Historical Trends in Base Metal Mining:
Backcasting to Understand the Sustainability of Mining

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ABSTRACT

The base metal mining sector has been and continues to remain an important endeavour in many parts of the world. The mining of copper, lead-zinc-silver and nickel has led to social and economic development but has also left significant and sometimes lasting environmental impacts. Metal mining is widely perceived to be unsustainable, often without question, since it is drawing down natural capital (ie. stock) – despite the productive output of mines now being considerably larger than at any time in history. What has underpinned this paradox ? and what are the long term trends in base metal mining ? and how can this knowledge be used to understand the current position and future challenges of base metal mining ? This paper will present long-term data on trends in base metal mining such as production, ore grades and economic resources, focussing on major mining countries such as Australia, Canada and the United States. By looking back to history, or 'backcasting' in sustainability language, we can better understand the historical challenges, patterns or factors that have shaped the base metal mining industry. This then helps us to understand the current and future challenges facing the base metals sector of the global mining industry. An oft-quoted saying for peak oil pundits is that of Saudi's former Oil Minister Ahmed Zaki Yamani: "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". Will the base metals mining sector go the same way ? That is, what has been the success rate for new technology, exploration, economics or perhaps environmental aspects which may constrain the sector or, conversely, help it to flourish ? This paper presents a unique insight into base metals over time, and provides a range of valuable but rarely compiled historical data.

Full Reference:

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INTRODUCTION

The base metals, namely copper (Cu), lead (Pb), zinc (Zn) and nickel (Ni) (amongst others), are an integral part of virtually every facet of modern infrastructure – from copper pipes, stainless steel, cables, chemicals, electronics to batteries and many other uses, they are essential for modern technology and society. Around the world, many base metal mines are renowned for their economic productivity, or sometimes for their lasting environmental legacy (or even both). The scale of base metal mining is now global and has reached scales beyond imagination a century ago – yet in terms of sustainability, mineral resources are widely perceived to be finite, with the obvious conclusion being that mining is therefore intrinsically 'unsustainable'. This is a significant paradox – metals production is larger than ever before in history, yet we commonly view mining, almost by definition, as unsustainably depleting natural stocks.

Part of the answer to this apparent riddle lies in careful examination of history – to understand the long-term evolution of the base metals sector it is critical to examine its development over time. In this way, the various factors such as exploration, technology, economics, social or other issues can be ascertained and accorded their place. In this way, more complex scenarios can be developed for the future of the industry, especially considering the parallels that are starting to be made between 'peak oil' and minerals, or 'peak minerals' (eg. [1,2]). There are many books, references and scholarly papers written on the overall history of Cu, Pb-Zn and Ni mining, and only the briefest of reviews is provided herein to complement the various data sets.

This paper presents a compilation of a range of available data on critical trends in base metal mining – namely mine production, ore grades and economic resources, with additional data on aspects such as waste rock presented where possible. The principal countries analysed include Australia, Canada and the United States, all major producers of base metals. Data is sourced mainly from government or industry periodicals, such as minerals yearbooks, company annual reports or other noteable sources. A brief summary of the methodology and major sources is given, followed by individual sections for each major class of base metal ore, such as Cu, Pb-Zn and Ni, finishing with a discussion of the critical findings from this research.

METHODOLOGY

In general, detailed compilations of annual mine site production data were compiled for Australia and Canada, with only sector totals available for Cu mining in the United States. Major references include:

- **Australia**: the study of Mudd [2] recently compiled all available data on base metal mining in Australia as part of a larger project on long-term trends across the entire Australian mining industry [3]. The report was the first of its kind, with all data included in appendices with considerable references utilised to create the master data sets over time.
- **Canada**: Canadian Minerals Yearbook [4], published by the federal agency Natural Resources Canada (NRC; and its predecessors) from 1944 to the present.
- **United States**: annual USBoM/USGS Minerals Yearbook, published by the federal agency US Bureau of Mines (USBoM) from 1933 to 1993 [5], and continued by the US Geological Survey from 1994 to the present [6], as well as the annual Mineral Commodity Summaries [7].

In addition, a variety of sources were used for production data over time, especially older historical data, including ABARE [8], Schmitz [9] and Kelly et al. [10]. A further source of information and data is the old annual industry periodical published a century ago by McGraw Hill, called "The Mineral Industry : Its Statistics, Technology and Trade", from 1892 to 1940 [11]. This was effectively the forerunner to the current minerals yearbooks, and is an excellent historical sourcebook.

The various individual mine data sets were summed to compare production totals with official reported annual mine production data. Although this data is not presented in this paper, in general, the compiled data represents between 90-100% of reported data (and occassionally higher, due either to incorrect national or mine site data; see [3]).

COPPER MINING

Copper has been an important metal in society for at least a few millennia, with uses ranging from agricultural and household tools, ornamental purposes through to weapons of war. It was the relentless rise of the Industrial Revolution throughout the nineteenth century, however, that would permanently change the status of Cu – making it a fundamental metal of modern society due to its widespread use in large scale piping networks for water supply and wastewater, combined with the discovery of electricity and the need for efficient power cables.

Production has steadily grown over time, from ~3 kt Cu in 1750 to 15.7 Mt Cu in 2008, shown in Figure 1. The early dominance of the USA in global Cu production until the mid-twentieth century is evident, followed by the inexorable rise of Chile in the past decade especially. Australia is generally following a gradual growth scenario, and is now approaching the USA in terms of recent production. Canada, on the other hand, appears to have peaked in the 1970's-80's and is effectively stagnant and perhaps in gradual decline.

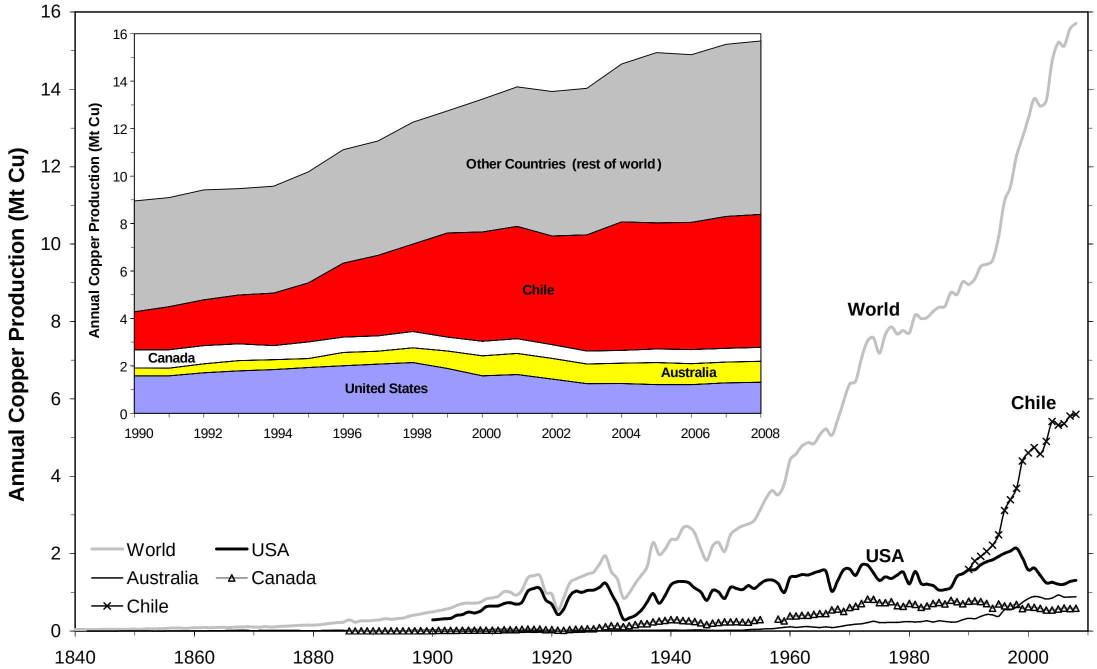

Figure 1 – Mined copper production over time by country (data sourced from [2-10])

In the early twentieth century, there are three major cutbacks in global Cu production visible in Figure 1. The first occurs around 1918-22, and is largely related to the turmoil in the Cu market following the end of World War I. The second cutback occurred from 1929-34 and is associated with the Great Depression. The last major cutback is linked to the tumultuous period of World War II, and occurred over 1943-47. Since this time, however, global Cu production has grown almost exponentially to its current level of 15.7 Mt Cu in 2008 – a trend unlikely to slow down in the medium term future. A compilation of the current top Cu mines in the world is given in Table 1.

The trends over time for ore grades in Australia, Canada and the USA are shown in Figure 2. The Australian data set clearly shows the rich oxidised ores (15-20 %Cu) mined in the middle 1800's, followed by the transition to lower grade (3-5 %Cu) but more extensive Cu sulfide ores by the late 1800's. The rise and fall of ore grade through the twentieth century can be attributed to the opening or closure of particular mines (eg. Mt Isa Cu, 1953), or the switch from low grade open cut to high grade underground mining (eg. Mt Lyell, 1920's), and then back to open cut mining (eg. Mt Lyell again and Mt Morgan, 1930's).

Table 1 Top Cu mines in the world (2008 data*)

	Mine	t Ore	%Cu	t Cu	t Waste Rock	Type	Company(s)
1	Escondida	147,578,000	1.03	1,281,400	316,287,000	OC	BHP Billiton / Rio Tinto
2	Codelco Norte#	125,330,000	0.849	896,308	306,221,000	OC	Codelco
3	Grasberg	70,765,000	0.83	521,200	231,401,550	OC/UG	Freeport McMoRan
4	Collahausi	49,694,800	1.03	464,400	108,793,364	OC	Anglo American / Xstrata
5	Rudna	29,400,000	1.64	429,400	no data	UG	KGHM Polska Miedź
6	Morenci§	258,383,000	0.33	407,800	13,330,000	OC	Freeport McMoRan
7	El Teniente#	47,220,000	0.999	404,738	no data	UG	Codelco
8	Antamina	30,438,000	1.25	343,700	86,130,000	OC	BHPB / Teck / Xstrata
9	Los Pelambres	49,932,000	0.76	339,200	no data	OC	Antofagasta
10	Taimyr#	15,037,000	2.74	338,435	no data	OC/UG	Nor'ilsk Nickel

*All data sourced from respective company annual reports; # / § 2007 / 2006 data only.

Note: This list is reasonably extensive, but there may be some mines missing due to private ownership and/or lack of available reporting.

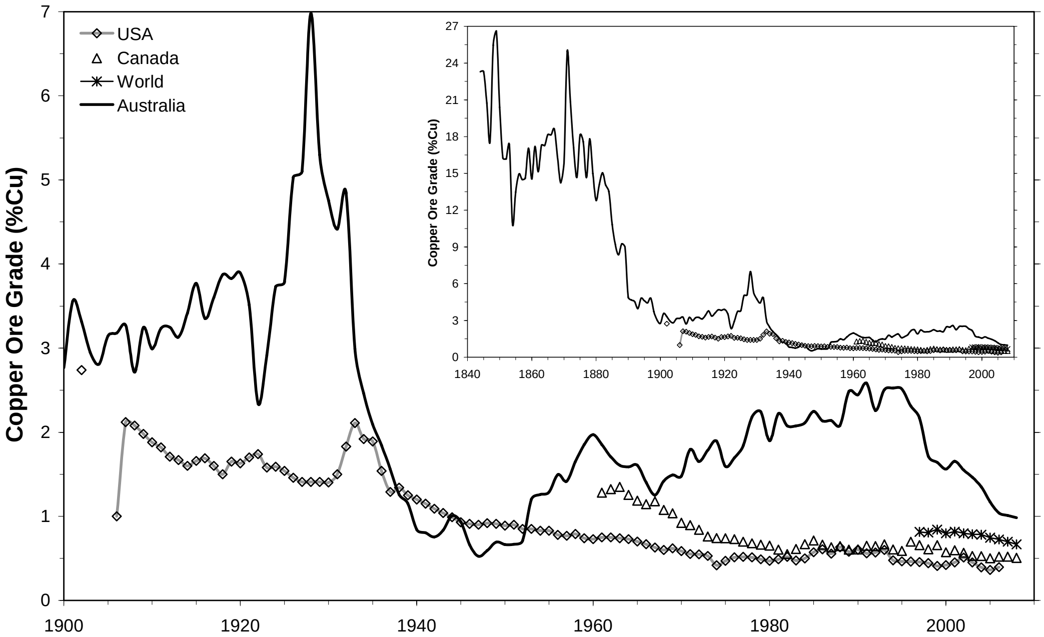

Figure 2 – Copper ore grades over time by country and approximate world average

Ore grade for Canada shows a long-term, steady decline over the past half century. There are many famous provinces in Canada, such as the Quebec Cu-Zn fields, Sudbury Ni-Cu field or the Cu-Au mines of British Columbia. Other states have also contributed, such as New Brunswick and Manitoba, but to a lesser extent in overall production. The long-term trend for Cu ore grade in the USA is a gradual decline, apart from a period of higher grade mining during the Great Depression. Production in the USA is dominated by the western states, especially Arizona and Utah, although the Lake Superior district was a major producer in the 1800’s to early 1900’s. The scale of US production is reflected in their relatively lower ore grades. Over the past two decades in the USA there has been a major shift to the use of heap leach-solvent extraction-electrowinning for low grade Cu ore. The USBoM/USGS data does not account for this source of low grade ore (0.2-0.5 %Cu), meaning that true average ore grades are somewhat lower than the data in Figure 2. Based on various production statistics from company annual reports (eg. Phelps Dodge, Rio Tinto, Asarco, etc.), it would appear that overall average ore grade, including both milled (or concentrated) and heap leached ore, would be about a third to half lower again. The compiled data for the world average ore grade, representing 60-80% of production, also shows a gradual declining trend over the past decade. Data for the ore grades of reserves typically follow milled ore (not shown).

A further important point is that the ore grades presented in Figure 2 only includes materials which are processed for Cu extraction – ie. ore. Based on the extent of waste rock in Table 1, every tonne of ore processed also necessitates the removal of at least 1.5 tonnes of waste rock (waste rock from underground mining is rarely reported). If waste rock was included in the ore grade, this would see a substantive reduction again, especially over the past few decades as open cut mining now dominates.

Economic Cu resources over time are presented in Figure 3, including average annual nominal and real price over time (data from [10]). The term 'resources' is used broadly, since the terminology varies. For example, the USGS uses the terms 'reserves' and 'reserves base' (see [6,7]), while Australia and Canada use reserves and resources, based on formal mineral deposit reporting codes (eg. JORC). In general, the underlying concepts are very similar, although caution is always warranted.

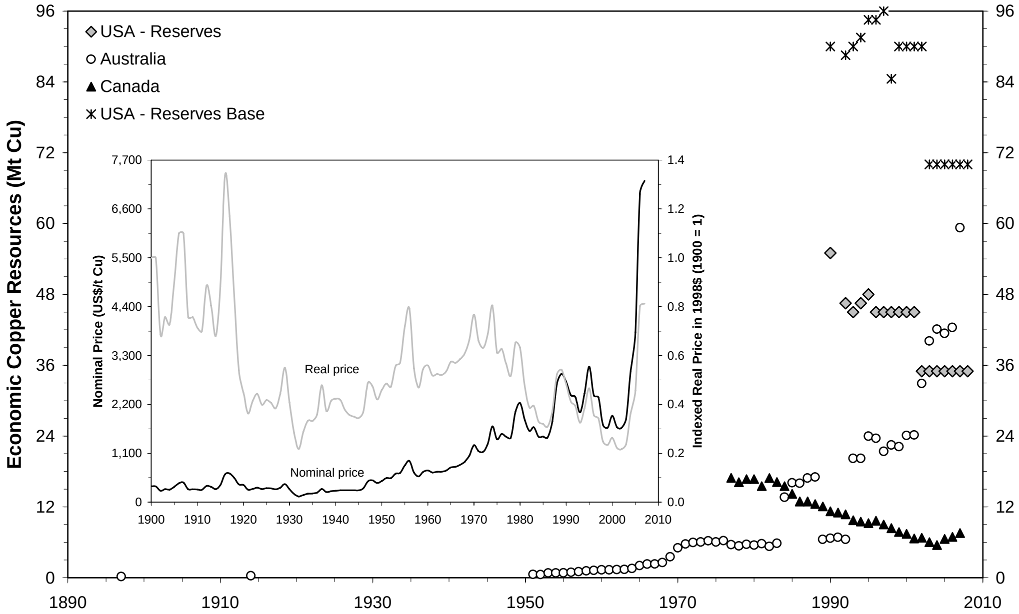

Figure 3 – Economic copper resources and indexed real price over time (1900 = 1)

The resources over time is variable for each country. The USA shows a stable trend over the 1990's but a gradual decline since 2000. The only recent success is the discovery by Rio Tinto of the ~2 km deep Resolution Cu deposit, beneath the old Magma Cu mines in Arizona. Canada shows a long-term decline, with no recent exploration success giving any prospect of a major increase. The small increases between 2004 to 2007 are due to re-assessments of economic resources during the mining boom.

In stark contrast, Australia has shown remarkable growth in economic Cu resources consistently since ~1950 – due to growing resources at known mines (eg. Mt Isa) as well as the discovery of major new deposits (eg. Northparkes, Olympic Dam, Ernest Henry, Prominent Hill). Based on ongoing exploration, it would appear that Australia can continue this trend, as resources continue to expand at Olympic Dam, Mt Isa and Prominent Hill, and recent major discoveries such as Carrapateena are evaluated. For example, Australia's estimated economic Cu resources in 2007 were 59.3 Mt Cu yet the reported mineral resource for Olympic Dam in 2007 was 67.5 Mt Cu alone – showing that the national estimate only includes formal reserves for Olympic Dam (8.83 Mt Cu) and not the full known resource (eg. 2008 – 73.2 Mt Cu).

Real Cu prices clearly show a long-term decline, with the recent mining boom pushing real prices to near historical highs – effectively demonstrating the ongoing availability of cheap Cu, mainly compared to alternatives such as recycling. However, it is not clear whether this trend will continue into the future given looming carbon costs to address greenhouse gas emissions and climate change. It is well recognised that as ore grades decline energy-carbon costs increase, which will feedback in some manner to Cu prices.

NICKEL MINING

Nickel mining was relatively minor in comparison to Cu, Pb-Zn and gold mining until the mid-twentieth century. The growing use and consumption of steel, especially stainless steel, has led to sustained demand for Ni, and hence nickel's growing importance in global mining. There are two main types of Ni ore, sulfide or laterite, with most production coming from sulfide ores while most known resources are laterite ores. Global Ni production was 1.61 Mt Ni in 2008, dominated by Russia, Canada, Indonesia, Australia and New Caledonia, shown in Figure 4 and major Ni mines compiled in Table 2 (see also [12]).

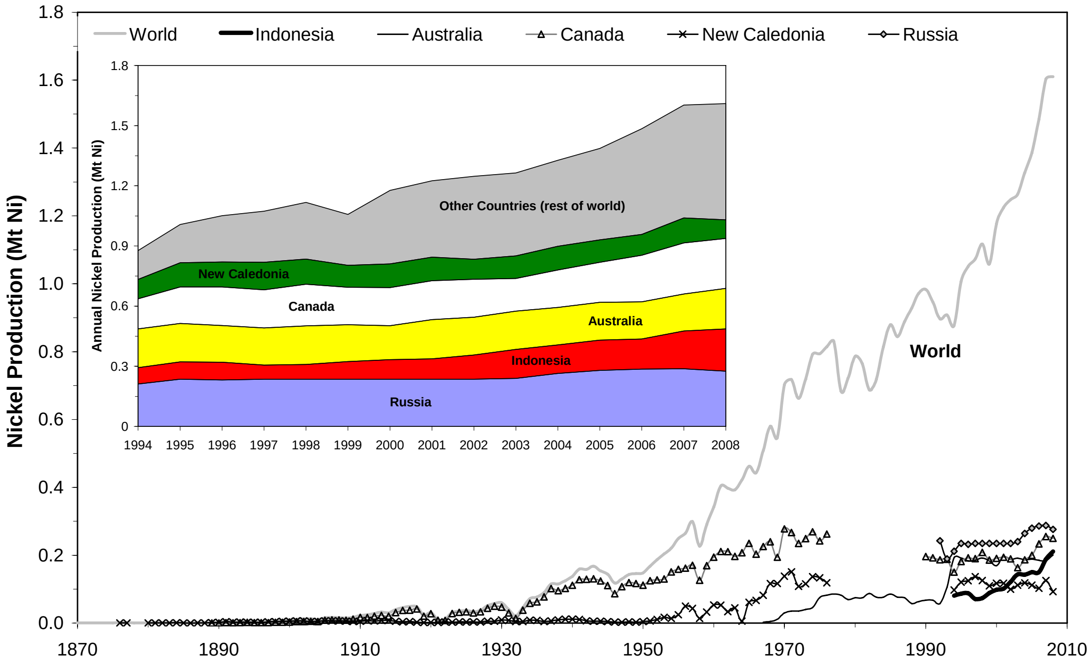

Figure 4 – Mined nickel production over time by country (data sourced from [2-10])

Production for all of the world's major Ni producers has been relatively steady, except for strong growth by Indonesia (due mainly to expansion at the Sulawesi Ni laterite project, majority owned by Vale Inco). Canada appears to have peaked around 1970, with production mostly steady since this time but showing signs of a gradual decline – at least until the recent development of the high grade Voisey's Bay Ni-Cu project in Labrador has led to a recovery in Ni production to 1970 levels again. Australia's Ni industry grew rapidly following the discovery of the Kambalda Ni field in central Western Australia in 1966, leading to a major Ni boom and an integrated sector including mining, smelting and refining [2].

Although data sets over time which show Ni ore type (sulfide / laterite) are not available on a world basis, most of the expected growth in Ni production will be from new Ni laterite projects, such as Goro and Koniambo in New Caledonia, Brazil and other tropical countries. Laterite ores require considerably more energy to process than sulfide ores, and often face major process challenges [2,12].

The only countries which have data available for ore grades over time are Canada and Australia, both since the 1960's and shown in Figure 5. Australia shows a long term decline, with two major step changes around 1975 and 1995, both corresponding to the end of major expansion phases in the Ni sector followed by periods of relative production stability. Canada, on the other hand, shows a very stable trend over the period presented. Unfortunately historical data for the Sudbury field is often lacking, since Inco and Falconbridge generally did not report ore grades and mine-derived metal production until the 1970's.

Table 2 Top Ni mines in the world (2008 data*)

	Mine	t Ore	% Ni	t Ni	Ore Type	Type	Company(s)
1	Taimyr[#]	15,037,000	1.56	193,996	sulfide	UG	Nor'ilsk Nickel
2	Sudbury (Vale Inco)	8,219,000	1.26	85,300	sulfide	UG/OC	Vale Inco
3	Voisey's Bay	2,385,000	3.50	77,500	sulfide	OC	Vale Inco
4	Sulawesi	4,675,000	2.10	72,385	laterite	OC	PT Inco / Vale Inco
5	Doniambo[§]	2,930,000	2.0	51,131	laterite	OC	SLN/Eramet
6	Mt Keith[†]	10,864,771	0.62	44,997	sulfide	OC	BHP Billiton
7	Leinster[†]	2,444,871	2.03	40,770	sulfide	OC/UG	BHP Billiton
8	Kola[#]	7,636,000	0.66	38,223	sulfide	UG	Nor'ilsk Nickel
9	Kambalda[‡]	1,268,761	2.80	33,063	sulfide	UG	BHP Billiton
10	Murrin Murrin	2,446,276	1.43	30,514	laterite	OC	Minara Resources

*All data sourced from respective company annual reports; [# / §] 2007 / 2006 data only; [†] Full data not reported, 1998-2004 data used as an approximation only; [‡] Full data not reported, since Kambalda now operates as a toll mill only; data estimated from mining only.

Note: This list is reasonably extensive, but there may be some mines missing due to private ownership and/or lack of available reporting.

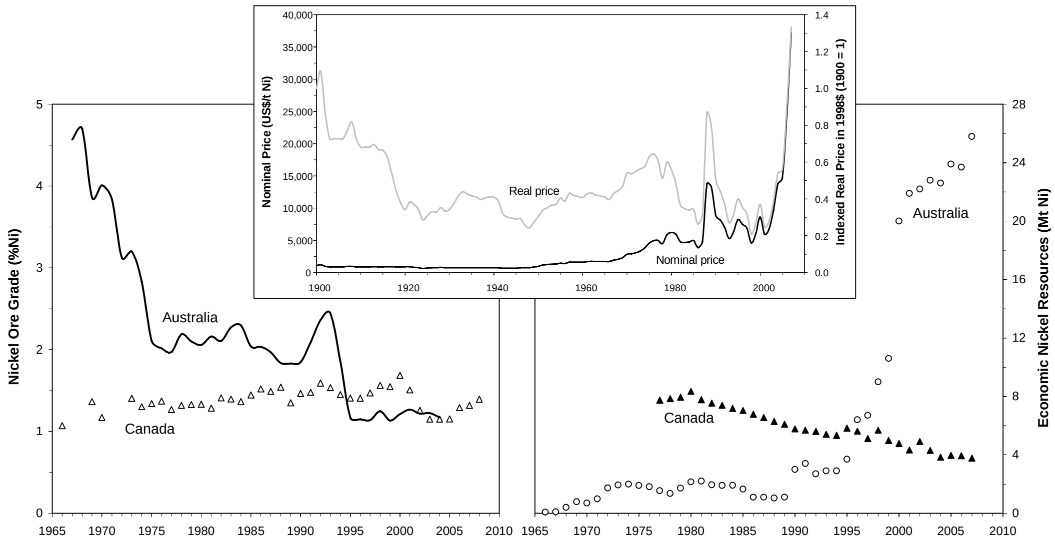

Figure 5 – Nickel ore grades (left) and economic resources (right) over time for Canada and Australia, with nominal and indexed real price over time (inset)

The extent of known economic resources for Canada and Australia is included in Figure 5, additional information and discussion is given by Mudd [2,12]. In Australia, a renewed 'Ni boom' occurred from 1995 – often colloquially known as the laterite boom. Around this time, there was a major focus on the development of Ni laterite resources in central Western Australia (WA) – long known but long neglected. The emergence of more robust process design and efficient materials and technology, namely 'high pressure acid leach' (HPAL) technology, promised to revolutionise WA's Ni sector. By the late 1990's there were three major projects being developed, at Murrin Murrin, Cawse and Bulong. All projects faced severe engineering and process related issues, eventually leading to the closure of Bulong and Cawse after only 1-2 years operation and Ni production well below proposed targets (the Cawse plant was later converted but again failed commercially). The Murrin Murrin project, however, managed to survive by the barest of margins – despite ongoing process challenges, corporate ownership issues and major court cases – until the recent mining boom meant that the Ni price made Murrin Murrin more readily profitable.

In stark contrast, Canada's economic Ni resources appear to continue to decline. The discovery of the Voisey's Bay Ni-Cu sulfide deposits in the early 1990's has not led to a major increase in economic resources, although it has clearly offset the fall in Sudbury. For comparison, Inco's ore reserves at Sudbury were 197.2 Mt in 1945 (grades not given), 290.1 Mt grading 2.92 %Ni+Cu for 8.47 Mt Ni+Cu in 1966 and yet in 2005 at Sudbury they were still 258 Mt grading 1.35% Ni, 1.39% Cu for 3.49 Mt Ni and 3.57 Mt Cu [4]. Between 1966 and 2005 Inco mined more than 300 Mt ore (including ore from Thompson). Total Inco and Falconbridge Ni resources alone in 2005 amounted to 8.03 Mt Ni – twice the 2007 Ni resources of 3.78 Mt Ni [4]. Therefore, although it may appear as though Ni resources are in decline, this is more an outcome of the strict protocols in place for reporting economic resources.

Overall, there are widespread global Ni resources, with the ultimate question being the increasing environmental costs as the Ni sector shifts from predominantly sulfide to laterite ores [12].

LEAD-ZINC MINING

The mining of Pb-Zn ores has been a mainstay economic activity in many mining centres around the world – such as Kimberley in British Columbia, Bathurst in New Brunswick, Broken Hill and Mt Isa in Australia and the Mississippi Valley in the USA. The sector has evolved in tandem with industrialisation, with the principal focus in the mid-late 1800's mainly on silver, with lead emerging as valuable by that century's end. Early in the 1900's, however, Zn was proving to be a problem in Pb-Zn ore treatment, since Zn was contaminating the smelting of Pb concentrates. The discovery of new process technology – *flotation* – was developed first for Broken Hill ore and proved highly successful in producing high quality separate Pb and Zn concentrates [2]. Flotation is often regarded as one of the most important mining technologies developed in the twentieth century, and is now become a critical component of virtually all sulfide-based ore projects (Ni, Cu, Pb-Zn, tin, etc.), and is even used in other sectors such as gold. Like Cu and Ni, Pb-Zn production has grown considerably throughout the past two centuries, though Pb growth has stagnated since 1974. Pb-Zn mining now includes a wide array of ore types and mining projects as well as increasing geographic diversity, especially the rapidly growing dominance of China in Pb-Zn. The major Pb-Zn producers continue to be China, Australia, Canada, Peru and the United States, followed closely by India, Kazakhstan, Ireland and Mexico. Global Pb-Zn production is shown in Figure 6.

The only available country data on ore grades over time is for Australia and Canada, included in Figure 6. For Australia, the Pb sector began at a modest scale at Northampton, north of Perth in Western Australia. Although the grades appear to be exceptionally high, this does not represent true ore grade as mined due to hand-sorting. The long-term decline in Pb grade for Australia is evident, and also shows the high grades from the early days of the Broken Hill field, mainly since rich oxidised ores were mined and smelted. The Australian Pb trend also reflects the increasing emphasis on Zn-rich ore types, due to the higher demand and price for Zn. In Australia, the main Pb-Zn projects developed over the past few decades include the Golden Grove Cu-Zn project, and the Mt Garnet and McArthur River projects (rich Zn, low Pb) – only the Cannington project has had high Pb grades (as well as very high Ag grades). As such, this has led to a gradual decline in Zn grades until 1980, after which time many of the above projects were developed, including the Century Zinc project in 1999 (high Zn).

The Zn ore grades in Canada have been relatively stable over the past ~50 years, showing only minor variation from year to year. Pb grades, however, have gradually declined. In both cases, this is largely related to the primary emphasis on Cu-Zn ores in Canada, showing lower Pb grades than if the estimate was made using Pb-Zn ores only. In the past decade, some historic Pb-Zn projects have closed due to lack of economic reserves, such as the Kimberley, Faro, Heathe-Newcastle and Polaris mines. The future ore grades are likely to be increasingly dominated by Cu-Zn projects, as the influence of Pb-Zn declines.

The extent of economic resources for Australia, Canada and the United States, similarly to Ni, is quite variable. Australia shows strong growth over time, especially for Zn, while the USA is relatively stable, though a major increase in the Zn reserves base occurred in 1998. Both contrast significantly with Canada which has shown substantial long-term declines in Zn but especially Pb resources. The growth in Australia has largely been a function of proving up more resources at known mines (eg. Mt Isa, Broken Hill, Golden Grove, McArthur River) plus some important new discoveries (eg. Cannington). This is in contrast to Canada, where the number of mines with Pb resources is now reduced to just four – Bathurst and Myra Falls (operating) and Caribou and Restigouche (temporarily closed).

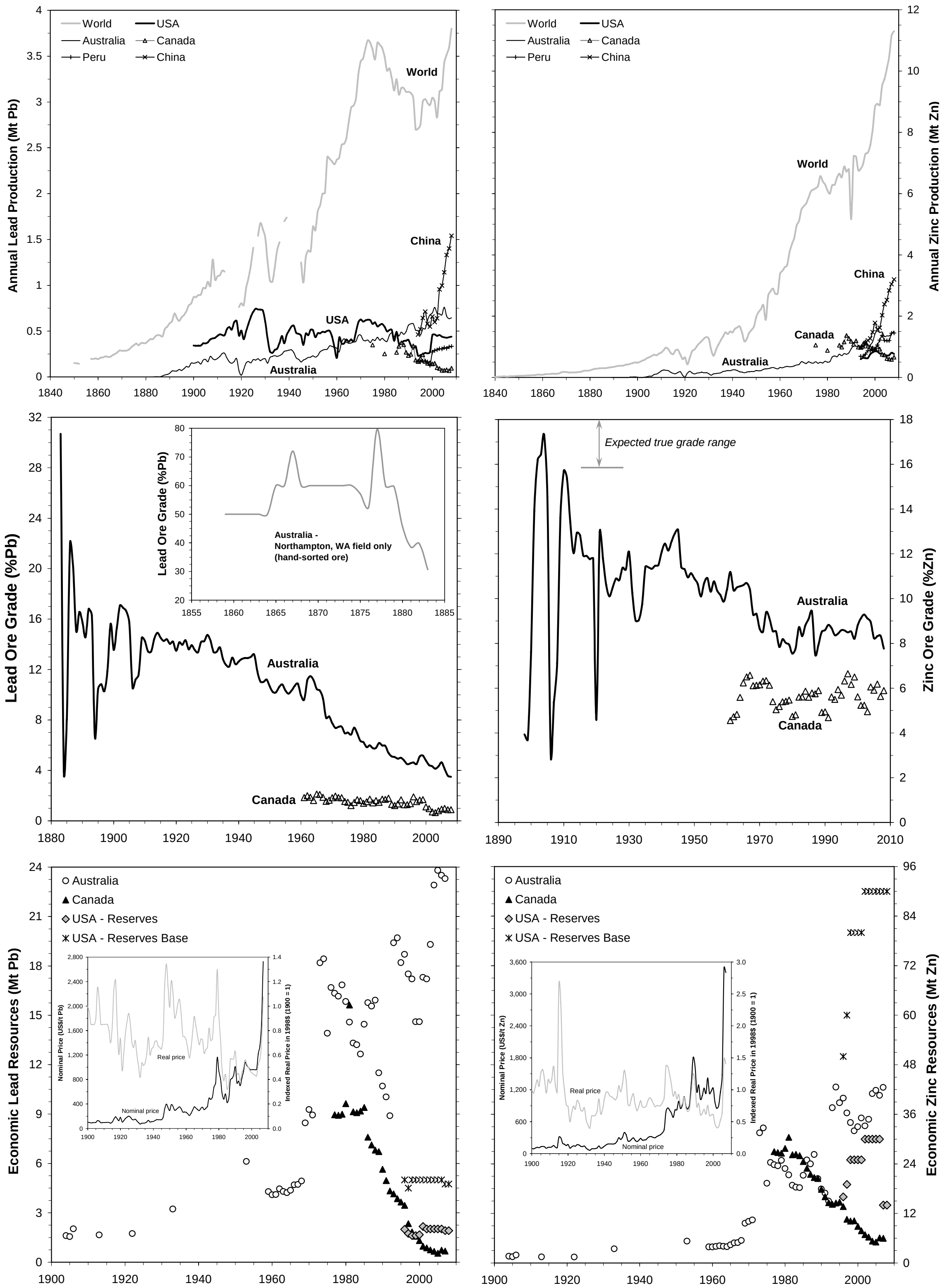

Figure 6 – *Top row*: Mined lead-zinc production over time by country (data sourced from [2-10]); *Middle row*: Lead-zinc ore grades over time for Australia and Canada; Bottom row: Economic lead-zinc resources over time for Australia, Canada and the United States, with nominal / indexed real price over time (inset).

The extent of Canadian Zn resources is being increasingly dominated by Cu-Zn ores, and given the lack of major new Pb-Zn discoveries in the past few decades, this is unlikely to change. The dominant area for Zn resources in the USA is Alaska, namely the Red Dog and Greens Creek mines. Minor resources are found in Idaho, Montana and Washington, though production is relatively small. As for Ni and Cu, real prices for Pb-Zn show a long-term decline plus a recent surge in prices due to the mining boom.

DISCUSSION AND CONCLUSIONS

The base metal sector is a large and important part of the global mining industry, providing metals for a wide variety of uses in modern society and technology. In order to better prepare for the future, it is important to understand the history of a technology, sector or industry – since this helps to understand crucial trends and therefore allow more informed projections for the future. This paper compiled and presented a wide array of publicly available data on production, ore grades and economic resources over time, focussed mainly on Australia, Canada and the United States. In general, Australia production continues to grow steadily with resources growing strongly. Canadian production and resources appears to show a decline over time, but some major companies do report larger economic resources, suggesting that any future decline is likely to be slower than in the recent past. Most ore grades show a gradual decline over the available data, except for Canadian Zn and Ni grades. This is critical since lower ore grades means more ore has to be mined and processed to maintain production – and given looming carbon costs, this represents a fundamental challenge to the future of the base metals sector. The data presented is a major part of the information required to underpin any debate about 'peak minerals' and the future of mining. That is, in order to better prepare for probable future challenges, it is important to understand the past and long-term trends – a proposition especially true for base metals and the coming nexus of 'peak minerals'.

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Backcasting is a planning method that starts with defining a desirable future and then works backwards to identify policies and programs that will connect that specified future to the present. The fundamentals of the method were outlined by John B. Robinson from the University of Waterloo in 1990. The fundamental question of backcasting asks: "if we want to attain a certain goal, what actions must be taken to get there?".