5.2 Potential costs of rehabilitating historic mines

The costs discussed in the previous section for the management and rehabilitation of historic sites are summarised in table 5.1. These costs suggest that the rehabilitation of potentially acid generating wastes at historic abandoned mine sites is likely to cost \$100 000 ha^{-1} or more. The costs of remediation of historic sites is greater than the operational costs of managing potentially acid generating wastes at operating sites estimated in section 4.3 to be between \$20 000 to \$50 000 per hectare. These costs do not include the costs of treating water in open cuts containing polluted water or the control of acid drainage from mine workings.

Table 5.1 Costs of rehabilitating historic sites in Australia

Mine Site	Date	Cost	Cost per unit
Agricola	1995–96 (work done)	\$1M	\$80 000 ha^{-1} disturbed site
Brukunga	1986 (proposal) 1995 (proposal)	\$2.3M for tailings dam Total cost of the order of \$12 million	 Covers \$100 000 to \$150 000 ha^{-1}
Captains Flat	1976 (work done) 1993 (proposal)	\$2.3M Proposal \$1.5M (covers etc) \$600 000 capital, \$80 000 per year water treatment	
Drake	1995–97 (work done)	\$255 000 (first stage of 3 to 5 year program)	
Horn Island	1992–94 (work done)	\$2.2 million	
Kangiara	1994 (work done)	\$95 000	
Mt Lyell	1996 (proposal)	\$8.5 to 19.5M	Covers \$120 000 to \$280 000 ha^{-1} (steeply sloping site)
NSW derelict mines	1995–2005 (commitment)	\$5M (acidity and other environmental issues) over 10 years	
Peelwood	1989–1997 (work done)	\$0.246M	Whole 7 ha site \$35 000 ha^{-1}
Rum Jungle	1983–1986 (work done)	\$18.6M (\$6.2M water treatment, \$2.8M dumps \$3.7M other earthworks \$3.5M engineering and management)	Tailings (removal to open cut) \$108 000 ha^{-1} or \$6 per m^3. Waste rock dumps (reshape and cover) \$67 000 ha^{-1} Whole site (including water treatment) \$91 000 ha^{-1}

6 Discussion and recommendations

6.1 Technologies used for managing sulphidic wastes

The comments on the questionnaires and visits to mine sites showed that a wide range of isolation, cover and encapsulation methods are being used to manage potentially acid generating tailings and waste rock. These include selective placement, encapsulation within waste dumps, isolation within waste emplacements, different cover designs and sometimes use of separate dumps for potentially acid producing wastes. A discussion of management strategies is given in section 2.3. Although most of these technologies appear to be suitable for the long-term management of potentially acid generating waste, few have been monitored over a long enough time to prove their effectiveness.

The aim of the waste management strategies is to effectively isolate the sulphidic wastes from water and oxygen and thereby stop or reduce the release of acidity and pollutants to the environment. The required level of isolation varies from mine site to mine site as it depends on climatic factors, the sensitivity of the receiving environment and regulatory requirements. At some sites, potentially acidic tailings are covered by non-acid generating tailings by scheduling when different rock types are processed. Potentially acid generating waste rock materials are placed within a dump of benign wastes, perhaps with 5 m or more of benign waste cover on the sides and the top. This is usually called encapsulation regardless of the how effective the waste is isolated from oxygen or percolating water by the covering of benign material. At other sites, the wastes are isolated by covering with an impermeable or low permeability cover. At some sites, potentially acid generating wastes are placed in a separate emplacement and covered with an impermeable or low diffusivity cover.

There is considerable uncertainty about what constitutes effective encapsulation or isolation of sulphidic wastes. There is a definitional problem with the words encapsulation, isolation and impermeable. Realistically for mine wastes, isolation is never complete and covers are not impermeable. The covers with the lowest hydraulic conductivity and lowest oxygen flux are those formed from geomembranes or clay layers that are maintained near saturation. Hence clay layers covered with water can be very effective in reducing the rate of pyrite oxidation and the release of pollutants, provided a high degree of saturation of the clay can be maintained. The effectiveness of clay layers covered with water is enhanced if organic material is allowed to accumulate above the saturated clay layer to create reducing conditions in and below the clay.

Water covers are not practical at most Australian mine sites because of the low rainfall and high evaporation. The required level of isolation must be achieved with a soil/clay cover which is subject to seasonal drying or with geomembranes. Under mine site conditions, it is difficult to construct soil/clay covers made of natural materials that have hydraulic conductivities less than about 10^{-8} m/s, (ie 0.3 m/y). Hence, most low permeability soil/clay covers could transmit up to 0.3 m of rainwater per year if the top of the layer was maintained at saturation.

In arid and semi-arid regions, most of the rainwater that infiltrates into covers is removed by evaporation. Covers should be designed to reduce the amount of water infiltrating to the potentially acid generating wastes to an acceptably low value. This can be achieved by maximising runoff or maximising evaporation. In arid areas, the covers can be designed to hold rain water that infiltrates during storms near the surface where most of the water can evaporate after the storm passes. The aim of cover design is to optimise the water balance in the cover to minimise the amount of water percolating into the potentially acid generating wastes.

Another issue of importance is deciding the design lifetime for emplacements containing potentially acid generating mine waste. In a geological timeframe, covers will be eroded and the wastes exposed. However, historically in Australia, many mine wastes have become resources and have been reworked as newer and more effective technologies have been developed. Many smaller historic mines have been incorporated into much larger and more efficient new mines. If mine wastes are likely to be reworked or to be combined with the wastes of a new larger project, it is not necessary to expect covers and waste emplacements to be effective forever. Nevertheless, waste emplacements need to be designed to meet a specified lifetime. The problem is similar for all land fills, including covers on municipal dumps.

Many mines extract oxidised material early in mine life and fresh sulphidic material later from greater depths. This deeper 'fresh' sulphidic rock is often potentially acid generating. Without effective management, dumps and spoil heaps will be constructed with an inverted profile, having the oxide wastes mined first near the bottom of the waste emplacement covered by the sulphide wastes mined later. This would leave the acid generating material exposed to oxygen and water allowing it to rapidly oxidise and produce contamination in the surface runoff. This sequence of operations has caused problems at some older open cut mines and dragline coal operations. Most new mines now take care to ensure that sulphide material is not left on the tops of dumps and the benign material is used to good effect.

Often the oxide material as well as being benign from an acidity viewpoint, has physical properties that allow it to be compacted to make an effective low permeability cover. The shape of open cut pits usually means there is more oxide waste than sulphide waste because the area of pit decreases with depth and the ore-to-waste ratio increases with depth which generally means there is usually more than sufficient oxide material, provided it has suitable physical properties, for isolating dumps containing sulphidic materials.

During visits to mine sites and discussions with environmental officers, it became clear that there is considerable uncertainty about what constitutes an effective strategy for managing potentially acid generating wastes. The rehabilitation plans at many sites are based on good ideas, but there is a lack of available information to show what is required to ensure that the rehabilitation will achieve the required level of isolation and long-term effectiveness. Questions for which answers were sought included:

- What is an adequately low hydraulic conductivity for covers on potentially acid generating tailings and waste rock?
- How should covers be designed to take advantage of climatic conditions?
- How thick should covers be to provide the required long-term control?
- What is a realistic time period to expect covers and waste emplacements to be effective?
- How should covers be designed to prevent rising salt in arid climates?
- How can an effective capillary break layer be constructed?
- How effective is mixing lime or other neutralising material with potentially acid generating wastes?
- What are the benefits of encapsulating potentially acid generating wastes within benign material in a waste dump?
- What defines benign materials?
- What is the level of confidence in predictions of time-scale for sulphides to oxidise?
- What is an adequate and acceptable strategy for managing potentially acid generating mine wastes?
- What is the long-term effectiveness of currently applied remediation strategies?

There is a clear need for a better understanding of the methods that can be used to control and limit pollution from the oxidation of sulphidic wastes and how to select the waste management strategy or strategies most appropriate for a given mine. The lack of knowledge on the effectiveness of the waste management strategies being used can leave mine owners facing significant long term risks.

Recommendation 1

It is recommended that a study be undertaken to:

- collect detailed information on the strategies being applied at the Australian mine sites managing potentially acid generating wastes,
- review monitoring information on past remediation works for information on the effectiveness of different strategies,
- assess the methods being used to predict the long term performance of strategies now being used at Australian mine sites to control the potential sulphidic oxidation in mine wastes,
- develop guidelines to assist mine managers select appropriate and adequate strategies for managing potentially acid generating wastes.

Difficulties in the interpretation of water analyses can occur where acid water produced in mine wastes is neutralised before the water reaches the surface. Hence it is possible for waste emplacements containing acid generating wastes to produce seepage water of neutral pH and high levels of sulphates and metals. In some cases what is said to be a high salinity problem is due to the oxidation of sulphides. Some responses to the questionnaire suggested a lack of awareness of the geochemistry occurring in mine waste dumps and some confusion about interpretation of water analysis results. This is particularly true in relation to the significance of high sulphate and heavy metal levels in near neutral water. A knowledge of geochemical processes occurring in the waste emplacement is important in the interpretation of seepage water quality results used for assessing the effectiveness of rehabilitation works undertaken to isolate potentially acid generating wastes.

6.2 Underground workings, adits and pit walls

Acid seepage from adits and open cuts filled with acid water can be a major source of pollution following the mining of sulphidic ore bodies.

From the survey results, it was estimated that about 15 operating sites have voids containing acid water (see section 3.3). This does not include historic and closed sites with water filled voids. Several historic sites, including Ardlethan, Rum Jungle and Mount Morgan, were left with opencut filled with acid water containing heavy metals. The presence of polluted water greatly limits the post-mining uses of water-filled voids and can be a source of contaminated water both to ground water and, in Wet seasons, to surface creeks and streams. Acidity can be generated from the oxidation of sulphides within the pit walls, or at some sites such as Rum Jungle, the pit was used for the disposal of acid process waters and tailings.

If the open cut is likely to fill with water after closure, the production of acid can be reduced by filling the void quickly with clean water to limit the length of time the pit wall is exposed to oxygen. At some sites, the water-filled void is linked with a local surface flow to ensure flushing with clean water which can also limit the rate of oxidation. If the water in the open cut is acid, it can be necessary to treat water in the pit, as was done at Rum Jungle, or control any overflow from the pits, as is being considered at Mount Morgan. Treatment of the water in the Rum Jungle open cuts cost $6.2 million and included modifying the surface water flows to ensure a regular flushing of the open cuts in the Wet season and limit the buildup of acidity.

Seepage of acidity from adits and underground workings can be a major source of pollution from closed mine sites. The main source of contaminated water from the Captains Flat and Mt Lyell mine sites is seepage from historic adits. There are many small historic sites in eastern Australia which continue to seep acid water from abandoned adits. In some cases, the flows from adits can be reduced by limiting the ingress of water to underground workings. However, the sealing of adits is usually difficult because water pressures can be very high. In many cases, the only solution for acid seepage from adits is long-term water treatment.

The potential for acid seepage from adits and underground workings and the build up of acidity in water filled voids are important considerations that must be considered at mine planning and regularly reviewed.

6.3 Mine planning

The results of this study have reinforced what others have said, viz that it is important to assess the likelihood of sulphidic oxidation in the mine wastes when the mine is being planned, to develop waste management strategies before mining starts and to regularly review the waste management plans as mining proceeds. Many mine sites are proactive on acid mine drainage issues and included consideration of the potential for sulphidic oxidation in their original mine plans. Often the acid mine drainage problems at mine sites are due to earlier operations before there was a proper understanding of the potential liability from acid mine drainage. Nevertheless, it is important that all mine operations properly assess the potential for sulphide oxidation.

Many companies take the potential liabilities from acid mine and acid rock drainage seriously. These companies accept that some mining projects would not now be considered viable because of the potential problems and costs of managing acid drainage. Although acceptable strategies appear to be possible for managing potentially acid generating wastes for almost any green field site, it is important that the costs for managing these wastes be incorporated in the overall mining costs when the feasibility of a new mining projects are being assessed.

Recommendation 2

It is recommended that mine managers be required to:

- assess the risk of sulphidic oxidation in mine wastes, pit walls and underground workings and the generation of contaminated water as a standard part of mine planning,
- integrate the management of any identified potentially acid generating wastes into mine operations,
- regularly review waste management plans based on experience and monitoring.

6.4 Waste characterisation

The initial step in the effective management of mine wastes is the characterisation of wastes for their potential to become acid generating. Waste characterisation methods were summarised in section 2.2 and are described in detail in Appendix A.

It is now generally accepted that all rock types should be characterised before operations begin so that the extent of potential sulphidic oxidation can be assessed and plans developed for placing any potentially acid generating waste where they will not cause problems. If potentially acid generating wastes are identified, it is also important to identify whether the operation will also produce benign materials suitable for covers and encapsulation.

During operations, many mines use simple analytical techniques like colour or total sulphur as a basis for managing wastes. For example, brown material might be assumed to be oxidised and benign, whereas grey material is considered to be sulphidic and potentially acid generating. Such use of secondary indicators can be valid provided that the different rock types have been properly characterised using recognised waste characterisation tests for their potential to form acid and a correlation established between the likelihood of forming acid and the secondary characteristic.

Information collected and discussions during the study show that most sites have tested only a small number (<100) of waste samples, and many sites are basing their waste management strategy on a very limited number of waste characterisation measurements or none at all (section 3.4). It is a matter of concern if mine sites do not have enough information to know if their wastes are potentially acid generating. This lack of information can leave mine sites exposed to a significant financial risk.

Recommendation 3

- It is recommended that mine managers and mine site environmental officers review the mine waste characterisation studies already undertaken to ensure that all rock types at their site have been tested and that enough tests are carried out to give confidence in the appropriateness of the waste management strategy.

The waste management techniques now available can predict with reasonable confidence the potential for mine wastes to oxidise and generate acid. These tests provide a reasonable prediction which is accepted by most regulators and industry officers.

The information collected during this study showed a wide variation in the number of waste characterisation tests undertaken for similar ore bodies and inconsistency in the interpretation of results of NAPP, NAG, ANC, column, etc tests. It was not possible in this study to assess the effectiveness of the waste characterisation carried out and whether claims of no likelihood of acid mine drainage were well based. It is in the nature of acid mine and acid rock drainage that confirmation of predictions of acid formation and non-acid formation might not become clear for many years. The lack of uniformity in types of tests used and the number of samples tested leads to difficulties in comparing characterisation results from site to site and from consultant to consultant.

Recommendation 4

- It is recommended that guidelines for the application of mine waste characterisation tests at Australian mine sites be prepared, including guidance on sampling procedures, how many samples should be tested, appropriate tests for different ore-bodies and interpretation of results.

6.5 Technology transfer and awareness

The management of potentially acid material is unforgiving; it must be done properly first time. It is a common view amongst experts in the industry that management of known potentially acid generating material is cost effective, but that the rehabilitation of acid mine drainage at the end of mine life is expensive. The costs of reducing the release of contaminated drainage to acceptable levels can be high if the management of any potentially acid generating wastes is not incorporated into mine planning. It is clear that management of sulphidic waste should be considered at all stages of mine planning and mine operations, and particularly at the project assessment stage.

Most State and Territory Governments now require new mining proposals to be assessed for their potential to generate acid drainage and the development of suitable management strategies if potentially acid generating materials are likely to be mined. In most States there are annual reviews of environmental plans that include monitoring the management of potentially acid generating material and assessing water quality measurements. Some environmental officers find that their internal company audits are a more stringent control than environmental regulations and regulatory authorities in ensuring that wastes are properly managed. Companies need to establish that their operations are not creating large future liabilities.

It is important for mining companies to ensure that environmental intentions expressed at the corporate level are followed through at mine sites. The staffing in the environment sections at mine sites is often relatively small and the level of resources limited. For effective management of sulphidic wastes, it is important that an appropriate waste management plan be implemented and responsibilities for managing this material are accepted by all staff at the site.

The amount of potentially acid generating wastes mined in Australia is likely to increase as open cut mines go deeper. Hence, it will become more important for mine environmental officers and mine management to be aware of acid mine drainage issues.

The effective management of potentially acid generating wastes requires the availability of expertise and knowledge about sulphide oxidation and acid generation. Some environmental officers, mine engineers, geologists and mine managers are very aware of the need to properly manage potentially acid generating mine wastes. They have a good knowledge of the need to characterise wastes, and are willing to aggressively address waste management if potentially acid generating wastes were identified at their site. However, there are also sites where staff have only a limited understanding of the potential for acid mine and acid rock drainage at their sites. Of course, mine environmental officers have to deal with a wide range of important environmental issues as well as potential acid generating wastes at their sites, and they have a range of diverse backgrounds. Understandably their level of expertise in managing acid mine drainage issue varies.

Recommendation 5

- It is recommended that environmental and acid mine drainage workshops and courses be used to facilitate technology transfer and encourage sharing of experience and research information on managing sulphidic wastes between mine sites.

The information collected for this report was in many respects not as definitive as was hoped. The results presented here should be widely discussed to improve the quality of the information and ensure that differing points of view are properly addressed.

Recommendation 6

- It is recommended that working groups be established with input from all stakeholders in the mining industry, including miners, mining companies, consultants, researchers, regulators and environmental protection authorities to identify acid mine drainage issues.

6.6 Climatic factors and ground water

The environmental impact and appropriate strategies for managing potentially acid generating waste depends on climatic factors. Percolating rainwater is the main mechanism for transporting pollutants to the receiving environment. The flow of water through waste emplacements depends on the rates of rainfall and evaporation, and the intensity and frequency of storms. Surface flows and erosion depend on storm intensity. The climatic conditions at Australian mine sites were described in section 3.8.

Rainfall, evaporation, storm intensity and climate affect the amount of water to be managed at a mine site, the sensitivity of the receiving environment, and the design of waste emplacements. In arid and semi-arid regions, many operating mine sites do not release any water under normal conditions. At these sites, most rainwater is used in mine operations with any excess in high rainfall periods stored in evaporation ponds. In higher rainfall regions, excess polluted water is treated before release. Whilst a mine is operating, polluted water from sulphide oxidation can usually be managed at a cost which is a small component of mine operation costs. However, at mine closure the amount of water to be managed usually increases because it is no longer used on site and there is an economic need to stop water treatment. Climatic factors are important in developing an appropriate water management scheme for mine closure.

The covers used on waste emplacements are designed to limit the flow of water and oxygen to sulphidic material. Many natural material covers depend on compacted clay. To be effective this must be maintained close to the optimum water content. This is often not possible in arid climates, where the high evaporation potential and the long Dry season leads to large variations in water content of covers. Some covers in arid areas are based on using the high evaporation potential to remove any infiltrating rain water. Storm intensity also affects how the cover needs to be designed to resist erosion. The storm intensity distribution shown in fig 3.7 shows that storm intensity is greatest around the northern coasts due to the effect of cyclones. An appropriate cover for waste emplacements in the arid zone will be different from the appropriate cover for a high rainfall zone.

The impact of acid drainage depends on the receiving environment. Drainage at arid mine sites, when it occurs, usually has only very local impact and land use pressures are low at most Australian sites. It is sometimes possible during mine operations to receive authorisation to release water at times of maximum flow during extreme events. After mine closure, this is more difficult because any seepage from mine waste emplacements is likely to occur long after the rainfall event when there is little flow to dilute the seepage.

6.6.1 Classification of climatic factors

The important climatic factors for the management of potentially acid generating wastes are rainfall, evaporation and storm intensity. Any classification involves a level of simplification and there are always sites near boundaries where assigning categories is difficult and other factors that are more important at one mine than another.

In the report on the management and impact of final voids, Mallet and Mark (1995) classified final voids into eight groups based mainly on the climatic zones, but also to some extent the type of mine, fig 6.1. These groups were: monsoonal open-pit mines, northern summer rain metal mines, Eastern Highlands metals mines, Bowen Basin coal mines, Hunter Valley coal mines, arid metal mines, arid iron ore mines, Tasmania temperate mines. The Mallet and Mark classification was developed for classifying final void issues and is not as suitable for acid mine drainage issues. Its main difficulty is the association with mine type which can exclude some mines that are different from the majority of sites in a region.

For acid mine and acid rock drainage, the standard climatic map from the Bureau of Meteorology (fig 6.2) can be used, or, better, a classification based on the evaporation, rainfall and storm intensity. These climatic factors will be characterised here by the annual median rainfall, the average pan evaporation and the design rainfall isopleths for 72 hours duration with a 50 year average recurrence interval (fig 3.1, 3.2 & 3.7).

Based on the annual rainfall and annual pan evaporation distributions shown in fig 3.4, mine sites in Australia group into three categories of rain and evaporation. These are as follows:

Category A Arid climates where annual pan evaporation exceeds 4 x annual rainfall

Category B Temperate/semiarid climates where annual pan evaporation exceeds annual rainfall but is less than 4 x annual rainfall

Category C Humid sites where annual rainfall exceeds annual pan evaporation which includes the west of Tasmania, the SW tip of Western Australia and Cape Otway in Victoria.

A sub-category is needed for storm intensity which is a major determining factor in the design of covers and water treatment systems. A sub-category H is proposed for regions subject to high storm intensities where the expected storm rainfall exceeds 300 mm over 72 hours for a 50 year recurrence interval. Sub-category L is used for regions with low storm intensity where rainfall is less than 300 mm over 72 hours for a 50 year recurrence interval. Hence the proposed five Categories are A_L, A_H, B_L, B_H and C_L. The Category C region does not have high intensity storms. The locations of these regions are shown on fig 6.3.

The proposed classification provides a geographic classification system that groups mine sites according to climatic limits that should be imposed on designs for waste management at Australian mine sites.

6.6.2 Ground water

The release of pollutants to ground water can be an important issue. The potential for ground water contamination has been largely ignored by industry and regulators except where there are ground water users in the immediate vicinity. If the base of waste emplacements is permeable, polluted water can percolate to the water table. Few sites seem to have assessed the impact of polluted drainage on ground water quality. If the ground water quality is very poor, then any likely contaminated water from mine wastes is likely to have little effect on potential future uses of ground water. However for sites where the water quality is fresh to brackish, the cleanup of groundwater pollution, should it be required later, can be very expensive and difficult.

For natural soils in humid regions, recharge can be 30 to 60% of precipitation and recharge is relatively uniform across the landscape. However, in arid and semi arid regions, most of the groundwater recharge tends to come from seepage losses in ephemeral streams (small and large) which form the regional drainage or runoff pattern (Bower 1989).

Recharge in arid regions is typically less than 5% and is often much less than 1% (Chapman & Sharma 1989). If this small recharge is applicable to covers on mine wastes, it would be many years before the water content in large mine waste emplacements reaches an equilibrium and seepage could occur.

In North America, it has been the costs of remediating ground waters that has led to large remediation costs at some sites late in mine life (see section 2.6). For many sites in arid regions in Australia, ground water is of poor quality and seepage volumes from waste emplacements are low. However, as shown in table 3.5, 58% of the mine sites surveyed had fresh or brackish pre-mining ground water.

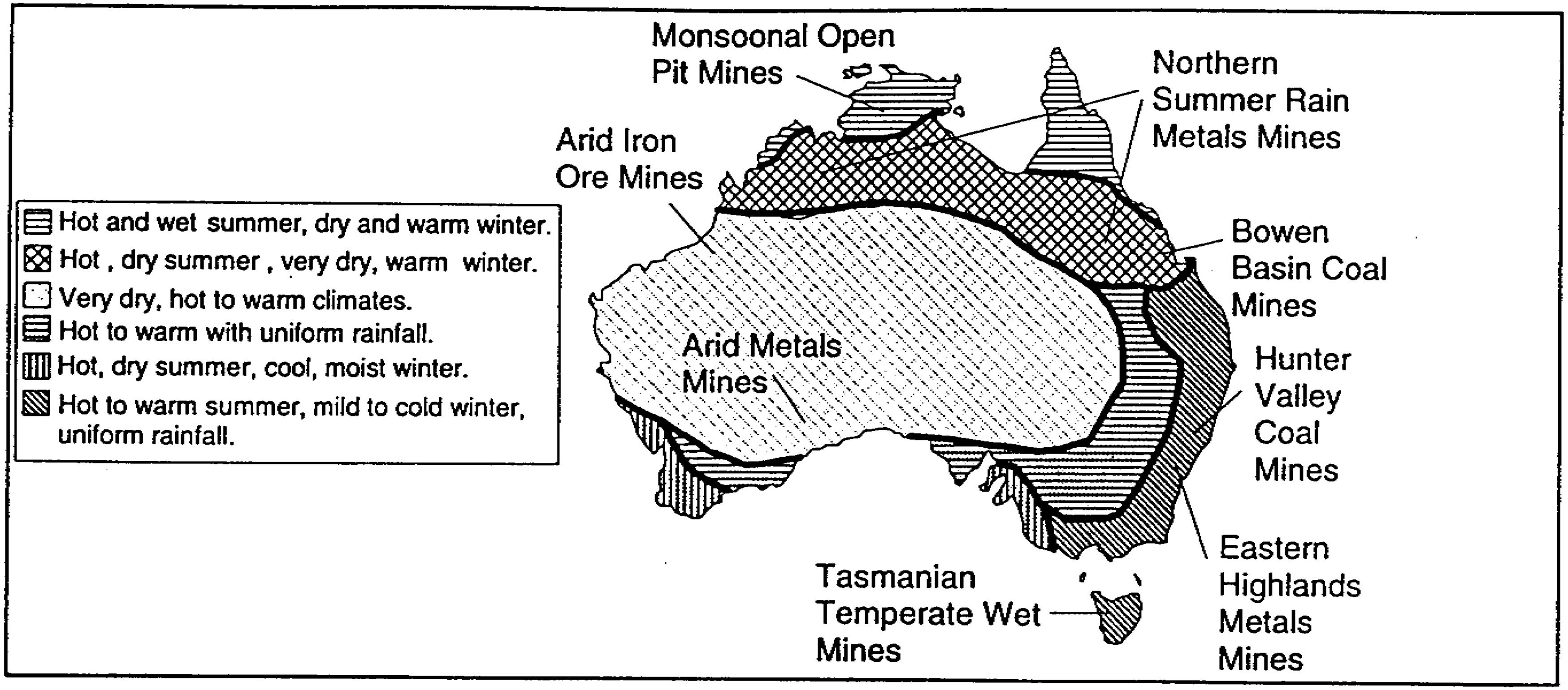

Figure 6.1 Zones proposed by Mallett and Mark (1995) for classification of mine site voids

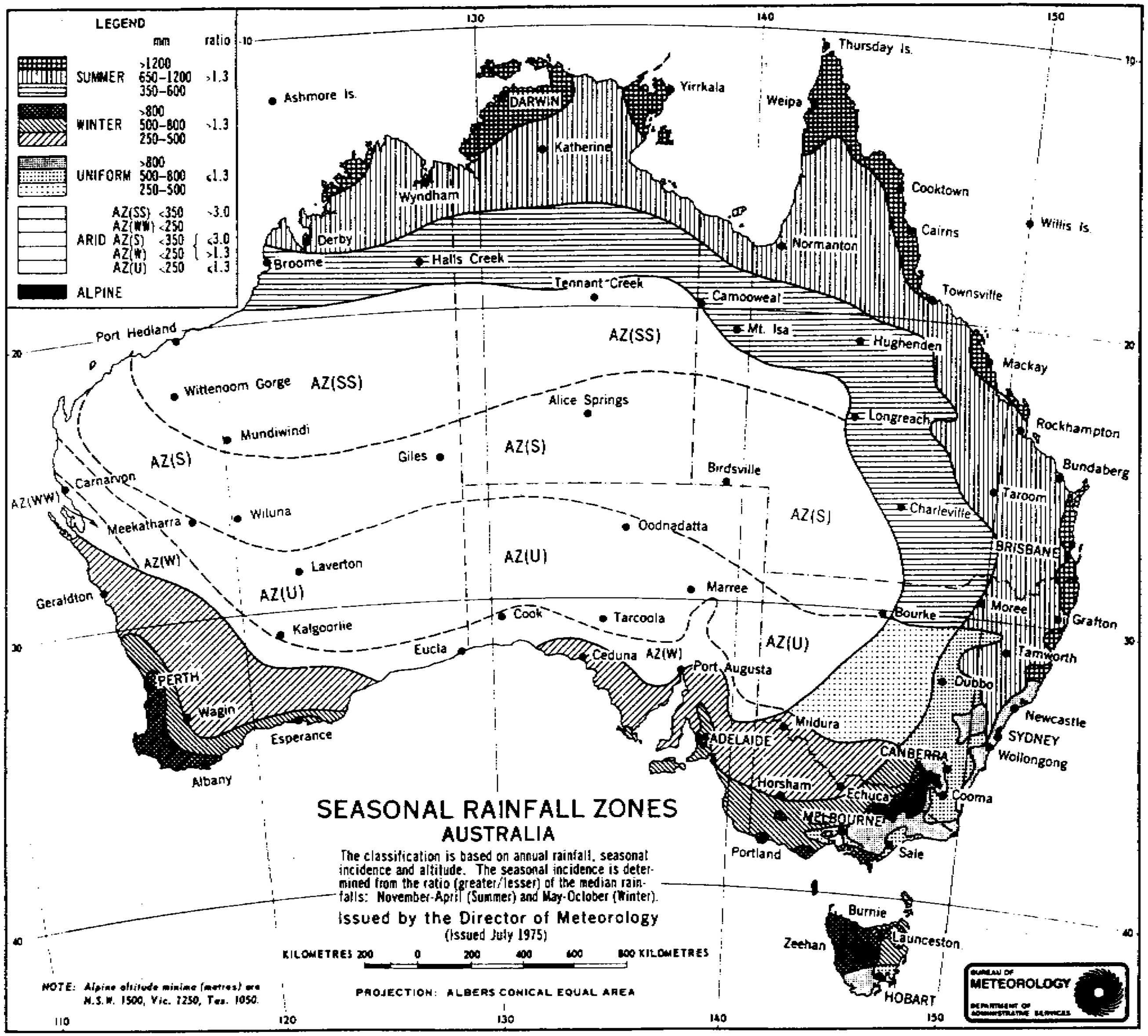

Figure 6.2 Australian seasonal rainfall zones (ABS 1994)

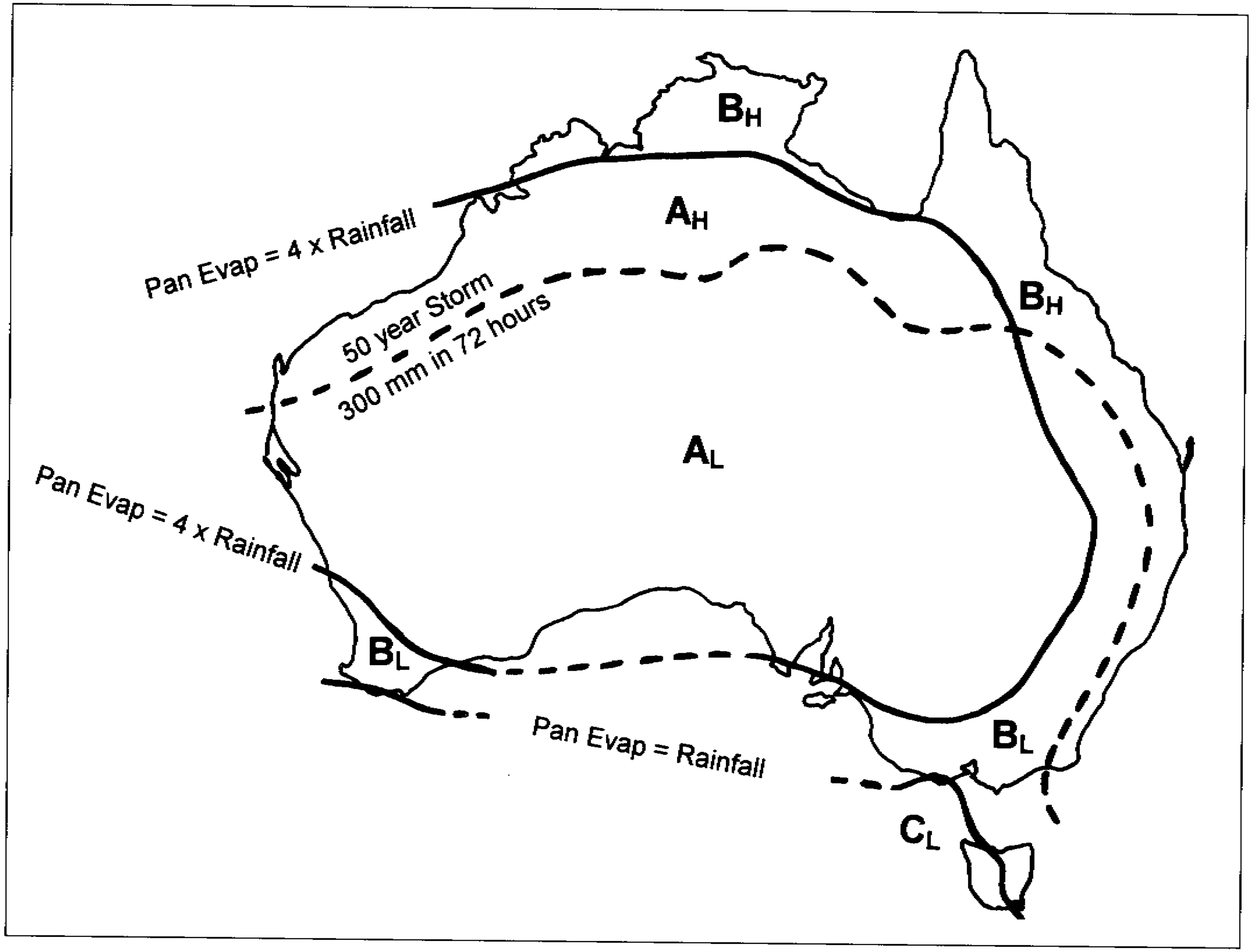

Figure 6.3 Zones proposed for classification of potential impact of mine wastes with acid generation potential

Zone A (arid) pan evaporation >4x rainfall; Zone B (intermediate); Zone C (wet) pan evaporation <rainfall.
Storm intensity L: L where maximum 3 day rainfall with 50 year recurrence <300 mm, H where max rainfall >300 mm.

6.7 Comparison with MEND estimates of liability for Canada

The estimated operational costs for managing potentially acid generating wastes in Australia are \$60 million ± \$20 million per year and, over an assumed average mine life of fifteen years, the total cost would be \$900 million. This cost is significantly less than the Canadian estimate of C\$2 to C\$5 billion financial liability for reactive (ie potentially acid generating) wastes in Canada (C\$1.00 = A\$0.97, 6 February 1997). The Canadian liability is based on the inventory of potentially acid generating wastes from past mining activities and estimated unit costs for remediation technologies, see section 2.3.

The amounts of potentially acid generating wastes in the two countries are roughly comparable. MEND estimated that Canada had 1.9 billion tonnes (12 500 ha) acid generating tailings and 750 million tonnes acid generating waste rock. This study suggests that an average mine site in Australia managing potentially acid generating wastes had 14 Mt of tailings covering 94 ha, and 20 Mt waste rock covering 46 ha. For the estimated 54 sites with significant potentially acid generating wastes, this gives a total of 750 Mt of tailings covering 5100 ha, and 1100 Mt of waste rock covering 2500 ha. There are additional mine sites in Australia managing minor amounts of potentially acid generating wastes. These figures suggest that Australia has more potentially acid generating waste rock and less potentially acid generating tailings than Canada.

The most significant difference between the two countries is in the rehabilitation costs per hectare. The costs estimated by MEND are much greater by a factor of five to eight than the costs reported by currently operating Australian mine sites. This difference is due to several factors including:

1. The costs derived by MEND are based on small to medium sized mines. Costs will be lower for larger mines where the surface area per tonne of waste is lower.
2. The costs reported in Australia are for operating sites where mine equipment is available and, in many cases, suitable cover material can be obtained from the normal mining activities. This can eliminate separate transport costs. The Canadian costs assume that all rehabilitation is carried out on closed sites. The costs for historic sites in Australia (section 5.2) are estimated to be \$100 000 ha^{-1} or more which is more comparable with the Canadian estimates.
3. The covers being used in Australia at operating mines are less complex than the covers on which the Canadian costs are based. Several Australian operating mines use compacted covers based on materials being dumped as part of the mining operation. This type of compacted cover is less expensive than the covers constructed from specially excavated materials considered in the Canadian study.
4. Most Australian mine sites are in semi-arid and arid climates which are very different from the Canadian conditions. Because of the high evaporation and consequent smaller percolation rates in wastes at Australian mine sites, waste management strategies are often different. Provided these strategies are effective, the costs to Australian miners will be much less than for Canadian miners.

6.8 Comparison with other mining and environmental costs

Although the costs for properly managing potentially acid generating mine wastes derived in chapter 4 are significant, they are a very small fraction of the costs of operating mine sites in Australia. The operating revenues reported by the Minerals Council of Australia (1996) for the Australian mining industry as a whole in 1995/96 was \$26.8 billion, including \$195 million spent on rehabilitating sites on which mining and mineral processing had been undertaken. The amount spent on rehabilitation includes the cost of environmental impact studies, but does not include amounts spent on research, pollution monitoring and control, cleanup and capital expenditures undertaken to minimise the environmental impact of mining and minerals processing plant and equipment.

It is useful to compare the problems of managing sulphide wastes at Australian mine sites with two other environmental issues where acidity plays a major role, viz soil acidification and acid sulphate soils.

Soil acidification occurs as agricultural practices cause soils to become increasingly acid to a point where plant growth and yield decline. The Land and Water Resources Research and Development Corporation (LWRRDC 1995) reported that about 35 million hectares in Australia could be classified as highly acidic ($pH_{Ca} < 4.8$). This area includes those soils that are acidic because of agricultural practices and those that are naturally acidic. In addition, more than 55 million hectares are moderately or slightly acidic (pH_{Ca} 4.9–6.0), and these are considered to have the potential to degrade to highly acidic. It is known that many soils in Victoria have acidified by 1 pH unit in the last 30–40 years.

Strategies for dealing with acidification of agricultural soils include application of lime, input of nutrients to maintain productivity as soils acidify and dependence on acid-tolerant species. The LWRRDC recommends the increased use of lime to maintain productivity. The amount of lime would need to increase from around 0.5 million tonne per year to 2.25 million tonnes per year to treat the 1.5 million hectares of extremely acidic soils, 0.75 million tonnes per year for the 7.4 million hectares of very acid soils and 1.5 million tonnes per year for maintaining the pH on the 7.7 hectares of mildly acid soils at risk of acidification. The costs are in the range of \$2 to \$60 ha^{-1} per year with the lower costs for sheep and the higher cost for milk and sugar production (LWRRDC 1995). The total costs of the additional 4 million tonnes per year of lime to control soil acidification appear to be between \$120 and \$240 million (based on \$30 to \$60 per tonne lime).

Acid sulphate soils are soils and sediments containing oxidisable sulphides. Acid sulphate soils of most concern in Australia are those laid down when the rise in sea level, which ended about 6500 years ago, caused sea water containing sulphates to cover organic detritus from mangroves. Pyrite was deposited under the anaerobic reducing conditions. The pyrite in acid sulphate soils oxidises to sulphuric acid if the sediments are exposed to oxygen by for example, lowering the water table, dredging sediments or draining land for agriculture (Melville et al 1996).

It is estimated that Australia has about 1 million hectares of acid sulphate soils along the eastern and northern coastlines containing about 1 billion tonnes of pyrite (Melville et al 1996). Acid sulphate soils affect agriculture, fisheries and civil constructions near estuaries. The area of acid sulphate soils is much greater than the area of potentially acid generating wastes at mine sites, and as it occurs in the highly populated coastal regions of Australia, it can lead to major restrictions on land use. The recommended management strategy is to avoid disturbing acid sulphate soils and leave the pyrite in the reducing environment in which it was formed. The difficulty is that large areas have already been disturbed by draining and excavation and many of these need remediation.

This comparison with other mining costs and other environmental issues shows that the management of sulphide oxidation in mine wastes has both similarities and differences with these other issues. The cost of managing pyritic oxidation in mine wastes is a significant fraction of the costs of remediating mine sites, and it is comparable with the costs of properly managing the acidification of agricultural soils, but the area of mine wastes is considerably less than the area of naturally occurring acid sulphate soils.

7 Conclusions

The OSS/ACMRR study into the extent of acid mine drainage in Australia has enabled information to be collected from a large number of mine sites and indirectly raised the awareness of the need to properly manage sulphidic materials at mine sites. The information collected and the comments received show that the management of sulphidic materials is an important environmental issue for the Australian mining industry.

Based on information collected during the OSS/ACMRR study, the additional operational cost on properly managing sulphidic mine wastes at Australian mine sites has been estimated to be about $60 million per year to the whole Australian mining industry. This cost is a very small fraction of the total annual costs of the Australian mining industry, but a significant proportion of the amount spent on environmental issues.

Potentially acid generating mine wastes can present a significant financial risk to mine owners. Historic sites like Mt Lyell, Rum Jungle or Mt Morgan demonstrate the scale of the environmental impact if the mining of sulphidic materials is not properly managed. Problems at these sites include acid generating mine wastes, acid water flowing from adits and opencuts containing acid polluted water. To minimise the financial risk, mining companies should characterise wastes for their acid generating potential and develop and implement appropriate mine plans and waste management strategies. Clearly it is important to identify the additional costs of managing any sulphidic material early when mine feasibility is being assessed.

Despite good work being undertaken at many mine sites, there are sites where the significance of sulphidic wastes is not fully appreciated and staff are having difficulties developing appropriate waste management strategies. This study identified a need to improve the level of knowledge and awareness of acid drainage issues at mine sites in Australia and to assess the long-term effectiveness of strategies being used for managing sulphidic wastes at Australian mine sites.

Acid mine drainage and acid rock drainage are important environmental issues for the Australian mining industry. An appropriate waste management strategy is essential at all sites mining sulphidic materials to ensure that acceptable levels of environmental impacts are achieved.

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