} \qquad \mathbf{(10)}$$

i,e. acid is produced during the initial flush of AMD (Equation 8) when jarosite is formed and then plays a further role after pyrite oxidation - if jarosite is leached, the soluble sulphate is removed and further acid is released (Equation 10).

Coprecipitation

Defined as the "precipitation of elements from solutions in which they would normally be soluble as the result of the precipitation of some other, more abundant element" (Sposito, 1983). Coprecipitation is greatest at high cation concentrations and high pH values. The extent to which the process takes place however correlates to the solubility and adsorption properties (an indication that similar bonding mechanisms are involved).

Adsorption

The term adsorption refers to the "binding of elements at the solution/mineral surface". The most important parameter affecting adsorption is pH; adsorption increases 0->100% in 1-2 pH units. The onset is characteristic of each metal. A mineral's surface charge changes from being positively charged at low pH to negatively charged as pH increases (i.e. with increasing OH- concentration), increasing the rate of adsorption of cations from solution (Naidu & Sumner, 1996). There is a specific pH at which the change over occurs (at which the net zero charge(pzc)), which can be used as an indication of whether a material will be positively or negatively charged (and therefore likely to adsorb anions or cations) at a particular pH (Thornber, 1992; Naidu *et al.*, 1994). Although all mineral surfaces adsorb, and have a pzc, the level of adsorption varies between mineral types. Surface area plays an important part in this. Materials such as Fe-oxides have a higher surface area per volume material compared with say quartz, and correspondingly the adsorbtion potential is much higher. The nature of the mineral type with respect to its susceptibility to ionic exchange is another factor. Clay, carbonates, quartz, feldspar and organic solids may be coated with hydrous Mn and Fe oxides and /or organic substances, thus altering their adsorption capabilities - especially in a water environment. Those with high adsorbtion levels (e.g. smectite) will adsorb a higher level of heavy metals from water carrying a high contaminant load. Adsorption onto colloids and subsequent transport this way is a common and often overlooked occurrence (McCarthy & Zachara, 1989).

The biggest cases of adsorbance at Wheal Ellen would be that of heavy metals on to iron oxides (hematite and goethite), with increasing pH. These metals could be released on lowering of pH again as the surface charge will be positive (less OH- on surface) and not attract cations any more. (Naidu *et al.*, 1994).

Ionic Exchange

On the surface of a mineral, or in the interlayers of phyllosilicates, a heavy element may be substituted for a more common element. Concentrations of heavy elements incorporated into a mineral in this manner are typically very low.

Effect of organic matter

In a natural system, the values may be altered by other factors, e.g. goethite surfaces become more negatively charged in the presence of humic substances (Thornber, 1992).

Dissolved organic carbon (DOC) has been found to be a significant soil solution component with respect to soil chemical processes including mineral weathering, metal leaching and toxicity, acid-base chemistry in natural waters, solubility control of metal ions in soils and dissolution and plant availability of nutrient ions such as P. The nature of interaction between trace metals in soil solution, dissolved organics in soil solution and solid surfaces may play a role in heavy metal contamination (Harter & Naidu, 1995).

A1.3 Current Rehabilitative Techniques

Using current knowledge of the processes governing AMD, newly developing mines aim to prevent (or at least minimise) AMD generation through appropriate site selection and mine planning. Clearly, this is too late for old mine sites such as Wheal Ellen where AMD is already active. Once sulphide oxidation has commenced, the process will continue until all sulphide is removed which may take hundreds to thousands of years. An array of methods of AMD amelioration are currently utilised worldwide as outlined below (Morin *et al.*, 1991; Ryan & Joyce, 1992; Jones & Chapman, 1995; White, 1995), although none is yet considered totally effective while still being cost efficient.

It is practically impossible to stop AMD generation once initiated, until all sulphides are removed (up to thousands of years), however if any contributing factors (sulphidic material, oxygen, water, oxidation catalysing bacteria) are eliminated or at least reduced, AMD production should decrease to an acceptable level and relieve associated environmental problems. Examples include removal of sulphide, storage underwater, impermeable capping, insoluble coating on sulphides or removal of catalysing bacteria. Alternatively, as water is the contaminant transport mechanism for generated acid and any heavy metals, options regarding management of water flow by engineering techniques are being considered as realistic alternatives for rehabilitation (Gilbert, 1995). In contrast, rather than trying to stop acid production, accelerated oxidation of all sulphides by leaching or microbiological action during the mine's life is a possible viable option.

Using any of the above methods to reduce acid generation will also effectively decrease the mobility of heavy metals but will not eliminate contamination by heavy metals already mobilised. Addition of neutralising material (e.g. lime, magnesite, limestone, dolomite) to create alkaline conditions will neutralise acid as it is produced and cause precipitation of heavy metals from solution (Blowes & Ptacek, 1994). Acid is also neutralised to a lesser degree through reactions with silicate and other minerals.

$$H_2SO_{4(aq)} + CaCO_{3(s)} + H_2O_{(l)} \rightarrow CaSO_4.2H_2O_{(s)}\ \text{(gypsum)} + CO_{2(g)} \qquad (11)$$

In order for this to be effective, sufficient alkali is required - acid base accounting. A local example, Brukunga Pyrite Mine currently is attempting to combat its massive AMD problems through a neutralisation plant. The plant is not a viable long term option, however, due to high costs (Agnew, 1994).

Acid is also naturally consumed through reactions with silicate minerals eg biotite (Equation (12)) or muscovite (Equation (13)), with kaolinite as the main product (Jambour & Blowes, 1994);

$$K(Mg,Fe)_3(Si_3Al)O_{10}(OH,F)_{2\,(S)} + 4Al^{3+}_{(aq)} + 3H_2O_{(l)} + 2H^+_{(aq)} \rightarrow$$
$$3Al_2Si_2O_5(OH)_{4(s)} + 2K^+_{(aq)} + 3Fe^{2+}_{(aq)} + 3Mg^{2+}_{(aq)} \qquad (12)$$

$$2KAl_3Si_3O_{10}(OH)_{2(s)} + 3H_2O_{(l)} + 2H^+_{(aq)} \rightarrow 3Al_2Si_2O_5(OH)_{4(s)} + 2K^+_{(aq)} \qquad (13)$$

Wetlands, described as "a complex assemblage of abiotic chemical processes, aerobic and anaerobic bacteria, emergent rooted plants, floating plants, epiphytes on the surfaces of plants and algae co-existing in a functional relationship" are a more recent method of combating all the effects of AMD (Jones & Chapman, 1995). Wetlands are sustainable and relatively low cost to initiate and maintain aesthetically pleasing and rely on a range of natural processes for success (Jones & Chapman, 1995). The principle functions of a wetland filter system include (Ryan & Joyce, 1992; Kwong & Van Stempvoort, 1994; Jones & Chapman, 1995);

- Dilution of contaminants
- Dispersion of contaminants
- Metal sulphide and iron precipitation by sulphate reduction (often catalysed by bacteria)
- Metal exchange by organic substrate

- Mn/Fe precipitation as pH increases
- Adsorption of dissolved metals onto suspended and bed sediments
- Aquatic plant uptake of removed metals
- Filtering of suspended solids
- Increasing pH due to NH_3/HCO_3 production from decaying matter

Revegetation

Once AMD and its associated contaminants have reached a satisfactory level, revegetation will in many cases be a prime concern. Eroded landscapes require the addition of topsoil. Variations aimed at improving the nutrient levels in depleted soils include the use of sewage, mulch and organic material to fertilise new plants and assist in surface stabilisation prior to the addition of seeds or seedlings (Ryan & Joyce, 1992). In conjunction with aesthetic improvement and erosion control, these measures in themselves may control acid generation in the short term (Morin *et al.*, 1991),

Monitoring

Each case of minesite rehabilitation is different (the type and amount of sulphidic material, topography, local climate, hydrological regime, environmental sensitivity, ecological setting etc), requiring separate consideration. Unfortunately, no set criteria exist outlining which method to use in any particular case. In the course of any amelioration or rehabilitation strategy, monitoring before, during and after implementation is essential (White, 1995).

Appendix A2
METHODOLOGY for SAMPLING and ANALYSIS

A2.1 Sampling

Solids

The majority of the samples used in this project consisted of solid surface material, being soils, dumped bedrock and mine wastes (sulphides, tailings, slag, gossan and secondary minerals). After a preliminary examination of the area, sampling was conducted so as to gain representatives of each of the mine materials (as opposed to random or grid sampling), whereas soils were sampled randomly along erosion gullies downslope of the mine, at various random background sites and within the suspected wetland area. Samples were labelled according to site, as outlined in Table A2.1

SOIL		
Prefix	Area	No
X	Mine material	
C	'Control' or background soil	
W	Western gully	
N	North-eastern gully	
S	South-eastern gully	
O	Cores	
MS	Mound spring and surrounds	
J	Arsenic labyrinth	
B	Upstream property	

WATER		
Prefix	Area	No
R	Rodwell Creek	
B	Bore	
D	Dam	
S	Spring	
MS	Mound spring	

Table A2.1 **Sample prefix definitions**

Sampling depth was approximately 50mm, despite the difficulties presented by such variation in the material and setting of the samples. Occasional exceptions to this sampling depth (e.g. profiles up to 80cm, surface crusting, slag runs) are noted where appropriate.

A soil shovel was used for all the solid sampling, except in the case of the two soil profiles, for which a spatula was needed to avoid overlap between each 10cm section. Individual samples were stored in a new plastic bag with an airtight seal until later laboratory analysis.

Core sampling involved driving 50cm long stainless steel tubes (4 cm diameter) into the sediments with a sledge hammer. Core profiles greater than 50 cm were collected by attaching an extension pole to the core tube which was then hammered. During transportation of the samples, each core was sealed from the atmosphere using putty plugs and rubber bungs. The cores were extruded into split plastic tubing. Each core was individually tightly wrapped in plastic and refrigerated to minimise any reactions with air prior to examination and analysis.

Water

Water samples were collected at regular intervals along Rodwell Creek and at various other spot sites depending on availability (bores, dams etc). All Rodwell Creek and 'mound spring' sample sites had a water depth of less than about 30cm, hence sampling at various depths was not considered practical. All sampling took place in the centre of the creek and at approximately middle depths. Care was taken to avoid disturbing the bottom sediments. Bore/spring samples were taken after a period of free flow to ensure sampling was representative of the whole water body. The dam sample was taken about 50 cm off shore at the mine surface run off entry point. Again the water was shallow (15cm), requiring only one mid-depth sample.

Each water sample was collected and stored in a new, tightly sealed, plastic bottle. During collection, the sample bottle was completely filled, thus preventing oxygenation of the contents. The pH of the water at each site was measured in the field, thus the samples were able to be acidified with dilute HCl to prevent precipitation of Fe^{3+} and other elements (Rayment and Higginson, 1992).

A2.2 Sample Preparation

Solids

A number of soil samples contained large rocks and/or coarse quartz grains thus required sieving (2.4mm mesh). Occasionally samples required breaking with a geological hammer. Three soil samples were divided into size fractions (<102µm, 102-212µm, 212-600µm, 600µm-1.2mm and 1.2-2.4mm) which were individually analysed.

pH, EC & ICP-AES

Preparation of all solid samples for pH, EC and ICP-AES analysis involved the 1:5 soil/water extraction method. This procedure has been widely used in Australia for many years, and is now generally regarded as the standard preparative method in most laboratories as an indication of potential solute characteristics (Rayment and Higginson, 1992).

Prior to extraction by water, each sample was air dried in an open dish. Most samples were only left overnight although some mound spring samples required air drying periods up to 7 days. Oven drying of the samples was not used because it necessitates a difficult conversion of the final result (Rayment and Higginson, 1992). All results reported are on an 'air-dry' basis.

Once dry, each sample was accurately weighed (10g ± 0.1g) and mixed with 50ml deionised water. The water and solid mix was mechanically agitated for one hour using the preferred end over end method (Rayment and Higginson, 1992), operating at 14 rpm at 20° C in a constant temperature room). After settling for around 20 minutes, each sample was tested for EC and pH. Measurements should be taken within 4 hours of the aqueous supernatant development to ensure validity.

The solutions were then filtered in preparation for ICP-AES analysis. Occasional samples containing extremely fine material were filtered using -45μm Millipore filter paper.

XRF

For determination of composition by XRF, samples not dry enough to crush without smearing were initially oven dried at a temperature of 105°C. Each sample needs to be a uniform fine silt size and all were ground either by hand (using a mortar and pestle) or mechanically (with a tungsten-carbide mill), depending on the nature of the material. Over night oven drying at 105°C removed any remaining moisture (this allows comparability between samples). The 'grab' weight method of sample weighing was then employed. This involves accurately weighing out approximately 1g of each sample, with 4g of flux and a varying amount (0.5 - 1.5g, increasing with the amount of sulphide believed present) of sodium nitrate ($NaNO_3$). The mixture was transferred to a Pt-Au crucible and oxidised in a furnace for about 10 minutes. The molten material was fused over a flame of approximately 1050° before being poured into a Pt-Au mould and cooled via air jets to create a glass disk.

XRD

Samples prepared for mineralogical determination by XRD required excess moisture removal by overnight oven drying at 60°C (higher temperatures may cause alteration of the mineralogy). Again, samples were finely crushed using either a mortar and pestle or a tungsten-carbide mill, depending on the nature of the sample. The resultant fine powder was pressed into an aluminium holder (approximately 1g in volume) and loaded into an automatic sample holder capable of holding 20 pressed powder samples simultaneously.

Sulphur Isotope Ratios

Sulphur isotope ratios were determined on both sulphides and sulphates. The sulphides were first identified via hand specimen examination under an optical microscope and confirmed by XRD analysis. The sulphates were examined by scanning electron microscope (SEM) and similarly confirmed with an XRD analysis. After identification, the samples were crushed either by tungsten-carbide mill or mortar and pestle to a fine silt size. The crushed sulphate samples were weighed out with accurately known weights of approximately 100mg copper oxide (Cu_2O) and 200mg silica (SiO_2). The two sulphides were similarly weighed with 100mg Cu_2O, although silica was not required. Each mixture was further crushed and homogenised in an agate mortar and pestle, mixed and placed in a glass tube with quartz wool seals.

From this stage onwards, solid and 'water' samples (see below) were treated in the same manner. The glass tubes were placed in a glass sheath and attached to a vacuum line. Once evacuated, the sample was heated (the maximum temperature depending on the sample; 1100°C (sulphates), 950°C (pyrite) and 900°C (sphalerite)). The evolved gases were passed through cooling tubes and the sulphur dioxide isolated through the use of differing cooling temperatures (using ethanol, propanol and dry ice). Once isolated, the SO_2 was collected in glass tubes, ready for analysis on the mass spectrometer.

SEM & EMP

Some samples were examined by electron beam techniques; the scanning electron microscope (SEM) and electron microprobe (EMP). Samples were oven dried (60°C) until excess moisture was removed. Dried samples were made into a polished resin block mount by standard techniques. Preliminary optical microscopy allowed the marking of relevant areas to be examined, with a carbon based texta. The blocks were carbon coated prior to examination.

Water

EC & ICP-AES

Little preparation other than acidification and filtering (size 52 filter paper or -45µm Millipore where required) was required for EC determination and analysis by ICP-AES.

Sulphur Isotope Ratios

Of the five samples to be analysed for sulphur isotope ratios, three contained a high level of suspended solid material (orange-red iron hydroxide precipitate and/or organic material). Prior to any preparatory work, this material was removed via Millipore, using -45µm filter paper. Each sample was heated on a hot plate until almost boiling. At this stage, if the pH was not below 3, required acidification with 5.0M HCl. Once acidified, 20 ml liquid barium chloride ($BaCl_2$) was slowly added while the sample was stirred. The amount added varied according to the level of sulphur in the sample as previously determined by ICP-AES analysis. The mixture was covered and left to cool overnight, during which time, any sulphate ions present formed barium sulphate precipitate. Once the precipitate settled, water was decanted. The precipitate was washed by mixing with approximately 500ml deionised water and left again to settle (a few hours). This process was repeated twice. After the final washing, as much water as possible was removed and the material left overnight in the oven at about 70°C to dry out. Once dried, the precipitate was scraped off and collected.

Ideally, 20mg of $BaSO_4$ is required for analysis, however two samples did not yield this much owing to the low sulphur content. However, there was still a satisfactory amount to work with. The solid barium sulphate was weighed out with approximately (but accurately known) 100mg of Cu_2O and 200-220mg SiO_2. In addition, two standards were prepares; (1) barium sulphate from seawater, and (2) another barite of known sulphur isotope ratio. The remainder of the procedure is as described for solids.

A2.3 Analytical techniques

Munsell Colours

All solid samples were described using standard Munsell colour charts. This incorporates the sample's hue (relation to red, yellow, green, blue and purple, as described by the letters 'R', 'YR' or 'Y' and ranging from 0 (red) to 10 (yellow)), value (lightness; ranging from 0 (black) to 10 (white)) and chroma (strength - the departure from the neutral of the same lightness; ranging from 0 (grey) to 20 (this level occurs infrequently)). All colour determinations were on air-dried samples.

EC

Both water samples and solid extracts were measured in the same fashion with the use of a Radiometer-Copenhagen CDM83 Conductivity Meter with digital display and a $k=3.16 *(1+DEV\%/100)$ conductivity cell ($k=3.002$ for current cell). The conductivity cell was dipped into each solution 3 times, with a value being recorded once the reading stabilised. All results are expressed in dSm^{-1}. The cell was rinsed with deionised water between samples to avoid cross contamination.

The reference solution for the measurements is made with 0.7455g potassium chloride (KCl, dried at 110°C for 2h) made up to 1.0L with CO_2 free deionised water. The final solution should have an EC of 1.413 dSm^{-1} at 25°C (Rayment and Higginson, 1992). EC values increase with temperature increase and so must not be measured at temperature greater than 25°C unless the appropriate corrections are applied (Rayment and Higginson, 1992). All measurements for this study were made at less than 22°C.

When the same suspension is to be measured for Cl^- concentration and pH determination (as it was in the case of this study), it is important to measure EC first in order to avoid contamination of the suspension by the pH reference electrode (Rayment and Higginson, 1992).

pH

Measurements were made with a pH meter (Radiometer PHM95) together with a combined electrode mounted in an electrode holder with a stirrer (Radiometer TTA80). Owing to the acidic nature of the samples, method 'A' was utilised (that pertaining to materials with an expected pH less than 7). The instrument was calibrated with pH 4 and pH 7 buffer solutions prior to use, at the specific temperature. The solution was stirred during measurement (this minimises changes in electrode potential due to the suspension effect and the electrode positioning). The electrode and stirrer were rinsed with deionised water between each measurement. Similarly to EC, results are reported on an 'air-dry' basis.

The pH of all water samples were determined in the field, thus removing risk of inaccuracy created by changes in concentration of dissolved gases (e.g. H_2S, Cl_2, O_2 and CO2), which could arise during transportation. Measurements were made with a portable pH meter. Calibration, using buffer solutions, took place prior to fieldwork.

ICP-AES

Both 'solid' and water samples were similarly analysed by a inductively coupled plasma atomic emission spectrometer (ICP-AES) against standards of an appropriate matrix at the CSIRO Division of Soils (S.A.).

Sulphur Isotope Ratios

Sulphur isotopes were measured using the Micromass Model 602E mass spectrometer at The University of Adelaide, Department of Geology and Geophysics. Samples with especially low gas volumes required the additional use of a "cold finger" (cooled with liquid nitrogen) during analysis.

XRD

A Phillips PW1800 microprocessor-controlled diffractometer was used, with Co, $K\alpha$ radiation, variable divergence slit and a graphite monochromator. Steps of 0.05°, 2θ with a 1 second count time per step were used to acquire the diffraction patterns. Resultant plots were placed on permanent files on an ABM PC/XT (Self, 1988), and interpreted using the software package XPLOT at CSIRO Division of Soils.

XRF

The instrument used was a Phillips PW1480 XRF system. A control program developed by Phillips and algorithms which had been developed by Keith Norrish and Paul Fazey of CSIRO, Division of Soils, were employed. Both major (Si, Al, Fe, Mn, Mg, Ca, K, Ti, P & S) and selected trace elements (Ba, Co, Cr, Cu, Ga, Ni, Pb, Rb, Th, U, V, Y, Zn, Zr, Sb*, Cd*, As*, Ce* & La*; * denotes element was not measured for entire sample selection) were analysed. Calculated errors for elemental concentrations are outlined in Table A2.2.

Major Elements	
Element	Error (%)
SiO_2	0.24
Al_2O_3	0.15
Fe_2O_3	0.07
MnO	0.005
MgO	0.07
CaO	0.06
K_2O	0.03
TiO_2	0.02
P_2O_5	0.004
SO_3	0.005

Trace Elements	
Element	Error (ppm)
Ba	14
Co	3
Cr	7
Cu	11
Ga	3
Ni	5
Pb	10
Rb	4
Sr	3
Th	6
U	5
V	4
Y	3
Zn	10
Zr	9
Sb	5
Cd	5
As	15
Ce	9
La	18

Table A2.2 **Error margins for XRF determined elemental concentrations**

SEM

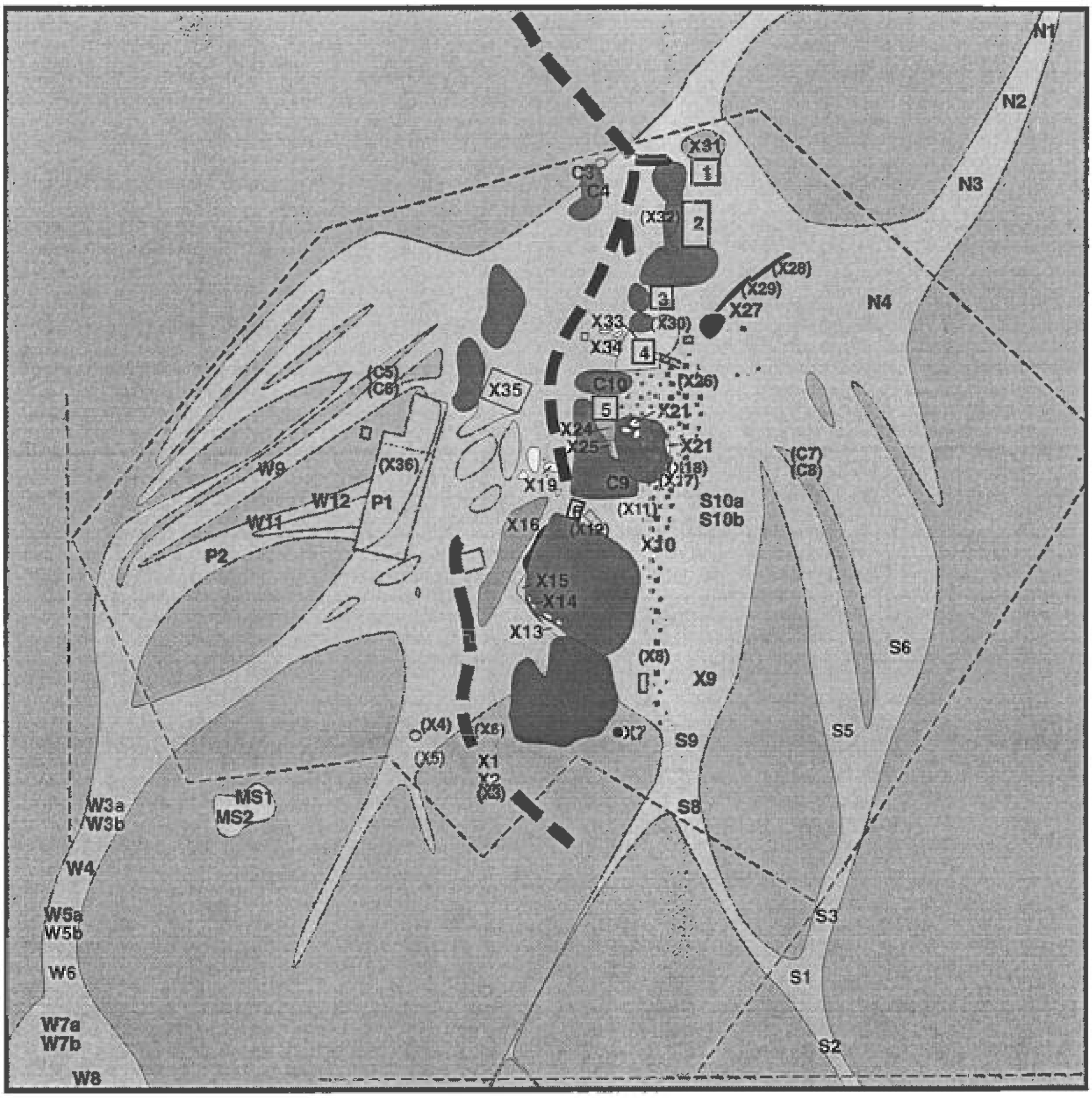
The instrument used for analysis was the Phillips XL20 at CEMMSA, University of Adelaide.

EMP

Analysis was conducted on a SX51 Electron Microprobe (EMP), at CEMMSA, University of Adelaide.

Appendix A3

SAMPLE SITE DESCRIPTIONS



Legend

▨	Sandstone (some soil cover, little vegetation)
▨	Dumped muscovite schist
▨	Dumped biotite schist
■	Dumped gossan
▨	Pyritic material
▨	Tailings
■	Slag
□	Secondary sulphates
▨	Newly deposited imported clay
▨	Native grasses
▨	Natural soak
⊡	Mine shaft
▭	Ruin
▭	Road
▭	Fence

Shafts

1	North Air Shaft
2	Spence Shaft
3	Middle Air Shaft
4	Main Engine Shaft
5	Scott Shaft
6	Bassett Shaft

0 30
metres

N

Figure A3.1 **All mine area sample sites. Those not used for analysis are bracketed.**

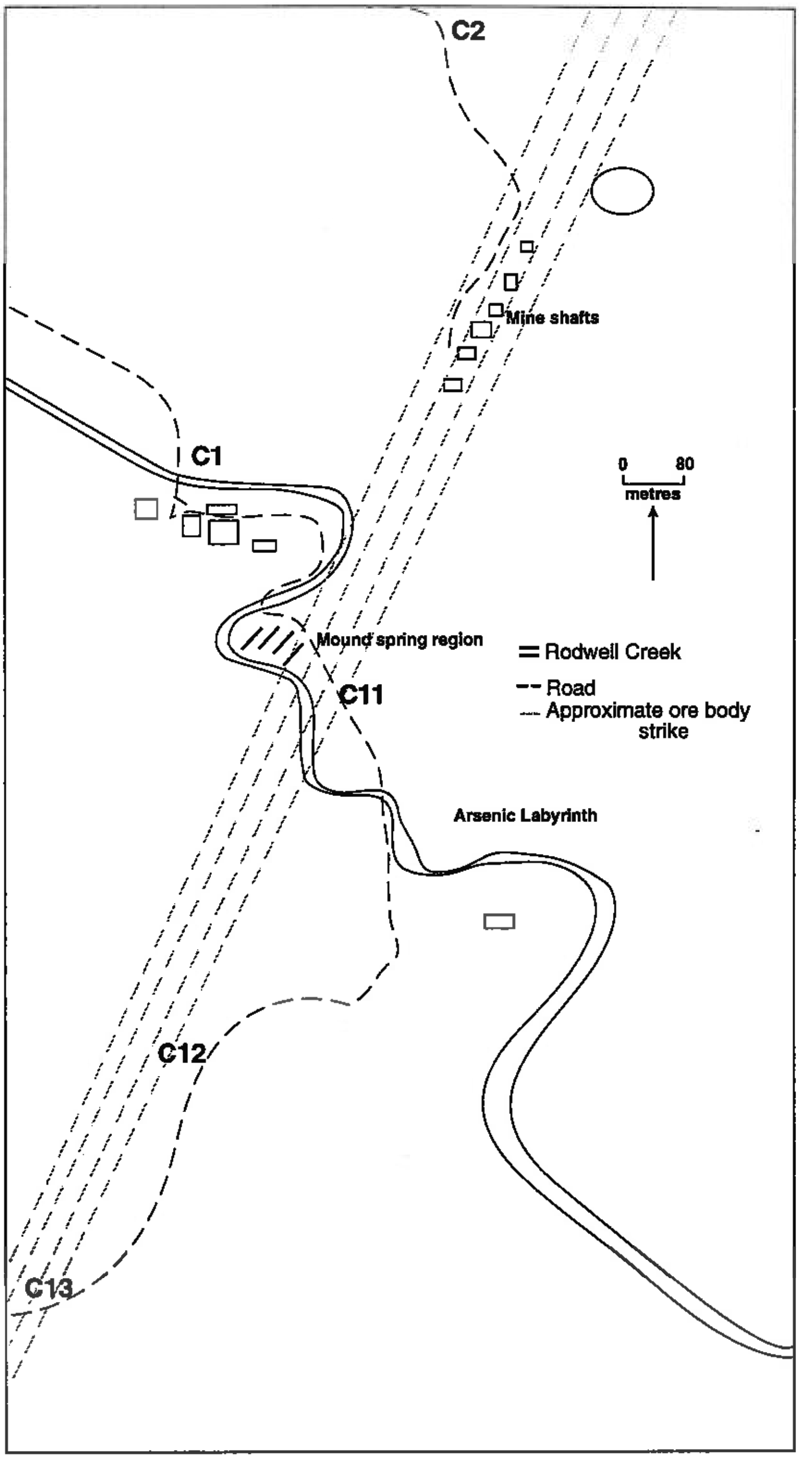


Figure A3.2 **Schematic diagram displaying background sample sites**

Table (A3.1) **Description of Mine Samples**

No.	**Site description**	**Classification**	Munsell Colour Desc.; Dry
MINE MATERIALS			
X1*	Very coarse 'gravel' chunks (cm scale) forming old road; inc. hematite. goethite, gossan and slag	Waste rock (road)	N/A
X2*	Fine grained old road material (appears to be crushed version of X1)	Waste rock (road)	N/A
X3	Solidified gravel forming edging of old road (again, similar compositionally to X1)	Waste rock (road)	N/A
X4	Soft vegetated soil inside old ruin; high organic content	Soil	10YR 3/3 dark brown
X5	V. coarse qaurtz grains and Fe rich material (eg hematite) washed down from shafts and old road	Soil	10YR 3/3 dark brown
X6	Very coarse 'gravel' chunks (cm scale) forming old road, similar to X1; supplies material to X5	Waste rock (road)	2.5YR 6/4 light yellow brown
X7*	Small (1m) gossan dump; gossan chunks approximately 2-8 cm in size	Gossan	N/A
X8	Soft vegetated soil inside old ruin; high organic content	Soil	10YR 3/3 dark brown
X9*	Coarse grained (up to 1cm) dumped quartz/gossan/iron oxide mix	Waste rock	10YR 6/4 light yellow brown
X10*	Material from shafts (4) and (5) with approximately 15% pyrite grains (approximately 2mm in size)	Sulphidic waste	2.5YR 6/6 olive yellow
X11	Partially weathered dumped muscovite schist intermixed with sulphate (predominantly jarosite)	Country rk/Sec. minerals	2.5YR 6/6 olive yellow
X12	Weathered muscovite schist washed down from shaft (6)	Country rock	10YR 4/4 dark yellow brown
X13*	Partially weathered dumped biotite schist intermixed with sulphate (predominantly jarosite)	Country rock (bt schist)	5Y 6/3 pale olive
X14*	Newly formed gossanous secondary minerals at base of recently dumped clay	Secondary minerals	5YR 3/4dark reddish brown
X15*	Highly weathered, dumped muscovite and biotite schists under clay (50cm depth)	Country rock (mica schists)	5Y 7/4 pale yellow
X16	Dumped pile of partially weathered (crumbly) muscovite schist, with secondary mineralisation	Country rock (mu schist)	10YR 6/3 pale brown
X17	Small (1m) lime dump (man made)	Neutralising material	N/A
X18	Concentrated mass of individual pyrite grains (2mm) under (50 cm depth) recently laid clay cover	Sulphidic waste	2.5YR 6/6 olive yellow
X19*	Very friable secondary sulphate mass with visible sulphide grains (1mm size)	Secondary minerals	2.5YR 6/4 light yellow brown
X20*	Partially weathered dumped micaceous schist intermixed with sulphate (predominantly jarosite)	Country rk/Sec. minerals	2.5Y 7/6 yellow
X21*	Newly formed white efflourescent secondary mineral crystals on new clay surface	Secondary minerals	2.5Y 8/0 white
X22*	Newly formed hard green/black/white secondary minerals on new clay surface	Secondary minerals	Various
X23	Small (1m) gossan dump; gossan chunks approximately 2-8 cm in size; similar to sample X7	Gossan	N/A
X24*	Surface dumped clay covering partially weathered sulphidic waste material (sample X25)	Country rock (biotite schist)	2.5YR 6/6 olive yellow
X25*	Concentrated mass of individual pyrite grains (2mm) under (30 cm depth) recently laid clay cover	Sulphidic waste	5Y 4/2 olive grey
X26	Soil at end of old 'railway' with visible (5%?) sulphide content (grains up to 1mm) from shaft (4)	Sulphidic waste	10YR 5/4 yellowish brown
X27*	Small pile (2m wide) of dumped slag from assay table	Slag	N/A
X28	Dumped slag from assay table forming run down gully (3m long)	Slag	N/A
X29	Small pile (2m) of dumped metallic waste material (man made substances)	Slag	N/A
X30	Friable, iron stained secondary sulphate	Secondary minerals	2.5YR 6/6 olive yellow
X31*	Dumped, partially weathered muscovite schist with occassional biotite schist lumps	Country rock (mu schist)	5YR 5/3 reddish brown
X32	Transported partially weathered (crumbly) biotite schist with intermixed secondary sulphate	Country rk (bt schist)/Sec. mins	5Y 7/4 pale yellow
X33	Transported partially weathered (crumbly) biotite schist with minor secondary sulphate levels	Country rk (bt schist)/Sec. mins	5Y 7/4 pale yellow
X34*	Coarse grained dumped quartz/gossan/iron oxide mix, contains muscovite flakes	Waste rock	7.5YR 5/2 brown
X35*	Pink, fine grained tailings material trapped by ruin	Tailings	7.5YR 4/4 dark brown
X36	Pink, fine grained tailings material trapped by ruin	Tailings	2.5YR 4/4 reddish brown
X37	Highly sulphidic rock (predominantly pyrite), with visible surface weathering (oxidation)	Sulphidic waste	N/A
X38*	Surface jarosite lump, surrounded by water transported soil	Secondary minerals	2.5Y 7/6 yellow

Table (A3.1) **Description of Mine Samples**

X39	Soil with significant sulphide content (20%) washed down from shafts (3) - (5)	Sulphidic waste	2.5YR 6/6 olive yellow
X40	Concentrated mass of individual pyrite grains (2mm) under (10 cm depth) recently laid clay cover	Sulphidic waste	5Y 4/2 olive grey
X41	Highly sulphidic rock (predominantly pyrite), with red-brown oxidised surface	Sulphidic waste	N/A
X42*	Highly sulphidic rock (predominantly pyrite), with minimal visible weathering effects	Sulphidic waste	N/A
X43	Highly sulphidic rock (predominantly pyrite), with minimal visible weathering effects	Sulphidic waste	5Y 4/2 olive grey
X44*	Surface jarosite lump, surrounded by water transported soil	Secondary minerals	2.5Y 7/6 yellow
X45	Coarse pyritic and quartz (purple stained) rich material washed down from shaft (4)	Sulphidic waste	N/A
X46*	Surface jarosite lump, surrounded by water transported soil	Secondary minerals	2.5Y 7/6 yellow
TAILINGS PROFILE			
P1	Profile through tailings material trapped by ruin	Tailings	10YR 3/3 dark brown
P1a*	surface	Tailings	10YR 3/3 dark brown
P1b*	10cm depth	Tailings	10YR 4/4 dark yellow brown
P1c*	20cm	Tailings	10YR 4/4 dark yellow brown
P1d*	30cm	Tailings	10YR 4/4 dark yellow brown
P1e*	40cm	Tailings	5YR 4/4 reddish brown
SOIL PROFILE			
P2	Profile through soil on eroded eroded hillslope		
P2a*	surface	Soil	7.5YR 4/4 brown - dark brown
P2b*	10cm depth	Soil	7.5YR 4/4 brown - dark brown
P2c*	20cm	Soil	7.5YR 5/4 brown
P2d*	30cm	Soil	7.5YR 5/4 brown
P2e*	40cm	Soil	7.5YR 5/4 brown
P2f*	50cm	Soil	7.5YR 5/4 brown
P2g*	60cm	Soil	7.5YR 5/4 brown
P2h*	70cm	Soil	7.5YR 5/4 brown
MOUND SPRING AREAS			
MS1*	V. fine soil from natural small soak, very high organic component	Soil	10YR 2.5/1 black
MS2*	Waterlogged soil (v. fine) with minor mica compoment,from base of natural small soak	Soil	2.5YR 3/2 dark - v. dark brown
MS3a*	Black, organic rich, water logged mound spring soil (10 cm)	Mound spring soil	5YR 2.5/1 black
MS3b	Black, organic rich, water logged mound spring soil (20 cm)	Mound spring soil	10YR 3/2 v. dark grey brown
MS4a*	Orange, organic rich, water logged mound spring soil (20 cm)	Mound spring soil	7.5YR 5/8 strong brown
MS4b	Orange, organic rich, water logged mound spring soil (30 cm)	Mound spring soil	7.5YR 5/8 strong brown
MS4c*	Orange, organic rich, water logged mound spring soil (40 cm)	Mound spring soil	5YR 4/6 yellowish red
MS5a*	Orange, water logged soil, near mound springs (10 cm)	Mound spring soil	7.5YR 5/8 strong brown
MS5b	Orange, water logged soil, near mound springs (20 cm)	Mound spring soil	7.5YR 5/8 strong brown
MS6a*	Black soil	Soil	10YR 5/2 greyish brown
MS6b*	Light brown sandy soil	Soil	10Yr 3/2 pale brown

Table (A3.1) **Description of Mine Samples**

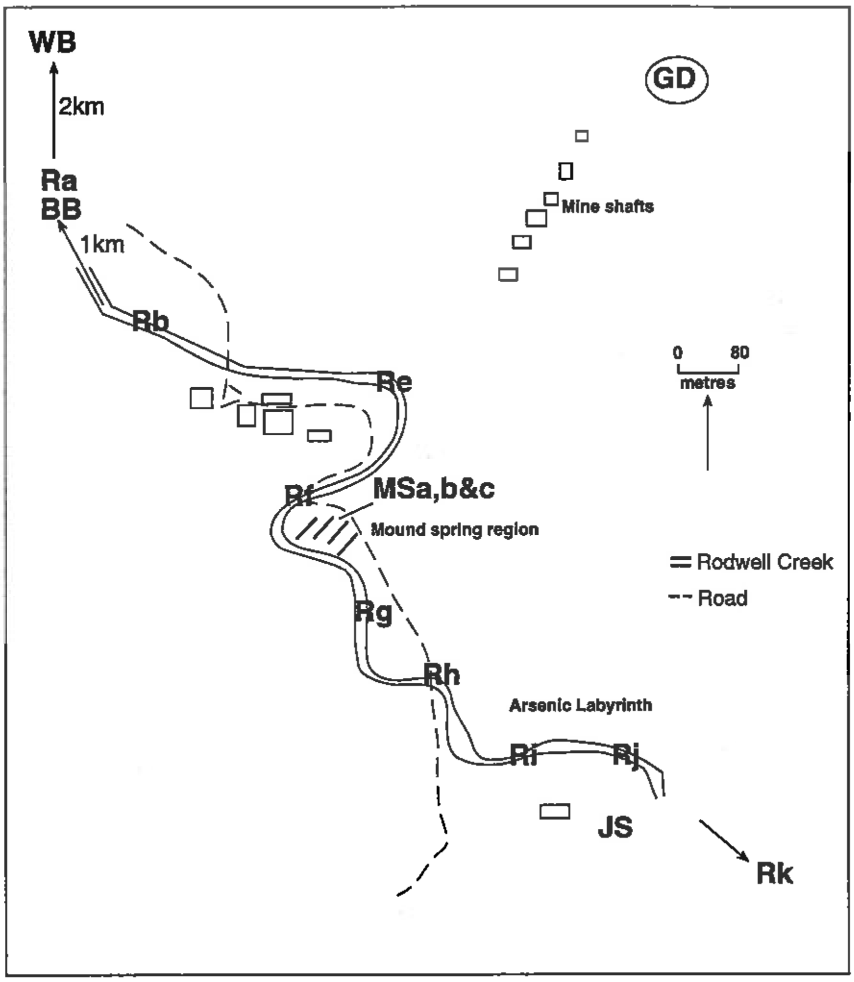
MS7*	Rocky material from limestone cliff adjacent to Rodwell Creek	Neutralising material	5Y 8/2 white
MOUND SPRING CORES			
Site 1	Core of mound spring flank (0-110 cm depth)		
	Black organic matter (0-12 cm depth)	Mound spring soil	10YR 2.5/1 black
O1*	Homogeneous, medium grain size, sands (12-48 cm depth)	Mound spring soil	5Y 5/1 grey
O2a*	Gradation of O1 - slightly sandier and lighter in colour (48-58 cm depth)	Mound spring soil	10YR 6/1 grey - light grey
O2b*	Red fine grained soil (FeO3 apearance) (58-83 cm depth)	Mound spring soil	7.5YR 4/4 brown - dark brown
O3*	Orange sandy clay (83-110 cm depth)	Soil	7.5YR 5/6 strong brown
Site 2	Core (50-80 cm depth)		
O4*	Orange sandy clay (50-80 cm depth)	Soil	7.5YR 4/4 brown - dark brown
WESTERN GULLY			
W0*	Transported soil in gully base; med - fine grained, minor fine grained mica constituent (<10%)	Soil	7.5 YR 4/4 brown - dark brown
W1*	Transported soil (med grained) & highly weathered micaceous schist in gully base	Soil	10YR 3/3 dark brown
W2*	Transported soil in gully base; med - coarse grained, <20% mica content	Soil	7.5 YR 4/4 brown - dark brown
W3a*	Transported coarse sandy seds in gully base (surface), quartz, mica & Fe oxides dominating	Soil	7.5 YR 4/4 brown - dark brown
W3b*	Transported soil from gully base (20-25 cm depth); v. coarse grained, similar to W3a	Soil	7.5 YR 4/4 brown - dark brown
W4*	Transported soil in gully base; med - coarse grained, compositionally similar to W3a	Soil	7.5 YR 4/4 brown - dark brown
W5a*	Transported soil in gully base; fine grained, minor fine grained mica constituent (<10%)	Soil	10YR 3/3 dark brown
W5b*	Transported sands in gully base (10 cm depth)	Soil	7.5 YR 4/4 brown - dark brown
W6*	Transported sandy seds in gully base, coarse grained, quartz, mica & Fe oxides dominating	Soil	7.5 YR 4/4 brown - dark brown
W7a*	Transported coarse sands in gully base	Soil	10YR 3/3 dark brown
W7b*	Organic rich clay in gully base (20-25 cm depth)	Soil	10YR 3/3 dark brown
W8*	Organic rich, waterlogged soil from Rodwell Creek; med grained, homogeneous	Creek sediments	10YR 3/3 dark brown
W9*	Transported soil in gully base (down hillslope); med grained with coarse quartz (10%)	Soil	7.5 YR 4/4 brown - dark brown
W10*	Transported soil in gully base (down hillslope), med grained, homogeneous	Soil	10YR 3/3 dark brown
W11*	Transported soil in gully base (down hillslope), med grained, homogeneous	Soil	10YR 4/3 brown - dark brown
W12*	Transported soil in gully base (down hillslope), med grained, homogeneous	Soil	7.5 YR 4/4 brown - dark brown
W12i*	Sieved fraction (<102 um)	Soil	7.5 YR 4/4 brown - dark brown
W12ii*	Sieved fraction (102-212 um)	Soil	7.5 YR 4/4 brown - dark brown
W12iii*	Sieved fraction (212-600 um)	Soil	7.5 YR 4/4 brown - dark brown
SOUTHERN GULLY			
S1*	Transported soil in gully base; med - coarse grained, quartz rich with significant mica (20%)	Soil	7.5 YR 4/4 brown - dark brown
S2*	Transported soil in gully base; coarse sands	Soil	7.5 YR 4/4 brown - dark brown
S3*	Transported soil in gully base; med grained, minor mica component (<5%), visible quartz grains	Soil	7.5 YR 4/4 brown - dark brown
S4*	Transported soil in gully base; med grained, visible quartz component	Soil	10YR 3/3 dark brown
S5*	Hard crusting on soil surface (soil unvegetated, although high organic content)	Soil	10YR 4/3 brown - dark brown
S6*	Transported soil in gully base; med - coarse grained, medium mica component (10%)	Soil	7.5 YR 4/4 brown - dark brown

Table (A3.1) **Description of Mine Samples**

S7*	Transported soil in gully base, med grained, homogeneous	Soil	10YR 4/3 brown - dark brown
S7i*	Sieved fraction (<102 um)	Soil	10YR 4/3 brown - dark brown
S7ii*	Sieved fraction (102-212 um)	Soil	10YR 4/3 brown - dark brown
S7iii*	Sieved fraction (212-600 um)	Soil	10YR 4/3 brown - dark brown
S8*	Transported soil in gully base; med grained, v. high (50%) coarse grained mica component	Soil	7.5 YR 4/4 brown - dark brown
S9*	Transported soil in gully base; med grained, v. high coarse mica (50%) and quartz component	Soil	7.5 YR 4/4 brown - dark brown
S10a*	Transported soil in gully base; med grained, dominantly coarse grained mica	Soil	7.5 YR 4/4 brown - dark brown
S10b*	Clumps of ferruginised shist (15 cm depth); large friable mica clumps	Rock	5YR 3/3 dark reddish brown
NORTHERN GULLY			
N1*	Transported soil in gully base (adjacent to dam); med - fine grained, homogeneous, clumped	Soil	5YR 3/3 dark reddish brown
N2*	Transported soil in gully base; coarse grained, scattered visibly mica flakes	Soil	7.5 YR 4/4 brown - dark brown
N3*	Transported soil in gully base; med grained, scattered visibly mica flakes	Soil	7.5 YR 4/4 brown - dark brown
N4*	Transported soil in gully base	Soil	10 YR 4/4 dark yellow brown
N4i*	Sieved fraction (<102 um)	Soil	10 YR 4/4 dark yellow brown
N4ii*	Sieved fraction (102-212 um)	Soil	10 YR 4/4 dark yellow brown
N4iii*	Sieved fraction (212-600 um)	Soil	10 YR 4/4 dark yellow brown
N4iv*	Sieved fraction (600 um- 1.2 mm)	Soil	10 YR 4/4 dark yellow brown
N4v*	Sieved fraction (1.2-2.4 mm)	Soil	10 YR 4/4 dark yellow brown
BENNETT PROPERTY			
B*	Dry Rodwell Creek bed sediments; med - fine grained, clumped, high quartz grain component	Creek sediments	2.5 YR 4/2 dark greyish brown
JAMES PROPERTY			
J1*	Surface slag chunks	Slag	N/A
J2	Hard clay with red rock clasts	Soil	10 YR 4/4 dark yellow brown
J3	Fine, soft transported soil	Soil	7.5YR 4/4 brown - dark brown
J4	Hard crusting (unvegetated)	Soil	10YR 3/3 dark brown
J5*	Sludge resulting from dumped sulphidic waste	Secondary minerals	10YR 4/1 dark grey
J6*	Newly formed green/black/white secondary minerals	Secondary minerals	Various
J7	Arsenic coated slag/gossan?? chunk	Secondary minerals	N/A
J8*	Red soil with white crusting from within arsenic labyrinth	Soil	5YR 3/3 dark reddish brown
J9	Transported gossan chunks	Gossan	N/A
J10*	Transported jarosite lump	Secondary minerals	5Y 8/3 pale yellow
J11*	Lump of magnesium oxide	Secondary minerals	7.5R 2.5/0 black
BACKGROUND SOILS			
C1*	Patchily vegetated creekside topsoil, high level of organic matter	Soil	10YR 4/4 dark yellowish bown
C2*	Patchily vegetated roadside topsoil (along orebody strike)	Soil	10YR 3/3 dark brown
C3*	Dark brown barren soil	Soil	7.5YR 4/4 brown - dark brown

Table (A3.1) **Description of Mine Samples**

C4*	Dark brown vegetated soil	Soil	7.5YR 4/4 brown - dark brown
C5	Hard crusty covering in erosion gully (no vegetation)	Soil	10YR 4/3 brown - dark brown
C6	Vegetated soil in erosion gully	Soil	10YR 4/3 brown - dark brown
C7	Hard crusty barren soil	Soil	10 YR 4/4 dark yellow brown
C8	Soft vegetated topsoil	Soil	10YR 3/3 dark brown
C9*	Yellow clay (brought in by MESA)	MESA transported clay	2.5Y5/4 light olive brown
C10*	Black clay (brought in by MESA)	MESA transported clay	10YR 4/1 dark grey
C11*	Vegetated roadside topsoil (along orebody strike)	Soil	10YR 3/3 dark brown
C12*	Vegetated roadside topsoil (along orebody strike)	Soil	10 YR 4/4 dark yellow brown
C13*	Vegetated roadside topsoil (along orebody strike)	Soil	10 YR 4/4 dark yellow brown
*** Denotes samples used for analysis in this study**			



Ra	Rodwell Ck - Approximately 1km upstream from mine
Rb	Rodwell Ck - Adjacent to limestone containing cliff
Rc	Rodwell Ck - Next to small bridge
Rd	Rodwell Ck - Reed rich, shalow water
Re	Rodwell Ck - Entry point of mine surface runoff
Rf	Rodwell Ck - Next to small bridge
Rg	Rodwell Ck - Adjacent to wetland area
Rh	Rodwell Ck - Next to small bridge
Ri	Rodwell Ck - Pooled area adjacent to "Arsenic Labyrinth"
Rj	Rodwell Ck - Reed rich water adjacent to "A.L." dump
Rk	Rodwell Ck - Approximately 2km downstream
GD	Dam - NE of mine
WB	Bore - Approximately 2km upstream of mine
BB	Bore - Approximately 1km upstream of mine
JS	Spring - Near the "Arsenic Labyrinth"
MS	Mound spring/wetland area

Figure A3.3 **Water sample sites (location and description)**

Appendix A4

RAW DATA

Table (A4.1): **XRF data of the major elements potentially contaminating mine materials**

Sample	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	K_2O	TiO_2	P_2O_5	SO_3	Sample
Dumped country rock (often partially weathered or high secondary mineral deposits between layers)											
X13	58.4	14.74	5.68	0.123	2.6	0.19	4.29	0.66	0.1	1.92	**X13**
X15	57.8	14.97	8.84	0.1	2.1	0.34	4.55	0.71	0.149	4.04	**X15**
X16 (A)	58.7	14.6	8.37	0.075	0.9	0.25	4.27	0.66	0.157	4.57	**X16 (A)**
X16 (B)	57.3	14.4	8.15	0.072	0.9	0.24	4.12	0.65	0.154	4.37	**X16 (B)**
X16 (ave)	58	14.5	8.26	0.074	0.9	0.25	4.2	0.66	0.156	4.47	**X16 (ave)**
X24	54.6	11.08	15.8	0.093	1.2	0.22	2.54	0.57	0.122	9.61	**X24**
X31	37.7	13.62	33.2	0.054	1.2	0.065	3.81	0.87	0.188	3.18	**X31**
X33	52.8	6.1	17.3	0.059	0.2	1.77	1.59	0.26	0.076	11.77	**X33**
Sulphidic waste material											
X10	51.7	6.8	24.3	0.08	0.4	0.42	1.18	0.31	0.054	24.3	**X10**
X25	10.66	1.59	57.7	0.037	0.3	0.023	0.43	0.088	0.074	63.2	**X25**
X42	0.76	0.11	59.9	0.053	0.1	0.034	0.014	0.041	0.091	129	**X42**
Gossan											
X7	31.5	2.95	40.5	0.032	0.2	0.085	1.02	0.11	0.058	7.48	**X7**
Tailings											
X35 (A)	63.3	11.38	10.56	0.053	1.1	0.94	2.17	0.72	0.074	1.96	**X35 (A)**
X35 (B)	63.5	11.45	10.6	0.055	1.2	0.95	2.17	0.72	0.075	1.97	**X35 (B)**
X35 (ave)	63.4	11.42	10.58	0.054	1.15	0.95	2.17	0.72	0.075	1.97	**X35 (ave)**
P1 a	65.3	11.11	10.24	0.061	1.3	0.76	2.45	0.52	0.083	2.38	**P1 a**
P1 b (A)	71.6	7.44	8.62	0.054	0.6	0.64	1.47	0.36	0.06	2.83	**P1 b (A)**
P1 b (B)	70.6	7.45	8.54	0.054	0.6	0.64	1.47	0.35	0.063	2.8	**P1 b (B)**
P1 b (ave)	71.1	7.45	8.58	0.054	0.6	0.64	1.47	0.36	0.062	2.8	**P1 b (ave)**
P1 c	73.3	10.69	4.8	0.035	0.9	1.08	1.93	0.39	0.065	1.05	**P1 c**
P1 d	73	10.79	4.34	0.033	0.9	1.2	1.88	0.38	0.047	0.94	**P1 d**
P1 e	64.6	7.7	14.34	0.04	0.6	0.59	1.58	0.3	0.073	2.94	**P1 e**
Fe-rich waste rock											
X1	18.6	3.35	53.2	0.057	0.4	1.55	1.05	0.26	0.13	7.56	**X1**
X2	51.1	6.14	18.5	0.038	0.2	0.32	1.73	0.4	0.093	18.3	**X2**
X9	76.1	6.7	9.35	0.087	0.5	0.39	1.37	0.33	0.063	2.43	**X9**
X34	39.5	4.27	38.1	0.047	0.3	0.36	0.89	0.22	0.068	5.07	**X34**

Table (A4.1): **XRF data of the major elements potentially contaminating mine materials**

Sample	SIO2	Al2O3	Fe2O3	MnO	MgO	CaO	K2O	TIO2	P2O5	SO3	Sample
Slag											
X27 (A)	51.8	6.61	12.77	0.055	0.6	0.53	1.1	0.28	0.079	1.33	X27 (A)
X27 (B)	51	6.51	12.76	0.052	0.5	0.52	1.07	0.29	0.065	1.23	X27 (B)
X27 (ave)	51.4	6.56	12.77	0.054	0.6	0.53	1.1	0.29	0.072	1.28	X27 (ave)
J1 (A)	25.7	5.45	47.5	0.164	1	7.99	1.06	0.27	0.19	11.13	J1 (A)
J1 (B)	25.9	5.45	47.9	0.168	1	8.16	1.09	0.28	0.201	11.26	J1 (B)
J1 (ave)	25.8	5.45	47.7	0.166	1	8.08	1.08	0.28	0.2	11.2	J1 (ave)
J7	15.3	1.77	52.6	0.052	0.2	0.12	0.35	0.15	0.062	23.9	J7
Secondary minerals											
X14	61.1	13.97	9.04	0.035	1.9	1.78	1.37	0.86	0.084	0.46	X14
X19	28.2	6.4	19	0.117	0.5	0.16	1.73	0.32	0.109	30.5	X19
X20	51.7	8.85	17.8	0.097	0.5	0.22	2.2	0.51	0.112	11.36	X20
X21	38.7	8.46	25	0.1	1.2	0.19	2.01	0.38	0.095	26.1	X21
X22	10.56	6.57	24.4	0.118	1.9	0.14	0.38	0.22	0.111	46.6	X22
X38	55	9.1	15.7	0.087	0.6	0.32	2.27	0.52	0.125	8.88	X38
X44	64.7	15.6	5.92	0.038	0.8	0.046	4.54	0.71	0.082	4.77	X44
X46	53.6	6.53	17.4	0.015	0.1	1.68	2.19	0.5	0.111	12.96	X46
J5	38.1	11.69	6.69	0.047	1.1	0.17	2.62	0.78	0.207	11.24	J5
J6	46.3	6.02	7.75	0.116	0.5	0.35	1.38	0.33	0.079	17.8	J6
J10	43.4	16	15.8	0.103	0.4	0.022	6.6	0.76	0.093	10.72	J10
J11	74.1	11.59	8.85	0.142	1.3	0.33	1.64	0.55	0.07	0.19	J11

Table (A4.2): XRF data of the trace elements potentially contaminating mine materials

Sample	Ba	Co	Cr	Cu	Ga	Ni	Pb	Rb	Sr	Th	U	V	Y	Zn	Zr	Sb	Cd	As	Ce	La
Dumped country rock (often partially weathered or high secondary mineral deposits between layers)																				
X13	1015	14	70	195	30	< 9.	11769	189	58	16	13	65	26	1559	203	272	92			
X15	1107	13	70	269	31	< 9.	18608	191	59	19	11	49	29	2656	198	298	84			
X16 (A)	1165	12	67	743	32	< 9.	23655	133	88	25	18	48	80	2633	244	293	88			
X16 (B)	1152	10	66	681	32	< 9.	22903	125	90	16	15	47	79	2564	280	289	82			
X16 (ave)	1159	11	67	712	32	<9	22379	129	89	20	17	48	80	2599	262	291	85			
X24	456	47	59	423	20	< 9.	4063	107	41	38	23	41	30	2725	237	148	57			
X31	805	108	62	3656	22	< 9.	8857	119	47	75	19	39	31	2703	232	212	70			
X33	661	45	37	852	25	< 9.	34243	62	107	57	20	13	16	5351	210	122	20			
Sulphidic waste material																				
X10	334	283	41	252	19	< 9.	13818	60	85	51	40	21	24	7218	269	65	16			
X25	64	1219	67	149	30	< 9.	2926	35	39	73	126	32	31	551	214	28	65			
X42	158	577	<14.	5695	20	< 9.	21842	41	63	185	163	< 9.	< 6.	37645	54	777	18	< 30.	60	<36.
Gossan																				
X7	850	60	49	1305	52	< 9.	104491	20	222	<12.	<10.	< 9.	< 6.	5901	75	241	38			
Tailings																				
X35 (A)	521	37	61	796	21	< 9.	9210	95	124	45	12	47	28	1149	242	127	60			
X35 (B)	575	44	55	836	23	< 9.	9278	88	128	37	12	38	28	1163	265	127	39			
X35 (ave)	548	41	58	817	22	< 9.	9244	92	126	41	12	43	28	1156	254	127	41			
P1 a	550	22	49	598	22	9	8506	108	123	27	16	37	24	734	278	155	45			
P1 b (A)	388	17	31	448	14	< 9.	7122	65	101	30	15	24	31	1404	597	91	28			
P1 b (B)	383	15	36	455	17	< 9.	7024	58	101	21	17	25	30	1346	590	91	39			
P1b (ave)	386	16	34	451	16	< 9.	7070	62	101	26	16	25	31	1375	594	91	33			
P1 c	614	15	36	350	17	< 9.	2639	80	144	12	<10.	31	24	431	260	116	47			
P1 d	480	14	38	254	17	< 9.	2102	79	151	16	14	27	28	460	238	106	38			
P1 e	432	72	36	972	19	< 9.	13206	54	99	70	13	26	20	1870	258	104	23			
Waste rock																				
X1	1069	126	70	1678	69	< 9.	59046	29	135	62	63	33	31	19228	207	98	<10			
X2	640	61	37	474	29	< 9.	31936	65	104	83	31	19	20	9562	219	160	46			
X9	357	31	34	283	16	< 9.	7267	64	79	37	16	20	26	3288	347	100	22			
X34	520	161	45	2465	39	< 9.	52509	27	84	120	<10.	< 9.	14	4900	213	60	24			
Slag																				
X27 (A)	480	68	75	488	41	38	4776	37	116	<12.	51	35	39	1976	316	65	45			
X27 (B)	452	70	57	558	44	29	4645	36	123	60	51	33	43	1640	335	79	<10			
X27 (ave)	466	69	66	594	43	34	4715	37	120	36	51	34	41	1803	325	72	28			
J1 (A)	288	152	90	6738	32	19	11906	20	244	<12.	46	35	35	70779	227	62	35			
J1 (B)	338	157	69	7245	39	< 9.	12773	11	265	14	71	34	51	71616	270	54	29			
J1 (ave)	313	154	80	6984	35	14	12340	16	256	13	59	35	43	71196	251	58	32			
J7	525	205	<14.	21792	27	< 9.	56514	< 7.	27	<12.	12	< 9.	< 6.	10478	56	369	< 9.	265	<18.	<36.
Secondary minerals																				
X14	313	21	78	79	22	20	6158	101	95	30	20	92	41	113	291	84	30			
X19	1034	40	73	809	26	< 9.	140795	79	18	<12.	20	12	6	33348	53	386	190			
X20	420	35	47	612	25	< 9.	19535	103	42	40	23	36	20	5236	258	150	43			
X21	391	381	49	1738	19	< 9.	10525	92	41	48	43	33	20	9361	150	133	58			
X22	56	440	47	2660	13	64	5172	37	21	70	76	30	88	21593	103	40	403			
X38	375	24	23	360	18	< 9.	1147	93	62	<12.	<10.	34	23	315	207	20	107	< 30.	63	<36.
X44	326	15	<14.	85	10	< 9.	239	101	165	19	25	30	27	469	214	137	41	< 30.	68	<36.
X46	1545	10	56	360	29	< 9.	18459	173	52	<12.	12	47	20	2029	216	322	57	< 30.	<18.	<36.
J5	1416	20	108	1086	13	< 9.	164937	112	74	<12.	17	32	14	7615	187	666	200			
J6	711	35	68	693	41	< 9.	87806	57	69	<12.	33	< 9.	16	58403	154	274	285			
J10	2033	< 6.	42	71	16	< 9.	2069	342	64	40	13	46	9	77	145	400	< 9.	50	37	<36.
J11	394	30	38	117	20	< 9.	499	69	52	<12.	<10.	32	43	2049	328	183	33	30	59	40

Table (A4.3): **XRF data of major elements to determine the nature and extent of contamination**

Sample	SIO2	Al2O3	Fe2O3	MnO	MgO	CaO	K2O	TiO2	P2O5	SO3	Sample
Transported Clay											
X9	76.1	6.7	9.35	0.087	0.5	0.39	1.37	0.33	0.063	2.43	**X9**
X10	51.7	6.8	24.3	0.08	0.4	0.42	1.18	0.31	0.054	24.3	**X10**
Topsoil											
C3	58.5	16.8	10	0.062	2	0.5	2.91	0.85	0.084	0.28	**C3**
C4	70.9	12.11	6.06	0.05	1.3	0.75	2.45	0.52	0.078	0.29	**C4**
P2 a (A)	59.2	16.5	10.69	0.06	2.3	0.72	3.89	0.71	0.041	0.55	**P2 a (A)**
P2 a (B)	58.7	16.4	10.56	0.058	2.2	0.71	3.82	0.7	0.042	0.54	**P2 a (B)**
P2 a (ave)	58.9	16.5	10.53	0.059	2.3	0.72	3.86	0.71	0.042	0.55	**P2 a (ave)**
P2 b	60.3	13.53	12.78	0.056	1.6	0.62	2.71	0.62	0.051	1.6	**P2 b**
P2 c	65	14.88	7.1	0.079	2	0.75	2.86	0.7	0.039	0.85	**P2 c**
P2 d	56.7	17.9	9.8	0.081	2.4	0.6	3.1	0.81	0.046	1.52	**P2 d**
P2 e	58.3	17.7	9.52	0.062	2.1	0.52	3.03	0.82	0.051	0.62	**P2 e**
P2 f	59.9	16.8	10.28	0.062	1.9	0.61	2.78	0.78	0.048	0.45	**P2 f**
P2 g	53.6	20.2	11.39	0.071	2.3	0.57	3.46	0.89	0.047	0.23	**P2 g**
P2 h	49.5	14.82	20	0.068	1.7	0.36	2.57	0.71	0.065	1.75	**P2 h**
Mound spring cores											
O1	84	7.83	1.74	0.024	0.5	0.71	1.82	0.38	0.034	0.29	**O1**
O2a	79.1	9.58	4.68	0.025	0.9	0.65	2.26	0.47	0.034	0.13	**O2a**
O2b	71.2	10.45	9.97	0.126	1.4	0.63	2.42	0.51	0.061	0.07	**O2b**
O3	68.4	12.69	9.72	0.039	1.5	0.7	2.76	0.61	0.068	0.07	**O3**
O4	71.9	11.11	4.51	0.108	1.3	2.55	2.38	0.51	0.047	0.06	**O4**
Mound spring samples											
MS3b	20.2	2.28	18.2	0.038	0.5	1.15	0.53	0.098	0.249	11.85	**MS3b**
MS4a	14.68	0.4	63.9	0.034	0.3	0.48	0.11	0.014	0.12	1.37	**MS4a**
MS4c	13.79	0.33	62.4	0.043	0.3	0.52	0.11	0.009	0.231	3.25	**MS4c**
MS5a	14	0.29	64.1	0.042	0.3	0.87	0.14	0.01	0.423	1.24	**MS5a**
MS6a	80.8	6.29	1.28	0.019	0.3	0.57	1.53	0.31	0.026	0.1	**MS6a**
MS6b	82.8	6.73	1.2	0.02	0.3	0.55	1.67	0.34	0.024	0.08	**MS6b**
MS7	17	1.82	2	0.069	14.6	27	0.61	0.05	0.026	0.16	**MS7**
Small soak (south west of mine)											
MS 1	66.6	13.16	5.14	0.065	1.7	1.2	2.79	0.6	0.083	0.15	**MS 1**
MS 2	63.6	15.3	6.97	0.071	2.3	1.19	3.49	0.66	0.076	0.17	**MS 2**

Table (A4.3): **XRF data of major elements to determine the nature and extent of contamination**

Sample	SIO2	Al2O3	Fe2O3	MnO	MgO	CaO	K2O	TIO2	P2O5	SO3	Sample
Western gullies											
W 0	68.5	12.55	7.51	0.058	1.5	0.58	2.61	0.55	0.067	0.73	W 0
W 1	70.3	11.81	8.51	0.04	1.4	0.22	2.58	0.55	0.053	0.53	W 1
W 2	62.5	6.54	19.1	0.047	0.5	0.38	1.37	0.26	0.059	2.56	W 2
W3A	55.6	5.86	24.6	0.064	0.5	0.28	1.2	0.29	0.055	2.83	W3A
W 3B	52	8.4	22.2	0.094	0.9	0.67	1.78	0.38	0.071	3.16	W 3B
W 4	50.6	6.84	28.2	0.111	0.6	0.19	1.33	0.26	0.064	3.29	W 4
W 5A	60.6	10.83	10.96	0.044	1.1	0.49	2.26	0.48	0.066	2.01	W 5A
W 5B	62.8	9.08	16.9	0.078	0.9	0.3	1.82	0.44	0.06	2.08	W 5B
W 6	48.8	7.23	31.5	0.151	0.6	0.22	1.46	0.4	0.076	3.02	W 6
W 7A	65.4	8.31	15.7	0.077	0.8	0.51	1.68	0.38	0.064	1.28	W 7A
W 7B	55.7	16.9	9.52	0.061	2	0.98	3.51	0.8	0.065	0.79	W 7B
W 8	73.7	7.78	10.02	0.049	0.7	0.58	1.56	0.32	0.068	0.83	W 8
W 9	58.7	14.81	12.74	0.059	1.6	0.31	2.79	0.73	0.089	1.04	W 9
W 10	67.9	13.13	7.32	0.087	1.4	0.61	2.85	0.63	0.07	0.51	W 10
W 11	71.1	12.42	4.89	0.052	1	0.58	2.56	0.55	0.065	0.18	W 11
W 12	64.3	12.31	7.99	0.054	1.2	0.81	2.41	0.59	0.089	0.74	W 12
W 12i	64	12.32	7.94	0.054	1.2	0.76	2.43	0.6	0.095	0.83	W 12i
W 12ii	68.7	13.21	6.78	0.051	1.2	0.81	2.34	0.57	0.087	0.52	W 12ii
W 12iii	53.6	14.65	8.76	0.064	1.4	1.38	2.84	0.76	0.112	1.07	W 12iii
Southern gullies											
S 1	69.3	8.96	13.6	0.118	0.9	0.28	1.7	0.38	0.054	2.26	S 1
S 2	71.8	7.94	7.75	0.09	0.8	0.52	1.52	0.38	0.042	1.48	S 2
S 3	72	6.97	13.15	0.087	0.6	0.29	1.26	0.3	0.051	3.32	S 3
S 4	64.5	13.38	10.81	0.068	1.6	0.48	2.61	0.71	0.061	1.02	S 4
S 5	76	11.7	6	0.055	1.2	0.7	2.3	0.54	0.064	0.83	S 5
S 6	63.1	5.74	13.75	0.123	0.5	0.41	0.9	0.25	0.056	3.18	S 6
S 7	74.5	11.86	4.73	0.065	1.3	0.75	2.37	0.49	0.046	0.45	S 7
S 7i	65.4	16.5	5.61	0.076	1.8	1.2	3.22	0.69	0.062	0.28	S 7i
S 7ii	73.6	12.3	4.25	0.06	1.3	1.06	2.38	0.48	0.042	0.29	S 7ii
S 7iii	74.4	11.51	4.76	0.069	1.3	0.72	2.25	0.47	0.043	0.58	S 7iii
S 8	61.3	8.27	14.95	0.107	0.9	0.25	1.65	0.38	0.052	2.6	S 8
S 9	64.9	9.21	14.01	0.095	1.1	0.33	1.92	0.47	0.048	2.41	S 9
S 10A	53.6	8.92	21.5	0.151	1	0.27	1.68	0.41	0.056	9.34	S 10A
S 10B	50.2	19.4	12.35	0.135	3.5	0.35	4.89	0.86	0.075	0.58	S 10B

Table (A4.3): **XRF data of major elements to determine the nature and extent of contamination**

Sample	SIO2	Al2O3	Fe2O3	MnO	MgO	CaO	K2O	TIO2	P2O5	SO3	Sample
Northern gullies											
N 1	62.9	9.78	5.33	0.099	1	0.43	1.91	0.43	0.047	0.18	N 1
N 2	73	8.45	14.65	0.125	0.9	0.28	1.62	0.31	0.078	1.23	N 2
N 3	59.4	8.37	4.82	0.075	1	0.39	2.05	0.36	0.114	0.22	N 3
N 4	64.6	9.89	12.63	0.068	1.2	0.32	1.95	0.41	0.049	1.45	N 4
N 4i	63.9	12.87	9.24	0.073	1.2	0.99	2.1	0.53	0.057	1.03	N 4i
N 4ii	76.6	8.56	8.63	0.063	0.9	0.52	1.54	0.32	0.039	0.89	N 4ii
N 4iii	66.1	9.62	14.59	0.071	1.1	0.26	1.96	0.42	0.051	1.82	N 4iii
N 4iv	57.2	15.9	12.28	0.081	2.2	0.28	3.31	0.83	0.054	1.5	N 4iv
N4 v	59.8	15.7	10.8	0.069	2.1	0.33	3.27	0.77	0.055	0.96	N4 v
Bennett property											
B	67.8	7.25	2.64	0.032	1.2	5.11	1.68	0.35	0.052	0.08	B
James Property											
J8	66.9	10.13	8.37	0.184	1.6	1.24	1.52	0.46	0.093	2.86	J8
Surrounding soils											
C 1	72.7	7.15	2.97	0.068	1.1	4.6	1.33	0.28	0.09	0.14	C 1
C 2	70.6	9.15	5.11	0.086	1.1	0.42	2.15	0.38	0.113	0.21	C 2
C3	58.5	16.8	10	0.062	2	0.5	2.91	0.85	0.084	0.28	C3
C4	70.9	12.11	6.06	0.05	1.3	0.75	2.45	0.52	0.078	0.29	C4
C9	55.8	16.2	9.18	0.039	2.6	3.84	1.7	0.92	0.064	0.5	C9
C10	62.7	15.2	5.06	0.096	1.9	3.02	1.45	1.1	0.057	0.11	C10
C 11	74.1	10.83	4.06	0.083	1.2	0.81	2.24	0.46	0.088	0.07	C 11
C 12	68.2	10.01	5.3	0.12	1.1	0.88	1.92	0.46	0.106	0.3	C 12
C 13	74.9	8.83	6.44	0.089	1.1	1.05	1.74	0.36	0.068	0.56	C 13
Secondary minerals											
X14	61.1	13.97	9.04	0.035	1.9	1.78	1.37	0.86	0.084	0.46	X14
X19	28.2	6.4	19	0.117	0.5	0.16	1.73	0.32	0.109	30.5	X19
X20	51.7	8.85	17.8	0.097	0.5	0.22	2.2	0.51	0.112	11.36	X20
X21	38.7	8.46	25	0.1	1.2	0.19	2.01	0.38	0.095	26.1	X21
X22	10.56	6.57	24.4	0.118	1.9	0.14	0.38	0.22	0.111	46.6	X22
X38	55	9.1	15.7	0.087	0.6	0.32	2.27	0.52	0.125	8.88	X38
X44	64.7	15.6	5.92	0.038	0.8	0.046	4.54	0.71	0.082	4.77	X44
X46	53.6	6.53	17.4	0.015	0.1	1.68	2.19	0.5	0.111	12.96	X46
J5	38.1	11.69	6.69	0.047	1.1	0.17	2.62	0.78	0.207	11.24	J5
J6	46.3	6.02	7.75	0.116	0.5	0.35	1.38	0.33	0.079	17.8	J6
J10	43.4	16	15.8	0.103	0.4	0.022	6.6	0.76	0.093	10.72	J10
J11	74.1	11.59	8.85	0.142	1.3	0.33	1.64	0.55	0.07	0.19	J11

Table (A4.4): XRF data of trace elements to determine the nature and extent of contamination

Sample	Ba	Co	Cr	Cu	Ga	Ni	Pb	Rb	Sr	Th	U	V	Y	Zn	Zr	Sb	Cd	As	Ce	La	
Transported Clay																					
X9	357	31	34	283	16	< 9.	7267	64	79	37	16	20	26	3288	347	100	22				X9
X10	334	283	41	252	19	< 9.	13818	60	85	51	40	21	24	7218	269	85	16				X10
Topsoil																					
C 3	597	27	88	415	25	30	917	166	107	35	23	63	39	512	346	178	63				C 3
C 4	493	28	50	230	20	< 9.	1636	109	121	27	13	36	32	458	306	144	52				C 4
P2 a (A)	1193	28	71	196	22	35	1128	168	125	33	14	75	31	649	241	217	83				P2 a (A)
P2 a (B)	1147	31	70	181	24	30	1124	154	119	22	12	68	28	656	235	207	90				P2 b (B)
P2 a (ave)	1170	30	71	188	23	33	1126	161	122	28	13	72	30	653	238	212	87				P2 a (ave)
P2 b	528	78	66	572	26	17	7280	120	109	37	14	59	28	1405	251	157	50				P2 b
P2 c	614	38	67	116	19	32	307	133	138	22	11	50	36	1165	297	158	72				P2 c
P2 d	542	53	82	152	24	33	96	166	102	15	18	72	43	2284	244	172	94				P2 d
P2 e	612	31	75	145	23	29	853	156	101	25	15	71	35	868	258	164	67				P2 e
P2 f	582	29	73	185	22	31	2576	144	109	23	15	68	29	474	244	153	55				P2 f
P2 g	607	32	90	137	26	36	983	186	103	25	13	81	27	359	241	187	52				P2 g
P2 h	511	59	75	650	27	20	15804	137	87	54	14	66	22	1793	225	157	21				P2 h
Mound spring cores																					
O1	504	17	21	42	16	< 9.	62	48	107	<12.	<10.	13	25	259	362	189	40	102	22	<36.	O1
O2a	444	23	36	45	14	< 9.	42	69	97	<12.	<10.	17	23	900	308	211	39	88	40	<36.	O2a
O2b	560	75	30	106	14	< 9.	50	81	107	<12.	<10.	36	31	1683	281	244	32	110	83	<36.	O2b
O3	563	23	33	72	14	11	90	103	107	<12.	<10.	38	28	1724	262	260	24	92	73	<36.	O3
O4	487	27	42	39	19	10	34	88	136	<12.	<10.	32	29	44	303	301	46	95	44	<36.	O4
Mound spring samples																					
MS3b	248	359	41	127	10	105	153	27	85	35	56	11	13	32439	107	N/A	N/A	N/A	41	<36	
MS4a	39	39	<14.	50	< 6.	< 9.	54	< 7.	66	<12.	<10.	< 9.	< 6.	20152	21	< 7.	< 9.	<20	<18.	<36.	MS4a
MS4c	39	87	<14.	<22.	< 6.	< 9.	25	< 7.	66	<12.	20	< 9.	< 6.	31783	35	< 7.	< 9.	40	<18.	<36.	MSc
MS5a	57	18	<14.	<22.	< 6.	< 9.	57	8	123	<12.	13	< 9.	9	20576	27	29	< 9.	89	20	<36.	MS5a
MS6a	421	11	17	198	13	< 9.	204	37	81	<12.	<10.	13	19	64	287	174	25	35	28	84	MS6a
MS6b	454	11	<14.	30	13	< 9.	32	47	83	<12.	<10.	12	21	39	308	188	25	20	33	<36.	MS6b
MS7	133	24	<14.	98	7	13	65	23	391	<12.	<10.	< 9.	< 6.	379	110	837	193	<20	<18.	<36.	MS7
Small soak (south west of mine)																					
MS 1	669	13	44	59	17	17	664	127	156	<12.	<10.	41	30	338	221	277	39	55	65	36	MS 1
MS 2	600	20	53	32	16	42	116	149	173	13	<10.	52	30	129	235	311	28	57	94	39	MS 2
Western gullies																					
W 0	657	19	44	133	14	12	2854	123	104	<12.	<10.	40	27	573	255	224	24	50	58	43	W 0
W 1	399	19	36	176	13	< 9.	2041	127	63	21	<10.	30	27	286	281	230	47	37	58	39	W 1
W 2	318	70	16	1172	13	< 9.	11204	50	63	37	<10.	20	17	2162	162	129	< 9.	83	<18.	<36.	W 2
W3A	331	90	<14.	1418	11	< 9.	17064	47	47	51	<10.	18	13	2769	127	120	< 9.	88	<18.	<36.	W3A
W 3B	511	74	24	1037	13	< 9.	24235	78	61	43	<10.	35	20	2719	177	151	< 9.	37	<18.	<36.	W 3B
W 4	441	80	14	1331	22	< 9.	28979	50	52	36	<10.	19	24	3966	147	126	< 9.	20	<18.	<36.	W 4
W 5A	455	30	37	509	15	< 9.	8481	95	78	13	<10.	31	21	1012	203	173	10	30	<18.	37	W 5A
W 5B	430	48	25	745	16	< 9.	14425	85	61	30	12	34	23	2019	178	169	< 9.	62	<18.	<36.	W 5B
W 6	411	90	<14.	1544	17	< 9.	20516	58	51	54	<10.	29	24	4384	140	124	< 9.	133	<18.	<36.	W 6

Table (A4.4): **XRF data of trace elements to determine the nature and extent of contamination**

Sample	Ba	Co	Cr	Cu	Ga	Ni	Pb	Rb	Sr	Th	U	V	Y	Zn	Zr	Sb	Cd	As	Ce	La	
C 4	493	28	50	230	20	< 9.	1636	109	121	27	13	36	32	458	306	52	144	N/A	N/A	N/A	C 4
C9	450	21	76	97	24	37	433	121	150	29	21	100	52	183	278	28	96	N/A	N/A	N/A	C9
C10	435	22	63	70	27	11	110	88	165	<12.	21	69	41	52	309	93	157	N/A	N/A	N/A	C10
C 11	533	12	31	26	12	< 9.	54	93	88	<12.	<10.	29	24	29	267	206	31	21	54	<36.	C 11
C 12	392	18	29	120	13	< 9.	1431	80	79	<12.	<10.	27	27	1940	258	188	29	25	44	<36.	C 12
C 13	377	28	30	387	10	< 9.	70	74	76	<12.	<10.	35	24	62	223	164	16	35	52	<36.	C 13
Secondary minerals																					
X14	313	21	78	79	22	20	6158	101	95	30	20	92	41	113	291	84	30				X14
X19	1034	40	73	809	26	< 9.	140795	79	18	<12.	20	12	6	33348	53	386	190				X19
X20	420	35	47	612	25	< 9.	19535	103	42	40	23	36	20	5236	258	150	43				X20
X21	391	381	49	1738	19	< 9.	10525	92	41	48	43	33	20	9361	150	133	58				X21
X22	56	440	47	2660	13	64	5172	37	21	70	75	30	88	21593	103	40	403				X22
X38	375	24	23	360	18	< 9.	1147	93	62	<12.	<10.	34	23	315	207	20	107	< 30.	63	<36.	X38
X44	326	15	<14.	85	10	< 9.	239	101	165	19	25	30	27	469	214	137	41	< 30.	68	<36.	X44
X46	1545	10	56	360	29	< 9.	18459	173	52	<12.	12	47	20	2029	216	322	57	< 30.	<18.	<36.	X46
J5	1416	20	108	1086	13	< 9.	164937	112	74	<12.	17	32	14	7615	187	668	200				J5
J6	711	35	68	693	41	< 9.	87808	57	69	<12.	33	< 9.	16	58403	154	274	285				J6
J10	2033	< 6.	42	71	16	< 9.	2069	342	64	40	13	48	9	77	145	400	< 9.	50	37	<36.	J10
J11	394	30	38	117	20	< 9.	499	69	52	<12.	<10.	32	43	2049	328	183	33	30	59	40	J11

Table (A4.4): XRF data of trace elements to determine the nature and extent of contamination

Sample	Ba	Co	Cr	Cu	Ga	Ni	Pb	Rb	Sr	Th	U	V	Y	Zn	Zr	Sb	Cd	As	Ce	La	
W 7A	342	43	23	639	13	< 9.	9395	69	79	23	<10.	26	25	1878	203	152	< 9.	63	<18.	<36.	W 7A
W 7B	762	28	62	455	22	17	7099	157	130	27	<10.	53	28	893	260	312	21	86	37	44	W 7B
W 8	464	33	17	444	13	< 9.	5655	62	80	25	<10.	22	20	1076	202	154	< 9.	70	20	<36.	W 8
W 9	556	42	50	409	19	< 9.	3939	136	75	26	<10.	52	34	968	245	215	18	75	54	46	W 9
W 10	583	30	43	175	16	12	727	132	82	13	<10.	42	45	404	304	231	26	40	93	50	W 10
W 11	607	14	37	98	13	11	655	113	98	13	<10.	36	32	162	295	227	32	54	75	38	W 11
W 12	571	22	43	407	15	10	3876	118	105	18	<10.	41	25	493	252	203	11	46	55	<36.	W 12
W 12I	578	28	41	398	18	< 9.	3734	114	101	16	<10.	43	26	440	252	205	11	40	53	<36.	W 12I
W 12ii	589	18	38	333	17	< 9.	3233	113	127	20	<10.	44	25	358	277	217	15	54	46	<36.	W 12ii
W 12iii	663	23	53	437	20	20	4782	136	136	22	<10.	46	29	452	412	266	22	36	72	41	W 12iii
Southern gullies																					
S 1	425	38	31	470	14	< 9.	8066	72	63	19	<10.	29	24	3080	216	130	< 9.	98	21	<36.	S 1
S 2	369	31	28	225	10	< 9.	3088	66	59	<12.	<10.	29	23	1379	272	144	12	61	<18.	<36.	S 2
S 3	364	42	18	389	9	< 9.	9168	59	58	14	<10.	25	17	2113	172	108	< 9.	70	<18.	<36.	S 3
S 4	562	17	51	169	17	11	2544	136	90	<12.	<10.	53	26	627	304	209	14	72	55	37	S 4
S 5	541	17	38	164	14	< 9.	1884	112	103	15	<10.	38	34	421	298	215	22	69	67	39	S 5
S 6	355	38	16	445	13	< 9.	19652	35	56	<12.	<10.	17	23	3413	273	98	< 9.	<20	<18.	<36.	S 6
S 7	565	18	38	67	15	< 9.	1065	112	111	<12.	<10.	34	30	362	256	201	24	36	64	<36.	S 7
S 7i	813	19	49	80	17	10	302	149	167	15	<10.	45	41	236	447	272	39	54	81	45	S 7i
S 7ii	587	13	36	78	15	< 9.	218	110	133	13	<10.	34	27	185	281	223	18	41	58	<36.	S 7ii
S 7iii	537	19	35	75	13	< 9.	749	107	108	<12.	<10.	31	25	279	255	179	29	55	56	43	S 7iii
S 8	408	40	25	557	13	< 9.	12499	80	61	20	<10.	31	21	3439	212	114	< 9.	61	<18.	<36.	S 8
S 9	485	34	29	474	15	< 9.	9666	96	74	33	<10.	37	20	2788	226	153	< 9.	109	<18.	<36.	S 9
S 10A	664	76	34	626	22	< 9.	45589	75	67	28	<10.	25	25	5256	210	116	< 9.	35	<18.	<36.	S 10A
S 10B	707	31	73	130	20	24	2058	240	76	17	<10.	83	22	442	199	362	21	60	50	<36.	S 10B
Northern gullies																					
N 1	476	21	31	169	9	< 9.	408	80	68	<12.	<10.	34	26	440	218	165	13	<10	50	<36.	N 1
N 2	523	53	28	628	13	< 9.	4797	69	59	26	<10.	28	30	1700	184	144	< 9.	101	47	53	N 2
N 3	414	13	26	38	12	< 9.	1712	82	53	<12.	<10.	27	23	157	215	179	13	<20	42	<36.	N 3
N 4	529	45	31	530	14	< 9.	6792	90	68	25	<10.	29	23	2015	192	150	< 9.	74	<18.	<36.	N 4
N 4i	571	23	31	396	14	< 9.	4716	96	151	23	<10.	37	36	957	550	210	13	62	48	<36.	N 4i
N 4ii	358	31	25	382	13	< 9.	4219	68	92	19	<10.	31	27	1080	232	166	13	92	30	<36.	N 4ii
N 4iii	491	46	27	643	13	< 9.	7979	92	59	25	<10.	40	20	2152	153	156	< 9.	90	<18.	<36.	N 4iii
N 4iv	559	24	60	586	18	< 9.	2937	169	78	16	<10.	55	28	919	227	247	16	85	68	<36.	N 4iv
N4 v	622	32	57	285	19	< 9.	3966	165	95	13	<10.	55	24	412	231	264	17	70	50	<36.	N4 v
Bennett property																					
B	378	14	23	36	12	< 9.	74	64	125	<12.	<10.	32	19	58	184	299	49	38	38	<36.	B
James property																					
J8	463	32	38	89	25	< 9.	34433	74	66	<12.	14	27	36	4759	244	166	78	40	<18.	36	J8
Surrounding soils																					
C 1	322	16	18	37	8	< 9.	163	56	111	<12.	<10.	17	23	104	264	258	40	34	30	<36.	C 1
C 2	492	15	27	38	13	< 9.	1623	91	60	<12.	<10.	25	31	153	267	184	25	28	51	<36.	C 2
C 3	597	27	88	415	25	30	917	166	107	35	23	63	39	512	346	63	178	N/A	N/A	N/A	C 3

Table (A4.5): **ICP data (major, trace elements and chloride)-Solid samples**

	Cl	Al	B	Ca	Cd	Co	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	Ni	P	Pb	S	Zn	
Code	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	Code
X38	3.60	1.00	<0.1	24.30	<0.1	0.10	<0.1	1.40	<0.1	0.50	5.20	0.40	<0.1	1.40	<0.1	<0.1	<0.1	36.80	2.50	X38
X44	4.20	0.20	<0.1	3.90	<0.1	<0.1	<0.1	<0.1	<0.1	2.40	2.30	1.00	<0.1	2.10	<0.1	<0.1	7.90	12.80	3.80	X44
X46	29.10	97.30	<0.1	22.30	0.20	1.20	<0.1	6.20	10.50	0.10	50.40	3.60	<0.1	3.10	0.20	<0.1	0.10	357.30	64.30	X46
SURROUNDING SOIL SAMPLES																		SURROUNDING SOIL SAMPLES		
MS1	240.70	4.01	0.16	12.05	<0.05	<0.05	<0.05	0.05	3.12	22.61	18.88	0.35	<0.05	144.84	0.14	0.73	<0.05	23.38	0.26	MS1
MS2	91.40	7.98	0.13	4.26	<0.05	<0.05	<0.05	<0.05	5.91	14.38	5.97	0.11	<0.05	60.19	0.15	1.95	<0.05	9.14	0.12	MS2
W0	30.30	<0.05	<0.1	6.93	<0.05	<0.05	<0.05	<0.05	<0.1	8.09	4.81	0.29	<0.05	11.82	<0.05	<0.1	0.16	9.38	1.85	W0
W1	41.90	0.34	<0.1	8.68	<0.05	<0.05	<0.05	0.27	<0.1	4.33	4.22	0.72	<0.05	2.02	<0.05	<0.1	3.78	3.56	2.29	W1
W2	144.00	8.71	<0.1	4.19	<0.05	<0.05	<0.05	0.87	0.34	3.63	1.63	0.14	<0.05	1.76	<0.05	<0.1	25.17	9.77	2.01	W2
W3a	11.00	0.64	<0.1	2.54	<0.05	<0.05	<0.05	0.29	<0.1	2.53	0.88	0.09	<0.05	1.17	<0.05	<0.1	4.89	9.17	1.12	W3a
W3b	3.30	0.58	<0.1	4.11	<0.05	<0.05	<0.05	0.26	<0.1	3.56	1.57	0.18	<0.05	1.62	<0.05	<0.1	7.02	14.00	1.49	W3b
W4	62.20	3.82	<0.1	5.40	<0.05	<0.05	<0.05	0.77	<0.1	3.93	2.50	0.38	<0.05	1.89	<0.05	<0.1	18.17	8.24	2.34	W4
W5a	29.40	1.05	<0.1	15.52	<0.05	0.06	<0.05	0.52	<0.1	5.21	4.84	0.39	<0.05	3.22	<0.05	<0.1	7.05	19.40	3.86	W5a
W5b	11.60	0.52	<0.1	6.17	<0.05	<0.05	<0.05	0.26	<0.1	3.43	3.06	0.32	<0.05	2.66	<0.05	<0.1	5.55	14.78	2.51	W5b
W6	15.10	0.33	<0.1	4.13	<0.05	<0.05	<0.05	0.27	<0.1	5.52	2.12	0.45	<0.05	1.97	<0.05	<0.1	9.04	8.85	2.18	W6
W7a	180.40	0.19	0.08	36.17	<0.05	<0.05	<0.05	<0.05	<0.1	15.60	19.87	0.15	<0.05	112.37	<0.05	<0.1	0.67	56.22	0.59	W7a
W7b	120.60	0.44	0.09	23.99	<0.05	<0.05	<0.05	<0.05	0.24	23.60	13.29	0.11	<0.05	93.45	<0.05	<0.1	0.58	56.31	0.54	W7b
W8	141.40	0.15	0.26	11.32	<0.05	<0.05	<0.05	<0.05	0.78	21.47	8.83	0.13	<0.05	105.72	<0.05	<0.1	<0.05	35.04	<0.05	W8
W9	15.90	0.10	<0.1	4.13	<0.05	<0.05	<0.05	0.09	<0.1	3.00	2.38	0.25	<0.05	3.16	<0.05	<0.1	1.22	5.19	0.62	W9
W10	45.00	0.65	<0.1	170.44	0.07	<0.05	<0.05	<0.05	<0.1	11.07	25.39	0.77	<0.05	35.63	<0.05	<0.1	0.18	185.77	16.32	W10
W11	60.30	1.35	<0.1	8.33	0.10	0.10	<0.05	0.06	<0.1	6.12	7.56	1.88	<0.05	17.65	<0.05	<0.1	0.26	13.82	4.53	W11
W12	116.00	15.49	<0.1	7.18	<0.05	<0.05	<0.05	2.85	<0.1	5.96	2.78	0.36	<0.05	4.66	0.05	<0.1	21.89	7.63	3.05	W12
S1	30.70	1.35	<0.1	4.86	<0.05	<0.05	<0.05	0.15	<0.1	2.46	1.80	0.20	<0.05	1.48	<0.05	<0.1	2.18	6.56	1.38	S1
S2	3.60	0.10	<0.1	2.00	<0.05	<0.05	<0.05	<0.05	<0.1	1.92	0.72	0.16	<0.05	1.29	<0.05	<0.1	0.22	6.72	1.10	S2
S3	63.20	3.60	<0.1	5.69	<0.05	<0.05	<0.05	0.33	<0.1	2.84	1.85	0.26	<0.05	1.82	<0.05	<0.1	6.28	4.62	2.91	S3
S4	112.40	8.09	<0.1	12.91	<0.05	0.05	<0.05	0.38	<0.1	5.30	5.42	0.54	<0.05	4.85	<0.05	<0.1	5.20	6.87	6.54	S4
S5	152.20	10.00	<0.1	38.54	0.08	0.09	<0.05	0.43	0.75	10.31	9.38	1.27	<0.05	14.28	<0.05	<0.1	1.56	38.28	13.08	S5
S6	8.60	0.17	<0.1	2.92	<0.05	<0.05	<0.05	<0.05	<0.1	1.51	0.68	0.06	<0.05	1.09	<0.05	<0.1	5.82	7.40	0.63	S6
S7	13.00	1.94	<0.1	9.01	<0.05	0.11	<0.05	<0.05	<0.1	3.00	6.71	1.17	<0.05	10.40	<0.05	<0.1	<0.05	29.62	9.55	S7
S8	41.70	4.27	<0.1	2.12	<0.05	<0.05	<0.05	0.23	0.36	1.27	0.81	0.13	<0.05	1.48	0.06	<0.1	4.37	13.59	2.16	S8
S9	6.50	2.51	<0.1	2.57	<0.05	0.06	<0.05	0.13	<0.1	1.03	2.19	0.12	<0.05	1.62	<0.05	<0.1	1.27	21.32	3.92	S9
S10a	27.90	12.16	<0.1	1.95	<0.05	0.20	<0.05	0.26	18.19	0.37	3.73	0.27	<0.05	0.66	<0.05	<0.1	3.31	77.82	12.24	S10a
S10b	16.80	21.86	<0.1	5.26	<0.05	0.24	<0.05	1.48	0.93	3.39	7.58	0.72	<0.05	2.34	<0.05	<0.1	0.31	78.40	16.17	S10b
N1	26.80	0.25	<0.1	5.11	<0.05	<0.05	<0.05	<0.05	0.20	7.39	3.49	1.26	<0.05	15.33	<0.05	<0.1	<0.05	8.50	1.32	N1
N2	100.30	4.35	<0.1	11.03	<0.05	0.06	<0.05	0.80	0.07	5.16	3.25	0.79	<0.05	1.66	<0.05	<0.1	12.16	1.74	3.68	N2
N3	64.00	3.01	<0.1	8.05	<0.05	0.06	<0.05	0.82	<0.1	4.95	3.44	0.53	<0.05	1.86	<0.05	<0.1	5.25	2.98	3.15	N3
N4	32.80	4.56	<0.1	3.58	<0.05	0.05	<0.05	0.51	<0.1	3.11	2.03	0.13	<0.05	1.17	<0.05	<0.1	4.51	10.38	3.89	N4
B	11.60	1.63	<0.1	9.78	<0.05	<0.05	<0.05	<0.05	1.23	5.66	3.95	<0.05	<0.05	27.32	<0.05	<0.1	<0.05	7.49	<0.05	B
C1	339.00	0.45	<0.1	56.63	<0.05	<0.05	<0.05	<0.05	0.56	42.83	17.34	<0.05	<0.05	162.37	0.08	1.76	<0.05	25.26	<0.05	C1
C2	170.80	0.40	<0.1	64.17	<0.05	<0.05	<0.05	<0.05	0.14	31.07	12.07	1.46	<0.05	11.64	<0.05	1.58	0.36	2.70	1.79	C2
C3	10.10	0.21	<0.1	1.98	<0.05	<0.05	<0.05	0.11	<0.1	4.74	1.54	<0.05	<0.05	14.26	<0.05	0.19	<0.05	10.58	2.04	C3

Table (A4.5): **ICP data (major, trace elements and chloride)-Solid samples**

	Cl	Al	B	Ca	Cd	Co	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	Ni	P	Pb	S	Zn	
Code	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	Code
C4	5.50	1.14	<0.1	0.34	<0.05	<0.05	<0.05	0.10	0.70	1.85	0.18	<0.05	<0.05	9.61	<0.05	0.36	0.11	1.86	0.23	C4
C9	15.70	<0.05	<0.1	11.69	<0.05	<0.05	<0.05	<0.05	<0.1	4.59	2.79	<0.05	<0.05	65.78	<0.05	<0.1	<0.05	26.39	<0.05	C9
C10	29.40	<0.05	0.25	4.88	<0.05	<0.05	<0.05	<0.05	<0.1	2.22	4.96	<0.05	<0.05	67.90	<0.05	0.13	<0.05	5.32	<0.05	C10
C11	5.80	3.09	<0.1	0.44	<0.05	<0.05	<0.05	<0.05	2.10	4.56	0.38	<0.05	<0.05	6.63	<0.05	0.45	<0.05	1.11	<0.05	C11
C12	11.80	0.81	<0.1	2.65	<0.05	<0.05	<0.05	<0.05	0.66	2.58	0.72	<0.05	<0.05	6.19	<0.05	0.38	<0.05	0.59	0.40	C12
C13	108.30	0.24	<0.1	56.63	<0.05	<0.05	<0.05	0.10	0.19	4.50	8.00	<0.05	<0.05	9.53	<0.05	0.40	<0.05	0.78	<0.05	C13
MOUND SPRING REGION																				MOUND SPRING REGION
O1	75.30	0.14	0.18	10.32	<0.1	<0.1	<0.1	<0.1	0.27	22.94	10.97	0.16	<0.1	73.90	<0.1	0.12	<0.1	53.11	<0.1	O1
O2a	113.10	0.22	0.13	3.46	<0.1	<0.1	<0.1	<0.1	0.20	17.26	4.43	<0.1	<0.1	78.03	<0.1	<0.1	<0.1	17.36	<0.1	O2a
O2b	108.00	0.83	0.11	3.40	<0.1	<0.1	<0.1	<0.1	2.97	16.80	3.64	0.11	<0.1	82.74	<0.1	<0.1	<0.1	16.04	0.13	O2b
O3	54.60	1.47	0.09	1.92	<0.1	<0.1	<0.1	<0.1	2.25	9.83	2.09	<0.1	<0.1	52.57	<0.1	0.76	<0.1	13.57	0.18	O3
O4	105.60	<0.1	<0.1	11.14	<0.1	<0.1	<0.1	<0.1	<0.1	12.90	5.44	<0.1	<0.1	106.86	<0.1	0.24	<0.1	21.08	<0.1	O4
MS3a	424.00	2.25	1.05	465.91	<0.1	8.32	<0.1	<0.1	192.23	54.42	210.24	23.33	<0.1	386.65	3.61	0.84	<0.1	1116.58	504.99	MS3a
MS4a	218.00	<0.1	0.12	18.94	<0.1	<0.1	<0.1	<0.1	<0.1	21.01	16.14	<0.1	<0.1	191.91	<0.1	0.15	<0.1	76.86	0.14	MS4a
MS4c	272.00	<0.1	0.13	29.51	<0.1	<0.1	<0.1	<0.1	<0.1	22.83	25.93	<0.1	<0.1	212.17	<0.1	<0.1	<0.1	91.36	0.59	MS4c
MS5a	508.00	<0.1	0.11	32.79	<0.1	<0.1	<0.1	<0.1	<0.1	41.03	29.02	<0.1	<0.1	348.97	<0.1	<0.1	<0.1	87.49	0.16	MS5a
MS6a	171.90	7.59	0.12	4.00	<0.1	<0.1	<0.1	<0.1	6.52	17.61	2.70	<0.1	<0.1	171.73	<0.1	0.57	<0.1	38.80	<0.1	MS6a
MS6b	201.60	0.95	<0.1	10.18	<0.1	<0.1	<0.1	<0.1	1.05	14.55	7.09	<0.1	<0.1	170.48	<0.1	<0.1	<0.1	42.07	<0.1	MS6b

Table (A4.6): ICP data (major, trace elements and chloride)-Water samples

	Cl	Al	B	Ca	Cd	Co	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	Ni	P	Pb	S	Zn	
Code	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	**Code**
Ra	1258	<0.1	0.2	62.7	<0.1	<0.1	<0.1	<0.1	<0.1	31.3	96.0	0.1	<0.1	652	<0.1	0.3	<0.1	13.6	<0.1	**Ra**
Rb	1562	<0.1	0.3	115.8	<0.1	<0.1	<0.1	<0.1	<0.1	40.2	120.0	<0.1	<0.1	895	<0.1	<0.1	<0.1	63.7	<0.1	**Rb**
Rc	1946	<0.1	0.4	114.9	<0.1	<0.1	<0.1	<0.1	<0.1	58.7	161.3	<0.1	<0.1	1151	<0.1	0.1	<0.1	106.6	<0.1	**Rc**
Rd	1586	<0.1	0.3	113.1	<0.1	<0.1	<0.1	<0.1	<0.1	45.8	130.6	<0.1	<0.1	936	<0.1	0.1	<0.1	67.7	<0.1	**Rd**
Re	1592	<0.1	0.3	111.2	<0.1	<0.1	<0.1	<0.1	<0.1	46.3	131.3	<0.1	<0.1	943	<0.1	0.1	<0.1	69.2	<0.1	**Re**
Rf	1546	<0.1	0.3	114.7	<0.1	<0.1	<0.1	<0.1	<0.1	45.8	129.2	<0.1	<0.1	914	<0.1	0.1	<0.1	69.9	<0.1	**Rf**
Rg	1616	<0.1	0.3	125.9	<0.1	<0.1	<0.1	<0.1	<0.1	50.7	136.6	<0.1	<0.1	942	<0.1	0.1	<0.1	90.5	<0.1	**Rg**
Rh	1708	<0.1	0.4	117.8	<0.1	<0.1	<0.1	<0.1	<0.1	62.1	149.8	<0.1	<0.1	1018	<0.1	0.1	<0.1	113.4	<0.1	**Rh**
Ri	1646	<0.1	0.4	117.5	<0.1	<0.1	<0.1	<0.1	<0.1	64.9	146.1	<0.1	<0.1	972	<0.1	0.1	<0.1	120.9	<0.1	**Ri**
Rj	1744	<0.1	0.4	132.8	<0.1	<0.1	<0.1	<0.1	<0.1	69.3	154.2	0.2	<0.1	1030	<0.1	0.1	0.1	142.2	0.2	**Rj**
Rk	1624	<0.1	0.4	127.1	<0.1	<0.1	<0.1	<0.1	<0.1	57.2	133.4	<0.1	<0.1	959	<0.1	0.1	<0.1	133.2	0.4	**Rk**
JS	826	<0.1	0.2	67.9	<0.1	<0.1	<0.1	<0.1	<0.1	39.3	68.7	<0.1	<0.1	477	<0.1	<0.1	<0.1	46.2	<0.1	**JS**
BB	1376	<0.1	0.3	78.6	<0.1	<0.1	<0.1	<0.1	<0.1	41.2	115.0	0.4	<0.1	751	<0.1	0.2	<0.1	17.7	0.1	**BB**
GD	1054	<0.1	0.3	92.2	<0.1	<0.1	<0.1	<0.1	<0.1	67.7	109.1	<0.1	<0.1	540	<0.1	0.1	<0.1	72.5	<0.1	**GD**
WB	730	<0.1	0.2	73.1	<0.1	<0.1	<0.1	<0.1	3.0	32.8	74.8	0.3	<0.1	331	<0.1	<0.1	<0.1	14.4	5.0	**WB**
MSa	870	<0.1	0.3	79.1	<0.1	<0.1	<0.1	<0.1	<0.1	48.8	93.8	0.5	<0.1	550	<0.1	0.1	<0.1	125.0	1.3	**MSa**
MSb	880	<0.1	0.3	78.3	<0.1	<0.1	<0.1	<0.1	<0.1	50.0	93.4	0.3	<0.1	552	<0.1	0.2	<0.1	126.3	0.9	**MSb**
MSc	864	<0.1	0.3	78.3	<0.1	<0.1	<0.1	<0.1	0.3	49.0	93.3	0.4	<0.1	556	<0.1	0.1	<0.1	125.5	2.9	**MSc**

Table(A4.7): Water extracted EC/pH data for all solid samples

EC/pH DATA

MINE SITE SAMPLES

Code	EC	pH
X1	1.06	4.34
X2	1.2	3.12
X7	0.75	4.45
X9	0.14	3.71
X10	0.64	3.32
X13	0.22	3.75
X14	0.27	7.78
X15	0.63	3.95
X16	0.29	4.02
X19	4.12	2.9
X20	3.8	2.89
X21	8.51	3.22
X22	30.8	2.71
X24	2.89	3.08
X25	2.22	2.71
X27	0.08	4.86
X31	0.07	5.03
X33	3.33	2.93
X34	0.66	3.11
X35	0.46	4.29
X27	0.13	4.56
X38	0.35	3.28
X44	0.13	3.71
X46	1.64	2.75

SOILP PROFILES

Code	EC	pH
P1a	0.28	3.49
P1b	0.17	3.52
P1c	0.27	3.65
P1d	0.52	3.73
P1e	1.07	3.89
P2a	1.22	3.51
P2b	0.93	3.72
P2c	1.74	3.77
P2d	3.16	3.79
P2e	0.98	3.81
P2f	0.43	3.91
P2g	0.23	3.96
P2h	0.22	3.89

MOUND SPRING REGION

Code	EC	pH
O1	0.55	6.25
O2a	0.49	7.03
O2b	0.51	6.97
O3	0.27	7.54
O4	0.57	8.55
MS3a	5.3	3.57
MS4a	1.14	7.09
MS4c	1.36	6.94
MS5a	2.01	7.26
MS6a	0.96	8.61
MS6b	0.94	8.57

EC/pH DATA

SURROUNDING SOIL SAMPLES

Code	EC	pH
C1	1.39	7.95
C2	0.74	3.56
C3	0.12	4.66
C4	0.05	5.32
C9	0.36	8.09
C10	0.36	8.25
C11	0.04	6.59
C12	0.04	6.52
C13	0.41	7.38
MS1	0.88	7.38
MS2	0.39	8.3
W0	0.2	4.05
W1	0.21	3.47
W2	1.3	2.59
W3a	0.21	3.41
W3b	0.18	3.49
W4	0.49	3.01
W5a	0.29	3.98
W5b	0.22	3.46
W6	0.14	3.85
W7a	0.84	4.31
W7b	0.7	6.95
W8	0.6	6.89
W9	0.14	3.74
W10	0.71	3.97
W11	0.35	3.49
W12	0.49	3.11
S1	0.25	3.11
S2	0.11	3.65
S3	0.46	3
S4	0.68	2.91
S5	1.11	2.73
S6	0.17	3.46
S7	0.28	3.65
S8	0.54	2.92
S9	0.32	3.32
S10a	1.1	2.65
S10b	0.77	2.89
N1	0.12	4.37
N2	0.66	2.88
N3	0.39	3.12
N4	0.28	3.32
B	0.1	8.85

JAMES' PROPERTY

Code	EC	pH
J1	0.47	4.53
J5	7.77	2.42
J6	11.43	3.23

Table (A4.8): EC/pH data for all water samples

EC/pH DATA - Water Samples				
EC (measured in the laboratory) and				
pH (measured in the field with a hand held meter)				
Number	**Code**	**Site**	**EC**	**pH**
1	Ra	Rodwell Ck	4.81	9.1
2	Rb	Rodwell Ck	5.54	8.2 (8.5)
3	Rc	Rodwell Ck	7.07	8.5
4	Rd	Rodwell Ck	5.89	8.5
5	Re	Rodwell Ck	5.95	8.5
6	Rf	Rodwell Ck	5.91	8.5
7	Rg	Rodwell Ck	6.1	8.3
8	Rh	Rodwell Ck	6.42	8.5
9	Ri	Rodwell Ck	6.09	8.4
10	Rj	Rodwell Ck	5.62	8.8
11	Rk	Rodwell Ck	6.01	8.9
12	JS	Spring	3.66	8.3
13	BB	Bore	4.99	6.6
14	GD	Dam	4.34	8.5
15	WB	Bore	2.8	N/A
16	MSa	MoundSpring	3.84	7.8
17	MSb	MoundSpring	3.69	8.4
18	MSc	MoundSpring	3.89	7.5

Table (A4.9): Assay values

Assay values from Wade and Cochrane (1954)				
Material	**Cu%**	**Pb%**	**Zn%**	**S%**
Slag	0.6	0.8	1.8	
Sulphide dump	0.1	10.9	13.5	
	0.1	15.4	4.2	15.7
Sulphide from shaft	0.2	0.5	4.8	45.8
	0.9	0.9	0.8	37.3
	0.2	0.6	0.8	42.4
	0	17.5	25.4	31.6
	0	16.5	25.5	34
	0.4	3.3	2.1	
Gossan from shaft	0.1	8.6	1	
	0.8	13.1	0.9	45.8
Gossan dump	trace	6.9	0.6	
	0.1	13	16.4	
	trace	7.1	0.8	
	0.4	1.8	0.5	
	trace	10.9	10.2	
Tailings	0.8	9.9	1.1	

Appendix A5

Electron Microprobe Data

APPENDIX A5: Electron Microprobe (EMP) data

Table numbers correlate to plate No.'s in the text (Chapters 3 and 4)

Table 3.1a(i) **X42 PYRITE with minor Zn content**

SiO2	0.0000	Si	0.0000
SO2	100.4889	S	50.2962
Al2O3	0.0000	Al	0.0000
As2O3	0.0322	As	0.0244
FeO	60.0197	Fe	46.6542
CuO	0.0329	Cu	0.0262
ZnO	0.2944	Zn	0.2365
PbO	0.0000	Pb	0.0000
K2O	0.0000	K	0.0000
total	160.8681		

Table 3.1a(ii) **X42 SPHALERITE**

SiO2	0.0000	Si	0.0000
SO2	58.7821	S	29.4213
Al2O3	0.0155	Al	0.0082
As2O3	0.0000	As	0.0000
FeO	11.8266	Fe	9.1930
CuO	0.0829	Cu	0.0662
ZnO	72.6990	Zn	58.4047
PbO	0.0000	Pb	0.0000
K2O	0.0624	K	0.0518
total	143.4743		

Table 3.1a(iii) **X42 GALENA with minor Zn & Cu content**

SiO2	0.0115	Si	0.0054
SO2	21.8669	S	10.9447
Al2O3	0.0000	Al	0.0000
As2O3	0.0281	As	0.0213
FeO	0.1831	Fe	0.1423
CuO	0.1454	Cu	0.1162
ZnO	0.8473	Zn	0.6807
PbO	74.7346	Pb	69.3773
K2O	0.0132	K	0.0109
total	97.8330		

Table 3.1c **X42 Fe SULPHATE with As & minor Zn, Pb & Cu coprecipitation**

SiO2	0.1392	Si	0.0651
SO2	5.7862	S	2.8961
Al2O3	1.0547	Al	0.5582
As2O3	4.0325	As	3.0542
FeO	68.5300	Fe	53.2694
CuO	0.1681	Cu	0.1343
ZnO	1.2444	Zn	0.9997
PbO	0.5562	Pb	0.5163
K2O	0.0119	K	0.0099
total	81.5232		

Table 3.1d(i) **X35 SILICEOUS TAILINGS MASS with minor Pb content**

SiO2	38.5730	Si	18.0308
SO2	0.1456	S	0.0729
Al2O3	17.5951	Al	9.3124
As2O3	0.0000	As	0.0000
FeO	7.2856	Fe	5.6632
CuO	0.1022	Cu	0.0816
ZnO	0.1094	Zn	0.0879
PbO	0.4332	Pb	0.4022
K2O	1.9300	K	1.6022
total	66.1740		

Table 3.1d(ii) **X35 Fe OXIDE with Zn & minor Pb, Cu and As coprecipitation**

SiO2	1.2037	Si	0.5627
SO2	0.3676	S	0.1840
Al2O3	0.1309	Al	0.0693
As2O3	0.1629	As	0.1234
FeO	67.3462	Fe	52.3492
CuO	0.3628	Cu	0.2898
ZnO	4.5691	Zn	3.6707
PbO	0.7512	Pb	0.6973
K2O	0.0253	K	0.0210
total	74.9196		

Table 3.1d(iii) **X35 Fe OXIDE with Zn & minor Pb, Cu and As coprecipitation**

SiO2	1.2037	Si	0.5627
SO2	0.3676	S	0.1840
Al2O3	0.1309	Al	0.0693
As2O3	0.1629	As	0.1234
FeO	67.3462	Fe	52.3492
CuO	0.3628	Cu	0.2898
ZnO	4.5691	Zn	3.6707
PbO	0.7512	Pb	0.6973
K2O	0.0253	K	0.0210
total	74.9196		

Table 3.1d(iv) **X35 PYRITE with minor Zn content**

SiO2	0.0000	Si	0.0000
SO2	96.1324	S	48.0662
Al2O3	0.0000	Al	0.0000
As2O3	0.0102	As	0.0073
FeO	57.1564	Fe	44.4451
CuO	0.0325	Cu	0.0260
ZnO	0.2834	Zn	0.2302
PbO	0.0000	Pb	0.0000
K2O	0.0000	K	0.0000
total	153.6149		

Table 3.1e(i) **X7 HEMATITE with Pb, Zn, As and Cu content**

SiO2	5.2971	Si	2.4761
SO2	1.8393	S	0.9206
AL2O3	0.2454	Al	0.1305
As2O3	0.2007	As	0.1520
FeO	73.6777	Fe	57.2708
CuO	0.1947	Cu	0.1555
ZnO	1.4626	Zn	1.1751
PbO	2.6772	Pb	2.4853
K2O	0.0000	K	0.0000
total	85.8947		

Table 3.1e(ii) **X7 ANGLESITE**

SiO2	0.0000	Si	0.0000
SO2	22.1351	S	11.0790
Al2O3	0.0000	Al	0.0000
As2O3	0.0202	As	0.0153
FeO	0.9704	Fe	0.7543
CuO	0.0149	Cu	0.0119
ZnO	0.0000	Zn	0.0000
PbO	72.9257	Pb	67.6981
P2O	0.0000	K	0.0000
total	96.0663		

Table 3.1g(i) **X7 HEMATITE (DARK GREY) with Pb & Zn content**

SiO2	4.8680	Si	2.2755
SO2	0.4631	S	0.2318
Al2O3	0.1084	Al	0.0577
As2O3	0.1784	As	0.1351
FeO	74.2681	Fe	57.7297
CuO	0.1219	Cu	0.0974
ZnO	0.9110	Zn	0.7319
PbO	2.7852	Pb	2.5855
K2O	0.0000	K	0.0000

Table 3.1g(ii) **X7 HEMATITE (LIGHT GREY) with high Pb content**

SiO2	2.4359	Si	1.1386
SO2	0.6231	S	0.3119
Al2O3	0.0002	Al	0.0001
As2O3	0.1002	As	0.0759
FeO	72.3854	Fe	56.2663
CuO	0.1145	Cu	0.0915
ZnO	0.0703	Zn	0.0565
PbO	9.6446	Pb	8.9532
K2O	0.0000	K	0.0000
total	85.3742		

Table 3.1h (i) **X7 GAHNITE**

SiO2	0.0242	Si	0.0113
SO2	0.0171	S	0.0086
Al2O3	32.4677	Al	17.206
As2O3	0.0000	As	0.0000
FeO	3.5134	Fe	2.7310
CuO	0.0275	Cu	0.0220
ZnO	21.3981	Zn	17.1907
PbO	0.0000	Pb	0.0000
K2O	0.0000	K	0.0000
total	57.4480		

Table 3.1h(ii) **X7 ANGLESITE with Zn coprecipitation**

SiO2	0.0000	Si	0.0000
SO2	22.3009	S	11.1619
Al2O3	0.0000	Al	0.0000
As2O3	0.0430	As	0.0326
FeO	2.6356	Fe	2.0487
CuO	0.1106	Cu	0.0884
ZnO	3.1096	Zn	2.4982
PbO	73.2079	Pb	67.9601
K2O	0.0000	K	0.0000
total	101.4180		

Table 3.2a(i) **X1 GOETHITE (MAIN MASS) with minor As, Pb & Cu content**

SiO2	3.0795	Si	1.4395
SO2	1.0058	S	0.5034
Al2O3	0.3616	Al	0.1914
As2O3	0.1641	As	0.1243
FeO	73.8848	Fe	57.4318
CuO	0.2297	Cu	0.1835
ZnO	2.6626	Zn	2.1390
PbO	0.3903	Pb	0.3623
K2O	0.0221	K	0.0183
total	81.8004		

Table 3.2a(ii) **X1 GOETHITE (DARK BAND) with Zn & minor Pb & Cu**

SiO2	2.9890	Si	1.3972
SO2	0.8960	S	0.4485
Al2O3	0.0114	Al	0.0061
As2O3	0.1313	As	0.0995
FeO	75.9478	Fe	59.0354
CuO	0.2871	Cu	0.2293
ZnO	2.7449	Zn	2.2052
PbO	0.3982	Pb	0.3696
K2O	0.0000	K	0.0000
total	83.4057		

Table 3.2b(i) **X1 QUARTZ with minor Zn content**

SiO2	84.0409	Si	39.2845
SO2	0.0833	S	0.0417
Al2O3	0.0000	Al	0.0000
As2O3	0.0000	As	0.0000
FeO	2.3255	Fe	1.8076
CuO	0.0000	Cu	0.0000
ZnO	0.1278	Zn	0.1027
PbO	0.0000	Pb	0.0000
K2O	0.0000	K	0.0000
total	86.5775		

Table 3.2b (ii) **X1 Fe OXIDE with Zn & minor Pb content**

SiO2	0.4917	Si	0.2298
SO2	0.0320	S	0.0160
AL2O3	0.2454	Al	0.1305
As2O3	0.0024	As	0.0018
FeO	87.7209	Fe	68.1868
CuO	0.0000	Cu	0.0000
ZnO	3.5543	Zn	2.8555
PbO	0.1110	Pb	0.1031
K2O	0.0000	K	0.0000
total	92.1576		

Table 3.2b(iii) **X1 GAHNITE**

SiO2	0.0628	Si	0.0294
SO2	0.0030	S	0.0015
Al2O3	54.5314	Al	28.8614
As2O3	0.0000	As	0.0000
FeO	6.0792	Fe	4.7254
CuO	0.0000	Cu	0.0000
ZnO	35.8687	Zn	28.8161
PbO	0.0000	Pb	0.0000
K2O	0.0000	K	0.0000
total	96.5563		

Table 3.2b(iv) **X1 'HEAVY' DEPOSITS (GAHNITE SURFACE) with very high Pb & Zn & minor Cu content**

SiO2	2.1596	Si	1.0095
SO2	6.8139	S	3.4105
Al2O3	0.0000	Al	0.0000
As2O3	0.0000	As	0.0000
FeO	10.2974	Fe	8.0044
CuO	0.7195	Cu	0.5747
ZnO	23.5467	Zn	18.9169
PbO	30.0424	Pb	27.8888
K2O	0.0000	K	0.0000
total	73.5887		

Table 3.2c(i) **X1 JAROSITE with minor Pb coprecipitation**

SiO2	0.0381	Si	0.0178
SO2	27.1894	S	13.6087
Al2O3	0.0429	Al	0.0227
As2O3	0.0680	As	0.0515
FeO	44.6761	Fe	34.7274
CuO	0.0795	Cu	0.0635
ZnO	0.0000	Zn	0.0000
PbO	0.8767	Pb	0.8138
K2O	3.8196	K	3.1709
total	76.7902		

Table 3.2c(ii) **X1 JAROSITE with high Pb & minor Cu coprecipitation**

SiO2	0.1518	Si	0.0710
SO2	25.0626	S	12.5442
Al2O3	3.2964	Al	1.7447
As2O3	0.0717	As	0.0543
FeO	36.0144	Fe	27.9945
CuO	0.1283	Cu	0.1025
ZnO	0.0000	Zn	0.0000
PbO	11.7455	Pb	10.9035
K2O	5.9836	K	4.9673
total	82.4542		

Table 3.2d(i) **X1 GALENA with minor Cu and Zn content**

SiO2	0.0535	Si	0.0250
SO2	25.7309	S	12.8787
Al2O3	0.0000	Al	0.0000
As2O3	0.1142	As	0.0865
FeO	2.5735	Fe	2.0004
CuO	2.2816	Cu	1.8227
ZnO	0.5065	Zn	0.4069
PbO	93.8558	Pb	87.1278
K2O	0.0270	K	0.0225
total	125.1634		

Table 3.2d(ii) **X1 SILICEOUS MATRIX with Pb & Zn & & minor Cu content**

SiO2	33.2956	Si	15.5639
SO2	1.4034	S	0.7024
Al2O3	6.5570	Al	3.4704
As2O3	0.0000	As	0.0000
FeO	36.8190	Fe	28.6200
CuO	0.9725	Cu	0.7768
ZnO	3.7418	Zn	3.0061
PbO	6.1992	Pb	5.7548
K2O	1.3466	K	1.1179
total	90.3352		

Table 3.2g **X19 ANGLESITE**

SiO2	0.0427	Si	0.0199
SO2	22.3475	S	11.1853
Al2O3	0.0608	Al	0.0322
As2O3	0.0406	As	0.0307
FeO	0.0561	Fe	0.0436
CuO	0.0000	Cu	0.0000
ZnO	0.0937	Zn	0.0753
PbO	73.3590	Pb	68.1004
K2O	0.0000	K	0.0000
total	96.0167		

Table 3.2h **X19 Fe SULPHATE with high Pb, Zn and minor Cu coprecipitation**

SiO2	0.6214	Si	0.2905
SO2	21.8414	S	10.9319
Al2O3	0.2119	Al	0.1121
As2O3	0.0694	As	0.0526
FeO	31.4048	Fe	24.4114
CuO	0.5373	Cu	0.4292
ZnO	2.8098	Zn	2.2574
PbO	18.7938	Pb	17.4466
K2O	0.1341	K	0.1113
total	76.4299		

Table 3.3a **X19 Fe/Pb SUPLPHATE with Zn & minor Cu coprecipitation**

SiO2	0.2258	Si	0.1055
SO2	18.3192	S	9.1691
Al2O3	2.3715	Al	1.2551
As2O3	0.0587	As	0.0445
FeO	20.2565	Fe	15.7457
CuO	0.3569	Cu	0.2851
ZnO	6.8783	Zn	5.5259
PbO	23.3269	Pb	21.6547
K2O	0.3065	K	0.2544
total	72.1045		

Table 3.3b(i) **X19 JAROSITE with high Pb, Zn & minor Cu coprecipitation**

SiO2	2.5433	Si	1.1888
SO2	20.4962	S	10.2586
Al2O3	13.9124	Al	7.3633
As2O3	0.0337	As	0.0255
FeO	28.0303	Fe	21.7884
CuO	0.2784	Cu	0.2224
ZnO	2.3650	Zn	1.9000
PbO	8.0341	Pb	7.4582
K2O	4.5718	K	3.7954
total	80.2651		

Table 3.3b(ii) **X22 Fe SULPHATE & Zn and Cu coprecipitation**

SiO2	0.6209	Si	0.2902
SO2	34.6618	S	17.3488
Al2O3	2.8142	Al	1.4894
As2O3	0.0000	As	0.0000
FeO	27.9386	Fe	21.7171
CuO	1.5594	Cu	1.2458
ZnO	7.2477	Zn	5.8226
PbO	0.0000	Pb	0.0000
K2O	0.0394	K	0.0327
total	75.0184		

Table 3.3c(i) **X22 Fe SULPHATE with Zn & minor Cu coprecipitation**

SiO2	1.6119	Si	0.7535
SO2	31.0775	S	15.5548
Al2O3	3.1213	Al	1.6520
As2O3	0.0000	As	0.0000
FeO	16.8316	Fe	13.0834
CuO	0.5214	Cu	0.4165
ZnO	3.6678	Zn	2.9467
PbO	0.0000	Pb	0.0000
K2O	0.0332	K	0.0275
total	56.9143		

Table 3.3c(ii) **X22 JAROSITE with Pb & minor Zn & Cu coprecipitation**

SiO2	9.7824	Si	4.5727
SO2	20.4701	S	10.2456
Al2O3	3.2962	Al	1.7446
As2O3	0.0778	As	0.0589
FeO	30.6410	Fe	23.8177
CuO	0.1734	Cu	0.1385
ZnO	0.4744	Zn	0.3811
PbO	1.9375	Pb	1.7986
K2O	2.6268	K	2.1807
total	69.4796		

Table 3.3d(i) **X22 HALOTRICHITE with Zn & minor Cu coprecipitation**

SiO2	0.0801	Si	0.0375
SO2	43.0886	S	21.5665
Al2O3	27.0855	Al	14.3353
As2O3	0.0000	As	0.0000
FeO	15.1333	Fe	11.7633
CuO	0.1704	Cu	0.1361
ZnO	5.6812	Zn	4.5642
PbO	0.0000	Pb	0.0000
K2O	0.0464	K	0.0385
total	91.3399		

Table 3.3d(ii) **X22 Fe OXIDE with negligable heavy metal content**

SiO2	0.0373	Si	0.174
SO2	0.1198	S	0.0600
Al2O3	0.3416	Al	0.1808
As2O3	0.0000	As	0.0000
FeO	89.1294	Fe	69.2817
CuO	0.0691	Cu	0.0552
ZnO	0.0000	Zn	0.0000
PbO	0.0793	Pb	0.0736
K2O	0.0000	K	0.0000
total	89.7766		

Table 3.3e(i) **X46 JAROSITE with negligable heavy metal content**

SiO2	0.1275	Si	0.0596
SO2	26.4166	S	13.2219
Al2O3	3.9317	Al	2.0809
As2O3	0.0805	As	0.0609
FeO	39.2785	Fe	30.5318
CuO	0.0318	Cu	0.0254
ZnO	0.0253	Zn	0.0204
PbO	0.0000	Pb	0.0000
K2O	6.0666	K	5.0345
total	75.9584		

Table 3.3e(ii) **X46 JAROSITE with minor Zn coprecipitation**

SiO2	0.1669	Si	0.0780
SO2	21.2267	S	10.6243
Al2O3	0.0414	Al	0.0220
As2O3	0.0413	As	0.0313
FeO	31.7168	Fe	24.6539
CuO	0.0556	Cu	0.0444
ZnO	0.1318	Zn	0.1059
PbO	0.0000	Pb	0.0000
K2O	5.9838	K	4.9676
total	59.3642		

Table 3.3g(i) **X16 Fe OXIDE (DARK) with Zn & minor Pb, As & Cu content**

SiO2	2.5662	Si	1.1996
SO2	0.6469	S	0.3238
Al2O3	0.4450	Al	0.2355
As2O3	0.1827	As	0.1384
CoO	0.0000	Co	0.0000
CuO	0.1567	Cu	0.1252
ZnO	2.2597	Zn	1.8154
PbO	0.9556	Pb	0.8871
K2O	0.0000	K	0.0000
total	74.9059		

Table 3.3g(ii) **X16 Fe OXIDE (LIGHT) with Pb & minor As, Zn & Cu content**

SiO2	1.6730	Si	0.7820
SO2	0.6105	S	0.3056
Al2O3	0.1422	Al	0.0753
As2O3	0.2481	As	0.1879
FeO	78.7088	Fe	61.1815
CoO	0.0000	Co	0.0000
ZnO	0.1554	Zn	0.1248
PbO	1.5901	Pb	1.4761
K2O	0.0221	K	0.0183
total	83.3563		

Table 3.3h(i) **X13 JAROSITE with minor Pb, Zn & Cu coprecipitation**

SiO2	0.0637	Si	0.0298
SO2	18.2381	S	9.1284
Al2O3	2.1801	Al	1.1538
As2O3	0.0578	As	0.0438
FeO	27.3564	Fe	21.2645
CoO	0.0000	Co	0.0000
ZnO	0.3715	Zn	0.2984
PbO	1.0264	Pb	0.9528
K2O	5.9151	K	4.9105
total	55.3364		

Table 3.3h(ii) **X13 JAROSITE with Pb & minor Zn coprecipitation**

SiO2	0.1926	Si	0.0900
SO2	21.1806	S	10.6012
Al2O3	8.3345	Al	4.4111
As2O3	0.0629	As	0.0477
FeO	24.4593	Fe	19.0126
CuO	0.0902	Cu	0.0721
ZnO	0.5108	Zn	0.4103
PbO	5.7407	Pb	5.3292
K2O	5.9744	K	4.9597
total	66.5460		

Table 4.1b(i) **W4 JAROSITE with minor Zn coprecipitation**

SiO2	0.1751	Si	0.0819
SO2	27.6899	S	13.8592
Al2O3	2.7513	Al	1.4561
As2O3	0.0000	As	0.0000
FeO	41.2595	Fe	32.0716
CuO	0.0161	Cu	0.0128
ZnO	0.1798	Zn	0.1445
PbO	0.0000	Pb	0.0000
K2O	4.5403	K	3.7692
total	76.6214		

Table 4.1b(ii) **W4 JAROSITE with Pb & minor Cu coprecipitation**

SiO2	0.0761	Si	0.0356
SO2	25.6665	S	12.8465
Al2O3	0.4090	Al	0.2165
As2O3	0.0493	As	0.0373
FeO	43.8377	Fe	34.0757
CuO	0.1748	Cu	0.1396
ZnO	0.0000	Zn	0.0000
PbO	1.3664	Pb	1.2685
K2O	5.3781	K	4.4647
total	76.9579		

Table 4.1c **W4 Fe OXIDE with Pb, Zn and minor Cu content**

SiO2	3.7216	Si	1.7396
SO2	1.0496	S	0.5253
Al2O3	0.2573	Al	0.1362
As2O3	0.1110	As	0.0841
FeO	69.5131	Fe	54.0336
CuO	0.9677	Cu	0.7730
ZnO	2.4307	Zn	1.9528
PbO	1.2922	Pb	1.1995
K2O	0.0008	K	0.0007
total	79.3727		

Appendix A6

XRD PLOTS AND INTERPRETATIONS

Appendix (A6)

XRD PLOTS AND INTERPRETATIONS

Plots are archived on the XRD storage computer at the CSIRO,
Division of Soils, South Australia.

Table (A6.1) **Mineralogy of selected samples as determined by XRD**

Mineral and Formula	Clay			Topsoil											Mound Spring									Country Rk				Waste Sulphide				Gos.	Tailings						Waste rock				Slag	Secondary minerals								Carb.	Mineral and Formula
	C9	X14	C10	C3	C4	P2a	P2b	P2c	P2d	P2e	P2f	P2g	P2h	W4	M3a	M4a	O1	O2a	O2b	O3	M6a	M6b	O4	X13	X15	X16	X31	X10	X25	X42a	X42b	X7	X35	P1a	P1b	P1c	P1d	P1e	X1	X2	X9	X34	X27	X19	X21	X22	X24	X33	X38	X44	X46	MS7	
Quartz SiO2	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	Quartz SiO2
MICAS																																																					**MICAS**
Muscovite 2M1 $KAl_2(Si_3Al)O_{10}(OH,F)_2$			•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•			•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	Muscovite 2M1 $KAl_2(Si_3Al)O_{10}(OH,F)_2$
Muscovite 2M2 $(K,Na)Al_2(Si,Al)_4O_{10}(OH)_2$	•	•	•																																										•		•						Muscovite 2M2 $(K,Na)Al_2(Si,Al)_4O_{10}(OH)_2$
Biotite 2M1 $K(Mg,Fe)_3(Si_3Al)O_{10}(OH)_2$																								•																													Biotite 2M1 $K(Mg,Fe)_3(Si_3Al)O_{10}(OH)_2$
Phlogopite 3T $KMg_3(Si_3Al)O_{10}(OH)_2$				•	•									•																																							Phlogopite 3T $KMg_3(Si_3Al)O_{10}(OH)_2$
CLAYS																																																					**CLAYS**
Kaolinite, 1A $Al_2Si_2O_5(OH)_4$	•	•	•	•	•	•	•	•	•	•	•	•	•	•										•		•	•																	•									Kaolinite, 1A $Al_2Si_2O_5(OH)_4$
FELDSPARS																																																					**FELDSPARS**
Albite, calcian, ordered $(Na,Ca)Al(Si,Al)_3O_8$			•														•	•	•	•	•	•	•																														Albite, calcian, ordered $(Na,Ca)Al(Si,Al)_3O_8$
Albite, calcian, disordered $(Na,Ca)(Si,Al)_4O_8$															•																									•													Albite, calcian, disordered $(Na,Ca)(Si,Al)_4O_8$
Albite, ordered $NaAlSi_3O_8$	•			•	•	•	•	•	•	•	•	•	•	•														•					•	•	•	•	•	•				•	•					•			•		Albite, ordered $NaAlSi_3O_8$
Anorthite, sodian, intermediate $(Ca,Na)(Si,Al)_4O_8$																								•																	•												Anorthite, sodian, intermediate $(Ca,Na)(Si,Al)_4O_8$
Microcline, intermediate $KAlSi_3O_8$		•	•	•	•	•								•			•	•	•	•	•	•	•										•	•	•	•	•	•															Microcline, intermediate $KAlSi_3O_8$
CHLORITES																																																					**CHLORITES**
Clinochlore1MIIB $(Mg,Al)_6(Si,Al)_4O_{10}(OH)_8$																	•			•							•	•	•							•	•	•			•			•				•		•			Clinochlore1MIIB $(Mg,Al)_6(Si,Al)_4O_{10}(OH)_8$
Clinochlore1MIIB Ferroan $(Mg,Fe)_6(Si,Al)_4O_{10}(OH)_8$																																													•		•		•				Clinochlore1MIIB Ferroan $(Mg,Fe)_6(Si,Al)_4O_{10}(OH)_8$
Clinochlore1MIIB Chromian $(Mg,Cr)_6(Si,Al)_4O_{10}(OH)_8$	•	•																																																			Clinochlore1MIIB Chromian $(Mg,Cr)_6(Si,Al)_4O_{10}(OH)_8$
SULPHIDES																																																					**SULPHIDES**
Pyrite FeS_2															•													•	•	•	•		•	•	•	•	•	•					•	•	•	•		•					Pyrite FeS_2
Sphalerite ZnS_2																													•	•	•															•							Sphalerite ZnS_2
Galena PbS																													•	•	•													•									Galena PbS
Chalcopyrite $CuFeS_2$																													?		•																						Chalcopyrite $CuFeS_2$
OXIDES																																																					**OXIDES**
Goethite FeO(OH)																•																							•	•		•											Goethite FeO(OH)
Hematite,syn Fe_2O_3														•												•	•					•	•	•					•	•	•	•	•	•									Hematite,syn Fe_2O_3
Ferrihydrite $Fe_5O_7(OH).4H_2O$																																																					Ferrihydrite $Fe_5O_7(OH).4H_2O$
Ferrohexahydrite $FeSO_4.6H_2O$																																													•								Ferrohexahydrite $FeSO_4.6H_2O$
Gahnite $ZnAl_2O_4$																																									•												Gahnite $ZnAl_2O_4$
Rectorite $NaAl_4(Si,Al)_8O_{20}(OH)_4.2H_2O$																																													•		•		•				Rectorite $NaAl_4(Si,Al)_8O_{20}(OH)_4.2H_2O$

Table (A6.1) Mineralogy of selected samples as determined by XRD

Mineral and Formula	Clay			Topsoil										
	C9	X14	C10	C3	C4	P2a	P2b	P2c	P2d	P2e	P2f	P2g	P2h	W4
SECONDARY SULPHATES														
Jarosite,syn $KFe_3(SO_4)_2(OH)_6$														•
Beudantite $PbFe_3[(As,S)O_4]_2(OH)_6$														
Anglesite.syn $PbSO_4$		•												•
Gypsum $CaSO_4.2H_2O$														
Rozenite $FeSO_4.4H_2O$														
Halotrichite $FeAl_2(SO_4)_4.22H_2O$														
AMPHIBOLE														
Tremolite $Ca_2Mg_5Si_8O_{22}(OH)_2$	•	•												
CARBONATES														
Calcite $CaCO_3$														
Dolomite $MgCaCO_3$														

Mineral and Formula	Cores									Country rock				Sulphide				Gos.
	M3a	M4a	O1	O2a	O2b	O3	M6a	M6b	O4	X13	X15	X16	X31	X10	X25	X42a	X42b	X7
SECONDARY SULPHATES																		
Jarosite,syn $KFe_3(SO_4)_2(OH)_6$										•	•	•	•	•	•			•
Beudantite $PbFe_3[(As,S)O_4]_2(OH)_6$																		
Anglesite.syn $PbSO_4$												•		•		•	•	•
Gypsum $CaSO_4.2H_2O$	•																	
Rozenite $FeSO_4.4H_2O$																		
Halotrichite $FeAl_2(SO_4)_4.22H_2O$																		
AMPHIBOLE																		
Tremolite $Ca_2Mg_5Si_8O_{22}(OH)_2$																		
CARBONATES																		
Calcite $CaCO_3$																		
Dolomite $MgCaCO_3$																		

Tailings						Waste rock				Slag	Secondary minerals								Carb.	Mineral and Formula
X35	P1a	P1b	P1c	P1d	P1e	X1	X2	X9	X34	X27	X19	X21	X22	X24	X33	X38	X44	X46	MS7	
																				SECONDARY SULPHATES
•	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•		Jarosite,syn $KFe_3(SO_4)_2(OH)_6$
														•				•		Beudantite $PbFe_3[(As,S)O_4]_2(OH)_6$
						•	•		•		•									Anglesite.syn $PbSO_4$
												•			•	•		•		Gypsum $CaSO_4.2H_2O$
											•		•							Rozenite $FeSO_4.4H_2O$
													•					•		Halotrichite $FeAl_2(SO_4)_4.22H_2O$
																				AMPHIBOLE
							•													Tremolite $Ca_2Mg_5Si_8O_{22}(OH)_2$
																				CARBONATES
																			•	Calcite $CaCO_3$
																			•	Dolomite $MgCaCO_3$