Sustainability and Mine Waste Management – A Snapshot of Mining Waste Issues

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Abstract

The modern mining industry is truly a global enterprise, and in the past decade has embraced the sustainability debate and the challenges and opportunities it presents. At first glance, however, the concept of 'sustainable mining' seems like an oxymoron – a logical misnomer. There is strong evidence, however, that although an individual mine may not be 'sustainable', when the sum of mines in a sector or region are considered together over time, the mining industry can be argued as contributing to sustainable development. This more complex view of sustainable mining is the new position of the modern mining industry, and moves beyond a simplistic notion of a single mine to a holistic view of the industry and its role in society. Further issues which need to be considered in conjunction are the fundamental trends in modern mining with respect to the effort required for a given unit metal or mineral production. This paper presents wide ranging data to address this area, showing that production is increasing at substantive rates (sometimes exponentially so), ore grades are in terminal decline, there is a major shift from underground to open cut mining, waste rock production is increasing at a dramatic rate, a gap in rehabilitation of formerly mined land, and the economic resources of some metals and minerals have increased while others have apparently stabilised. In parallel to these critical trends, the modern mining industry is moving to improved sustainability performance and transparency through detailed reporting. The principal protocol is the United Nations' voluntary 'Global Reporting Initiative' (GRI), which stipulates a range of data on social, economic, environmental and human rights performance. In Australia, the statutory 'National Pollutant Inventory' (NPI) is also relevant for mining and associated processing activities. Although both the GRI and NPI report a range of useful environmental data on mining, they both fail to mandate complete disclosure of large volume mine wastes such as tailings and waste rock – despite the considerable scale of these wastes and the potential environmental legacy and liability they represent. Based on the available data from sustainability reports, it can be demonstrated that aspects such as greenhouse emissions and energy and water consumption are sensitive to ore grade. This means that, combined with the substantive solid wastes with modern mining, the resource intensity (or ecological footprint) of mining looks set to increase in the future. Fundamentally, the vast scale of modern mine waste presents significant engineering challenges to meet an ever more complex array of environmental requirements, social expectations, corporate policies and statutory demands. Although we may be able to continue to find new mineral deposits in the near future, improve technology or favourable economics will facilitate the processing of higher cost resources, it is the environmental cost which will, in the medium to longer term, govern the real availability of metals and minerals. In summary, the vast scale of modern mine waste will continue to challenge the sustainability of the modern mining industry and requires eternal vigilance by all involved – regulators, shareholders, governments and communities.

1 INTRODUCTION

The issue of waste management is correctly perceived to be a major issue for municipal councils and the manufacturing, construction and chemicals industries. There is less recognition, however, of the vastly larger quantity of solid wastes produced by the mining industry. The reasons for this are most likely due to the perceived relatively benign nature of mine wastes, remoteness from population, apparent success in mine waste management, or other factors.

One of the most fundamental questions the mining industry is currently grappling with – on a global scale – is how sustainable is this substantive generation of solid wastes ? This question is extremely difficult to answer, and requires substantive data and other issues to be put into context.

The mining sector has been increasingly advocating and implementing sustainability across the industry, and many companies are now actively reporting on sustainability performance alongside corporate financial reporting. There is very little research, however, which seeks to link the traditional production side of mining and its solid wastes to the sustainability agenda, and very little examining mine wastes within sustainability frameworks and emerging sustainability reporting regimes.

This paper is part of longer term research in addressing the fundamental area of mine wastes and sustainability. It will present a succinct overview of the sustainability debate as applied to mining and its associated waste streams, followed by a presentation of key trends in modern mining which continue to affect the degree of wastes produced, finishing with an analysis of sustainability issues.

2 SUSTAINABILITY AND MINING : BEYOND THE OXYMORON

The concept of positive and negative impacts from mining endeavours is not new – with significant treatises dating back to Georgius Agricola in 1556 (Agricola, 1556) and earlier. Following the near-continual global mining boom since the mid-twentieth century, there has been wide-ranging debate about the sustainability of modern mining. This section presents a brief review of sustainable development as commonly applied to mining.

The most common starting point for sustainability is the definition proposed by the 1987 World Commission on Environment and Development (WCED, or the 'Brundtland Commission'), namely 'to meet the needs of the present without compromising the ability of future generations to meet their needs' (WCED, 1990). Although this is a somewhat open definition, in the context of mining, this is generally taken to include the ongoing availability of resources and a productive environment and healthy community at both current and former mining sites (eg. Azapagic, 2004; Cowell *et al.*, 1999).

An individual mine or mineral deposit is commonly argued as 'unsustainable' since it perceived as a finite or non-renewable resource. Although this is perhaps obvious, the reality is that the cumulative sum of all mines and mineral deposits over time have not yet been depleted – we are producing more minerals and metals today than ever before, and commonly there is at least similar quantities or more known in remaining resources at operating mines and undeveloped mineral deposits. There is strong global evidence that 'non-renewable' mineral resources are a complex function of exploration, technology, supply-demand, economics as well as social and environmental constraints – the cumulative effect of which has historically ensured abundant supply of most minerals and metals.

A major gap in the sustainability debate for mineral resources is the 'environmental cost' – the pollution legacy, solid wastes, and so on. A major driver in this regard is the almost universal long-term declines in ore grades. For example, in Australia lead-zinc-silver mining at Broken Hill in 1900 had average ore grades of ~18% Pb, ~16% Zn and ~350 g/t Ag while in 2005 ore grades were 4.2% Pb, 7.6% Zn and 45 g/t Ag (Mudd, 2007a). Similarly, long-term declines in ore grades are now well recognised for global gold mining (Mudd, 2007b). This means moving more ore for a given production – or with continually expanding production – an ever-increasing amount of ore. Following processing the residual solid waste becomes known as 'tailings'. Concurrently over recent decades, due to the abundance of cheap diesel and associated earth-moving machinery, there has been a major expansion of the use of open cut mining techniques over underground mining. Thus, for every tonne of ore mined there is an equal or greater amount of overburden or waste rock which also needs to be mined – giving rise to the vast amounts of total solid wastes by modern mining.

A critical issue for tailings and waste rock is the potentially increasing scale of environmental liabilities associated with them. The safe storage of tailings, in large engineered storage dams, requires major design, construction, operation and decommissioning costs. A review of the literature shows that catastrophic failures of tailings dams are still occurring – sometimes leading to major environmental impacts and even human fatalities (eg. ICME *et al.*, 1997; ICME and UNEP, 1998; Kumah, 2006). Additionally, the nature of many mineral deposits now being processed is that the associated waste rock may contain sulfidic minerals. When exposed to fluctuating cycles of infiltration and oxygen (ie. air), the sulfides oxidise and cause acid and/or metalliferous drainage ('AMD') (see Taylor and Pape, 2007). The escape of AMD into the surrounding environment often leads to extreme environmental impacts, sometimes for tens of kilometres downstream from a mine site. When this occurs, the large scale of environmental impacts can also have severe social and/or economic impacts. The effort required to plan, manage and rehabilitate tailings and waste rock is no simple feat and the global mining industry is expending significant effort in improving standards.

From a sustainability perspective it must be asked – how long can these relentless increases in the scale of mine wastes continue ? This is, of course, a loaded question and very difficult to answer. As part of any attempted answer, it is clearly important to understand the history of these issues, as this can give critical insights into future directions for the scale of mine wastes in Australia and globally.

Given the number of major legacy mines, combined with the introduction of more rigorous environmental legislation from 1970's, the mining industry has worked hard over the past three decades to improve environmental management, mostly successfully in industrialised countries.

Following the lead of the 1992 Earth Summit, a more comprehensive shift in thinking began in the mining industry – that of sustainability. From the mid-1990's numerous mining companies began to release environmental reports, variably detailing their performance with respect to water, energy, greenhouse emissions, tailings, rehabilitation, etc. These reports were broadened to include social and economic aspects of mines and companies and are now commonly termed 'sustainability' reports. With the recognition of the need for consistency in reporting, the 'Global Reporting Initiative' (GRI) was established by the United Nations in 1997, and the third edition of the GRI Sustainability Reporting protocol was released in October 2006 (GRI, 2006). A pilot mining sector supplement was released in February 2005 (GRI, 2005). Thus, when combined with traditional financial reporting, there is increasing publicly reported data with which to quantify the issue of mine wastes and associated sustainability issues (especially life-cycle costs and comparative waste ratios).

The remainder of this paper will focus on long-term trends in modern mining, such as ore grades, mining technique and associated mine wastes, rehabilitation issues and economic resources, followed by a review of sustainability reporting protocols applicable for mine wastes, and ending with a discussion of good practice and areas for continuing improvement. The key data presented is mostly from a major sustainability study of the Australian mining industry (Mudd, 2007d).

3 MAJOR MINE WASTE TRENDS

3.1 Overview – Mineral Production

As noted previously, the production of almost all minerals and metals is universally continuing to increase over time, some exponentially. This is a key driver – especially with the "super-cycle" global mining boom at present being driven by insatiable demand for metals and minerals from China (and to a lesser extent India). The historical data for metal and mineral production in Australia is shown in Figure 1, and ore commonly a reflection of global production. The critical issue is to note the general trend for all series shown – gradual growth followed by an exponential increase over recent decades.

3.2 Ore Grade Trends

The available data for the trends in ore grades for select metallic and other minerals is presented in Figure 2. A general trend is indicated for all series included. Each series has its particular influences, such as initially rich oxidised ores being mined followed by lower grade sulfide ores (eg. Cu, Pb-Zn-Ag), or changes in the major mines operating (exhausted, opened, etc). Further details for each metal or mineral are given in (Mudd, 2007d). For bulk minerals (bauxite, iron ore), impurities can often be as important as the ore grade though data is rarely available for both aspects (see Mudd, 2007d).

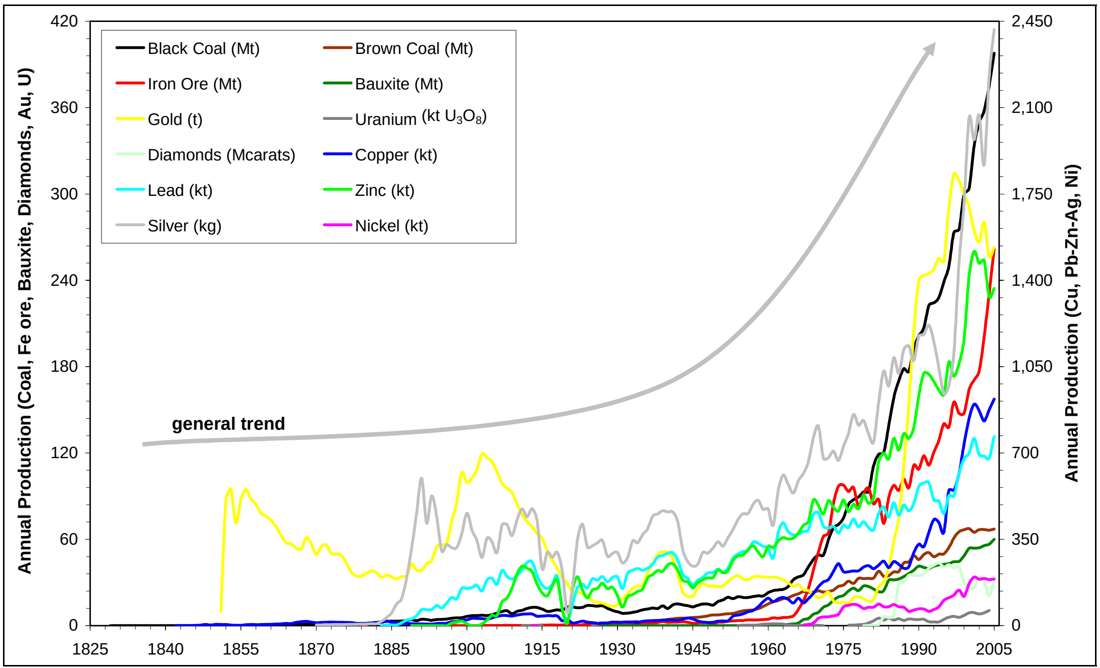

Figure 1. Historical Australian metal and mineral production (1825-2005) (Mudd, 2007d)

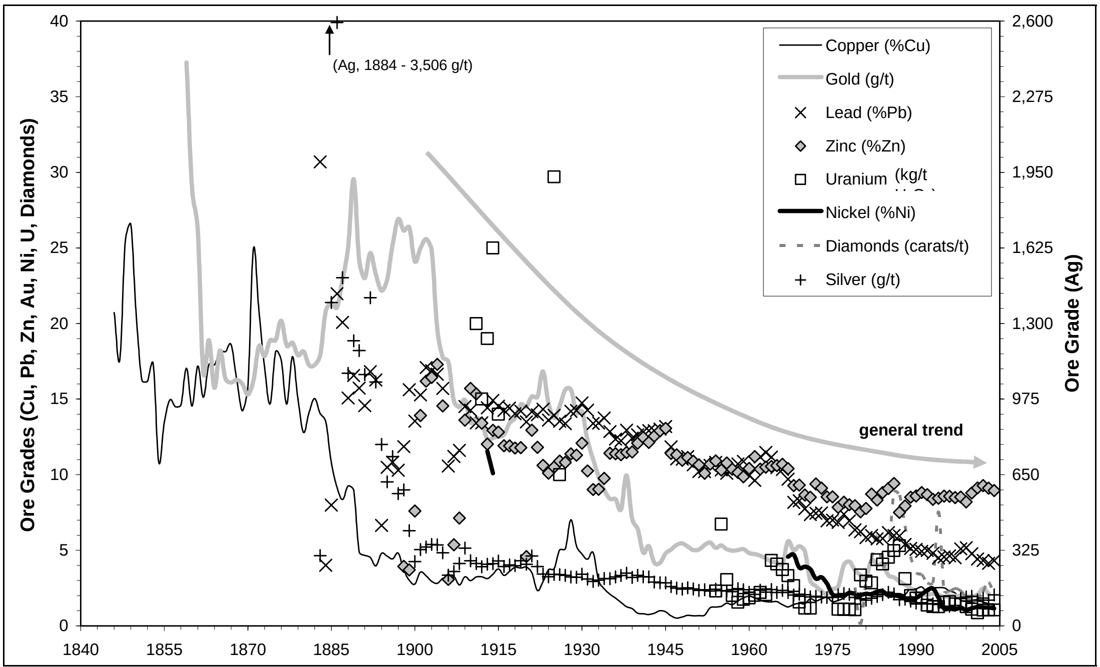

Figure 2. Historical trends in average Australian ore grades (~1845-2005) (Mudd, 2007d)

3.3 Open Cut Mining Trends

The major shift to large-scale open cut mining in the latter half of the twentieth century is the singular reason behind the extent of solid wastes now produced by the mining industry. Although data remains incomplete for some metals (eg. gold, copper, nickel), for others accurate statistics are reported (eg. coal, uranium), or it is known that no underground mines exist (eg. iron ore, bauxite, mineral sands). The available data for open cut mining, as the proportion of ore, is shown in Figure 3. In general, this is very similar to the contained metal, though as open cut mining is often lower in grade it is slightly lower if presented as the proportion of metal. As with ore grades, an individual series is often linked to major mines opening or closing. The introduction of economic large-scale open cut mining was led by the copper industry, with the great mines at Mt Lyell and Mt Morgan in the early twentieth century, and was progressively implemented at many other mines and sectors (further details in Mudd, 2007d).

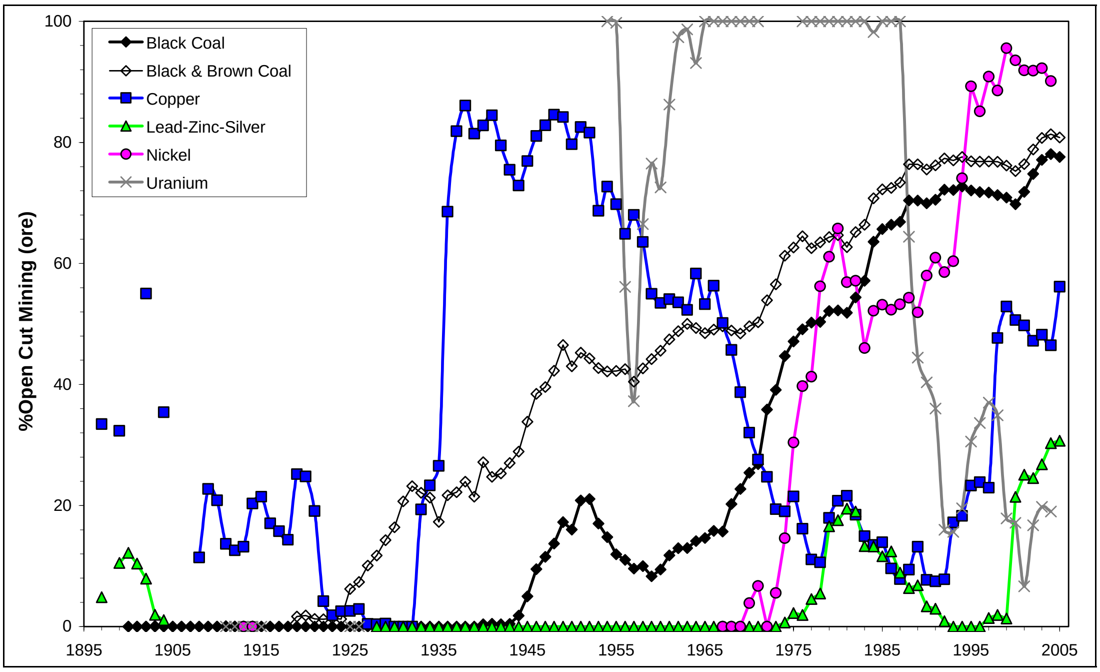

Figure 3. Historical trends in proportion of Australian open cut mining (by ore) (Mudd, 2007d)

3.4 Waste Rock / Overburden Trends

The extent of waste rock or overburden produced by mining is closely linked to the use and scale of open cut mining. The available data is summarised in Figure 4, though incomplete public reporting of data by many companies means that the data presented is a minimum for all commodities presented (though brown coal, uranium and diamonds are close to complete, some mines are still missing data). The reason behind the extra-ordinary growth in waste rock and overburden production is the combination of rapid metal / mineral production growth combined with the significantly increasing use and scale of open cut mining. For example, although the extent of open cut mining for copper was high in the 1930's to mid-1950's (when Mt Isa began underground copper mining on a large scale), the scale of the Mt Lyell and Mt Morgan mines during this period was minor in comparison to the modern generation of open cut mines such as Ernest Henry, Cadia Hill or Century.

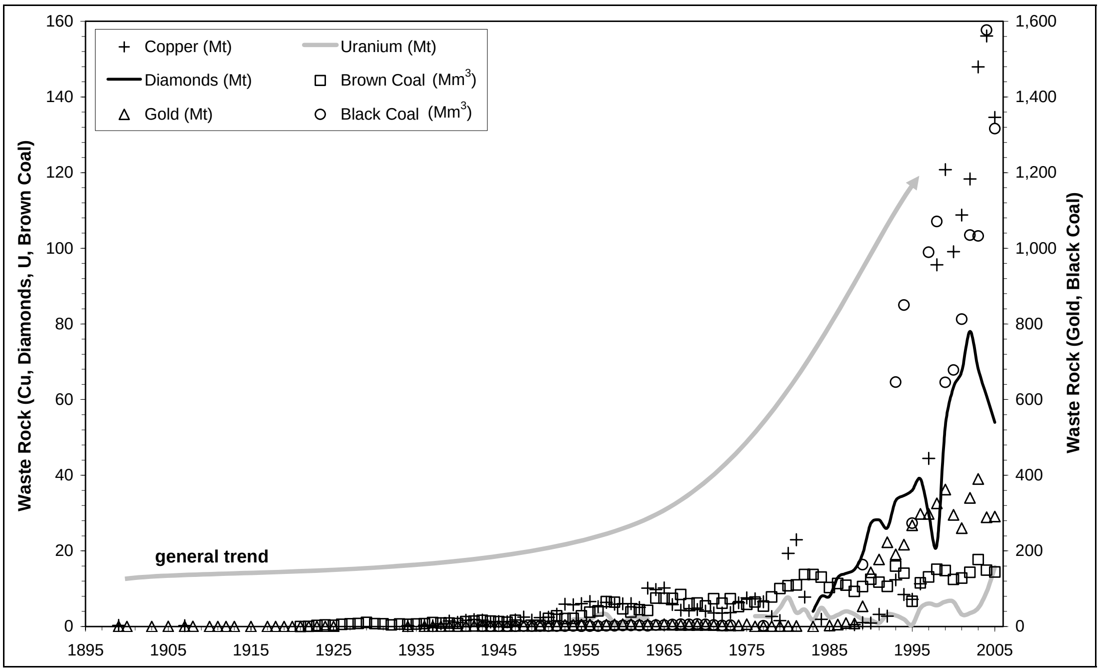

Figure 4. Historical trends in waste rock and overburden in Australia (Mudd, 2007d)

Further to the extent of open cut mining, the ratio of waste rock to ore mined is also critical. The available waste rock or overburden data relative to ore milled is shown in Figure 5. When combined with increasing production, for many commodities the ratio of waste rock (or overburden in coal mining) to ore is gradually increasing over time. This is particularly the case for copper, gold and black coal. The ratio for brown coal is approximately stable over time (due to the unique nature of the Latrobe Valley brown coal field). The data for diamonds shows the initial development of the Argyle open cut mine, with high ratios declining gradually over time, followed by the expansion and extension of the Argyle pit in the late 1990's (Argyle is now transitioning to an underground mine, with lower ratios to be expected in the future). For uranium, the high initial ratios show the development of the Rum Jungle project and the low quantity of ore processed in the early years, with the years after the late 1950's being variable depending on the select mines in development and operation.

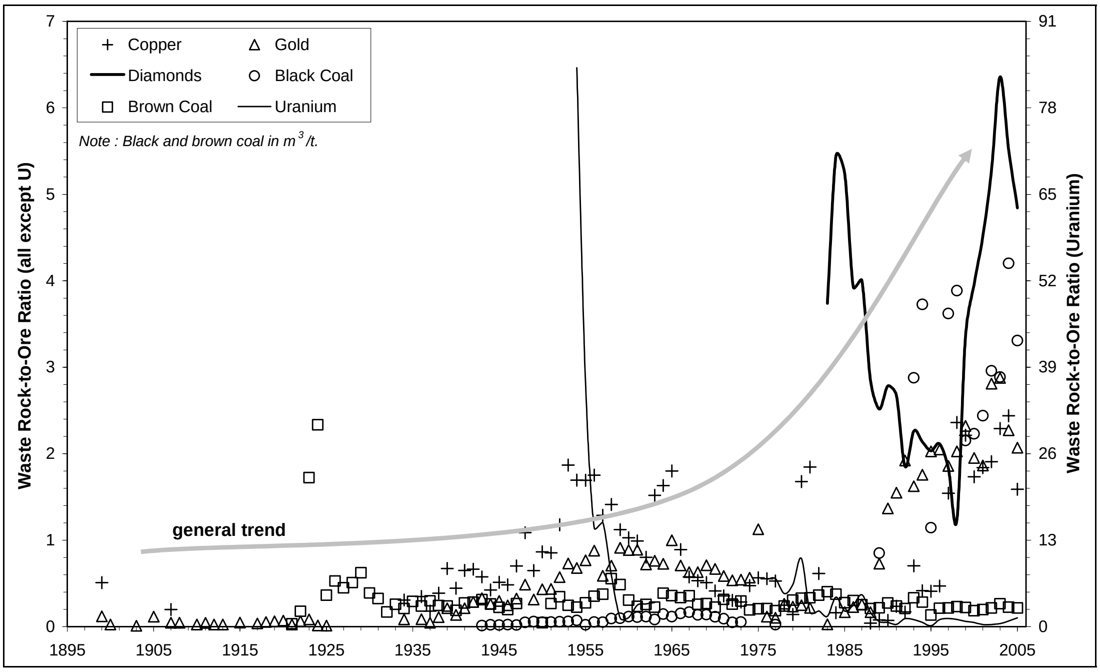

Figure 5. Historical trends in waste rock-to-ore ratios in Australia (data derived from Mudd, 2007d)

3.5 Mine Closure and Rehabilitation

A major sustainability aspect of the modern mining industry is the degree and extent of effort for rehabilitating and closing mine sites. In essence, this involves returning mined land to some type of functional purpose or land use, and ensuring that long-term potential pollution risks are minimised. The nature and extent of rehabilitation works are invariably site-specific, but commonly include placing engineered soil covers over tailings and waste rock deposits, possibly backfilling open cuts, sealing of underground mines, re-contouring for water resources, revegetation, ecosystem re-establishment, etc. There is a burgeoning literature on what constitutes 'sustainable' mine closure and rehabilitation, with the joint industry-government handbooks the most recent efforts (see Bell, 2006; Mulligan, 2006).

A major issue in mine closure and rehabilitation is the 'legacy' remaining. In effect, success should mean that there is no negative impact remaining, and ideally should move towards a positive residual legacy. This will, of course, be highly variable across numerous individual mines, but as an industry the net effect over space and time is cumulative. There is very little high quality data on the long-term success of rehabilitation works on formerly mined land, with evidence for both failure and success. In Queensland 73,586 ha has been disturbed by mining while only 20,313 ha had been rehabilitated by June 1997 (Anderson, 2002) – these numbers have increased substantially since. For Western Australia, it is estimated that a total of 165,040 ha has been disturbed by mining while only 36,952 ha has had preliminary rehabilitation to 2003 (Mudd, 2004). This gap is likely to be similar across Australia, let alone the question of the long-term success of engineered rehabilitation works. An example of an unsuccessful rehabilitation of waste rock is shown in Figure 6


Figure 6. Rehabilitation of waste rock, Rum Jungle, July 2007, ~25 years after rehabilitation : (left) White's waste rock dump and acid mine drainage, (right) adjacent East Finniss River during the dry season (no flow) showing the cumulative effects of acid mine drainage. *(photos – author)*

3.6 Economic Resources

The extent of available mineral resources is often a key issue raised in the debate on sustainable mining. The major factors which have allowed Australia to continually expand production over recent decades are that new resources have been discovered, better technology allowing exploitation of lower grade deposits has been developed (especially for gold), as well as the relatively cheap cost of energy to facilitate open cut mining. The economic resources for many minerals over time are shown in Figure 7. In addition, there are commonly similar amounts known in sub-economic or inferred mineral resource categories. In general, most economic mineral resources in Australia have grown either steadily (eg. lead) or experienced sudden increases (almost all, eg. iron ore, bauxite, nickel, gold) due to new provinces or mines being discovered or the advent of new technology (eg. carbon-in-pulp for gold and high pressure acid leaching for nickel). Based on data in Mudd (2007d), future production from most resources will not increase average ore grades or quality. For some minerals (eg. coal, iron ore), the true extent of economically (or technologically) recoverable resources remains open to conjecture, though some resources appear to have stabilised. An often implicit aspect of the future viability of much of these resources is the extent of open cut mining, tailings and waste rock involved – though this is rarely discussed in a strategic sustainability context as outlined in this paper.

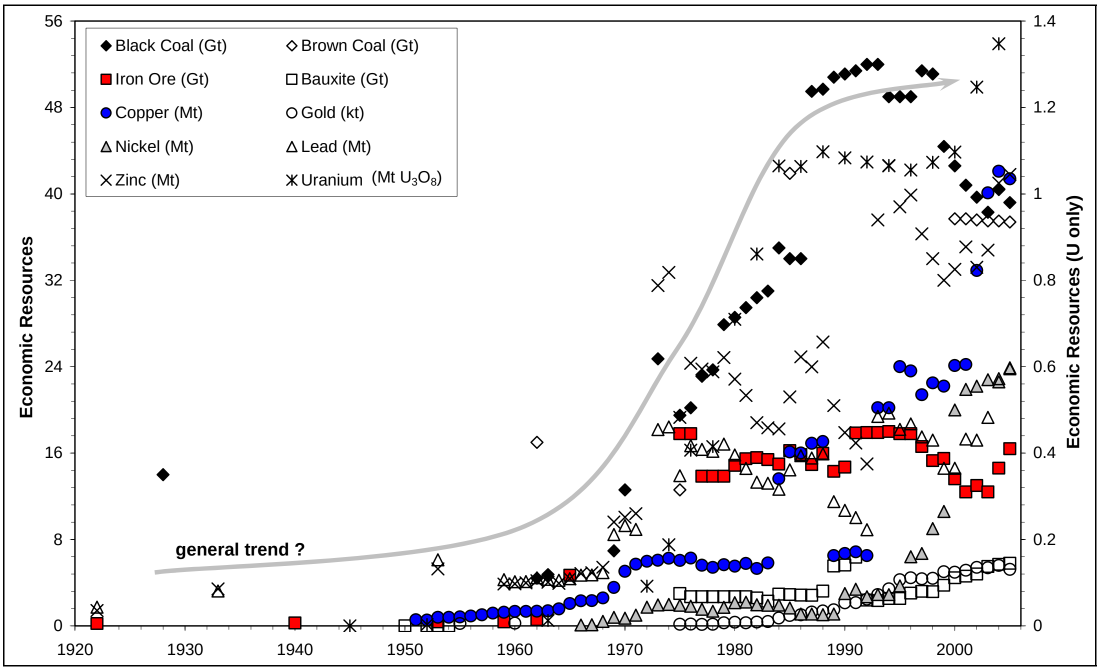

Figure 7. Historical trends in waste rock-to-ore ratios in Australia (data derived from Mudd, 2007d)

4 SUSTAINABILITY REPORTING AND MINE WASTE ISSUES

4.1 Sustainability Reporting

The global mining industry is moving to report on their sustainability performance alongside their financial performance. In the mid-1990's this was primarily led by a select number of large mining companies but is now being undertaken by numerous mining companies. As discussed previously, there has been an evolution from environmental management through to sustainability to now include social and economic aspects of mines and the industry.

To meet the growing need for sustainability reporting and to ensure greater consistency between companies and different industry and government sectors, the United Nations established the 'Global Reporting Initiative' (GRI) in 1997 together with government, civil society and industry bodies. Under the GRI, a broad range of data and information is now reported under specific categories of social, economic, environmental, human rights and societal indicators. Though voluntary, the GRI continues to be adopted more broadly across the mining industry, and is expected to grow rapidly in the future.

Separately to the GRI, many countries now have statutory pollutant release reporting requirements in place. In Australia this is the 'National Pollutant Inventory' (NPI, 2001) while in the USA is the 'Toxic Release Inventory' (TRI). Similar systems are also in some European countries, and they are intended to underpin 'State of the Environment' style assessment of the health of the environment.

Overall, these and other emerging reporting regimes allow the public disclosure of various relevant data for mining. This includes greenhouse emissions, other gaseous pollutants (eg. sulfur dioxide), particulates, water usage, impacts on water resources, energy sources and consumption, amount and nature of solid wastes (eg. hazardous, putrescible, etc), as well as wealth of labour, economic and social data. The sections below will focus on the solid waste issues associated with such protocols.

4.2 Global Reporting initiative (GRI)

Under the current third edition of the GRI Protocol (GRI, 2006) and the additional mining sector supplement (GRI, 2005), the primary indicator for solid mine wastes is 'EN22', which is the "total weight of waste by type and disposal method". It clearly includes wastes such as landfill (putrescible material), metal scraps, inert solids (eg. cement), construction waste, solid chemical wastes, used tyres, and the like. There is widespread inconsistency, however, in whether EN22 explicitly includes solid wastes such as tailings and waste rock. The mining sector supplement goes on to state that "large volume wastes" – tailings and waste rock – should be reported after a site-specific risk assessment (pp 29, GRI, 2005). Therefore some companies who use the GRI as their sustainability reporting basis do not publicly disclose tailings and waste rock data under EN22 while some companies give variable levels of information. Two examples of the solid waste reporting under EN22 are shown in Figure 8, and highlight the variable way in which data is reported. In both cases the data does not distinguish between tailings or waste rock – which are fundamentally different in terms of their scale and nature with respect to long-term environmental risks. Curiously, some companies report tailings and waste rock data as part of financial performance while others do not.

ENVIRONMENTAL	2005
Mineral Waste Management *(Includes destination of Tailings / Waste Rock) (Million Tons)*	
Inpit-Backfill	54.15
Underground	
Tailings Dam	
Sub-Sea	
Rock Dumps	12.58
Stockpiles	
Other (e.g., used as road base, construction material)	

	Units	2005	2004	2003	2002	2001
Overburden, tailings and slag	tonnes	**47,000,000**	17,000,000	42,000,000	49,000,000	25,000,000

Figure 8. Two examples of tailings and waste rock reporting under GRI's solid waste indicator (EN22)

4.3 National Pollutant Inventory (NPI)

In Australia, the NPI only considers those emissions of pollutants which are effectively released to the environment and defines waste rock and tailings facilities as land transfers only (pp 30-31, NPI, 2001) – leaving waste rock and tailings data outside the scope of reportable NPI emissions (though any escape from a waste rock or tailings facility would still be reportable to the NPI). This is a critical weakness in the NPI accounts, as both tailings and waste rock have the potential to become major point sources of listed pollutants such as cyanide and various metals (eg. Sb, As, B, Cd, Cr, Co, Cu, Pb, Mn, Hg, Ni, Se, Zn). A simple search of the facilities in the databases via the NPI website (www.npi.gov.au) reveals that some major sites of acid mine drainage (eg. Mt Lyell, Tasmania) are included in the facilities reporting under the NPI, while others are not (eg. Mt Morgan, Queensland). Given the vast quantities of mine wastes now produced annually in Australia, there would be a very substantive quantity of listed NPI pollutants contained within tailings and waste rock yet they are excluded from, or least poorly addressed by, such accounting and reporting systems.

4.4 Resource Intensity or Eco-Efficiency of Mineral Production

An emerging area of sustainability research in mining is the application of life cycle analyses, especially with a view to estimating resource intensity or eco-efficiency of metals and mineral products. The increasing GRI-based or NPI data being reported provides an opportunity to quantify these aspects more accurately than has been possible in the past. The combined tailings and waste rock data is given by metal / mineral in Table 1. As can be seen, there are major gaps in quantifying the solid waste burden for numerous metals, such as Al, Fe, Ni, Pb, Zn and Ag. For bulk commodities such as bauxite and iron ore, sporadic data for existing mines suggests that waste rock is at least equal to ore mined, with beneficiation of raw ore also producing some tailings though only saleable product is reported (eg. most bauxite and iron ore projects include a beneficiation plant).

Table 1. Solid waste burden for mining in Australia (2005)

Metal / Mineral	Production	Ore Grade	Open Cut (%ore)	Tailings	Waste Rock	Solid Waste Burden
Bauxite	59.96 Mt	*No data*	100%	*No data*	*No data*	*No data*
Black Coal	397.73 Mt	*No data*	~77.6%	*No data*	~1,850 Mm^3	>7 t/t coal§
Brown Coal	67.15 Mt	*No data*	100%	*No data*	~15 Mm^3	~0.36 t/t coal
Copper	918 kt	~1.15% Cu	%56.2	~80 Mt	>135 Mt	>235 t/t Cu
Diamonds	30.65 Mcarats	2.75 carats/t	100%	11.1 Mt	~55 Mt	~2.2 Mt/carat
Gold	263 t	~1.9 g/t	>45%	~140 Mt	>300 Mt	>1.67 Mt/t Au
Iron Ore	261.71 Mt	*No data*	100%	*No data*	*No data*	*No data*
Lead Zinc Silver	767 kt 1,367 kt 2,417 t	~4.64% Pb 8.26% Zn 135 g/t Ag	~30.7%	~18 Mt	*No data*	>8.5 t/t Pb+Zn
Nickel	189.3 kt	~1.2% Ni	~90%	~18 Mt	*No data*	>95 t/t Ni
Uranium	11,249 t U_3O_8	0.105% U_3O_8	~19%	~11 Mt	~15.7 Mt	~2,375 t/t U_3O_8

§ Based on a dry density for overburden of 1.6 t/m^3.

In addition to the solid waste burden, data reported under the GRI in particular allows the estimation of more accurate life cycle costs for metals and minerals, such as greenhouse emissions, energy, reagent and water consumption. A detailed analysis of these aspects for gold mines is given by Mudd (2007b, 2007c) and for uranium mines is given by Mudd and Diesendorf (2007), with further research in progress for copper and other metals. A summary of key data is provided in Table 2. As demonstrated by this research, the 'resource intensity' (or ecological footprint) of these metals is clearly sensitive to the ore grade being processed, which, when combined with the long-term decline in global ore grades, points to a fundamental sustainability challenge to the modern mining industry : the resource intensity looks set to increase gradually over time. Examples are shown in Figure 9.

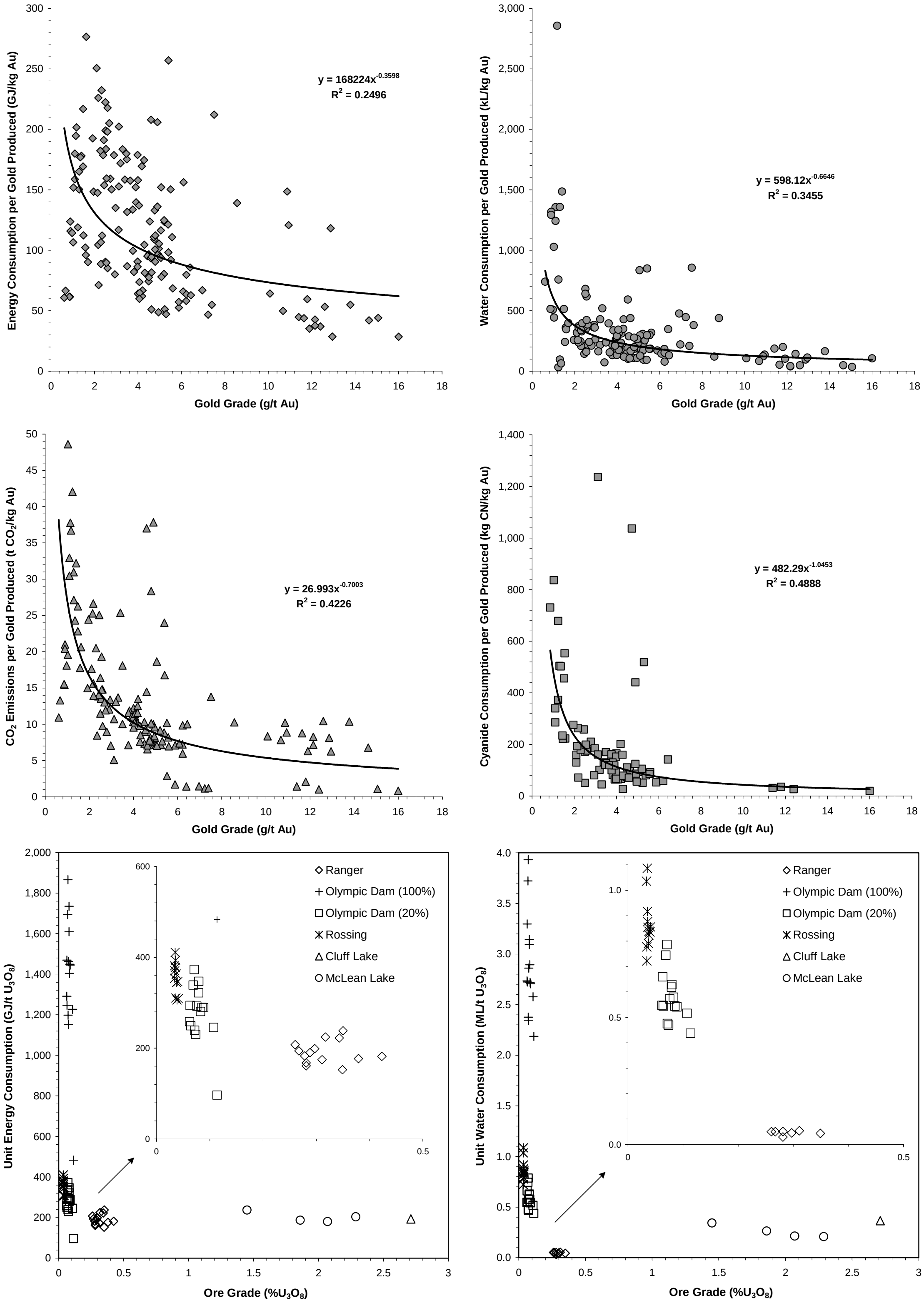

Figure 9. Resource intensity aspects of : (top and middle rows) gold mining in Australia (Mudd, 2007c); (bottom) global uranium mining (Mudd and Diesendorf, 2007)

Table 2. Sustainability and life-cycle costs for gold and uranium (global mines)

	Energy Consumption	Water Consumption	Greenhouse Emissions	Other
Gold	143 GJ/kg Au	691,000 L/kg Au	11.5 t $CO_{2\text{-}e}$/kg Au	141 kg cyanide/kg Au
Uranium†	222 GJ/t U_3O_8	414,000 L/t U_3O_8	27.4 t $CO_{2\text{-}e}$/t U_3O_8	-

† Based on weighted average of all mines.

5 CONCLUSION

Moving from a production philosophy through improved environmental management to now embracing the 'triple bottom line' of sustainability – social, economic and environmental components – the debate and the performance of the modern mining industry, both in Australia and globally, has clearly made important progress over recent decades. This paper has presented some ongoing research into quantifying various aspects of the sustainability of modern mining, especially the emerging sustainability reporting regimes becoming increasingly adopted by mining companies.

In terms of the major trends in modern mining, a number of fundamental aspects have been shown :

- **Exponentially increasing production** – almost all minerals and metals show strong growth over time, especially over the past three decades;
- **Declining ore grades (or quality)** – while early mines processed rich ores, average industry grades for most metals and minerals are now commonly lower, with known economic resources suggesting this decline in ore grades will continue. In addition, the quality (mineralogy) of mineral deposits are generally becoming more complex and difficult to process;
- **Open cut mining** – since the mid-twentieth there has been major shift in mining technique from underground to open cut mining, especially in some sectors such as coal, gold and nickel;
- **Waste rock / overburden** – combined with the increase in open cut mining, there has been an exponential increase in the waste rock or overburden excavated in modern mining. For most metals and minerals the quantity of waste rock / overburden excavated is significantly higher than the ore processed or product mined, and this ratio is increasing over time – presenting a major challenge in mine rehabilitation;
- **Mine rehabilitation** – the extent of mine rehabilitation still shows a major gap, mainly due to older legacy mines, though there remains concern over the long-term effectiveness of mine rehabilitation and closure approaches, especially as the scale of mine sites continues to grow;
- **Economic resources** – although often perceived as 'non-renewable', the extent of economic mineral and metal resources has often increased over time in Australia, though many appear to have stabilised. Growing production continues to exacerbate pressure on remaining resources;
- **Sustainability reporting** – the emergence of sustainability reporting protocols, such as the voluntary Global Reporting Initiative or the statutory National Pollutant Inventory, are helping to improve the transparency of modern mines, though there still remains clear reluctance to explicitly report all relevant data such as waste rock, tailings and other aspects;
- **Resource intensity** – the modern solid waste burden of metals and minerals is substantive, and continues to increase. Additionally, the resource intensity, in terms of inputs and outputs, is significant and very sensitive to ore grade, leading to the realisation that the resource intensity is likely to gradually increase in the future as mines shift to lower grade deposits. This makes more comprehensive sustainability reporting even more critical.

This paper has presented a range of data on the extent of solid wastes in the modern mining industry as well as various issues affecting the quantity and nature of tailings and solid wastes. Fundamentally, the vast scale of modern mine waste presents significant engineering challenges to meet an ever more complex array of environmental requirements, social expectations, corporate policies and statutory demands. The emerging sustainability reporting protocols will facilitate ongoing improvement and transparency, but consistency needs to be improved. Although we may be able to continue to find new mineral deposits in the near future, improve technology or favourable economics will facilitate the processing of higher cost resources, it is the environmental cost which will, in the medium to longer term, govern the real availability of metals and minerals. In summary, the vast scale of modern mine waste will continue to challenge the sustainability of the modern mining industry and requires eternal vigilance by all involved – regulators, shareholders, governments and communities.

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