An analysis of historic production trends in Australian base metal mining

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Abstract

The base metal mining sector, including copper, lead–zinc–silver and nickel, has been a prominent and critical feature of the Australian minerals industry. The various mines and fields have been producers of world significance, including Broken Hill, Mt Isa, Mt Lyell, Olympic Dam, Cobar and Kambalda. The long-term production trends in the base metal sector governing these historic fields remain relatively undocumented. This includes trends in ore grades, mining technique (open cut versus underground), solid wastes produced (tailings and waste rock), technology (e.g., milling) and known economic resources. This paper presents these results for the Australian base metals sector — arguably the first such systematic compilation undertaken. A historical overview is discussed for each major commodity to outline the principal developments and changes for that commodity, followed by the presentation of mining and milling trends. Overall, the key trends are declining ore grades versus increasing metal production and ore milled, and increased open cut mining and associated waste rock (though this latter aspect remains significantly under-reported). The extent of known economic resources has steadily increased for all commodities analysed, principally due to the inclusion of lower grade ores and/or difficult to treat ores (such as nickel laterites) or new deposit discoveries. Based on present mine plans and proposals, future metal production will increasingly shift towards lower ore grades and larger open cut mines to maintain production levels. There are sufficient known economic resources for about three decades or more, providing a basis to sustain the existing base metal industry but beyond this timeframe is difficult to predict. These trends point to the need to accurately report complete data on base metal mining and milling as key inputs into quantifying mineral resource trends as well as the environmental aspects of “sustainable mining”.

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1. Introduction

The history of base metal mining in Australia is indeed extensive and the industry would appear to be well positioned for the future. Many such mineral fields are well known in Australian history — including Moonta–Wallaroo, Mt Lyell, Broken Hill, Mt Isa, Cobar, Rosebery, among many others. The continuing and steady growth in the mining and milling of base metal ores in Australia, however, is less well known.

In order to better predict future trends in the Australian mining industry (a discipline now termed “sustainable mining”), it is important to analyse the available historical record. Historical trends can be used for a variety of purposes — research to highlight the effect of significant mineral discoveries (or their depletion), social impacts (e.g., strikes, wars), the advent of
new techniques and technologies, or economic analyses. The extent to which data exist as well as its relative availability (ignoring the effort required to synthesize such a large data set) is quite surprising.

This paper presents the results of such a study on the history of base metal ore mining and metal production in Australia, namely copper (Cu), lead–zinc–silver (Pb–Zn–Ag) and nickel (Ni). The structure includes a review of the survey methodology adopted, together with principal references used, followed by a section for each principal base metal ore, namely Cu, Pb–Zn–Ag and finally Ni. An historical account of events for each sector is included to discern the principal effects that can be identified in the presented data sets and graphs. This historical annotation is not intended to be a thorough economic, scientific or engineering analysis of that sector — it is purely intended as a guide to the compiled data sets and graphs.

This paper presents, arguably for the first time, the best available data sets for Australian totals of the quantities of ore milled, average ore grades, metal production, the extent of open cut and underground mining, waste rock (overburden) produced, as well as known economic resources over time. These trends should prove a valuable basis for further historical insight of the present and possible future scale of the minerals industry in Australia, especially concerning the key issues of mineral resource and environmental sustainability.

2. Methodology

A detailed annual data set of individual mines was compiled to calculate Australian totals for mining and milling of Cu, Pb–Zn–Ag and Ni ores. All sourced data have been compiled and converted to metric units — namely ore mined, ore grades, metal production, mining technique (open cut or underground mining), waste rock (overburden) and known economic resources. 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. All references used for individual mines/fields are detailed in the Appendix. A location map showing major mines/fields across Australia is given in Fig. 1.

There are a number of historical periodic or regular reports published with data on the Australian mining industry. These include:

- Annual Mineral Industry Review (Years 1948–1987) by the (former) Bureau of Mineral Resources (BMR) (now Geoscience Australia) (BMR, various years);
- Australian Commodity Statistics (Years 1995–2005) by Australian Bureau of Agricultural and Resource Economics (ABARE) (ABARE, various years-a,b);
- mining industry statistical periodicals — Jobson’s Mining Year Book (Years 1957–2004) (Riddell, various years), Register of Australian Mining (Years 1980–2004) (RIU, various years), and Australian Mines Handbook (Years 1976–2004) (LP and Minmet, various years);
- State Department of Mines (their current equivalents) — annual reports, industry statistical reviews, research reports, geological bulletins and the like (e.g., Andrews, 1911a; NSWDM, various years; WADoIR, various years);
- The Mineral Industry: Its Statistics, Technology and Trade (Years 1892–1940) published by McGraw Hill (Anonymous, various years);
- BMR’s Australian Mineral Industry Production and Trade, 1842–1964 (Kalix et al., 1966);
- numerous mining company annual and quarterly reports and/or supplied data;
- numerous mining profession and scientific monographs and publications, covering mining, metallurgy, geology, engineering or history (e.g., Dunkin, 1953; Hooper and Black, 1953; Knight, 1975; Woodcock, 1980; Hughes, 1990; Woodcock and Hamilton, 1993; Berkman and Mackenzie, 1998).

The following rules were applied in compiling and assessing 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 (e.g., 1987/1988 would be recorded in 1988; considered sufficient for overall trends over time-scales of decades);
- assayed ore grade was sought, with yield data corrected for recovery (if known);
- co-product or by-product mines with significant production have been incorporated into each specific commodity (e.g., a Cu–Zn mine would be included in both sectors);
- in cases where sources conflicted, the data considered closest to or most consistent with a company source was adopted.

The inclusion of co-products and by-products into each commodity introduces a small degree of double accounting. It was considered important to do this to
assess the true extent of ore processed to produce that metal. In general, it is clear that a mine should be included (e.g., Golden Grove in Cu and Pb–Zn–Ag), while for others it is somewhat subjective (e.g., Broken Hill). Overall, the amount of metals produced from co-by-product mines is small (e.g., ∼5% for Cu). This does, however, become a major issue when comparing the gold (Au) sector with other metal sectors or assessing the total ore throughput for the whole metals sector of the Australian mining industry.

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 1800s a key issue is that not
all production was reported to State Mines’ Departments (despite the urging to do so for posterity), including some ores or concentrates exported overseas with no records. 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 its specific sector, the calculated production is graphed as a percentage of reported production. The “calculated production” is derived by the summation of all individual mine production from the compiled data set. The reported production is the official annual production of that metal. Thus, for each metal a value of >90% would suggest that the data presented effectively covers that metal sector for that given year. Given the variable data sources, it is possible that the proportion of production could be >100%. This could be due to a variety of factors, including errors in individual mine production, rounding errors, financial versus calendar year, and/or incorrect reported Australian production.

The extent of Australian economic base metal resources is published by Geoscience Australia and includes data from 1975 to 2004 for most minerals (GA, various years). All pre-1975 resources data is obtained by collating individual mines. It should be noted that the formal basis for reporting ore resources has changed considerably over time, say 1900 to 2004 (e.g., the Joint Ore Reserves Code or ‘JORC’; AusIMM et al., 2004). However, 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 reserves over this period.

Overall, there is a minor degree of uncertainty in the assembled data sets. When different data sources for specific mines are compared, the correlations are very close. The net effect on trends in the data is therefore considered to be negligible. For examining trends over temporal scales up to two centuries, this uncertainty is not significant as the overall trends show larger change than the uncertainty in the data (e.g., Cu ore was ∼15–25% Cu in the mid-1800s but is presently 0.2–3% Cu). For most of the time period presented, the compiled data represents more than 90% of base metal production in Australia.

3. Copper

3.1. History

Copper mines hold an important place in Australian mining history, as they were the first base metal deposits to be discovered and worked on a notable scale from 1842, almost a decade before the gold rush began in 1851.

The 1840s saw several Cu discoveries in South Australia (SA) close to Adelaide at Kapunda, Montacute, and Burra followed in 1861 by the Moonta–Wallaroo field on the Yorke Peninsula. The SA mines, especially Burra, contained exceedingly rich ore ranging from 15 to 25% Cu — rapid development led to the construction of mines, smelters and soon boom towns became established (O’Neil, 1982). The total SA output, dominated by the Burra mine, saw SA become widely known as the “Copper Kingdom” and supplied about 10–20% of world production (Dickinson, 1990; Bampton and Taylor, 2000). In the early 1870s the Burra mine trialled open cut mining but converted back to underground mining just before closure in 1877 (Dickinson, 1942; Higgins, 1956; Drexel, 1982). The low Cu prices prevailing between 1875 and 1900, together with increasingly difficult mining conditions, led to the closure of almost all mines except the Moonta–Wallaroo field, which merged their previously independent operations in 1889 to stay profitable (O’Neil, 1982).

The dominance of SA also started to be challenged by the eastern states. The rich Peak Downs Cu mine in central Queensland (QLD) opened in 1862. In 1867 the Clonchurry Cu–Au field was discovered in remote western QLD while the Cobar Cu–Au field was discovered in northern New South Wales (NSW) in 1869. These fields rapidly proved to be of major importance, though they suffered from the tyranny of distance, lack of abundant water resources, economic fuel supplies and the want of capital (e.g., Brooke, 1975; Brooks, 1990). Similarly to SA, these mines initially exploited rich oxidised Cu ores grading some 15% Cu or higher.

By the late 1800s, however, some major structural changes were being forced on Australia’s Cu industry (Brown, 1908; Carne, 1908). Most importantly, the prolonged depressed Cu price forced the closure of many smaller mines, leaving only large companies and fields surviving. Another major issue was the exhaustion of the rich oxidised ores and the need to process and smelt the more abundant but lower-grade sulphide ores. By the 1890s, both the Moonta–Wallaroo and Cobar fields had declined in ore grade to ∼4.3% Cu. This created serious challenges for the industry, which worked even harder to maintain production. A major aspect of their success in this regard was the increasing mechanisation of the mines and smelters.

The development of the Mt Lyell Cu–Au–Ag mine in 1894 on Tasmania’s (TAS) west coast heralded a new era in Australian mining, even globally, as the first Cu mine to successfully implement pyritic smelting —
thereby negating the need for coke to fuel the smelters. Mt Lyell was arguably Australia’s largest and most complex mining project by this time, involving the construction of the Abt rack-and-pinion railway system to traverse the steep terrain, large flux quarries, the first pyritic smelters in the world and another Australian first with the famous ‘Iron Blow’ mine at Mt Lyell being developed through large-scale open cut mining (the previous attempt at open cut mining at Burra was small in comparison and unsuccessful). The Mt Lyell field was still in production in 2005 with significant ore resources remaining (29.4Mt at 1.37% Cu; 2005 Edition, TDM, various years).

However, the field has caused severe environmental damage locally and downstream due to the generation of acid mine drainage (AMD) from tailings and waste rock discharged to the Queen and King Rivers reaching the Macquarie Harbour (Koehnken, 1997).

The early 1900s continued to prove challenging for various Cu mines. The ongoing complexities of World War I, labour disputes, declining ore grades and increasing costs versus depressed prices led to the effective complete closure of the Moonta–Wallaroo and Cobar fields by 1923 — only small numbers of tributers continued mining.

The only significant new Cu mine developed around the early 20th Century was the 1906 entry of the Mt Morgan Au mine as a Cu–Au producer. Ore production was through a mixture of underground and open cut mining. Mt Morgan faced a strenuous decade in the 1920s as economic problems coupled with a major fire destroyed the mine in 1925. Mt Morgan was redeveloped as a dedicated large-scale open cut operation in 1931, remaining in production until 1982 with tailings re-processing until 1990 (Parbo, 1992). Similarly to Mt Lyell, the Mt Morgan mine has caused significant environmental impacts on the Dee River due to AMD (Sullivan et al., 2005).

The mid-to-late 20th Century produced a variety of new Cu fields and deposits, especially between 1975 and 2000. Until Mt Isa started large-scale Cu production in 1953, most Cu was produced as a co-product with Au and/or Ag at Mt Lyell, Mt Morgan and the Cobar field. A major trend throughout the latter half of the 20th Century was the use of open cut mining. Most Cu mines have been associated with Au and/or Ag production, while some Pb–Zn–Ag mines also produce (or have produced) Cu as a co/by-product (e.g., Broken Hill, Captain’s Flat, Rosebery, Woodlawn, Thalanga).

A chronology of Cu mines from 1940 includes:

- 1948 — Discovery and development of the Tennant Creek Cu–Au field;
- 1953 — Mt Isa starts large-scale Cu production (in parallel to existing Pb–Zn–Ag operations);
- 1964 — CSA Cu–Ag underground mine in the Cobar field is re-developed into a major producer (including small by-products of Pb–Zn);
- 1960s–1970s — old SA mines are re-worked by open cut, such as Kanmantoo, Burra and Mt Gunson, including the newly discovered Cattlegrid deposit;
- 1988 — Olympic Dam Cu–U–Au–Ag underground mine, northern SA, is bought on-stream;
- 1990s — Re-development of many small to moderate scale Cu mines across the Cloncurry field, including major new mines at Osborne (underground, 1995), Gunpowder–Mt Gordon (underground/open cut), Eloise (1996), Ernest Henry (open cut, 1997);
- 1993 — Nifty Cu open cut mine, east of the Pilbara, northern Western Australia (WA);
- 1994 — Northparkes Cu–Au open cut/underground mine, central NSW;
- 1998 — Cadia Hill Cu–Au open cut mine, central NSW;
- 2000 — Ridgeway Cu–Au underground mine, adjacent to Cadia Hill.

The discovery of the giant Olympic Dam deposit in 1975 by Western Mining Corporation (WMC) heralded a previously unrecognised style of mineral deposit, that of iron oxide copper–gold or ‘IOCG’ deposits, and has enabled a major advance in mineral resource exploration. The Olympic Dam deposit is also highly unusual in its metal association consisting of Cu, uranium (U), Au, Ag and rare earths. Significant greenfields Cu deposits are still being discovered (e.g., Prominent Hill, SA), though most known Cu resources are lower grade than current operations, broadly average around 1% Cu or lower and are, at present, commonly proposed as open cut mines. By 2005, Australia had produced 17.81Mt Cu, of which 11.18Mt Cu (63%) was produced from current operations, broadly average around 1% Cu or lower and are, at present, commonly proposed as open cut mines. By 2005, Australia had produced 17.81Mt Cu, of which 11.18Mt Cu (63%) was produced from 1985 to 2005.

3.2. Production results

The compiled statistics for Cu mining are shown in Figs. 2–6, with total production from major Cu mines/fields in Table 1 (important co/by-product Cu mines/fields are given in the Pb–Zn–Ag and Ni production sections, Tables 2 and 3, respectively).

The ore milled, average ore grade, estimated extent of open cut mining and waste rock (as reported) are shown in Fig. 2. For pre-1890 data, there is a lack of historical annual data on which to complete the graph. As shown later in Fig. 5, there is a major gap in
calculated production for this period, though some sparse data exist which has been incorporated into Fig. 2. The proportion of open cut mining between 1872 to 1875, based on data compiled for Burra, is clearly an over-estimate due to the low extent of data for this period (data represents only 6 to 17% of Cu production). Assuming an average grade of 17.5% Cu for these years leads to an estimate of the proportion of between 3 and 4% ore derived from open cut mining compared to the 20 to 50% shown.

Despite the lack of comprehensive pre-1890 data, it is certain, based on numerous historical works and mining/geological overview publications, that the period from 1842 to the mid-1870s saw very rich Cu ore mined in the range of 15–25% Cu (e.g., Burra, SA; Peak Downs, QLD; see Brown, 1908; Carne, 1908; Dickinson, 1942; Dickinson, 1944). By around 1890, ore grades had declined to about 4.3% Cu, from which time excellent data are available.

The impact of closing down open cut mining at Mt Lyell during the 1920s, along with the forced closure of Mt Morgan, is clearly visible in Fig. 2 as this led to an increase in average ore grade during the 1920s (i.e., North Lyell underground ore). However, with the resumption of large-scale open cut mining at both sites in the 1930s the average ore grade rapidly declined towards 1% Cu, reaching a historic low of 0.53% Cu in 1947. In 2005 average ore grade was 1.10% Cu, declining from a recent historic high of 2.58% Cu in 1991.

The waste rock data in Fig. 2 is a minimum since the respective companies have not publicly reported such
data for several major open cut mines. This primarily relates to the period 1995–2005, with additional annual waste rock possibly of the magnitude of 25 to 60 Mt. There is only sparse data on waste rock for underground mines. It can be observed that the reported quantity of waste rock, since the mid-1990s, is significantly higher than the quantity of ore milled. This is important since it is the waste rock at several Cu mines which has been primarily responsible for long-term environmental impacts (e.g., Mt Lyell, Rum Jungle, Mt Morgan).
present there are proposals being investigated for converting the underground mines of Olympic Dam and Mt Isa to large open cut mines, potentially producing ~40Mt/year of ore, giving renewed emphasis on the need to report waste rock data.

The relative dominance of individual states changing over time is evident from Figs. 3 and 4, with SA, QLD and TAS each leading Australian Cu production at various times.

The degree of completeness for the ore mined and milled, in terms of calculated versus reported Cu production or the fraction of Australian Cu production, Fig. 5, is low and quite variable prior to about 1890. From 1890 data becomes more widely available and reported annually, especially by state agencies, with calculated production generally representing more than 85% of Australian Cu production. The years where the fraction of Cu production exceeds 100% can only be attributed to inconsistencies between mine production and reported Australian production.

Australian Cu production versus economic resources, Fig. 6, indicates sustained growth in both Australian production and resources over the latter half of the 20th Century (1950–2000). As of December 2004, it is estimated that Australia has 42.1Mt Cu in economically demonstrated resources, with an additional 4.9 and 29.9Mt Cu of sub-economic and inferred resources, respectively (2005 Edition, GA, various years). This compares to estimated global economic Cu resources of 490Mt Cu (2005 Edition, GA, various years).

The Cu resources of probable future mines, as well as re-development projects, include:

- Mt Isa potential open cut, 277Mt at 1.0% Cu (Wallis, 2005);
- Olympic Dam proposed open cut, 3980Mt at 1.1% Cu (2004 Edition, WMC, various years-b);
- Roseby, QLD, 103Mt at 0.7% Cu (UR, 2004);
- Cadia East, NSW, 830Mt at 0.35% Cu (2005 Edition, Newcrest, various years);
- Telfer Au–Cu open cut project, WA, with 527Mt at 0.18% Cu (2005 Edition, Newcrest, various years);
- Prominent Hill, SA, with 101Mt at 1.5% Cu (Oxiana, 2005).

Based on presently known economic resources and 2005 production of 918kt Cu, there are sufficient resources to maintain existing Australian Cu production for approximately 45 years. As noted above, known Cu ore resources are commonly lower grade than present
### Table 1
Major copper mines/fields — production statistics

<table>
<thead>
<tr>
<th>Mine/field</th>
<th>Principal operating period</th>
<th>Metals mined</th>
<th>Mine type</th>
<th>% Ore open cut</th>
<th>Ore milled Mt</th>
<th>Ore grade</th>
<th>Production</th>
<th>Waste rock Mt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burra (13)</td>
<td>1845–1877</td>
<td>Cu</td>
<td>UG/OC</td>
<td>~25</td>
<td>0.24</td>
<td>22</td>
<td>52.4</td>
<td>~0.47</td>
</tr>
<tr>
<td></td>
<td>1972–1983</td>
<td></td>
<td>OC</td>
<td>100</td>
<td>2.11</td>
<td>1.77</td>
<td>~40</td>
<td>4.8</td>
</tr>
<tr>
<td>Moonta–Wallaroo (12)</td>
<td>1860–1923</td>
<td>Cu</td>
<td>UG</td>
<td>~9.1</td>
<td>3.7</td>
<td>~0.34</td>
<td>336</td>
<td>~1.7</td>
</tr>
<tr>
<td>Mt Lyell (11)</td>
<td>1894–2005</td>
<td>Cu–Ag–Au</td>
<td>UG/OC</td>
<td>~47</td>
<td>135.2</td>
<td>1.2</td>
<td>1489</td>
<td>~39</td>
</tr>
<tr>
<td>Mt Gunson–Cattlegrid (14)</td>
<td>1898–1994</td>
<td>Cu–Ag–Au</td>
<td>OC</td>
<td>~100</td>
<td>9.0</td>
<td>~1.7</td>
<td>~142.4</td>
<td>0.452</td>
</tr>
<tr>
<td>Kanmantoo (16)</td>
<td>1846–1875</td>
<td>Cu</td>
<td>UG</td>
<td>0.024</td>
<td>8.5</td>
<td>~2</td>
<td>~2</td>
<td>No data</td>
</tr>
<tr>
<td></td>
<td>1970–1976</td>
<td></td>
<td>OC</td>
<td>100</td>
<td>4.13</td>
<td>0.99</td>
<td>~40</td>
<td>23.556</td>
</tr>
<tr>
<td>Olympic Dam (15)</td>
<td>1888–2005</td>
<td>Cu–U–Ag–Au</td>
<td>UG</td>
<td>~6.5</td>
<td>~5.1</td>
<td>~301</td>
<td>~11</td>
<td>~17</td>
</tr>
<tr>
<td>Nifty</td>
<td>1994–2004</td>
<td>Cu</td>
<td>OC</td>
<td>~13.2</td>
<td>~2.0</td>
<td>~174.5</td>
<td>~44</td>
<td>~12.2</td>
</tr>
<tr>
<td>Tennant Creek (19)</td>
<td>1948–1999</td>
<td>Cu–Ag–Au</td>
<td>UG</td>
<td>~45</td>
<td>~6.5</td>
<td>~301</td>
<td>~11</td>
<td>~17</td>
</tr>
<tr>
<td>Ernest Henry (3)</td>
<td>1997–2005</td>
<td>Cu–Au</td>
<td>OC</td>
<td>100</td>
<td>83.64</td>
<td>1.15</td>
<td>~852.5</td>
<td>32.65</td>
</tr>
<tr>
<td>Gunpowder–Mt Gordon (5)</td>
<td>1970–2003</td>
<td>Cu</td>
<td>UG/OC</td>
<td>~20</td>
<td>~8.5</td>
<td>~2.0</td>
<td>~156</td>
<td>~30</td>
</tr>
<tr>
<td>Mt Isa (Cu)</td>
<td>1943–2005</td>
<td>Cu</td>
<td>UG</td>
<td>~4</td>
<td>214.7</td>
<td>3.27</td>
<td>6701</td>
<td>~2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OC</td>
<td>&lt;5</td>
<td>49.74</td>
<td>0.85</td>
<td>~374</td>
<td>~426</td>
</tr>
<tr>
<td>Mt Morgan (1)</td>
<td>1883–1990</td>
<td>Cu–Au</td>
<td>UG/OC</td>
<td>7.8</td>
<td>15.48</td>
<td>3.0</td>
<td>~438</td>
<td>~12.42</td>
</tr>
<tr>
<td>Osborne (6)</td>
<td>1995–2005</td>
<td>Cu–Au–Ag</td>
<td>UG</td>
<td>~20</td>
<td>~8.5</td>
<td>~3.4</td>
<td>~438</td>
<td>~41.6</td>
</tr>
<tr>
<td>Eloise (65)</td>
<td>1996–2004</td>
<td>Cu–Au–Ag</td>
<td>UG</td>
<td>~20</td>
<td>~8.5</td>
<td>~3.4</td>
<td>~438</td>
<td>~16.5</td>
</tr>
<tr>
<td>Selwyn Field (7)</td>
<td>1989–1998</td>
<td>Cu–Au</td>
<td>UG/OC</td>
<td>~20</td>
<td>~8.5</td>
<td>~3.4</td>
<td>~438</td>
<td>~16.5</td>
</tr>
<tr>
<td>Cobar–CSA (67)</td>
<td>1911–2004</td>
<td>Cu–Ag–Pb–Zn</td>
<td>UG</td>
<td>~20</td>
<td>~8.5</td>
<td>~3.4</td>
<td>~438</td>
<td>~16.5</td>
</tr>
<tr>
<td>Cadia Hill (9)</td>
<td>1998–2005</td>
<td>Cu–Au</td>
<td>UG</td>
<td>~20</td>
<td>~8.5</td>
<td>~3.4</td>
<td>~438</td>
<td>~16.5</td>
</tr>
<tr>
<td>Ridgeway (9)</td>
<td>2000–2005</td>
<td>Cu–Au</td>
<td>UG</td>
<td>~20</td>
<td>~8.5</td>
<td>~3.4</td>
<td>~438</td>
<td>~16.5</td>
</tr>
<tr>
<td>Cloncurry Field (2)</td>
<td>1867–1881</td>
<td>Cu–Au–Ag</td>
<td>UG/OC</td>
<td>~20</td>
<td>~8.5</td>
<td>~3.4</td>
<td>~438</td>
<td>~16.5</td>
</tr>
<tr>
<td>Cobar Field (8)</td>
<td>1889–1961</td>
<td>Cu–Au–Ag</td>
<td>UG</td>
<td>~20</td>
<td>~8.5</td>
<td>~3.4</td>
<td>~438</td>
<td>~16.5</td>
</tr>
<tr>
<td>Northparkes (10)</td>
<td>1994–2005</td>
<td>Cu–Au</td>
<td>UG/OC</td>
<td>~20</td>
<td>~8.5</td>
<td>~3.4</td>
<td>~438</td>
<td>~16.5</td>
</tr>
<tr>
<td>Girilambone (66)</td>
<td>1993–2002</td>
<td>Cu</td>
<td>UG</td>
<td>~20</td>
<td>~8.5</td>
<td>~3.4</td>
<td>~438</td>
<td>~16.5</td>
</tr>
<tr>
<td>Highway–Reward</td>
<td>1998–2005</td>
<td>Cu–Au–Ag</td>
<td>UG/OC</td>
<td>~62</td>
<td>3.72</td>
<td>5.56</td>
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Note: By/co-product from Cu–Zn–Ag and Pb–Zn–Ag mines/fields can be seen in Table 2 (Golden Grove, Teutonic Bore, Rosebery, Broken Hill, Woodlawn, Hellyer, Thalanga and Mt Garnet).

a Production based on annual data; some confusion exists between contained and extracted Cu.
b Still operating at the end of 2004.
c Uranium ore grade 0.075% U3O8, production 41,252 t U3O8.
d See Pb–Zn–Ag data (Table 2).
e This is from mining of the Black Rock open cut only (mainly 1957 to 1965); no waste rock from underground mining reported.
f Includes Great Australia, etc.
g Includes Great Cobar, Queen Bee, Chesney, Nymagee, Mt Hope, Gladstone, Burraga, CSA, New Cobar, Budgerygar, and other small mines (Au–Ag grades and production approximate only).
### Table 2

<table>
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<tr>
<th>Mine/field (map reference)</th>
<th>Principal operating period</th>
<th>Metals mined</th>
<th>Mine type</th>
<th>% Ore open cut</th>
<th>Ore milled Mt</th>
<th>Ore grade</th>
<th>Production</th>
<th>Waste Rock Mt</th>
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<td>Woodlawn (28)</td>
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<td>14.58</td>
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<td>Northampton (34)</td>
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<td>UG</td>
<td>~3 0.5&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>Rosebery&lt;sup&gt;d&lt;/sup&gt; (30)</td>
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<td>Century Zinc (20)</td>
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<td>McArthur River (39)</td>
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<td>UG/OC</td>
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<td>Golden Grove (35)</td>
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<td>Cu–Zn–Ag–Au</td>
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<td>~33</td>
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<td>Magellan (38)</td>
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<sup>a</sup> Still operating at the end of 2004.

<sup>b</sup> Some Northampton production is beneficiated concentrate only, not as-mined ore.

<sup>c</sup> Includes Magnet, Montana, Oceana, Mt Farrell, North Mt Farrell and minor mines.

<sup>d</sup> Includes Hercules and Que River.

<sup>e</sup> This is from mining of the Black Rock open cut only (1960s); no waste rock from underground mining reported (open cut mining of Pb–Zn–Ag ore re-started in 2005).
operations and proposed as open cut mines, keeping downward pressure on ore grades and upward pressure on environmental aspects such as solid wastes, energy, water and pollutant emissions per Cu produced (e.g., t CO₂/t Cu).

Overall, the compiled data give an excellent representation of Cu mining and milling in Australia from the 1840s to 2005. The cumulative production, resources and ore grades over time for Mt Isa and Mt Lyell are shown in Figs. 7 and 8, respectively. Although similar

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**Table 3**

Major nickel mines/fields — production statistics

<table>
<thead>
<tr>
<th>Mine/field</th>
<th>Principal operating period</th>
<th>Metals mined</th>
<th>Mine type</th>
<th>% Ore open cut</th>
<th>Ore grade</th>
<th>Production</th>
<th>Waste rock</th>
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<tr>
<td></td>
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<td></td>
<td>%Ni</td>
<td>kt Ni</td>
<td>kt Cu</td>
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<td>Ni–Cu–Co</td>
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<td>3.13</td>
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<td>Scotia (41)</td>
<td>1970–1977</td>
<td>Ni–Cu–Co</td>
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<td>Nepean (41)</td>
<td>1970–1987</td>
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<td>UG</td>
<td>–</td>
<td>3.15</td>
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<td>Carr Boyd (41)</td>
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<td>Ni–Cu–Co</td>
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<td>Redross (41)</td>
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<td>Ni–Cu–Co</td>
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<td>0.403</td>
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<td>Spargoville (41)</td>
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<td>0.601</td>
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<td>Windarra (59)</td>
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<td>Ni–Cu</td>
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<td>Forrestania (43)</td>
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<td>Sally Malay (45)</td>
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<td>Ni–Cu–Co</td>
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<td>Murrin Murrin&lt;sup&gt;d&lt;/sup&gt; (47)</td>
<td>1999–2004</td>
<td>Ni–Co</td>
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<td>~11.75</td>
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<td>Caswe (49)</td>
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<td>Ni–Co</td>
<td>OC</td>
<td>100</td>
<td>1.128</td>
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<td>Bulong (50)</td>
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<td>1.233</td>
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<td>31.45</td>
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<td>OC</td>
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<td>1.128</td>
<td>1.32</td>
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<sup>a</sup> Still operating at the end of 2004.
<sup>b</sup> No data is known to estimate the proportions of ore derived from underground and open cut mining.
<sup>c</sup> Murrin Murrin does not report actual ore milled nor ore grades (only metal production); all values above estimated from the only available data in quarterly and annual reports.
<sup>d</sup> Caswe was originally closed in early 2001 and later re-opened under a new process operating regime though no data is available since late 2000.

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**Fig. 7.** Mt Isa copper production plus remaining resources, ore grades.
graphs could be developed for other major Cu mines, Mt Isa and Mt Lyell are good examples of the long-term changes at major mineral fields and the associated cumulative trends in production, ore grades and economic resources.

The principal events in the evolution of the Australian Cu industry are clearly discernable in Figs. 2–8—the early dominance of SA, the emergence of QLD, NSW and TAS, the start and temporary closure of open cut mining at Mt Lyell and Mt Morgan, the development of Mt Isa, and the near exponential increase in production in the period from 1950 to the present. Overall, total production is dominated by Mt Isa (6.70Mt Cu), Mt Lyell (1.49Mt Cu) and Olympic Dam (1.96Mt Cu) with ~5% of Cu being sourced as a co/by-product from Pb–Zn–Ag and Ni operations.

4. Lead–zinc–silver

4.1. History

Following on from the Cu, Au and tin booms of the previous decades, the 1880s was the decade for lead–silver (Pb–Ag), and later zinc (Zn) from the 1900s. It is the 1880s to which can be attributed, directly and indirectly, the establishment of the majority of Australia’s foremost mining companies—the Broken Hill Proprietary Company Ltd (BHP), now BHP Billiton Ltd), Zinc Corporation, North Broken Hill Ltd (NBH), Broken Hill South Ltd (BHS) and Pasminco Ltd (now Zinifex Ltd)—the Broken Hill field has been particularly dominant in this regard. Through Broken Hill, Australia became world-renowned as a major producer of Ag, Pb and Zn.

Throughout the mid-1800s there were minor attempts at mining Pb–Ag ores, such as Glen Osmond near Adelaide in 1841, the Northampton field of central western WA from 1852, the small Yerranderie and Captain’s Flat fields in eastern NSW in the 1870s, and the Chillagoe field in northern QLD towards the end of the 1870s (Legge and Haslam, 1990). In general these early mines were of a relatively small and commonly unprofitable nature (or at least very limited periods of profitable working).

General interest in Pb–Zn–Ag mining was low—Cu, Au and tin were the minerals of proven abundance and profitability. In the 1880s several major new fields were discovered—Thackaringa–Silverton in 1876 (but not confirmed until 1880) and Broken Hill in 1883 in far western NSW, and the Chillagoe field in northern QLD towards the end of the 1870s (Legge and Haslam, 1990). In general these early mines were of a relatively small and commonly unprofitable nature (or at least very limited periods of profitable working).

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The confirmation of the Thackaringa–Silverton field led to a small rush, especially following discovery of the Umberumberka deposit. In the end the rush was relatively short-lived and failed to deliver significant profits but led prospectors to the real prize nearby. In September 1883, boundary rider Charles Rasp discovered what he thought was a prominent outcrop of ‘tinstone’—which turned out to be Pb–Ag ore and the Broken Hill ‘line of lode’ was on its way to world renown.

The Broken Hill Proprietary Company Ltd (BHP) was registered on 10 August 1885 and the development of mining, milling and smelting operations began. Later in 1885, the northern end was taken up by the Broken Hill North Silver Mining Company Ltd (later North Broken Hill Ltd or NBH) while the southern end was
pegged by the Broken Hill South Silver Mining Company Ltd (BHS). Remaining areas along the line of lode were soon pegged by numerous hopeful companies, most backed by British investors eager to participate in the latest Australian mineral rush. By the end of the decade Broken Hill was a world-renowned Ag field with increasingly important Pb production. At this stage there was no interest in Zn — the focus was squarely on the rich Ag grades being mined from oxidised ore in the weathered zone by BHP and others (Jaquet, 1894; Andrews, 1922).

Over the following two decades the Broken Hill field had to solve two critical challenges — the decline of readily mineable and easily smelted oxidised ore and the Zn problem (i.e., no economic recovery technology and limited market interest in Zn relative to Pb–Ag). The early mining of the oxide ore lead to easy milling and smelting but the rapidly declining Ag grades of this ore forced the field to address the challenge of future ore sources (Jaquet, 1894; O’Malley, 1988). By this stage there was known to be very large resources of deeper sulphide ore (mainly within the NBH and BHS leases) but there was no method at that time for economic milling. Engineers and metallurgists set to work and developed an array of processes for concentrating the sulphide minerals from fresh ore (e.g., the Wilfley Table) (Raggatt, 1968; O’Malley, 1988; Parbo, 1992).

In order to continue improving economic efficiency on the Broken Hill field, the zinc problem then had to be solved. In 1904 it was estimated that the tailings dumps contained 6.69Mt grading 6% Pb, 19% Zn and 184g/t Ag (Woodward, 1965) — but there was no known method for efficient Zn recovery. Metallurgical expertise was again mobilised and the method of flotation was invented with great success, including key variants of the method (Raggatt, 1968). The technology was applied to the Zn-rich tailings by the British-backed Zinc Corporation (ZC) in 1905, among other companies, and later modified to a froth flotation technique for fresh ore. The use of flotation went on to revolutionise the milling of numerous sulphide ores around the world (O’Malley, 1988; Lynch, 1992; Bear et al., 2001). By 1910 the future again seemed assured for coming decades.

The Broken Hill field saw a 20-month-long strike from 1919, which, when combined with the economic impacts of World War I and a disastrous fire at the Port Pirie smelter in 1921, caused great economic pain for the field and most of its companies due to the loss of production (this period is clearly evident in the figures) (Andrews, 1922).

The Broken Hill ethos of continually evolving mining and metallurgical practices has helped to underpin the profitability of several companies (Raggatt, 1968). Many of the companies who started life in the Broken Hill field have gone on to invest in and/or develop many other mines or industries across Australia. For example (Woodward, 1965; Raggatt, 1968; Griffiths, 1998):

- Large smelting centres at Port Pirie, SA, and Cockle Creek, NSW;
- BHP initiated iron ore mining in SA in 1903, initially for flux at the Port Pirie Pb smelters but later steel production at Newcastle in 1915 (primarily as a way to provide for its future beyond Broken Hill);
- Many Broken Hill company directors, engineers and metallurgists went on to important roles in guiding other mining companies and ventures to prosperity;
- The 1916 creation of the Electrolytic Zinc Company of Australasia Ltd (EZ) to establish a Zn refinery near Hobart, TAS (initially partly-owned by most Broken Hill companies);
- BHS developed the CSA mine at Cobar in the mid-1960s;
- The Zinc Corporation formed the Consolidated Zinc Corporation, which in 1962 was merged with UK’s Rio Tinto Zinc (RTZ) to form Conzinc Riotinto Australia Ltd or ‘CRA’ (now fully integrated with RTZ to form Rio Tinto Ltd/Plc, a dual-listed Anglo-Australian company); BHS and NBH were taken over by CRA/Rio Tinto in 1980 and 2000, respectively.

The ties with the Broken Hill field have now been effectively closed by all companies. The exit of the founding BHP occurred in 1939, while the operations of North Broken Hill and the Zinc Corporation (which included BHS from 1980) were merged into a single independent company in 1987 called Pasminco Ltd (now Zinifex, who sold the operation to Perilya Ltd in 2002). The ore resources at Broken Hill as of March 2005 are, remarkably, 17.73Mt grading 5.9% Pb, 9.9% Zn and 63g/t Ag (2005 Edition, Perilya, various years). Despite an air of inevitability there remains some optimism for the great lode (e.g., Plimer, 2004).

In northwest QLD in February 1923, to the west of the Cloncurry Cu field, the Mt Isa Pb–Zn–Ag field was discovered by John Campbell Miles. However, the field’s potential was slow to be realised, due primarily to the lower ore grades compared to Broken Hill, the more difficult nature of the finer grained ore to mill and smelt, the small quantity of easily treatable oxidised ore and Mt Isa’s significant remoteness (Berkman, 1996). Unlike Broken Hill, however, the entire field was quickly amalgamated into a single operating company by late 1925 — Mt Isa Mines Ltd (MIM) (Raggatt, 1968) (MIM was recently taken over by Swiss-based Xstrata Ltd in mid-2003).
The complete control by MIM soon proved to be a significant advantage — the field needed intensive capital to finance it into production. Operations at Mt Isa required completely new infrastructure on a large-scale, including roads, a long-distance railway, a new town, as well as major mining and metallurgical facilities (Raggett, 1968). The development of Mt Isa in the late 1920s was arguably Australia’s first mega-scale and planned mining and smelting project (Mt Lyell, though significant for its time, was much smaller in scale relative to Mt Isa). The pioneering effort was based on a 1928 ore resource of 21.2 Mt grading 6.1% Pb, 8.2% Zn and 115 g/t Ag (Legge and Haslam, 1990). For comparison, in 1928 the Broken Hill field milled 1.2 Mt at 14.3% Pb, 11.2% Zn and 205 g/t Ag while known ore resources were of the order of 15 Mt at 13.7% Pb, 12.1% Zn and 186 g/t Ag (based on data compiled).

When Mt Isa began production in 1931 the world Pb market was effectively collapsing. By 1932 the price of Pb had fallen by more than half, forcing MIM to continue to seek further financial assistance and again in 1939. MIM delivered a small profit for 1936/37, but it was not until after World War II and the development of a large Cu operation that MIM finally delivered ongoing profits. In 1947–1948 the Hilton and George Fisher Pb–Zn–Ag deposits were discovered 20 km north of Mt Isa (Legge and Haslam, 1990). As of June 2005, the total Pb–Zn–Ag ore resources at Mt Isa, including Hilton, George Fisher, Black Rock and potential ‘Isa open cut’ resources, were 467 Mt grading 4.7% Pb, 7.4% Zn and 95 g/t Ag (2005 Edition, Xstrata, various years).

Throughout the latter half of the 1900s numerous, and often significant, discoveries of Pb–Zn–Ag or similar ores have been made, including:

**Lead–zinc–silver**
- 1955 — McArthur River-HYC, NT;
- 1964 — Woodcutters, NT;
- 1966 — Beltana–Aroona, SA;
- 1970 — Lady Loretta, QLD;
- 1971 — Sorby Hills, WA;
- 1972 — Elura, NSW;
- 1976 — Abra, WA;
- 1978 — Cadjeput–Blendevale, WA;
- 1989 — Century Zinc, QLD;
- 1990 — Cannington, QLD;
- 1991 — Magellan, WA.

**Copper–zinc–silver**
- 1978 — Benambra, VIC;
- 1979 — Golden Grove, WA.

**Lead–Zinc–Silver–Copper–Gold**
- 1969 — Woodlawn, NSW
- 1974 — Que River, TAS;
- 1975 — Thalanga, QLD;
- 1983 — Hellyer, TAS.

The McArthur River-HYC deposit (the HYC stands for “Here’s Your Chance”) was discovered by MIM geologists in 1955. Ore resources were effectively as large as the Broken Hill or Mt Isa fields with strong Zn grades but of a lower overall Pb–Ag grade and containing very finely disseminated sulphides — making the ore very difficult to treat (Beattie and Leung, 1993). Prior to development in the mid-1990s resources were estimated at 227 Mt grading 4.1% Pb, 9.2% Zn, 41 g/t Ag and 0.2% Cu (Logan et al., 1990). The milling problems took MIM some decades of research to overcome, inventing new ‘Isamill’ grinding technology in the process (Enderle et al., 1997; Pease et al., 2006) to produce a saleable mixed Pb–Zn concentrate (as opposed to separate concentrates from standard Pb–Zn–Ag operations). Commercial operations started in 1995.

Most of the above-listed deposits have now been developed. Some higher grade mines, such as McArthur River and Century Zinc (high Zn) and Cannington (high Pb–Ag) have made considerable contributions to production and stabilising or even increasing average Australian Pb–Zn–Ag ore grades in the short-term (see Fig. 9).

Although the original emphasis at Broken Hill was on Ag and then quickly shifting to Pb, the primary profitability and overall importance in the Pb–Zn–Ag sector is now placed on Zn production, which is now more than double the production of Pb. Based on presently known resources, future Pb–Zn–Ag production will be derived, like Cu, from generally lower grade ores and proposed larger open cut mines (see next section). By 2005, Australia had produced 36.1 Mt Pb and 44.4 Mt Zn, with 34% and 51%, respectively, being produced between 1985 and 2005.

### 4.2 Production results

The compiled statistics for Pb–Zn–Ag mining are shown in Figs. 9–15, with total production from major Pb–Zn–Ag mines/fields given in Table 2. The long-term trends of ore milled and ore grades (Figs. 9 and 10), are dominated by Broken Hill for most of the period presented. The data for the Northampton field (WA) from 1850 to 1883 is not included since it is was a very small production and only beneficiated concentrate data are available — not as-mined ore grades. Prior to 1913 the annual data for the Broken Hill field was not reported consistently, though data for some years and some companies are available either from NSWDM (various years) or the online archives of the NSW Department of Mines (the ‘DIGS’ system). Due to the changing milling and smelting sites of this period, and the fact that a considerable degree of the mined metals were refined in states other than NSW (e.g., SA or exported to Europe), there is some confusion over the extent of Broken Hill-
derived production (hence the variability in calculated versus reported production until about 1900). The period 1883–1912 is therefore based on approximate data. This early period is also based on effective metal yields from the ore, whereas from 1913 onwards, full reporting by NSWDM (various years) is based on actual assayed ore grades and individual mine production. The drop in ore milled, ore grades and production for 1920 is related to the prolonged strike at Broken Hill.

The high variability in Zn grades until 1910 is related to the problem of Zn extraction. As data prior to 1913 is commonly based on yield and not assay grade, only the payable Zn quantity in concentrates is available and the true Zn grade therefore remains unknown. From the 1890s, given the shift to sulphide ores and the published assay grades of ore resources for some of the major Broken Hill companies (e.g., BHP, NBH, BHS), it is most likely that true Zn grades were comparable to Pb of around 20% Zn (e.g., the tailings dump by 1904 contained 19% Zn), as marked on Fig. 9. The short-term decline in Zn grades from 1930 to 1935 is due the start up of Mt Isa in 1931, which focused on higher
grade Pb–Ag ore (∼10.5% Pb, ∼170 g/t Ag) in its early years with lower Zn grades (∼4%) while Zn production began in 1935 from combined Pb–Zn–Ag ore (∼8.3% Pb, ∼10.5% Zn, ∼200 g/t Ag). Further peaks in Zn grades are related to temporary mining of higher grade ores, deposit variability, and/or the start and expansion of new mines (e.g., Rosebery, TAS, in 1936).

With respect to open cut mining there are two major issues — early open cuts at Broken Hill and waste rock data. Firstly, there is only minimal data shown for open cut mining prior to about 1960. To overcome the geotechnical stability problems of underground mining at Broken Hill, some open cut mining was undertaken to relieve underground rock stresses. The data to estimate the fraction of ore derived from this work is approximate only, with open cut ore reaching ∼10% in the late 1890s. No significant further open cut mining is understood to have occurred. Secondly, there is no waste rock data included due to the fact that the respective companies have not publicly reported such data. This is despite several open cut mines being developed since 1970, including Woodlawn (NSW), Woodcutters (NT), Century Zinc (QLD), Blackwoods, Potosi and others at Broken Hill as well as minor open cuts at Rosebery–Hercules (TAS). For the new Black Star open cut at Mt Isa (started in 2005), the waste:ore ratio is 4 (Wallis, 2005). The Century Zinc project has a total mine life waste:ore ratio of ∼5.5 (QNRME, 2000). At present, like Cu, there are proposals being investigated for converting the underground mines of McArthur River and Mt Isa to large open cut mines, again reinforcing the need to report waste rock data.

There is no data on waste rock for underground mines. An important example in this regard is that it is possible to generate AMD impacts from waste rock at underground mines, with Captain’s Flat in NSW being a prominent example.

The long-term trends in the proportion of Pb–Zn production, Fig. 11, show a clear, sustained shift towards greater Zn than Pb (as noted by Legge and Haslam, 1990). This is also facilitated by the development of the Cu–Zn mine at Golden Grove or Zn-dominant ores such as Century Zinc and McArthur River. Further comment on this issue is provided in the discussion section.

The Pb–Zn production by mine/field is shown in Figs. 12 and 13. The dominance of Broken Hill for nearly a century is clearly visible, as well as the strong contribution of Mt Isa and other recent mines in the latter decades of the 20th Century. In a similar pattern to Cu, there have been numerous Pb–Zn–Ag mines developed in the past few decades, including some mines with higher than average grades such as Cannington (high Pb–Ag) and Century Zinc and McArthur River (high Zn). A common feature of several of the mines/fields is the by-products produced, especially Cu and Au (see Table 2).
The degree of completeness for the ore mined and milled, in terms of calculated versus reported production or the fraction of Australian Pb–Zn production (Fig. 14), is generally excellent and very close to 100%. As discussed above, prior to 1913 full data was not reported plus there was confusion over the extraction of metals in


NSW versus that of interstate or overseas. Due to the dominance of Broken Hill, and available data for Mt Isa, from 1913 to about 1988 the data represents very close to 100% for Pb and Zn. From 1988 to 2005 the calculated production is more variable but still generally >90%.

Fig. 14. %Lead and %Zinc production — reported versus calculated.

Fig. 15. Australian lead–zinc production and economic resources.
Australian Pb–Zn production versus economic resources (Fig. 15), indicates sustained growth in both production and resources, though Pb has not grown to the same degree as Zn. As of December 2004, it is estimated that Australia has 22.9/41.0Mt Pb/Zn in economically demonstrated resources, an additional 12.2/23.4Mt Pb/Zn of sub-economic resources as well as 21.6/25.2Mt Pb/Zn inferred resources, respectively (2005 Edition, GA, various years). The estimated global economic Pb–Zn resources are 70/222Mt Pb/Zn, respectively (2005 Edition, GA, various years).

The Pb–Zn–Ag resources of potential future mines include the Mt Isa proposed open cut, 314Mt at 3.2%, 4.0% and 70.7g/t Pb, Zn Ag, respectively (Wallis, 2005); McArthur River proposed open cut, 42.8Mt at 10.4% Zn (Pb–Ag grades not stated, but for the global mineral resource are \(\sim\) 5.7% Pb and 57g/t Ag), including an estimated waste:ore ratio of \(\sim\) 4.3 (URS and MRM, 2005). Resources at existing mines are generally of similar grades to production to date.

Based on presently known economic resources and 2005 production of 767kt Pb and 1.37Mt Zn, there are sufficient resources to maintain existing Pb–Zn–Ag production for approximately 25 years. As noted above, known Pb–Zn–Ag ore resources, like Cu, are mostly all lower grade than present operations and proposed as open cut mines, keeping downward pressure on ore grades and upward pressure on environmental aspects such as solid wastes, energy, water and pollutant emissions per unit metal produced (e.g., t CO₂/t Cu). The ore milled and grades over time for Broken Hill and Mt Isa are shown in Figs. 16 and 17, respectively, with cumulative production plus resources for Mt Isa shown in Fig. 18. Overall, the compiled data give an excellent representation of Pb–Zn–Ag mining and milling in Australia.

5. Nickel

5.1. History

The large-scale production of nickel (Ni) is one of Australia’s most recent additions to its mining industry — and has filled an important gap in the nation’s mineral self-sufficiency. The earliest production of Ni was from the Zeehan field of western TAS. Approximately 585t of Ni were produced intermittently between 1910 and 1938 from about 10,000t of ore Ni–Cu sulphide ore from the Five Mile group of small mines. The ore graded 8 to 17% Ni and 5 to 14% Cu, though only half of the ore was sold in 1913 and 1914. Despite broad Ni interest, the difficulty in mining these small deposits and the collapse of the Zeehan field around this time led to no further activity for several decades (McIntosh Reid, 1925; Hughes, 1965).
Between 1953 and 1965, a number of important Ni prospects were discovered, namely (Marston, 1984; Pratt, 1996):

- 1953 — Claude Hills–Wingellina prospects in the Tomkinson and Blackstone Ranges of the remote corner region of north-west SA (bordering WA);
- 1955 — Beaconsfield Ni laterite prospect, north-east TAS;
- 1957 — Greenvale Ni laterite prospect, northern QLD;
- 1965 — Marlborough Ni laterite prospects, central QLD.

However, these prospects were extremely isolated (Claude Hills–Wingellina) and/or very difficult to mill (Ni laterites). They occurred at a time, however, when world Ni demand and production was growing significantly.

In late January 1966 Western Mining Corporation (WMC) discovered a 2.7 m intersection of 8.3% Ni sulphide ore from 145.7 m depth — indicating an important Ni prospect at Kambalda, south of Kalgoorlie, WA (Woodall and Travis, 1979). Exploration sufficiently proved up Kambalda and WMC announced their discovery and intention to proceed with development on 4 April 1966 (Raggatt, 1968; Parbo, 1992).
The Kambalda region, in Archaean geology, had not been considered prospective for Ni sulphide deposits and the global significance of the find was immediately realised — and Australia’s Ni boom began (Woodall and Travis, 1979). It is perhaps curious that the numerous indications of Ni mineralisation in the broader region had been missed for some decades in a major mining centre such as Kalgoorlie (Raggatt, 1968). By the end of 1966 WMC announced an ore reserve of 1.93 Mt grading 4.15% Ni containing 81 kt Ni — a considerably higher grade than Canadian mines though smaller in size (at this time, Canada was the world’s major Ni producer, averaging 236 kt Ni/year from ore grading ~1.2% Ni; see CDEMR, various years). Kambalda ore, like Canadian ores, commonly contains around 0.2 and 0.35% Cu. The WMC management moved quickly to capture the strong Ni market and began construction of a new mine/mill at Kambalda while exploration was still continuing (Marston, 1984).

The Kambalda mill came on-stream in mid-1967 and by the end of the year had produced 2.1 kt Ni from ore averaging 4.6% Ni. The project was in a state of almost continuing expansion for many years. Perhaps the most important aspect of the unprecedented rapid development of Kambalda, especially with hindsight, was that the major Canadian Ni mines underwent protracted labour strikes from 1966 to 1969 — thereby facilitating WMC’s access to supply the world market and strong profitability in the critical early years (Marston, 1984). The ongoing exploration efforts proved the Kambalda region to be very rich in Ni deposits, with WMC’s Kambalda reserves by 1975 estimated at 24.55 Mt at 3.23% Ni plus the 7.69 Mt at 3.4% Ni already processed (Marston, 1984).

The Kambalda discovery ignited a Ni exploration boom across Australia, but particularly WA. By 1970, numerous Ni deposits had been discovered of varying economic potential, with some already in the process of development, including (Marston, 1984; Pratt, 1996):

- 1968 — Kambalda field — Scotia, Nepean, Redross, Wannaway, and others in the Widgiemooltha–Spar- groville belt south of Kambalda;
- 1969 — further Kambalda discoveries, Mt Windarra near Laverton, Mt Keith near Wiluna, Carr–Boyd Rocks;
- 1970 — Yakabindie and further low-grade deposits near Wiluna; Black Swan high-grade Ni sulphide deposit north-east of Kalgoorlie;
- 1971 — Perseverance deposit near Agnew (now called Leinster); the Forrestania Ni field 260 km south-west of Kalgoorlie (on the edge of the south-west WA wheatbelt);
- 1972 — Sherlock Bay Ni deposit in the western Pilbara.

The pace of discovery and delineation of Ni resources, especially in WA, is perhaps unparalleled. By June 1976 WA Ni sulphide resources had been estimated at 85.6 Mt of ore at 2.4% Ni and a further 755 Mt of ore at 0.6% Ni, containing 2.1 and 4.8 Mt Ni, respectively (Woodall and Travis, 1979). By the mid-1970s an integrated Ni industry had been developed in Australia. This included several mines in WA, Kwinana refinery south of Perth (1970), Kalgoorlie smelter (1972) and the Greenvale Ni laterite mine and associated Yabulu refinery in QLD (1974). The Ni sulphide mines were mostly very profitable for their owners, especially WMC, although Greenvale–Yabulu took some years before proving profitability. Production and development stabilised from the mid-1970s, with the difficult market conditions for Ni in the 1980s dampening industry expansion (Marston, 1984; Pratt, 1996).

Due to WMC selling all of their Kambalda mines to junior companies (operating the Kambalda mill on a toll basis), an exact resource position remaining on the field is now somewhat difficult. Prior to this strategy, WMC stated total ore resources of 17.3 Mt of ore grading 3.26% Ni, containing 564 kt Ni (1999 Edition, WMC, various years-b). Based on exploration results since this time and an analysis of numerous junior miners’ annual reports, Ni ore resources are still likely to be of the same magnitude and grade.

From the early 1990s the Ni industry has undergone a major expansion, bought about by a stronger Ni market, the development of new milling technology for difficult laterite deposits and several new mines coming on-stream:

- 1994 — WMC’s Mt Keith mine, WA, processing 10–11 Mt/year of 0.6% Ni sulphide ore;
- 1997 — high-grade Black Swan Ni sulphide mine, WA (~4.5–9% Ni);
- 1999 — Cawse and Bulong Ni laterite mines, WA, using new ‘high pressure acid leach’ (HPAL) technology (reviewed by Whittington and Muir, 2000);
- 2000 — Murrin Murrin Ni laterite mine, WA, using HPAL technology;
- 2000 — high-grade Cosmos Ni sulphide mine, WA (~7–9% Ni);
The advent of the ‘high pressure acid leach’ technology for processing Ni laterite ores has been controversial, partly as they were the first HPAL mills built globally to process Ni laterite ores in four decades (the only prior HPAL mill was at Moa Bay, Cuba, built in 1959). The HPAL mill was promoted as a robust, workable technology offering low capital and unit production costs (as discussed by Bacon et al., 2000; Moskalyk and Alfantazi, 2002; Reid and Barnett, 2002; King, 2005). The initial performance of the three WA Ni laterite mines, however, has been much less than hoped — all three projects have (or had) capital and operating costs higher than feasibility study estimates and failed financially (Reid and Barnett, 2002; O’Shea, 2003). Bulong and Cawse were operated for about two and a half years before closure, both struggling to maintain production targets. Cawse was sold to OM Group in December 2001, who closed the refinery section and altered the mill to produce a mixed carbonate concentrate (no data is available since this time). Murrin Murrin, after considerable technical and financial problems, appears to have overcome some of the difficulties but has never expanded to reach the intended Stage II rate of 115 kt Ni/year by 2000 (e.g., 1998 Edition, AN, various years, p. 12). Annual production over 2001 to 2004 ranged from 25 to 30 kt Ni/year (around 67% of Stage I nameplate capacity of 45 kt Ni/year; O’Shea, 2003).

The Yabulu Ni laterite refinery, based on the Caron process and originally built in the early 1970s to treat Greenvale and later Brolga ore, began importing laterite ore from the Pacific rim in the late 1980s, mainly Indonesia and New Caledonia. After various ownership changes, Yabulu is now owned by BHP Billiton. In 2004 BHP Billiton committed to developing the Ravensthorpe Ni laterite mine in WA with an intermediate Ni hydroxide product to be treated at Yabulu. The Ni laterite resources at Ravensthorpe are 389Mt at 0.62% Ni and 0.03% Co (2005 Edition, BHPB, various years).

Following several years of exploration efforts, Allegiance Mining NL began development during 2005 of a medium-size Ni mine at Avebury west of Zeehan — finally demonstrating the TAS west coast as a major Ni field.

### 5.2. Production results

The compiled statistics for Ni mining are shown in Figs. 19–21, with total production from major Ni mines/fields given in Table 3. A somewhat unusual feature of Australian Ni production is the dominance of one company — Western Mining Corporation (WMC) — their mines or majority-controlled joint ventures have produced about 67% of Australian Ni.

The earliest production of Ni from the Zeehan field in Tasmania was high grade, as shown in Fig. 19, though uneconomic. The emergence of the Kambalda region as a world-class Ni province led to a rapid rise in Ni production. The initial ore grades in the late 1960s were high, ~4% Ni, but began a gradual decline. Within a decade the overall average Ni ore grade in Australia was 2% Ni, largely influenced by the start of the Greenvale Ni–Co laterite mine in QLD. With the new Ni mines developed over the period 1995 to 2004 commonly being low grade laterite or disseminated sulphide deposits, the average ore grade has now declined to about 1.2% Ni.
The complete shift from underground to open cut mining is also evident, due to mines such as Greenvale–Brolga, Mt Keith and recent Ni laterite mines. There is no waste rock data included due to the almost complete absence of reported data, as the respective companies have not publicly reported such data. For the Greenvale–Brolga mines, based on data compiled, the ore mined was 31.26 Mt while about 24 Mm³ waste rock were extracted (about 35 Mt).

The contribution of Ni laterite ores (Fig. 20), based on Greenvale–Brolga and the recent WA mines, has been important and is likely to grow in the future if the technological challenges can be overcome profitably.

The degree of completeness for the ore mined and milled, in terms of calculated versus reported production or the fraction of Australian Ni production (Fig. 21), is generally excellent and close to 100%. Australian Ni production versus economic resources (Fig. 21) indicates sustained growth in both production and resources. A key feature of Australian Ni resources, is that although economic resources appeared somewhat stagnant between 1972 to 1989, the total identified resources were significant and continued to grow substantially (e.g., Marston, 1984; Pratt, 1996). The large increase in economic Ni resources since 1990 has been due to the conversion of some of the identified (or uneconomic) resources to economic status (e.g., Mt Keith, Murrin Murrin). As of December 2004, it is estimated that Australia has 22.6 Mt Ni in economically demonstrated resources, with an additional 4.1 and 19.5 Mt Ni of sub-economic and inferred resources, respectively (2005 Edition, GA, various years). The economic Ni resources are held in 9.7 and 12.9 Mt Ni of sulphide and laterite resources, respectively (2005 Edition, GA, various years). The estimated global economic Ni resources are 61.8 Mt Ni (2005 Edition, GA, various years).

Some possible future Ni projects include the proposed Yakabindie open cut Ni sulphide mine with 290 Mt at 0.58% Ni (2005 Edition, WMC, various years-b); Anomaly 1 open cut Ni sulphide mine with 36.3 Mt at 0.74% Ni (2004 Edition, JM, various years); Honeymoon Well with 131.5 Mt at 0.75% Ni (2004 Edition, LionOre, various years); and the Kalgoorlie open cut Ni laterite mine with 891 Mt at 0.74% Ni and 0.05% Co (2004 Edition, Heron, various years).

Based on presently known economic resources and 2004 production of 185 kt Ni, there are sufficient resources to maintain existing Ni production for more than 100 years. Similarly to Cu and Pb–Zn–Ag, future production will have to come from increasingly lower grade sulphide ores as well as more difficult laterite ores — providing a significant challenge for environmental

![Fig. 20. Nickel production by sulphide versus laterite.](image)

![Fig. 21. Nickel production and economic resources (left); %Nickel production — reported versus calculated (right).](image)
requirements such as solid wastes, energy, water and pollutant emissions per unit metal produced (e.g., t CO₂/t Cu). The processing of Ni laterites is particularly energy intensive, leading to major process control infrastructure required for pollution control as well as the challenges with respect to the volume of emissions (Kemp and Wiseman, 2004). The ore milled and grade with cumulative production plus resources over time for the Kambalda field is shown in Fig. 22.

6. Discussion and implications

The production trends compiled for Australian base metal mining presented herein raise numerous issues. The trends are presented only as a function of time. In reality there are numerous factors which clearly contribute to or control base metal mining and metal production. These can be broadly grouped as:

- Supply/demand, market conditions and economics;
- Social issues (e.g., strikes, wars);
- Exploration effort and success rates;
- Technological innovation (exploration, mining, milling and rehabilitation);
- Environmental constraints.

Economic conditions can affect a mine or field in several ways. Over the past century, real prices for Cu, Pb, Zn and Ni gradually decline (e.g., Nicol, 2001; Kelly et al., 2004). In order to meet increasing demand, this has forced the unit cost of production downwards as well as leading mines to larger magnitudes in order to achieve lower unit costs from economies of scale. This process generally favours larger orebodies as well as higher grade operations (i.e., above industry average for that time). As mining operations increase in scale, this allows a decline in the economic cut-off grade for mining and milling. Additionally, metal demand can directly influence supply. There are several times during the period of review when a decline in production can be attributed to economic downturns (e.g., the early 1930s depression), or conversely when increasing production can be attributed to strong demand (e.g., 1990s onwards). Given the global nature of metal markets, the cost of metal production in Australia should be compared with the cost of imports. The overall trends in base metals clearly need to be considered in light of prevailing Australian and global economic conditions.

The extent and success of exploration is a critical aspect of base metal mining, which is clearly linked to economic conditions as well as government policies of the day. Since the 1950s, given rising demand for metals, exploration was widespread and resulted in major new discoveries across Australia (as noted in historical overviews). Some of these discoveries gave rise to a new class of mineral deposit which had previously been unknown (e.g., the Kambalda Ni–Cu–Co field and Olympic Dam Cu–U–Au–Ag deposit), in turn leading to further major discoveries (e.g., the Ernest Henry and Prominent Hill Cu–Au deposits). It is of course not possible to predict the extent and nature of future mineral deposit discoveries (beyond mere speculation), though it remains clear that increasing exploration effort is required as well as the application of geological theory and technological innovation.
A major feature of all aspects of the mining cycle, that is from exploration through mining and milling to rehabilitation, is that of increasing technological innovation throughout the 20th Century (e.g., Aplan, 1979; O’Malley, 1988; Bear et al., 2001). For example, the development of flotation milling has allowed a wide variety of sulphide deposits to be mined and milled and the efficient recovery of contained metals such as Pb, Zn and Cu. Further to this, increasing sophistication in exploration technology, particularly geophysics, is leading to the discovery of new deposits in areas with little or no mining previously. Many Cu projects developed in the latter two decades of the 20th Century included the use of solvent extraction-electrowinning (SX-EW) technology for producing a pure copper cathode (e.g., Olympic Dam, Nifty, many Cloncurry field projects). Australia, as well as adopting major new technologies from overseas (e.g., cyanide milling for gold), has made significant contributions to mineral processing technology in a global sense (O’Malley, 1988).

Environmental constraints on base metal mining are a relatively recent feature of the base metal mining sector, and include pollution control (e.g., air emissions from smelters and mills), management of water, tailings and waste rock, and finally minisite closure and rehabilitation (e.g., Guerin, 2006). A significant aspect of the environmental costs of base metal mining is the existing and potential legacy of AMD, especially linked to waste rock. As noted previously, some mines have caused major environmental impacts from waste rock-derived AMD reaching local waterways and ecosystems (e.g., Mt Lyell, Rum Jungle, Mt Morgan). Although legislative requirements and community expectations now require rehabilitation, the lack of reporting of waste rock data would suggest that the waste rock–AMD link is not being broadly made within the mining sector. The understanding of various engineering approaches to waste rock rehabilitation to minimise AMD has certainly evolved rapidly over the past two decades, but questions still remain over the long-term performance of these approaches.

For Pb, concerns over the environmental impacts of its use (e.g., fuel/petrol, paints) has led to a slowing of growth in Pb demand (relative to Zn), which has affected the economics of Pb mining. By comparison, the broad range of applications for Zn, Cu and Ni with little perceived environmental impacts has seen continuing and rising demand for these particular metals. In terms of mining, this is part of the reason for the major shift in focus from Pb to Zn in Pb–Zn–Ag mining, though it is also related to the fact that Pb–Zn–Ag deposits being mined are gradually declining in Pb grade and recent deposits brought into production have been low in Pb.

For future base metal projects, three major environmental issues that they will have to contend with are energy and water consumption and emissions — energy and emissions due to concerns over climate change impacts (e.g., t CO₂/t Cu) and water resources due to strong, competing demands for water. As ore grades continue to decline, this will place significant upward pressure on energy and water consumption and emissions per unit metal produced. These aspects of ‘sustainable mining’ are becoming more widely recognised (e.g., Nicol, 2001; Norgate and Rankin, 2002; Guerin, 2006).

A possible solution to this is the invention of new process technology, but predicting if and when such technology becomes available is not possible (and would be pure speculation). As noted in the respective historical overviews, several precedents for new technologies do exist in history, including pyritic smelting at Mt Lyell, flotation technology, and new Ni laterite processing technology (HPAL). The critical issue is whether any new technology will lower not just economic costs but also lower energy, reagent and water consumption per unit metal produced.

Finally, it can be expected in the future that the environmental costs of primary metal production will be commonly compared with those of secondary supply (recycling). This will become especially significant as possible carbon tax schemes arising from climate change protocols are implemented. This leads to further complex influences on the issues of supply–demand and the economics of base metal mining.

The combined impacts of these various aspects and issues in base metal mining on project scales, economics and environmental impacts is difficult to predict. It is possible to extrapolate the trends in the various graphs using statistical techniques. For example, it is possible to predict annual production over the next 50 years using a linear or polynomial regression and therefore assess the extent to which existing resources can meet this cumulative production. However, there is no value in predicting future events of exploration success, technological innovation and environmental constraints as any attempt would almost certainly be incorrect. Overall, it does point to fundamental concerns about the mineral resource and environmental sustainability of existing base metal mining and milling in Australia — a concern shared by many in industry, government and the community.

7. Conclusions

The base metal mining sector has been a prominent and critical feature of the Australian minerals industry for almost two centuries. This paper has compiled and
analysed the available historical production data sets, establishing key trends in mining and milling over this period, including:

- Continually increasing production, verging on exponential for Cu (showing that at least historically supply has kept pace with demand);
- Long-term decline in ore grades (a function of changing economics, technological innovation, and the types of mineral deposits being mined);
- Increasing scale of individual mines, with large-scale open cut mining becoming progressively more common;
- Exponential increases in waste rock production, especially by open cut mining (waste rock data is mostly not reported by underground or open cut mines);
- Steady to significant increases in known economic resources over time, especially for Cu and Ni though Pb–Zn–Ag appear to have plateaued (e.g., 2004 Edition, GA, various years);
- Technology has played an absolutely critical role—from exploration through to mining and milling.

All base metals (Cu, Pb–Zn–Ag, Ni) are dominated by a small number of large mines/fields as well as a range of moderate and smaller mines. There are sufficient known economic resources for about three decades or more, providing a basis to sustain the existing industry but from generally lower grade ores. Beyond this time, however, new resources will need to be identified. Whether such projects will continue to remain viable is a vexed issue—these past trends raise clear concerns over the sustainability of base metal mineral resources.

The debate over the future of base metal mining in Australia is inextricably linked to a thorough awareness of the past. Through this detailed knowledge and analysis of the trends in modern mining, such as ore grades, solid wastes, technology, resources and the like, a more considered perspective can be articulated for the current debate on mineral resource trends as well as the environmental aspects of “sustainable mining”.

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Appendix A. References for individual mines and fields

Notes:

1) Periods include years for which production data is available.
2) Production and data may not be continuous during the period shown.
3) For some projects, years for which no production are available is not included.
4) Reference to company annual reports also includes quarterly reports.

var. = various years of publication.

A.1. A. Copper

Queensland

- Cloncurry Field (1883, 1898–1981) (Anonymous, various years; QDM, various years);
- Eloise (1996–2004) (BR, various years; RIU, various years);
- Ernest Henry (1997–2005) (MIM, various years; RIU, various years; Xstrata, various years);
- Great Australia (1996–1997) (CMC, various years; QNRME, various years; RIU, various years);
- Gunpowder–Mt Gordon (also known as Mammoth) (1970–2004) (Brooks, 1965; Mitchell and Moore, 1975; Richardson and Moy, 1998; BMR, various years; QDM, various years; WM, various years);
- Herberton–Chillagoe Field (1883–1942) (Connah, 1965; QDM, various years);
- Highway–Reward (1998–2003) (GR, various years; QNRME, various years; RIU, various years);
- Mt Cuthbert (1997–2002) (Cavaney, 1975; Stuart, 2000; MM, various years; MU, various years);
- Mt Isa (Cu) (1943–2005) (Bennett, 1965; Moyses, 1965; Mathias and Clark, 1975; Smith, 1975; BMR, various years; MIM, various years; QDM, various years; Xstrata, various years);
- Mt Morgan (including Mt Chalmers and tailings re-processing) (1882–1990) (Carne, 1908; Staines, 1953; Anonymous, 1965; Frets and Balde, 1975; MML, 1980; Taube, 1990a, b; QDM, various years; RIU, various years);
OK–Mt Molloy (1883–1930) (QDM, various years);
Osborne (1995–2005) (Adshead et al., 1998; Kaesehagen and Boffey, 1998; PD, various years; PP, various years);
Red Dome (1991–1997) (Nethery and Barr, 1998; Niugini, various years; RIU, various years);
Selwyn (1989–1998) (Fortowski and McCracken, 1998; AR, various years; RIU, various years);
Mt Garnet–Surveyor, Thalanga — see Lead–zinc–silver.

New South Wales

• Cadia Hill (1998–2005) and Ridgeway (2000–2005) (Newcrest, various years), also (Welsh, 1975; Suppel and Clarke, 1990);
• Cobar field, including Great Cobar–Chesney, CSA, Nymagee, New Occidental, Burraga and numerous smaller mines (1870–1922) and CSA (1963–2004) (Carne, 1908; Andrews, 1911a, 1991b, 1928; Kenny, 1923, 1928; Russell and Lewis, 1965; Brooke, 1975; Thompson, 1980; Brown, 1983; Scott and Phillips, 1990; Suppel and Clarke, 1990; Haskard and Chaplain, 1993; Shi and Reed, 1998; BMR, various years; CRA; GSM, various years; NSWDM, various years; NSWDMR, various years; RIU, various years), including data provided by Cobar Mines Pty Ltd (R Morland, personal communication, 31 March 2005);
• Girilambone (intermittent, 1993–2002) (Kenny, 1923; Suppel and Clarke, 1990; Fogarty, 1998; NSWDM, various years; NSWDMR, various years; Straits, various years);
• Northparkes (1994–2005) (Heithersay, 1986; LP and Minmet, various years; North, various years; RT, various years);

Victoria

• Benambra — see Lead–zinc–silver.

Tasmania

• Hellyer, Que River and Rosebery — see Lead–zinc–silver;
• Mt Lyell (1894–2005) (Harcourt Smith, 1897; MLMRCL, 1902; Clark, 1904; Carne, 1908; Nye and Blake, 1938; Anonymous, 1940; David, 1950; Alexander, 1953; Dunkin, 1953; BCGLO, 1956; McLeod, 1965; Moyses, 1965; Raggatt, 1968; Reid, 1975; Hills, 1990; Blaine, 2000; Anonymous, various years; BMR, various years; RGC, various years; TDM, various years).

South Australia

• Burra (1845–1877, 1972–1983) (Sidney, 1852; Austin, 1863; Carne, 1908; Treloar, 1929; Dickinson, 1942, 1990; Higgins, 1956; Johnson, 1965; Wright, 1975; Cumming and Drew, 1987; Robertson, 1995; Armstrong, 2002; Bailey, 2002; BMR, various years; SADM, various years-a,b);
• Kanmantoo (1846–1874, 1970–1976) (Austin, 1863; Carne, 1908; Dickinson, 1942; Anderson, 1980; Both, 1990; Dickinson, 1990; BMR, various years; SADM, various years-a,b);
• Kapunda (1843–1912) (Austin, 1863; Carne, 1908; Dickinson, 1944; Johnson, 1965);
• Moonta–Wallaroo (1860–1923) (Austin, 1863; Ward, 1924; Flint, 1983; Cumming and Drew, 1987; SADM, various years-a,b);
• Mt Gunson/Cattle Grid (intermittent, 1941–1943, 1974–1989) (Johns, 1965; Gelding, 1980; Houston et al., 1982; Dickinson, 1990; Tonkin and Creelman, 1990; Bampton and Winzar, 1993; PIRSA, various years; SADM, various years-a,b);
• Olympic Dam (1988–2005) (Mudd, 2006; BHPB, various years; WMC, various years).

Western Australia

• Horseshoe Lights (Loxton, 1993; RIU, various years);
• Miscellaneous Western Australian Mines/Fields, including Ashburton, Day Dawn, Whim Creek, West Pilbara, Mt Malcolm, Yalgoo, Murchison, Peak Hill, and Northampton, (Low, 1963; Campbell, 1965; Reynolds et al., 1975; Marston, 1979; WADM, various years);
• Nifty (1993–2004) (Straits, various years; WMC, various years-a,b);
• Ravensthorpe–Phillips River Field (1900–1971) (Ellis, 1953; Low, 1963; Ellis and Lord, 1965; Marston, 1979; BMR, various years; WADM, various years);
• Radio Hill, Sally Malay — see nickel;
• Golden Grove, Teutonic Bore — see Lead–zinc–silver.

Northern Territory

• Miscellaneous Northern Territory Mines (Balfour, 1990; QDM, various years);
• Mt Diamond (1956–1957, 1971–1973) (Mudd, 2006; BMR, various years; MB-NTA, various years);
• Rum Jungle (1954–1971) (Barlow, 1965; Lowson, 1975; Mudd, 2006);
• Tennant Creek Field (1948–1999) (Balfour, 1989; Wedekind and Love, 1990; BMR, various years; Normandy, various years; NTDME, various years; RIU, various years).

A.2. B. Lead–Zinc–Silver

Queensland

• Century Zinc (2000–2005) (Pasminco, various years; Zinifex, various years);
• Cannington (1997–2005) (BHP, various years; BHPB, various years);
• Herberton–Chillagoe Field (1883–1942) (Connah, 1965; QDM, various years);
• Mt Garnet–Surveyor (2003–2005) (Connah, 1965; KZ, various years);
• Mt Isa (Pb–Zn–Ag) (1931–2005) (David, 1950; Bennett, 1965; Moyes, 1965; Raggatt, 1968; Mathias and Clark, 1975; Berkman, 1996; Wallis, 2005; BMR, various years; MIM, various years; QDM, various years; Xstrata, various years);
• Thalanga (1988–1999) (Breen and Nice, 1993; Taylor and Rozman, 1993; PM, various years; RGC, various years).

New South Wales

• Broken Hill (1883–2005) (Jaquet, 1894; Clark, 1904; Curtis, 1908; Andrews, 1922; Lewis et al., 1965; Pratten, 1965; Woodward, 1965; Raggatt, 1968; Lines et al., 1987; Mackenzie and Davies, 1990; Anonymous, 1892; BHP, various years; BMR, various years; NSWDM, various years; Pasminco, various years; Zinifex, various years);
• Captain’s Flat (1884–1962) (Carne, 1908; Wilkins and LGMPL, 1948; LGMPL, 1953; Glasson and Paine, 1965; NSWDM, various years);
• Cobar–CSA (1905–1995, year of last Pb–Zn–Ag production) — see copper;
• Elura–Endeavour (1983–2005) (BMR, various years; CBH, var.; Pasminco, various years; Zinifex, various years);
• Miscellaneous small mines, including Sunny Corner, Silver King, Mt Costigan, New Lewis Ponds, Glenn Innes, Webb’s Consols, Pyes Creek and unspecified mines (1884–1965) (NSWDM, various years);
• Peak (1996–2002) (Pb–Zn production) (RIU, various years; RT, various years);

Victoria

• Benambra (1993–1997) (Denehurst, various years).

Tasmania

• Hellyer (1985–1999) (BMR, various years; TDM, various years);
• Que River (1981–1991) (BMR, various years; TDM, various years);
• Rosebery (1913–2005) (Hills, 1919; Finucane, 1932; Anonymous, 1940; Hooper and Black, 1953; Hall et al., 1965; Burton, 1975a, b; Lees et al., 1990; Berry et al., 1998; BMR, various years; Pasminco, various years; TDM, various years; Zinifex, various years);
• Zeehan Field, including Magnet, Murchison River, Montaona, Oceana, Mt Farrell/North Mt Farrell, Mt Stewart, Five Mile/Dundas—Cuni and Mt Wright (1893–1960) (Ward, 1908; Twelvetrees and Ward, 1910; Nye, 1923; McIntosh Reid, 1925; Anonymous, 1940; Groves, 1965; Solomon, 1965; Woodcock, 1965; Burton, 1975a; BMR, various years.; TDM, various years).

South Australia

• Beltana–Aroona (1903–1997) (Rangott, 1980; Carmichael, 1993; Pasminco, various years; RIU, various years; SADM, various years-a, b).

Western Australia

• Cadgebush–Pillara (Lennard Shelf) (1988–2004) (Murphy et al., 1986; BHP, various years; LP and Minmet, various years; RIU, various years; WM, various years);
• Golden Grove (1991–2005) (Newmont, various years; Normandy, various years; RIU, various years);
• Magellan (2005) (IWI, various years);
• Miscellaneous small mines/fields, including Pilbara, West Pilbara, Ashburton, Kimberley and West Kimberley (1901–1959) (Blockley, 1971; WADM, various years);
• Northampton Field (1850–1967) (Maitland, 1900; Campbell, 1965; Blockley, 1971; WADM, various years);
• Teutonic Bore (1981–1985) (BMR, various years; WADM, various years).

**Northern Territory**

• McArthur River (1995–2005) (MIM, various years; Xstrata, various years);
• Mt Evelyn/Moline (1967–1970) (BMR, various years; MB-NTA, various years);
• Woodcutters (1985–1999) (Aztec, various years; BMR, various years; Nicron, various years; Normandy, various years; NTDME, various years; RIU, various years), including additional data provided by NTDPIFM (NT Department of Primary Industries, Fisheries and Mines, personal communication, Deonnie Brennan, 19 December, 2003).

**A.3. C. Nickel**

**Queensland**

• Greenvale (1974–1992) and Brolga (1993–1995) (Parianos et al., 1998; BMR, various years; QDM, various years; QNI, various years), including additional data provided by QNI (Queensland Nickel International Ltd, personal communication, Brian Watt, 13 February 2004).

**Western Australia**

• Black Swan (1997–2004) (MPI, various years);
• Bulong (1999–2002) (O’Callaghan, 2003; PR, various years);
• Cawse (1998–2000) (CME, various years);
• Cosmos (2000–2004) (JM, various years);
• Emily Ann–Maggie Hays (2001–2004) (LionOre, various years);
• Forrestania (1995–1998, missing data for some years) (Frost et al., 1998; RIU, various years);
• Kambalda Field (WMC operated and other mines feeding the Kambalda mill) (1967–2004) (Botica, 1980; Palmer, 1980; Marston, 1984; Cowden and Roberts, 1990; Gresham, 1990; Hill and Gole, 1990; Stone and Masterman, 1998; AM, various years; BMR, various years; IG, various years; Mincor, various years; Reliance, various years; RIU, various years; Titan, various years; View, various years; WADM, various years; WMC, various years-b);
• Leinster–Agnew (1978–2004) (Hepburn-Brown, 1993; Libby et al., 1998; BMR, various years; RIU, various years; WADM, various years; WMC, various years-b);
• Mt Keith (1994–2004) (WMC, various years-b);
• Mt Windarra–South Windarra (1973–1991) (Tastula, 1980; Reddell and Schmullian, 1990; Larke, 1993; BMR, various years; WMC, various years-b);
• Murrin Murrin (2000–2004) (AN, various years; MR, various years);
• Radio Hill (1998–2002, 2004) (Fox, various years; Titan, various years);
• Sally Malay (2004) (SMM, various years);

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