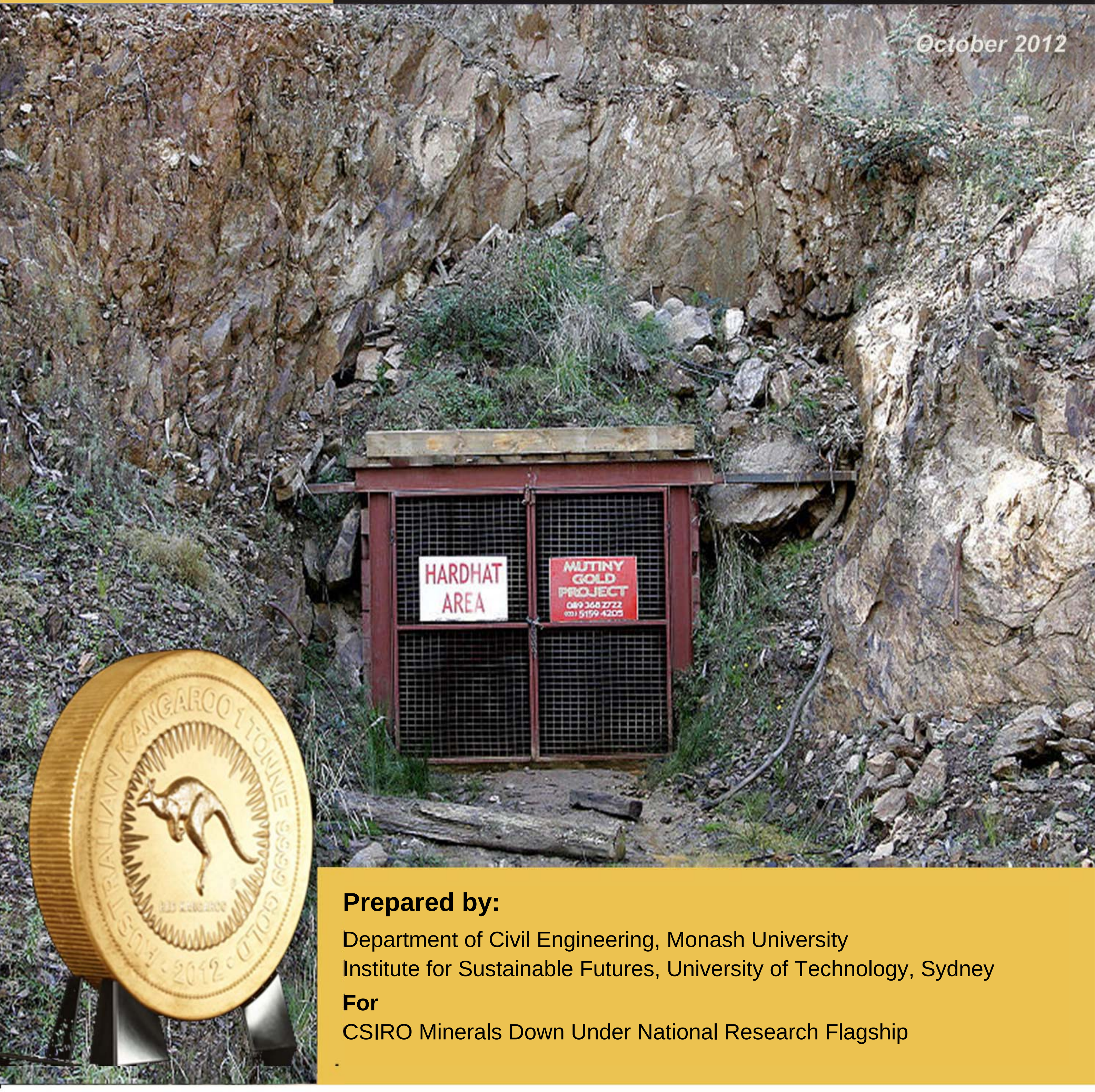
CLUSTER
RESEARCH
REPORT
No. 1.11

Gold resources and production: Australia in a global context

G. Mudd, D. Giurco, S. Mohr, L. Mason



October 2012

Prepared by:

Department of Civil Engineering, Monash University
Institute for Sustainable Futures, University of Technology, Sydney

For

CSIRO Minerals Down Under National Research Flagship

National Research FLAGSHIPS Minerals Down Under
CSIRO
The University of Queensland Australia
Curtin University of Technology
CQUniversity Australia
ANU The Australian National University
University of Technology Sydney

ABOUT THE AUTHORS

Department of Civil Engineering: Monash University

The Department of Civil Engineering, within the Faculty of Engineering at Monash University aims to provide high quality Civil Engineering education, research and professional services globally for the mutual benefit of the students, the staff, the University, industry, the profession and the wider community

For further information visit www.eng.monash.edu.au/civil/

Research team:
Dr. Gavin M. Mudd, Senior Lecturer;
Mr. Zehan Weng, Research Assistant.

Institute for Sustainable Futures: University of Technology, Sydney

The Institute for Sustainable Futures (ISF) was established by the University of Technology, Sydney in 1996 to work with industry, government and the community to develop sustainable futures through applied research. Our mission is to create change toward sustainable futures that protect and enhance the environment, human well-being and social equity. We seek to adopt an inter-disciplinary approach to our work and engage our partner organisations in a collaborative process that emphasises strategic decision making.

For further information visit www.isf.uts.edu.au

Research team:
Dr. Steve Mohr, Senior Research Consultant;
Ms. Leah Mason, Senior Research Consultant;
Dr. Damien Giurco, Research Director.

CITATION

Cite this report as:

Mudd, G., Giurco, D., Mohr, S., Mason, L. (2012). *Gold resources and production: Australia in a global context*. Prepared for CSIRO Minerals Down Under Flagship, by the Department of Civil Engineering (Monash University) and the Institute for Sustainable Futures (University of Technology, Sydney), October 2012. ISBN978-1-922173-47-8.

ACKNOWLEDGEMENT

This research has been undertaken as part of the Minerals Futures Research Cluster, a collaborative program between the Australian CSIRO (Commonwealth Scientific Industrial Research Organisation); The University of Queensland; The University of Technology, Sydney; Curtin University; CQUniversity; and The Australian National University. The authors gratefully acknowledge the contribution each partner and the CSIRO Flagship Collaboration Fund. The Minerals Futures Cluster is a part of the Minerals Down Under National Research Flagship, http://www.csiro.au/Organisation-Structure/Flagships/Minerals-Down-Under-Flagship/mineral-futures-collaboration-cluster.aspx.

Cover image: Gold mine in Victoria, Australia (Fir0002/Flagstaffotos) and 1 tonne gold coin (Perth Mint)

CONTENTS

FIGURES

TABLES

1. BACKGROUND

This report forms part of the Commodity Futures component of the Mineral Futures Collaboration Cluster as a case study on gold in Australia. The Commodity Futures project focuses on the macro-scale challenges, the dynamics, and drivers of change facing the Australian minerals industry. The Commodity Futures project aims to:

- Explore plausible and preferable future scenarios for the Australian minerals industry that maximise national benefit in the coming 30 to 50 years
- Identify strategies for improved resource governance for sustainability across scales, from regional to national and international
- Establish a detailed understanding of the dynamics of peak minerals in Australia, with regional, national and international implications
- Develop strategies to maximise value from mineral wealth over generations, including an analysis of Australia's long-term competitiveness for specified minerals post-peak.

This report covers the case study on gold mining in Australia and assembles a valuable 'bottom-up' data compendium on available resources and production. It also explores changes in environmental and technological challenges facing gold-related mining and mineral industries in Australia in a global context.

1.1. Aim

The aim of this report is to provide a comprehensive data source on gold resources and production. In addition, discussion of the link between resources, technology and changing environmental impacts over time provides a basis for informing future research priorities in technology and resource governance models.

Given that gold has shown boom-bust cycles in the past, it is therefore important to assess in detail the current state of Australia's gold industry, especially in comparison to global trends and issues, with a view to ensuring the maximum long-term benefit from Australia's gold mining sector. This report aims to achieve such a detailed study – examining key trends in gold mining, such as economic resources, production and environmental issues, and placing these in context of the global gold industry. In this manner, it is possible to assess the current state of Australia's gold industry and facilitate informed debate and decision making on the future of the sector.

1.2. Introduction

Gold is a lustrous, yellow metal which is malleable and relatively chemically inert. Throughout human history, gold has enjoyed a special place as a preferred metal for jewellery and signifying wealth and power – with widespread gold use by the ancient Egyptians and across Europe and Asia. After the discovery of gold in California in 1848 and eastern Australia in 1851, massive gold rushes ensued which saw hundreds of thousands of people flock to the areas to strike it rich. The biggest boom was to come from the discovery of the Witwatersrand Basin in northern South Africa in 1886. Gold was a central factor in the rapid economic development of these otherwise fledgling colonies.

By the mid-20th century, however, the role and importance of gold had substantially declined and its production was relatively minor throughout the world (except for South Africa, which still dominated). In the 1970s, two key events propelled gold to a new and even bigger boom – the deregulation of the gold price and the development of carbon-in-pulp (CIP) process technology. These two outcomes led to a major global revival of the gold mining industry, since lower grade ores could be readily processed using CIP technology and the sustained higher prices ensured profitable operations.

At the start of the 21st century, gold mining was a major economic activity for Australia, USA, South Africa (but declining), and many countries around the world. Global production over the 2000s has been somewhat stagnant, averaging around 2,500 tonnes per year (or about 80.4 million ounces or 'oz'[1]). The ongoing rise in demand (particularly from India. but also China) as well as global financial uncertainty has been a major factor in the continuing rise in the gold price, reaching record highs of some $48,000 per kilogram (i.e. ~$1,500/oz) in early 2011 – which is helping to reverse the trend of stagnant production.

Australia remains a major global gold producer, with production of ~261 tonnes in 2010 (ABARE, var.-a), and is ranked second behind China with ~345 tonnes (USGS, var.-a). The USA held third place in 2010 with ~230 tonnes, while South Africa and Russia both produced ~190 tonnes. A perceived advantage of Australia's gold industry is extensive gold mineral resources and highly prospective regions for new discoveries or additions to existing deposits or mines.

For some regions around the world, especially developing nations, small scale and artisanal mining can be an important source of gold. Whilst it supports livelihoods and communities, it is not without significant environmental impacts and health impacts for miners. Given that this activity is extremely limited in Australia, this report will not cover this part of the global gold industry – although small scale and artisanal gold mining remains a crucial nexus between social, environmental and economic issues in these regions.

---

[1] Metric units are used throughout this report, but given the enduring popularity of the ounce in the gold industry, limited reference is still made to this unit where reasonable.

The dominant uses of gold continue to be jewellery and storage of financial value[2], with both uses lending themselves to long product life and easy recycling. A minor proportion of gold is used in electronics, dentistry and other areas. This makes gold very unique in comparison to almost all other mineral and metal commodities, which have utilitarian uses such as pipes, cars, infrastructure, energy, chemicals, and so on.

---

[2] In 2011, jewellery and financial demand was 48.3% and 36.6%, respectively (WGC, var.); see later section.

2. THE GOLD MINING SECTOR

2.1. Brief history of gold mining

Throughout recent human history, gold has enjoyed a special role as a preferred metal for jewellery and signifying wealth and power – with widespread gold use by various ancient societies, across Europe and Asia. The possession of gold was therefore tightly controlled to ensure that the state had control of wealth and power (especially monarchies).

This monopoly was broken when gold was found in California in the United States of America (USA) in 1848 – and, given it was 'finders keepers', this lead to a population surge in 1849 with immigrants hoping to strike it rich. In 1851, gold was discovered in eastern Australia and the world saw another major gold rush – hundreds of thousands of people flocked from Europe, including some from China, to strike it rich in Australia. In 1886, gold was discovered in northern South Africa, an area to become known as the Witwatersrand Basin, and this region dominated global gold production for the next century. Gold was a central factor in the rapid economic development of these otherwise fledgling colonies, as well as conflicts such as the second Boer War in South Africa (1899-1902).

Following the Boer War, South Africa rose to global dominance of gold production and remained the world's leading annual producer until 2007 when China took over the mantle of world's largest producer. South African production grew rapidly after the Boer War, rising to 289.2 t by 1916 and rising gradually to a peak of 448.1 t in 1941, averaging 370 t/year throughout the 1930-40s (Hartnady, 2009; Mudd, 2007a). After World War 2, however, gold production staged remarkable growth and surged to a new peak of 1,000 t in 1970 – mainly due to the development of deep new fields at Carletonville, Klerksdorp, Free State and Evander (Hartnady, 2009). Since this high point the decline in South African gold production has been terminal – and in 2010 was only 190 t (USGS, var.-a). Over a period of about 125 years, South African production has totalled some 51,500 t – about three times its nearest rival, the USA, with some 17,400 t (data updated from (Mudd, 2007a). Throughout the vast majority of the twentieth century, South Africa dominated annual world gold production, led by its rich endowment in the Witwatersrand Basin.

By the 1970s, the US Bureau of Mines had developed a new method of using cyanide to leach gold. The process involved the use of carbon to adsorb cyanide-gold complexes suspended in a pulp, and became known as carbon-in-pulp or CIP. The advent of CIP was a breakthrough for gold processing, as it was a very robust and reliable gold extraction process, could obtain high recoveries and was generally insensitive to water quality – allowing even highly saline brines to be used. The use of CIP allows low grade ores to be processed as well as the emergence of heap leaching for gold (Close, 2002; Mudd, 2007a).

Around the same time as the development of CIP process technology (and its close variants), the gold price began to rise. Historically, the gold price had been constant and maintained by governments. However, in 1968, this financial system was failing and private gold prices were allowed to fluctuate while government accounts still used the fixed price. In 1975 the gold price was left completely to the market – and it began a strong and permanent rise.

Combined, the emergence of CIP technology and the rising gold price led to an astounding resurgence in gold exploration and mining worldwide – led by countries such as the USA, Australia, Canada and increasingly less developed countries such as Ghana, Peru and most recently China emerging as the world leader from 2007. A new global record for annual production of 2,616 t was reached in 2001, with production since averaging ~2,500 t.

2.2. Historical gold price

The price of gold was fixed at a constant value for centuries, largely to facilitate regulation and control of gold ownership. Throughout the 1800s the price in the British Empire, and colonies such as Australia, was set at £3.17s.10d/oz (or £3.89/oz) (Officer & Williamson, 2010) (~US$600/kg; (Kelly *et al.*, 2010). The price was increased slightly during the 1930s Great Depression, leading to a relatively minor boom in production terms though this was primarily helpful in socio-economic terms. The principal structural problem facing gold miners was a constant price, declining ore grades and increasing production costs – gradually leading to many mines becoming unprofitable and fields closing down.

In 1970, the gold price was $1,036 per kilogram (or $32 per ounce), or in US currency US$1,156/kg (US$36/oz) – but due to partial deregulation of the private gold price in 1968, it had reached $3,951/kg by 1975 (US$5,184/kg) (ABARE, var.-b). In 1975, the gold price was fully deregulated, and by 1980 had reached $17,280/kg (US$19,695/kg). Since this time, the gold price fluctuated in this range, but began to rise consistently from 2004 and reached record historical highs of $48,000/kg in early 2011. The long-term trend in nominal prices of the day and real prices relative to US$1998 is shown in Figure 1.

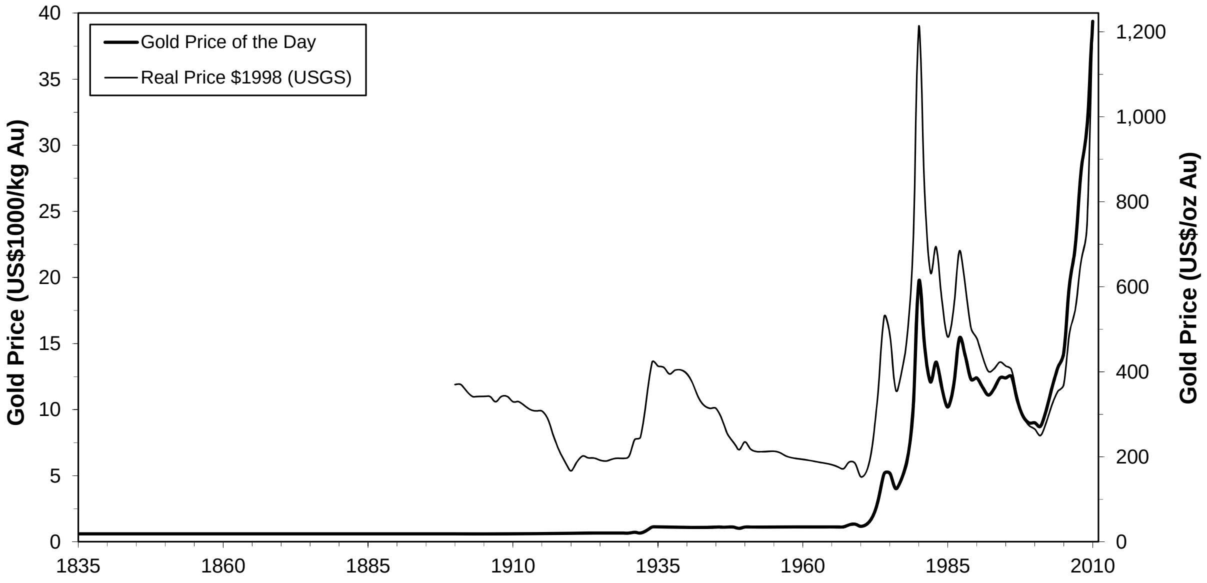


Figure 1: Gold prices in nominal (prices of the day) and real prices (inflation-adjusted to US$1998) (data combined from (Kelly *et al.*, 2010; Officer & Williamson, 2010)

2.3. Historical gold demand

The major demands for gold have historically always been for jewellery and financial uses, with jewellery now the principal demand. Of the total yearly supply of gold to the market, 90% goes to fabricated products, and 10% to private investors and monetary reserves. Jewellery accounts for 85% of world gold fabricated each year (USGS 2005). The most important countries for demand are India, China and, to a moderate extent, those in the Middle East. Gold demand by source and country/region is shown in Figure 2.

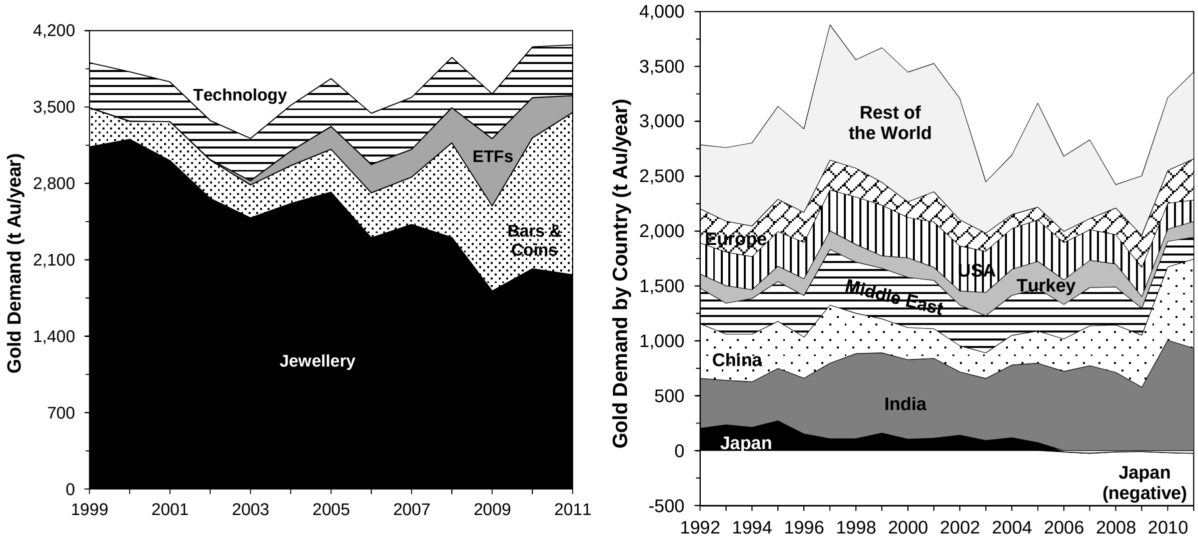


Figure 2: Gold demand by type (left) and country (right) (data from (WGC, var.)

Note: differences are due to WGC data.

In many developing countries, there still remains a functional overlap between gold jewellery and money. Most of the gold mined in the last millennia still exists in an above ground, trillion-dollar 'potential stockpile' adding a unique twist to the 'sociotechnical landscape' for gold.

The technological uses for gold are primarily electronics, but (WGC, var.) statistics also include dentistry in this category. The recent establishment of ETFs, or Exchange Traded Funds, has provided a new demand for gold, and they allow people to invest in the price of gold backed by physical gold bullion. The rise of ETFs has offset the general decline in jewellery demand throughout the 2000s. The ongoing rise in demand in India and China is generally making up for declines across the rest of the world, especially countries like Japan which now effectively sells gold rather than demanding it (i.e. negative demand).

The variety of uses that global culture has for gold highlights significant differences in drivers for different metals.

2.4. Gold ores

2.4.1. Types of gold ores

Gold can be found in a wide variety of economic ore types, in either stand-alone ores or in conjunction with a range of other metals such as copper, silver, zinc, and others. Gold can be extracted from polymetallic ores as a co- or by-product, depending on relative grades, market prices and ore processing configuration. In general, the dominant source has been gold-only ores, but increasingly gold is being extracted from copper-gold, silver-gold or other polymetallic deposits (e.g. Pb-Zn-Ag-Cu-Au).

The principal types of economic gold ores include (McKibben, 2005; USEPA, 1994):

- **Archaean Gold-Quartz Conglomerates ('Palaeoplacers')**: lithified and metamorphosed coarse sediments of Archaean age (about 2.5 billion years old), with both placer and hydrothermal models proposed for gold emplacement. The biggest example is the Witwatersrand gold field of South Africa, which has produced more than a third of the world's gold.
- **Orogenic Lode**: metamorphosed rocks formed during orogenic (mountain-building) events, occurring near major tectonic shear zones. The ages of orogenic gold deposits can range from Archaean to Mesozoic or Tertiary (about 250 to 2.5 million years ago). The 1849 gold rush of California was based on the Mother Lode orogenic gold district.
- **Epithermal**: deposits formed during shallow volcanism, and associated hydrothermal fluid movements, giving rise to high grade veins and/or disseminated low grade ores. Famous examples include Cripple Creek in Colorado, USA and Lihir Island in Papua New Guinea.
- **Carlin-Type**: a hybrid somewhere between orogenic and epithermal deposits, and contains finely disseminated low grade ores. The name is based on the dominant example of the Carlin District in Nevada, USA.
- **By-Product**: gold is commonly found in association with porphyry and skarn copper deposits (e.g. Bingham Canyon, USA; Grasberg, West Papua, Indonesia), volcanogenic massive sulfide deposits (e.g. Mt Lyell, Tasmania; Golden Grove, Western Australia), or iron oxide copper-gold deposits (e.g. Olympic Dam, South Australia).
- **Placers**: gold can often be found enriched in some alluvial sediments, due to weathering of nearby primary ores. Placer operations can range from a single person panning for gold through to large scale dredging works, though overall placer-derived gold is relatively minor in global terms. Some important areas for placer mining include Alaska and the Yukon in North America or New Zealand.

In general, gold can be widely found in a metallic (or native) state, often associated with silver, but it can also form sulfide or other specific minerals with elements such as telluride, mercury, arsenic, antimony or others. The mineral form of gold plays a key role in a deposit's characteristics, such as high or low grades and refractory or readily extractable, and the ability to efficiently extract it with different ore processing technologies.

2.4.2. Defining gold ore reserves and resources

In the gold rush days, miners would simply prospect for new exposures of visible gold reefs, or through alluvial panning of river sediments. When a new field was discovered, this was mined until it appeared that the gold had been exhausted, or economics made further efforts unattractive. Many fields during the gold rush times were thereby subject to rapid boom/bust cycles of population immigration and emigration.

For the gold mines that did last the decades into the middle 20th century, however, a more sophisticated approach was developed to mine planning and development. By the 1950s, it was common for gold mines to estimate remaining reserves through advance drilling and assaying and mine development, with blocks or stopes of ore outlined forming the basis for ongoing mining and gold production. For example, the gold mines of Kalgoorlie in 1950 had ~10.5 Mt of ore reserves yielding[3] ~7.8 g/t and containing ~82.4 t outlined in underground mine development and processed about ~1.6 Mt ore/year yielding ~7.5 g/t for ~12.3 t/year (Campbell, 1953). Thus, in 1950, the Kalgoorlie 'Golden Mile' only had 6.5 years remaining – yet it is still operating in 2011, having been in continuous operation (including the massive expansion as part of the 'SuperPit' in 1989).

From a geochemical perspective, the average concentration of gold in the upper continental crust is 1.5 µg/kg (i.e. parts per billion or ppb, also mg/t) (Rudnick & Gao, 2003), making gold a relatively rare element compared to most other metals mined. In general, an economic gold ore needs a concentration of several parts per million – or grams per tonne (g/t). In the earliest days of the gold rush, ore grades for hard rock gold mines would average nearly an ounce per tonne or 20-30 g/t (with the gold often visible at this grade), whereas a modern gold mine can now process grades as low as 0.5 g/t profitably (typically using heap leach, with the gold being invisible), and by-product mines having grades as low as 0.1 g/t.

From the early 1970s, following a range of high profile cases of poor reporting of mineral resources in the Australian mining industry (e.g. the Poseidon nickel affair, or Nabarlek uranium reserves bungle; see Sykes, 1995), the industry developed a systematic code to estimate mineral reserves and resources. The code was named after its committee, the Joint Ore Reserves Committee Code – or 'JORC' Code, with its first edition released in 1974, and many updates and revision have been issued since. The most recent version of the JORC Code was released in 2004 (AusIMM et al., 2004), and is compulsory for all mining and exploration companies listed on the Australian Stock Exchange – as well as now being expected as a minimum standard by financiers and shareholders to ensure high quality estimates and certainty for the large investments required in mining projects. There are also equivalent codes in other major mining countries such as Canada (i.e. National Instrument 43-101; see (OSC, 2011), United Kingdom/Western Europe (see PERRRC, 2008) and South Africa (i.e. SAMREC; SAMRCWG, 2009).

---

[3] Yield is gold extracted only, and is not assay or true ore grade.

The two primary aspects that the JORC code considers are geological and economic probability in claiming a mineral resource as 'economic'. However, there are a range of important 'modifying factors' that are important – such as mining, metallurgical, economic, marketing, legal, environmental, social and governmental factors. Furthermore, there are two primary categories of mineral resources – ore reserves and mineral resources. The typical distinction is that ore reserves have a very high economic and geologic probability of profitable extraction, while mineral resources have a reasonable geological probability but are less certain economically. Short definitions are:

- **Ore Reserves:** assessments demonstrate at the time of reporting that economic extraction could reasonably be justified. Ore Reserves are sub-divided in order of increasing confidence into Probable Ore Reserves and Proved Ore Reserves.

- **Mineral Resources:** the location, quantity, grade, geological characteristics and continuity of a Mineral Resource are known, such that there are reasonable prospects for eventual economic extraction; not all modifying factors have been assessed and hence some uncertainty remains. Mineral Resources are sub-divided, in order of increasing geological confidence, into Inferred, Indicated and Measured categories, and can be reported as inclusive of ore reserves, or separate and in addition to ore reserves.

To avoid possible confusion with the JORC code, all reference to 'resources' will be used in the general sense as discussed in Appendix A. When the specific terms of ore reserves or mineral resources are used, they are intended to be consistent with the JORC code. For completeness, the full definitions of ore reserves, mineral resources and their sub-categories are included in Appendix A. A conceptual relationship of ore reserves and mineral resources is shown in Figure 3.

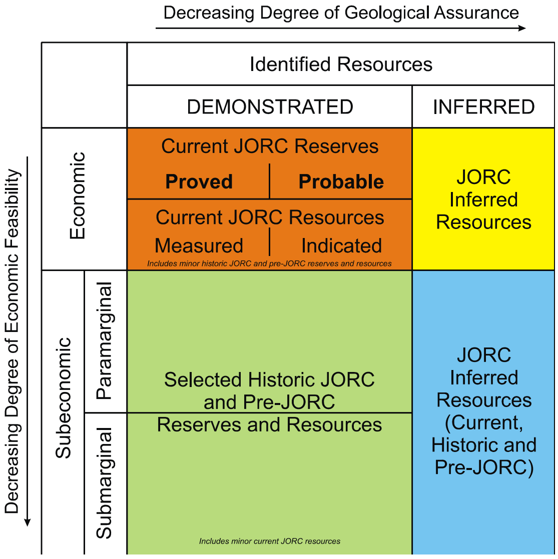


Figure 3: Differing categories and relationships between ore reserves and mineral resources (Lambert et *al.*, 2009)

The United States Geological Survey (USGS) use 'reserves' and, until very recently the category of 'reserves base' (see (USGS, var.-a). These are broadly similar to JORC's ore reserves and mineral resources, respectively, although the USGS also allow for greater inclusion of inferred mineral resources in the reserves base category (Appendix A). An excellent analysis of JORC, and its comparison to other systems is given by (Lambert et al., 2009). In 2010, the USGS stopped using reserves base, due to its higher uncertainty and confusion it caused in comparison to formal codes such as JORC.

For an exploration or mining company, the reporting of an economic gold reserve or resource therefore comes down to the tonnage of ore (e.g. 1 Mt), its assay grade (e.g. 1 g/t) and the contained amount of gold (e.g. 1 t) – estimated based on extensive drilling and metallurgical testing, relevant statutory approvals for development, mine planning, ore processing design, economic and environmental assessments and so on.

Given the long time frames and large funding required, only the minimum effort is expended to bring a project into full production profitably, and thus with ongoing exploration, efficiencies, or changing economics (such as a rising gold price), a gold mining project may often last considerably longer than its initial reserves may suggest.

2.5. Overview of gold mining and processing technologies

In the height of the gold rush era, most gold was won through manual labour, using methods such as pans and sluicing. As the alluvial fields were exhausted, attention quickly moved to the underlying source quartz reefs. For the vast majority of mines, gold was extracted using underground mining techniques until the advent of the 1980s gold boom, during which time moves were made to large scale, low-grade open cut mines.

In recent decades, a wide variety of underground mining techniques have been developed, ranging from narrow vein techniques for high-grade ores and reefs (e.g. Witwatersrand Basin), to moderate size stopes or even large scale block cave mines. Underground mines are used where the deposit is deep or inaccessible via open cut, and are commonly based on relatively high grades (i.e. >5 g/t). Lower grade ores are excluded during underground mines.

An open cut mine is typically dug using trucks and shovels. Given the cheap relative cost of diesel (until recently), open cut mining is commonly cheaper and extracts most or all of the gold ore, but produces considerable quantities of waste rock. The emergence of ammonia nitrate fuel oil (ANFO) explosives from the 1960s was also a key factor in making open cuts economically viable (Mudd, 2007b).

At some gold projects, they may have several open cut and underground mines in operation simultaneously. Many mines may start as open cuts and as waste-to-ore ratios increase, an underground extension may then be developed. A schematic of a typical gold mining layout is given in Figure 4.

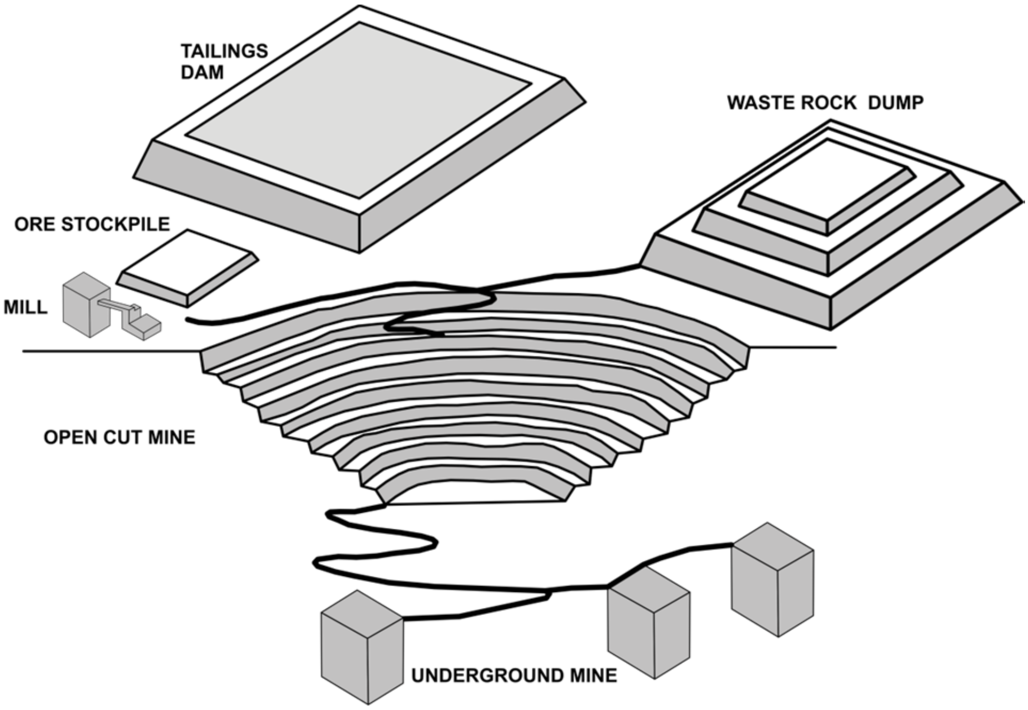


Figure 4: Schematic of a combined open cut and underground mining project (Mudd, 2009a)

Gold can be an especially difficult metal to extract from rocks, depending on mineral form and ore grades, and as such a variety of methods have evolved over time to facilitate economic extraction. In general, very few chemicals dissolve gold, with the main methods using mercury or cyanide. Mercury is direct but not very efficient, as well as being highly toxic. Cyanide is highly selective in dissolving gold and is generally highly efficient, recovering a high fraction of the gold. The discovery of dissolved gold's strong affinity for carbon by the US Bureau of Mines was a major breakthrough in the early 1970s, which rapidly evolved into the carbon-in-pulp (CIP) technology for gold ore processing.

A schematic of the overall approach to gold ore processing is shown in Figure 5, including all major variants of technologies currently in use. The primary technologies include:

- **Carbon-in-Pulp (CIP):** gold is leached from crushed and slurried gold ore using cyanide, the solution is then treated in a separate vessel with activated carbon and the loaded carbon then eluted for gold.
- **Carbon-in-leach (CIL):** gold is leached from crushed and slurried gold ore using cyanide with activated carbon in the same vessel, the loaded carbon is then separated and eluted for gold.

Another possible variation in gold ore processing is the use of thiosulfate , which can also dissolve gold but is less efficient and not as robust as cyanide-based technology (for further details, see Muir & Aylmore, 2004; Heath et al., 2008). The use of thiosulfate would most likely be combined with in situ leach mining methods, but the approach appears to remain uneconomic at present.

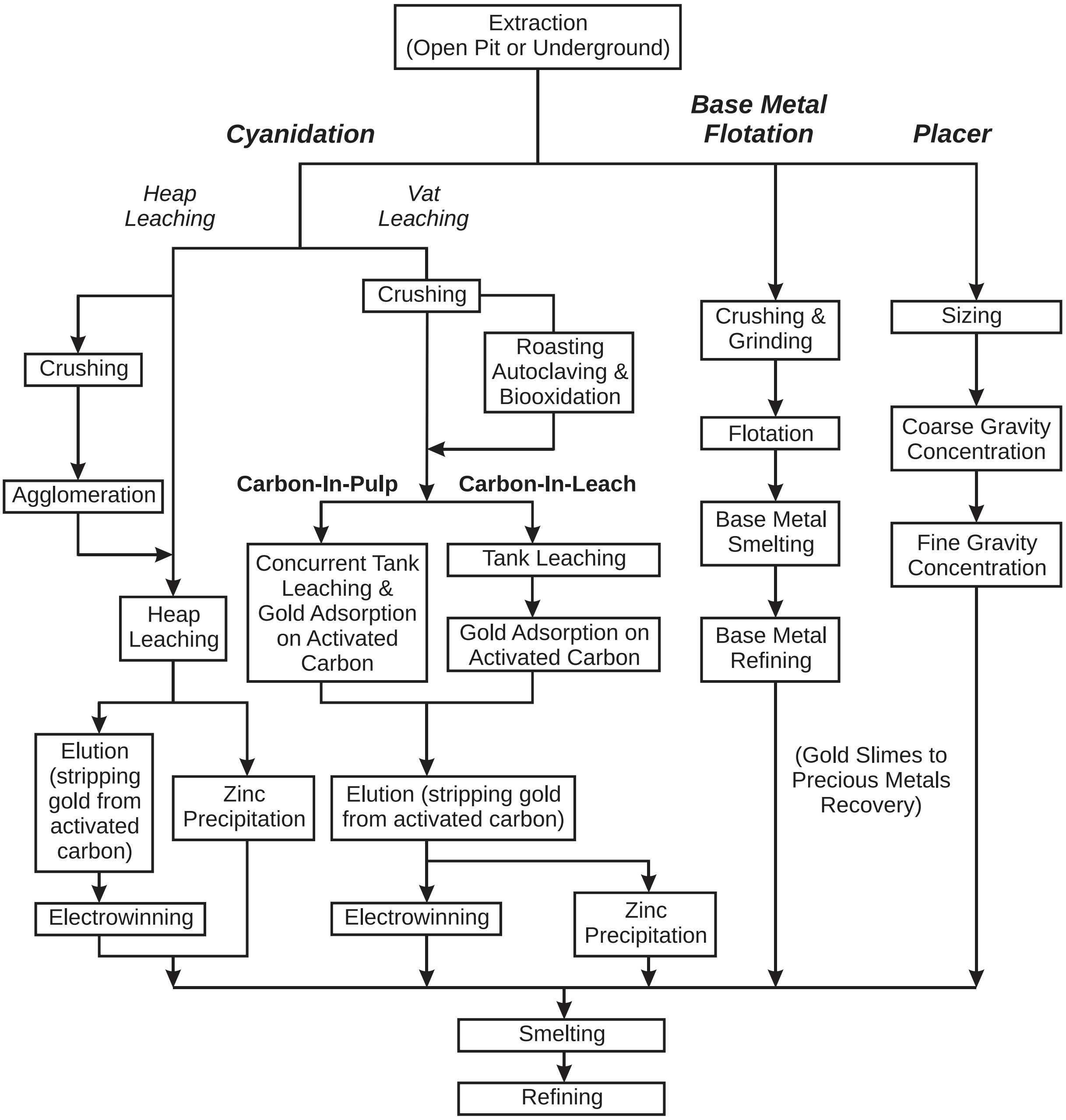


Figure 5: Overview of principal process configurations for gold ore processing and extraction (redrawn from (USEPA, 1994)

- **Merrill Crowe:** gold is precipitated from solutions using zinc dust, which is then separated and further processed.
- **Flotation:** passing air bubbles through an ore slurry containing reagents such as oils allows sulfide minerals to attach to bubble surfaces, preferentially concentrating the sulfides which can then be collected as an enriched concentrate.
- **Gravity:** due to gold's heavy molecular mass, when it is free form it can be readily extracted using simple methods which rely on gravity separation techniques, such as gold panning or sluicing or during crushing and grinding.
- **InLine Leach Reactor (ILR):** specially designed cyanide leach reactor to treat concentrates (a proprietary technology from Gekko Systems), and can be operated in continuous or batch mode.

- **Mercury amalgam:** when mercury is added to gold ore, a gold-mercury amalgam is formed, which can readily be recovered and the gold extracted, although at significant risks of environmental and worker exposure due to mercury's high toxicity.
- **Bioxidation:** bacteria are used in controlled reactors to oxidise the sulfide minerals and liberate the gold from within the sulfide minerals.
- **Roasting:** for refractory sulfide gold ores, roasting (heating the ore) can be used to convert the sulfide to sulfur dioxide and liberate the gold from within the sulfide minerals.
- **Autoclaves and Oxidation Reactors:** for some refractory gold ores, contained reactor vessels are used to process ores at high temperatures and/or pressures to facilitate rapid oxidation and release of gold for subsequent processing.
- **Heap Leach:** for low grade gold ores, rather than processing, ores are placed in large engineered piles (or heaps) and cyanide solutions irrigated across the surface, with the resultant gold-rich solution from the bottom of the heap processed for the gold.
- **Alluvial and Placer Operations:** for alluvial sedimentary gold resources, gold can be extracted by excavation and gravity-based processing methods to extract the gold. Alluvial and placer mines were dominant in the early days of the California and eastern Australia gold rushes, but today represent a minor proportion of gold produced (e.g. Canada, New Zealand).

Although it would be easy to expect that all gold projects simply mine, crush, grind and process ore using CIP/CIL, the reality is that process flowsheets are becoming more complex over time, using a combination of process steps and stages to achieve the most efficient balance between capital and operating costs and maximum recovery is more the norm (as shown later in current gold projects) (see Longley, 2004, and later sub-sections).

3. GLOBAL GOLD MINING DATA

3.1. Historical gold production

The production of gold was relatively minor in scale and localised to small regions in Europe and the Middle East until the gold rushes from 1849 onwards – when gold production began a long inexorable rise through several boom/bust cycles as new fields were discovered or economics or technology changed.

The long-term history of gold production is shown in Figure 6, annotated by the major historical events of the global gold industry. All data is sourced from (ABARE, var.-b; Govett & Harrowell, 1982; Kelly et al., 2010; Schmitz, 1979). From 1848 to 2010, approximately 140,350 tonnes of gold has been produced, with cumulative and annual production by major countries shown in Table 1.

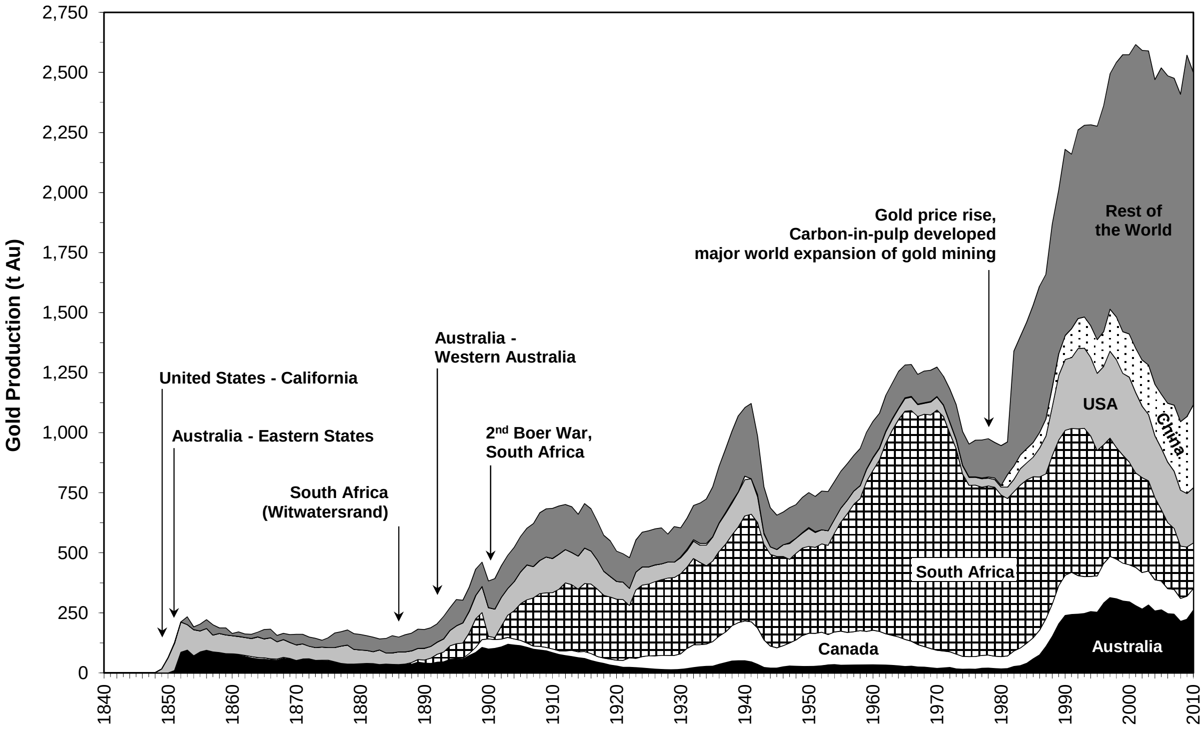


Figure 6: Historical gold production by country (data updated from (Mudd, 2007a)

From Figure 6, it is clear that there are several key phases of gold mining: (i) the 1850s western American and eastern Australia gold rushes; (ii) the 1890s South African and Western Australian gold rushes; (iii) the 1930s Depression-era mini-boom, helped significantly by surges from Canada; (iv) the 1960s surge in South Africa due to the development of the new Carletonville, Klerksdorp, Free State and Evander fields and innovative technologies for increasingly deep mining; and finally (v) the 1980s gold boom facilitated by deregulation of the gold price and the development of carbon-in-pulp cyanide process technology. Each of these phases have a particular major theme, such as new discoveries, changing economics, new technology, or a combination of any or all of these factors. The 1980s gold boom, which in reality is still ongoing, was made possible by all of these features – allowing world gold production to reach an all-time historic high of 2,616 t in 2001, and remaining around 2,500 t/year since.

Table 1: Approximate total gold production by country (1848-2010) and 2010 production by country (data from (ABARE, var.-a; Mudd, 2007a; USBoM, var.; USGS, var.-a, b)

Country	Cumulative Production (t Au)
South Africa	51,500
United States	17,400
Australia	12,250
Canada	10,350
China[#]	~4,900[#]
World	**140,350**

Country	Production in 2010 (t Au)[§]
China	345
Australia	261
USA	230
South Africa	190
Russia	190
Peru	170
Indonesia	120
Ghana	100
Canada	90
Uzbekistan	90
World	**~2,500**

[#] China data is incomplete, covering 1930 to 2010 but with several years missing (mainly late 1930s, mid-1940s and 1950s). Production rose from 2.5 t in 1976, to 7.0 t in 1980 and surged to 52.9 t in 1981 and rose steadily to 345 t in 2010.

[§] Preliminary data.

Given the difficulty in predicting the confluence of technology, markets and exploration discoveries, it is difficult to predict with any certainty whether new records for world gold production can be achieved, though there are certainly some optimists.

A seismic shift in world gold production occurred in 2007 when South Africa lost its century-old crown of the world’s biggest gold producer to China – in many ways a sign of shifting sands in the global mining industry. Unfortunately, data on China’s gold industry is considered very sensitive and is not publicly available, making it impossible to compare and contrast China’s gold industry with other countries.

3.2. Current mines and economic resources

Gold mining has occurred or continues in most regions around the world, with the ebb and flow of the boom-bust cycle evident wherever gold mining ensues. This section briefly documents the major gold mines and economic resources around the world. Unfortunately, data on China is very limited, and despite its status as the world’s biggest producer, reliable and regular data is mainly derived from the few western companies operating in China, or other global sources such as the USGS.

3.2.1. Producing gold mines

A detailed compilation of major gold mines was developed for this report, shown in Table 2, including ore type (i.e. CuAu, Au, AuCu), mine type, processing statistics, waste rock and the principal process configuration used. Only mines producing more than 10 t/year were included. This data represents about a third of 2010 global production of ~2,500 t, and shows the dominance of large mines. At some projects, data is yield only, while others do not clearly report (either in annual reports or online through websites) their process configuration. Waste rock data is mostly reported for open cut mines (with some exceptions), but is never reported for underground mines.

The variation in ore grades is evident, ranging from 0.38 g/t at Bingham Canyon (a Cu-Au-Ag-Mo porphyry deposit) to 24.88 g/t at Gosowong (an epithermal deposit), with most between 0.8 to 5 g/t. The average ore grade is 1.4 g/t while the average waste rock-to-ore ratio is at least 2.4 (given some mines do not report waste rock data).

Table 2: Major global gold mines producing >10 t Au/year (2010 data)

Mine	Country	Metals	Mt ore	g/t Au	kg Au	%Eff.	Mt WR	Process	%OC	%UG	Company (%interest)
Grasberg	Indonesia	CuAuAg	83.122	0.92	62,822	82.15	344.956	Flotation	63	37	Freeport McMoRan$^{82\%}$, Rio Tinto$^{9\%}$, Indonesia Gov't$^{9\%,\#}$
Nevada Group	USA	Au	25.401	2.54	53,959	83.48	143.051	various†	*81*‡	*19*‡	Newmont
Yanacocha	Peru	Au	59.442	0.87	45,468	87.62	105.011	HL, MC, CIP/CIL	100		Newmont$^{51.35\%}$, Condesa$^{43.65\%}$, IFC$^{5\%}$
Goldstrike	USA	Au	7.251	6.41	38,533	82.89	104.952	Autoclave, Roast, CIL	*85*‡	*15*‡	Barrick Gold
Cortez	USA	Au	4.409	8.64	35,485	93.16	106.190	HL, CIL	*85*‡	*15*‡	Barrick Gold
Veladero	Argentina	Au	30.697	1.51	34,863	75.29	41.875	HL, CIP/CIL	100		Barrick Gold
Vaal River Group	South Africa	Au	14.1	2.17	30,198	98.91		CIP, CIL		100	AngloGold Ashanti
Olimpiada	Russia	Au	7.377	3.77	18,162	65.36	50.035	Bio-oxidation	100		Polyus Gold
West Wits Group	South Africa	Au	2.9	8.40	25,284	103.8		CIP		100	AngloGold Ashanti
Lagunas Norte	Peru	Au	20.006	1.34	25,129	93.95	6.644	HL, CIP/CIL	100		Barrick Gold
Lihir	PNG	Au	5.687	5.22	25,094	84.55	38.690	Autoclave, CIL	100		Newcrest Mining
SuperPit	Australia	Au	12.155	2.30	24,507	87.78	57.221	Roast, CIL	96.8	3.2	Newmont$^{50\%}$, Barrick Gold$^{50\%}$
Kupol	Russia	AuAg	1.163	18.04$^{@}$	22,973$^{@}$	109.5$^{@}$		Gravity, CIP/CIL, MC	*~50*‡	*~50*‡	Kinross Gold$^{75\%}$, Chukotka Gov't$^{25\%}$
Batu Hijau	Indonesia	CuAu	43.375	0.65	22,921	81.13	60.112	Flotation	100		Newmont$^{45\%}$, Sumitomo$^{35\%}$, PT Pukuafu Indah$^{20\%}$
Tarkwa	Ghana	Au	23.630	0.98	22,872	98.67	112.424	HL, CIL	100		Gold Fields$^{71.1\%}$, IAMGold$^{18.9\%}$, Ghana Gov't$^{10\%}$
Boddington	Australia	AuCu	26.619	1.03	22,641	82.70	46.071	Flotation, CIP	100		Newmont
Driefontein	South Africa	Au	6.084	3.6	22,076	100.8		CIP		100	Gold Fields
Telfer	Australia	AuCu	22.944	1.06	21,165	87.27	24.721	Flotation, Gravity, CIP	74.5	25.5	Newcrest Mining
Kumtor	Kyrgyz Rep.	Au	5.594	4.02	17,659	78.53	110.872	Flotation, CIL	100		Centerra Gold
Kloof	South Africa	Au	4.299	4.1	17,624	99.99		CIP		100	Gold Fields
Porgera	PNG	Au	5.201	3.77	16,990	86.64	28.425	CIP	*85*‡	*15*‡	Barrick Gold$^{95\%}$, PNG Gov't$^{5\%}$
Newmont Africa	Africa	Au	7.595	2.64	16,950	84.54	35.194	CIL	100		Newmont
Ok Tedi	PNG	CuAu	22.191	0.97	15,129	70.28	16.6	Flotation	100		Ok Tedi Mining
Paracatu	Brazil	Au	42.658	0.45	15,003	78.15		Flotation, Gravity, CIL	100		Kinross Gold
St Ives	Australia	Au	6.649	2.19	14,553	99.80	34.145	HL, CIP	76.9	23.1	Gold Fields

Mine	Country	Metals	Mt ore	g/t Au	kg Au	%Eff.	Mt WR	Process	%OC	%UG	Company (%interest)
Bingham Canyon	USA	CuAuAgMo	53.551	0.38	14,493	71.22		Flotation	100		Rio Tinto
Gosowong	Indonesia	Au	0.579	24.88	13,763	95.54		CIL, MC		100	Newcrest Mining
Rosebel	Suriname	Au	12.832	1.1	12,938	91.66	39.455	Gravity, CIL	100		IAMGold$^{95\%}$
Alumbrera	Argentina	CuAu	37.428	0.46	12,603	73.20	60.123	Flotation	100		Xstrata$^{50\%}$, Goldcorp$^{37.5\%}$, Yamana Gold$^{12.5\%}$
Sunrise Dam	Australia	Au	3.617	3.40	12,313	100.0	15.309	Gravity, CIL	85.7	14.3	AngloGold Ashanti
Beatrix	South Africa	Au	3.051	4.0	12,188	99.87		Gravity, ILR, CIL		100	Gold Fields
Pogo[§]	USA	Au	0.875	~16[§]	12,100	~86[§]		Gravity, CIP		100	Sumitomo
Cadia Hill	Australia	Au	17.512	0.82	11,621	81.00	5.627	Flotation, Gravity	100		Newcrest Mining
Round Mountain	USA	Au	30.348	0.50	11,479	75.65	26.521	HL, Gravity, CIP/CIL	100		Barrick Gold$^{50\%}$, Kinross$^{50\%}$
Geita	Tanzania	Au	4.7	2.36	11,103	100.1		CIL	100		AngloGold Ashanti
Fort Knox	USA	Au	25.735	0.79	10,877	53.50		HL, Gravity, CIP	100		Kinross Gold
AGA Mineração	Brazil	Au	1.6	7.21	10,512	91.12		HL, Roast, CIP/CIL	100		AngloGold Ashanti
Jundee	Australia	Au	1.581	7.20	10,419	91.52		CIP/CIL	100		Newmont
		Totals	**684.4**	**1.40**	**824.5 t**	**~87.8**	**»1,625**				

[#]Grasberg is a joint venture between Freeport McMoRan Copper & Gold, Rio Tinto and the Indonesian Government, with the interests varying each year depending on where ore is sourced from and processed. [†]Newmont's Nevada Group operates 14 mills, using a mix of roasters, autoclaves, flotation and CIP-CIL processing. [‡]Open cut/underground split based on reported resources (actual mining data not reported). [@]Kinross only report in 'gold equivalent' ounces (gold plus 'equivalent value' in silver production), hence the approximate data and excessive recovery – based on reserve-resource data, gold and silver grades are about 10 and 135 g/t, respectively (a ratio of 1:13.5 gold:silver). [§]2010 data not yet reported, values approximated based on 2007-2009 data. WR – waste rock; HL – heap leach; MC – Merrill Crowe; CIP/CIL – carbon-in-pulp/leach; ILR – intensive leach reactor. **Red-bold text** is yield only, **blue-bold text** is assumed (data in both cases is not reported). This table is extensive but not exhaustive, as some countries and companies do not report (e.g. China). Further process configuration from (Adams, 2005; Adams & Wills, 2005).

A surprising outcome is the variability in process configurations adopted. That is, there are many mines still using gravity steps, as well as some using flotation to produce a gold concentrate that is then either leached or roasted. For large copper-gold projects the principal step remains flotation only with the gold later recovered during smelting. At some projects, the use of more specialised process technology, such as autoclaves, roasters or bio-oxidation, is critical and often means the difference between a profitable project or no mine. While carbon-in-pulp or carbon-in-leach remains the dominant process technology, it is increasingly being used in conjunction with a more comprehensive approach to process design and linked to ore characteristics.

3.2.2. Economic gold resources

The US Geological Survey publishes a compilation of world gold reserves through their annual Mineral Commodities Summary report (USGS, var.-a), and shown in Table 3. These assessments, however, are very coarse, and, commonly, the data may not change for several years or more. In addition, if one compares the national resource estimates from federal agencies in Canada and Australia, there are invariably significant differences from the USGS data. For example, in 2008 the USGS report Canadian reserves as 2,000 t compared to the official estimate by Natural Resources Canada of 947 t (NRC, var.). Similarly, the USGS report 2008 Australian reserves as 5,000 t yet Geoscience Australia report economically demonstrated gold resources (equivalent to the USGS reserves category) as 6,255 t (GA, var.). An interesting contrast is China, where production in 2010 was estimated to be 345 t yet reserves are only 1,900 – given the scale of China's gold industry and their favourable geological endowment, it is hard to believe the value of 1,900 t. For comparison, the 2002 edition of the USGS Mineral Commodities Summary states China's gold reserves as 1,000 t and a further reserves base of 4,300 t, values which remained similar up until 2009 (noting that the USGS stopped using the reserves base category from 2010). Therefore, for this report, all principal data will rely on national estimates or detailed compilation of company reported mineral resources based on statutory codes (e.g. JORC, SAMREC, NI43-101) as this is more direct, and appears to be more reliable, than USGS reserves data.

Table 3: USGS 2010 gold reserves by country (t Au) (USGS, var.-a)

Country	Reserves	Country	Reserves
Australia	7,300	**China**	1,900
South Africa	6,000	**Uzbekistan**	1,700
Russia	5,000	**Mexico**	1,400
Chile	3,400	**Ghana**	1,400
Indonesia	3,000	**Papua New Guinea**	1,200
USA	3,000	**Canada**	990
Brazil	2,400	**Rest of the World**	10,000
Peru	2,000	**World**	**51,000**

The majority of gold mining companies are publicly listed on their respective national stock exchange, with some listed in dual jurisdictions, leading to the ready abundance of data on economic gold resources in countries such as Australia, Canada, South Africa and the USA, or countries where these companies operate. Unfortunately, countries such as China and Russia and their respective companies, in general, do not publicly report mineral resource data in the same manner (though Russia is rapidly catching up), and this remains a key gap in any global analysis of gold mineral resources.

Recent economic geology research by (Schodde, 2010) has shown that, at least in the western world, the amount of gold discovered each year is generally declining despite surging exploration budgets, shown in Figure 7. This is also resulting in a major long-term rise in the discovery cost of gold, related to the maturity of major fields, the need to explore deeper as well as declining ore grades (or resource quality)

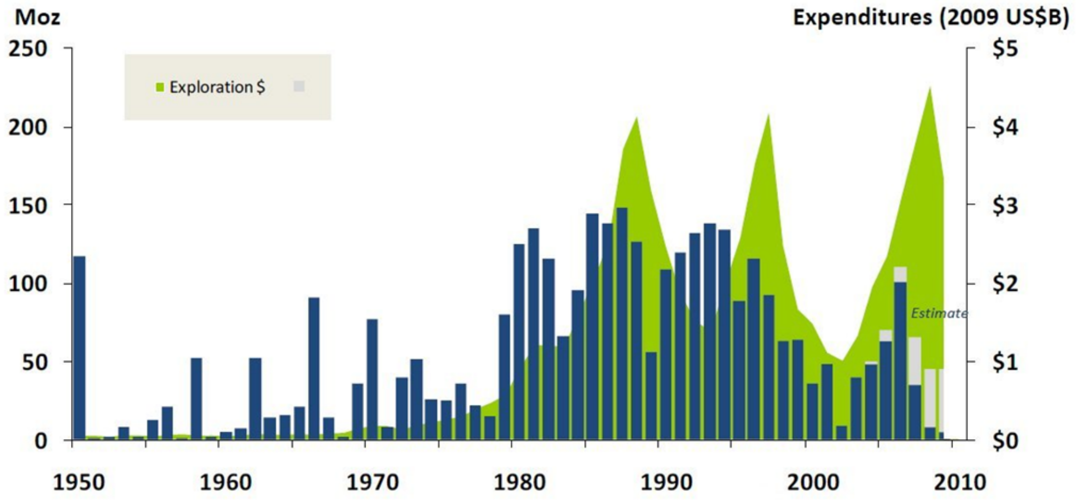


Figure 7: Historical western world gold discovery and exploration expenditure (MinEx Consulting best estimates) (Schodde, 2010)

A detailed compilation of total gold mineral resources attributable to the largest gold companies was compiled and is shown in Table 4, only showing those which report greater than 300 t contained gold.

Table 4: Attributable gold mineral resources >300 t Au by major companies (2010 data)

	Company	Mt ore	g/t Au	t Au	Ore Types	Country of Origin
1	Gold Fields	1,999.2	4.10	8,194.4	Au	South Africa
2	Barrick Gold	7,619.4	1.03	7,812.2	Au, CuAu	Canada
3	AngloGold Ashanti	2,909.8	2.35	6,838.0	Au	South Africa
4	Harmony Gold	2,911.0	2.02	5,875.2	Au, CuAu	South Africa
5	Newmont	4,621.6	0.90	4,138.3	Au, CuAu	USA
6	Polyus Gold	2,191.6	1.66	3,645.4	Au	Russia-Kazakhstan
7	Goldcorp	3,977.6	0.83	3,307.3	Au, CuAu	Canada
8	Kinross Gold	4,517.2	0.72	3,252.1	Au	Canada
9	BHP Billiton	9,226.0	0.33	3,053.5	CuAu	Australia-South Africa
10	Freeport McMoRan Cu & Au	6,178.8	0.48	2,993.2	CuAu	USA
11	Newcrest Mining	5,660.9	0.46	2,593.0	Au, AuCu	Australia
12	Seabridge Gold	3,949.8	0.60	2,357.5	AuCu, Au	Canada
13	DRDGold	1,461.6	1.28	1,870.9	Au	South Africa
14	Northern Dynasty	5,388.5	0.31	1,668.4	CuAu	USA-Canada
15	IAMGold	959.1	1.49	1,430.6	Au	Canada
16	Yamana Gold	3,236.4	0.44	1,416.5	Au, CuAu	Canada
17	Xstrata	6,498.1	0.21	1,347.1	Cu-Au	Sth Africa-Aust.-Canada
18	Agnico-Eagle Mines	423.9	2.89	1,226.0	Au	Canada
19	Ivanhoe Mines[§]	3,404.3[§]	0.35[§]	1,197.0[§]	CuAu	Canada
20	Central Rand Gold	145.9	7.86	1,146.6	Au	UK-South Africa
21	Antofagasta	9,907.6	0.12	1,140.2	CuAu	Chile-UK
22	Simmer & Jack Mines	274.8	4.03	1,106.4	Au	South Africa
23	Rio Tinto	2,645.0	0.41	1,082.2	CuAu	UK-Australia
24	Norilsk Nickel	3,247.0	0.24	775.0	NiCu, CuAu	Russia
25	Eldorado Gold	1,046.5	0.90	942.4	Au	Canada-China
26	Anglo Platinum	6,783.4	0.14	937.1	PGMs	South Africa
27	Randgold Resources	257.8	3.48	896.4	Au	South Africa
28	NovaGold Resources	910.4	0.93	848.1	Au, CuAu	Canada
29	Wits Gold	134.9	5.84	787.3	Au	South Africa
30	Buenaventura	971.1	0.77	745.0	Au, CuAu	Peru
31	Great Basin Gold	115.6	6.18	714.4	Au	Canada
32	Impala Platinum	3,436.6	0.21	713.5	PGMs	South Africa
33	New Gold	1,406.5	0.49	694.2	Au, CuAu	Canada
34	Gold One International	191.2	3.53	674.8	Au	South Africa-Australia
35	Fresnillo	600.6	1.04	623.7	AgAu	Mexico
36	Lihir Gold[#,†]	292.4[#,†]	1.89[#,†]	552.3[#,†]	Au	Australia
37	Imperial Metals	1,905.5	0.28	533.4	CuAu	Canada
38	Centerra Gold	191.0	2.70	515.8	Au	Canada-Kyrgyz Rep.
39	Vale	1,206.8	0.42	511.1	CuAu	Brazil
40	International Minerals	863.8	0.59	506.3	AgAu	USA-Canada
41	Centamin Egypt	304.6	1.49	452.6	Au	Australia-Egypt
42	Benguet Corp	1,040	0.41	426.4	CuAu	Phililppines
43	Taseko Mines	1,010	0.40	409.0	AuCu	Canada
44	Bougainville Copper[‡]	1,064[‡]	0.37[‡]	393.7[‡]	CuAu	Australia-PNG
45	Boliden	2,539.0	0.15	371.8	CuAu	Sweden
46	European Goldfields	241.3	1.49	359.4	CuAu, PbZn, AuAg	UK-Greece
47	Inmet Mining	6,487.8	0.05	351.7	CuAu, PbZn	Canada
48	NGEx Resources	1,482.3	0.23	345.1	CuAu	Canada
49	OZ Minerals	488.4	0.69	337.7	CuAu	Australia
50	Polymetal	119.4	2.76	330.1	AuAg, Au	Kazakhstan-Russia
51	Philex Mining Corporation	415.5	0.79	326.5	CuAu, Au	Philippines
52	Golden Star Resources	136.7	2.29	313.3	Au	Canada
53	Andina Minerals	449.8	0.70	312.9	Au	Canada
54	Citigold	22.8	13.5	307.2	Au	Australia
	Totals	**129,471**	**0.66**	**85,700.3**		

Note: This table is extensive but not exhaustive, as some countries and companies do not report, especially China and other Asian countries (e.g. the giant Muruntau-Zarafshan gold mine formerly operated by Newmont but now owned by the Government of Uzbekistan).

[§] Includes attributable resources through equity in Ivanhoe Australia. [†] Lihir Gold was taken over by Newcrest Mining in September 2010.
[‡] Rio Tinto has 53.58% ownership of Bougainville Copper (not included in the Rio Tinto total).

Table 4 (above) shows that South African gold companies remain dominant in controlling world gold resources, even though the production is no longer centred in South Africa. Other major gold companies are mainly from Australia and Canada, with only single companies listed from Russia, Brazil, Sweden and Peru.

An important point to note about Table 4 is that the resources for some companies are based almost entirely on one super-giant deposit, such as Olympic Dam for BHP Billiton, Oyu Tolgoi for Ivanhoe Mines or Grasberg for Freeport McMoRan – which are all copper-gold resources, a clearly dominant ore type in Table 4.

Although South Africa has lost the crown of world's biggest gold producer, and appears to be a clear case of a post-peak gold producer (see (Hartnady, 2009), the reality is more subtle and complex. Although there are certainly inherent geologic and mining limits for gold in South Africa, it appears that in the post-Apartheid era, the bigger factors are social and environmental issues (e.g. (McCarthy, 2010) and currency exchange rates – since gold is often sold in US$ but costs incurred in South African Rand.

To further illustrate the complexity, a brief analysis has been conducted of reported gold resources for South Africa. Almost all gold producers in South Africa are members of the Chamber of Mines of South Africa (CMSA), with CMSA reporting economic ore reserves every quarter for almost the past decade (CMSA, var.). This data is shown in Figure 8 (below), and demonstrates the general decline in contained gold in ore reserves, albeit with some major fluctuations (presumably due to changing economic conditions) – ore grade, however, of fresh reserves has remained relatively constant at close to 6 g/t while ore grade for tailings has gradually declined (again, presumably related to improving economics). In general, ore reserves only represent those areas of a mine ready for extraction and do not include additional mineral resources, which would substantially increase the amount of gold from that shown.

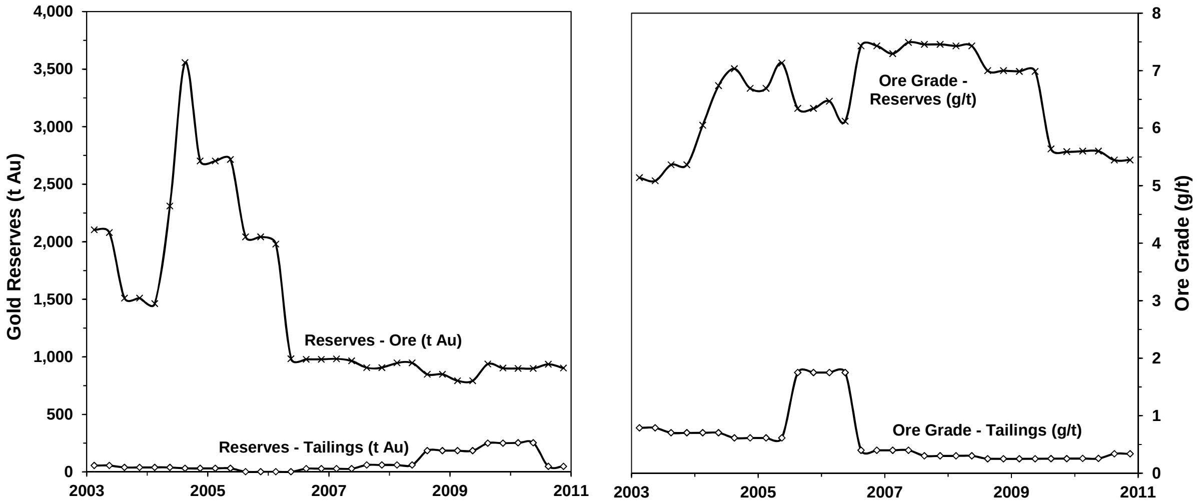


Figure 8: Gold ore reserves for Chambers of Mines of South Africa members (CMSA, var.)

Note: the sudden increase in tailings grades 2005-2007 are most likely due to poor economics leading to higher grades for reserves.

In contrast, a compilation of the total gold mineral resources reported by four major South African gold companies shows a different picture. For Gold Fields, Harmony Gold, AngloGold Ashanti and DRDGold, all ore reserves and mineral resources for their operations in South Africa were compiled, shown in Figure 9 (below).

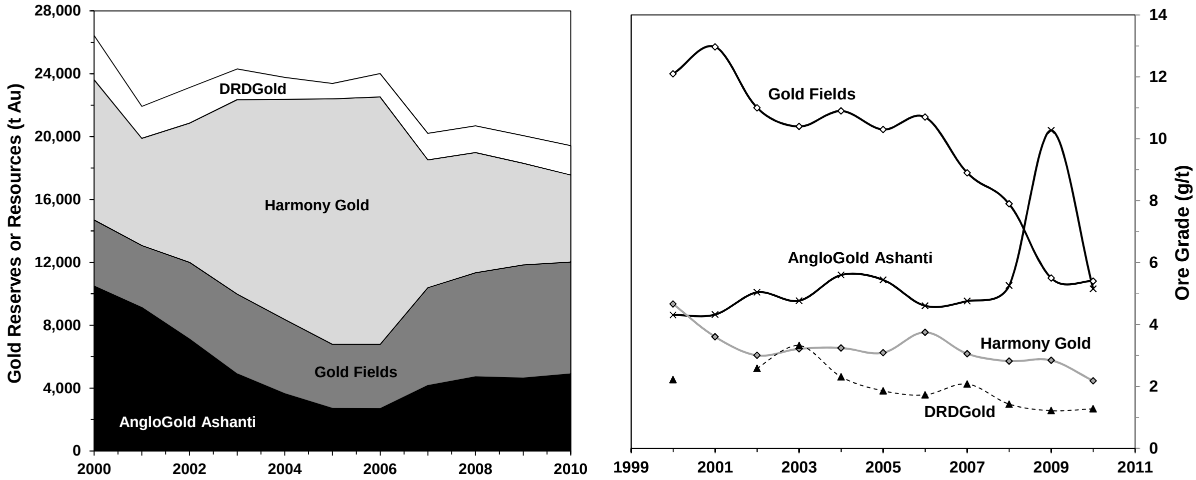


Figure 9: Gold mineral resources over time of four major South African gold companies

Note: all data derived from respective company annual reports.

The data in Figure 9 (above) demonstrates that there are still substantial gold resources remaining in South Africa at reasonable ore grades, with substantial amounts of low grade tailings also becoming increasingly economic to reprocess. The total mass of tailings from the Witwatersrand field is approximately 6.3 billion tonnes (Gt) (data updated from (Mudd, 2007a), and based on various tailings reprocessing projects, if one assumes a typical average grade of 0.25 g/t, this gives some 1,575 t alone – or more than 6-fold reported tailings reserves from (CMSA, var.) but still substantially less than fresh ore reserves and resources.

The gold industry of South Africa, however, has left a heavy legacy of social dislocation from the Apartheid era as well as major and growing environmental impacts from acid and metalliferous drainage (AMD) (McCarthy, 2010), with examples shown later in Figure 13. Furthermore, the Witwatersrand gold reefs invariably contain low concentrations of uranium – making the ore radioactive and raising legitimate concerns over radiation exposure issues as well as AMD impacts (see Winde & Sandham, 2004).

Given the apparently terminal decline of the Witwatersrand gold industry, it is becoming increasingly difficult for government, community and industry to develop a viable strategy to address the gravity and long-term cumulative nature of the impacts. Thus the key challenges for South Africa are not so much the remaining gold resource base, but the best way forward to balance immediate and long-term economic and social needs with environmental remediation of past practices and legacies.

3.3. Key industry trends

There are a variety of key industry trends in the gold mining industry, and these are briefly discussed below.

3.3.1. Declining ore grades

Although it has long been recognised that gold ore grades are gradually declining, it is only recently that quantitative data has been compiled to accurately show the historical statistics and trends (e.g. USA – (Craig & Rimstidt, 1998); Brazil – (Machado & Figueiroa, 2001); Australia – (Mudd, 2007b); South Africa and Canada – (Mudd, 2007a). Ore grades over time are shown in Figure 11, based on recently updated data sets.

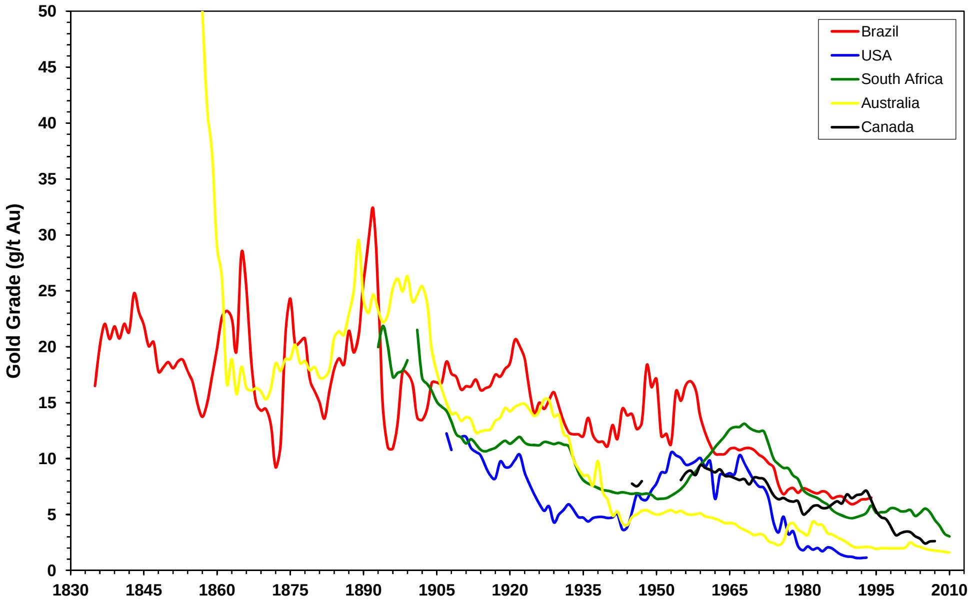


Figure 10: Gold ore grades over time (data updated from (Mudd, 2007a)
Note: Brazil is the Morro Velho mine only (Machado & Figueiroa, 2001).

3.3.2. Variability of economic resources

Some countries show long-term declines in reported economic gold resources, such as Canada and South Africa, while some such as Australia show strong increases over time. In global terms, reported economic resources remain somewhat stagnant, although as shown in section 3.2.2, it is possible to show that national or global estimates can often under-estimate economic gold resources as reported by companies using formal mineral resource codes. When economic resources are considered with respect to annual production, the trend in years remaining is often stable in most cases, declining in some, or increasing as is the case for Australia. The reported data for economic gold resources, by country and globally, as well as years remaining are shown in Figure 11.

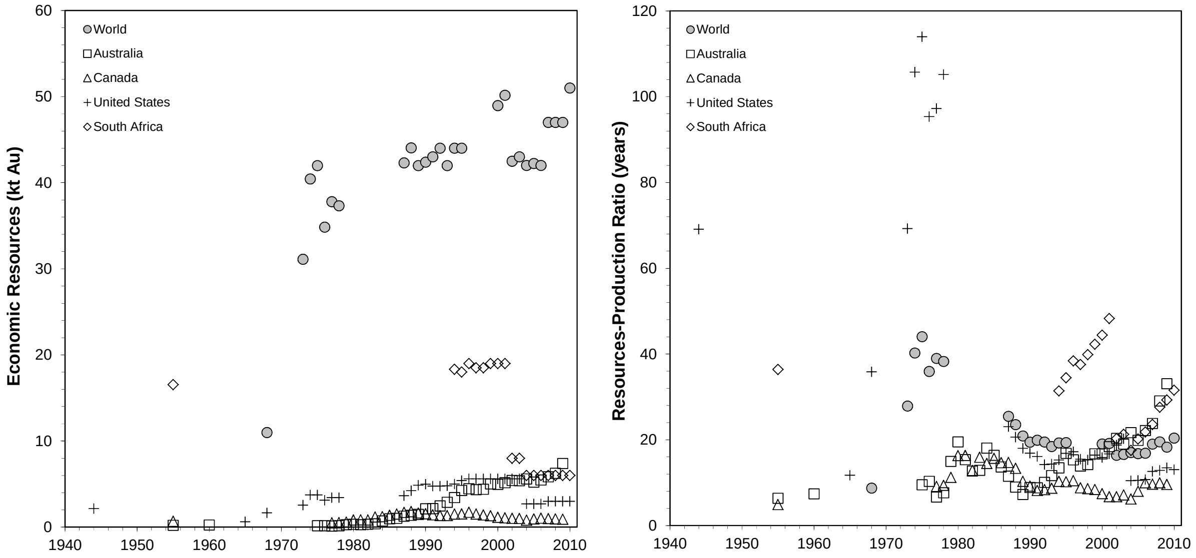


Figure 11: Economic gold resources for some countries (left) and years remaining (right) over time (data updated from (Mudd, 2007a)

3.3.3. Increasing open cut mining and waste rock

For the mines in Table 2, ~87.4% of the ore is sourced from open cut mines, with a minimum waste rock of 1.6 Gt (some mines do not report waste rock data). Open cut mining leads to effectively permanent changes in land use (unless the open cut is completely backfilled), and this represents a significant cumulative impact. In addition, the large mass of waste rock now mined annually also requires pro-active management and rehabilitation, and increases long-term environmental risks – especially if AMD risks are present. Unfortunately, there are no long-term data sets for the extent of open cut mining over time except for Australia (discussed later). A moderate time period of data is reported for Canada by (NRC, var.) from 1977 to 2006, showing a steady rise from 6.4% to 75.6% of ore being sourced from open cut mines. The available data for waste rock and waste rock-to-ore ratios are shown in Figure 12.

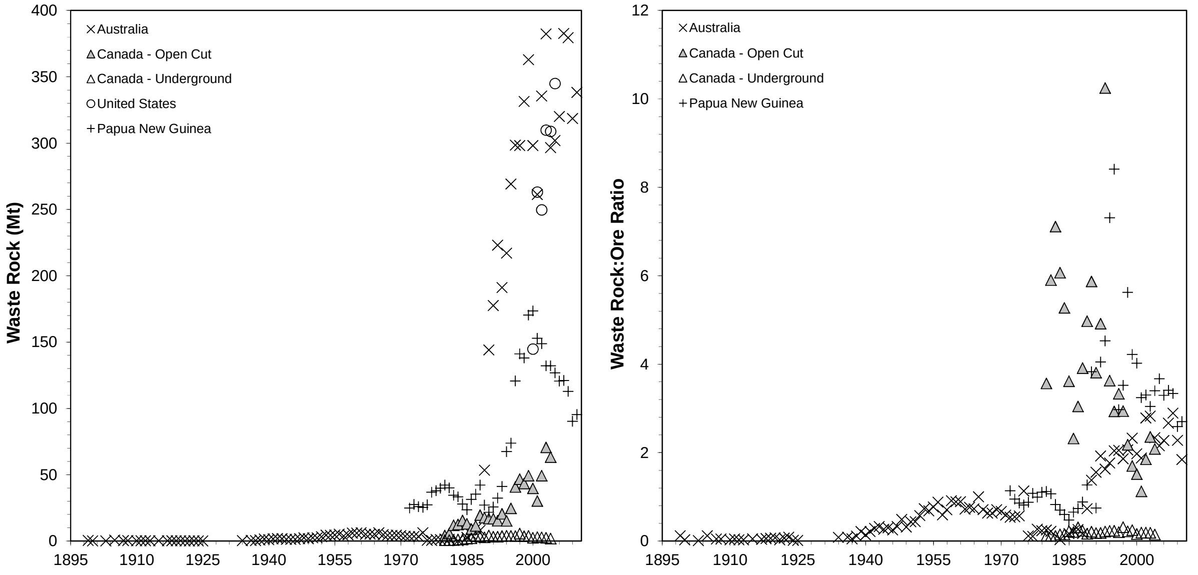


Figure 12: Minimum annual waste rock (left) and waste rock-to-ore ratios (right) over time (data updated from (Mudd, 2007a)

3.3.4. Increasing mine depth

In some countries, near-surface gold deposits have long been exhausted and mines have progressively mined deeper to maintain production. This is epitomised by South Africa, where mines now regularly operate between 2 to 4 km depth (e.g. TauTona). AngloGold Ashanti is now looking to mine even deeper below 4 km to access an exploration target of more than 2,000 t.

While increasing deposit depth commonly leads to underground mining, larger scale open cut mines are being developed in some countries to facilitate profitable projects from large deep deposits (e.g. Boddington in Australia and Yanacocha in Peru). These are often low-grade ores that would be uneconomic as underground mines.

3.3.5. Increasing environmental constraints

There are a number of major environmental constraints facing the gold industry globally, and this sub-section will only briefly examine the principal issues. Examined collectively, they represent significant barriers to future expansion of the gold mining sector, and can sometimes affect ongoing operations at existing mines.

- **Mine Waste Management**: modern gold mining produces massive amounts of tailings and waste rock that requires pro-active planning and management. At some mines, riverine tailings disposal is used at the Porgera and Tolukuma projects, Papua New Guinea (PNG), and this has caused major environmental and social impacts. A small number of mines also use marine tailings disposal, which also causes significant ecosystem impacts – including the former Misima (PNG) and Minahasa (Indonesia) gold mines, as well as operating mines at Lihir (PNG), Simberi (PNG) and Batu Hijau (Indonesia). In developed countries (such as Australia, Canada, USA), environmental regulators have significant influence over mining operations but there are often major concerns raised by local communities over issues such as dust, noise, groundwater impacts and the like. With declining ore grades globally, mine waste management will continue to be a pivotal issue in the ongoing viability and scale of the gold mining sector.
- **Water Resources**: gold mining consumes a significant quantity of water, and its increasing scale also links to catchment impacts on water resources. In arid or semi-arid regions of the world, especially South Africa, Australia and the USA, the security of water supplies can be a constraint or even barrier to project development.
- **Land Use**: although most gold mining occurs in brownfields regions (where there is a history of previous mining), increasingly new projects are being examined or developed in areas of high conservation or cultural value. Many communities believe that there is no compatibility between gold mining in such areas, and this often leads to major social controversy. As such, land use policies can constrain or even prohibit gold mining.
- **Greenhouse Gas Emissions**: gold mining is energy intensive, with the primary sources being diesel for trucks and electricity for the process plant. This means that gold leads to significant greenhouse gas emissions, principally carbon dioxide (CO_2). For a mine with

an ore grade of 3.5 g/t Au, Norgate and Haque (2012) estimated that the carbon intensity would be about 18,000 t CO_2/t Au. Given the global need to reduce emissions to limit the long-term impacts of climate change, many countries around the world have enacted policies to either tax emissions or establish a cap-and-trade system for emissions. There is a clear need for the gold sector to address fuel sources, such as the switch from diesel to biodiesel, as well as low emissions renewable energy sources for electricity.

- **Chemicals**: the use of cyanide is extensive in large-scale gold mining, while mercury is widely used in artisanal or small-scale mining. Due to major tailings dam failures, which led to extensive cyanide contamination of rivers (e.g. Baia Mare, Romania; Omai, Guyana), the gold sector has established the Cyanide Code to ensure that cyanide is transported, used and managed safely. In contrast, some civil society and environmental groups argue that cyanide should be completely banned due to its toxicity and inherent environmental dangers.

The above constraints can be very acute at existing gold mines, or even proposed gold mines, and the increasing availability of information is assisting local communities to become more informed about the risks as well as the benefits of gold mining. Figure 13 shows major impacts of acid mine drainage in the West Rand region of Johannesburg, South Africa.

Figure 13: Gold tailings dumps, acid and metalliferous drainage (AMD), dust and environmental and social conditions in the West Rand, Johannesburg, October 2010 (photos – Mudd, October 2010)

4. GOLD MINING IN AUSTRALIA

4.1. Historical Australian production

There is perhaps no other industrial endeavour that has had such a profound effect on the Australian nation as gold – economically, socially, environmentally and politically. Although there had been numerous observations of the presence of gold in many parts of eastern Australia before 1850, they were not considered of any consequence by their discoverers. The great Californian gold rush, which started in 1848, 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, continuing cycles of boom and bust have characterised the gold industry across Australia, involving wars, depressions and difficult markets. Numerous books and monographs tell the story of the 1850's gold rush and its progression throughout Australia into the early 1900's. Only a brief history is given herein for completeness in reference to the production and resources data, thereby enabling key events to be discerned.

The first Australian gold discovery that led to actual mining operations is believed to be the Victoria mine (originally mined for copper), about 18 km northeast of Adelaide (Horn & Fradd, 1986). It was discovered on 4 April 1846 but quickly proved disappointing, only producing 0.75 kg (i.e. 24 oz). Although there were numerous other occurrences reported around south-east Australia by the end of 1850, like the Victoria mine, they had been of little significance (or this was missed) and did not attract economic attention.

The principal sequence of economic gold fields being discovered and confirmed in various states is:

- 1851 – *February* – New South Wales (Ophir-Bathurst) (Woodall, 1990);
- 1851 – *July* – Victoria (Clunes) (Annear, 1999);
- 1852 – *August* – South Australia (Echunga) (Horn & Fradd, 1986);
- 1852 – Tasmania (Mangana) (Nye & Blake, 1938);
- 1867 – Queensland (Gympie) (Parbo, 1992);
- 1870 – Northern Territory (Pine Creek) (Ahmad *et al.*, 1999);
- 1885 – Western Australia (Kimberley) (Maitland, 1900).

The scale of the 1850's gold rush across Australia was immense. For example, between 1851 to 1860, about 40% of world gold production came from Australia, with the majority from Victoria and New South Wales (Campbell, 1965). Almost all of this production came from alluvial and near surface prospecting. This led to the influx of immigrants from all over the world to the Australian gold fields, causing a major and sustained rise in the total population.

The fields were the centres of emerging prosperity and helped to forge many regional towns and economic centres, many of which survived long after the fields lost their productivity.

Over the decade 1851 to 1860, Australian gold production for 1851 was 9.9 t (320,000 oz), soared to 86.4 t in 1852 and 96.3 t in 1853 and remained stable around 80-90 t/year until 1858. Peak production occurred in 1856 of 96.5 t.

The peak production from the easily won surface gold (alluvial) occurred in 1858 and fell rapidly after this time, with the gold industry then shifting extraction to hard rock mines, primarily quartz reefs (Bowen & Whiting, 1975; Raggatt, 1968). This led to the creation of mining syndicates and companies to cope with the rapidly increasing scale and challenges of individual mines (Fahey, 2001; Woodland, 2002).

This change allowed relatively steady gold production for a period, especially from the major fields of central Victoria, though with increased labour and processing requirements (e.g. batteries). At the turn of 1890, however, Queensland had caught up to Victoria, which by then had begun a gradual decline – the Queensland surge was mainly due to the rich Mt Morgan mine near Rockhampton (with the extensive profits later leading to the establishment of British Petroleum or BP thanks to original Mt Morgan investor William Knox Darcy). This early period of gold production, as well as the social benefits, also saw some severe events such as the Eureka Stockade rebellion at the Ballarat gold field in December 1854 and anti-Chinese riots in some places (e.g. Clunes in VIC as well as Lambing Flat and Burrangong in NSW).

Australian gold production gradually declined towards the late 1800's until the discovery of the rich Coolgardie and Kalgoorlie fields in central Western Australia in 1892 and 1893, respectively. At this time Australian production rose from around 40 t/year over 1889-1892 to reach a new record high of 119.4 t by 1903, of which some 53.7% came from Western Australia. By the turn of the century at 1900 all states had active gold mining and prospecting of various scales. The then gold boom was being driven almost entirely by the Coolgardie-Kalgoorlie fields. In contrast to other states, the Western Australian gold rush was characterised by a very minor amount of alluvial gold with most gold quickly being dominated by hard rock mining and milling (e.g. see data in (WADM, var.). Over 1894 to 1896 a total of 960 new WA-based mining and prospecting companies were floated on the London stock exchange (Woodall & Travis, 1979).

The Western Australian rush rapidly increased Australia's gold output to record levels by 1903, but overall Australian production began a steady decline from this time. The period of World War 1 in Europe, from 1914 to 1918, made further progress for the gold industry difficult. Problems facing many mines included declining ore grades, maintaining a skilled labour supply, increased production costs and a static gold price (but declining in real terms). This forced many mines to close by the early 1920's (Travis & Marston, 1990).

Australia reached a near-historic low in production of 13.3 t in 1929 (throughout the 1920's production hovered around 20 t/year). A minor resurgence in gold mining began in 1932, due to the doubling of the gold price, and reached 51.2 t in 1939, but this was not sustained as World War 2 caused major challenges across the sector. In the 1950's the Commonwealth government introduced a gold mining subsidy scheme, without which several mines would have faced premature closure (Travis & Marston, 1990). Production throughout the 1940's to 1970's generally ranged between 15-30 t/year, including another near-historic low of 15.6 t in 1976.

The discovery of major new gold deposits (or fields) was relatively slow throughout most of the 1900's until the 1970's. In 1971, geologists of BHP and Newmont discovered the large and remote Telfer deposits in northern Western Australia (Royle, 1990). In 1980, following up on earlier geological studies over 1976-78 by the Western Australian Geological Survey and Alwest Pty Ltd, Reynolds Australia Pty Ltd confirmed the surprise discovery of the large Boddington gold deposits south-east of Perth (El-Ansary & Collings, 1990).

From this point forward the gold industry has sustained a remarkable turnaround. The invention of carbon-in-pulp (CIP) cyanide milling technology in the USA (as well as its closely related variant of carbon-in-leach or CIL) facilitated the development of large, low grade deposits through open cut mining (or underground mining, or even both in some cases) (Close, 2002; Huleatt & Jaques, 2005; La Brooy et al., 1994; O'Malley, 1988). This coincided with a sustained increase in the real price of gold, which moved from some US$1,000/kg (US$30/ounce) to reach as high as US$26,000/kg (US$800/ounce), stabilising around US$10,000-14,500/kg (US$300-450/ounce) (e.g. (Kelly et al., 2010; Morgan, 1993).

These two factors combined to facilitate a major resurgence in exploration and production across Australia, led by Western Australia but with Queensland, New South Wales and the Northern Territory also making significant contributions. From the early 1980's the pace of exploration had climbed dramatically and many major new gold resources were outlined, often simply by re-visiting old mines and delineating the low-grade ore around previously mined higher grade lodes. Between 1979 and 1988 there were 16 major gold deposits delineated which contained at least 10 t, including the Boddington-Hedges field of south-west WA at 93.5 t and the Kambalda-St Ives field at 117.9 t (Woodall, 1990).

Australian gold production in 1989 had surged to 204 t, stabilised at around 280-310 t/year over 1996-2003, with a record of 313.6 t in 1997. Production throughout the 2000s has been about 250 t/year. A significant degree of gold is now also produced as a co-product or by-product, particularly with copper.

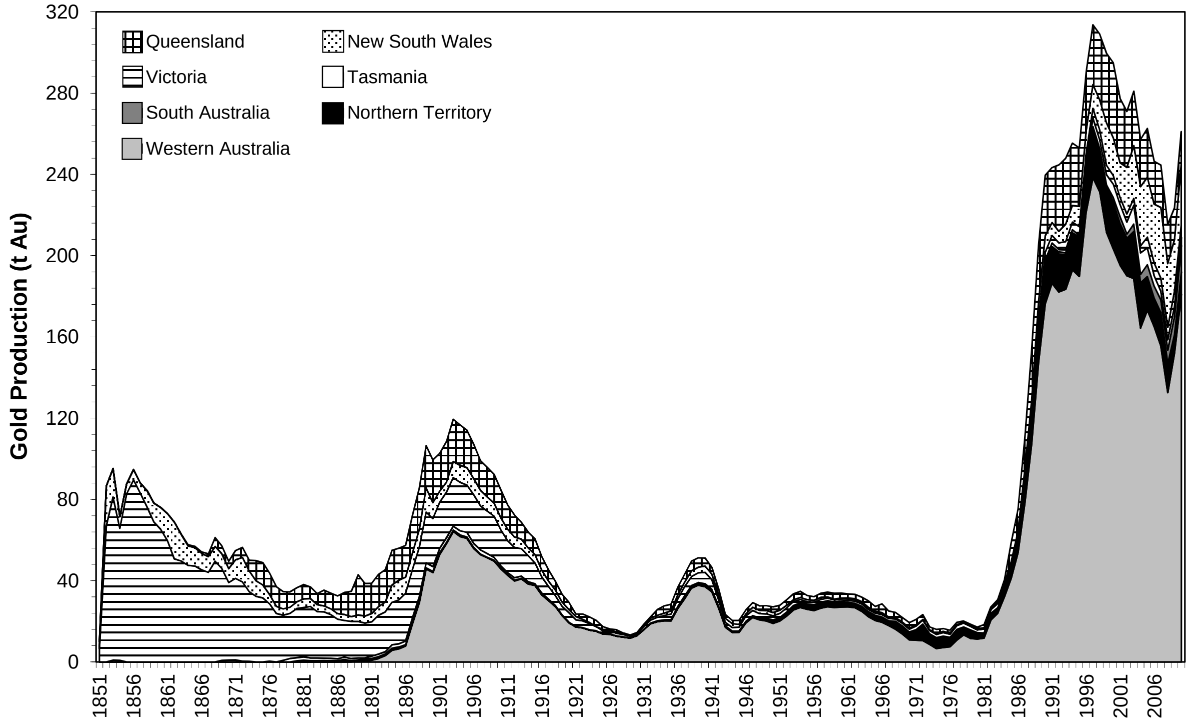
Based on known resources and projects (as reviewed in subsequent sections), the Australian gold industry is likely to still have some decades of prosperity, though concern often surfaces from within the gold mining sector about the longevity of resources and the relatively rapid mining cycle for gold deposits. Table 5 shows Australian cumulative and 2010 production.

Table 5: Cumulative Australian gold production by state, 1851-2010, and 2010# production (t Au) (data updated from (Mudd, 2009a)

State	Cumulative	2010#
Victoria	2,403.8	6
New South Wales	941.5	30
Queensland	1,408.2	16
Tasmania	214.6	4
South Australia	88.4	13
Northern Territory	566.3	11
Western Australia	6,644.7	181
Australia	**12,267.5**	**261**

#Production data for 2010 is preliminary only.

Gold production over time is shown in Figure 13(a), including proportion by state (Figure 13(b)), and the proportion of gold production by ore type in Figure 14.



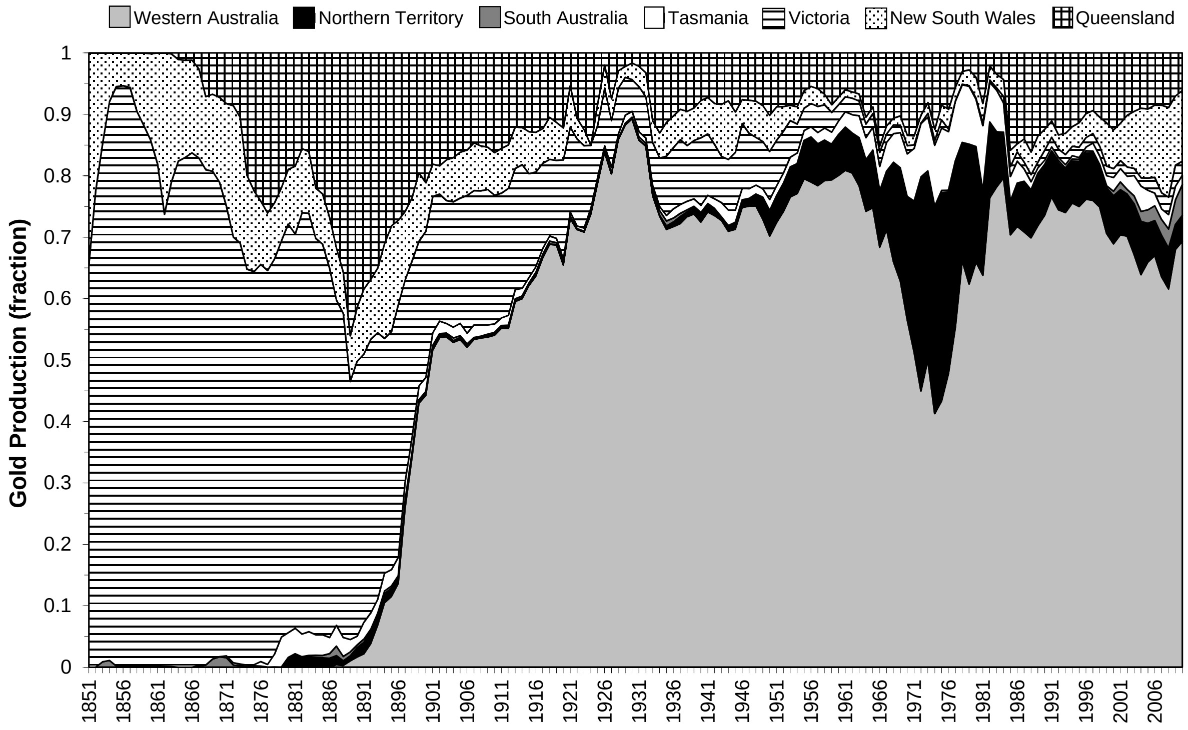


Figure 13: Historical Australian gold production by state (a) and by proportion (b (data updated from (Mudd, 2007b)

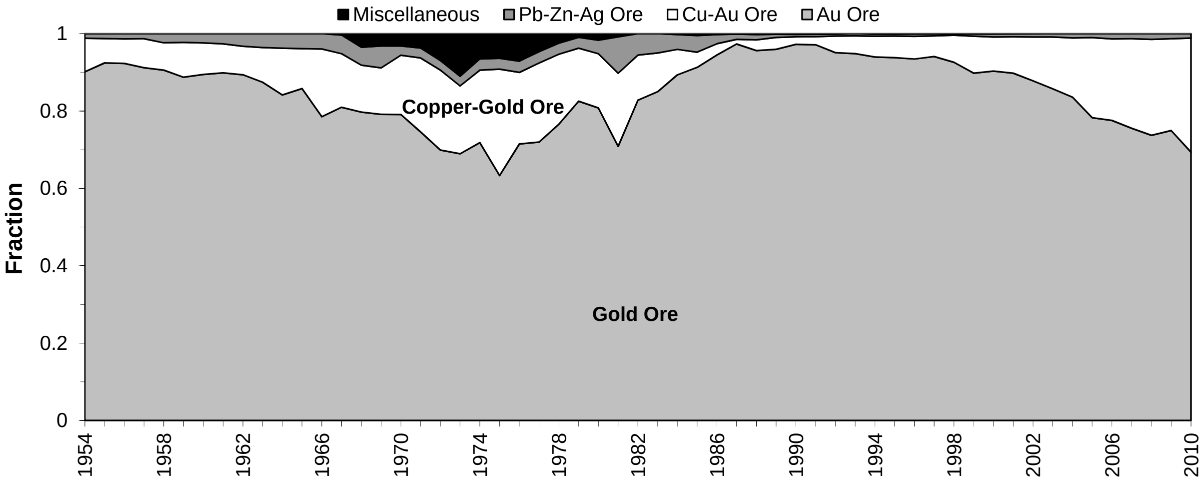


Figure 14: Historical Australian gold production by ore type (data updated from (Mudd, 2007b)

4.2. Current mines and economic resources

Australia has numerous operating gold mines as well as extensive resources, concentrated in major fields in every state and the Northern Territory. Major gold mines, their configuration and reported economic resources are analysed in detail below.

4.2.1. Producing gold mines

A compilation of Australian gold production by mine was developed for this report and is given in Table 6, showing a total of 61 mines. The total gold is 260.0 t, compared with preliminary 2010 Australian production of 260 t (based on quarterly data from (ABARE, var.-a). Of these, only 6 mines produced more than 10 t, using mine and mill configurations suited to extracting and processing different ore grades and types. Numerous projects do not state their processing technology (either in annual reports or on websites), and in these cases it has been assumed that the primary ore process stage is either CIP or CIL. It is surprising, however, that most new gold projects are building more complex mixes of technology in ore processing. For example, the recent re-development of both the Boddington and Telfer mines incorporate flotation as well as CIP/CIL technology and produce both a gold-copper concentrate as well as gold ore.

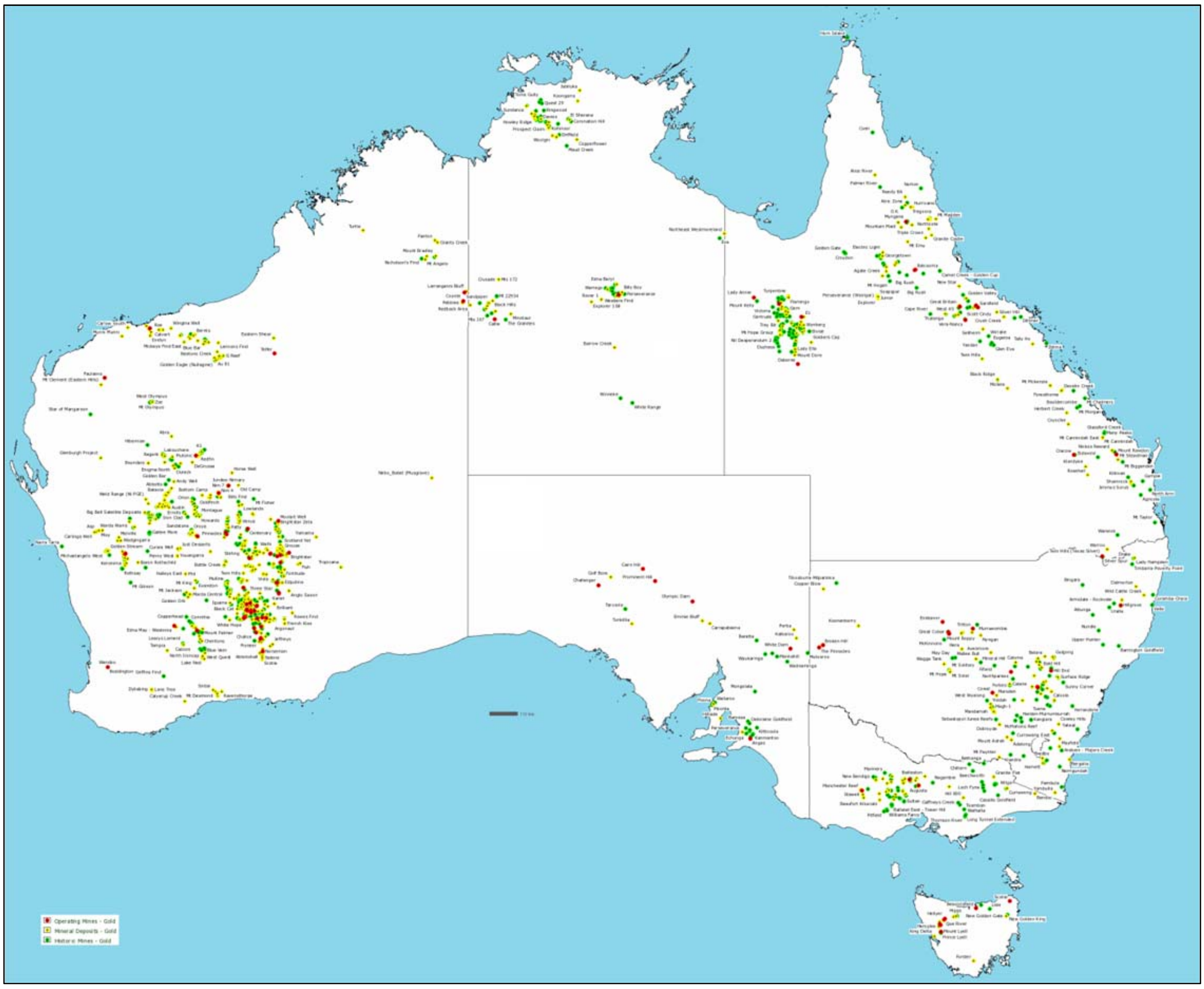


Figure 15: Locations of historic and operating Australian gold mines and remaining economic deposits (map generated on 7 February 2012) (GA *et al.*, 2011)

Note: the main purpose is to show the extent of former, existing and possible future gold mines across Australia.

Table 6: Australian gold mines (2010 data)

Mine	State	Metals	Mt ore	g/t Au	g/t Ag	%Cu	kg Au	kg Ag	t Cu	%Eff.	Mt WR	Process	%OC	%UG	Company (%interest)
SuperPit	WA	Au	12.155	2.30			24,507			87.78	57.221	Roast, CIL	96.8	3.2	Newmont$^{50\%}$, Barrick Gold$^{50\%}$
Boddington	WA	AuCu	26.619	1.03		0.12	22,641		26,309	82.70	46.071	Flot, **CIP/CIL**	100		Newmont
Telfer	WA	AuCu	22.944	1.06	**0.6**	0.17	21,165	**13,766**	33,213	87.27	24.721	Flot, Grav, HL, **CIP**	74.5	25.5	Newcrest Mining
St Ives	WA	Au	6.649	**2.19**			14,553			**99.8**	34.145	HL, CIP	76.9	23.1	Gold Fields
Sunrise Dam	WA	Au	3.617	**3.40**			12,313			**100.0**	15.309	Gravity, CIL	85.7	14.3	AngloGold Ashanti
Cadia Hill	NSW	AuCu	17.512	0.82		0.17	11,621	5,400	26,026	81.00	5.627	Gravity, Flot	100		Newcrest Mining
Jundee	WA	Au	1.581	7.20			10,419			91.52		**CIP/CIL**		100	Newmont
Yilgarn South Group[#]	WA	Au	2.192	4.83			9,765			92.18		Gravity, CIL, CIP		100	Barrick Gold
Lake Cowal	NSW	Au	7.210	1.58			9,268			81.51	27.780	Flot, CIL	100		Barrick Gold
Kanowna Belle	WA	Au	1.725	5.01			7,806			90.39		**CIP/CIL**		100	Barrick Gold
Tanami	NT	Au	2.421	3.36			7,775			95.58		**CIP/CIL**	100		Newmont
Prominent Hill	SA	CuAuAg	9.537	0.82	2.96	1.32	6,108	19,152	112,171	78.01	53.353	Flotation	100		OZ Minerals
Higginsville	WA	Au	1.265	4.24			5,157			96.12		CIP	11.3	88.7	Avoca Resources (Alacer Gold)
Paddington Group[#]	WA	Au	3.434	1.54			4,914			93.11	18.639	CIP	96.2	3.8	Norton Gold Fields
Agnew	WA	Au	0.815	**5.82**			4,733			**99.8**		CIP	23.7	76.3	Gold Fields
East Kundana	WA	Au	0.340	**13.40**			4,561			**100.2**		**CIP/CIL**		100	Barrick$^{51\%}$, Tribune$^{36.75\%}$, Rand$^{12.25\%}$
Ridgeway	NSW	AuCu	4.312	1.23		0.46	4,330		17,351	81.60		Gravity, Flot		100	Newcrest Mining
Plutonic	WA	Au	1.745	2.74			4,230			88.36		**CIL**		100	Barrick Gold
Southern Cross Group[#]	WA	Au	1.098	3.85			3,866			91.42		CIL		100	St Barbara
Gwalia-Leonora Group[#]	WA	Au	0.731	5.19			3,636			95.85		CIP		100	St Barbara
Ravenswood	QLD	Au	4.755	0.85			3,585			89.20		CIP	86.1	13.9	Resolute Mining
Frog's Legs	WA	Au	0.652	5.75			3,416			91.16		*(toll treated)*		100	Avoca Resources (Alacer Gold)
Cracow	QLD	Au	0.486	7.03			3,154			92.31		CIP		100	Newcrest$^{70\%}$, Catalpa Res.$^{30\%}$
Fosterville	VIC	Au	0.818	4.57			3,124			83.61		BIOX™, CIL		100	Northgate Minerals
Carosue Dam	WA	Au	2.401	1.49			3,066			85.59		Gravity, CIL	100		Saracen Mineral Holdings
Peak	NSW	AuCu	0.775	4.23			2,960			90.30		Flot, Gravity, CIL		100	New Gold
Wattle Dam	WA	Au	0.136	**21.34**			2,924			**101.1**		CIL		100	Ramelius Resources
Challenger	SA	Au	0.640	4.99			2,923			91.57		CIP		100	Dominion Mining
Mt Rawdon	QLD	Au	3.431	0.92			2,878			91.53	12.686	Gravity, CIL	100		Newcrest Mining
Ernest Henry	QLD	CuAu	9.838	0.34		0.69	2,838		74,595	84.85	16.782	Flotation	100		Xstrata
Coolgardie-Three Mile Hill	WA	Au	1.040	2.49			2,388			92.08		CIL	96.9	3.1	Focus Minerals
Stawell	VIC	Au	0.826	3.23			2,223			83.28		Flot, Gravity, CIL		100	Northgate Minerals
Daisy Milano-Mt Monger	WA	Au	0.367	5.89			2,154			99.86		CIP	35.2	64.8	Silver Lake Resources
Wiluna	WA	Au	0.541	4.72			2,154			84.41		BIOX™, **CIL**		100	Apex Minerals

Mine	State	Metals	Mt ore	g/t Au	g/t Ag	%Cu	kg Au	kg Ag	t Cu	%Eff.	Mt WR	Process	%OC	%UG	Company (%interest)
Olympic Dam	SA	CuAuAg U	7.046	0.54	5.01	1.88	2,128	17,634	131,800	56.00	0.564	Flot, Smelter leach		100	BHP Billiton
Northparkes	NSW	CuAu	5.248	0.51		0.82	2,031		39,000	75.88		Flotation		100	Rio Tinto$^{80\%}$, Sumitomo$^{20\%}$
Paulsens	WA	Au	0.162	10.8			1,670			95.21		Gravity, CIL		100	Northern Star Resources
Bronzewing	WA	Au	1.566	1.18			1,639			88.44	12.179	Gravity, CIL	100		Navigator Resources
Central Norseman	WA	Au	0.383	4.37			1,616			96.45		Gravity, CIL		100	Norseman Gold
Beaconsfield	TAS	Au	0.296	6.16			1,487			81.49		**CIL**		100	Beaconsfield Gold
Pajingo	QLD	Au	0.262	5.69			1,401	1,698		94.15		CIL		100	Conquest Mining
Henty	TAS	Au	0.276	5.2			1,343			93.46		Gravity, CIL		100	Unity Mining
Western Tanami	NT	Au	0.220	6.26			1,322			96.03		CIP	36.5	63.5	Tanami Gold
South Kalgoorlie	WA	Au	0.804	1.92			1,308			84.68		**CIL**	100		Avoca Resources (Alacer Gold)
Edna May	WA	Au	1.543	0.89			1,255			91.13		CIL	100		Catalpa Resources
White Dam	SA	Au	2.156	0.96			1,243			59.88	3.425	HL, **CIL**	100		Exco Resources$^{75\%}$, Polymetals$^{25\%}$
Bendigo-Kangaroo Flat	VIC	Au	0.206	6.2			1,140			89.34		Flot., Gravity, CIL		100	Unity Mining
Golden Grove	WA	PbZnAg CuAu	1.597	0.71	37.0	2.37	1,129	59,169	34,291	**100.0**		Flotation		100	Minerals & Metals Group
Duketon-Moolart Well	WA	Au	0.756	1.46			1,018			92.17	5.817	Gravity, **CIP**	100		Regis Resources
Rosebery	TAS	PbZnAg CuAu	0.725	1.72	125.0	0.38	981	78,709	2,087	78.84		Flotation		100	Minerals & Metals Group
Osborne	QLD	CuAu	1.026	0.89		2.33	840		22,676	91.82		Gravity, Flot.		100	Barrick Gold **(#2)**
Warrior-Charters Towers	QLD	Au	**0.165**	4.4			706			**97.5**		CIL		100	Citigold
Sandstone/Tuckabianna	WA	Au	0.317	1.90			564			93.88	0.745	Gravity, CIP	100		Troy Resources
Mt Morgans	WA	Au	0.134	4.33			558			96.21		Gravity Intense Leach	98.3	1.7	Range River Gold
Mt Lyell	TAS	CuAuAg	2.120	**0.3**	**3**	**1.21**	**382**	**3,816**		60.00		Flotation		100	Vedanta Resources
Laverton-Brightstar	WA	Au	0.225	1.67			340			90.81		**CIP/CIL**	100		A1 Minerals
Comet Vale	WA	Au	0.021	12.91			265			96.20		MC (soon to be CIP)		100	Reed Resources
Leonora (Nav.)	WA	Au	0.114	2.17			225			90.79		Gravity, CIL	100		Navigator Resources
Mt Garnet Group	QLD	PbZnAg CuAu	0.957	0.29	22.9	2.03	106	14,800	17,773	38.77	3.025	Flotation	6.6	93.4	Kagara Zinc
Angas	SA	PbZnAg CuAu	0.392	**0.35**	28.2	0.23	95	7,699	145	70.00		Flotation		100	Terramin Australia
Cadia East	NSW	AuCu	0.079	0.79		0.36	51		240	81.87		Gravity, Flot.		100	Newcrest Mining
		Totals	**183.4**	**1.60**			**260.0 t**	**221.8 t**	**538 kt**	**~88.6**	**»338.1**[§]		**72.3**	**27.7**	

[#]This is a group of mines and/or mills, with production data reported collectively as one unit. [§]Not all waste rock is reported, hence the 338 Mt is a minimum. WR – waste rock; Flot – flotation; Grav – gravity; HL – heap leach; MC – Merrill Crowe; CIP/CIL – carbon-in-pulp/leach. **Red-bold text** is yield only, **blue-bold text** is assumed (data in both cases is not reported).

4.2.2. Economic gold resources

An annual assessment of Australia’s economic and sub-economic gold resources is published by Geoscience Australia (GA, var.), with data from 1975 to 2009 and shown in Figure 16 (below). Date for 1955 is from BCGLO(1956), while data for 1960 comes from McLeod (1998). In general, this data illustrates that there is a clear long-term trend of increasing resources, demonstrating success in exploration and mine development.

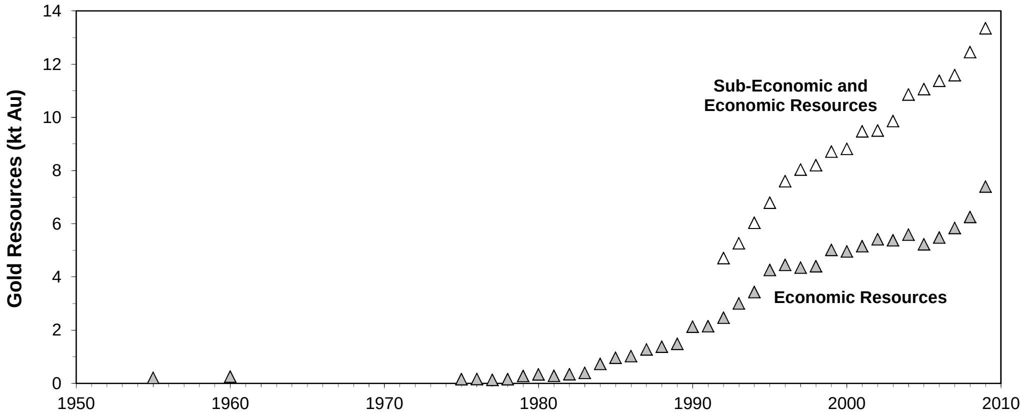


Figure 16: Long-term trends in Australia’s economic and sub-economic gold resources

A key feature of the trends in resources is the increasing dominance by a few major resources, especially the super-giants such as Olympic Dam and the Cadia Valley group (Cadia Hill, Ridgeway, Cadia East). As shown by (Schodde, 2010), the growth in Australia’s economic resources over the past decade has come entirely from Olympic Dam and the Cadia Valley group. This suggests that a peak in exploration success may be occurring, whereby most sites are only replacing gold mined. The reality is more complex, however, since major new deposits are being discovered (the prime example being Tropicana) as well as further work to shift sub-economic to economic resources (e.g. Boddington, Telfer).

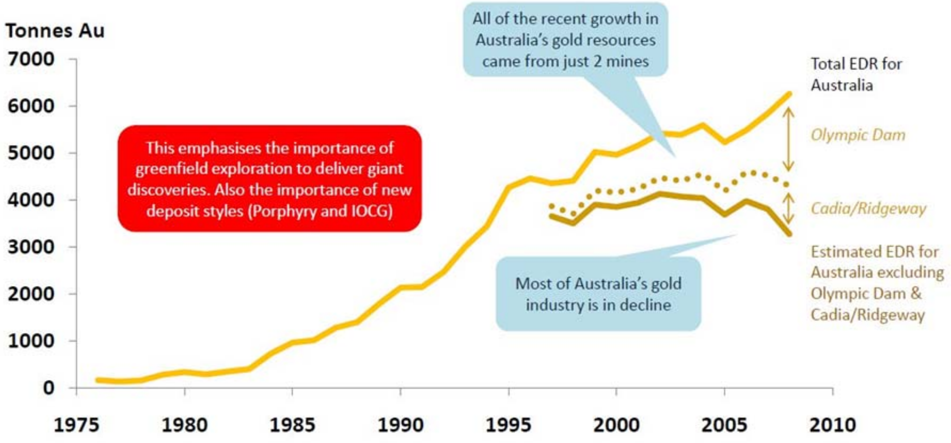


Figure 17: Australia’s economic gold resources and the influence of the Olympic Dam and Cadia Valley projects (Schodde, 2010)

A detailed compilation of Australia's individual economic gold resources reported by various companies has been undertaken for 2010. A total of 320 deposits were compiled, with some including numerous small deposits as one combined resource, while others include several large deposits which are reported separately (and often mined separately also). Metals extracted at the site (e.g. Au, Au-Cu) have been used as a further classification. The 25 largest resources are shown in Table 7, combined resources by metals extracted in Table 8, and number of deposits by state and resources in Table 9. The grade-tonnage relationships are shown in Figure 19 and cumulative frequency by tonnage and ore grade in Figure 20.

Table 7: Top 25 Australian gold resources (2010 data)

Mine	State	Status	Metals	Mt ore	g/t Au	t Au	Company (%interest)
Olympic Dam	SA	Operating	CuUAuAg	9,226	0.33	3,053.5	BHP Billiton
Cadia East	NSW	Operating	AuCu	2,347	0.44	1,032.7	Newcrest
Boddington	WA	Operating	AuCu	1,531.2	0.59	899.1	Newmont
Telfer Main Dome	WA	Operating	AuCu	369	0.88	324.7	Newcrest
Superpit	WA	Operating	Au	215.7	1.47	316.6	Barrick$^{50\%}$, Newmont$^{50\%}$
Warrior-Charters Towers	QLD	Operating	Au	22.75	13.5	307.2	Citigold
Mt Todd-Batman/Quigleys	NT	Care & Maint.	Au	300.1	0.81	244.0	Vista Gold Corp.
Prominent Hill	SA	Operating	CuAuAg	285.4	0.79	225.9	OZ Minerals
Sunrise Dam	WA	Operating	Au	90.21	2.43	219.2	Anglo Gold Ashanti
St Ives Group	WA	Operating	Au	81.3	2.6	211.4	Gold Fields
Paddington Group	WA	Operating	Au	103.8	1.73	179.6	Norton Gold Fields
Cadia Hill	NSW	Operating	AuCu	408	0.42	171.4	Newcrest
Telfer West Dome	WA	Operating	AuCu	247	0.65	160.6	Newcrest
South Kalgoorlie	WA	Operating	Au	68.72	2.0	137.4	Alacer Gold
Lake Cowal	NSW	Operating	Au	118.9	1.15	136.7	Barrick
Mt Elliott	QLD	Deposit	CuAu	570	0.24	135.0	Ivanhoe Australia
Agnew Group	WA	Operating	Au	26.8	4.7	126.0	Gold Fields
Gwalia-Leonora Group	WA	Operating	Au	20.85	5.99	125.0	St Barbara
Tanami	NT	Operating	Au	23.1	5.16	119.3	Newmont
Central Norseman	WA	Operating	Au	21.51	5.40	116.1	Norseman Gold
Carrapateena	SA	Deposit	CuUAuAg	203	0.56	113.7	OZ Minerals
Ridgeway	NSW	Operating	AuCu	155	0.73	113.2	Newcrest
Carosue Dam Group	WA	Operating	Au	62.75	1.6	100.4	Saracen Mineral Holdings
Northparkes	NSW	Operating	CuAu	365	0.27	99.7	Rio Tinto$^{80\%}$, Sumitomo$^{20\%}$
Lindsay's	WA	Deposit	Au	32.90	2.90	95.4	Carrick Gold
			Totals	**16,896**	**0.52**	**8.763.7**	

Table 8: Australian gold resources by primary metals (320 deposits, 2010 data)

Ore Type	Number	Mt ore	g/t Au	t Au
Au	212	2,938.0	1.97	5,798.1
AuAg	3	18.9	0.59	11.1
AuCu	13	5,242.8	0.56	2,923.4
Au-misc.	6	18.8	2.52	47.4
CuAu±Ag	40	3,001.4	0.34	1,014.2
CuAu±misc.	6	245.7	0.27	67.0
CuUAu±Ag	2	9,278.0	0.33	3,017.7
NiCuPGMsAu	3	44.2	0.25	11.1
PbZnAgCuAu	32	306.4	0.57	173.9
Sb-Au	3	7.8	5.44	42.5
Totals	**320**	**21,102**	**0.62**	**13,106.3**

The critical role of giant deposits is clear, since 45% of the 13,106 t of gold resources are contained in the Olympic Dam, Cadia Valley, Boddington and Telfer mines.

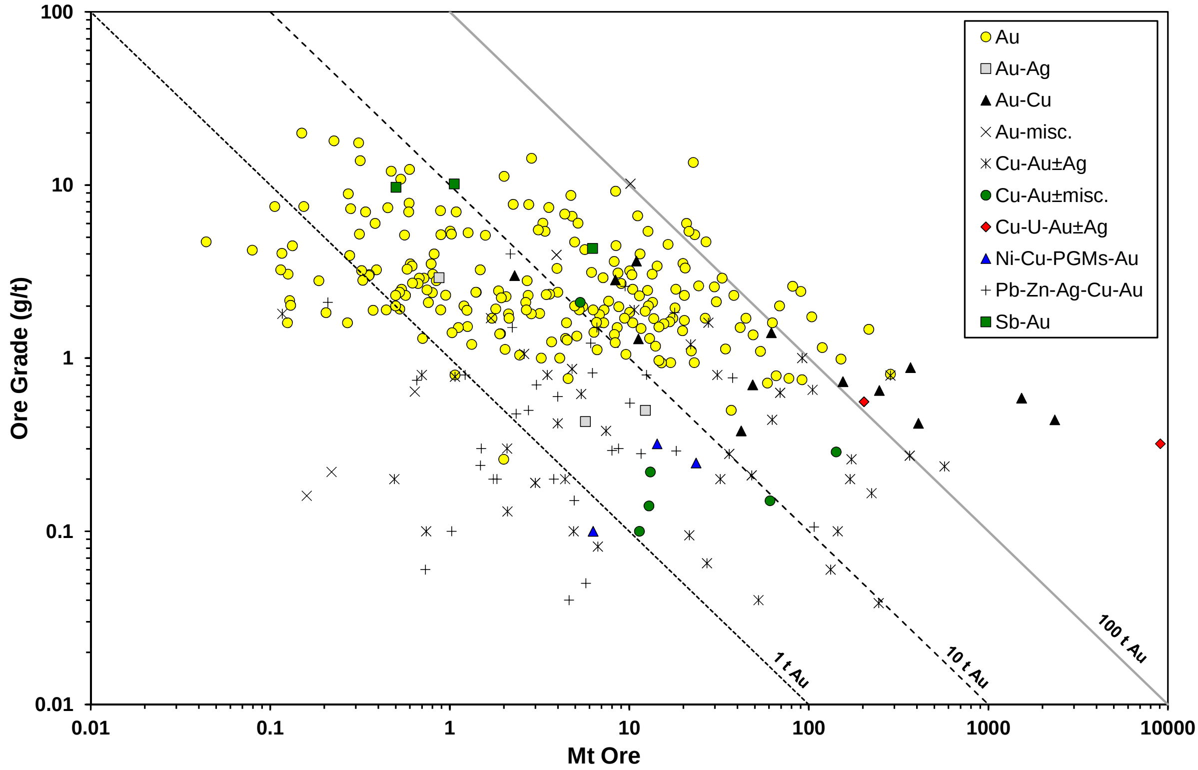


Figure 18: Grade-tonnage curve for Australian gold resources (320 deposits, 2010 data)

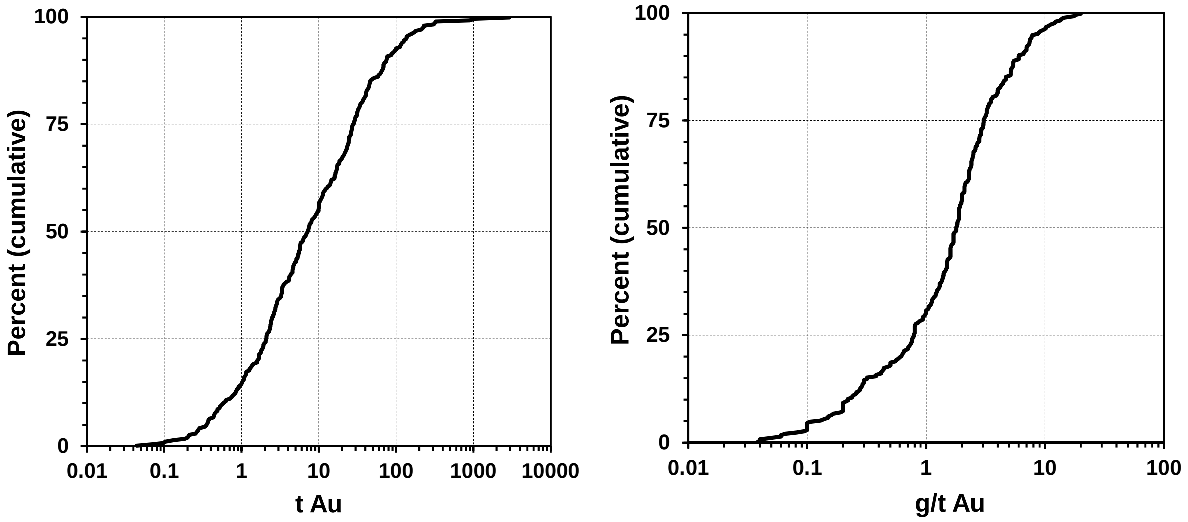


Figure 19: Cumulative frequency curves for Australian gold resources: contained gold (left); ore grades (right) (320 deposits, 2010 data)

In comparing Australia with the world, Australia is certainly in a strong position (see Table 3 earlier) with extensive economic and sub-economic resources, although as shown for South Africa (Figures 8 and 9) and the world (Table 4), it is possible to show greater gold resources than the USGS or other national data. Our extensive resource base will ensure that Australia continues to be a major global gold producer.

Table 9: Australian gold resources by state (320 deposits, 2010 data)

Ore Type	Number	t Au
Queensland	53	1,408.2
New South Wales	47	941.5
Victoria	14	174.1
Tasmania	9	103.0
South Australia	18	3,552.3
Western Australia	159	5,509.9
Northern Territory	20	702.7
Totals	**320**	**13,106.1**

5. ISSUES AFFECTING COMPETITIVENESS

5.1. Data on key industry trends

The key industry trends affecting the gold industry in Australia are declining ore grades, increasing mine waste (tailings and waste rock) and increasingly complex ore to process. These trends are associated with additional environmental damage from increased production of waste rock, and increased water and energy use when production grades and throughputs are increased (See ABARE 2000 for further detail). Increasing greenhouse gas emission intensity associated with these trends also presents a challenge to competitiveness.

The following sections provide some preliminary analysis of the trends for waste rock production in Australian mines, and water intensity, energy intensity and greenhouse gas intensity for a global data set of gold mines, a large proportion of which are located in Australia.

Based on previous research by (Mudd, 2007a, b), the key metrics adopted in this study will be energy, greenhouse and water intensity. The specific metrics will be per tonne of ore processed (i.e. MJ/t ore, kL/t ore, kg CO2/t ore) or per kilogram of gold (i.e. MJ/kg Au, kL/kg Au, kg CO2/kg Au). The original data sets have been expanded and factors such as electricity source and mine type included in the analysis where possible. The data set includes mines from all over the world as well as a large fraction of Australian gold mines.

5.1.1. Waste rock production and issues *(Australian mines)*

An extensive historical data set was compiled by (Mudd, 2009a), which included ore grades and mine waste (where available), but there is no reported data over time on whether the ore processed is simple or more complex. Although annual tailings data are not normally reported, given ore grades of grams per tonne, the ore milled is a clear indicator of annual tailings generation. For waste rock, although numerous mines report data as part of normal corporate reporting, there are some mines that do not report such data. As such, the waste rock data is a minimum only, although it does cover most open cut mines (it is rare for underground mines to report waste rock data). The long-term Australian trends in ore grades, ore milled and waste rock are shown in Figure 21.

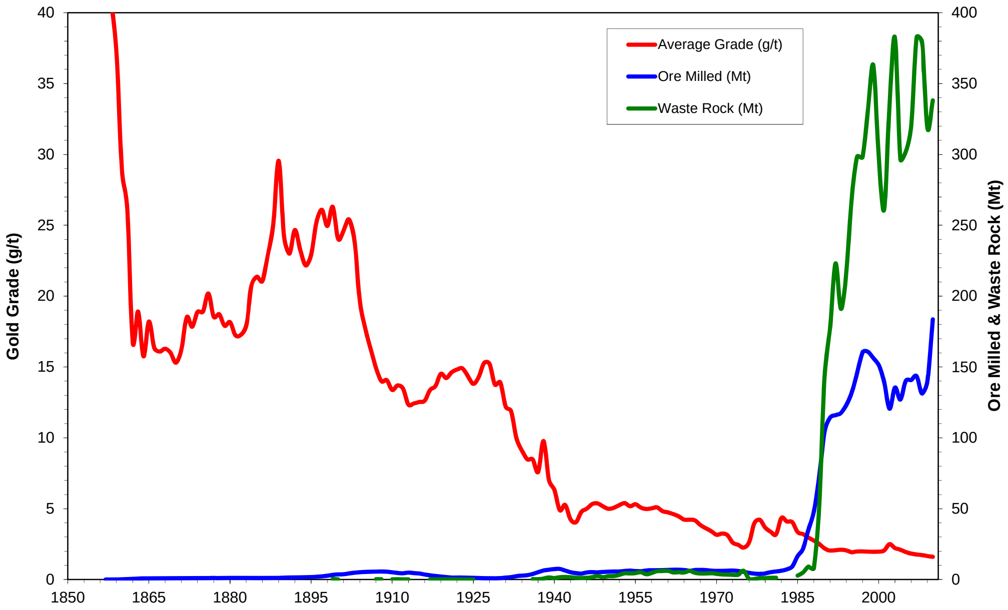
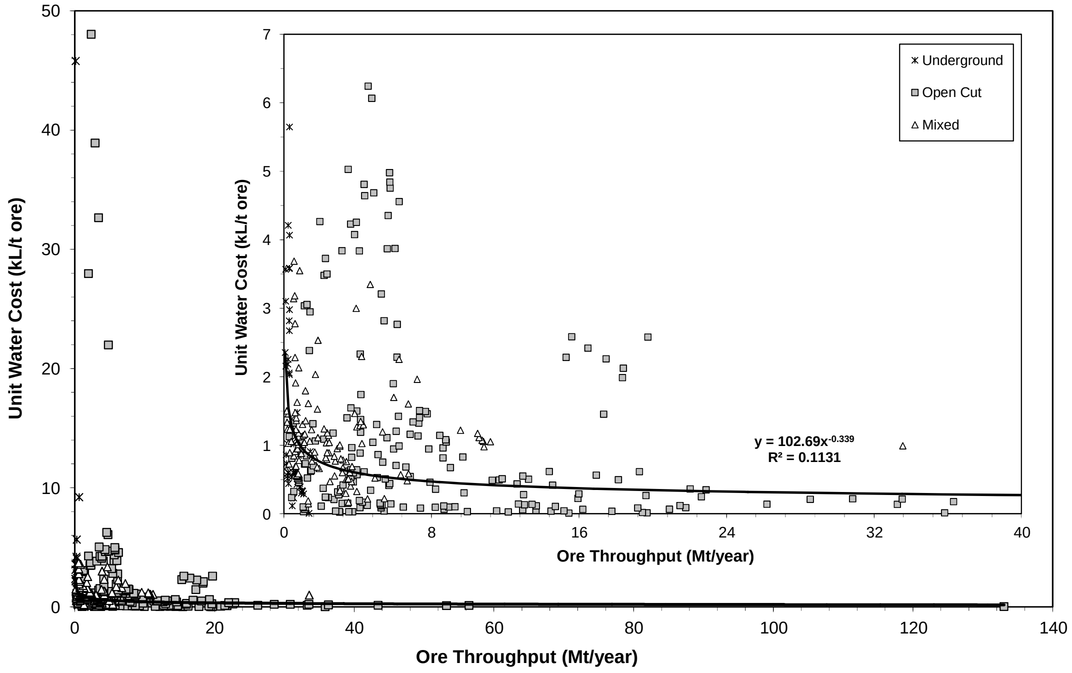


Figure 21: Long-term trends in ore grade, ore milled and (minimum) waste rock for Australia (data updated from (Mudd, 2009a) Note: many gold mines do not report waste rock data, and the data shown is therefore minimum only.

5.1.2. Water intensity and issues *(global data set)*

The relationship between water and gold mining is complex and highly variable, and is further discussed in (Mudd, 2008, 2009b, 2010). To examine the relationships and possible trends for gold mining, the data from (Mudd, 2007b) was re-analysed, including some additional years of data. The primary aspect added was mine type – underground, open cut or combined (i.e. mixed), with the relationships between water intensity and ore throughput and ore grade shown in Figure 22 (overleaf).



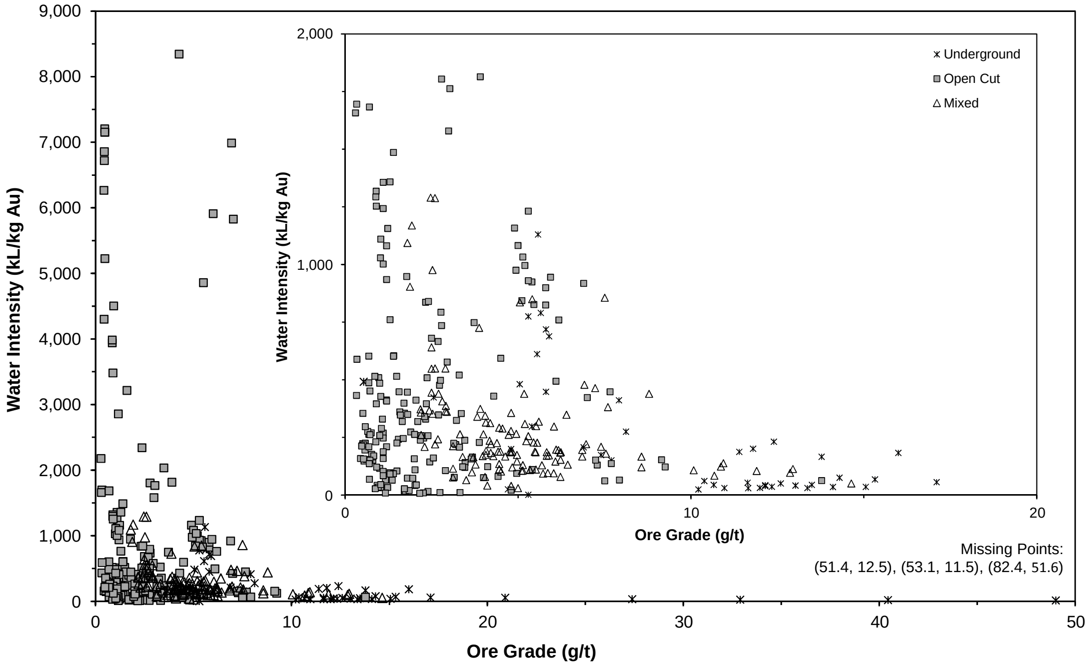


Figure 22: Water intensity of gold production – (i) unit water intensity versus ore processing scale (top); (ii) unit water intensity versus ore grade (bottom).

What this figure illustrates is that as ore grades or ore throughput decline, there is a higher chance of having a high water-intensity (either as kL/t ore or kL/kg Au). However, it is also clear that there are mines that have a low water-intensity at low grades or throughputs– suggesting that it may be possible to achieve significant water savings.

The extent of site-specific factors which underpin water intensity require further research, but given declining ore grades, competing uses for water in some regions and possible risks due to climate change, water intensity will be a growing and real issue for the gold industry.

5.1.3. Energy intensity and issues *(global data set)*

The relationship between energy and gold mining is complex and highly variable, and is further discussed in (Mudd, 2009b, 2010). To examine the relationships and possible trends for gold mining, the data from (Mudd, 2007b) was re-analysed, including some additional years of data. The primary aspect added was mine type – underground, open cut or combined (i.e. mixed), with the relationships between energy intensity and ore grade shown in Figure 23.

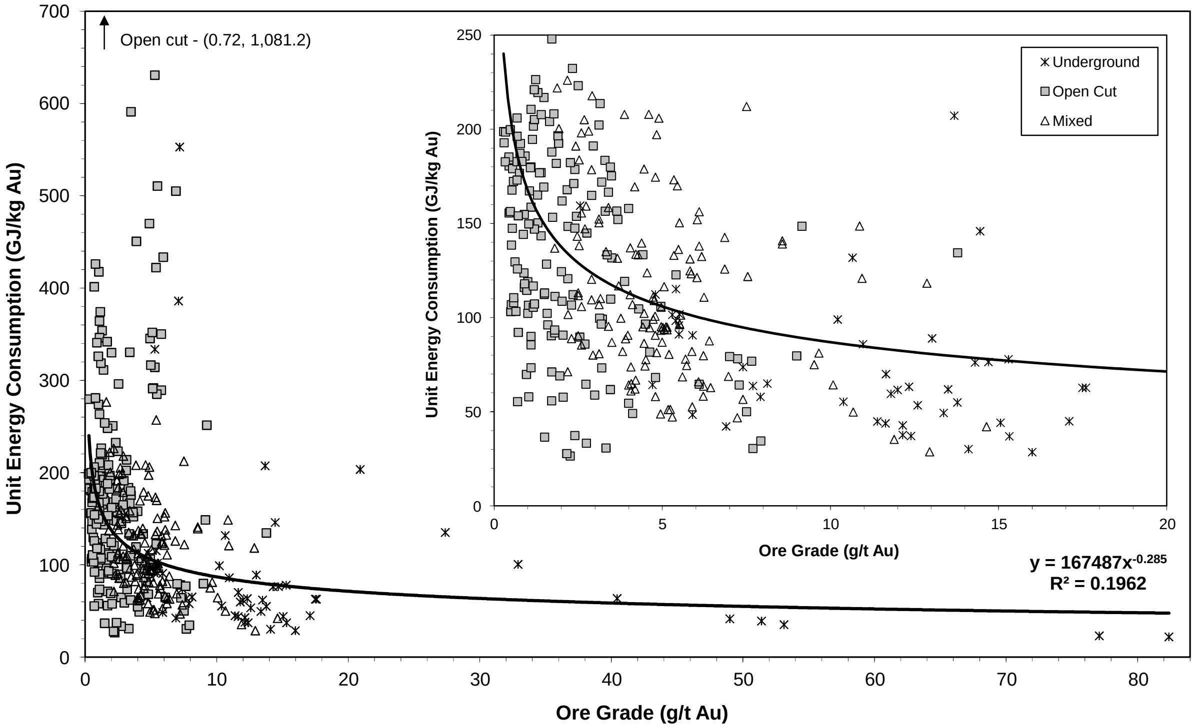


Figure 23: Unit energy intensity of gold production versus ore grade

Similarly to water, there is substantial scatter for all mines, although higher-grade mines typically have lower energy intensity. There are a range of issues with the data reported by various companies, including total energy consumption only and not by direct and indirect energy, and the lack of energy sources being described fully (especially by inputs such as diesel or electricity by fuel type). Furthermore, energy intensities would be closely linked to mine configurations, such as processing configuration, grind size, project age, mine depth and scales, and so on.

The extent of site-specific factors which underpin energy intensity require further research, but given declining ore grades, and especially the intimate links between energy sources, greenhouse gas emissions and climate change, energy intensity will be a growing and substantial issue for the gold industry.

5.1.4. Greenhouse gas emissions intensity and issues *(global data set)*

The relationship between greenhouse gas emissions (GGEs) and gold mining is complex and highly variable, and is further discussed in (Mudd, 2009b, 2010). To examine the relationships and possible trends for gold mining, the data from (Mudd, 2007b) was re-analysed, including some additional years of data. The primary aspects added were mine type and dominant electricity source (coal, gas, hydro, etc.), with the relationships between GGEs intensity and ore grade shown in Figure 24. The relationship between energy and GGEs intensity is shown in Figure 25.

Similarly to water and energy, there is substantial scatter for all mines, although higher-grade mines typically have a lower GGEs intensity. There are a number of issues with the data reported by various companies. For instance, most available data on GGEs are total figures rather than data broken down either by source (such as diesel or electricity by fuel type), or by energy type (direct and indirect). Furthermore, as GGE intensities are intimately linked to energy consumption, and any aspect affecting energy mix at a particular site would also affect GGEs. As seen in Figure 24 (below), in general, gold mines using coal-based electricity (the red series) have a typically higher GGEs intensity for the same energy intensity compared to hydroelectricity-based mines.

As noted in the previous analysis of energy intensity, the extent of site-specific factors which underpin GGEs intensity require further research, but given declining ore grades, and especially the intimate links between energy sources, greenhouse gas emissions and climate change, greenhouse gas intensity of energy sources will be a growing and substantial issue for the gold industry.

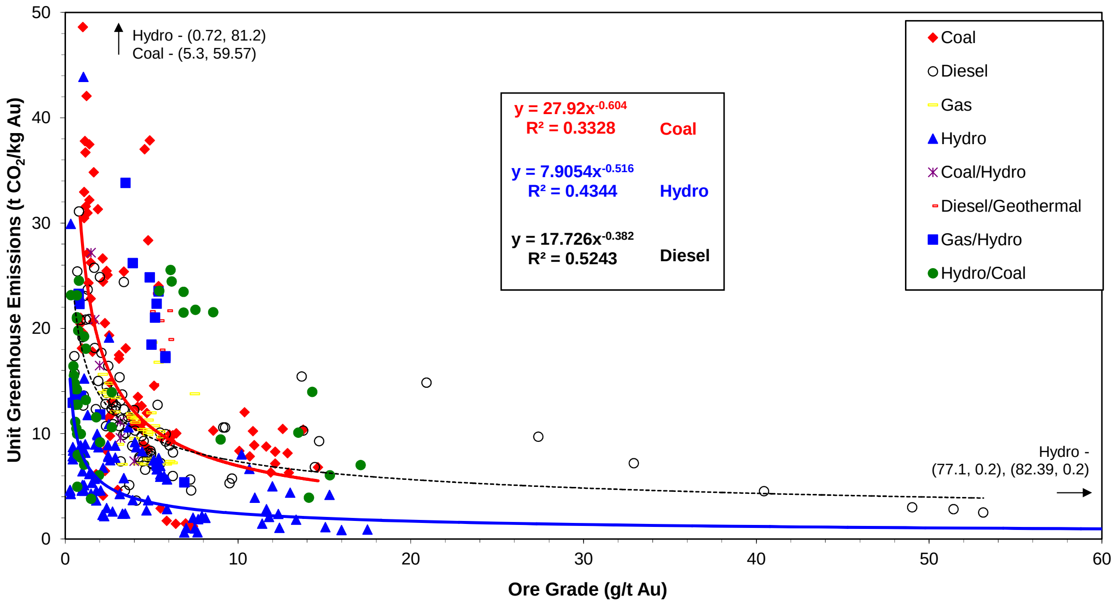


Figure 24: Unit greenhouse gas emissions intensity of gold production versus ore grade

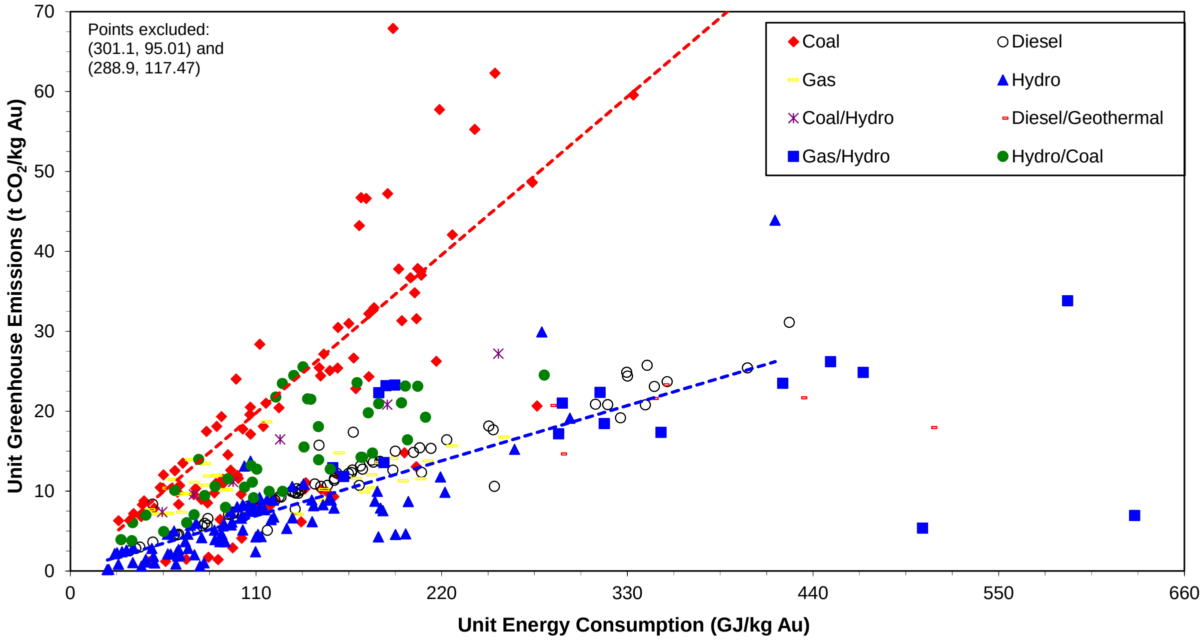


Figure 25: Unit greenhouse gas emissions intensity of gold production versus unit energy intensity

In summary, these analyses indicate that increased production will create significant environmental and social impacts that will need to be mitigated by techniques, processes and technologies that will make substantial rather than incremental changes to the performance of gold mining operations. A high gold price appears to play a very important role in justifying continued operation, under existing terms for Australian gold mining. Additional costs for key inputs such as water and energy may increase the marginality of these operations. In Australia, where water is the subject of conflict between state jurisdictions as well as between different industry sectors, and communities, the need for significantly improved performance may prove critical to the continuing viability of operations. Similarly, the reliance of the mineral industry in Australia on fossil fuels for stationary and transport energy creates a need for new approaches to energy use and generation if carbon costs and energy supply issues are to be overcome.

5.2. Future considerations

5.2.1. Open cut mining and waste rock

In relation to energy issues – liquid fuels used particularly in open cut mining are a key consideration. The volume of waste rock being moved to allow a much smaller volume of useful ore to be extracted and processed are likely to become more problematic as the cost of liquid fuels increases. As grades decrease, the ratio of waste to valuable rock becomes larger; making fuel use even less productive than it might be in another application. Additionally, the cost of the greenhouse gas emissions associated with the burning of fossil fuels for transport applications at mining operations will be one of the first impacts of putting a price on carbon for the majority of mining operations in Australia. Electric vehicles are one answer to this question, however without significant changes to electricity generation, greenhouse gas emissions will still be a consideration. Greater use of renewable energy at mining operations may be one way to improve performance in this area.

5.2.2. Water use

Water use is increasing but water efficient processes to reduce this are not currently well developed. For the Western Australian mining industry, it was estimated that the mining industry "develops 95% of its own water supplies" from groundwater and surface water sources (75% and 25% respectively). The report uses data from a small survey[4] carried out for this study to support a figure of $700 million as the cost of water discovery and development, and ongoing costs of approximately $100 million per annum (ECS 2004).

Overuse of water (drawing on groundwater sources faster than they can be recharged) is described in this report, is justified on the basis that other users could not use it in existing forms (ECS 2004), however this view does not consider non-human users, or the indirect ecological services provided by these low-quality ground and surface water sources.

5.2.3. Energy use

A review of gold ore processing by (Longley, 2004) argued that combining process steps such as gravity and/or flotation followed by cyanide leaching would lead to reduced energy consumption, improved safety due to lower cyanide requirements and considerably less tailings contaminated by cyanide.

For example, Newmont's Nevada Group operations, which are based on 8 open cut and 6 underground mines and a complex of 14 mills, the proportion of refractory gold processed has increased from 65% in 2001 to 79% in 2010 (Newmont, var.). Refractory ores, commonly consisting of gold-enriched sulfides, require more complex and higher cost processing methods, thereby embedding higher unit gold production costs. This trend is closely related to the depletion o near surface oxide ores, which are easier to process, and the increasing proportion of deeper but more refractory sulfide ores. As such, Newmont has had to adapt and configure their ore processing to suit these characteristics – leading to the complex system now in place.

5.2.4. Chemical use

Hilson's study (2006) of alternatives to cyanide use as a "reagent of choice" indicated that these had not gained significant uptake. Candidates included Thiourea leaching of gold, Thiocyanate, Thiosulfate leaching, Coal-oil agglomeration and halides, which were assessed in terms of economic and environmental criteria such as Capital outlay, Extraction costs, Availability, Detoxification/recycling costs,Toxicity from emissions, handling and

---

[4] 24 sites, two of which were excluded due to the fact that they "obtain most water from the Water Corporation with minimal self supply". Projects included 7 gold mines, 6 iron ore operations, 2 nickel, 2 heavy mineral sands, one base metals and one tantalite project. The total water licences held were 185 GL/a of water of which 101 GL was used in 2003. Total use represented 51% of the allocation (Table 4). Surface water sources, including dewatering or recovery from open pits or underground operations accounted for 25% of water with 75% from bores.

environmental toxicity as well as "process applicability". More recent research to develop a thiosulfate or cyanide free process at CSIRO for in situ leach techniques in Australia are not yet proved commercially.

5.3. Environmental reporting and responsible supply chains

The global gold industry has been at the forefront of sustainability reporting, which has emerged in particular since the 2002 Earth Summit in Johannesburg (Mudd, 2007a, 2009b). Sustainability reporting involves reporting against key areas of performance with respect to social, economic and environmental aspects, and reports are often published in parallel with traditional corporate annual reporting. The most popular protocol now used is the Global Reporting Initiative (GRI), now in its third edition (GRI, 2006), which is combined with a specific mining sector supplement (GRI, 2010). Notwithstanding, there are still very significant impacts from mining as shown via the No Dirty Gold campaign (NDG, 2012).

The GRI includes a range of quantitative and qualitative indicators that enable assessments of annual sustainability performance. For environmental aspects, the indicators include direct and indirect energy consumption, direct and indirect greenhouse gas emissions, water consumption, materials inputs, impacts on water resources, environmental expenditure, spills.

Current ethical supply chain initiatives are seeking to further increase transparency in the sector through initiatives such as Fair Trade and Fair Mined Gold (see FFG, 2012) and the Responsible Jewellery Council (see RJC, 2012).

6. SUMMARY AND CONCLUSIONS

Australia is currently the second largest gold producer in the world. While there are indications that there are large amounts of gold still potentially available, the operations that are producing the most gold are very large deposits such as Olympic Dam and Cadia Valley. As noted earlier, growth in Australia's economic resources over the past decade has come entirely from these operations, however, major new deposits are still being discovered (the prime example being Tropicana), and work to shift sub-economic to economic resources (e.g. Boddington, Telfer) is also being undertaken. While there has been a decline in demand for jewellery during the 2000s, other changes to gold use, such as the establishment of ETFs or Exchange Traded Funds, have provided a new demand for gold and offset this decline.

This study has identified that gold production throughout the 2000s has been about 250 t/year, with a significant amount now produced as a co-product or by-product. Known resources and projects (as reviewed in previous sections) indicate that the Australian gold industry is likely to still have some decades of activity, however key industry trends affecting the competitiveness of the Australian gold industry are declining ore grades, increasing mine waste (tailings and waste rock) and increasingly complex ore to process.

Additional pressure on production is likely to come from increasing costs and/or reduced access to water and energy, as well as the phasing in of a cost for greenhouse gas emissions (although these may be felt only in terms of reduced fuel rebates). Energy costs are increasing at the same time as energy use in total is growing. Water use is also climbing, and this appears to be the case regardless of whether prices are high (due to increasing throughput) or falling (due to the increased intensity of water use in improving grades).

The extent of site-specific factors which underpin water usage, energy usage and the emission of GGEs requires further research, and greater emphasis on reporting consistent data. Nonethless, given declining ore grades, and especially the close links between energy sources, water use, greenhouse gas emissions and climate change, energy intensity will be a growing and substantial issue for the gold industry.

Finally, although it is recognised here and elsewhere, that chemical use does not *necessarily* lead to environmental damage, incidents involving toxins such as mercury and cyanide do occur. At present, technology is not making a adequate progress in addressing environmental and economic competitiveness issues despite increasing conflict and public discussion of environmental and social impacts of mining.

For these reasons, this study concludes that while gold prices will continue to have a significant impact on whether gold will be mined in Australia, additional social and financial pressure is likely to arise from environmental damage associated with maintaining existing levels of production and attempts to significantly increase production.

7. REFERENCES

ABARE, var.-a, Australian Mineral Statistics, Australian Bureau of Agricultural and Resource Economics (ABARE), Canberra, ACT, Years 1988 to 2011.

ABARE, var.-b, *Australian Commodity Statistics*. Australian Bureau of Agricultural and Resource Economics (ABARE), Canberra, ACT, Years 1995 to 2010 (formerly Commodity Statistical Bulletin, 1986-1994).

Adams, M, 2005, *Summary of Gold Plants and Processes*. Developments in Mineral Processing, 15 (Advances in Gold Ore Processing): pp 994-1013.

Adams, M & Wills, B A, 2005, *Special Issue - Advances in Gold Ore Processing*. Developments in Mineral Processing, 15 (Advances in Gold Ore Processing).

Ahmad, M, Wygralak, A S & Ferenczi, P A, 1999, *Gold Deposits of the Northern Territory*. NT Geological Survey, NT Department of Mines & Energy, Report 11, Darwin, NT, 101 p.

Annear, R, 1999, *Nothing but Gold: The Diggers of 1852*. Text Publishing, Melbourne, VIC, 329 p.

AusIMM, MCA & AIG, 2004, *Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves : The JORC Code*. Joint Ore Reserves Committee (JORC) of The Australasian Institute of Mining and Metallurgy (AusIMM), Minerals Council of Australia (MCA) and Australian Institute of Geoscientists (AIG), Parkville, VIC, December 2004, 20 p.

BCGLO, 1956, *Gold Resources of the British Commonwealth*. British Commonwealth Geological Liaison Office (BCGLO), British Commonwealth of Nations Scientific Liaison Offices, London, UK, 57 p.

Bowen, K G & Whiting, R G, 1975, *Gold in the Tasman Geosyncline, Victoria*. In “Economic Geology of Australia and Papua New Guinea - 1 : Metals”, C L Knight (Ed.), Australasian Institute of Mining & Metallurgy, Parkville, VIC, pp 647-659.

Campbell, J D, 1953, *The Structure of the Kalgoorlie Goldfield*. In “Fifth Empire Mining & Metallurgical Congress : Geology of Australian Ore Deposits”, A B Edwards (Ed.), Australasian Institute of Mining & Metallurgy, Parkville, VIC, Vol. 1, pp 79-93.

Campbell, J D, 1965, *Gold Ore Deposits of Australia*. In “Eighth Commonwealth Mining and Metallurgical Congress”, J McAndrew (Ed.), Australasian Institute of Mining & Metallurgy, Parkville, VIC, Vol. 1 - Geology of Australian Ore Deposits, pp 31-38.

Close, S E, 2002, *The Great Gold Renaissance: The Untold Story of the Modern Australian Gold Boom 1982-2002*. Surbiton Associates Pty Ltd, Melbourne, VIC, 295 p.

CMSA, var., *Quarterly Ore Reserves*. Chamber of Mines of South Africa (CMSA), Johannesburg, South Africa, Quarters March 2003 to December 2010, Accessed 25 April 2011, www.bullion.org.za/content/?pid=54&pagename=Quarterly+Analysis.

Craig, J R & Rimstidt, J D, 1998, *Gold Production History of the United States*. Ore Geology Reviews, 13: pp 407-464.

ECS, 2004, Water and the Western Australian Minerals and Energy Industry: Certainty of Supply for Future Growth, report prepared for the Chamber of Minerals and Energy of Western Australia by ECS, July 2004

El-Ansary, M & Collings, P, 1990, *Boddington Gold Mine*. In “Geological Aspects of the Discovery of Some Important Mineral Deposits in Australia”, K R Glasson & J H Rattigan (Ed’s), Australasian Institute of Mining & Metallurgy, Parkville, VIC, Monograph 17, pp 91-94.

Fahey, C, 2001, *Labour and Trade Unionism in Victorian Goldmining : Bendigo, 1861-1915*. In "Gold: Forgotten Histories and Lost Objects of Australia", I McCalman, A Cook & A Reeves (Ed's), Cambridge University Press, Oakleigh, VIC, pp 67-84.

FFG, 2012, Fairtrade & Fairmined Gold. www.fairgold.org.

GA, var., *Australia's Identified Mineral Resources*. Geoscience Australia (GA), Canberra, ACT, Years 1992 to 2010, www.ga.gov.au.

GA, DITR & MCA, 2011, *Australian Mines Atlas Online*. Geoscience Australia (GA), Commonwealth Department of Industry, Tourism and Resources (DITR) and Minerals Council of Australia (MCA), Canberra, ACT, Accessed 9 August 2011, www.australianminesatlas.gov.au.

Govett, M H & Harrowell, M R, 1982, *Gold : World Supply and Demand*. Australian Mineral Economics Pty Ltd (AME), Sydney, NSW, December 1982.

GRI, 2006, *Sustainability Reporting Guidelines*. Global Reporting Initiative (GRI), Amsterdam, The Netherlands, September 2006, 44 p, www.globalreporting.org.

GRI, 2010, *Sustainability Reporting Guidelines & Mining and Metals Sector Supplement*. Global Reporting Initiative (GRI), Amsterdam, 55 p, www.globalreporting.org.

Hartnady, C J H, 2009, *South Africa's Gold Production and Reserves*. South African Journal of Science, 105(9/10): pp 328-329.

Heath, J A, Jeffrey, M I, Zhang, H G & Rumball, J A, 2008, *Anaerobic Thiosulfate Leaching: Development of In Situ Gold Leaching Systems*. Minerals Engineering, 21(6): pp 424-433.

Hilson, G. & Monhemius, AJ, 2006, "Alternatives to cyanide in the gold mining industry: what prospects for the future?" in Journal of Cleaner Production 14 (2006): pp 1158-1167.

Horn, C M & Fradd, W P, 1986, *Gold Mining in South Australia - The First Fifty Years*. Geological Survey of South Australia, SA Department of Mines, Adelaide, SA, August 1986, 81 p.

Huleatt, M B & Jaques, A L, 2005, *Australian Gold Exploration 1976–2003*. Resources Policy, 30: pp 29-37.

Kelly, T D, Matos, G R, Buckingham, D A, DiFrancesco, C A, Porter, K E, Berry, C, Crane, M, Goonan, T & Sznopek, J, 2010, *Historical Statistics for Mineral and Material Commodities in the United States*. US Geological Survey (USGS), Data Series 140 (Supersedes Open-File Report 01-006), Version 2010 (Online Only), Reston, Virginia, USA, Accessed 16 April 2011, minerals.usgs.gov/ds/2005/140/ (Last updated 28 Oct. 2011).

La Brooy, S R, Linge, H G & Walker, G S, 1994, *Review of Gold Extraction From Ores*. Minerals Engineering, 7(10): pp 1213-1241.

Lambert, I, Meizitis, Y & McKay, A D, 2009, *Australia's National Classification System for Identified Mineral Resources and Its Relationship With Other Systems*. The AusIMM Bulletin: Journal of the Australasian Institute of Mining and Metallurgy, December(No. 6): pp 52-56.

Longley, R, 2004, *Beyond CIP/CIL - A Combination of Existing Technologies Utilising Gravity, Flotation and Intensive Leach May Herald the Future for Gold Ore Processing*. Proc. "AusIMM Metallurgical Plant Design and Operating Strategies", Australasian Institute of Mining & Metallurgy, Perth, WA, September 2004, 12 p.

Machado, I F & Figueiroa, S F d M, 2001, *500 Years of Mining in Brazil : A Brief Review*. Resources Policy, 27: pp 9–24.

Maitland, A G, 1900, *The Mineral Wealth of Western Australia*. Western Australian Geological Survey, Bulletin No 4, Perth, WA, 150 p.

McCarthy, T S, 2010, *The Impact of Acid Mine Drainage in South Africa*. South African Journal of Science, 107(5/6): 7 p.

McKibben, M A, 2005, *Gold*. In "Encyclopedia of Geology", R C Selley, L R M Cocks & I R Plimer (Ed's), Elsevier, Amsterdam, Netherlands, pp 118-127.

McLeod, I R, 1998, *Historical Development of the Australian Mineral Industry*. In "Year Book Australia 1998", Australian Bureau of Statistics (ABS), Canberra, ACT, ABS Catalogue No. 1301.0.

Morgan, H M, 1993, *Overview of the Australasian Gold Industry*. In "Australasian Mining and Metallurgy : The Sir Maurice Mawby Memorial Volume Second Edition", J T Woodcock & J K Hamilton (Ed's), Australasian Institute of Mining & Metallurgy, Parkville, VIC, Monograph 19, Vol. 2, pp 801-804.

Mudd, G M, 2007a, *Global Trends in Gold Mining: Towards Quantifying Environmental and Resource Sustainability ?* Resources Policy, 32(1-2): pp 42-56.

Mudd, G M, 2007b, *Gold Mining in Australia : Linking Historical Trends to Environmental and Resource Sustainability*. Environmental Science and Policy, 10(7-8): pp 629-644.

Mudd, G M, 2008, *Sustainability Reporting and Water Resources: a Preliminary Assessment of Embodied Water and Sustainable Mining*. Mine Water and the Environment, 27(3): pp 136-144.

Mudd, G M, 2009a, *The Sustainability of Mining in Australia : Key Production Trends and Their Environmental Implications for the Future*. Department of Civil Engineering, Monash University and Mineral Policy Institute, Melbourne, VIC, October 2007; Revised April 2009, 277 p, users.monash.edu.au/~gmudd/sustymining.html.

Mudd, G M, 2009b, *Sustainability Reporting and Mining - An Assessment of the State of Play for Environmental Indicators*. Proc. "SDIMI 2009 - Sustainable Development Indicators in the Minerals Industry Conference", Australasian Institute of Mining and Metallurgy, Gold Coast, Queensland, 6-8 July 2009, pp 377-391.

Mudd, G M, 2010, *The Environmental Sustainability of Mining in Australia: Key Mega-Trends and Looming Constraints*. Resources Policy, 35(2): pp 98-115.

Muir, D M & Aylmore, M G, 2004, *Thiosulphate as an Alternative to Cyanide for Gold Processing - Issues and Impediments*. IMM Transactions C – Mineral Processing and Extractive Metallurgy, 113(1): pp C2-C12.

NDG, 2012, No Dirty Gold Campaign. www.nodirtygold.org.

Newmont, var., *Annual Report and Information Handbook*. Newmont Mining Corporation, Denver, Colorado, USA, Years 1999 to 2010.

Norgate, T & Haque, N, 2012, *Using Life Cycle Assessment to Evaluate Some Environmental Impacts of Gold Production*. Journal of Cleaner Production, 29-30: pp 53-63

NRC, var., *Canadian Minerals Yearbook*. Mining Sector, Natural Resources Canada (NRC), Ottawa, Ontario, Canada, Years 1944 to 2009, www.nrcan-rncan.gc.ca/mms-smm/busi-indu/cmy-amc-eng.htm.

Nye, P B & Blake, J B, 1938, *The Geology and Mineral Deposits of Tasmania*. TAS Geological Survey, TAS Department of Mines, Bulletin No 44, Hobart, TAS, 119 p.

O'Malley, G B, 1988, *The Mineral Industries*. In "Technology in Australia 1788-1988 : A Condensed History of Australian Technological Innovation and Adaptation During the

First Two Hundred Years", Australian Academy of Technological Sciences and Engineering, Melbourne, VIC, pp 733-777.

Officer, L & Williamson, S H, 2010, *The Price of Gold (British and USA Official Prices, London and New York Market Prices)*. Measuring Worth, Accessed 23 April 2011, www.measuringworth.com/gold/.

OSC, 2011, *National Instrument 43-101 - Standards of Disclosure for Mineral Projects, Form 43-101F1 and Companion Policy 43-101CP*. Ontario Securities Commission (OSC), Toronto, Canada, June 2011, 44 p.

Parbo, A, 1992, *Down Under - Mineral Heritage in Australasia : An Illustrated History of Mining and Metallurgy in Australia, New Zealand, Fiji and Papua New Guinea*. Monograph 18, Australasian Institute of Mining & Metallurgy, Melbourne, VIC, 319 p.

PERRRC, 2008, *Pan European Code for Reporting of Exploration Results, Mineral Resources and Reserves*. Pan-European Reserves-Resources Reporting Committee (PERRRC), December 2008, 53 p.

Raggatt, H G, 1968, *Mountains of Ore : Mining and Minerals in Australia*. Lansdowne Press, Melbourne, VIC, 416 p.

RJC, 2012, Responsible Jewellery Council. www.responsiblejewellery.com.

Royle, D Z, 1990, *An Exploration Case History in the Telfer Mine Corridor*. In "Geological Aspects of the Discovery of Some Important Mineral Deposits in Australia", K R Glasson & J H Rattigan (Ed's), Australasian Institute of Mining & Metallurgy, Parkville, VIC, Monograph 17, pp 49-56.

Rudnick, R L & Gao, S, 2003, *Composition of the Continental Crust*. In "Treatise on Geochemistry", H D Holland & K K Turekian (Ed's), Elsevier Pergamon, Vol. 3 of 9, Chap. 3.01, 64 p.

SAMRCWG, 2009, *South African Code for the Reporting of Exploration Results, Mineral Resources and Mineral Reserves (The SAMREC Code)*. South African Mineral Resource Committee Working Group (SAMRCWG), The Southern African Institute of Mining and Metallurgy (SAIMM) and Geological Society of South Africa (GSSA), Johannesburg, South Africa, www.samcode.co.za, 61 p.

Schmitz, C J, 1979, *World Non-Ferrous Metal Production and Prices, 1700-1976*. Frank Cass & Co, London, UK, 432 p.

Schodde, R, 2010, *The Declining Discovery Rate – What is the Real Story?* Proc. "AMIRA International's 8th Exploration Managers Conference", AMIRA, Yarra Valley, Victoria, 22-23 March 2010, 31 p.

Sykes, T, 1995, *The Money Miners : The Great Australian Mining Boom*. Reprint Edition, Allen & Unwin, Sydney, NSW, 396 p.

Travis, G A & Marston, R J, 1990, *Discovery and Development of the Archaean Gold Deposits of Western Australia*. In "Geological Aspects of the Discovery of Some Important Mineral Deposits in Australia", K R Glasson & J H Rattigan (Ed's), Australasian Institute of Mining & Metallurgy, Melbourne, VIC, Monograph 17, pp 29-41.

USBoM, var., *Minerals Yearbook*. US Bureau of Mines (USBoM), USA, Years 1933 to 1993.

USEPA, 1994, *Technical Resource Document - Extraction and Beneficiation of Ores and Minerals : Volume 2 Gold*. Special Waste Branch, Office of Solid Waste, US Environmental Protection Agency (USEPA), EPA 530-R-94-013, Washington DC, USA, August 1994, 392 p.

USGS, var.-a, *Minerals Commodity Summaries*. US Geological Survey (USGS), Reston, Virginia, USA, Years 1996 to 2011, minerals.usgs.gov/minerals/pubs/mcs/.

USGS, var.-b, *Minerals Yearbook*. US Geological Survey (USGS), Reston, Virginia, USA, Years 1994 to 2009, minerals.usgs.gov/minerals/pubs/myb.html.

WADM, var., *Annual Report*. WA Department of Mines (WADM) (now part of the WA Department of Industry and Resources), Perth, WA, Years 1896 to 2007.

WGC, var., *Gold Demand Trends Quarterly (online)*. World Gold Council (WGC), Years 1996 to 2011, Accessed 24 April 2012, www.gold.org/investment/statistics/demand_and_supply_statistics/.

Winde, F & Sandham, L A, 2004, *Uranium Pollution of South African Streams - An Overview of the Situation in Gold Areas of the Witwatersrand*. GeoJournal, 61: pp 131-149.

Woodall, R, 1990, *Gold in Australia*. In "Geology of the Mineral Deposits of Australia and Papua New Guinea - Vol 1", F E Hughes (Ed.), Australasian Institute of Mining & Metallurgy, Melbourne, VIC, Monograph 14, pp 45-67.

Woodall, R & Travis, G A, 1979, *Mineral Deposits of Western Australia : Gold*. In "Mining in Western Australia", R T Prider (Ed.), University of Western Australia Press, Perth, WA, pp 57-74.

Woodland, J G, 2002, *R H Bland and the Port Phillip and Colonial Gold Mining Company*. M Arts Thesis, School of Historical and European Studies, La Trobe University, Bundoora, VIC, 179 p.

APPENDIX A

To be consistent with the Australian mining industry, this report adopts the specific Joint Ore Reserves Committee (or 'JORC') Code definitions (AusIMM *et al.*, 2004). Based on the JORC Code, the analysis and reporting of ore reserves and mineral resources for the mining industry have very specific and statutory meanings:

Mineral Resources

A 'Mineral Resource' is a concentration or occurrence of material of intrinsic economic interest in or on the Earth's crust in such form, quality and quantity that there are reasonable prospects for eventual economic extraction. The location, quantity, grade, geological characteristics and continuity of a Mineral Resource are known, estimated or interpreted from specific geological evidence and knowledge. Mineral Resources are subdivided, in order of increasing geological confidence, into 'Inferred', 'Indicated' and 'Measured' categories.

- ***Inferred Resource***: that part of a Mineral Resource for which tonnage, grade and mineral content can be estimated with a low level of confidence. It is inferred from geological evidence and assumed but not verified geological and/or grade continuity. It is based on information gathered through appropriate techniques from locations such as outcrops, trenches, pits, workings and drill holes which may be limited or of uncertain quality and reliability.
- ***Indicated Resource***: that part of a Mineral Resource for which tonnage, densities, shape, physical characteristics, grade and mineral content can be estimated with a reasonable level of confidence. It is based on exploration, sampling and testing information gathered through appropriate ***techniques*** from locations such as outcrops, trenches, pits, workings and drill holes. The locations are too widely or inappropriately spaced to confirm geological and/or grade continuity but are spaced closely enough for continuity to be assumed.
- ***Measured Resource***: that part of a Mineral Resource for which tonnage, densities, shape, physical ***characteristics***, grade and mineral content can be estimated with a high level of confidence. It is based on detailed and reliable exploration, sampling and testing information gathered through appropriate techniques from locations such as outcrops, trenches, pits, workings and drill holes. The locations are spaced closely enough to confirm geological and grade continuity.

Ore Reserves

An 'Ore Reserve' is the economically mineable part of a Measured and/or Indicated Mineral Resource. It includes diluting materials and allowances for losses, which may occur when the material is mined. Appropriate assessments and studies have been carried out, and include consideration of, and modification by, realistically assumed mining, metallurgical, economic, marketing, legal, environmental, social and governmental factors. These assessments demonstrate at the time of reporting, extraction could reasonably be justified. Ore Reserves are subdivided in order of increasing confidence into 'Probable Ore Reserves' and 'Proved Ore Reserves'.

- ***Probable Reserve***: the economically mineable part of an Indicated, and in some circumstances, a Measured Mineral Resource. It includes diluting materials and allowances for losses, which may occur when the material is mined. Appropriate assessments and studies have been carried out, ***and*** include consideration of and modification by realistically assumed mining, metallurgical, economic, marketing, legal, environmental, social and governmental factors These assessments demonstrate at the time of reporting that extraction could reasonably be justified.
- ***Proved Reserve***: the economically mineable part of a Measured Mineral Resource. It includes diluting materials and allowances for losses that may occur when the material is mined. ***Appropriate*** assessments and studies have been carried out, and include consideration of and modification by realistically assumed mining, metallurgical, economic, marketing, legal, environmental, social and governmental factors. These assessments demonstrate at the time of reporting that extraction could reasonably be justified.

In concept, the relationship between resources and reserves and the level of confidence in the estimates are shown in Figure A1 (see also a recent article by (Lambert *et al.*, 2009).

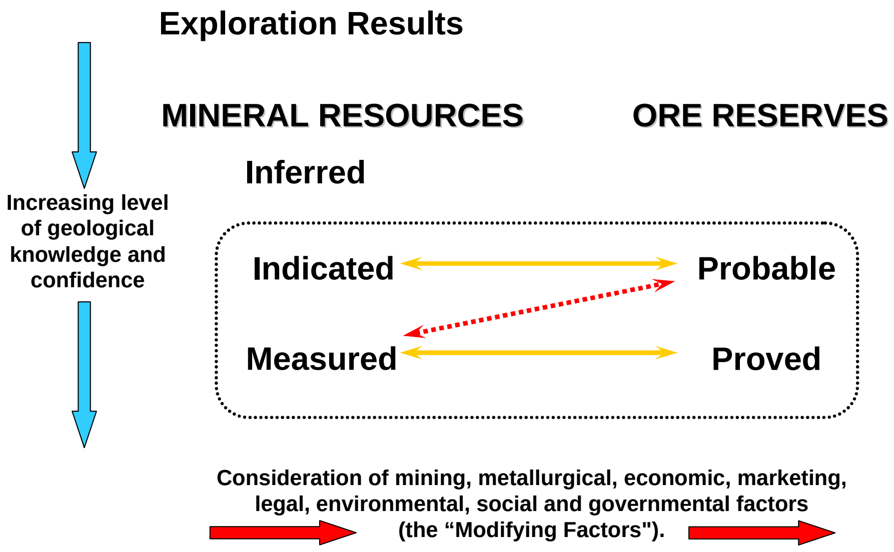


Figure A1: The relationship between mineral resources and ore reserves under the JORC Code (AusIMM *et al.*, 2004)

The USGS ‘McKelvey’ System

The US Geological Survey classifies economic mineral resources based on a very broad concept of economic, marginal and sub-economic resources. Their system is based on the early work of McKelvey, and has different meanings to those used by the JORC Code. The USGS system is explained in their annual reports, such as the Mineral Commodity Summaries (USGS, var.-a) or Minerals Yearbook (USGS, var.-b). The main categories used are ‘reserves’ and ‘reserves base’:

- ***Reserves***: that part of the reserve base that could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials; thus, terms such as "extractable reserves" and "recoverable reserves" are redundant and are not a part of this classification system.
- ***Reserves Base***: that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the in-place demonstrated (measured plus indicated) resource from which reserves are estimated. It may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently sub-economic (sub-economic resources). The term 'geologic reserve' has been applied generally to the reserve-base category, but it also may include the inferred-reserve-base category; it is not a part of this classification system..

It should be noted that from 2010 the USGS stopped using the reserves base category, since this often created confusion in comparison to formal codes such as Australia's JORC, South Africa's SAMREC or Canada's NI 43-101. Furthermore, the reserves base estimates were often not updated regularly, leading to the false notion that they were static – despite exploration success, economics or technology (or other factors) leading to constant change and evolution in code-based mineral resource estimates. This report does not make use of any reserves base data.

Use of the Terms 'Reserves' or 'Resources'

To be consistent with the JORC Code (and its international siblings), this report will only use the term 'reserves' in the formal sense of the JORC Code – while the term resources may be used in a broader sense than the strict JORC meaning.