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ANALYSIS

Valuing copper mined from ore deposits

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Abstract

Some of Earth's largest metalliferous ore deposits form in response to thermal fluid circulation through its crust. A large hydrothermal copper deposit recently drilled on the mid-Atlantic ridge, formed episodically over a period of about 50,000 years during a heat flow of ~2 W m^{-2}. The total average energy expended on the formation of this deposit is about 1.5×10^{18} J, which has a present-day thermal equivalent cost of US\$$1.4 \times 10^{9}$. This equates to a natural production cost of US\$33,000/ton copper, about 10–20 times the present market value of copper. Similarly, concentrating trace amounts of copper held in ordinary rocks into deposits of economics significance, using modern mining and smelting processes, would cost about 12–25 times the present-day value of copper. Current market prices for copper thus appear to be significantly undervalued. Based on thermodynamic principles, this result may be used to evaluate cryptic externality cost associated with mineral exploitation.

Keywords: Earth resources; Copper ore; Hydrothermal services; Pollution; Externalities

1. Introduction

Mineral deposits are capital grown out of a number of interactive geological processes that occasionally converge to concentrate useful minerals into these natural stockpiles (ores). Exploitation of ore deposits is important business because its minerals are scarce in an economic sense. Yet minerals (or metals) like copper are not physically scarce; in fact there is a superabundance of them in most natural rock and fluid systems. Economic scarcity exists because Nature's ore "factories" produce only limited marginal concentrations for economic extraction. In turn, this economic scarcity drives polarized exploitation that often results in cryptic external side effects, the costs of which are particularly difficult to estimate when "the margin" is shifted by large amounts, as is the case for many global costs such as those related to environment pollution, climate change and poverty. Obtaining a better sense of the total value of ore deposits (to humans) is therefore useful to explore. One way to approach this is to compare the relative energy expended by Nature's ore-producing "factories" to that expended by human technology to produce a similar ore deposit. This permits the deri-

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vation of an embodied energy value of ore deposits with which to further evaluate externality costs of the mining industry. Although this approach is quite different from normal economic concepts of valuation, in that it does not derive direct replacement costs or future values, this type of analyses does provide an appropriate follow-up to other, relatively new valuation concepts in ecological economics (cf. Daly and Townsend, 1993; Constanza et al., 1997; Balmford et al., 2002).

Here, I first derive an estimate of the amount of energy Nature expends in a modern environment of actively forming copper deposits. I then use this to calculate the present-day value of copper as a function of Nature's investment and compare this to the energy (and cost) that would be expended in mining and extracting copper from ordinary rocks using present-day technologies. The results of these two independent cost-estimates for the concentration of copper are remarkably similar. The results indicate also that copper-production costs of Nature appear to be at least an order of magnitude greater than the present market value of copper. I explore if the differences might represent some of the hidden costs of modern mining.

2. Hydrothermal mineral deposits

Many of the largest metalliferous ores of Earth have formed in response to fluid circulation in its crust (Sawkins, 1990). This process is a by-product of Earth's thermal decay. Hot magma, intruding the outer crust of Earth, cools efficiently when it interacts with crustal fluids because such fluids promote more effective heat loss through convection rather than conduction. The hot convecting crustal fluids in turn promote preferential solution of elements, such as copper, present in trace amounts throughout all rocks (silicates) of the solid crust. In cooler, near surface environments, precipitation of ore minerals (as sulfides) from such concentrated solutions creates ore deposits (Fig. 1) that may be economic to mine given prevailing (or anticipated) market conditions. Unfortunately, there are very few mineral deposits on the continents of the world for which enough robust data is available to constrain how long it takes to form an ore deposit, and from which in turn to quantify the total energy extended by Nature during its formation. In contrast, hydrothermal flux involved in actively concentrating metals into ores is reasonably well-constrained at mid-ocean ridges, where almost 25% of Earth's heat is continuously lost during the formation of new oceanic crust (Pelayo et al., 1994; Baker et al., 1996). Spectacular mineral-laden vents (black-smokers) are the surface manifestations of actively forming ore deposits immediately beneath the ocean floor (Alt, 1995; James and Elderfield, 1996). These deposits form during the interaction between hot magma rising and cold overlying seawater that penetrates the newly formed crust. This "water-cooled" reactor is a natural geological factory for mineral deposits (Fig. 1A). About 35% of the global oceanic heat loss occurs by such hydrothermal flow, and 10–30% of this hydrothermal heat loss occurs at the mid-oceanic ridge through newly formed crust less than 1 million years old. This equates to a heat flux of 1–3 W/m^2, or between 10 and 100 MW/km of mid-oceanic ridge (Pelayo et al., 1994; Baker et al., 1996).

3. Value of copper produced by Earth's oceanic hydrothemal processes

Geology, geochemistry and geochronology on dredge samples and drill-cores from a hydrothermal vent field in the central Atlantic, the TAG field, has located an actively forming mineral deposit comparable in size to the largest massive sulfide ores on land (Humphris et al., 1995; Herzig et al., 1998; Hannington et al., 1998). The TAG deposit formed over a period of some 50,000 to 100,000 years (Humphris et al., 1995; Hannington et al., 1998; You and Bickle, 1998). Estimates of the total amount of sulfides based on drilling the deposit are close to 4 million tonnes of ore with a range of 1–5 wt.% copper and with an estimated total contained metal in the deposit of 30,000 to 60,000 tons of copper (Hannington et al., 1998; Table 1). The chemistry of the hydrothermal fluids and the geology of the deposit indicate that hydrothermal activity was episodic and active for only about 10% of the time (Hannington et al., 1998; James and Elderfield, 1996; Table 1). Given a heat flow of 1–3 W m^2 over 50,000 years, the minimum total energy expended on the formation of the deposit is in the order of $8–23 \times 10^{17}$ J (see Table 1). The thermal equivalent of a reasonable

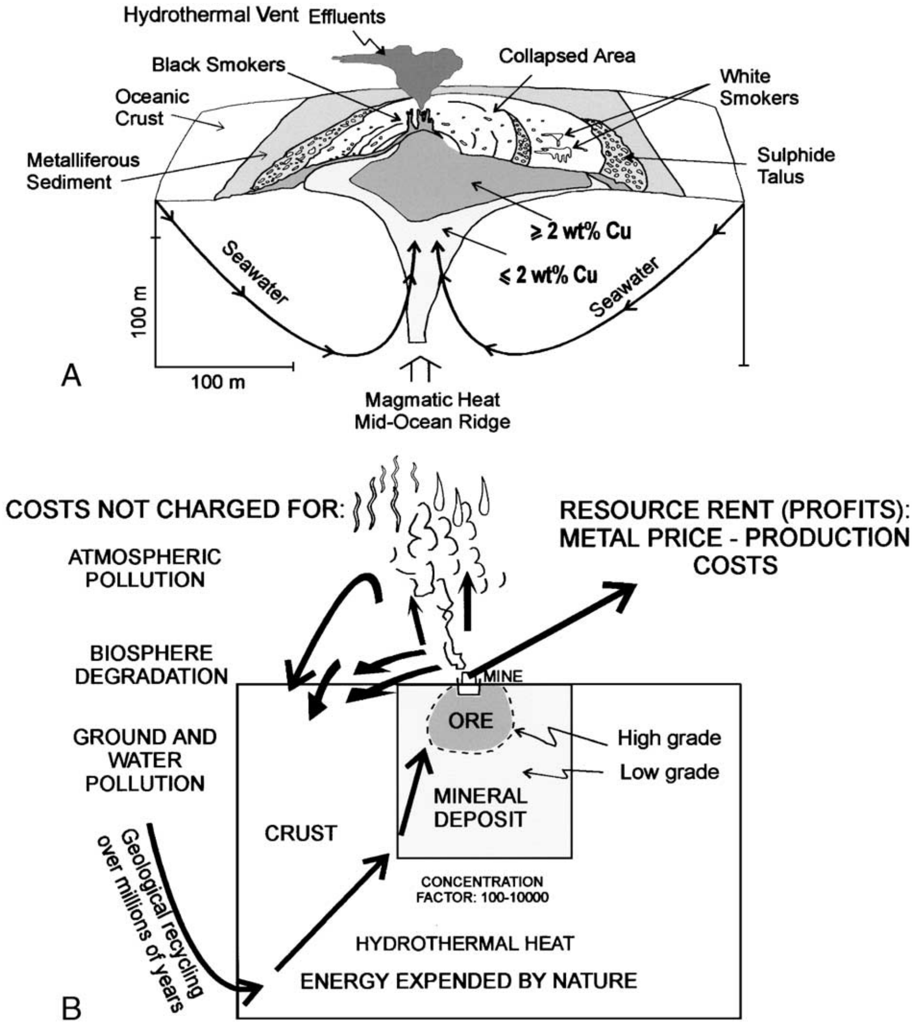

Fig. 1. Formation and exploitation of hydrothermal metal deposits. (A) Schematic representation of the TAG hydrothermal copper sulphide deposit presently forming along the mid-Atlantic ridge at 3650 below sea level. This is the only example of mineral deposit on which sufficient age and thermal data has been collected to quantify its total energy-budget of formation: see Table 1 (modified from Humphris et al., 1995; Herzig et al., 1998). (B) Heuristic model of concentration and dispersal processes involved in formation and exploitation of a hydrothermal deposit.

quality coal would cost in the order of US\$6 to 20 billion and thus US\$k10–66 per ton of copper generated (Table 1). Thus, an average value of copper formed at 2 W/m^2 over 50,000 years is US\$31,000/ton. Since the present market price ranges between about US\$1600 and 3200/ton copper (from a low in 1999 to a high in 2004; see Table 1), it “costs” Nature on average about 10–20 times more to concentrate copper in these hydrothermal deposits than what we pay for copper today (Table 1).

As with most hydrothermal copper deposits, other metals like gold and silver are also present. If these were produced at the same time as the copper extraction, this may lower the energy cost of the deposit. Indeed extraction of these “sweeteners” provides additional revenues for many mining ventures of hydrothermal ore deposits. However, these trace metals occur in such small amounts (measured in concentrations of 10^{-4}% to 10^{-7}%) that they are insignificant relative to the uncertainties associated

Table 1
Nature's service cost of hydrothermal concentration of copper in ore bodies formed along mid-ocean ridges with variable spreading rates

Mid-ocean ridge spreading rate	Slow	Intermediate	Fast
1. Watt/m^2	1	2	3
2. Watt/deposit area	49 107	98 214	147 231
3. Energy expended (in joules)	77×10^{17}	15×10^{18}	23×10^{18}
4. Total energy at 10% efficiency (in joules)	77×10^{16}	15×10^{17}	23×10^{17}
5. Equivalent thermal energy in tons of coal	3.4×10^7	7×10^7	1×10^8
6. Total energy cost in US$	6×10^8	1.4×10^9	2×10^9
7. Cost of hydrothermal copper in US$:			
(a)	2.0×10^4	4.6×10^4	6.6×10^4
(b)	1.3×10^4	3.1×10^4	4.4×10^4
(c)	1.0×10^4	2.3×10^4	3.3×10^4
8. Ratio hydrothermal costs to present copper market value:			
(a)	6–13	14–29	21–41
(b)	4–8	10–19	14–28
(c)	3–6	7–14	10–21

1. From Pelayo et al. (1994).
2. Radius of deposit area = 125 m (from Hannington et al., 1998).
3. Using minimum age of 50,000 years for the TAG deposit (You and Bickle, 1998).
4. Based on episodic activity. 10% of total age of deposit (Hannington et al., 1998). These are minimum energy values since focused heat flux through deposit areas is probably much greater (James and Elderfield, 1996).
5. At 23×10^3 MJ/ton of coal.
6. At US$20/ton coal (SA Coal Report; D. Spalding, personal communication. 1999).
7. Based on an estimated range of total metal content for the TAG deposit: (a) = 30,000 ton Cu; (b) 45,000 ton Cu; (c) 60,000 ton Cu (Hannington et al., 1998).
8. At US$1600–3200 ton of copper (London Metal Exchange, July 1999 = US$1660; March 2004 = US$3233).

with the length of time it takes to form the deposits, and hence the total amount of energy expended during their formation. These trace metals are thus neglected in this analyses.

4. Cost of extracting copper from rocks using present-day available technology

Copper, like other metals, occurs in trace amounts in all crustal rocks (less than 0.01%; Fig. 2). Recovering such copper is not currently economic given the current supply and demand. Concentrations of 100 to 10,000 times are needed to produce copper deposits of economic significance. In rocks, the trace metals of interests are bound in silicate minerals, whilst in most ore deposits the metalliferous elements are concentrated in sulfide minerals from which they can be readily extracted using present-day mining and smel-

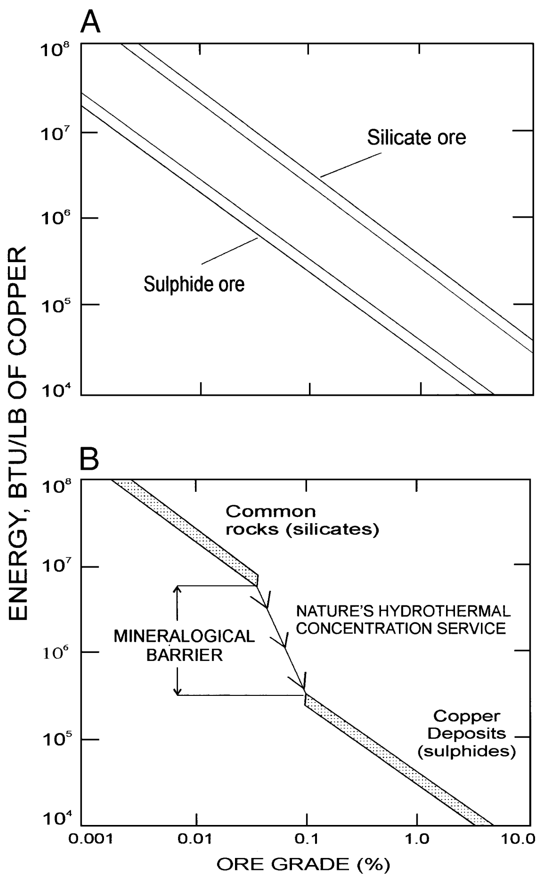

Fig. 2. Energy requirements for the exploitation of ore deposits. Modified from Skinner (1979). (A) Comparison of the energy needs for mining, concentrating and producing copper from sulfide and silicate ores. Present-day ores of lead, zinc, molybdenum, tin, iron and many other metals plot on the same curve as copper produced from sulfides. Production of aluminium from clays, copper from manganese modules, beryllium from beryl and other silicate and oxide solid solution ores, plot on the silicate curve, (B) Energy requirements across the mineralogical barrier to produce copper from deposits and common rocks, based on today's extraction technology. Note that Nature provides the "free" concentration across this economic barrier through energy released in hydrothermal processes.

ting technology. Although, in principle, there is no limit to the amount of copper that could be mined from ordinary rocks, it requires substantially more energy to mine copper from silicates (rocks) than from sulfide ores (Fig. 2B). The economic geologist Skinner (1979) termed this the mineralogical barrier to cheap mining for many metals; a pure economist would simply refer to this as an economic barrier. Since Nature "jumps" across this barrier when it forms hydrothermal ores, the enrichment process can also be viewed as Nature's hydrothermal concentration service. Using state-of-the-art mining and smelting processes, Skinner (1979) calculated the amount of energy required to concentrate 1 ton of copper from 0.01% copper held in rock silicates to be the equivalent thermal energy of nearly 2000 tons of bituminous coal. At a present-day cost of US$20/ton for the required quality coal, it would roughly cost about US$40,000 to mine a ton copper from ordinary rocks, which is almost 12–25 times what it costs to buy copper extracted from sulfide ores. In essence this quantifies the cost of the 'backstop technology' for copper; and this compares well with that calculated for Nature's "cost" of producing hydrothermal copper sulfide deposits along the mid-ocean ridges.

5. Discussion and conclusion

The relative service 'costs' of Nature to concentrate copper are about 10–20 times greater than copper's present market value. One reason for this difference might be because cryptic costs associated with exploiting mineral deposits are not included in the market price. For example, economists battle to admit into their natural resources equations important hidden social and environmental costs (externalities) associated with exploitation of ore deposits. This means that rents from ore deposits are not equitably shared and that mineral resources are generally under-appreciated and over-discounted (Hotelling, 1931; Clark, 1973; Dasgupta and Heal, 1979; Hartwick and Olewiler, 1986: Daly and Townsend, 1993; Davidson, 2000).

Natural resource economists have addressed externality costing in two different ways. On the one hand, traditional natural resource accounting has concentrated on incrementally internalising externality costs through increasing the complexity of economic equations. They have introduced the effects, for example, of improved exploitation technology; resource substitution; depletion and intergenerational equity; environmental abatement and more recently anticipated anthropogenic-induced global warming (Hartwick, 1977, 1990, 1991; Smith, 1980; Solow, 1986; Nordhaus, 1994, 2001; Van Dieren, 1995; Wigley et al., 1996; Hasselmann et al., 1997; Conrad, 1999). A critical question pertaining to the allocation of nonrenewable resources in this neoclassical economic approach is: How much of a resource should be extracted today using marginal considerations? Whereas this approach has clarified much about natural resource rents, and guides natural resources exploitation and legislation of many developed nations, it has not been particularly successful in estimating externality costs when "the margin" is shifted by a large amounts, as is the case for many global problems such as those related to global warming, environmental pollution and biodiversity loss, and those sustaining poverty and diseases in the developing world.

More recently ecological economics has taken a different, almost inverted approach to assess natural resources capital. Their "total analysis" approach views Earth's natural processes as a service industry which provides, for example, fresh water and fertile soils (Daly, 1990; Constanza et al., 1997; Davidson, 2000). The estimated minimum aggregate of Earth's services (more specifically its ecosystems) is larger than the Gross World Product (GWP; Constanza et al., 1997; Balmford et al., 2002). Using this approach, for example, the minimum annual cost of globally consumed fresh water provided by Nature's hydrological cycle alone is estimated to be about US$3000 billion, or about 12% of the GWP (Postel and Carpenter, 1997). There is considerable skepticism and debate about these cost estimates and the methodology used to obtain these estimates (Pimm, 1997; Forum, 1998; England, 1998). It is constructive, therefore, to estimate similar costs for exhaustible resources such as minerals, using a different method. Our results indicate that for mineral exploitation industry, such an approach is worth exploring further.

It can be argued from thermodynamics that the entropic nature of economic processes degrades natural resources and pollutes the environment, which in turn depletes social health and wealth (Georgescu-Roegen, 1971; Binswanger, 1993). Exploitation of ore deposits re-distributes raw materials contained in these deposits as pollutants into the biosphere (including humans), the atmosphere, the hydrosphere and the soils of the Earth (Fig. 1B). Some of these resources are retained in a form in which they can be easily recycled, but much is dispersed as pollutants that are presently considered too costly to recoup. Setting a reasonable exploitation tax to internalize some of these costs might be gleaned from considering Nature's service cost in concentrating these pollutants into ore deposits in the first place.

In the analyses outlined here, we have simply considered a unit cost of coal to approach the issue of externality costs. Yet the same externality issue applies even more to coal than it does to copper; and the energetic replacement value of coal would, intuitively, be much higher than that as well. This may appear to be part of an infinite regression. The emphasis here, however, is on using a relative energy value for comparative purposes; with time as society will place different future values on energy-units and redefine replacement values of natural resources, so will externality costs fluctuate. With cheaper and cleaner energy, some of these externalities may even become irrelevant. Evaluating this will require a lot more new research.

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