Sustainable Mining : An Evaluation of Changing Ore Grades and Waste Volumes

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Abstract

The mining industry has, to varying degrees, been an important contributor to the economic wealth of nations all over the world. The first academic treatise to address the broader mining debate in society was 'De Re Metallica' by German philosopher Georgius Agricola in 1556, a text which remains as relevant today. The advances in technology over more recent centuries has enabled larger and lower grade orebodies to be mined compared to the previous century, a trend which has greatly accelerated over the last fifty years or so. The debate about the rate of extraction versus known resources remains a pivotal issue in moving modern industrial society towards sustainable development. The global mining industry, as a contribution to the 2002 Earth Summit, recently published the landmark 'Minerals Mining & Sustainable Development' (MMSD) reports to argue their case for 'sustainable mining'. The MMSD reports cover a wide range of issues, including social impacts, abandoned mine sites and facilities, conservation, economics, land use, technology and corporate governance, as well as the need to move towards a greater degree of recycling in many basic mineral commodities and metals. In general, most commodities have increased production over time, some dramatically. Given that, in general, the grades of the ore from which the minerals or metals are extracted are decreasing over time, with some metals more rapidly than others, this means that the quantities of wastes over time must be increasing considerably over time as production continues to intensify. The MMSD reports, however, do not present any data or systematic analysis on the changing ore grades of the major mineral commodities and metals produced in modern times or their associated waste volumes (principally tailings and waste rock or overburden). The balance between ore sourced from open cut versus underground mines is also important since open cut mines involve the excavation of a greater quantity of waste rock to access the ore of interest. This paper will analyse the principal mineral commodities produced in Australia, namely coal (black and brown), gold, iron ore, lead-zinc, diamonds, aluminium, uranium and nickel. The production data for these commodities over the last century in Australia will be presented, combined with the available data on ore grades and waste produced, followed by a discussion of the apparent trends in the various commodities and the implications for the concept of 'sustainable mining'.

1 Introduction

The debate about the social and environmental impacts of mining has a long history, captured by the German scholar Georgius Agricola in 1556 (Hoover & Hoover, 1950) :

> *"… the strongest argument of the detractors is that the fields are devastated by mining operations … Also they argue that the woods and groves are cut down, for there is need of an endless amount of wood for timbers, machines, and the smelting of metals. And when the woods and groves are felled, then are exterminated the beasts and birds, very many of which furnish a pleasant and agreeable food for man. Further, when the ores are washed, the water which has been used poisons the brooks and streams, and either destroys the fish or drives them away. Therefore the inhabitants of these regions, on account of the devastation of their fields, woods, groves, brooks and rivers, find great difficulty in procuring the necessaries of life … Thus it is said, it is clear to all that there is greater detriment from mining than the value of the metals which the mining produces." (pp 8)*

Overall, Agricola argued passionately that the overall benefits from mining far outweighed the localised impacts and that metal mining was a core part of the foundation of modern society. The debate in more recent times is still largely the same as outlined by Agricola – environmental and social impacts of mining as well as the use of metals for military purposes versus the economic and social benefits from metal mining and the broad-based need for metals in modern technology.

The past decade has seen an increasingly focused debate on the need to shift modern mining to a more sustainable footing. The approach to describing what is "sustainable mining" varies considerably, largely dependent on whether the view is from industry, government or community groups. This paper will examine the concept of "sustainable mining" as argued by various groups, followed by a detailed analysis and compilation of the history of metal mining in Australia over the last century or so. A discussion of the merits of different perspectives will then be presented, leading to some recommendations for improved reporting by the mining industry to allow a better understanding and quantification of "sustainable mining".

2 The Mining Cycle

The extraction of useful materials from the earth is an ancient practice that has evolved over the millennia to the present day where the scale is often considerable. While virtually all elements are now extracted and used to some degree, the major minerals or metals currently being mined include coal, iron ore, copper, gold, titanium, lead, zinc, silver, nickel, tin, uranium, manganese, phosphate, diamonds and aluminium.

In general, the principal methods of physically extracting minerals include alluvial, open cut, underground and solution mining. For example, heavy mineral sands generally use alluvial mining methods to obtain titanium concentrates, underground mining is often practiced for lead-zinc mining, potash or sulfur utilizes solution mining whereas many other commodities use a mix of open cut and underground mining. After the ore is mined, it is then milled and/or smelted by a variety of techniques to eventually produce a refined metal or product. The most important aspects include deposit size, ore grade and impurities, mining, milling and smelting techniques and the extent of rehabilitation following project completion. A typical cycle for a particular mine is exploration (discovery of the ore deposit), development, operation and followed by rehabilitation, as shown in Figure 1.

Figure 1 – Typical Mining Cycle

3 Defining Sustainable Mining

The definitions of sustainable mining vary widely, generally along the lines of whether an environmental, government or industry perspective is adopted. The concept of sustainable mining commonly focuses on two key questions – resource depletion/availability and environmental/social impacts.

The first major report to address these key issues was the Club of Rome report "The Limits to Growth" (Meadows *et al.*, 1972) (a contemporary response to Agricola). During the 1980s, the United Nations auspiced the World Commission on Environment and Development (WCED), culminating in the final report titled "Our Common Future" in 1987 (known as the Brundtland Report) (WCED, 1990). Following this, the Australian Government launched the "Ecologically Sustainable Development" working groups, including one dedicated to mining which reported in November 1991 (ESDWG, 1991). In preparing for 2002 Earth Summit, the mining industry globally launched the "Minerals Mining & Sustainable Development" (MMSD) process to argue their case for sustainable mining (IIED & WBCSD, 2002).

The Club of Rome report (Meadows *et al.*, 1972) argued from an environmental perspective that many mineral resources are being mined at unsustainable rates compared to known reserves, due mainly to population growth and economic development. It was acknowledged that this was dependent on technology, social and economic issues, but it was argued that the increasing use of mineral resources was a key factor in the increasing pollution burden of modern society. Modern mining was therefore most likely "unsustainable".

The Brundtland Report argued that the impacts of energy production were a key determinant of sustainability, due to the depletion of resources (eg. oil) as well as the biosphere's ability to absorb by-products such as greenhouse gases (pp 103) (WCED, 1990). The sustainability of other minerals was considered less problematic, due to relatively stable consumption at that time and the changing nature of technology and the use of recycling and substitution. The official Australian response to the Brundtland Report identified the key issues for mining were resource depletion/discovery, in situ (environmental) impact, land use for conservation versus mining, and the greenhouse effect (pp 41-44) (WCED, 1990).

The ESD Working Group argued that sustainable mining had to incorporate technological efficiency, greenhouse gas releases, land use planning, improved environmental management systems, co-ordination of decision making, better use of information through research, and public involvement, education and training (ESDWG, 1991).

The MMSD Final Report argued that there were nine key challenges for the global mining industry to address the move towards sustainability : (i) economic viability, (ii) land use planning, (iii) national economic development (eg. poverty reduction), (iv) social impacts, (v) environmental impacts and management, (vi) integrated approach to using minerals, (vii) information reporting, (viii) artisanal and small-scale mining, and (ix) mineral sector governance (IIED & WBCSD, 2002). Within this framework, many more specific issues were also identified, such as the large amount of waste rock produced by modern mining, acid mine drainage, and mining in protected areas (eg. national parks).

As can be seen, the concept of sustainable mining varies widely, but generally includes social, environmental and economic aspects. In general, the question of resource scarcity is not considered as urgent in the current debate though the issue of environmental/social impacts is certainly very prominent (Young, 1992). However, these issues are inextricably linked due to the increasing scale of modern mining which exploits lower grade but larger orebodies, often through sizeable open cut mines. The volume of wastes generated is now some orders of magnitude higher than a century ago, which in some extreme cases has led to severe impacts for long distances from mine sites. In order to predict the future sustainability of the mining industry, it is therefore critical to examine the trends of ore grades and the amount of materials mined for a given mineral production.

4 The Australian Mining Industry

4.1 Economic Value

The mining industry in Australia has always been closely associated with economic development and continues to be a prominent contributor to economic activity. Within the global context, Australia is a major mineral producer and exports numerous commodities around the world, a major source of income and revenue. For the 2000-01 financial year, approximately 53,000 people were employed in the Australian mining industry with a turnover of some $55 billion (ABARE, 2003).

4.2 Methodology

In order to assess the sustainability of Australian mining, a detailed compilation of the production history of mining and milling across all states in Australia has been undertaken, with a view towards establishing the extent of the changes in ore grades for various minerals and metals as well as quantifying the production of wastes (where possible). Some limited data on minesite rehabilitation has also been collected.

There are a number of periodic or regular reports published on the Australian mining industry. These include the “Annual Mineral Industry Review” by the former Bureau of Mineral Resources (BMR), various statistical publications, State Department of Mines reports, Annual Reports of agencies (eg. state) and mining companies, as well as the older series “The Mineral Industry : Its Statistics, Technology and Trade” on the global mining industry. For some specific minerals (eg. coal), industry associations and consultants also compile annual data over time. All sources are detailed under references at the end of this paper.

The extent of and quality data varies considerably across all of these publications, with gaps for some years inevitable. The reporting of data is not always consistent, such as mineral yield versus assayed ore grade, concentrate versus ore, plus inconsistencies between publications.

In general, the following rules were applied in assessing and compiling reported data :

- company data takes precedence over other sources;
- calendar year was adopted where possible, otherwise financial year data was applied in the year it was reported (eg. 1987/88 would be recorded in 1988; considered sufficient for overall trends);
- assayed ore grade was sought, with yield data corrected for recovery (where known);
- all data was converted to SI units (eg. tonnes and kilograms);
- alluvial mining has not been included (due to the difficulty of equivalence);
- where sources conflicted, the data considered closest to or most consistent with a company source was adopted (a minor degree of subjective judgement was required here).

The compilation of data is mostly finished but not yet complete. As such, the following results and discussion should be regarded as preliminary. This type of analysis is believed to be unique in Australia, indeed globally. A final report with full data is due soon.

4.3 Results : Australian Mineral Production

The production of prominent minerals and coal is shown in Figures 2 and 3, with the estimated total production by state given in Table 1. Mineral production is centred mainly within Western Australia, Queensland and New South Wales, with Tasmania, Victoria, South Australia and the Northern Territory mainly being important for particular minerals (eg. gold).

Table 1 – Total Australian Mineral Production by State

	VIC	NSW	QLD	TAS	SA	NT	WA	Aust	Period
Bauxite (Mt)	0.217	0.235	313.7	0	0	~163.5	»432[#]	~1,114	1927-2002
Black Coal (Mt)[§]	22.7	3,543	2,709	23.7	96.2	0	168.4	6,763	1829-2002
Brown Coal (Mt)[§]	1,793	-	-	-	-	-	-	1,793	1919-2002
Copper (kt)	17.2	1,874	6,581	1,552	2,026	364	576	15,675	1842-2002
Diamonds[*]	-	~0.3	-	-	-	~0.21	~628.7	~629.2	1867-2002
Gold (t)	2,359	706	1,242	163	38	439	5,330	10,190	1851-2002
Ilmenite (kt)	<0.5	»432[#]	»1,396[#]	0.56	1.04	<0.5	»25,816[#]	50,251	1934-2001
Iron Ore (Mt)	0.04	4.5	0.67	68.0	~220	6.88	3,482	4,002	1901-2002
Lead (kt)[#]	~53.6	»22,045[#]	»7,068[#]	»2,091[#]	~18.1	431.5	598.0	~35,532	1883-2002
Manganese (kt)	0.44	76.4	158.4	0.76	62.7	53,083	5,550	59,127	1946-2002
Nickel (kt)	0	0	327.4	0.6	0	0	~2,541	2,868.3	1967-2002
Rutile (kt)	<1	»4,041[#]	»2,895[#]	40	~2	<1	1,934	10,810	1934-2001
Silver (t)	55.0	30,389	13,336	3,321	30.1	174	573	71,950	1870-2002
Tin (kt)	13.7	180.5	175.0	385.8	<0.1	6.0	48.6	~810	1870-2002
Uranium (t)	0	0	8,893	0	31,543	84,349	0	124,805	1954-2002
Zircon (kt)	<0.5	»3,972[#]	»2,202[#]	39[†]	0.37	<0.5	8,869	16,368	1934-2001
Zinc (kt)[#]	~19.5	»20,790[#]	»6,432[#]	»4,758[#]	~371	1,441	2,219	~39,980	1883-2002

[*] Mcarats [#] Data incomplete. ~ Data approximate only. » Much greater than.
[§] Raw (not washed).

References & Data Sources : ABARE, BMR, DM's, mining company annual reports and/or supplied data, (Brown, 1908; Carne, 1908; Kalix *et al.*, 1966; Mudd, 2003).

4.4 Results : Changing Ore Grades and Waste Volumes

The results for the quantity of ore milled, ore grade, waste rock production and the proportion of ore derived from open cut mining over time for gold, copper, lead-zinc, nickel, diamonds and uranium, are shown in Figures 4 to 6. For most graphs, they represent 100% (or very close to this) of the ores mined and milled for that mineral or metal(s).

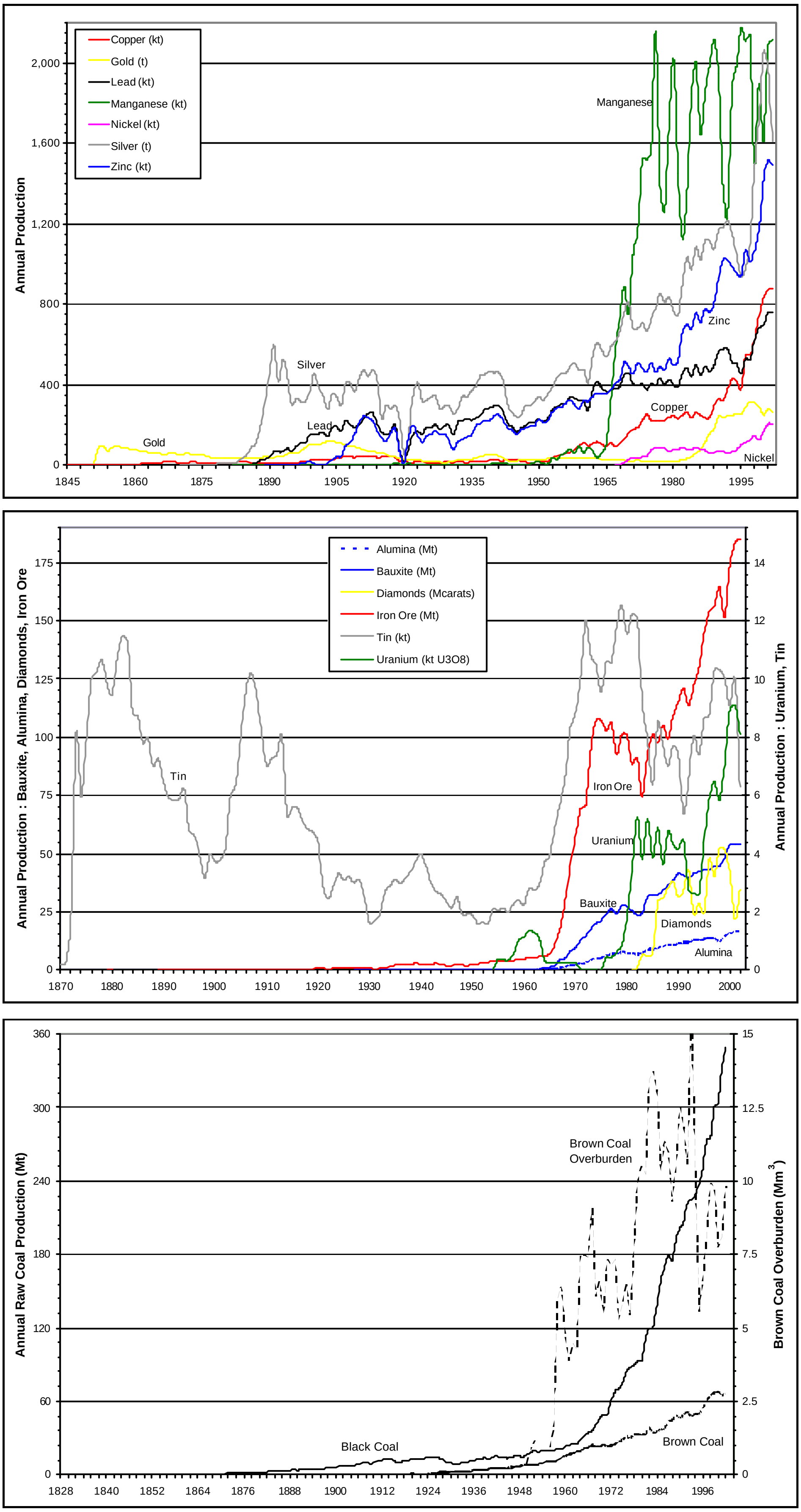

Figure 2 – Annual Mineral and Coal Production in Australia
(Note : Brown coal overburden includes all Loy Yang and Hazelwood data & Yallourn 1956-1992)

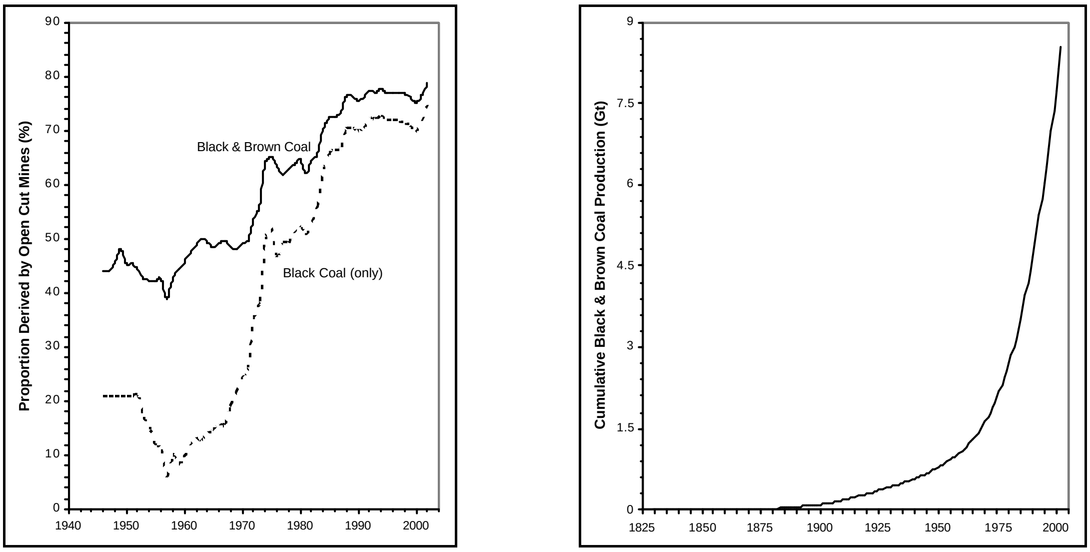

Figure 3 – Open Cut Coal Mining and Total Cumulative Coal Production

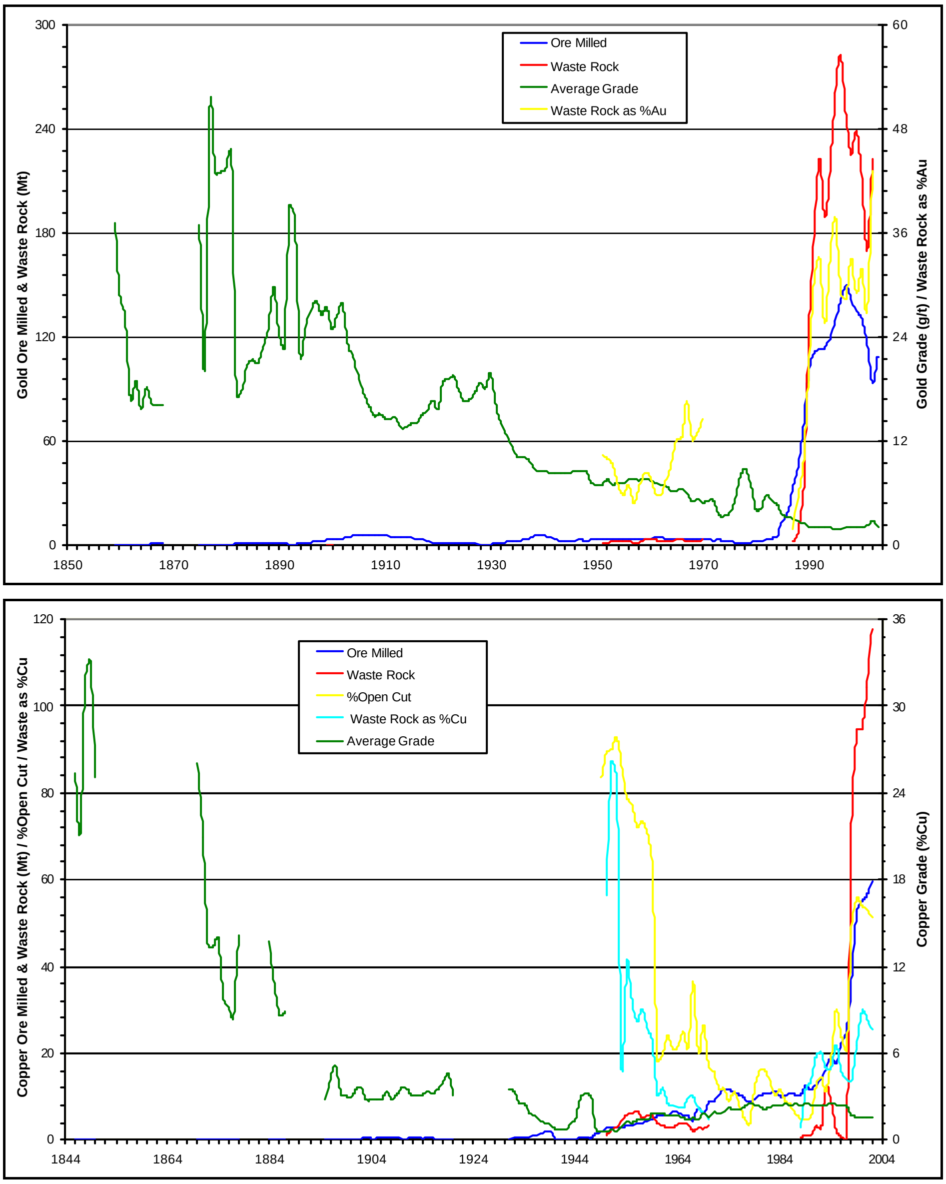

Figure 4 – Ore Milled, Ore Grades, Waste Rock and %Ore Open Cut : Gold and Copper

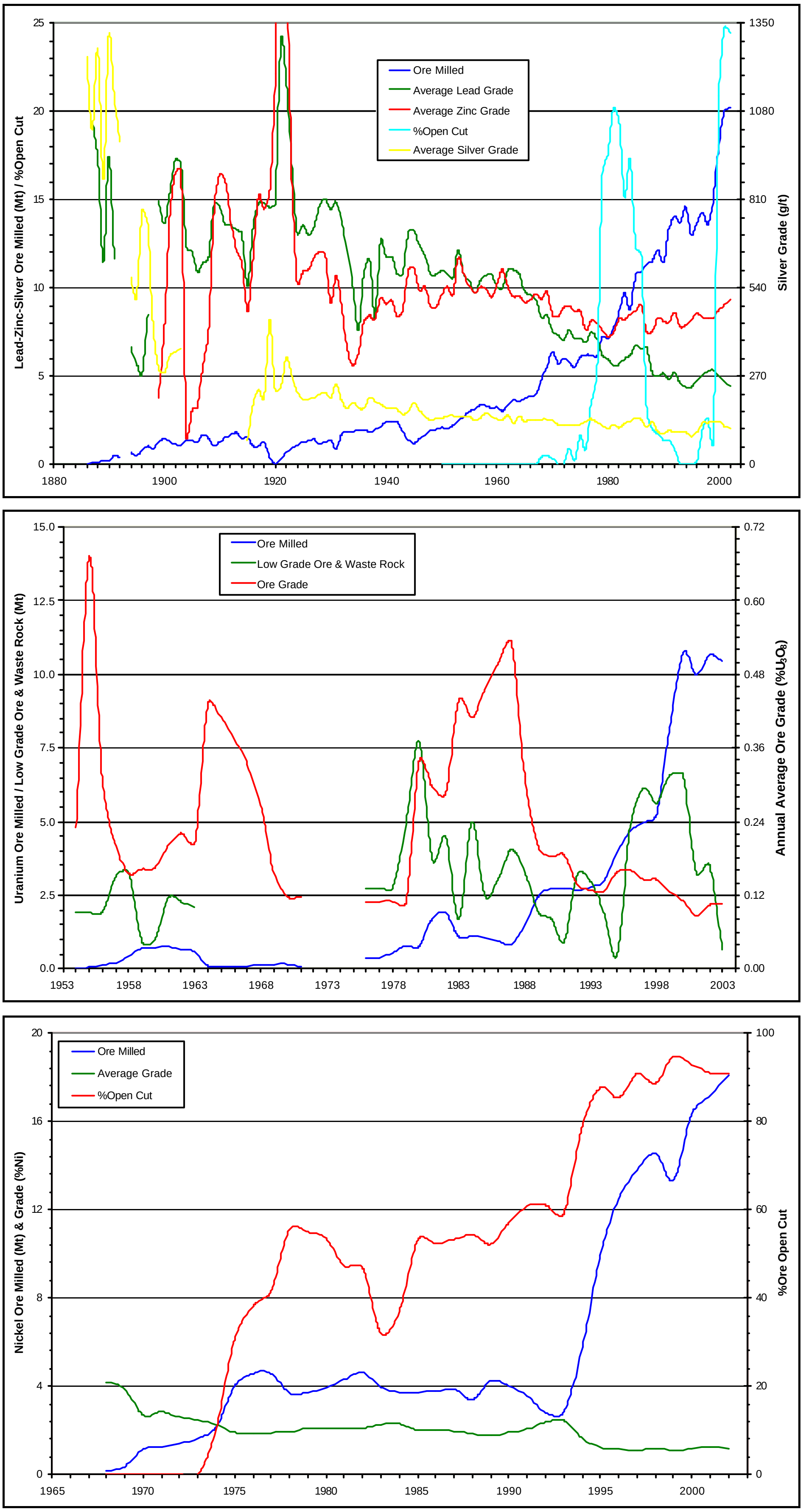

Figure 5 – Ore Milled, Ore Grade, Waste Rock and %Ore Open Cut : Lead-Zinc-Silver, Uranium and Nickel

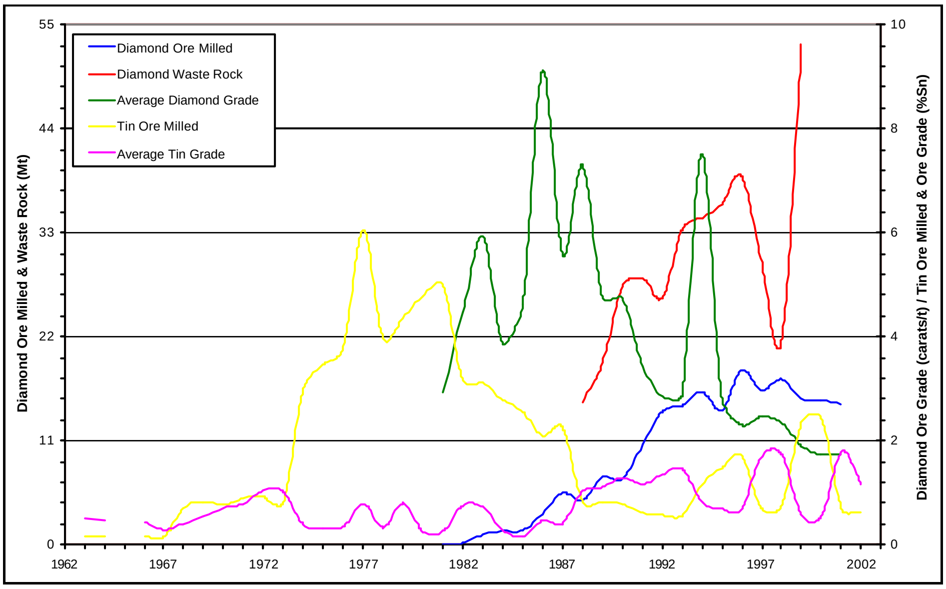

Figure 6 – Ore Milled, Ore Grade and Waste Rock : Diamonds and Tin
(Note : Although tin grade appears to increases, data for Greenbushes, WA, is incomplete)

4.5 Results : Cumulative Minesite Rehabilitation

As there is nationally compiled data on mineral production across Australia, there is now also the need to compile the appropriate data on the extent of rehabilitation of former and current mine sites as well as the long-term success of such efforts. At present, there is no standard approach for this aspect, with some states collating data while others do not appear to. The most recent data for Western Australia is given in Table 2.

Table 2 – Extent of Rehabilitation of Mine Sites in Western Australia

	2003 Annual (ha)			**Cumulative Total to 31 Dec 2003**		
Activity	Disturbed by Mining	Preliminary Rehabilitation	Revege-tation	Disturbed by Mining	Preliminary Rehabilitation	Revege-tation
Borefields & pipelines	9	4	6	1,930	415	85
Camp site	8	3	2	1,366	394	304
Exploration	57	15	6	4,980	1,513	836
Mine Infrastructure	395	182	166	51,171	5,263	4,037
Open Cuts	655	285	109	35,678	8,815	6,105
Tailings Dams/ Evaporation Dams	271	319	278	33,693	2,753	2,117
Waste Rock Dumps/ Heap Leach Piles	632	695	828	36,222	17,799	11,639
Total	**2,027**	**1,503**	**1,395**	**165,040**	**36,952**	**25,123**

Reference : Data Courtesy of WA Department of Industry & Resources (WADOIR)

Thus, in Western Australia, there is still a large tract of land that has yet to be rehabilitated. The actual areal extent of operating mines is not known, but as the data in Table 2 shows, the total area of impacts for mining is principally controlled by open cuts, tailings dams, water management dams, infrastructure, waste rock and ore/heap leach stockpiles. A similar pattern has been noted for Queensland (Anderson, 2002), and is likely to be a similar challenge in all states as well as globally.

5 Discussion : Is the Australian Mining Industry Sustainable ?

Overall, it can be seen that ore grades in Australia are gradually reducing, with some, such as gold, declining rapidly over the past century (tin being the exception). This general trend has also been noted for gold mining in the USA (Craig & Rimstidt, 1998) as well as internationally for many minerals (IIED & WBCSD, 2002). This has two major implications – firstly, it takes more ore for a given unit of mineral production, and secondly, to continually expand mineral production requires an even more significant increase in ore throughput. Clearly there has been exploration success in Australia in recent decades to allow this situation to develop, whereby almost all minerals have undergone major increases in production from progressively lower grade ores. Although it has not yet been possible to collate production versus known economic resources for given minerals in Australia, there does not appear to be much concern about potential mineral scarcity in the immediate future.

As noted in some graphs, there is a strong trend towards the use of open cut mines. For copper, the major mines of Mt Lyell and Mt Morgan led the introduction of large-scale open cut mines throughout the first fifty years of the twentieth century. As new mines such as Mt Isa began copper production, however, the trend shifted back to underground mining until recently with the startup of Nifty (WA), Cadia (NSW), and numerous mines in the Cloncluury-Mt Isa copper belt of Queensland. The extent of open cut mining has generally been minor in scale for lead-zinc mines until the recent startup of the Century Zinc project (QLD). The prominence of large-scale, low grade nickel mines such as Mt Keith and Murrin Murrin in WA has caused the shift from mostly underground to mostly open cut mining for nickel. Although percentage open cut mining for a commodity has been estimated based on ore, there would be only minor difference if the the proportion was calculated using the contained mineral. The immense scale of gold mining over the past 25 years has meant that it has not been possible to estimate the proportion of open cut mining for gold, though anecdotally it would be reasonable to expect a significant fraction (eg. half). The picture is further complicated for gold given that numerous mines operate both open cut and underground mines and do not distinguish the ore from each source during milling.

For most minerals, there is little or no waste rock data, with only a limited number of mines or companies publicly reporting the quantities produced each year in their annual corporate or environment reports. The waste rock shown for gold mining, which is more than the ore milled, only represents approximately 30-40% of the gold produced in the 1990's – much data is missing and not reported by the gold industry. Similarly, for copper, the waste rock data in the 1950's represented up to 80% of Australian copper production (ie. Mt Lyell and Mt Morgan), but in the 1990s it only represents 12-30% of copper production (including Cadia, Red Dome and Nifty) – that is, still not all operating mines.

A major issue associated with the scale of open cut mines and the waste rock they produce is acid mine drainage – oxidation of sulfidic minerals within waste rock (and/or tailings). Thus, as well as reporting the total quantities of solid wastes produced for a given mine site, is important to assess and report on this critical issue. The MMSD report (IIED & WBCSD, 2002) fails to articulate both the scale and seriousness of waste rock production in mining.

The trends shown by these numerous graphs are important in understanding the links between the environmental and social impacts of modern large scale mining and the resource base from which the minerals are produced. In Australia, the Fimiston 'Super Pit' open cut gold mine in Kalgoorlie (WA) was recently opened in 1989 and the substantive Cadia copper-gold

(NSW) and Century Zinc zinc-lead-silver (QLD) open cut mines were recently opened in the past decade. There is currently potential proposals for substantial open cut mines at Mt Isa copper (QLD), Olympic Dam copper-uranium-gold-silver (SA) as well as possibly at McArthur River lead-zinc-silver (NT). The exact future trend is uncertain but it is likely that open cut mining will continue to be a major feature of the Australia mining industry for the forseeable future.

As noted by (IIED & WBCSD, 2002), there is a trend for increasing mineral production from developing countries. The Australian trends are very evident in many of these large mines around the world – large, low grade deposits being mined through considerable open cuts (Young, 1992). Good examples include Escondida in Chile, Grasberg in West Papua, Ok Tedi in Papua New Guinea and Bingham Canyon in Utah, USA, among numerous others. At most if not all of these open cut mines, it is the management and rehabilitation of both waste rock as well as tailings which is proving to be a major economic and environmental burden. For sites such as Grasberg and Ok Tedi, the only economic solution to waste disposal is riverine disposal – a practice which has led to significant and wide-spread environmental impacts.

A major issue which has not been given its due weight in the current sustainable mining debate is that of long-term rehabilitation. The recent generation of mines in Australia is rarely less than fifty years old, often being half that. While most modern mines have been developed under stricter legislation to mitigate both short- and long-term environmental impacts, there is still a legacy of abandoned mines from earlier generations of mines when there were no effective legal requirements for rehabilitation. It is encouraging to see that many mining companies now report the area of land that they both disturb and rehabilitate each year in their environmental reports, as well as keeping cumulative respective totals.

The extrapolation of the long-term effectiveness of rehabilitation works is far from certain, however, despite the best engineering and science that can be bought to bear. If, in the long-term, there remains the gap between abandoned and rehabilitated land, the potential liability and scale of environmental problems could be sizeable. Considerable effort has been required to rehabilitate some former and/or abandoned mine sites, such as Captain's Flat (NSW), Brukunga (SA), Mt Lyell (TAS) and Rum Jungle (NT), and the fact that ongoing monitoring often identifies various problems raises legitimate concerns regarding any optimistic extrapolation of minesite rehabilitation performance over the long-term. Add to this the vast number and bigger scale of modern mines (due to open cut mining, tailings and waste rock), it can be demonstrated that significant uncertainty remains regarding the mining cycle and its long-term environmental sustainability.

6 Conclusions – Is the Australian Mining Industry Sustainable ?

To answer the question of whether the Australian mining industry is sustainable, it is necessary to first determine one's perspective. From a production perspective, the answer would clearly have to be yes, since new technology and bulk earth moving machinery have combined to make it profitable to exploit larger, lower grade ore deposits and yet still significantly increase production over time. From an environmental perspective, however, the answer is clearly uncertain and fraught with challenges. Can rehabilitation technology keep pace with scale of modern mining ? Will the increasing burden of waste rock and tailings per unit mineral production continue to hamper serious efforts at sustainability ? These are not easy questions to answer, but it is abundantly clear that the environmental burden of mining per unit mineral production is and will continue to increase for the forseeable future.

To properly position the mining industry to answer these strategic questions requires that all the requisite data be publicly reported on an annual basis and regularly collated and published by a state or federal department or another organisation. At present, a considerable amount of relevant data is not reported. Thus, to help assess "sustainable mining", all mining companies need to be reporting the quantity of ore milled, ore grades of all minerals extracted, the amount and nature of solid wastes produced such as waste rock and tailings (especially impurities and potential for acid mine drainage), all relevant environmental monitoring during operations and the extent and long-term success of rehabilitation works. Only over time with this data in hand can we begin to more accurately assess whether mining remains both economically, socially and environnmentally sustainable.

7 Acknowledgements

This paper is a based on a broader research project examining the sustainability of mining in Australia. There have been many people and agencies who have helped generously to date, including the Tasmanian, Western Australian, Northern Territory and New South Wales 'Department of Mines' (their respective equivalents); Techa & Alice from the Mineral Policy Institute; Daniel Keane; various Monash University Librarians; Barlow-Jonker Pty Ltd; numerous mining companies (though not all asked were helpful); Minmet Australia Pty Ltd, and many others. There are also innumerably more individual references upon which the broader research of this paper is based on. If people would like the raw data upon which the graphs are based, please feel free to request it or ask for more specific detail regarding references. This paper is of course the author's own views.

8 References & Data Sources

Primary Data Sources

ABARE	Australian Bureau of Agricultural & Resource Economics : • *Australian Commodities Statistics*. Published Yearly. • *Australian Mineral Statistics*. Published Quarterly (1988 to 2003).
BMR	Bureau of Mineral Resources, Geology & Geophysics (now Geoscience Aust.): • *Annual Mineral Industry Review*, Years 1948 to 1987.
ABS	Australian Bureau of Ststistics.
DM's	State Department of Mines (or equivalent) Annual Reports, reports and journals.
Others	Mining company Annual Reports; industry associations and consultants : • *Australian Aluminium Council.* • *Australian Gold Council.* • *Australian Coal Association*. • *Barlow-Jonker Pty Ltd.* • *Minmet Australia Pty Ltd.*
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