have not been estimated. This information was needed to provide a basis for assessing the priorities for future research and development into the management of potentially acid generating mine wastes and the control of acid mine drainage in Australia.

1.1 OSS/ACMRR study of acid mine drainage in Australia

In order to better understand the impact of acid drainage in Australia and to provide a basis for assessing long-term management options, the Office of the Supervising Scientist (OSS) and the Australian Centre for Minesite Rehabilitation Research (ACMRR) initiated this study to prepare a status report on acid mine drainage in Australia. The study is supported by the Minerals Council of Australia (see copy of letter dated 23 May 1996 from David Buckingham, Executive Director Minerals Council of Australia in Appendix C1).

The coverage of this study includes all mine sites where sulphidic oxidation in mine wastes or mine workings leads to the release of contaminated drainage with off-site impacts.

The objectives of the study are:

- to quantify and characterise the generation of contaminated drainage by sulphidic oxidation from historic and current mining activities in Australia;
- to develop a classification scheme to characterise the potential for off-site impacts from sulphidic oxidation in mine wastes;
- to compare the cost at the national level of managing sulphidic oxidation in mine wastes and any resulting contaminated drainage with other mining and environmental costs;
- to make recommendations based on the information received to improve the understanding and management of acid mine drainage in Australia.

Information was collected on the extent and management of sulphidic oxidation and acid drainage at operating, historic and derelict mines in Australia. Mining operators, environmental officers, industry representatives, state government departments and others were asked about their experience with acid mine drainage and how it is currently managed at operating and historic mine sites.

2 Background

2.1 Pyrite oxidation

The release of acid mine/rock drainage is due to the oxidation of pyrite and other sulphides in mine wastes and mine workings. The pyrite oxidation process will be briefly described to provide a basis for the discussion on the strategies used to control the oxidation of pyrite and the release of polluted waters. The oxidation of pyrite occurs when the mineral is exposed to air and water. At mine sites, this can occur in tailings dams, waste rock dumps, pit walls and in underground workings.

The pyrite oxidation process is complex and involves several chemical, biological and electrochemical reactions. The rate of reaction depends on many factors including the surface morphology of pyrite, the oxygen concentration, the pH, the presence of bacteria and the presence of acid-consuming materials. The oxidation process has been extensively studied under laboratory conditions, and more detailed descriptions of the steps and complexities of the oxidation process are available in the literature (eg Evangelou 1995, Hutchinson & Ellison 1992).

The rate of pyrite oxidation is highest at low pH where some of the rate limiting steps are catalysed by bacteria. However, the non-microbial pyrite oxidation rate increases as pH increases (Evangelou 1995). The oxidation rate is also very dependent on the form of the pyrite; some forms oxidise very rapidly on exposure to oxygen and water, whilst others can be found unoxidised even after many years on the surface of dumps.

The rate of oxidation of pyrite in mine materials is usually many orders of magnitude slower than rates observed under laboratory conditions. As well as rate limiting chemical and bacterial processes at the microscopic level in the mineral grains, a series of physical processes can limit the supply of oxygen and the movement of water through mine materials.

The conditions for sulphidic oxidation differ in the different types of mine materials. Waste rock dumps at mine sites are large in volume, contain a number of different minerals and are usually very heterogeneous. Tailings emplacements are also large in volume, usually relatively homogeneous and have a relatively low permeability. The walls of opencuts and underground workings are still in the original rock, somewhat fractured, but can be relatively heterogeneous.

The control of potentially acid generating wastes at mine sites depends on finding a step or steps in the oxidation and release processes that will minimise the oxidation rate and so control the release of pollutants to the environment.

2.2 Prediction of acid generation potential

The first step in managing mine wastes should be to identify the wastes that are potentially acid generating. The chemical methods used in Australia for classifying mine wastes as acid generating, potentially acid generating or non-acid generating are described in Appendix A, which was prepared by Dr Josick Comarmond, ANSTO Environment Division.

Acid generation in mine wastes depends on the balance between acid production capacity and acid neutralising capacity in the matrix, the specific minerals present and the availability of water and oxygen. The pyrite oxidation process is a multi-step process, and some steps are more rapid under acid conditions. Mine wastes that have an acid neutralising capacity at least 3 times the acid production potential will not become a source of acid drainage (see Appendix A).

In summary, the methods used most commonly in Australia for predicting the likelihood of mine wastes generating acid are (see Appendix A for details):

Static tests

Acid base accounting (ABA) methodology

Acid base accounting is a screening test to determine the capacity of mine wastes to generate acid and includes: measurements of paste pH and salinity, acid potential (AP) or maximum potential acidity (MPA), acid neutralising capacity (ANC), and net acid production potential (NAPP).

The net acid production potential (NAPP) is the difference between the acid potential (AP) of a material and its neutralising capacity (ANC). It is the theoretical balance between a sample's capacity to generate acid from oxidation of sulphides and its capacity to neutralise any acid generated. It is expressed in units of kg H_2SO_4/tonne. If a sample has a NAPP of less than –20 kg H_2SO_4/tonne it is generally considered to be non-acid generating, between –20 and +20 kg H_2SO_4/tonne there is a degree of uncertainty, and above +20 kg H_2SO_4/tonne it is classified as potentially acid generating.

Net acid generation (NAG) test

The NAG test is a relatively simple test based on the use of hydrogen peroxide to oxidise the sulphides. This test has been developed for field use. A sample with a final NAG pH greater than 4 is considered to be non-acid generating. If the NAG pH is less than 4, the sample is acid generating. This sample is titrated to pH 7 to determine the NAG value. If the NAG value is less than about 5 to 10 kg H_2SO_4/tonne, the sample has a low capacity for acid formation. A NAG value greater than 10 kg H_2SO_4/tonne indicates the sample has a high capacity for acid formation.

Kinetic tests

Leach tests

Leach tests are a laboratory measurement of the leaching behaviour of the waste under conditions that simulate field conditions. Leach tests are used to: determine relative rates of acid generation, neutralisation, and metal depletion; test control/treatment techniques; compare leaching behaviour of different mine rock classes and types; predict drainage water quality; select or confirm mine rock management and control options; and provide confirmation of predictions based on the findings of the ABA and NAG tests.

The prediction of sulphide oxidation behaviour of mine wastes is essential for effective environmental planning. For mine operators, the failure to identify wastes that are potentially acid generating or acid generating can result in large unplanned remediation costs late in mine life, whereas the false identification of wastes as potentially acid generating or acid generating, when they are not, can mean unnecessary work is carried out to manage the wastes.

2.3 Management strategies for potentially acid generating mine wastes

If some of the waste is identified as potentially acid generating, the mine should develop appropriate strategies to manage these wastes, as well as assess whether underground working and the pit wall might also be sources of acidity. The management strategy should depend on the proportion of potentially acid generating wastes, predicted rate of acid generation, the net acid production potential, climatic conditions, the types and quantities of material available for covers, the sensitivity of the receiving environment and the release criteria to be met.

The environmental impact of acid mine drainage occurs when the oxidation products, particularly heavy metals, sulphates and acidity, are transported by water to surface or ground waters. The consequences of acid drainage depend on the pH, the chemical composition and volume of the contaminated drainage and the assimilative capacity of the receiving environment. The off-site impacts of sulphidic oxidation in mine wastes at sites in arid regions can be different from those in high rainfall regions.

In general, the long-term aims in managing potentially acid generating wastes are to reduce the rate of oxidation and to limit the transport of oxidation products to the accessible environment (Ritchie 1992, 1995, Marszalek 1996, Hutchinson & Ellison 1992). The rate of oxidation can be reduced by limiting the supply of oxygen to the oxidation sites. The generation of acid can be reduced by increasing the neutralising capacity of the wastes by adding lime or other neutralising agents. Bactericides and surfactants can be used to reduce the bacteria that catalyse the oxidation. The release of pollutants from mine wastes can be reduced by limiting the amount of water available to transport pollutants to surface and ground waters. The strategies selected for managing potentially acid generating wastes will depend on some or all of these factors.

The methods used in Australia to manage sulphidic wastes depend on the properties of the wastes, the climatic conditions and the sensitivity of the receiving environment. The impact and the management of acid mine and acid rock drainage have many site-specific factors, but there are also many features that are common across the industry. Some of the strategies currently used for management of potentially acid generating wastes and controlling the environmental impact are (eg Ritchie 1995, Marszalek 1996):

- isolation of the potentially acid generating material so that it is enclosed above and on the sides by low hydraulic conductivity material with low oxygen permeability (often compacted clays or geomembranes);
- selective placement of potentially acid generating waste rock at specific locations within waste dumps;
- selective placement of potentially acid generating tailings under non-acid generating tailings;
- placement of water covers to reduce ingress of water and oxygen;
- placement of soil/clay multilayer covers using low permeability natural materials or geomembranes to restrict ingress of water and oxygen;
- encapsulation of potentially acid generating waste within a dump so that there is a thickness of benign or oxide waste surrounding the potentially acid generating material;
- use of specific waste dumps for isolation of potentially acid generating wastes;
- mixing of wastes with acid neutralising material to increase the acid neutralisation capacity of the emplaced wastes;
- establishment of surface water controls and construction of water treatment facilities to ensure released water meets discharge criteria;
- establishment of wetlands to reduce the level of pollutants in water released to the off-site environment;
- use of bactericides to reduce bacterial activity in acid producing materials.

The selection of the waste management option appropriate for a particular mine site depends on the site specific conditions. It is not the place here to attempt to evaluate the effectiveness of the different technologies, but the often long time for acid drainage to become evident means that it can be many years before the effectiveness of any strategies can be fully assessed.

Methods used at Australian mine sites to monitor the effectiveness of the waste management strategy used for sulphidic wastes include:

- monitoring seepage water quality and volumes;
- measurement of the water balance of waste emplacements;
- use of lysimeters to measure water percolation rates;
- measurement of oxygen levels within waste rock dumps and tailings dams;
- measurement of oxygen flux;
- derivation of oxidation rates from measurements of temperature distributions within mine wastes.

2.4 Acid mine drainage in Australia

The need to characterise and manage mine wastes for their acid generating potential is now well recognised. In 1995, the Australian and New Zealand Mineral and Energy Council (ANZMEC) issued baseline environmental guidelines that are considered to be the minimum appropriate for operating mines in Australia. The guidelines require that 'prediction of the development of acid generation processes and resultant drainage water quality is essential for the evaluation of the long term environmental impacts of waste dumps, tailings impoundment structures and mine excavations. Information obtained should be used to develop suitable mine closure structures.'(ANZMEC 1995, p 6)

Both the Western Australia Department of Minerals and Energy and the Northern Territory Department of Mines and Energy have recently published reviews of acid drainage in their jurisdiction (Williams 1995 for WA, and Zhou 1994 for NT). Noller and Parker (1996) discussed the use of wetlands as a cost effective means of cleaning up acid drainage water from tropical mine sites.

Australian State and Territory governments are moving to require mining companies to be pro-active in their management of acid generating and potentially acid generating wastes. The governments are becoming increasingly aware that acid mine drainage can become a real liability where State and Territory governments can become responsible for remediation of mine sites left without proper and effective remediation.

In January 1995, the Queensland Department of Minerals and Energy issued technical guidelines for the assessment and management of acid drainage (DME 1995). This 13-page guideline provided advice on how to identify, evaluate and deal with mine wastes which have the potential to generate acid drainage or be affected by the products of sulphide oxidation.

In 1996, the Northern Territory Department of Mines and Energy adopted a policy on combating acid mine drainage. The Northern Territory requires provision for interception of drainage, separation of waters based on quality, and testing for acid generation potential as a basis for dumping strategies. The policy notes that 'there is some disagreement on what constitutes "best practice" among some experts and, in some cases, consideration of "what seemed to be a good idea at the time" has not received rigorous investigation or validation'.

In Tasmania, the Environment Improvement Programs (EIPs), which mining companies must prepare and which become legally binding commitments, are seen as a means of ensuring continuous improvement on environmental issues like acid mine drainage.

The likelihood of acid formation in mine wastes is directly related to the geology of the ore body. The OZMIN mineral deposits database developed by the Australian Geological Survey Organisation (AGSO) contains geological, production and resource information compiled from the published literature for more than 900 of Australia's major and more significant mineral deposits. Unfortunately for this study, while OZMIN records the nature of the ore and gangue mineralogy present, it does not record information on concentrations of individual minerals in the deposit. Hence it is only possible to determine from the database whether the geologist recorded the presence of pyrite or any other mineral.

2.4.1 OZMIN Database of Australian mineral deposits

The OZMIN mineral deposits database developed by the Australian Geological Survey Organisation (AGSO) contains geological, production and resource information compiled from the published literature for more than 900 of Australia's major and more significant mineral deposits (Ewers & Rayburn 1994). OZMIN records the operating status of a deposit (whether an operating mine, historic mine, undeveloped deposit, etc) and the nature of the ore and gangue mineralogy present, but does not have information on the concentrations of individual minerals in the deposit.

For this OSS/ACMRR study, maps were prepared of data from the OZMIN database to identify deposits containing pyrite and pyrrhotite that could give rise to potentially acid generating. The maps were prepared by Dr Greg Ewers of the Australian Geological Survey Organisation (AGSO). Only deposits which correspond to operating or historic mines were selected from OZMIN (627 deposits) for preparation of the maps.

Figure 2.1 is a map showing the distribution of operating and historic mines overlayed on geological regions. Names of the geological regions are listed on fig 2.2. Of the 627 mines used in the maps, 417 were historic and 210 were operating mines. This map shows which geological regions are mineral bearing. Very few mines are found in the large sedimentary basins of Australia.

Figure 2.3 is a map showing those mines (both operating and historic) where the OZMIN database records pyrite and/or pyrrhotite as being present and those where these minerals are absent. The absence of pyrite/pyrrhotite means the geologist did not to recorded their presence either because these minerals are genuinely absent (eg deposits of opal, silica sand, bauxite, magnesite, etc) or because they were they were finely disseminated and not visually evident in the drill cores. Coal deposits have been identified separately because the database contains no information on their sulphide mineralogy. Figure 2.3 shows that deposits with identified in the OZMIN as containing pyrite occur in as a scattering in most geological regions. Some of the mine sites known to be mining potentially acid generating rock, eg in the Pine Creek Geosyncline, are not identified as containing pyrite/pyrrhotite.

Figure 2.4 is similar to map 2.3 but also identifies which of those deposits containing pyrite and/or pyrrhotite are identified in OZMIN as containing carbonate gangue minerals that could provide acid neutralising capacity.

In OZMIN, each deposit has been classified according to a set of mineral deposit models developed by Cox and Singer (1986). A mineral deposit model is a systematic arrangement of information describing the essential attributes or properties of a group or class of mineral deposits. The models are constructed (as far as possible) to be independent of site-specific attributes not common to the group, but it should be recognised that no two deposits are identical, and there can be significant variations within each model. For this study, Ewers classified each of the Cox and Singer models into three categories:

- high-sulphide deposits (on average >5% total sulphide),
- medium-sulphide deposits (on average 2–5% total sulphide), or
- low-sulphide deposits (on average <2% total sulphide).

These nominated percentages and decisions as to whether a class of deposits are either high- rather than medium-sulphide or medium- rather than low-sulphide are somewhat subjective. The classification of the Cox and Singer models into these three sulphide categories is listed in table 2.1. It should be noted that individual deposits within a deposit model will have a range in sulphide contents, and a group of deposits regarded as a 'medium-sulphide deposit type' may contain some deposits that are high sulphide or low sulphide. There are a significant number of deposits in OZMIN which either do not fit the Cox and Singer classification (eg the Au-Cu-Bi deposits in the Tennant Creek Block, coal deposits, opal deposits, etc) or where the information is not sufficient to assign a deposit model—these deposits were classified as 'unknown'.

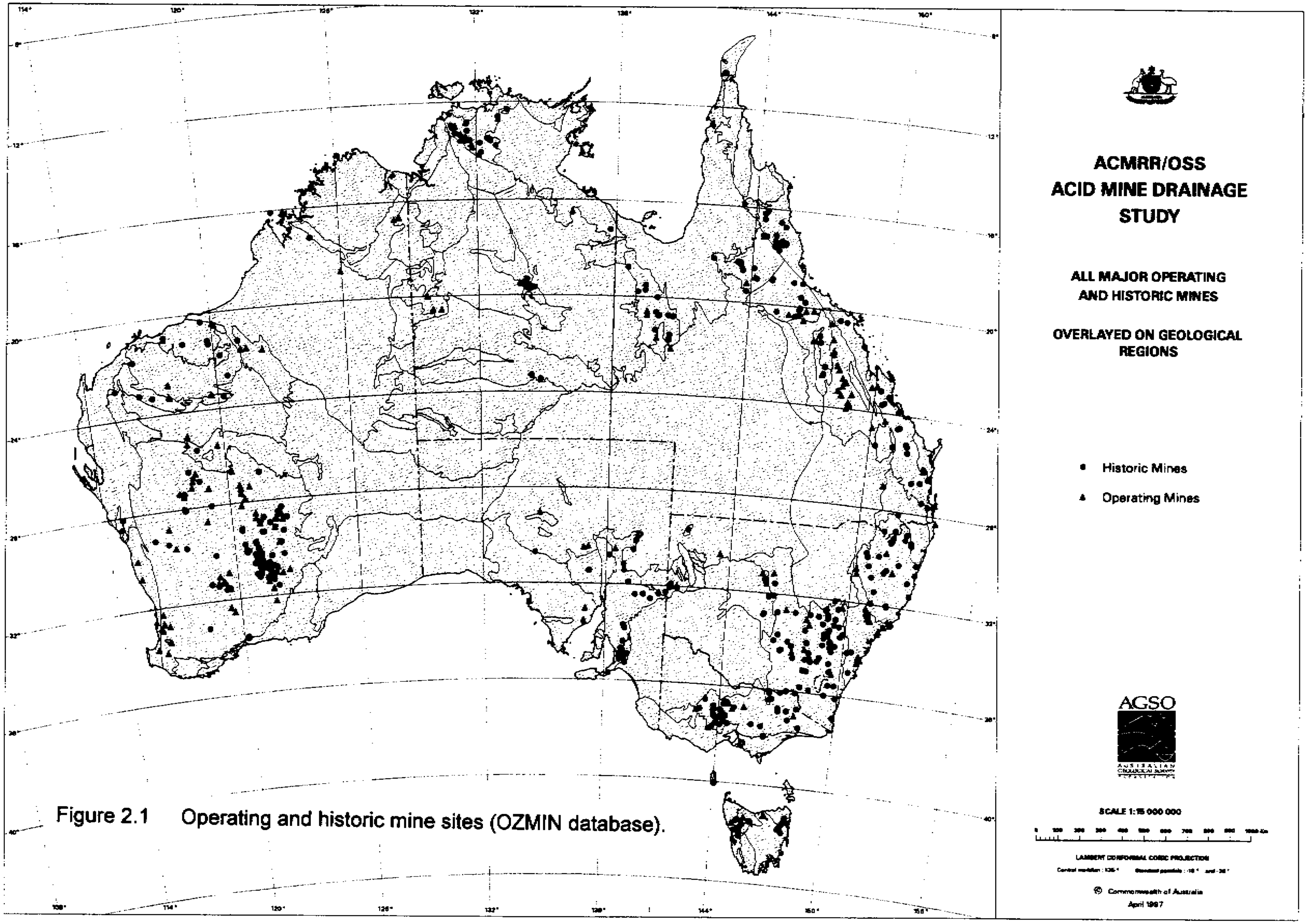

Figure 2.1 Operating and historic mine sites (Ozmin database)

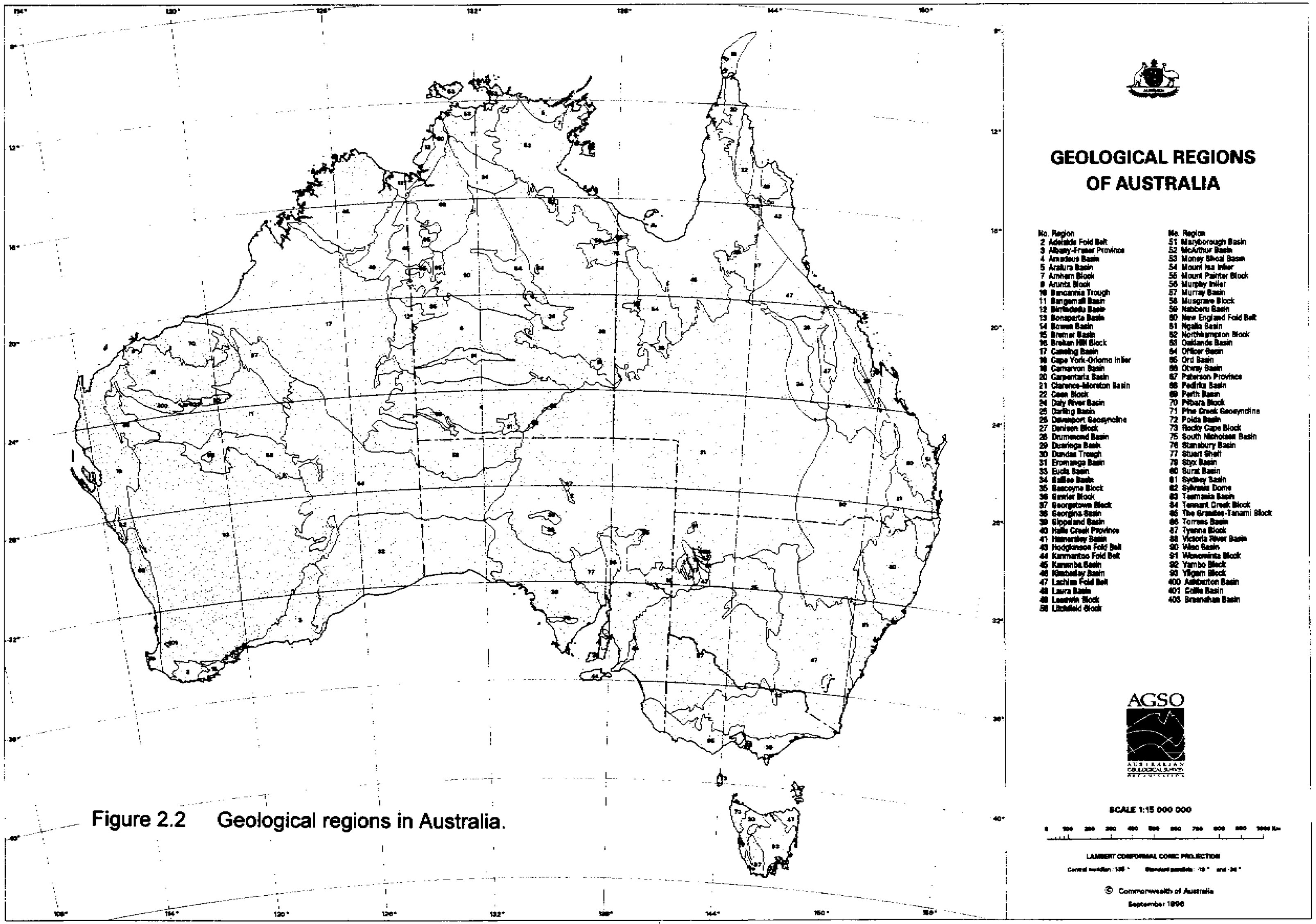

Figure 2.2 Geological regions in Australia.

Figure 2.2 Geological regions in Australia

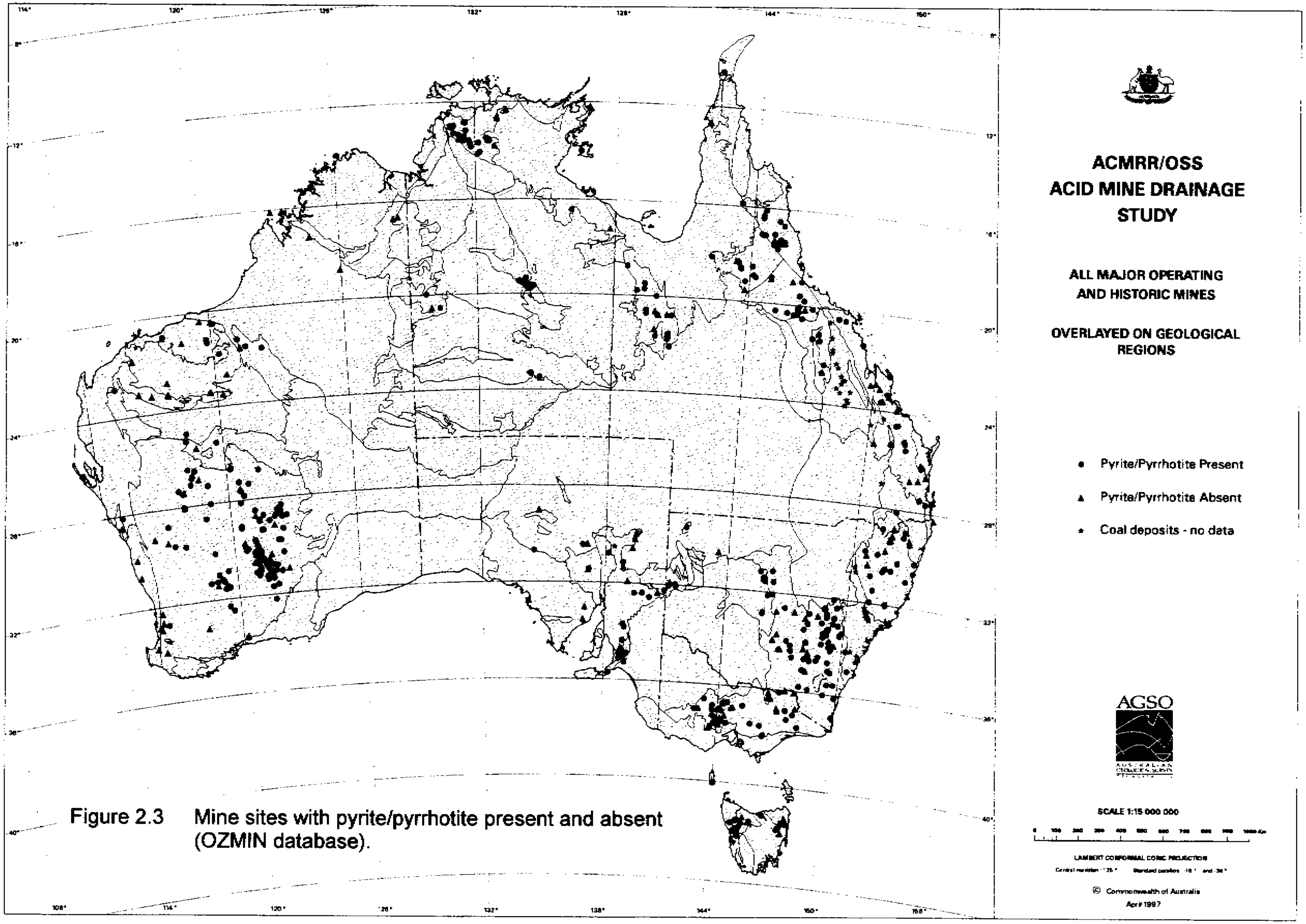

Figure 2.3 Mine sites with pyrite/pyrrhotite present and absent (Ozmin database)

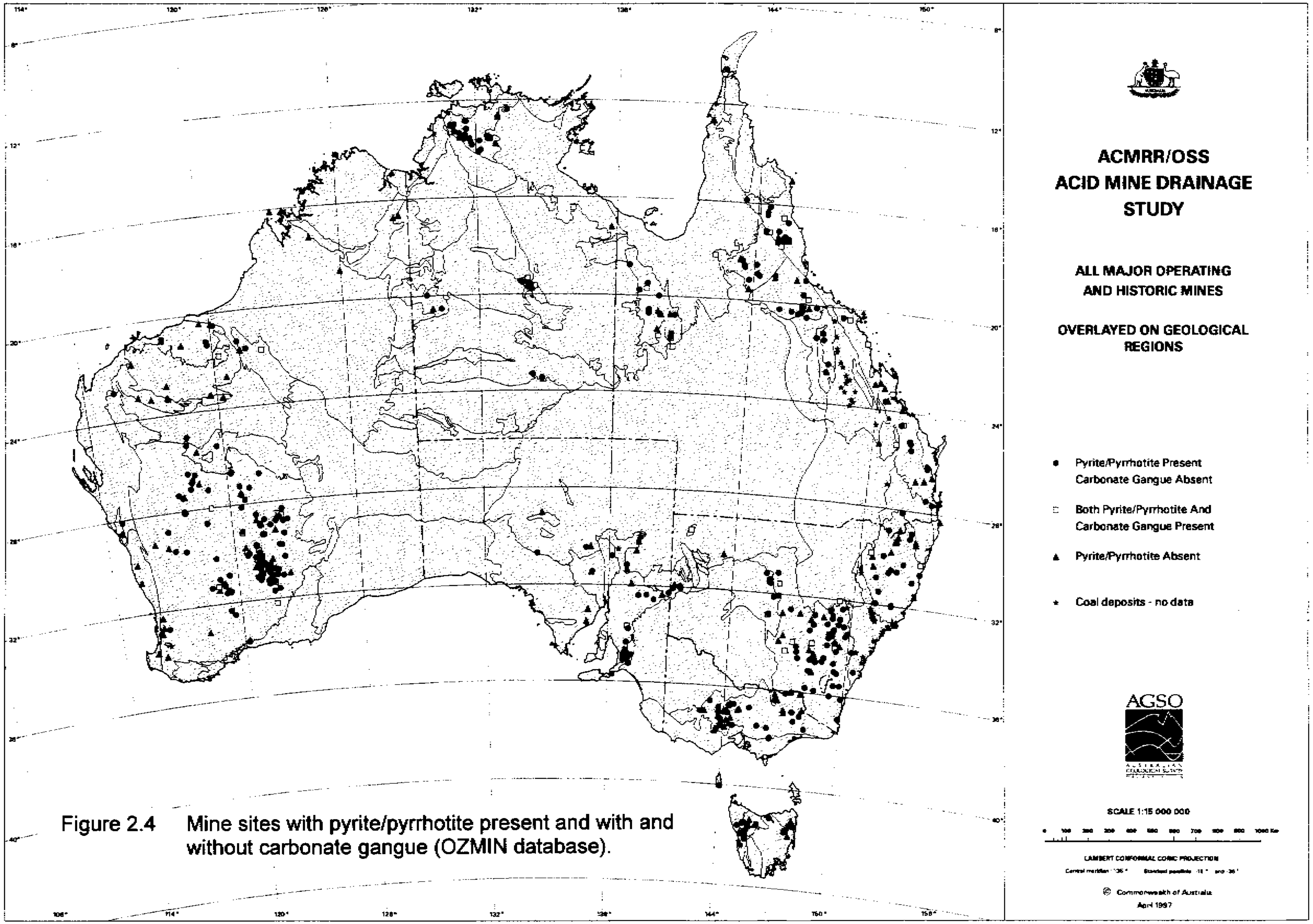

Figure 2.4 Mine sites with pyrite/pyrrhotite present and with and without carbonate gangue (OZMIN database).

Figure 2.4 Mine sites with pyrite/pyrrhotite present and with and without carbonate gangue (Ozmin database)

Figure 2.5 is a map showing the estimated level of sulphides in the mineral deposits based on mineral deposit models. The proportions of mine sites in the four categories are 10% high sulphide, 6% medium sulphide, 63% low sulphide and 20% unknown. The presence or absence of carbonate in the gangue mineralogy in each of the four categories has been shown on the map by different symbols. This map provides an indication of the mineral deposits where acid mine drainage could become an issue. Figure 2.5 shows that deposits with high pyrite are scattered through most geological regions. Geological regions with a greater proportion of high or medium sulphide levels include the Mt Isa Inlier (Qld), Georgetown Block (Qld), the northern parts of the Lachlan Fold Belt (Qld and NSW), Broken Hill Block (NSW/SA) and the Dundas Trough (Tas). These regions do contain mine sites managing potentially acid generating wastes, but there are other sites in the same regions where acidity is not a problem.

The distribution of mine sites in fig 2.5 indicates regions where a greater proportion of mine sites will be managing sulphidic wastes. However, as means of classifying potential for acid generation, the distribution of deposits with high and medium sulphide levels is not very satisfactory because the equivalent level of neutralising capacity is difficult to quantify. Even mines with low sulphide deposits can produce wastes with potential acid generation if the neutralising capacity is low. The other difficulty is that the acid generation potential of wastes can vary in different rock types in the same deposit and the gangue.

Williams (1995) tried to classify mineral deposits in Western Australia using the geoenvironmental models of mineral deposits developed by GS Plumlee and others at the US Geological Survey. However, he had difficulty assigning the Western Australian deposits to the Plumlee models because the information available in the literature on the mineral deposits was often not adequate to characterise the mine wastes for acid generation potential.

Williams also found that the Plumlee classification was geared to the geology of the western cordillera in North America and is not as suitable for the range of Australian deposits (RD Williams, US Bureau of Land Management, pers comm, 9 May 1996).

Despite the limitations, the AGSO maps do provide a useful picture of where mining occurs in Australia and indicates regions where acid mine drainage could be an issue.

2.5 Acid mine drainage in Canada

Acid mine and rock drainage is of major concern to the Canadian mining industry. The Canadian Mine Environment Neutral Drainage (MEND) program was established in 1989 in response to the recognition that acid drainage was the largest single environmental problem facing the Canadian mining industry. MEND is a cooperative program financed and administered by the Canadian mining industry, the Canadian government and provincial governments costing C$18 million over the life of the program (C$1.00 = A$0.97, 6 February 1997). The MEND program is expected to finish in 1997 (MEND 1996).

Many mines in Canada are required to establish trust funds to cover the effect of acid drainage from mine wastes. The Equity Silver mine in British Columbia, Canada, for instance had to establish a reclamation trust fund of C$32 million to produce sufficient income to cover the annual cost of operating and maintaining collection and treatment facilities. (Murray et al 1995). In addition, concern about acid mine drainage (AMD) was a major factor in the decision in 1993 not to develop the $550 million Windy Craggy mining project in British Columbia (MEND 1996).

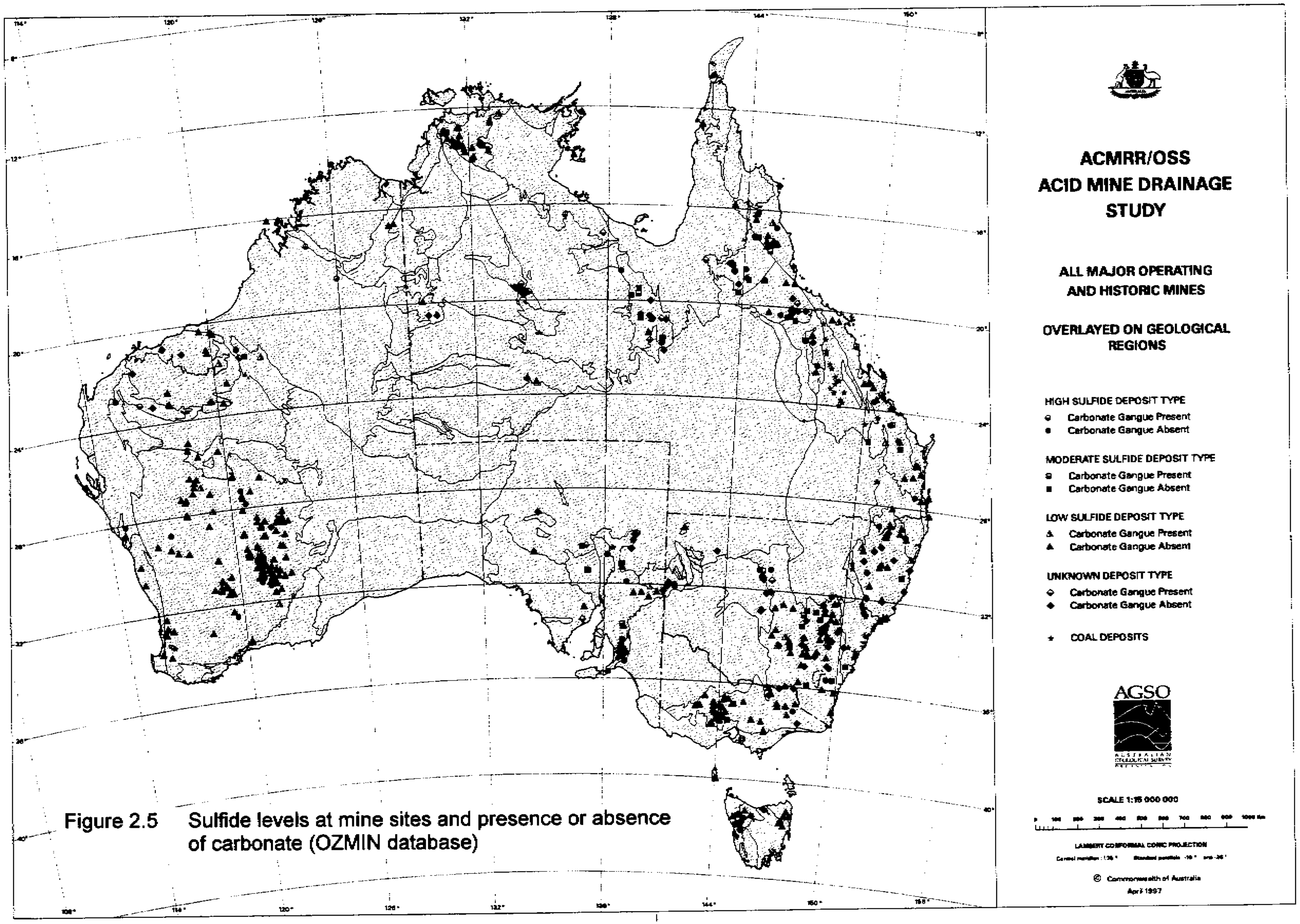

Figure 2.5 Sulfide levels at mine sites and presence or absence of carbonate (OZMIN database)

Figure 2.5 Sulphide levels at mine sites and presence or absence of carbonate (Ozmin database)

Table 2.1 Cox and Singer (1986) deposit models and estimated sulphide content

No.	Deposit model	Sulphides
0	Unknown	
Deposits related to mafic and ultramafic intrusions in stable environments		
1	Stratiform mafic/ultramafic Ni-Cu	High
2a	Stratiform mafic/ultramafic Cr	Low
2b	Stratiform mafic/ultramafic PGE	Low
3	Stratiform mafic/ultramafic Fe-Ti-V	Low
Deposits related to mafic-ultramafic in unstable areas		
5a	Duluth Cu-Ni-PGE	High
5b	Noril'sk Cu-Ni-PGE	High
6a	Komatiitic Ni-Cu	High
6b	Dunitic Ni-Cu	High
7a	Synorogenic-synvolcanic Ni-Cu	High
7b	Anorthosite Ti	Low
8a	Alpine type podiform Cr	Low
8c	Limassol Forest Co-Ni	High
8d	Serpentine-hosted asbestos	Low
8d	Alaskan PGE	Low
Deposits related to alkaline intrusions		
10	Carbonatite	Low
12	Diamond pipes	Low
Deposits related to felsic phanero-crystalline intrusive rocks		
14a	W skarn	Low
14b	Sn skarn	Low
14c	Replacement Sn	Medium
15a	W veins	Low
15b	Sn veins	Low
15c	Sn greisen	Low

No.	Deposit model	Sulphides
Deposits related to felsic porphyro-aphanitic intrusions		
16	Climax Mo	Low
17	Porphyry Cu	Medium
18a	Porphyry Cu, skarn related	Medium
18b	Cu skarn	Medium
18c	Zn-Pb skarn	High
18d	Fe skarn	Medium
18e	Carbonate-hosted asbestos	–
19a	Polymetallic replacement	High
19b	Replacement Mn	Low
20a	Porphyry Sn	Low
20b	Sn-polymetallic veins	Medium
20c	Porphyry Cu-Au	Medium
21a	Porphyry Cu-Mo	Medium
21b	Porphyry Mo, low F	Low
22a	Volcanic-hosted Cu-As-Sb	High
22b	Au-Ag-Te veins	Low
22c	Polymetallic Ag-Pb-Zn veins	High
Deposits related to subaerial mafic extrusive rocks		
23	Basaltic Cu	Medium
Deposits related to marine mafic extrusive rocks		
24a	Cyprus massive sulphide	High
24b	Besshi massive sulphide	High
24c	Volcanogenic Mn	Low
24d	Blackbird Co-Cu	High

Table 2.1 cont.

No.	Deposit model	Sulphides
Deposits related to subaerial felsic to mafic extrusive rocks		
25a	Hot spring Au-Ag	Low
25b	Creede epithermal veins	Medium
25c	Comstock epithermal veins	Low
25d	Sado epithermal veins	Low
25e	Epithermal quartz-alunite Au	Medium
25f	Volcanogenic U	Low
25g	Epithermal Mn	Low
25h	Rhyolite-hosted Sn	Low
25f	Volcanic-hosted magnetite	Low
26a	Carbonate-hosted Au-Ag	Low
27a	Hot spring Hg	Low
27b	Almaden Hg	Low
27c	Silica-carbonate Hg	Low
27d	Simple Sb	Medium
Deposits related to marine felsic to mafic extrusive rocks		
28a	Kuroko massive sulphide	High
28b	Volcanogenic Fe formation	Low
Deposits in clastic sedimentary rocks		
29a	Quartz pebble conglomerate U	Low
29b	Olympic Dam Cu-U-Au	Medium
30a	Sandstone-hosted Pb-Zn	High
30b	Sediment-hosted Cu	Medium
30c	Sandstone U	Low
31a	Sediment-hosted Zn-Pb	High
31b	Stratiform barite	Low
31c	Emerald veins	Low

No.	Deposit model	Sulphides
Deposits in carbonate rocks		
32a	Carbonate-hosted Pb-Zn	High
32b	Carbonate-hosted Zn	High
32c	Kipushi Cu-Pb-Zn	High
Chemical-sedimentary rocks		
34a	Sedimentary Fe formation	Low
34b	Sedimentary Mn	Low
34c	Upwelling type phosphate	Low
34d	Warm-current type phosphate	Low
Deposits related to regionally metamorphosed rocks		
36a	Low-sulphide Au-quartz veins	Low
36b	Archaean greenstone Au	Low
37a	Unconformity U-Au	Low
37b	Gold in flat faults	Low
Deposits related to surficial processes and unconformities		
38a	Lateritic Ni	Low
38b	Laterite type bauxite	Low
38c	Karst type bauxite	Low
39a	Placer Au-PGE	Low
39b	Placer PGE-Au	Low
39c	Shoreline placer Ti	Low
39d	Diamond placers	Low
39e	Alluvial placer Sn	Low

In 1994, MEND conducted a survey of acid generating wastes in Canada. The survey showed that Canada had about 7 billion tonnes (covering 44 000 hectares) of metal-mine and industrial mineral tailings and about 6 billion tonnes of waste rock. Of this, about 1.9 billion tonnes (12 500 hectares) of tailings and 750 million tonnes of waste rock were acid generating (Feasby & Jones 1994). It has been suggested that the estimate of the amount of waste rock could be on the low side (MEND 1995).

Acid drainage is not the only concern in the closure of mine sites in Canada, but where it occurs, it can be the most costly component. For a small Canadian mine, the cost of treating 250 000 tonnes of acid generating waste rock in a 10 ha dump was estimated to be C$2.5 million of a total closure cost of C$3.45 million. If the wastes had not been acid producing, the costs of rehabilitating the same amount of wastes would have been reduced by a factor of ten to about C$250 000 (Feasby & Jones 1994).

MEND developed indicative costs of managing acid producing wastes by a range of treatments (Feasby & Jones 1994, Feasby & Tremblay 1995):

- collect and treat seepage water from waste rock and/or tailings by conventional low density sludge lime treatment for 100 or more years;
- place a water cover on tailings, assumed to require water treatment for 10 years and perpetual embankment maintenance;
- place a soil cover on tailings, assumed to require water treatment for 50 years;
- transport waste rock to the pit, add alkalinity and cover with soil, assumed to require water treatment for 5 years;
- place a dry multilayer cover on the waste rock after recontouring, assumed to require water treatment for 100 years.

Net present value (NPV) of costs were calculated based on a discount rate of 3%. An annual cost was included for maintaining a presence at the site: $120 000 for each 100 ha of tailings and each 25 million tonnes of waste rock. Table 2.2 summarises the estimated Canadian costs for different types of treatments (Feasby & Jones 1994).

Table 2.2 Estimated total cost for managing existing acid-producing mine waste in Canada. Costs in C$billions (Feasby & Jones 1994).

Option	Up-front costs	Maintenance costs		Total costs
		Annual	NPV	
Tailings:				
Treat seepage	0.10	0.045	1.42	1.52
Water cover	1.08	0.052	0.45	1.53
Soil cover	2.07	0.044	1.10	3.18
Waste rock:				
Treat seepage	0.02	0.012	0.38	0.40
Return to pit	2.04	0.007	0.03	2.07
Soil cover	0.37	0.009	0.28	0.65

On the basis of this analysis, MEND concluded that the total acid drainage liability in Canada ranged from C$1.92 to C$5.25 billion, with the lowest cost option being to collect and treat in perpetuity the seepage water from tailings and waste rock, and the highest cost option being to place soil covers on tailings and return waste rock to the pit. These estimated costs are equivalent to C$0.8 per tonne of tailings or C$120 000 per hectare for perpetual water treatment, and C$1.7 per tonne of tailings or C$250 000 per hectare for multi-zone dry cover. This is consistent with the amount of between C$20 and $30 per square metre ($200 000 to $300 000 per hectare for multizone covers given by Feasby and Tremblay (1995). For the reactive waste rock, the costs are equivalent to C$0.54 per tonne for treatment of seepage to C$2.80 per tonne for return to the pit. For the study, MEND assumed that average waste rock dumps would contain 400 000 tonnes of waste rock per hectare, ie height 20 to 25 m (Feasby & Jones 1994, Feasby & Tremblay 1995).

In order to improve the estimate of costs, MEND sponsored an independent costing analysis by GEOCON, a Division of SNC♦Lavalin Environment Inc (MEND 1995). This study estimated costs of different technologies for managing potentially acid generating wastes at actual mine sites. The aim was to estimate realistic values for such site specific items such as the availability of borrow materials and transport distances. These site-specific conditions can lead to great variations in costs at different sites. The analysis estimated the costs of applying the following technologies:

Composite soil cover consisting of a fine rockfill obtained by selective grading of the dump, a 0.4 m thick sand and gravel or sand layer, a 0.6 m clay till type material layer, a 0.4 m sand and gravel layer and an erosion protection layer (either 0.4 m riprap or grass vegetation (total thickness 1.4 to 1.8 m). If the waste was already producing acidity, it was assumed that there would be a transition period over which seepage water would be collected and treated.

Self sustained water cover of 0.7 or 1 m deep with a minimum for design conditions of 0.3 m and only be suitable for tailings. If the tailings were generating acidity, it was assumed that the 0.3 m fine sand would be placed on the tailings. Otherwise, no sand layer would be necessary.

Maintained water cover the same as a self-sustained water cover except that a pumping facility would be needed.

Plastic liner cover consisting of a 1.5 mm (0.060 inch) HDPE liner with a 0.4 m thick bedding (on waste rock only) and a grass vegetated 0.6 m sand/till cover over the liner. It was assumed that the liner would need to be replaced after 200 years.

Collect and Treat seepage water.

Simple soil cover (or vegetative cover) consisting of a 0.3 m thick layer of pit run coarse sand or gravel, a 0.7 m of compacted till type material, and a 0.3 m layer of lightly compacted till or other accepted material. It was assumed that this would also involve collection and treatment of seepage.

Waste removal and placement underwater in a pit.

The estimated costs of applying the technologies are summarised in table 2.3. The tables in the GEOCON report only give costs for waste rock in dollars per tonne (MEND 1995). The costs for waste rock in dollars per hectare in table 2.3 were derived from support data in the report. GEOCON assumed that cover and construction materials were available within 1 to 4 km of the site. The costs derived by GEOCON ranged from C$71 000 to $404 000 per hectare, with the lowest costs being collect and treat seepage water in perpetuity. GEOCON concluded that besides underwater disposal, the best and proven technology to deal with AMD is the collect and treat option which is also the least expensive option (MEND 1995).

Table 2.3 Cost of AMD technologies derived by GEOCON (MEND 1995)

	Technology	Cost
Waste rock	Collect and treat	C\$0.26–0.64 t^{-1} C\$105 000–117 000 ha^{-1}
	Collect and treat with simple soil cover	C\$0.34–0.85 t^{-1} C\$137 000–158 000 ha^{-1}
	Composite soil cover	C\$1.07–1.31 t^{-1} C\$428 000–243 000 ha^{-1}
	Plastic liner cover	C\$1.59 t^{-1} C\$290 000 ha^{-1}
Tailings	Collect and treat	C\$214 000–238 000 ha^{-1}
	Collect and treat with simple soil cover	C\$200 000–264 000 ha^{-1}
	Composite soil cover	C\$291 000–415 000 ha^{-1}
	Self-sustained water cover	C\$71 000–349 000 ha^{-1}
	Plastic liner cover	C\$296 000–404 000 ha^{-1}

Based on the total amount of wastes, GEOCON estimated that the total Canadian liability was C$1.8 to 2.9 billion for tailings and C$0.4 to 0.9 billion for waste rock. GEOCON noted that this does not represent the total liability for acid mine drainage because it does not include open pits and underground workings (MEND 1995). In general the cost estimates for managing acid producing wastes in Canada derived by GEOCON were higher than those estimated by MEND (Feasby & Jones 1994), however both costs are of the same order of magnitude.

2.6 Acid mine drainage in the United States

The United States has a large number of sites where acid mine drainage is a major issue. Initially the main problems identified were associated with the coal mines in the eastern states where over 7000 km of streams were considered to be seriously affected by acid drainage from coal mines (Ferguson & Erickson 1988). In addition, many hard rock mines sites in the western United States, particularly in Idaho and Colorado, have been found to have major water quality problems. The US Forestry Service estimated that 5000 to 10 000 miles (8000 to 16 000 km) of streams in the US were affected by acid drainage from active and inactive mines and waste rock piles (USEPA 1995).

Because of the large potential liability associated with acid drainage from abandoned mine sites, regulators in North America now insist on conservative control strategies and payment of large performance bonds. At the Golden Sunlight mine in Montana, operated by Placer Dome Inc, a progressive performance bond of US$41 million was required by the State of Montana, the US Bureau of Land Management and the US Bureau of Mines. Golden Sunlight is a relatively dry mine site where evaporation exceeds rainfall (Murray et al 1995).

The Summittville abandoned mine and mines near Leadville in Colorado have been declared Superfund sites by the USEPA because of acid rock drainage from the sites. The USEPA was spending US$50 000 per day on containment and treatment. In 1996, the USEPA had obligated $104 million towards cleanup of the Summittville site (V Ketellapper, USEPA, 20 March 1996). The State of Colorado estimated cleanup costs for Leadville to be of the order of US$290 million in 1986. US regulators estimate the liability from sulphate contamination of groundwater at a large operation in Utah to be in the range of US$500 million to US$1200 million (Murray et al 1995).

A total of 136 abandoned coal mine sites with a total area of 460 ha in south west Pennsylvania were reclaimed between 1980 and 1992. Wetlands were constructed on 11 sites to mitigate acid mine drainage, and a soil cover was used on 2 sites. The average cost of reclamation was US$9500 per acre (equivalent to A$31 000 ha^{-1}) (Bogovich 1992).

3 Survey of acid drainage at mine sites in Australia

Information for this study was collected during visits to mine sites, by discussions and meeting with company environmental officers, State Chambers of Mines, officers from State Departments responsible for mining and environmental issues and by distribution of questionnaires to mine sites where the mineralogy suggested there was a chance of having to manage potentially acid generating wastes.

3.1 Visits and meetings

Discussions were held with a wide range of people who had experience and knowledge of acid mine drainage in Australia, including corporate officers of mining companies who were responsible for environmental issues, State Government officials responsible for regulating the environmental issues at mine sites and other consultants and experts. In addition, eighteen representative mine sites were visited for discussions with mine environmental officers to gain a better understanding of local conditions and the options for managing potentially acid generating wastes. Some visited sites were dealing with significant amounts of potentially acid generating wastes, whilst others had very little. Mine sites were visited in most States, and included gold, coal and base metal mines as well as some of the classic historic mines known to generate acid drainage. The major visits and meetings are listed in Appendix C2.

3.2 Questionnaire

A questionnaire was prepared which contained a series of questions about surface water management, ground water, open cuts, underground workings, waste characterisation, the types of wastes and the acid generating potential of mine wastes. A copy of the questionnaire is in Appendix C3.

A database of mine site contacts was purchased from the Australian Mining Series Pty Ltd, which provided names of up to four executives at each operation, the mine address, fax and phone number and a short description of the operation. The database contained information on 531 significant mining operations in Australia, including metal mines, gold mines, coal mines, major quarries, new mines under development and significant prospects.

Of the 531 sites in the database, 317 sites were considered to have a potential need to manage potentially acid generating wastes. These included antimony, base metal, coal, copper, diamond, gold, iron ore, mineral sands, nickel, pegmatite, sapphire, vanadium and uranium mines. The number of sites in each category are listed in table 3.1. It was decided to include mineral sands mines in the survey because some sites do have acidity problems, even though the type of acidity and solutions can be more related to the presence of acid sulphate soils.

The types of mines excluded from the survey include:

- sites under development, including at exploration, at feasibility and at project identification stage where mine plans are still being developed;
- sites mining resources with high neutralising capacity, including, bauxite, gypsum, lime, limestone, magnesite and magnesium;