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ROOTING HABITS OF LODGEPOLE PINE (*PINUS CONTORTA*) IN RELATION TO SOIL CHARACTERISTICS ON COPPER-COBALT MINE SPOILS

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ABSTRACT

Many studies have shown that applying a layer of topsoil over acid mine spoils increases the survivability of vegetation; however, the penetration of roots through the topsoil and into the spoil material is not well documented. This study reports current findings on rooting depth of lodgepole pine (*Pinus contorta* Dougl. ex Loudon) in relation to spoil characteristics from a 24-year old reclamation project on copper-cobalt mine spoils of the Blackbird Cobalt mine near Salmon, Idaho. Site preparation in the early 1970's included topsoiling over acid spoils along with incorporating fertilizer, mulch, and lime. A mixture of native and introduced seeds was broadcast onto the site, and lodgepole pine saplings were then planted. In 1999, pits were dug next to lodgepole pine trees to collect soil profile samples and to assess rooting depth. The spoil material was slightly acidic, had low organic matter content, and contained high concentrations of Al, Ca, Co, Pb, and other minerals. The depth of topsoil at these pits averaged around 20 cm and generally had lower concentrations of heavy metals. Large lateral roots of the lodgepole pines were shallow and, for the most part, remained in the topsoil horizon. Medium and fine-sized roots penetrated the spoil material up to 120 cm. Because the roots penetrated spoil materials, lodgepole pines may be considered as a feasible candidate for reclamation processes.

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INTRODUCTION

Rooting habits of lodgepole pine (*Pinus contorta*) have been extensively studied in various soil types and under diverse conditions (Gail and Long 1935, Horton 1958, Bishop 1962, Bowen et al 1975, Coutts 1982, Nadeau and Pluth 1997). A few studies have shown that under 'normal' conditions the lateral roots of lodgepole pines tend to originate within the top few centimeters of the soil surface and remain within 60 cm (2 feet) of the surface as they grow outward (Gail and Long 1935, Horton 1958, Bishop 1962). In extreme cases, lateral roots can reach a radius of 8 m and vertical roots a depth of over 3 m (Stone and Kalisz 1991). Horton (1958) found that roots for this species reach a maximum area of coverage by about 30 years.

Physical and chemical factors of the soil combine to influence rooting habits of vegetation (Klepper 1987, Sabey et al 1987). Physical factors include soil structure, texture, temperature, and water content (Klepper 1987). Soil compaction, which can be caused by the use of heavy equipment, can alter these factors and may create zones impenetrable to roots, decrease water infiltration, and restrict air supply to plant roots (Sabey et al 1987). Soil chemical factors, such as toxicity, mineral deficiencies, pH levels, amounts of organic matter, and cation exchange capacity, also play an important role in influencing root distribution (Klepper 1987). Determining how roots react in the presence of various physical and chemical conditions is a complicated process as these conditions are very much interrelated and species specific. For example, aluminum toxicity reduces root penetration, but only at low pH levels (Barber 1995).

Lodgepole pine is a pioneer species, which makes it important in reclamation practices (Peattie 1980); however, little is known about the penetration of lodgepole pine roots into acid mine spoils. This paper helps elucidate this issue by studying the rooting habits of lodgepole pine planted in 1976 on copper-cobalt mine spoils near Salmon, Idaho, in relation to physical and chemical soil characteristics found on the site.

STUDY SITE

Blackbird mine is located southwest of Salmon, Idaho, within the Salmon-Challis National Forest. Mining for gold and copper on Blackbird mine began around 1893 and continued until World War II when the government found that the area had potential to yield cobalt. After that, various private firms took over and, in 1949, the mine was converted to an underground copper-cobalt mine. Mining continued until 1960 when the mine was shut down. Three years later, it reopened as a surface pit and underground mine, and continued operating until 1967. It has been largely inactive since that time (Farmer et al 1976).

The study site is located on an overburden spoil waste pile of the Blackbird mine at 2,365 m (7,760 feet) in elevation. Annual precipitation ranges between 60 and 100 cm, most of which falls in winter as snow. This waste pile has been estimated to contain 1 million cubic meters of overburden waste material, with a maximum fill depth of 23 meters (Farmer et al 1976).

METHODS

In the spring of 1974, the overburden waste pile was topsoiled with 20 to 25 cm of soil which was excavated from the surrounding forest and mixed with burnt lime at a rate of 2,030 kg/ha (1,800 lb/acre). The area sat fallow for the summer, and in October, an additional 4,470 kg/ha (4,000 lb/acre) of burnt lime was incorporated into the topsoil. The site was then seeded with a mixture of native and introduced grasses. Following the seeding, the area was fertilized at a rate of 1,420 kg/ha (1,300 lb/acre) of liquid 10-34-0 fertilizer and mulched with 3,050 kg/ha (2,700 lb/acre) of wood fiber. During the summer of 1975, an additional 254 kg/ha (225 lb/acre) of a slow-release 26-3-5 fertilizer was applied, and in September, 5,080 kg/ha (4,500 lb/acre) of agricultural crushed limestone was used to relime the site (Farmer and Richardson 1981). In 1976, lodgepole pine saplings were planted at 10-foot intervals across the site.

In August 1999, 5 pits were dug with a backhoe in order to collect soil samples and determine rooting habits of the lodgepole pines growing on the site. The pits were dug approximately 5 cm away from the base of the tree, and the depth of each pit extended just beyond the deepest roots. The depth of large roots, (> ½" in diameter), medium roots (½" > ¼"), and fine roots (< ¼"), was also recorded. The height and crown diameter of each tree was measured, and the percent of the tree that was discolored was recorded. The age of the tree was roughly estimated by counting the number of whorls (1 whorl/year). The trees were aged to help determine if they were the ones planted in 1976, or if their presence represented natural regeneration, as some natural regeneration was evident on the site. While digging by one of the trees, a main lateral root was hit, and the tree fell over. This pit was abandoned and the results presented here are based on the 4 remaining pits.

Soil samples were collected from various levels in the soil horizon. Since there were few visible horizons, samples were taken from the topsoiled layer and from layers corresponding to the depths at which the aforementioned roots stopped growing. Analyses of the soil included: abundance of minerals, pH, CEC, electrical conductivity, and organic matter content[1].

RESULTS

Four mature trees were chosen that represented the health and size of most of the planted trees on the reclaimed area. Table 1 shows the age estimates as well as the height, crown diameter, and % discoloration of each tree. Trees 1a, 3-1, and 3-3 appear to be those planted in 1976. Tree 3-2 was about 5 to 6 years younger, was much larger than the others, and appears to be a product of natural recruitment.

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[1] Soil analyses were performed at the Soils and Plant Analysis Lab at Brigham Young University in Provo, Utah.

Table 1. Size, age, and % discoloration of each tree. Each site refers to an individual lodgepole pine.

Tree Characteristics	Sites			
	1a	3-1	3-2	3-3
Height (cm)	370	470	515	440
Crown diameter	180	225	320	250
# of whorls (age)	25	27	19	28
% Discoloration	60	40	85	80

The depth of the large lateral roots correlated closely with the depth of the topsoil, while medium and fine roots penetrated deeper into the spoil material (Table 2). The soil surface had a plate-like structure in all 4 pits. Pit 1a had a 5-cm thick compacted and cemented layer in the 15 to 20 cm horizon. Although there were no cemented layers that might inhibit root elongation in the other pits, the spoils in all 4 pits were composed of 60% to 80% rock fragments ranging in size from small pebbles to rocks measuring10 cm in length.

Table 2. Depth of topsoil and large (> ½" in diameter), medium (½" > ¼"), and fine roots (< ¼").

Topsoil and Root Sizes	Sites			
	1a	3-1	3-2	3-3
Topsoil Depth	15 cm	23 cm	30 cm	20 cm
Large Roots	15 cm	20 cm	35 cm	26 cm
Medium Roots	110 cm	120 cm	70 cm	26 cm
Fine Roots	120 cm	120 cm	110 cm	90 cm

Soil nutrient values greatly impact root distribution. Nutrient concentrations that promote normal plant growth are listed in Table 3, and the values of the nutrients found at the study site are presented in Table 4.

Table 3. Commonly held nutrient values for normal plant growth (taken from Lowe 1998).

Properties	Low	Adequate	High
% OM	< 2%	2 – 3%	>3%
pH	<7	7	>7
El. conductivity		0 – 4	>4
Cu (ppm)		0 – 0.2	>0.2
Fe (ppm)	<5	5	>5
K-available (ppm)	<60	60 – 80	>80
Mn (ppm)	<0.5	0.5	>0.5
NO_3-N	<10	10 – 40	>40
P (ppm)	<11	11	>11
Zn (ppm)	<1.5	1.5	>1.5

The percentage of organic matter at each pit was highest in the topsoil and drastically decreased with increasing depth. No pit had adequate OM. Pit 3-3 had almost half as much as pit 1a, and all pits were virtually void of OM at the deepest levels. pH levels varied in each pit but tended to decrease (become more acidic) in all pits from the topsoil horizon to the deeper spoil layers. The trend in electrical conductivity (EC) went from high to low with increasing depth, but none were as drastic as in pit 1a. There was a wide range of variation in cation exchange capacity (CEC) between pits and at different depths within pits, but values were usually higher in the topsoil than at deeper depths.

Table 4. Soil properties at various depths for all 4 pits.

Site, Horizon Depth	% OM	pH	EC (mmhos/cm)	CEC
1a, 0 – 15cm†	**1.77**	**7.46**	**6.0**	**8.04**
1a, 15 – 20cm	0.05	7.94	4.0	7.57
1a, 20 – 34 cm	0.29	7.0	1.44	6.09
1a, 34 – 120cm	0.14	6.76	2.25	3.43
3-1, 0 – 23cm	**1.53**	**6.73**	**0.48**	**1.61**
3-1, 23 – 30cm	0.33	6.93	2.75	2.74
3-1, 30 –35 cm	0.77	7.08	0.35	1.87
3-1, 35 -100cm	0.28	6.07	0.55	1.26
3-2, 0 – 16cm	**0.81**	**6.60**	**0.29**	**1.65**
3-2, 16-30cm‡	**0.32**	**6.90**	**0.44**	**4.13**
3-2, 30 -100cm	0.15	6.20	0.20	4.83
3-3, 0 – 20cm	**0.93**	**6.18**	**2.0**	**4.57**
3-3, 20 -120cm	0.06	6.05	1.42	3.57

† Values in bold print represent topsoil layers.
‡ Most grass roots stopped 16cm, but the topsoil layer continued to 30cm.

Results from analyses on the abundance of various elements found in each pit are listed in table 5. Note the high amounts of As, Ca, Co, Cu, Fe, K, P, and Pb in the cemented 15-20 cm layer in pit 1a. This layer also had the highest pH of all layers in all pits. The large roots of this lodgepole didn't penetrate this layer, and this tree was the smallest of the 4.

The horizons in pit 3-1 show a distinct pattern. The abundance of all minerals but NO_3-N decreased drastically from the surface horizon to the second horizon. It then increased from the second to the third layer. All but 2 minerals were more abundant in the third layer than in the surface horizon. Abundance then dropped in the fourth layer.

Looking across all layers, pit 3-2 exhibited lower amounts of Al, As, Co, Cu, and P than other pits. This was the largest tree but also had the highest percent discoloration.

As depth increased, concentrations of several of the minerals also increased (eg. Cu and Pb). Conversely, some of the elements decreased with increasing soil depth (eg. Zn and NO3-N), while many showed both patterns.

Table 5. Abundance of minerals in 4 soil pits. Units are parts per million unless stated otherwise.

Site, Horizon Depth	Al	As	Ca (EX)†	Co	Cu	Fe	K-AV	Mg (EX)	Mn	NO_3-N	P	Pb	Zn
1a, 0 – 15cm‡	**2753**	**5.1**	**2216**	**13.2**	**9.2**	**31.8**	**288**	**37.3**	**8.8**	**3.36**	**24.0**	**14.7**	**0.33**
1a, 15 – 20cm	3210	48.9	2692	54.3	44.6	67.9	576	80.3	3.9	2.37	97.1	33.5	0.17
1a, 20 – 34 cm	3209	15.0	504	18.0	9.3	37.2	323	117.5	1.4	2.25	20.0	31.8	0.21
1a, 34 – 120cm	2660	3.3	442	13.7	9.8	31.6	291	128.3	2.4	2.52	11.2	24.9	0.23
3-1, 0 – 23cm	**3162**	**8.0**	**849**	**13.2**	**35.2**	**49.0**	**237**	**21.9**	**4.7**	**2.31**	**16.4**	**27.8**	**0.69**
3-1, 23 – 30cm	1170	2.9	342	5.6	4.0	18.5	138	18.2	0.9	2.58	3.3	8.9	0.2
3-1, 30 – 35cm	4306	28.6	1933	146.7	76.6	37.0	339	33.4	1.2	6.78	53.8	44.2	1.05
3-1, 35 -100cm	2843	12.0	334	23.4	40.5	43.4	269	15.2	1.3	4.36	27.0	31.9	0.38
3-2, 0 – 16cm	**1280**	**0.93**	**557**	**7.2**	**8.1**	**45.5**	**166**	**40.2**	**5.0**	**2.43**	**11.6**	**20.0**	**0.31**
3-2, 16 – 30cm	**1622**	**1.67**	**1260**	**7.8**	**3.8**	**33.8**	**144**	**77.3**	**2.3**	**1.80**	**5.9**	**13.3**	**0.24**
3-2, 30 -100cm	1530	5.96	499	35.5	34.1	25.5	282	35.0	12.0	1.71	13.3	25.0	0.32
3-3, 0 – 20cm	**2036**	**2.5**	**558**	**9.6**	**18.5**	**61**	**182**	**29.5**	**8.5**	**5.63**	**15.0**	**17.3**	**0.31**
3-3, 20 -120cm	2551	10.6	467	13.1	43.2	66.7	323	12.9	0.57	4.19	42.0	31.0	0.16

† EX stands for the amount of the element in the soil that is exchangeable.
‡ Bold horizon depths represent topsoil layers.

DISCUSSION

The results presented here are based on 4 lodgepole pines. Although there is little statistical strength in such a small sample, these results are important because they show trends in root distribution on copper-cobalt mine spoils.

It is difficult to determine why the roots of these lodgepole pines behave the way they do by just looking at these results. It is important to keep in mind that each soil factor influences other factors. For instance, Cu is more soluble in acid soils than in alkaline soils, and the uptake of Cu is inhibited by high organic matter (Neuman et al 1987). These spoils are slightly acidic, which make Cu more soluble, and they are also very low in organic matter, which should increase the uptake of Cu.

pH influences the availability of other nutrients as well (Tucker et al 1987). The pH of the spoils at this site fall within a range that would enhance the availability of Fe, Mg, Mn, N, P, and Zn.

The large lateral roots of these trees generally stayed within the topsoil horizon. Besides pit 1a, none of the sites had a compacted layer that would have acted as a physical barrier to root penetration. pH levels were usually highest in the topsoil which could decrease the availability of the previously mentioned elements. However, it is not known whether these roots remain in this horizon because of better soil conditions or if they simply follow the same distribution of lateral roots of other lodgepole pines as described by Gail and Long (1935), Horton (1958), and Bishop (1962). Future research on this site should include a study of the rooting habits of lodgepole pine from the surrounding undisturbed forest.

Although the large lateral roots remained near the soil surface, medium roots grew to a wide variety of depths, and the fine roots of the 4 trees grew to depths between 90 and 120 cm. All pits had high amounts of Al, Cu, Fe, K, Mn, and P and exhibited deficiencies in Zn and No_3-N throughout the layers. The fine roots may have stopped between 90 and 120 cm because of unfavorable conditions such as low OM and NO_3-N and increases in toxicity of elements such as Al, Co, Cu, and Pb. Some lower horizons appear to have concentrations of these ions high enough to correspond to the hotspots discussed by Farmer et al (1976). Soil samples below 120 cm would have aided in determining if the trend in increasing toxicity continued and limited fine roots to this depth.

This study has examined the rooting behavior of lodgepole pines on copper-cobalt mine spoils 24 years after reclamation practices began. Rooting behavior on this spoil is similar to that found on undisturbed sites. The fact that medium and fine roots penetrate the spoil material, and thus help stabilize the soil, shows that this species may be a good candidate for reclamation activities.

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An International Perspective on the Environmental Management of Sulfidic Mine Wastes

by
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Abstract: The environmental management of sulfidic mine wastes is one of the most important issues facing the minerals industry not only in Australia but around the globe. In the past, inappropriate management techniques have led to a legacy of significant environmental impacts including acid drainage (AD) which results from the oxidation of sulfidic minerals exposed to atmospheric conditions and subsequent release of acidic solutions containing high concentrations of metal pollutants. These are transported to ground and surface water and can severely impact the immediate and surrounding environment. It is therefore vital now and in the future that sulfidic mine wastes are well managed to prevent a repeat of historical environmental problems.

In Australia, it has been estimated that the minerals industry faces liabilities of about A$0.9 billion for managing potentially acid forming sulfidic mine wastes at current mine sites. Liabilities associated with abandoned and historic sites have not yet been quantified. From an international perspective, these costs pale into insignificance as it has been estimated that the cost of reclamation of abandoned mine sites in the USA alone is between A$150 billion and A$750 billion.

In recent times, our understanding of the challenges associated with AD has increased and strategies have been developed to improve the environmental management of sulfidic mine wastes. In 1998, the Australian Minerals and Energy Environment Foundation (AMEEF) supported an International Travelling Scholarship to gather information from a number of overseas countries facing similar environmental problems to Australia. This paper provides a summary of the main findings of the AMEEF Travelling Scholarship and presents some of the techniques used to manage sulfidic mine wastes and control/remediate AD. A number of case studies are presented to highlight the application of promising management strategies in the field.

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1.0 INTRODUCTION

The environmental management of sulfidic mine wastes is one of the most significant and complex environmental issues facing the mining industry not only in Australia but around the world. In the past, inappropriate or non-existent environmental management techniques have led to a legacy of ongoing environmental problems including acid drainage.

Acid drainage (AD) occurs when sulfidic minerals (*eg.* pyrite, FeS_2) react with oxygen and water on exposure to atmospheric conditions, especially in the presence of bacteria such as *Thiobacillus ferrooxidans*. The resultant acidic solutions may mobilise metals such as Al, Cu, Fe, Mn and Zn from the surrounding matrix, transport these to ground and surface water, and affect the immediate and surrounding environment (CMA, 1992). In nature, the geological processes leading to the development of acidity generally occur over a very long period of time and contaminants can be assimilated by the receiving environment. In contrast, anthropogenic activities such as mining, can disturb and expose large volumes of sulfidic waste minerals in a relatively short time. The acid generation rate may be far in excess of that which the receiving environment can handle and the effects on the downstream ecosystem can be devastating. Environmental impacts can continue long after mining operations are complete as shown in the Rio-Tinto region of Spain where historical mines have been a source of ongoing pollution for more than two millennia (Taylor, 1997).

When the topic of AD is raised in Australia, a number of famous historical mine sites spring to mind (*eg.* Captains Flat, Rum Jungle and Mount Lyell) as particularly acute examples of the significant ongoing environmental problems that can occur if the potential for acidity and contaminated leachate is not considered and managed accordingly. Even when the AD potential is considered in the initial Environmental Assessment phase of a mining project, constant vigilance and monitoring is required as unexpected challenges can arise during the production phase and at cessation of mining (Tarlinton, 1995).

Liability associated with managing sulfidic mine wastes at current Australian mine sites has been estimated at A$900M (Harries, 1997) and has not yet been quantified for abandoned and historic sites. The Australian minerals industry has dramatically improved its environmental performance over the past few decades and recognises that it should contribute to the remediation and rehabilitation efforts at historical mine sites. Recent initiatives such as the Australian Mineral Industry's *Code for Environmental Management* will help to minimise the risk of AD in future and improve the industry's public image. Continuous improvement in environmental management and performance forms an integral part of the *Code* and it is important that the most appropriate techniques to manage sulfidic mine wastes and to control and remediate AD are implemented to prevent a repeat of historical environmental problems.

In recent times, our understanding of the challenges associated with AD has increased and strategies have been developed to improve the environmental management of sulfidic mine wastes. In 1998, the Australian Minerals and Energy Environment Foundation (AMEEF) supported an International Travelling Scholarship to gather information from a number of overseas countries facing similar environmental problems to Australia. This paper provides a summary of the main findings of the AMEEF Travelling Scholarship and presents some of the techniques used to manage sulfidic mine wastes and control/remediate AD. A number

of case studies are presented to highlight the application of promising management strategies in the field.

2.0 BACKGROUND

The main sources of AD at mine sites are waste rock dumps, stockpiles, tailings impoundments and abandoned mine areas. The environmental impacts of AD include the release and transport of highly acidic contaminated leachates into the downstream environment. Even where neutralisation of the generated acidity occurs through interaction with carbonate minerals, contaminants can remain mobile at neutral pH.

The successful management of sulfidic mine wastes and control or remediation of AD requires an understanding of the geochemistry of the problem and factors influencing the rate of acid generation. A number of factors can influence the process including oxygen and water availability, microbial activity, pH, temperature, ferrous/ferric iron equilibrium, physical nature of the waste material and the presence of any neutralising minerals. These factors will vary from site to site and management practices for dealing with the problem may also have to be varied to suit particular site conditions.

The management process should involve initial characterisation of the various rock types likely to be generated during mining activities. An evaluation of similar mining operations in the region may also provide some indication of the acid forming nature of the regional ore bodies and host rocks. Examination of drill core can provide useful information on sulfide mineralogy and presence of any potentially neutralising materials. Sampling techniques should reflect the geological variability and complexity in rock types and the level of confidence required in predictive ability.

As well as a geological assessment, characterisation of mine rock types can be achieved using a number of static and kinetic geochemical tests. The variety of these tests available are well documented and have been the subject of much research (AMIRA, 1996; Miller *et al.,* 1997). Geological modelling of the acquired information can form the basis of initial mine planning strategies (Scott *et al*., 1996).

The oxidation of pyrite is a complex multi-staged process (MCA, 1992) but is often summarised as:

$$\textbf{1.} \quad FeS_2 + 15/4\ O_2 + 7/2\ H_20 = Fe(OH)_3 + 2\ H_2SO_4$$

From reaction 1, it is clear that the formation of AD requires at least three components: oxygen, water and reactive sulfidic rock. Management techniques used to deal with sulfidic mine wastes containing reactive pyrite are numerous, but typically aim to reduce the rate of oxidation and limit the transport of oxidation products to the receiving environment. These objectives can be achieved by limiting the supply of oxygen to the reactive sulfides and minimising the amount of water available to transport contaminants to surface and ground waters. The net amount of acid formed by a particular waste can be reduced by adding neutralising agents such as lime or utilising bactericides which limit the bacteria that catalyse the oxidation. Bacterial catalysis only becomes important below pH 3.5, however, bactericides can work effectively if combined with neutralising material and natural organic

fertilisers which stimulate the growth of vegetation and benign microbes. Covers, caps and seals can be used to isolate or encapsulate sulfidic waste materials and minimise oxygen and/or water access. Oxygen exclusion can effectively prevent sulfide oxidation but may be difficult to achieve. Capping materials which have been successfully used to minimise oxygen diffusion include water, compacted soils and geofabric materials. The most appropriate strategy for managing sulfidic mine wastes may utilise a combination of some or all of the above methods.

The plethora of strategies used in Australia for managing potentially acid forming sulfidic mine wastes have been reviewed (Miller, 1995; Harries 1997) and practical engineering options for minimising AD or controlling its effects have been described (Watson, 1995; Marszalek, 1996). Where management strategies have been absent or ineffective and AD is apparent, a number of active and passive treatment and control techniques are available. The subject of AD treatment has recently been critically reviewed in some detail (Parker & Robertson, 1999).

Active treatment (*eg.* neutralisation with alkaline reagents) tends to be expensive and produces a metal rich precipitated sludge requiring separate disposal. Treatment may have to be continued for many years after mine decommissioning. However, if the contaminated leachate contains dissolved metals in sufficient concentrations, funds generated from metal recovery may offset operating costs. Passive treatment techniques (*eg.* constructed wetlands) have been the subject of some research (Tyrrell, 1995) and are becoming more prevalent but there is a paucity of information regarding their long term effectiveness and ongoing maintenance costs. Passive treatment techniques are probably most beneficial when used to treat relatively low acidity and low flow AD streams.

Traditional active and passive treatment techniques do not significantly reduce the total sulfate load released that, at sufficiently high concentration, may be toxic to downstream freshwater biota. The use of sulfate reducing bacteria in conjunction with both active and passive treatment techniques has shown some promise in improving the quality of mine waste waters impacted by AD in particular reducing sulfate concentrations (Robertson, 1998; Tyrrell *et al*., 1998).

The effectiveness of the selected management strategy should be monitored to ensure that predictions are accurate and no long term financial or social liability exists. Monitoring should be considered an essential part of sulfidic mine waste management as regulating authorities need to be convinced of the integrity of the overall strategy and are unlikely to accept transfer of responsibility without confirmation of predictions by comprehensive scientific studies with good field data.

On-site monitoring should include geotechnical, hydrological, physical and chemical studies. Off-site monitoring should include chemical and biological studies to provide further information on the effectiveness of the selected control/remediation strategy and give some indication of short and long term ecosystem rehabilitation success.

3.0 CASE STUDIES - AMEEF TRAVELLING SCHOLARSHIP

This paper highlights one Australian case study and three selected overseas case studies investigated as part of the AMEEF Travelling Scholarship undertaken from May to June 1998. The Scholarship involved travel to New Zealand, The USA, Canada and The Netherlands and included visits to an international conference on mine rehabilitation, sixteen mine sites and six research centres. The majority of the Scholarship was spent in North America and included visits to a number of active mine sites currently managing sulfidic mine wastes and several historical mine sites having a legacy of ongoing environmental degradation due to inappropriate management of sulfidic mine wastes.

3.1 Australia - Mt. Lyell

The Mt. Lyell Mine is located in a high rainfall environment (2.5 - 3 m/yr) on the west coast of Tasmania and has a history of mining activities over more than a century which have resulted in substantial modifications to environmental conditions. Disposal of sulfidic waste rock across the lease has left a legacy of ongoing environmental impacts. AD emitted from underground workings and waste rock dumps at the mine site has severely impacted on water quality downstream in the Queen and King Rivers and Macquarie Harbour.

Some 55 Mt of sulfidic waste rock, at an average of 10% pyrite, has been historically disposed of in more than 10 waste rock dumps across the surface of the Mt Lyell lease with scant regard for possible environmental impacts (EGi, 1993). Modelling of the pyritic oxidation rates in the abandoned West Lyell open cut waste rock dumps by the Australian Nuclear Science and Technology Organisation (ANSTO) has revealed that leachate from these dumps will continue to be a source of AD for an estimated 600 years (ANSTO 1994 a, 1994b).

The Mt Lyell mine ceased operation in December 1994 and the Tasmanian State Government granted Copper Mines of Tasmania Pty. Ltd. (CMT) a mining lease the following year for redevelopment of Mt. Lyell and indemnity from actions concerning pollution from previous occupation and use of leased land. The Environmental Management Plan (EMP) for the Mt. Lyell redevelopment has committed CMT to be responsible for waste rock dumps generated from current and future activities and to ensure that environmental management is in line with the principles of best practice (Robertson *et al*., 1997).

The Author has first hand experience of the environmental standards at the CMT operation having carried out the duties of Environmental Superintendent at the mine in 1996 and 1997. The Company treats a portion of the AD generated with alkaline tailings prior to sub-aqueous disposal of neutral tailings/AD mixture in a new A$12M tailings dam built in 1995, thus ending the historical practice of tailings disposal in the Queen River. Nevertheless, the ongoing legacy of AD from historical waste rock dumps and underground workings continues and contributes over two tonnes of dissolved copper per day, as well as other metal pollutants, to the downstream Queen and King Rivers and Macquarie Harbour (Clarke, 1997). The nature and possible remediation of this AD have been the subject of much research including the Mount Lyell Research, Remediation and Demonstration Program (MLRRDP) (Koehnken, 1997).

In recent years funds have been made available from the Australian Federal Government to establish a Solvent Extraction Electrowinning (SXEW) treatment plant alongside the mining operation to remove the majority of the dissolved copper from the most pollute streams. The SXEW plant is due to be commissioned this year whilst the feasibility of using an active Solvent Reducing Bacteria (SRB) plant as a final polishing step in the water treatment regime is being investigated (NTBC, 1997).

3.2 New Zealand - Golden Cross Mine

The Golden Cross mine lies at the head of the Waitekauri Valley, 10 km northwest of Waihi in an area that was farmed prior to mining. This hard rock gold mine is located in the Coromandel region on the East Coast of New Zealand's North Island, carries a large bond to ensure environmental protection and final rehabilitation. Coeur Gold NZ Ltd announced the mine's closure in December 1997 and has completed an extensive decommissioning program with site activities including remediation of tailings, open cut and underground areas. Potentially acid forming waste rock from around the site has been encapsulated by inert waste rock within the open pit area which is being progressively refilled and rehabilitated .

Extensive drainage and earthmoving work has now stabilised the tailings dam area which is partially capped with inert waste rock. One of the main management objectives for the tailings dam closure is to reduce the volume of water in the dam as ongoing treatment of this water will be required into the future. A series of constructed wetland facilities have been constructed to treat water from the tailings surface and under drains as well as discharge from underground workings. Water quality and aquatic life downstream from the mine are regularly monitored by the company as well as independent agencies and controls on the treated water discharge into the Waitekauri River are based on extensive studies of water quality and freshwater life. Studies carried out by the Company show young trout to be the most sensitive to minor changes in water quality, and the water is treated to a standard to protect them and their habitat. It is interesting that water quality criteria for gold mining operations are more stringent than for other industries in New Zealand.

Final rehabilitation of the mine site is now all but complete with underground workings having progressively being allowed to flood. The Company plan to develop a commercial forestry program on site and use projected future income from timber sales to offset a significant proportion of current decommissioning costs. Post mining land use is a topic which is likely to receive increased attention in the future (Kuhn, 1998).

Many lessons can be learned from the Golden Cross mine in terms of experience in managing sulfidic mine wastes. Clearly, identification of the potential for AD should be undertaken at the environmental assessment stage and the selected management strategy should be integrated into forward planning (and budgeting). The overall cost of environmental management can be drastically reduced if carried out progressively during the project life rather than retrospectively, especially if disturbed land can be rehabilitated and returned to productive use following decommissioning.

3.3 USA - Bingham Canyon

The cost of reclamation of abandoned mine sites in the USA is estimated to be between AS150 billion and A$750 billion (MSU,1998). Approximately 15,000 km of rivers and streams are impacted by AD from coal and metalliferous mining and on United States Forest Service lands alone there are between 20,000 and 50,000 mines generating AD (USDA,1993).

The Travelling Scholarship involved spending seventeen days in the USA allowing attendance at one international conference (ASSMR, and inspection of a total of nine historical and/or active metalliferous mine sites in five states including Alaska, Colorado, Missouri, Montana and Utah.

The Bingham Canyon Copper Mine operated by Kennecott Utah Copper located near Salt Lake City in Utah is almost 4 km wide by 1 km deep and is the largest man-made excavation on earth. It is one of only two man made structures visible from space, the other being the Great Wall of China. The Company employs large-scale open pit mining methods to excavate sulfidic materials (160,000 tons of copper ore and 290,000 tonnes of waste rock per day). Following mineral processing, the concentrated ore reports to flash smelting and refining facilities which recover 99.9 % of sulfur dioxide emissions and are claimed to be the cleanest in the world. The sulfur is converted to sulfuric acid and about 1,000,000 tons of acid is produced annually for the domestic market.

An extensive water management system segregates waters of different quality to put each water type to its most beneficial use. Stormwater and snowmelt from above the mine site is routed around any area of disturbance in order to protect its purity and is partially used as process water. Contaminated water from within the mine and other operating areas is captured and diverted into the process system. The company recycle approximately 60 % of total water demand which is vital given the arid environment in which the mine is situated,

There are several waste rock disposal areas around the site and an A$80M investment in an extensive leach and stormwater capture system has turned a dissolved copper liability into a resource of 20 tons of solid copper daily. A series of French drains and cut-off walls capture 98% of the total flow and work is in progress to capture the rest. A major demonstration reclamation project covers over 80 hectares of waste rock on the site as the operators study the feasibility of various reclamation techniques for final decommissioning. The use of sulphate reducing bacteria (SRB) for the active treatment of contaminated ground water seepage from mining areas has been piloted at the mine in collaboration with Paques Bio Systems BV of the Netherlands. The system utilises CO_2 gas as a carbon source instead of *eg*. biosolids as this provides a more easily controlled and uniform supply for pilot studies.

Tailings from the Kennecott operation are stored in a 2300 hectare impoundment using a peripheral discharge system to maintain surface moisture and minimise dust. Excess water is recycled back to the production circuit and the perimeter embankments of the impoundment are revegetated as the dykes are raised. Kennecott has spent over A$300M on site rehabilitation initiatives in recent years and an agreement has been reached with the US EPA to keep the Company's Utah properties off the NPL of Superfund sites. Major activities include the re-establishment of native vegetation to ensure sustainable habitats for wildlife. Over 100,000 trees have been planted in recent years and these efforts have helped to control significant historical problems associated with flooding and soil erosion.

3.4 Canada - Equity Silver Mine

A total of fifteen days were spent in Canada which allowed inspection of five historical and/or active metalliferous mine sites and five research centres in three Provinces. The collective liability from sulfidic mine wastes in Canada has been estimated to be between A$2 and 5 billion (Feasby and Jones, 1994) with potentially acid generating metalliferous sites covering over 15,000 hectares (Feasby et al, 1991).

The Equity Silver mine owned by Placer Dome Inc. is located near Smithers in the semi-humid alpine environment of central British Columbia. The mean annual precipitation is around 700 mm which exceeds the total annual potential evaporation which is between 300 and 500 mm. The mine was closed in 1994 with the requirement for a bond in excess of $A60M to ensure complete financing for site reclamation. Since closure, approximately 77 Mt of sulfidic waste rock has been reshaped (20° slopes), compacted and covered (A$38,000/hectare) to minimise sulfide oxidation and AD. The dumps were originally constructed by end dumping and later in 10 m lifts with waste rock typically containing 2-3% pyritic sulfide. An uncompacted and revegetated 0.3m thick till cover overlies a 0.5m thick clay layer compacted to a minimum of 95 % of the saturated proctor density of $1.9tm^{-3}$ at an optimum gravimeter water content of approximately 14 %. Monitoring equipment has been installed below the cover of the waste rock facility to measure temperature, oxygen concentration, thermal conductivity, water content, matrix suction and water infiltration (Wilson, 1995). The monitoring has been carried out as part of a five year study project carried out by the University of Saskatchewan which has revealed that water infiltration has been reduced from about 70 to 2 percent. One indication of reduced sulfide oxidation due to reduced oxygen diffusion into waste rock since cover implementation is the fact that waste rock dumps no longer vent to atmosphere during winter months (Wilson, 1998).

Extensive drainage structures have been installed to capture AD from dumps prior to treatment at a lime plant to pH 8.5 at an annual cost of over A$1.2 M. The plant effluent is discharged to settling ponds where metal complexes settle out as calcium sulfate/metal hydroxide sludge. Clear supernatant decanted from sludge settling ponds into a diversion pond and is discharged to the environment during spring. Treatment capacity varies between 60 to 150 L/s depending on acidity levels and average lime use is around 5000 tonnes. The treatment system typically reduces the concentration of dissolved metal contaminants such as Cu, Fe and Zn from 116, 1340 and 154 mg/L to 0.01, 0.05 and 0.04 mg/L, respectively. It is expected that the annual treatment costs will diminish as the cover takes effect but it is likely that ongoing treatment will be required for at least the next 100 years.

Other remediation activities conducted on-site include flooding of the 120 hectare tailings impoundment to a depth ranging from 2 to 7 metres and progressive flooding of final void areas resulting from open pit mining activities to a depth of 350 m. The flooding of the tailings area has been particularly successful in improving water quality in this area although elevated ammonia concentrations are still apparent in the supernatant water probably due to the breakdown of cyanide used in the gold extraction process. Additional water treatment techniques are being considered but it is likely that ammonia will naturally degrade and concentrations reduce to acceptable levels with time.

In Canada, regulators are actively discussing the merits of introducing construction standards and decommissioning criteria to enable tailings impoundments to withstand maximum possible flood (MPF) and maximum creditable earthquake (MCE) events. These discussions

are perhaps not surprising given the highly publicised failures of sulfidic tailings impoundments and significant pollution events in some parts of the world in recent years (Sassoon, 1998).

3.5 Canada - MEND program

No discussion on AD in Canada would be complete without at least a brief mention of the Canadian Minesite Environment Neutral Drainage (MEND) program which began in 1989. It was established as a co-operative research organisation to facilitate co-operation between the Canadian mining industry and government organisations to develop technology to prevent and control AD. The MEND program has been successful in reducing the liability from sulfidic mine wastes by at least C$400 million, from an investment of C$18 million over eight years. The main findings of the MEND program were discussed in detail at the 4th International Conference on Acid Rock Drainage (ICARD) held in Vancouver in June 1997 (Feasby *et al*., 1997).

The MEND program has confirmed that, given appropriate climatic conditions, the use of water covers and underwater disposal is the best prevention technology for managing sulfidic mine wastes. However, if oxidation is already in progress, ongoing maintenance of containing embankments may be required. Natural or engineered underwater systems with an organic surface or sedimentation layer minimise the risk of oxygen dissolved in water from oxidising sulfides. The use of multi-zone earth covers has also been shown to be an effective, if expensive, management tool for handling sulfidic mine wastes.

Much research has been applied to the use of "dry" covers and has concluded that a variety of materials, including waste materials from other industries (*eg.* urban biosolids and forestry waste) provide excellent potential at lower cost for generating moisture retaining, oxygen consuming surface barriers.

A number of disposal technologies to reduce acid generation have been investigated. These include: the use of depyritised tailings as cover materials; blending of different waste rock types; and mixing with alkaline materials prior to covering or backfilling into mined out areas. The MEND experience is that results from passive treatment systems such as engineered wetlands and anoxic limestone drains have been disappointing whereas trials using sulfate reducing barriers and engineered biosulfide processes are much more promising.

The MEND program partners have agreed that additional co-operative work is required to further reduce the liability and to confirm results of large-scale field tests of MEND developed technologies. A three year initiative called MEND 2000 is now in progress which will allow project management and monitoring to continue alongside various technology transfer initiatives including an internet site (http://www.nrcan.gc.ca/mets/mend). Information exchange with similar research projects such as the Mitigation of Environment Impact from Mining Waste (MiMi -Sweden) and the Acid Drainage Technology Initiative (ADTI – USA) has been identified as a priority.

MEND is represented on the International Network on Acid Prevention (INAP) which was formed in 1998 and brings together the best expertise in the world to identify the research needs and opportunities with respect to sulfidic mine waste management and control and remediation of AD. At least 18 multi-national mining companies, a number of expert

consultants and representatives from Government organisations have shown a keen interest in this forum to discuss the issues of waste characterisation and material management. One of the key findings is the need to establish an international communications network with links to relevant government or private institutes in various countries where available information on international research projects can be collected and the results reviewed and disseminated to program participants.

INAP was officially launched last year in Australia at the 23rd MCA Annual Environmental Workshop in Melbourne (Brehaut,1998). This is an excellent initiative and it is possible in the future that the information benefits of INAP will be made more widely available, through internet access for example, to assist less well financially endowed organisations. One of the themes of the MCA Workshop was the need to assist smaller mining operators to tackle a variety of environmental challenges including the appropriate management of sulfidic mine wastes to minimise the risk of AD. Community perceptions of the mining industry can easily be tarnished by the environmental performance of the smaller operator, often most at risk from developing significant environmental problems. If the mining industry is to further improve its reputation in terms of environmental performance then any steps that can be taken to lend the smaller operators a guiding hand should be implemented wherever possible.

4.0 DISCUSSION AND CONCLUSIONS

The objective of this paper is to provide readers with an international perspective on the environmental management of sulfidic mine wastes by describing the findings of several case studies in Australia, New Zealand and North America. Some of the findings and conclusions discussed below were gathered from additional case studies undertaken as part of the 1998 AMEEF Travelling Scholarship and these case studies are not described in this paper. A copy of the full report on the AMEEF Travelling Scholarship will be made available when this paper is presented at the 2000 Billings Land Reclamation Symposium.

There is no single magic solution to managing sulfidic mine wastes and minimising the risk of AD. Successful management and disposal requires a good understanding of the geochemical processes involved and the utilisation of a range of management techniques appropriate to the particular site characteristics. In New Zealand, recent experiences demonstrate that significant financial benefits can be gained by incorporating the management and disposal of sulfidic mine wastes into mine planning, development and operation, especially if disturbed land can be rehabilitated and returned to productive use following decommissioning.

For new and active mines, more emphasis should be placed on preventing or controlling the acid forming processes rather than dealing with environmental problems. Mining companies have many more control options if measures are progressively put in place at the construction and mining stages rather than at the decommissioning stage. If sulfidic mine wastes are exposed and react to produce acidity, the process is extremely difficult to stop. Collection and treatment of AD is an expensive, ongoing last resort which should only be used if appropriate control measures cannot be implemented or have failed. It is also apparent that acidity can be produced from sulfidic mine wastes many years after the disposal area has been established. Ongoing treatment can be required for decades and treatment and remediation costs must be considered in site rehabilitation provisions.

In North America, a number of mining companies carry substantial site reclamation bonds particularly those handling potentially acid forming sulfidic mine wastes. Regulating authorities are becoming more reluctant to accept transfer of responsibility and are developing decommissioning criteria for sulfidic waste facilities that are extremely difficult to satisfy such that future operators may be faced with “perpetual leases”. It is vital that the Australian Minerals Industry adopt a pro-active and self-regulatory approach to the management of sulfidic mine wastes to avoid similar developments being adopted in Australia. If adopted, these developments could have serious economic consequences for the Australian Minerals Industry.

If Australian regulating authorities can be convinced of the integrity of the selected management strategy or control/treatment technique they are more likely to accept transfer of responsibility and be assured that no long term financial, environmental or social liabilities exist. In this respect, it is important to provide confirmation of environmental predictions using comprehensive scientific studies with good field data. Extensive on-site monitoring should be complemented by off-site monitoring studies to give some indication of ecosystem rehabilitation success. This strategy will allow access to mineral resources in the future and ensure the long-term sustainability of both the minerals industry and the environment.

In the Australian context, it is important that the most appropriate techniques used to manage sulfidic mine wastes and to control and treat AD are identified and implemented to prevent a repeat of historical environmental problems. Implementation of initiatives described in the Australian Mineral Industry Code for Environmental Management, will help to reduce the risk of AD in the future.

In North America, dry covers and liners of soil (or geofabric) in conjunction with a vegetative cover have been used with some success to minimise the entry of water or oxygen into sulfidic waste materials, and control sulfide oxidation. However, dry covers can be expensive and as with may other management techniques, have to incorporate plans to control surface and ground water movement. The long term stability and effectiveness of dry covers also remain the subject of some debate. Similar questions remain unresolved regarding passive AD treatment systems (*eg.* constructed wetlands) which are becoming more widely used in The USA. Passive systems tend to be more successful if built to sufficient scale to deal with the magnitude of the pollution problem or used as a final polishing step in conjunction with other treatments such as passive biotreatment or active lime neutralisation.

Active treatment of AD can be a highly successful, if expensive, method of protecting the environment. However, very strict regulatory criteria including high construction standards imposed by some authorities may necessitate significant capital expenditure as well as ongoing operating costs. For some mining operations, the overall cost of the active AD treatment system can be offset by the recovery of clean water, marketable metals and other mineral resources from heavily contaminated AD. New active treatment technologies are now emerging (*eg.* sulfate reducing bacteria (SRB)) which may provide a more efficient, lower cost option for the treatment of AD (Vegt de, 1997; Scheeren, *et al.*, 1993).

Other technologies being tested in North America to handle sulfidic tailings materials include: direct revegetation of tailings using lime and fertiliser amendments; use of tailings as backfill for mined out areas; covers of partially decomposed domestic waste or digested sewage sludge combined with alkaline material; and the use of depyritised tailings covers achieved either by amending the final metallurgical process or by reprocessing of historically deposited tailings.

The results of the Canadian MEND program indicate that, given appropriate climatic conditions, sub-aqueous or wet covers are the best preventative technology to manage sulfidic mine wastes. Additional organic surface or sedimentation layers minimise the risk of oxygen dissolved in water from oxidising reactive sulfides. Multi-zone earth covers are also an effective, if expensive, management tool for handling sulfidic mine wastes. MEND studies also suggest that "dry" covers incorporating waste materials from other industries hold promise for generating moisture retaining, oxygen consuming surface barriers. Management techniques involving: depyritised tailings covers; blending of different waste rock types; and mixing with alkaline materials prior to covering or placing back into mined out areas have also shown promise. Results from passive treatment systems such as engineered wetlands and anoxic limestone drains have been disappointing whereas trials using sulfate reducing barriers and engineered biosulfide processes are much more promising. The MEND 2000 program will allow project management and monitoring of projects to continue alongside various technology transfer initiatives. These national research projects will be complimented in the future by international co-operation through INAP, for example. The formation of this organisation will help to identify international research

needs and opportunities, facilitate global networking and will hopefully allow relevant information to be accessed by all interested parties in the future.

It could be argued that the climatic conditions in Australia are considerably different from those found overseas. However, the challenges are in many ways similar, in particular the need for inexpensive and robust technologies to manage sulfidic mine wastes and to control and treat AD. The best results are likely to be achieved by using a range of environmental management techniques that are in harmony with natural processes rather than attempting to engineer solutions that may not be sustainable in the longer term.

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