ICSG – Environmental & Economics Committee
The Growth of Productivity in Copper Mining and The Long Term Evolution of The Reserve Base

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Copper has very rarely traded at marginal cash costs, it has averaged 53% above marginal cash costs on a month by month basis since 1995.
Over the last twenty years, nearly every commodity has traded at a significant premium above marginal cash costs

A simple, but manifestly incorrect, heuristic has arisen in the analysis of commodity prices which states that the long term or fair commodity price is set by the marginal cash cost of production. While it is easy to see the attractiveness of this approach, it is markedly at odds with reality. It fails to describe reality in two profound ways. In the first place because each commodity has a trading history that is markedly different from every other and in the second place because nearly all commodities trade at a very significant premium to marginal cash costs.

![Average Long Term Premium Above Marginal Costs](image-url)

Source: Bloomberg, CRU, AME, Bernstein Analysis & Estimates
China’s demographic dilemma – the urgency behind industrialisation.

There is normally a very good fit between demographics and wealth: rich societies have fewer children but are sufficiently productive to afford ageing.

China stands as the exception to this rule: a not yet urbanised society with a developed world demographics – a difficult combination.

Source: IMF, NBS. Bernstein analysis
A new model for global growth: we derive a 99.8% correlation between physical capital and output

- Output is given by the level of capital which is simply the accumulation (less depreciation) of commodities over time.
- The change in output is proportional to the level of commodity production.
- Unlike classical growth models, there is no “residual” in our model so there is no need to posit any additional factor beyond physical capital as a determinant of output.
The evolution of metal intensity – acceleration, inflection and decline

- Under the classical approach, commodity intensity ought to decline over time. This is not what we observe in reality.
- Our model predicts periods of rising commodity intensity and better captures the historical trends.

Metal Intensity Over Time As Per Our Model

Metal Intensity Versus Output As Per Our Model

Global Copper Intensity Over Time

Global Copper Intensity Versus Output since 1900

Source: Maddison, Mitchell and Schmitz, ICSG and Bernstein analysis
There is a very strong relationship between the level of copper stock and output.

Unsurprisingly, a very strong relationship exists between the overall level of capital stock in a country and its output. We link the metal intensity in different time periods by assuming that the rate of overall economic growth is accompanied by a corresponding development in capital stock.

- China has a copper stock of 27kg/capita – just 37% of the levels in the USA, 26% of Japanese levels and 16% of South Korean or German levels.

Source: Wood Mackenzie, USGS, Mitchell, Bernstein analysis and estimates
We use copper consumption and capital stock to derive the copper intensity curve for China.

Our analysis gives rise to the following trend line for China’s copper intensity.

- We use the relationship between copper stock and output in Japan to model China.
- If we assume that copper productivity in China mirrors that seen in Japan, the development of China’s copper stock and its economy ought to follow the same pattern.

![China Copper Intensity Forecast](chart)

Source: Wood Mackenzie, USGS, Mitchell, Bernstein analysis and estimates
Geological abundance and industrial use are highly correlated.

**Use and Availability of Major Industrial Commodities**

![Graph showing the relationship between geological abundance and annual production for various elements.](image)

*Source: USGS, Bernstein analysis and estimates*
Copper is the most over-utilised major commodity.

- Copper stands out as the most over-utilised commodity relative to the underlying geological endowment.
- Copper stands as the most over-exploited metal with a production of 16.4x that implied by the underlying relationship between abundance and use.

Source: USGS, Bernstein analysis and estimates
Chile is unique – there are no new Chiles.

- Chile’s geology is unique and radically different from China – the second largest copper miner. Expectations that there will ever be a repeat of the Chilean copper boom are misplaced.

![Graph showing global copper endowment](image-url)

- **Chile**
- **USA**
- **Peru**
- **DRC**
- **Zambia**
- **Poland**
- **Canada**
- **China**

Source: USGS, Bernstein analysis and estimates
The development of the current reserve base will not be enough.

Source: Wood Mackenzie, ABMS, Bernstein analysis and estimates
The growth of productivity in mining – it is getting harder!

The dramatic increases in mining productivity seem in the 1970s through to the 1990s have run their course, it is getting increasingly hard to overcome the effects of geological complexity.

Source: Schmitz, USGS, Measuring Worth, Bernstein analysis & estimates
The last period of falling copper prices was driven by the rise of the Chilean copper industry whilst now we are witnessing its senescence. During the last period of trend declines in nominal prices, productivity grew faster than wages.

1990 to 2003 – Price and Productivity CAGRs

<table>
<thead>
<tr>
<th>Change in Mining Productivity</th>
<th>Change in Mining Wages</th>
<th>Change in Copper Price</th>
</tr>
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<tbody>
<tr>
<td>11.0%</td>
<td>8.9%</td>
<td>-2.1%</td>
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</table>

Mining productivity growth exceeded wage inflation and commodity prices fell

2004 to 2012 – Price and Productivity CAGRs

<table>
<thead>
<tr>
<th>Change in Mining Productivity</th>
<th>Change in Mining Wages</th>
<th>Change in Copper Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3.1%</td>
<td>7.3%</td>
<td>8.2%</td>
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</tbody>
</table>

Wage inflation exceeds mining productivity growth and commodity prices rise

The exact opposite is now true. Wages continue to rise and yet productivity has declined dramatically.

Source: Cochilco, Bernstein analysis & estimates
New copper development will prove harder than many anticipate.

- Even if massive new finds are encountered, the history of Pebble and Oyu Tolgoi tells us that it will take 20 to 30 years for these finds to deliver commercially meaningful metal (compared to 10 years for Escondida).

- It takes many years to develop a copper project and the average time required to move a project from discovery to production has been increasing steadily over time.

Source: USGS, Bernstein analysis and estimates

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What the long term history of copper shows us is the dependency of the price on the reserve base.

- Two structural periods of declining prices.
- Both driven by the rapid development of the global copper reserve base. First in the USA then in Chile.

Source: USGS, Bernstein analysis and estimates
But what have we seen in practice?

Despite its academic pedigree the empirical evidence for the validity of Hotelling’s Rule is almost entirely lacking, so what has gone wrong? If we understand this we will understand what it is that actually drives structural trends in commodity prices.

Source: Schmitz, USGS, Bernstein analysis & estimates
The first problem...what do we actually mean by historic commodity prices.

At the middle of the 19th century the “real” copper price was about the same as it is today, but what does this comparison tell us? Could I employ people to produce copper in the same way now as then and what would be the cost of copper if I did?

Source: Henderson
What historic prices tell us is almost entirely a function of the choice of deflator.

What we mean by the price of copper at any point in the past is, in large measure, arbitrary. A case can be made for any figure between US$675 and US$22,000,000 per tonne. What history actually tells us requires pretty significant interpretation.

Source: Schmitz, USGS, Measuring Worth, Bernstein analysis & estimates
Or, put another way, the labour requirement in copper is made clear.

We have seen the labour input into copper mining fall from ~5 years to ~0.06 years, a 100 fold decrease in cost over a two hundred year period...this is the true measure of how far commodity prices have declined, something entirely hidden by looking at CPI.

Equivalent Man Years to Produce a Ton of Copper + Trend

\[ y = 5.5866e^{-0.019x} \]

\[ R^2 = 0.9205 \]

Source: Schmitz, USGS, Measuring Worth, Bernstein analysis & estimates
The basic problem is revealed if we look at the energy it takes to produce copper.

- It takes ~30,000kwh to produce a tonne of copper.
- We can deliver that energy in human form (equivalent to ~130 man years of effort) or we can use mechanical means to deliver it.
- The use of capital (mechanisation) reduces the need for human forms of energetic input and appears as an increase in the productivity of human labour.
- Thus cost deflation in mining is revealed as driven by two factors, energy getting cheaper or the displacement of human beings as the source of that energy.
- By far the dominant factor in the reducing price of copper has been the ability to use less labour rather than that energy has become cheaper.
- But there is a limit to how far this process can continue. Once the ability to strip labour out of mining begins to bite, the full impact of energy cost escalation is felt.

Source: Schmitz, USGS, Measuring Worth, Bernstein analysis & estimates
Capitalisation, or mechanisation, stands as the cause of this vast increase in productivity...

Over the course of history the dominant input factor in mining was human labour, it was the process of mechanisation and an ever greater reliance on capital that slowly changed this and so drove the huge increases in mined productivity.

Source: Kendrick, ABS, Bernstein analysis & estimates
Mining is already the most capital intensive activity in any industrial economy.

Mining is already the most capital intensive industrial activity, it is getting harder and harder to strip labour out of mining in favour of capital.

Source: Kendrick, ABS, Bernstein analysis & estimates
So how does Hotelling’s Rule actually work in mining?

The most important feature of the decline in the cost/price of copper (or the increase in the productivity in copper mining) is that it has enabled us to mine ever lower grade of copper deposits.

Source: Gerst, USGS, Bernstein analysis & estimates

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At the same time, the decline in grade allowed for a huge increase in reserves.

There is an inverse relationship between grades and costs (lower grades mean higher cost) but there is also an inverse relationship between grade and quantity (there is a lot more low quality material than high quality material). The increase in labour productivity allowed grades to drop by half and thus reserves to increase twentyfold.

Source: Gerst, Wagenhals, USGS, Bernstein analysis & estimates

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The rise of the copper porphyries.

By allowing for the ever greater exploitation of ever lower grade material eventually the lowest grade ore body of all, the copper porphyry, became the mainstay of global copper production.

Copper Production by Ore Type

Source: Gerst, USGS, Bernstein analysis & estimates
100 years of grades and reserves.

Over the last one hundred years, we see an exponential relationship between grades and reserves...but the critical question is how does the reserve base respond to increases in productivity going forward?

Grade-to-Reserve Relationship (1900 to 2010)

R² = 97%

Reserves — Mt Cu
Reserve Grade — % Cu

Source: Gerst, Wagenhals, USGS, Bernstein analysis & estimates
Grade to resource profile.

Over the last 35 years we have far more data points, but observe the same exponential relationship between grade and resource size.

Source: Wood Mackenzie, Bernstein analysis & estimates
Resource conversion success.

But we also observe a declining ability to convert that resource into reserve. The lower the quality of the material, the harder it is to find an economic solution to its exploitation.

Source: Wood Mackenzie, Bernstein analysis & estimates
The cause of the exponential grade-resource relationship.

- The distribution of grade to tonnage follows a lognormal distribution. Essentially this is to be expected if we assume that geology is the product of random events, i.e. It requires this factor and this factor and this factor etc.

- As productivity improves the grade of material that we allow to qualify as reserves declines, i.e. We can afford to mine lower quality sections.

- As the grade declines the size of the resource increases.

- The increase in the resource base appears to grow exponentially with the decline in the average grade of the resource.

- The growth in production is a function of the growth in reserves. Mines are built with a 20-30 year LOM, so the apparent reserve life simply reflects this engineering choice.

Source: Bernstein analysis & estimates
Exponentially increasing resources cannot continue indefinitely.

In the example lognormal distribution given previously the exponential increase in resource comes to an abrupt halt once the cut-off grade falls below the mode of the grade PDF. Moving from 1.8% to 0.9% cut-off causes a seventy fold increase in resource, from 0.9% to 0.45% a 6 fold increase, but soon lowering the cut-off grade delivers nothing.

Source: Bernstein analysis & estimates
The standard objection to Hotelling’s Rule is that it is the margin of a commodity producer that should grow at the cost of capital rather than the commodity price.

So, if costs are falling, Hotelling’s Rule can deliver falling commodity prices.

But, against traditional measures of real commodity prices, this effect is far too rapid to deliver a structural explanation of the failure.

In other words, most analysis starts with far too low a copper price (i.e. one deflated using CPI) and consequently there is very little room for copper prices to fall versus any non-zero cost of capital.

Starting at a “real” price of say US$10,000/t it can explain departures that last ~15 years at most.

Consequently, most literature rejects this as a solution to the problem.

Source: Bernstein analysis & estimates
So What Has Hotelling’s Rule Missed (2/3)?

- The standard approach to the impact of cost declines assumes that prices have been roughly stable in real terms.

- It underestimates how far prices have actually fallen and the time scale over which this has happened.

- Assuming that we start at a much higher initial price (as per that given by a labour deflated copper price), we can see a truer picture of productivity versus the cost of capital.

- But note, prices fall exponentially only over the period of increasing labour productivity.

- On this basis, the empirical evidence for a failure of Hotelling’s Rule is far less clear.

- By underestimating how much productivity has improved in the past, most approaches to mining price analysis overestimate how much further there is to go.

Source: Bernstein analysis & estimates
So What Has Hotelling’s Rule Missed (3/3)?.

+ Hotelling’s Rule requires a well defined finite reserve base and does not clearly distinguish between reserves (that which is economic to mine) and resources (that which is geologically present).

+ It requires that the reserve base be known independently of the cost of production and the price of the commodity (i.e. that the reserve is given as an external “fact”).

+ The mathematics of the derivation of the rule is that of optimising profitability of the exploitation of the mine given the constraint of finite reserves. It is this constraining boundary condition that implies that prices rise at the cost of capital.

+ But reserves are not known independently from costs or prices, but are instead a function of these two variables.

+ We cannot use reserves to determine price when it is simultaneously price that determines reserves.

+ The critical question becomes, what causes the reserve base to change, is it price or productivity?
Head-grade to reserve grade…what does this tell us?

- Both the declines in grade and the change in proportion between head and reserve grade indicate a structural revision to the global mine plan for the production of copper metal.

Source: Wood Mackenzie, Bernstein analysis and estimates
The relationship between copper grade and price is very strong.

- Copper prices and grades track each other. This immediately suggests the structural form for a multivariate regression that explains (without the introduction of specious exogenous regime shifts and Heaviside functions), the copper price evolution over the last 35 years.

Source: Wood Mackenzie, Bernstein analysis & estimates
We use this as the basis of a simple multivariate regression, which almost perfectly describes the copper price.

- We know that global grades are going to continue declining as currently sub-economic resources rather than the accelerated exploitation of existing high grade reserves are called to satisfy demand growth. The IMF provides a useful global GDP forecast. Finally, we can assume relative stability in warehouse inventories.
90% of the movement in copper price is explained by grade, GDP and inventories.

- A regression of the form \( Price = a + b_1 \times \text{Grade} + b_2 \times \text{GDP} + b_3 \times \text{Inventory} \) explains nearly 90% of the variation in copper price over the last 35 years.

- By far the most important element is grade. This relationship gives the effective real world cost increase implied in grade decline.

Source: Bernstein analysis and estimates
90% of the movement in copper price is explained by grade, GDP and inventories.

- Under any scenario, the transition occasioned by dropping the cut-off grade so that the head grade moved below the reserve grade implies prices well in excess of US$10,000/t.
- We know that global grades are going to continue declining as currently sub-economic resources rather than the accelerated exploitation of existing high grade reserves are called to satisfy demand growth.
- The IMF provides a useful global GDP forecast. Finally, we can assume relative stability in warehouse inventories. Even the most conservative grade profile gives rise to prices well in excess of US$10,000/t. It is only a question of when not if this occurs.

Source: Bernstein analysis and estimates
Conclusion

+ The real history of copper prices is best seen using the labour deflator. This shows the dramatic increase in productivity that mining has achieved over the last hundred years.

+ It is the substitution of human effort by capital that has enabled us to mine minerals at ever lower grade.

+ In response to the ability to mine at ever lower grade, the reserve base of metal has grown exponentially. It is this growth in reserves that has, so far at least, forestalled the impact of Hotelling’s Rule.

+ But productivity in mining cannot continue indefinitely...there is a hard stop at zero labour and we are approaching (or have already passed) this point.

+ There is also a limit to the gain in reserves that can be achieved through lowering cut-off grades. Grades cannot fall below zero.

+ For the first time we are approaching a situation where the reserve based is constrained in the Hotelling's Rule sense of the term.
Disclosure Appendix

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Rating Guide: O - Outperform, M - Market-Perform, U - Underperform, N - Not Rated

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