Gold mining in Australia: linking historical trends and environmental and resource sustainability

Gavin M. Mudd *

Institute for Sustainable Water Resources/Department of Civil Engineering, Monash University, Clayton, Vic. 3800, Australia

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ABSTRACT
The mining of gold has been and continues to be an important aspect of Australian industry. Gold mining moved quickly from fossicking and alluvial sources in the 1850’s to hard rock mining. This paper presents, arguably for the first time, a detailed historical compilation of Australian gold mining production data. This data is then analysed in the context of sustainability, focussing particularly on mineral resource sustainability and the broader aspects of environmental impacts now commonly reported by some mining companies in annual sustainability performance reports. The key trends which are demonstrated by the data include a long-term decline in ore grade, increased open cut mining, substantive increases in tailings and waste rock production, as well as showing the impact of new technologies and economics on available gold resources. The available environmental data on material and energy inputs to and pollutant emissions from gold production is also presented, showing a clear sensitivity to ore grade. In terms of sustainability, these relationships raise significant issues such as increasing greenhouse footprint per unit gold produced, potential impacts on energy and water consumption, as well as overall gold resource sustainability. The paper presents a unique case study of the resource and environmental sustainability of the Australian gold mining sector with major implications for sustainability policy and reporting.

1. Introduction

There is perhaps no other industrial endeavour that has had such a profound effect on Australia as gold (Au)—economically, socially, environmentally and politically. Although there had been several observations of the presence of gold in many parts of eastern Australia before 1850, the 1849 Californian gold rush created a sudden and intense interest in gold in Australia. In February 1851 near Bathurst, west of Sydney, gold was found in payable quantities: Australia’s golden age had begun. Prospecting greatly accelerated and gold was found in central Victoria by July 1851. By the end of 1851, the rush was in full swing and gold was flowing freely throughout the Victorian and New South Wales colonies. For many of the following decades, cycles of boom and bust have characterised the gold industry across Australia, involving wars, economics, mineral resource exhaustion/discoveries and new technologies. The most recent boom in gold mining since ~1980 has been facilitated by the sustained rise in the average gold price, large scale-low cost mining fleets and techniques plus the development of new cyanide milling technology (e.g. carbon-in-pulp or ‘CIP’) (Close, 2002). In the financial year 2005/2006 refined gold exports were valued at $7.12 billion (ABARE var.-a, 1995–2006), making it one of Australia’s top ranked export sectors.

The long-term trends in gold mining have received very little quantitative attention, although they are anecdotally recognised (e.g. Aswathanarayan, 2003; Ritchie, 2003). Understanding historical trends is critical in gaining insight into current challenges faced by the gold sector as well as predicting future challenges, some of which are already on
the horizon while others are emerging. For example, the need for deeper exploration, milling different ore types, solid waste management (tailings and waste rock), declining ore grades and environmental aspects such as energy, water and reagent consumption and pollutant emissions—issues which have often been faced in the past (e.g. Fahey, 2001; Hancock, 1993). State agencies have often compiled and reported standard production data (ore processed, gold yield), while environmental aspects have recently started to be reported by some companies. Thus, it is possible to compile the historical record of data to provide a substantive basis to analyse these critical issues and explore possible relationships between them to inform sustainability policy and reporting.

This paper presents the results of a detailed compilation of available gold mining statistics in the context of the resource and environmental sustainability of gold mining. As such, the data reported includes gold production (as t Au), ore milled (as t ore), ore grade (as g/t Au), hard rock mining technique by open cut or underground mining, waste rock (as t solid waste) and economic gold resources (as t Au) over time from the 1850’s. In addition, more recent data on environmental sustainability from 1991 is presented for energy consumption (GJ/t ore, GJ/kg Au), water consumption (kL/t ore, kL/kg Au), cyanide consumption (kg CN/kg Au) and pollutant emissions (kg CO₂/t ore, t CO₂/kg Au).

This is arguably the first such systematic compilation of all the above data, presenting a valuable case study of the resource and environmental sustainability of the gold mining sector in Australia, which has major policy implications relevant to all major gold mining companies and countries.

2. Methodology and approach

A detailed annual data set of individual states was compiled to calculate Australian totals for mining and milling of gold ores. In general, most states commonly reported gold mining data, often up to the early 1980’s (beyond this time reporting has left statistical and industry data to a separate review or to industry). Since this time a variety of sources have been used to compile state totals based on individual mines (mainly from company reports and/or industry periodicals). The waste rock, where available data permits, was compiled for both underground and open cut mining to facilitate comparison of the total solid wastes produced for a given metal production. A location map showing major mines/fields across Australia is given in Fig. 1. The references used for each state and all company sources for environmental data are given in Appendix 1 (Supplementary material) with compiled master data sets in Appendix 2 (Supplementary material).

Fig. 1 – Australian gold mines and deposits (approximate only, adapted from the online Australian Mines Atlas (GA et al., 2007).
calendar year was adopted (or calculated) where possible, otherwise financial year data was applied in the year it was reported (e.g. 1987/1988 would be recorded in 1988; considered sufficient for overall trends over timescales of decades);

- assayed ore grade was sought, with yield data corrected for recovery (if known). It is only in recent decades that true assay grades of gold ore have been reported, with most data up to the 1970’s based on yield only;

- co-product or by-product mines with significant production have been included.

The inclusion of co-product and by-product mines introduces a small degree of ‘double accounting’. This is a major issue when comparing the gold sector with other metal sectors or assessing the total ore throughput for the entire metals sector of the Australian mining industry. For analysing gold only, however, this ‘double accounting’ is not significant and is required to estimate the true extent of ore processed to produce the gold in a given year. Further to this, the gold ore grade of base metal mines is commonly within the normal range for gold-only mines.

The extent and quality of data vary considerably across publications while reporting of data is not always consistent, such as metal yield versus assayed ore grade, metal or concentrate versus ore. Discrepancies can exist for the same years between different publications. For much of the data from the 1800’s a key issue is that not all production was reported to State Mines’ Departments (despite repeated urging to do so for posterity). For other aspects, such as waste rock or the sourcing of ore from open cut or underground, there is commonly no reporting of data.

In order to assess the degree to which the data set represents gold production, calculated production is graphed as a percentage of reported production. The ‘calculated production’ is derived by the summation of all individual states’ production from the compiled data set. The reported production is the official annual production of gold (see Appendix 1). For each year a value greater than 80% suggests that the data presented effectively covers gold production for that year. Given the variable data sources, it is possible that the proportion of production could be greater than 100%. This could be due to a variety of factors, including errors in individual state production, rounding errors, financial versus calendar year and/or incorrect reported Australian production.

The extent of Australian economic gold resources is published by Geoscience Australia and includes data from 1975 to 2005 for most minerals (GA var., 2000–2005). Some pre-1975 resources data are available (see later section), however, it should be noted that the formal basis for reporting ore resources has changed considerably over time (e.g. the Joint Ore Reserves Code or ‘JORC’; AusIMM et al., 2004; Stephenson, 2001). Given the generally small number of major mines reporting resources prior to 1975, it is considered useful to compare the different data to assess the magnitude of changes in economic resources over this period.

The data for environmental aspects is presented as a whole to ensure a broad analysis of the gold mining sector. The aspects analysed include energy, water and cyanide consumption and carbon dioxide emissions. This is considered reasonable as there have been no major changes in technology or approach for gold mining and processing (despite differences between various sites such as heap leaching, different mill configurations, mixed mine sources and the like). All environmental data used is that reported by companies in annual public environment or sustainability reports (see Appendix 1). The environmental data for co-product or by-product mines has been excluded since these mines invariably have significantly different mill configurations (e.g. producing concentrates rather than bullion or doré). Since 1980, approximately 80–90% of gold in Australia has been produced by gold-only mines, showing that the resource intensity of these mines is representative. Although the amount of gold now being produced by base metal mines is gradually increasing and reached 49 t Au in 2005 (mostly Cu–Au mines), this is still only ~20% of total gold produced for that year. For each graph a statistical regression is shown and discussed with results.

Overall, there is only minor degree of uncertainty in the assembled data sets. For examining trends over a period of 150 years, this uncertainty is not significant as the overall trends show larger change than the uncertainty in the data (e.g. gold ore averaged >30 g/t in the mid-1800’s but is presently ~2 g/t). From 1890 onwards the compiled data generally represents more than 80% of gold production in Australia.

### 3. Results

The compiled data for gold are presented in various figures and summarised in tables (master data sets for production are given in Appendix 2, Supplementary material). Comments are made on each figure for clarity.

Australian gold production is shown in Fig. 2, including actual production and fraction by state. The relative dominance of Victoria in the mid-1800’s and Western Australia since the 1890’s is evident. The minor but important contributions from other states is also apparent. Total production by state is given in Table 1.

The average grade of Australian gold ore is shown in Fig. 3. As noted in the methodology, gold mining was invariably reported as the yield of gold from a tonnage of ore. No data is available prior to 1857, with only sparse data about until 1890 (due to the lack of full reporting to and by state mining agencies). The hard rock mining of gold from quartz and lode systems was also in its infancy in the 1850’s, with a considerable amount of the gold being produced from alluvial prospecting and fossicking—hard rock mining only began to dominate after 1860 (Fahey, 2001).

The quantity of ore milled and waste rock produced by mining is shown in Fig. 4. The impact of the Coolgardie-Kalgoorlie gold discoveries are notable, as well as the 1930’s gold resurgence. The most significant aspect is the boom in gold ore milling and waste rock production made possible by CIP technology, the gold price rise and associated exploration success to develop lower grade deposits on a large scale. It
must be noted that the waste rock since 1980 is a minimum only, as numerous companies do not report annual waste rock data with the same rigour as ore milled and gold production. The ratio of waste rock to ore varies considerably, both between mines, mine type (open cut/underground) and over the life of a mine. It is evident, based on the various mines developed over this most recent period that since about 1985 annual waste rock production has exceeded the amount of ore milled, and may now be several times the amount of ore milled.

Table 1 – Australian reported gold production by state (1851–2005) (t Au)

<table>
<thead>
<tr>
<th>State</th>
<th>Production (t Au)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Queensland</td>
<td>1315.6</td>
</tr>
<tr>
<td>New South Wales</td>
<td>791.0</td>
</tr>
<tr>
<td>Victoria</td>
<td>2371.4</td>
</tr>
<tr>
<td>Tasmania</td>
<td>191.2</td>
</tr>
<tr>
<td>South Australia</td>
<td>48.8</td>
</tr>
<tr>
<td>Western Australia</td>
<td>5856.4</td>
</tr>
<tr>
<td>Northern Territory</td>
<td>501.4</td>
</tr>
<tr>
<td>Australia</td>
<td>11,076 t Au</td>
</tr>
</tbody>
</table>

Fig. 2 – Australian gold production over time: actual and by state fraction.
The mining technique, either underground or open cut, is commonly not reported or clearly distinguished for gold mining. The data is further complicated by many recent gold mines or projects which obtain ore from several sites, including open cut and underground mines. For example, the Kalgoorlie West (Paddington-Kundana) and Kanowna Belle operations of Placer Dome (now Barrick Gold), sourced ore from more than 20 mines in 2003 (pp. 4) ([PDAP, 2003]). Based on a review of the various mines and for those mines that do report ore sourced from open cut and/or underground mines, the minimum gold produced by open cut mining is included in Fig. 4. The lack of unambiguous reporting since 1980 means that the proportion of gold produced from open cut mining is likely to be significantly higher than Fig. 4 suggests (prior to 1980 the only major gold-producing open cut mines were the Mt Lyell and Mt Morgan copper-gold mines, though some minor gold producers operated small open cuts for brief periods).

The extent of calculated versus reported production is shown in Fig. 5, including reported production, calculated production as well as the proportion of calculated versus reported production. The gradual rise in disclosure of production data is evident, with the proportion of gold production rising from <5% in 1860 to ~80% or higher from 1890 onwards. The remaining part of the missing data is made up by alluvial gold, including dredging (generally <5% of gold production).
produced), reprocessing tailings (not included in data sets) plus unreported production data. The data sets compiled, overall, represent the long-term production trends in the Australian gold industry agreeably.

The economic resources of gold in Australia and the world are shown in Fig. 6, graphed against Australian and world annual gold production as well as gold price data. The combined impact of the stronger gold price and new CIP

![Fig. 6 - Australian and world economic gold resources, and Australian and US gold price over time.](image)

<table>
<thead>
<tr>
<th>Table 2 - Compilation of Australian economic gold resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine/resource</td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>1 Olympic Dam</td>
</tr>
<tr>
<td>2 Telfer</td>
</tr>
<tr>
<td>3 Cadia East</td>
</tr>
<tr>
<td>4 Boddington Extended</td>
</tr>
<tr>
<td>5 Bendigo</td>
</tr>
<tr>
<td>6 SuperPit</td>
</tr>
<tr>
<td>7 Warrior/Charters Towers</td>
</tr>
<tr>
<td>8 Plutonic</td>
</tr>
<tr>
<td>9 Cadia Hill</td>
</tr>
<tr>
<td>10 Kalgoorlie West Field</td>
</tr>
<tr>
<td>11 Lake Cowal</td>
</tr>
<tr>
<td>12 South Kalgoorlie</td>
</tr>
<tr>
<td>13 Mt Magnet</td>
</tr>
<tr>
<td>14 St Ives</td>
</tr>
<tr>
<td>15 Gwalia/Leonora</td>
</tr>
<tr>
<td>16 Sunrise Dam</td>
</tr>
<tr>
<td>17 Ridgeway</td>
</tr>
<tr>
<td>18 Granny Smith</td>
</tr>
<tr>
<td>19 Tanami-Granites</td>
</tr>
<tr>
<td>20 Agnew</td>
</tr>
<tr>
<td>Sub-total</td>
</tr>
<tr>
<td>Total resources—base metals/polymetallic ores (5)</td>
</tr>
<tr>
<td>Total resources—copper–gold ores (14)</td>
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<td>Total resources—gold–copper ores (10)</td>
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<tr>
<td>Total resources—gold ores at operating mines (39)</td>
</tr>
<tr>
<td>Total resources—gold ores at deposits/prospects (131)</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Note: Resource data is based on JORC-reported total mineral resources. All information sourced from the most recent company reports, plus (GA et al., 2007; RIU var., 1978–2006). Most data is either June or December 2005, with some mines from 2004 or early 2006. The total number of mines for each ore category is in brackets.
The energy and water consumed by gold mining is presented in Figs. 8 and 9 in terms of unit gold production and unit ore processed, respectively. The correlation coefficients for unit energy consumption with respect to ore grade and ore throughput are 25.0% (power regression) and 30.8% (logarithmic regression), respectively; while for unit water consumption with respect to ore grade and ore throughput they are 34.6% (power regression) and 7.7%, respectively (logarithmic regression).

The consumption of cyanide in the milling of gold ores was, historically at least, not commonly reported. With the evolution of environmental/sustainability reporting by numerous gold companies, it is becoming more widely recognised as a key aspect to report in the performance of a gold mine (as well as a key financial operating cost). The available data for cyanide consumption per unit gold production is presented in Fig. 10 with respect to ore grade; the correlation coefficient is 48.9% (power regression).

In general, there appear to be no significant trends over time for all key resource intensity aspects analysed (energy, water and cyanide consumption and carbon dioxide emissions), and as such these graphs have not been included. The data is provided in Table 3.

The issue of climate change, and industry-derived greenhouse emissions such as carbon dioxide (CO$_2$), is becoming a critical issue to mining globally (e.g. IIED and WBCSD, 2002). The unit CO$_2$ emissions from gold mining are presented with respect to ore grade and annual ore throughput in Fig. 11; the correlation coefficients are 42.3% (power regression) and 11.6% (logarithmic regression), respectively.

4. Discussion

The issue of sustainability is a vexed and challenging concept for gold mining. There are two main themes considered in this paper—mineral resource sustainability and the environmental costs or resource intensity of extracting gold. In this regard,
a number of fundamental trends are evident in the historical and recent data compiled within this paper.

The first 40 years of gold mining was dominated by the central Victorian goldfields. By the late 1880's Queensland gold production had reached noteworthy levels of 15–20 t Au/year, but was quickly surpassed by the Coolgardie-Kalgoorlie discoveries of central Western Australia in the 1890's, from which time this region has dominated Australian gold production ever since. Annual Australian gold production peaked at 119 t Au in 1903, but began a gradual fall as both ore grades declined, costs increased and the gold price remained fixed—eventually forcing the closure of numerous gold mining regions. The short-term increase in the gold price of the 1930s gave hope for a sustained resurgence but this proved short-lived as the world plunged into war at the end of the decade.

The period from the early 1980s has seen a remarkable rise in gold production, with annual production passing the 1903 peak every year since 1988. Annual gold production over the past decade has ranged from 265 to 314 t Au. This most recent period, apart from the broad uptake of CIP milling technology and variants, is also notable for exploration success (driven by the sustained high gold price), new exploration techniques and the development of large scale-low cost mining fleets (Close, 2002; Huleatt and Jaques, 2005; La Brooy et al., 1994; O'Malley, 1988).

With respect to ore grade, Fig. 3, the earliest reported data during the mid-1800's demonstrates that the ores were relatively rich and often yielded more than 30 g of gold per tonne of ore treated. The true assay grade of this ore is not known, as only gold yield was reported. The remnant tailings from this early era were later re-processed and a further yield of several grams per tonne was often obtained by the application of extra grinding and/or amalgam (e.g. Smyth, 1869; VDM, 1870–2005). Following the breakthrough of cyanide-based gold extraction in the 1890’s, tailings were often then re-processed again to yield additional gold (tailings-derived gold production is not included in the master data sets for ore milled, gold production and ore grade/yield). It is not until the 1970’s that gold mines began to report true assay grade of their ore, allowing for true accounting of production, although some mines still only report yield. The true gold ore grade for Australia has therefore declined from the order of 40 g/t (or possibly higher, after accounting for tailings reprocessing) in the mid-1800’s to the current value of ~2.1 g/t (the average over the period 1991–2005). This compares to ore grades for Brazil of ~6.5 g/t in the early 1990’s (Machado and Figueiroa, 2001), to the USA where ore grades were ~1.2 g/t in the early 1990’s (Craig and Rimstidt, 1998) and South Africa with ore grades of ~5 g/t over 1995–2005 (CMSA, 2006).
The ore grade is also important in that it effectively determines the amount of tailings produced for a given gold production. The early approach to tailings management was often discharge to a local flat, floodplain, gully or stream, which has led to localised impacts and concerns over reagents (e.g. mercury) or impurities (e.g. arsenic) in many regions (especially central Victoria; Byrcroft et al., 1982; Churchill et al., 2004; Ellice et al., 2001). Sometimes tailings were deposited with a degree of effort to contain them for future reprocessing, though with variable success (see Smyth, 1869). In recent decades, tailings are now managed through engineered tailings dams, which present major economic costs for any new gold mine (Ritcey, 1989; Vick, 1990). Although various standards now exist for the design, operation, closure and rehabilitation of tailings dams at a state, national and international level, there have still been numerous failures of gold tailings dams internationally (Aswathanarayana, 2003; DITR, 2007a; Earthworks and Oxfam-America, 2004; Kumah, 2006; Lottermoser, 2003; Stenson, 2006; UNEP and ICOLD, 2001). Tailings can be a cause of major concern for local communities for a proposed, operating or even closed gold mine, and therefore require significant attention throughout the life-cycle of a gold mine (e.g. Cheney et al., 2001; Cooke, 2004; Earthworks and Oxfam-America, 2004; Logsdon et al., 1999; Mu¨ezzinog˘lu, 2003; Stenson, 2006). As ore grades continue to decline, increasing unit tailings volumes will place more pressure on tailings dams in the life-cycle costs of gold mining (Aswathanarayana, 2003; Azcue, 1999). It is therefore crucial that improved reporting of tailings management be included within the context of sustainability reporting.

The amount of ore milled, minimum extent of open cut-derived gold and associated waste rock also correlate very closely to the boom-bust cycle of gold mining (comparing

### Table 3 - Resource intensity of Australian gold mining over time

<table>
<thead>
<tr>
<th>Year</th>
<th>Water consumption kl/kg Au</th>
<th>Greenhouse gas emissions t CO$_2$/kg Au</th>
<th>Energy consumption GJ/kg Au</th>
<th>Cyanide consumption kg CN/kg Au</th>
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<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Standard deviation</td>
<td>No. mines</td>
<td>Average</td>
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<td>390</td>
<td>3</td>
<td>12.6</td>
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<td>1992</td>
<td>335</td>
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<td>1995</td>
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<td>2000</td>
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<td>2001</td>
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<td>2002</td>
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<td>2004</td>
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<td>2005</td>
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<th>Year</th>
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<th>Energy consumption GJ/t ore</th>
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</tbody>
</table>

The ore grade is also important in that it effectively determines the amount of tailings produced for a given gold production. The early approach to tailings management was often discharge to a local flat, floodplain, gully or stream, which has led to localised impacts and concerns over reagents (e.g. mercury) or impurities (e.g. arsenic) in many regions (especially central Victoria; Byrcroft et al., 1982; Churchill et al., 2004; Ellice et al., 2001). Sometimes tailings were deposited with a degree of effort to contain them for future reprocessing, though with variable success (see Smyth, 1869). In recent decades, tailings are now managed through engineered tailings dams, which present major economic costs for any new gold mine (Ritcey, 1989; Vick, 1990). Although various standards now exist for the design, operation, closure and rehabilitation of tailings dams at a state, national and international level, there have still been numerous failures of gold tailings dams internationally (Aswathanarayana, 2003; DITR, 2007a; Earthworks and Oxfam-America, 2004; Kumah, 2006; Lottermoser, 2003; Stenson, 2006; UNEP and ICOLD, 2001). Tailings can be a cause of major concern for local communities for a proposed, operating or even closed gold mine, and therefore require significant attention throughout the life-cycle of a gold mine (e.g. Cheney et al., 2001; Cooke, 2004; Earthworks and Oxfam-America, 2004; Logsdon et al., 1999; M¨uezzino˘glu, 2003; Stenson, 2006). As ore grades continue to decline, increasing unit tailings volumes will place more pressure on tailings dams in the life-cycle costs of gold mining (Aswathanarayana, 2003; Azcue, 1999). It is therefore crucial that improved reporting of tailings management be included within the context of sustainability reporting.

The amount of ore milled, minimum extent of open cut-derived gold and associated waste rock also correlate very closely to the boom-bust cycle of gold mining (comparing...
The period up until the early 1980’s was characterised by predominantly underground mining of good grade ore (i.e. ~5–20 g/t). Although there were some small open cut gold mines prior to this time, their contribution was very minor and were often short-lived. The sources of gold derived from open cut mining and the associated waste rock were almost entirely from Mt Lyell in Tasmania and Mt Morgan in Queensland—both large scale Cu–Au projects (see Mudd, 2007). From 1982, however, the modern gold boom has facilitated more wide-spread open cut mining for gold as well as the mining and processing of lower grade ores. This has allowed the mining and processing of entire lode systems rather than selective mining of the higher grade veins or portions of a mineral deposit. The introduction of ammonia–nitrate fuel oil (ANFO) explosives technology from the 1960s was also pivotal in facilitating the increasing scale of open cut mines due to its lower cost and safety advantages (O’Malley, 1988; Oliver, 1979).

A critical aspect of this recent boom in gold mining is that waste rock is significantly under-reported as a component of mining. The compiled data, Fig. 4, is a minimum only as numerous open cut gold mines do not report waste rock data (also including copper–gold mines). This is important since it is the waste rock at several historic mines which has been primarily responsible for long-term environmental impacts (DITR, 2007b; EA, 1997). For example, the historic Mt Morgan mine site has left a major legacy of pollution in the Dee River due to acid mine drainage (Sullivan et al., 2005; Unger and Laurencont, 2003). There are numerous other gold mines/major producers across Australia which have also left an environmental legacy of varying scales due to acid mine drainage issues. Waste rock is a major cost in open cut mining, and is becoming an increasingly significant cost during rehabilitation and post-closure risks due, in large part, to increasing attention and scrutiny of potential acid mine drainage issues.

On the basis of data compiled, the waste rock-to-ore ratio for an open cut mine can vary from a lower value of 2–23 (or higher), with typical values between 3 and 8 (see also Tyrwhitt et al., 1993). Waste rock data reported for underground mining is very uncommon, with waste:ore ratios most likely less than 0.3 (waste rock is typically kept underground). The extent of waste rock mined and its characteristics are clearly fundamental issues, especially the waste rock-acid mine drainage link, but this still remains under-recognised and reported on by the Australian gold mining sector. This represents a major area for improvement with respect to sustainability policy and reporting.

When the total amount of solid wastes are estimated based on 2 g/t ore, the production of 1 t Au creates approximately 500,000 t of tailings and at least 1,500,000 t of waste rock. If a gold grade of 1 g/t is assumed, these values become 1,000,000 t of tailings and at least 3,000,000 t of waste rock. When added to other inputs and pollutant emissions, it can be seen that gold is a highly resource intensive metal to extract.

The individual scale of gold mines varies substantially, ranging at present from relatively small ore throughputs of 0.2 Mt/year to very large throughputs greater than 10 Mt/year. In general, higher grade mines (>10 g/t) have a low annual throughput, but for lower grade mines (<2 g/t) the annual throughput is variable. A mine with a large annual ore throughput will invariably be processing lower grade ores.

The economic resources of gold has increased dramatically, almost exponentially (Fig. 6), since 1978 when resources were estimated at 154 t Au. As of December 2005, Australian economically demonstrated gold resources were 5225 t Au (2005 Edition) (GA, var.) (some 64% of this is considered to be JORC-standard). In addition, a further 1433 t Au of sub-economic and 4403 t Au of inferred resources are identified (2005 Edition) (GA, var.). The combined total of 11,061 Au is equal to the past 155 years of gold production in Australia. A significant proportion of these resources are contained in several world-class deposits/mines greater than 100 t Au (namely Telfer, Cadia, Kalgoorlie SuperPit, Boddington, Olympic Dam, etc.; see Table 2). Significantly, the grade of these...
deposits are generally lower than current gold mines, and are of the order of 0.5–2 g/t. The average grade of all resources in Table 2 is ~1.06 g/t (which represents 84% of reported Australian economic gold resources and sub-economic/inferred resources). The British estimated economic resources within the Commonwealth in 1955 (BCGLO, 1956), with the compiled data for Australia giving an estimated gold ore grade of about 2.65 g/t containing 209 t Au. For comparison, Woodall (1990) estimated reserves and indicated gold resources of 1644 t Au contained in 532.5 Mt of ore grading 3.09 g/t, with a further 389 t Au contained in base metal/polymetallic or by-product ore deposits (566 Mt at 0.69 g/t) (pp 66), for a total of 2033 t Au grading 1.85 g/t.

The Australian resource life or resources-to-production ratio for gold, Fig. 7, has been gradually increasing over the past 25 years. The early 1980’s saw a rapid increase in resource life, followed by a decline as production climbed, and increasing again as production stabilised and exploration continued to be successful in delineating new economic resources. Although this shows that the gold sector has been able to keep pace with rapidly rising production over this time, the future remains unclear as a range of issues combine to create some uncertainty. This includes the need for deeper exploration, new greenfields discoveries rather than brownfields expansions, increasing discovery costs, land use and access issues, fluctuating commodity prices and cycles, and the need for improved exploration technologies (e.g. Huleatt and Jaques, 2005; Jaques and Huleatt, 2002; Parry, 1998; Schodde, 2004). The resource life for gold in the USA was estimated from the mid-1980’s to mid-1990’s at a constant value of 18 by Craig and Rimstidt (1998), despite increasing production during this time. Globally, resource life had increased sharply by 1975 to 44 years, but has gradually declined as production grew, maintaining a steady range of 15–20 years since 1990. Global resource life is closely linked to economic gold resources in South Africa, which has shown significant drops in recent years due to mine closures and reassessments (USGS, 1996–2006).

The unit energy consumption in gold mining, Fig. 8, with respect to ore grade and ore throughput, highlights some key issues. Although some mines have shown a decline in energy costs over time due to savings and the implementation of efficiency measures, other mines have increased unit energy consumption (sometimes despite energy savings efforts). Over the past decade, it is therefore difficult to conclude that energy is being utilised more efficiently, as it will depend on a range of site-specific issues. For energy consumption relative to gold ore grade and annual ore throughput, inverse exponential patterns are apparent for both graphs. As ore grade and throughput decline, unit energy consumption increases, rising significantly as ore grade falls below 6 g/t or throughput falls below 5 Mt/year.

The energy cost of gold production ranges from 30 to 275 GJ/kg Au, with an average of 123 GJ/kg Au. In terms of ore processed, energy consumption ranges from 0.02 to 1.6 GJ/t ore with an average of 0.31 GJ/t ore. It is important to note that this is not a full life-cycle energy account, as this would also have to include the energy involved in mine and mill construction, all machinery, chemicals, water supply and the energy required for rehabilitation and ongoing monitoring and maintenance. At present only operational (direct) energy consumption is commonly reported (as new mines are developed there are opportunities to report important data on construction energy costs for gold mining, which is being done for some new gold mines internationally).

The unit consumption of water, Fig. 9, follows similar patterns to that of energy. As ore grades and throughputs decline unit water consumption increases. There remains some degree of scatter in water consumption as annual ore throughput declines, although this is most likely related to site-specific issues and the differing climates and water resources for various mines. It is clear that lower grade gold projects require more water per unit gold than higher grade projects. In general, lower ore grades are combined with higher throughputs but given this scale it may mean a significant need for total water. The quality of water resources for each gold mine has not been assessed, as this is commonly not reported in environmental data.

The water cost of gold production ranges from 35 to 2855 kL/kg Au, with an average of 325 kL/kg Au. In terms of ore processed, water consumption ranges from 0.1 to 5.4 kL/t ore with an average of 0.88 kL/t ore. Although this is not a full life-cycle water balance, it can be reasonably expected that the substantial majority of water is used during operations.

Recently, the concept of “virtual water” has been proposed to account for the water embodied in commodities such as agricultural crops (Allan, 1993; Hoekstra and Hung, 2005). The term ‘embodied water’ is more inline with the concept as applied to energy. With respect to metals, Norgate and Lovel (2006) used life-cycle assessment techniques to show that gold is the metal with the highest embodied water, calculating an average of 252.1 kL/kg Au while metals such as Cu, Ni, Pb, Zn, Al, Ti and steel were generally between 0.005 and 0.1 kL/kg metal (including different process routes). They assumed a cyanide-in-leach (CIL) plant and electrowinning/smelting plant processing gold ore grading 3.6 g/t and using 0.76 kL/t ore, with the high embodied water largely a function of gold’s very low ore grade relative to other metals (i.e. grams per tonne compared to percent). The concept of embodied water has received very little application to minerals to date (including gold), but the high embodied water of gold will mean that it will come under increasing scrutiny in the future as various sustainability indices become more widely adopted.

The use of cyanide in gold mining is becoming an increasingly sensitive issue (Logsdon et al., 1999; Muezzinoğlu, 2003; Stenson, 2006). Given this, plus perceived commercial considerations, it is perhaps understandable that not all companies report cyanide consumption. There is still a useful amount of data available, shown in Fig. 10. With respect to ore grade there is a significant increase in cyanide consumption per unit gold produced as grade falls below ~5 g/t. Although there is only a small number of data points below 2 g/t, they suggest a strong exponential increase in cyanide consumption below this value. While the degree of cyanide consumption is invariably related to ore mineralogy, grinding, process water quality, mill design, use of heap leaching and the like, Fig. 10 shows a very useful relationship in terms of the gold sector as a whole.

The emission of greenhouse gases, principally carbon dioxide, is a major global challenge (IPCC, 2007). It is important...
to assess the emissions of carbon dioxide from gold mining (Fig. 11), especially with respect to issues such as declining ore grades, as the extent of future emissions from the gold sector will come under increasing scrutiny (e.g. Ranford et al., 1998). There is some evidence that unit emissions are increasing over time; some mines demonstrate minor savings while others show increases, including major sudden increases (often left unexplained in sustainability reports). For unit carbon dioxide emissions per gold produced with respect to ore grade there is a clear inverse exponential relationship evident, with an inflection point at ~4 g/t. Below this grade, unit emissions increase rapidly as ore grade declines. With respect to ore throughput, an inverse exponential relationship is evident though it is generally only small tonnage mines below 1 Mt/year which have relatively high unit carbon dioxide emissions per tonne of ore processed.

Given the statistically small number of gold mines reporting environmental data in a given year (generally ranging from 3 to 18), no time series trends of these aspects for the sector as a whole is considered realistic since the individual mines generally represent a small number of years. However, for the purposes of illustrating the relationships between ore grade, ore throughput and resource intensity, the compiled data represents the broad aspects of the gold industry in Australia very well; despite the numerous differences between mine sites.

The relationships for energy, water and cyanide consumption as well as carbon dioxide emissions are particularly significant as future projects are likely to be lower grade and large tonnage projects (e.g. Boddington Expansion). Therefore, the environmental costs of gold production, in terms of these particular resource aspects, would appear to be likely to progressively increase in the near future as grades continue to gradually decline. There is already some evidence to suggest this trend in Australia, as greenhouse emissions from the industrial processes sector (which includes mining) have risen from 28.0 Mt CO₂ equivalent in 1990 to 32.3 Mt CO₂ equivalent in 2003 (AGO, 2005), with a similar magnitude in increases for this sector noted for Western Australia by EPAWA (2006). No data is known to specifically assess the gold sector within national and state greenhouse emissions inventory assessments. Although the increase in greenhouse emissions also corresponds to expansion of the mining industry over this time, there is no data at present to discern changes over time in unit emissions for various sectors of the mining industry (e.g. iron ore, copper, lead–zinc–silver, gold).

The data presented and analysed herein raises a number of issues with respect to sustainability reporting. In recent years a number of relevant environmental and sustainability reporting protocols have been developed. They include the Australian statutory ‘National Pollutant Inventory’ (NPI) (NPI, 2001), the more corporate-style ‘Global Reporting Initiative’ (GRI) (GRI, 2006), including the GRI Mining Sector Supplement (GRI, 2005), as well as the ‘International Cyanide Management Code’ (ICM) (ICM, 2002) specifically relevant to gold mining.

Firstly, most protocols are voluntary to adopt (except for the NPI), thereby allowing some companies to choose not to follow them (though this is less likely in the future as uptake of the GRI increases, for example). Secondly, the protocols do not require consistent and compulsory reporting of key aspects such as waste rock, cyanide, water quality and quantity, and the like (and reporting omissions are often left unjustified by companies). For example, GRI leaves the proportion of recycled water (EN10) as an ‘additional’ indicator and not ‘core’ for reporting purposes. While the reporting of wastes by type and destination (EN22) is core, and is supposed to include hazardous and non-hazardous wastes, some mining companies who use the GRI still do not report waste rock under EN22. The additional GRI Mining Sector Supplement (GRI, 2005) proposes wastes under EN22 as “site waste, e.g. waste oils, spent cell lining, office, canteen and camp waste, scrap steel, tyres and construction waste” (pp. 27), and further discusses the need to report “large volume wastes” – waste rock and tailings – as a function of a site risk assessment (pp. 29). Thirdly, many industrialised countries either have or are developing systems such as the Australian National Pollutant Inventory to facilitate more accurate assessment of pollutant/contaminant loads being released to the environment, especially with respect to ‘State of the Environment’ style reporting. 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; leaving waste rock and tailings data outside the scope of reportable NPI emissions (though any escape from waste rock or tailings facilities would be reportable to the NPI). As a bare minimum the quantity of waste rock and tailings should be a core reporting indicator by GRI, NPI and others (for combined financial, environmental and social reasons), with further details noting the nature of the wastes; especially with respect to leaching and/or acid mine drainage issues. The recent cyanide code (ICM) does not require public reporting of cyanide consumption even though a gold mine could be certified for its cyanide management regime. The NPI collates and reports on total cyanide emissions but it specifically does not report nor allow data to be analysed on an individual site basis (since emissions are not the same as reagent consumption in gold ore processing). The common lack of waste rock, tailings and cyanide reporting does not facilitate accurate sustainability assessment nor allow claims to be tested.

Finally, the various codes and protocols, especially the GRI, are still very new and have not been in use long enough as yet to allow industry to adopt them widely and report more consistently across various companies and mines. Given the deficiencies identified above, there remains room for major improvement with respect to mining generally, as well as gold mining specifically. With more comprehensive reporting it may be possible to improve the correlations between aspects such as energy, water and cyanide consumption, greenhouse emissions and production variables such as mine type, ore grade and ore throughput.

At present there is significant research effort being devoted into trying to develop breakthrough technologies for mineral processing that are less resource intensive. For example, the primary mission for the recently established Australian Cooperative Research Centre for Sustainable Resource Processing is “to progressively eliminate waste and emissions in the minerals cycle” (CSRP, 2005). It is extremely difficult to conceive of a gold mining project which ‘eliminates’ tailings and waste rock from its production process; though the objective is indeed noble. Historically, a range of new
technologies have facilitated gold mining and production, with the recent gold boom strong evidence for this (e.g. Close, 2002; La Brooy et al., 1994; O’Malley, 1988; Prasad et al., 1994). Whether new technologies can be developed which achieve the aim of lower resource intensity in the context of the progressively lower grade resources being mined is a vexed issue and ultimately beyond prediction; it is certainly a major technological, economic and sustainability challenge.

5. Conclusion

The historical and current data compiled and analysed in this paper presents a unique case study on the environmental and resource sustainability of the Australian gold mining sector. The future of gold mining is difficult to predict; hence the importance of analysing in detail and linking both historical and contemporary data. Overall, the data sets presented point to the following conclusions:

• ore grades will continue to decline, albeit at a gradually decreasing rate;
• economic resources continue to be found, though numerous issues will continue to influence future discovery;
• solid waste burden (waste rock plus tailings) will continue to increase, especially as open cut mining continues to expand; yet waste rock movement and tailings management are significantly under-reported at present;
• there is still no consistency for the complete reporting of mine-mill production and environmental/sustainability data, though protocols such as GRI and NPI may lead to improvements in the future if they are modified and enhanced;
• the resource intensity of gold production appears to follow defined inverse-exponential relationships; as ore grade or annual ore throughput decline the unit consumption or unit CO₂ emission rate goes up, sometimes significantly.

The industry has faced adversity at several periods in the past and sustained itself, taking full advantage of market conditions and technological advances as they have occurred. The industry has for the past 4 years averaged a resource life of 20 years; historically the highest ratio of resources to production. Future production will ensure that ore grades continue to decline, albeit at a more gradual rate than in the past. Given the sensitivity of environmental costs or resource intensity to ore grade, this will lead to significant pressure on the environmental performance of gold mining in a broad sustainability context; especially due to resource consumption, pollutant emissions and the legacy of increasing volumes of tailings and waste rock. The gold mining sector in Australia could well be argued as sustainable from a mineral resource basis; however, the escalating environmental costs are likely to increasingly dominate sustainability assessments in the future. For society to make an informed choice and policy judgement on the sustainability of gold mining, it is vital that reporting continue to improve in breadth, depth and transparency. References cited in Supplementary Material (Appendices). The sustainability of the gold mining industry therefore, as with many times in the past, continues to hang in the balance.

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Appendices. Supplementary data


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Gavin M. Mudd has been an active researcher and advocate on the environmental impacts and management of mining for over a decade. He has been involved with many aspects of the industry with a particular specialty in brown coal wastes, uranium mining, groundwater and environmental management. Dr. Mudd maintains an independent perspective, and has undertaken research for mining companies, community groups and indigenous organisations. He has written extensively on the multi-disciplinary nature of the environmental aspects of mining in Australia and globally, developing a distinctive view on the apparent oxymoron of “sustainable mining.”