Will Sustainability Constraints Cause 'Peak Minerals' ?

G M Mudd[1,#], J D Ward[2]

[1] Institute for Sustainable Water Resources / Department of Civil Engineering, Monash University, Clayton, Melbourne, Australia [#]Gavin.Mudd@eng.monash.edu.au

[2] School of Chemistry, Physics & Earth Sciences, Flinders University, Adelaide, Australia

Major Theme : Designing Sustainable Global Solutions

Sub-themes : Resource Depletion, Addressing Climate Change

Abstract

The mining of apparently finite mineral resources is almost unanimously considered as 'unsustainable' – yet the scale of modern mineral production is vast and continues to grow exponentially, especially in the face of what could be the biggest global mining boom in history. In recent years there has been increasingly public debate about the concept of 'Peak Oil' – that is, oil is a 'finite' resource and there are those advocating that production will soon peak and enter an inevitable but permanent decline (quickly becoming an uneconomic commodity shortly after this point). Despite much discussion of 'Peak Oil', there is little analysis of the same fundamental issues for minerals and metals. Recent research has begun to compile major data sets on mineral production trends, such as economic resources, ore grades, waste rock (overburden), as well as water, energy, greenhouse and chemical costs of mineral production. At present, there are major global efforts underway to improve energy and water efficiency as well as significantly reduce greenhouse emissions and thereby combat climate change. The compiled data on the environmental costs of mineral production is then used to consider the "sustainable" future of mining, i.e. in a future of declining greenhouse emissions and increasing energy and water efficiency. Ultimately, the world may not physically 'run out' of copper, coal, gold or other minerals, but aggregate production must peak and decline as new mining operations become increasingly constrained by low grade mineral deposits, greenhouse emissions and water. Thus, the concept of 'Peak Minerals' does appear to be significant, with the timing and severity of the peak fundamentally related to other sustainability constraints.

1 Introduction

In the sustainability journey, there is rarely a challenge to the concept of 'finite' mineral resources – after all, many famous mines and fields have long since closed down. Yet in reality, global mineral production is the highest in history and still growing rapidly – often exponentially. Although there is widespread debate about the end of oil and 'Peak Oil', there is relatively little research applied to mineral resources and understanding the likely future sustainability constraints for modern mining – especially with respect to critical aspects such as economic resources, ore grades, solid waste burdens and energy, water and pollution costs such as greenhouse emissions. This paper is the beginning of such research into modern mining – and develops a range of scenarios to challenge various assumptions used in sustainability analyses. The paper presents the application of 'Peak' curves combined with recent research on energy and water costs for mineral production as well as greenhouse emissions. The outcome is a unique combination of the mining of a 'finite' resource with critical sustainability constraints such as energy, water and climate change. Overall, the paper makes a valuable contribution to the rapidly growing debate about 'Peak Minerals'.

2 Sustainability and the Mining of 'Finite' Mineral Resources

There is a famous and well cited saying by Saudi's Ahmed Zaki Yamani that *"The Stone Age came to an end not for the lack of stones and the oil age will end, but not for the lack of oil"* (Yamani was Saudi Arabia's Oil Minister from 1962 to 1986, and a very prominent figure in OPEC) (pp 169, Leggett, 2005). Although this could be interpreted in many ways, it is perhaps most commonly meant to imply that even though some resources are perceived as 'finite' and extracting them is therefore 'unsustainable', there are always opportunities for future societies to meet their needs such as alternative resources or technology.

At present there is active global debate about 'Peak Oil' – that is, has world oil production reached a maximum rate and about to fall dramatically due to the impending exhaustion of the finite resource? After all, oil is widely believed to be a finite resource, and exploiting it will eventually have to come to an end – the main question remaining is 'when' (see for instance Bakhtiari, 2004; Bentley, 2002; Heinberg, 2007; Mohr & Evans, 2008; Silverman, 2004). In 1956, American oil geologist M King Hubbert recognised that all mainland oil fields in the USA followed a basic pattern: rapid growth, a peak and then decline (Hubbert, 1956). Hubbert then applied simple bell curves to quantify this 'peak' production behaviour, giving rise to the concept of 'Peak Oil'. He then made a then bold and controversial prediction that mainland USA would peak in oil production between 1962-1970, depending on the extent of recoverable resources assumed and shown in Figure 1. This prediction has been effectively proven correct as mainland US oil production peaked in 1971 (Bartlett, 2000; Bentley, 2002).

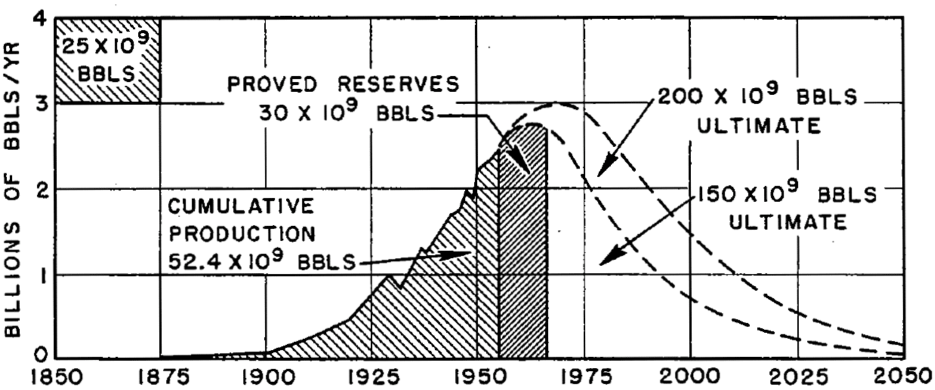

Figure 1: Hubbert's 1956 prediction of US mainland oil production (Hubbert, 1956)

There is, however, very little debate applying similar analyses to mineral commodities such as coal, copper, gold, nickel, uranium and so on. Similarly to oil, mineral resources are widely perceived to be 'finite' with their mining being intrinsically 'unsustainable'. In many life cycle assessments and sustainability analyses, the mining of mineral resources is referred to as resource depletion and consistently labelled as unsustainable (eg. Akao & Farzin, 2007). Indeed mining by definition means exhaustion of a resource.

In stark contrast, the reality in many places around the world could not be further from this common position in sustainability methodology – mineral production continues to expand exponentially in many countries, especially for those endowed with a rich mineral resource inheritance such as Australia, South Africa, Canada, Chile, China, the United States and many others. A recent major study of Australia by Mudd (2007a) showed increasing economic mineral resources over time for most mineral commodities (eg. Cu, Ni, Zn, mineral sands, uranium), though some commodities had appeared to reach an upper limit (eg. coal, iron ore). Mineral production has continued to grow for most commodities, often exponentially, making Australia a major player in global mining.

The application of Hubbert-style curves to mineral production and resources should not merely be a simple mathematical exercise – there are clearly some major differences between oil and mineral resources. For example, oil forms in large regional geologic structures (eg. anticlines), and it is argued that virtually all of the world's oil-prone geologic structures are already tested and understood with respect to the presence of major oil fields – evidence for this is a long-term global decline in new oil discoveries (Bentley, 2002). For minerals, on the other hand, the size of a given mineral deposit is a minute fraction of a geologic province, and even in a well explored and exploited region, it is still possible to find new deposits – even close to existing deposits or former mines (eg. gold, copper). The extent of mineral resources is therefore more likely to be a complex function of evolving exploration effort, technology and economics and other issues (eg. environmental or social constraints) over time (Mudd, 2007a,b).

In addition to the extent of mineral resources over time, critical factors in understanding the sustainability of mining include environmental costs, namely solid waste burden, declining ore grades as well as energy, chemicals and water inputs and pollution outputs – especially greenhouse emissions (Mudd, 2007a). It is widely demonstrated that as ore grades decline the energy and greenhouse costs increase, generally exponentially (see Cook, 1976; Norgate & Rankin, 2002; Mudd, 2007c; Mudd & Diesendorf, 2008), with examples shown in Figure 2.

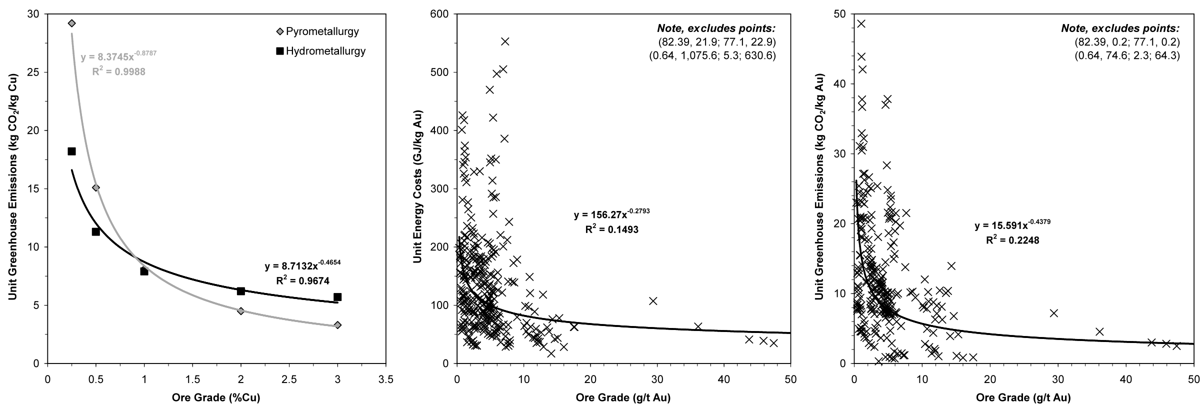

Figure 2: Greenhouse-ore grade relationship for Cu (left; Norgate & Rankin, 2002); energy/greenhouse-ore grade relationships for gold (middle/right; Mudd, 2007c)

For many metallic commodities such as copper, gold, nickel, lead and zinc, there is clear evidence of declining ore grades over the past several decades (eg. Ruth, 1995; Mudd, 2007a,b) – leading to the outcome of an increasing unit cost over time. If production continues to grow, this leads to an ever-increasing energy and greenhouse cost. In the context of the global climate change challenge, this is a formidable issue and is likely to present a major sustainability limit to future mineral production – well beyond whether a given mineral resource is perceived as finite.

3 Projecting Future Mineral Production

Given that mineral resources often increase over time in Australia and elsewhere around the world (with some exceptions), the central Hubbert hypothesis of finite resources may not be suitable for minerals. In this way the famous Yamani saying may be true for minerals in the same manner he perhaps intended it for oil – but what will control the future of mineral production and resources ?

It is a central hypothesis of this paper that future environmental costs, especially greenhouse emissions (ie. carbon), will play a major role in the shape of future mineral production. In this regard, three principal scenarios are developed to illustrate the potential scales and trends of future mineral production. Specifically, the scenarios are:

1. ***Hubbert peak curve*** – developed from historical data for annual and cumulative production and the most recent estimate of mineral resources, using the equation one below;

$$Q(t) = \frac{Q_{max}}{(1 + \alpha e^{\beta t})}$$

where $Q(t)$ is cumulative production at time t; Q_{max} is total finite resource available; α and β are constants (adapted from Cavallo, 2004).

2. ***greenhouse emissions constraints*** – using the unit greenhouse costs for mineral production versus grade and assume achieve certain levels of greenhouse emissions reductions by 2050.

These scenarios will be developed for copper and gold mining in Canada, Australia and the United States. All data and relationships for gold mining are obtained from the work of Mudd (2007c), while copper production data and relationships are sourced from :

- Canada – NRC (various)
- Australia – Mudd (2007a)
- United States – USBM (various), USGS (various-a,b)
- Greenhouse-grade relationship – Norgate & Rankin (2002)

4 Results and Discussion

4.1 Annual and Cumulative Production

The results for actual and modelled gold and copper production are compiled in various graphs shown in Figures 3 and 4, including economic reserves over time. There are clear differences between each country, specifically:

- **Canada** – Au and Cu production peaked in 1991 (175 t Au) and 1973 (824 kt Cu), respectively. Economic Au resources rose from 493 t Au in 1977 (first national reporting), peaked in 1988 at 1,801 t Au but have gradually declined to 1,032 t Au in 2006. Although gold exploration is finding additional ore, often at lower grades, the trend over time is clearly not leading to replacement of mined gold nor an increase. Economic Cu resources also follow a similar pattern, with the first resources reported in 1977 being 16.91 Mt Cu and declining ever since to the 2006 resources of 6.92 Mt Cu. For both Au and Cu, the rise and fall in annual production has followed changes in economic resources.

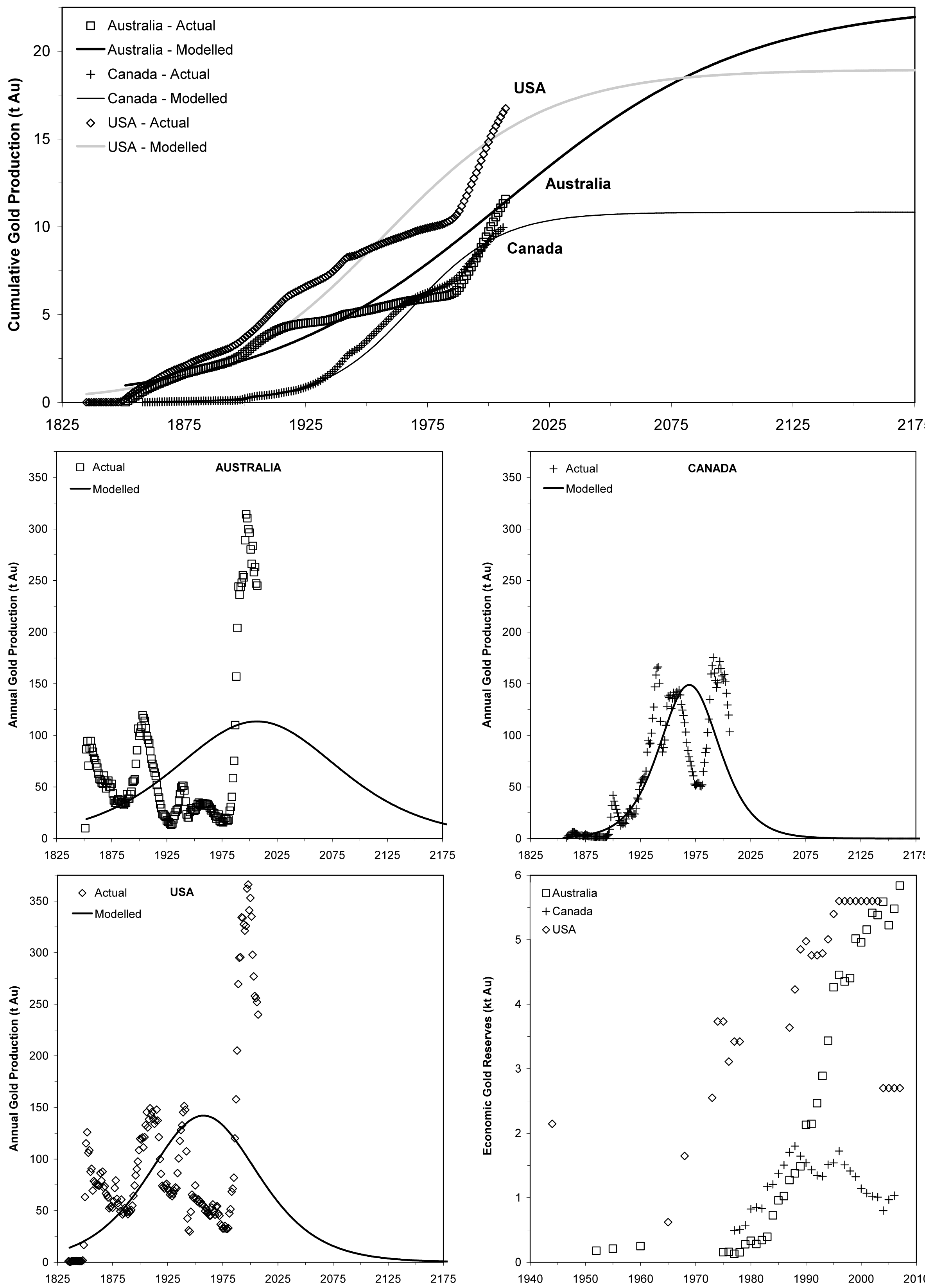

Figure 3: Gold mining: (i) actual and modelled cumulative production (top); (ii) actual and modelled 'peak' production (middle and bottom left); (iii) economic reserves (bottom right)

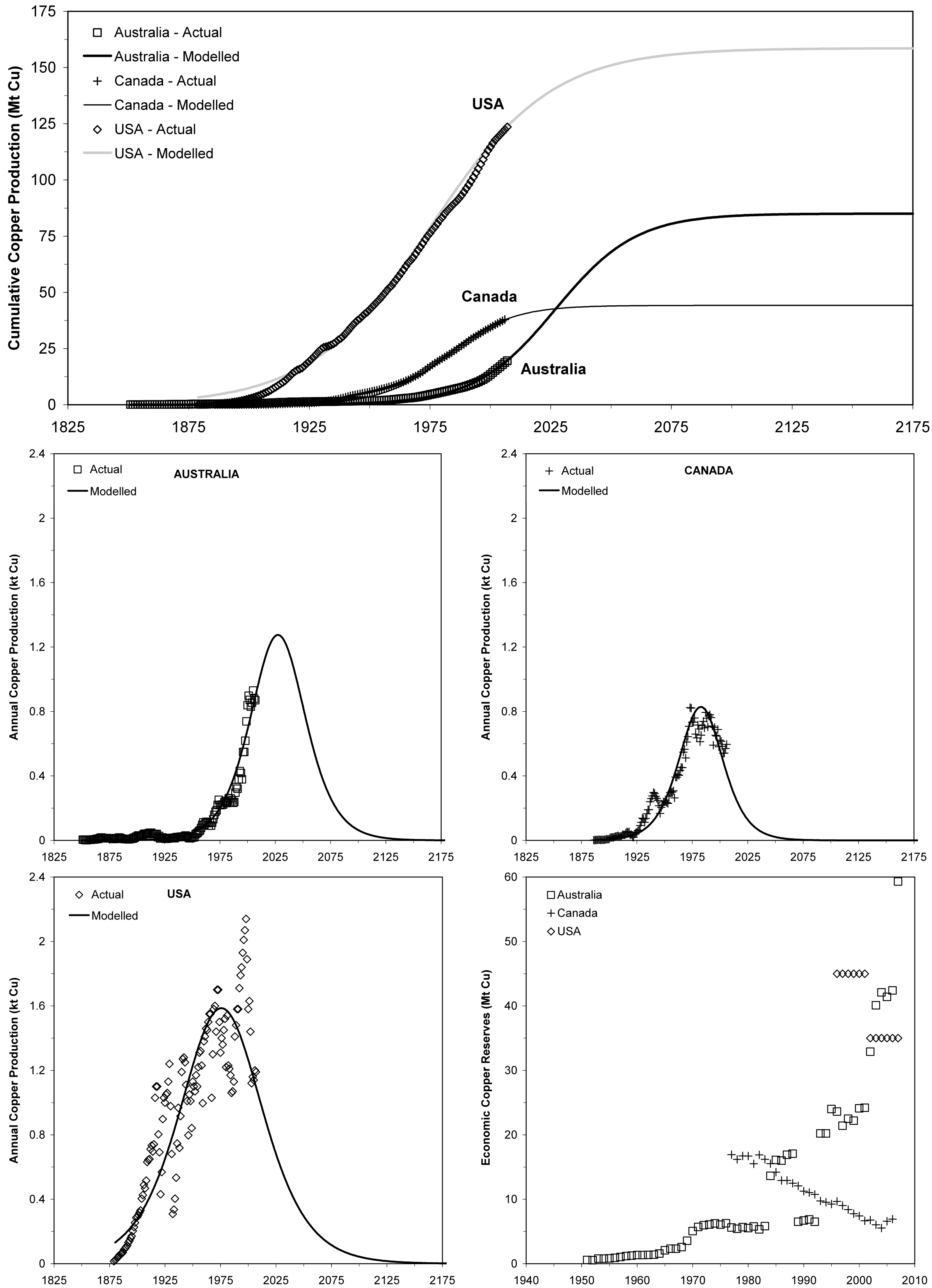

Figure 4: Copper mining: (i) actual and modelled cumulative production (top); (ii) actual and modelled 'peak' production (middle and bottom left); (iii) economic reserves (bottom right)

- **Australia** – Au production peaked in 1997 at 314 t Au and was 245 t Au in 2007; Cu production has continued to grow, effectively exponentially, reaching 930 kt Cu in 2005. Based on new Cu projects being developed or considered for development, it is expected that Cu production will continue to grow in the future significantly (eg. expansions at Olympic Dam, Mt Isa and Cadia-Ridgeway, plus new mines at Roseby, Prominent Hill, Carrapateena, etc.). Over time, both Au and Cu resources have increased significantly by 2007 to 5,839 t Au and 59.3 Mt Cu, respectively. In addition, there are sub-economic Au and Cu resources of 5,746 t Au and 47.2 Mt Cu, respectively (this resources category also shows significant increases over time).
- **United States** – Au production peaked in 1992 at 334 t Au and was 240 t Au in 2007; Cu production peaked in 1998 at 2.14 Mt Cu but declined rapidly to 1.19 Mt Cu in 2007 due mainly to mine closures from difficult market conditions. New or dormant Cu projects could see a rise in Cu production in the near future, but it is unclear if production could exceed the 1998 peak. Both Au and Cu resources have gradually declined, now being about 2,700 t Au and 35 Mt Cu, respectively. In addition, there are sub-economic Au and Cu resources of 3,700 t Au and 70 Mt Cu, respectively.

It is common in the mining industry for sub-economic resources to be converted to economic resources over time, as further work is completed and market conditions permit development. As such, it can be expected that Au and Cu resources in Australia and the United States in particular will remain effectively stable (or even increase) for some time to come. The prognosis for Canada is for long-term gradual declines in economic resources (in the event of no new major discoveries).

Overall, it appears that Australia is not yet at 'peak' Au or Cu production, while the United States is arguably close to peak and Canada is clearly past it's peak. Thus, the three countries provide contrasting cases for the usefulness of this analytical technique for determining 'peak production'. Furthermore, while the Cu curves yielded a reasonable match between historical and actual production, the Au curve was unsatisfactory for all three countries. This indicates that the technique does not provide a uniformly reliable predictive tool for all minerals.

4.2 Sustainability Constraints

Because the Hubbert-style bell curves above did not provide a satisfactory fit to historical data for Au production, it is necessary to seek a better model for making future predictions. Here we present a model based on sustainability constraints, namely a greenhouse emissions "cap". Given that the annual Au production is similar for Australia and the United States, a common scenario is presented. A constant annual Au production of 250 t Au is assumed (ie. ~2007 production), with the following relationships (taken or adapted from Mudd, 2007c):

Australia	Ore Grade Over Time	**Grade** = $1.1486\text{x}10^{17}\ e^{-0.01924\,(\textbf{year})}$	R^2 *89.2%*
	Unit CO_2 Intensity Versus Grade	**Unit CO_2** = $26.726\ (\textbf{year})^{-0.689}$	R^2 *41.5%*

Based on combining production and ore grade over time, the unit greenhouse intensity can be used to estimate total greenhouse emissions. In addition, a scenario of reducing greenhouse emissions was assumed to be based on Australia's (current) broad 'aspirational' targets of 108% of 2000 emissions for 2008, followed by reduction targets of 20, 50 and 90% by 2020, 2050 and 2100, respectively (with linear interpolation between these years). This is only intended to be an indicative scenario for the purposes of illustrating the effect on annual Au production (and not anything else). From this scenario, new Au production is estimated based on the fraction of emissions this allows relative to 2000 and the unit emissions intensity at this time. Although cyanide has not been included here, it has a similar relationship to ore grade as greenhouse emissions, meaning cyanide consumption would also grow rapidly into the future as grades declined. The derived future production scenario for Au is given in Figure 5.

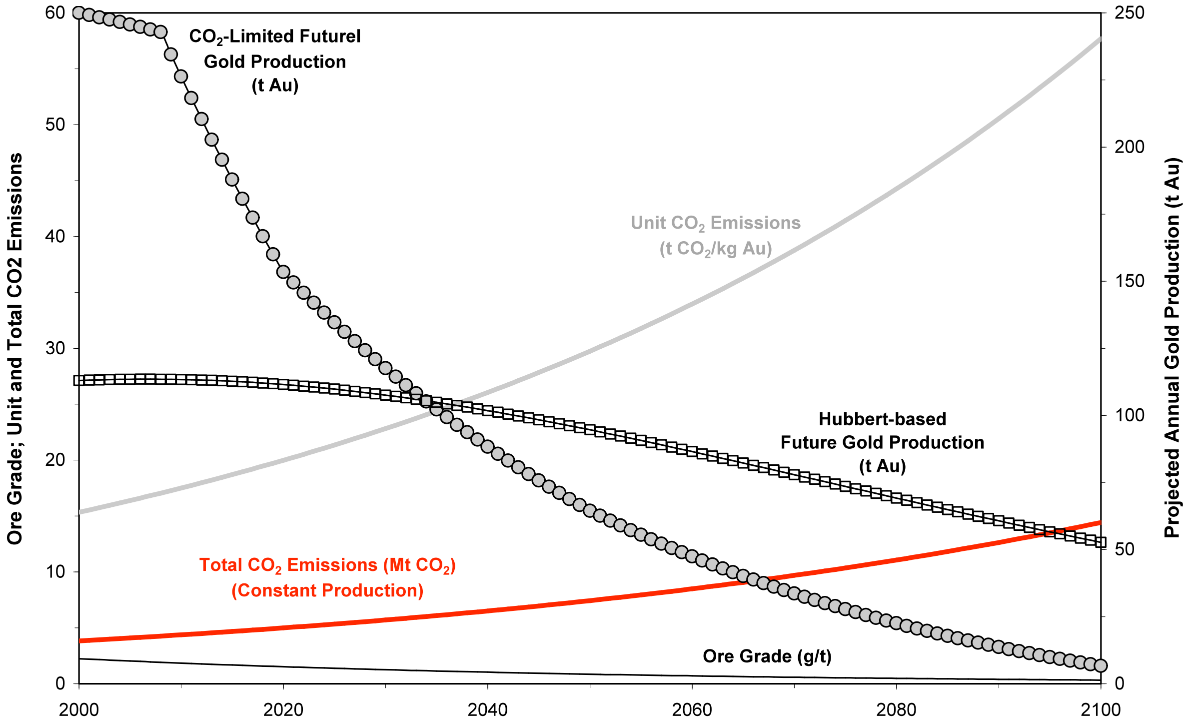

Figure 5: Predicted future gold production comparing unconstrained production (constant 250 t Au/year; red line), Hubbert-style peak production curve (square marked line) and greenhouse emissions-constrained production (circle marked line)

The projection in Figure 5 shows that in the longer term, although there may be sufficient Au resources still available for production (ie. the Hubbert curve beyond ~2035), the assumption of a basic greenhouse emissions scenario clearly leads to major constraints on future annual Au production.

Clearly, of course, there are considerably more factors at play and issues to consider in the greenhouse emissions intensity of gold mining. Firstly, average ore grade is more complex than merely a function of time – being influenced by new discoveries, technology, economics and mining techniques (especially any dilution effects). For example, the recent increase in the price of gold has led to many Australian mines processing lower grade material to maximise total gold extracted over a given mine life. Despite this, however, the long-term evidence for several countries does give weight to the inevitable decline of gold ore grades over time (Mudd, 2007c). Secondly, the principal sources of greenhouse emissions are diesel consumed in mining fleets as well as indirectly from electricity (the exact mix is mine-specific). At present, there appears to be no useful technology even being investigated for CO_2 capture from mining fleets, with perhaps the closest ideas being considered are new technology diesel engines (ie. improved efficiency) and the lower CO_2 intensity biofuels – though the extent of actual CO_2 reductions from biofuels (and the potential for their widespread production given agricultural land constraints) remains contentious. In the same manner, the reductions of greenhouse emissions from electricity will be dependent on either breakthroughs in clean coal technology or the large scale development of geosequestration – both of which are some decades away and unlikely to help gold miners reduce their total emissions within the timeframes suggested for action on climate change. Finally, given the inevitable carbon costs being implemented by governments around the world, either through trading or taxes, gold miners could simply pay for their carbon intensity – though this would push up costs and could make many marginal gold mines uneconomic.

As an example, assuming a carbon cost of \$20/t CO_2, an average CO_2 intensity of 11.5 t CO_2/kg Au (Mudd, 2007c) gives an added cost of \$230/kg Au (or \$7.15/oz). If the unit intensity increases to 57.7 t CO_2/kg Au, as long-term (by 2100) projections suggest is likely, this would lead to an increased cost of \$1154/kg Au (or \$35.89/oz).

Another issue which will also be extremely critical in the coming decades for gold mines will be the impact of 'peak oil' and the cost of diesel. This is beyond the scope of this paper, but the economic costs of diesel into the future under various hypothesized peak oil scenarios could easily be much more significant than the impacts of carbon costs to mitigate climate change.

In 2007, for the first time since about 1905, South Africa was no longer the world's leading gold producer – the position now being adopted by China. There are a few major factors contributing to South Africa's demise as a gold producer, such as social issues (eg. black economic empowerment, HIV/AIDS), currency and economics (particularly the price of gold in Rand), the increasing depth of mines making them marginal or unviable and so on – but declining ore grades has been critical in exacerbating these factors (eg. early 1970's grade averaged 12-13 g/t, but is now ~5 g/t). Given the lack of information on China's gold production, no discussion can be presented of their gold industry and its associated issues.

Further to carbon costs, two crucial issues for gold mining are energy and water – and both are dependent on ore grade in the same manner as greenhouse emissions (Mudd, 2007c). That is, as grades decline, more energy and water is required for a given production – placing even further pressure on gold production. Alternative options for energy supplies exist, but are highly site-specific (eg. Canadian sub-arctic versus the arid lands of the Witwatersrand in South Africa). Water can be recycled easily in gold mining, and some mines already do this, and this is perhaps the easiest challenge to address compared to carbon and energy costs.

5 Conclusions

This paper sought to present, analyse and project future mineral production, focussing on gold and copper production in Australia, Canada and the United States. There is clear evidence that metallic mineral resources are different to oil, and as such, the application of Hubbert-style peak production curves gives less than ideal fits between modelled curves and actual data (particularly the case for gold). However, this is not the main issue, as sustainability constraints such as greenhouse emissions will be more relevant in predicting future production. Based on a detailed scenario developed for future gold mining, it is clear that when a case for carbon constraints is applied to gold production, it leads to lower long-term production than the Hubbert-style peak production curve would suggest is possible. Therefore, future gold and other mineral production should be considered to be constrained by sustainability issues such as greenhouse emissions – in the face of no action to the contrary.

Ultimately, the world may not physically 'run out' of copper, coal, gold or other minerals, but aggregate production must peak and decline as new mining operations become increasingly constrained by lower grade mineral deposits, greenhouse emissions, energy costs and water. Thus, the concept of 'Peak Minerals' does appear to be significant, with the timing and severity of the peak fundamentally related to the complex combination of sustainability, technology, economic and other constraints.

6 References

Akao, K-I & Farzin, Y H, 2007, *When is it Optimal to Exhaust a Resource in a Finite Time ?* Ecological Research 22(3), pp 422-430.

Bakhtiari, A M S, 2004, *World Oil Production Capacity Model Suggests Output Peak by 2006–07*. Oil & Gas Journal 102(16), pp 18–20.

Bartlett, A A, 2000, *An Analysis of U.S. and World Oil Production Patterns Using Hubbert-Style Curves*, Mathematical Geology 32(1), pp 1-17.

Bentley, R W, 2002, *Global Oil & Gas Depletion: An Overview*, Energy Policy, 30, pp 189-205.

Cavallo, A J, 2004, *Hubbert's Petroleum Production Model: An Evaluation and Implications forWorld Oil Production Forecasts*. Natural Resources Research, 13(4), pp 211-221.

Cook, E, 1976, *Limits to Exploitation of Nonrenewable Resources*. Science, 191 (4228), pp 677-682.

Heinberg, R, 2007, *Out of Time ? The End of Oil*. Public Policy Research, September-November 2007, pp 197-203.

Hubbert, M K, 1956, *Nuclear Energy and the Fossil Fuels*. Proc. "Spring Meeting, Southern District, Division of Production, American Petroleum Institute", San Antonio, Texas, USA, March 1956, 57 p.

Leggett, J, 2005, *Half Gone: Oil, Gas, Hot Air and the Global Energy Crisis*. Portobello Books, London, UK, 322p.

Mohr & Evans, 2008, *Peak Oil: Testing Hubbert's Curve via Theoretical Modelling*, Natural Resources Research 17(1), pp 1-11.

Mudd, G M, 2007a, *The Sustainability of Mining in Australia: Key Production Trends and Their Environmental Implications for the Future*. Research Report No RR5, Department of Civil Engineering, Monash University and Mineral Policy Institute, October 2007 (see http://civil.eng.monash.edu.au/about/staff/muddpersonal/rr5/).

Mudd, G M, 2007b, *An Analysis of Historic Production Trends in Australian Base Metal Mining*. Ore Geology Reviews, 32 (1-2), pp 227-261.

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

Mudd, G M & Diesendorf, M, 2008, *Sustainability of Uranium Mining : Towards Quantifying Resources and Eco-Efficiency*. Environmental Science & Technology, 42 (7), pp 2624-2630.

Norgate, T E & Rankin, W J, 2002, *The Role of Metals in Sustainable Development*. Proc. "Green Processing 2002 – International Conference on Sustainable Processing of Minerals", AusIMM, CSIRO and AMEEF, Cairns, QLD, May 2002, pp 49-55.

NRC, various, *Canadian Minerals Yearbook*. Natural Resources Canada (NRC), Ottawa, Ontario, Canada, Years 1944–2005 (http://www.nrcan.gc.ca/mms/cmy/pref_e.htm).

USBM, various, *Minerals Yearbook*. US Bureau of Mines (USBM), Years 1933–1993, USA.

USGS, various-a, *Minerals Commodity Summaries (Au/Cu)*. US Geological Survey (USGS), Years 1996–2006, Reston, VA, USA (http://minerals.usgs.gov/minerals/pubs/mcs/).

USGS, various-b, *Minerals Yearbook*. US Geological Survey (USGS), Years 1994–2004, Reston, VA, USA (http://minerals.usgs.gov/minerals/ pubs/myb.html).

Silverman, M P, 2004, *Book Review – Hubbert's Peak: The Impending World Oil Shortage, Kenneth D. Deffeyes, Princeton University Press*. American Journal of Physics 72(1), pp 126-127.