Global Mineral Exploration and Production—The Impact of Technology

By Michael D. Doggett[1]

Introduction

Many of the largest, highest grade, closest to surface, closest to market mineral deposits have been depleted or currently are in production. Over the next half century, the competition for land use among diverse sectors of an ever-increasing population will intensify. Mining companies struggling to improve the traditional bottom line will be forced to support a triple bottom line incorporating the costs and benefits of environmental and social responsibilities. Under these conditions, the ability of the international mineral sector to find and produce required amounts of metallic, nonmetallic, and fuel commodities hinges on technological innovation. While it would be naive to trust blindly in technology to overcome all aspects of depletion, it also would be imprudent to ignore past contributions of technology to an industry that ranks among world leaders in productivity. An analysis of global mineral exploration and production over the past 50 years reveals some interesting trends, which can be used to project where the mineral sector is headed in the years to come. A case study focusing on copper supply raises a series of questions about the tradeoffs between depletion and technology.

Database

This study examines trends in exploration and production for seven metals—copper (Cu), gold (Au), lead (Pb), molybdenum (Mo), nickel (Ni), silver (Ag), and zinc (Zn). Although silver is produced as a primary metal and as a byproduct of both gold and base-metal mines, for the purposes of this study, it is lumped together with base metals. This grouping allows the isolated analysis of gold as an exploration target and primary metal.

Exploration expenditure series have been compiled from a wide range of sources, including Natural Resources Canada, Statistics Canada, Australian Bureau of Statistics (1965–91), Metals Economics Group, and the "Mining Journal," and from previously compiled exploration series in Cranstone and others (1987), Doggett and Mackenzie (1987), Mackenzie and Doggett (1989, 1992), Doggett (1994), Mackenzie, Doggett, and Ortiz (1997), and Mackenzie, Doggett, and Thompson (1997). Extrapolating from country statistics tabulated in different ways means that the values presented are approximations. This is particularly true in the early decades covered by the study. The expenditures are meant to represent grassroots and onsite exploration but not costs related to acquisition of properties.

Production statistics have been tabulated from a number of sources as well, including the former U.S. Bureau of Mines (USBM) and Statistics Canada (1946–98). The series for production generally is more complete and reliable than that for exploration expenditures. Some minor inconsistencies exist due to changes over time in recording Western world, non-Communist world, and total world data.

Value-of-production series have been compiled by using the production series and average annual metal prices for the seven metals. These values represent the gross sales value of the metal production. Wherever possible, the London Metal Exchange prices have been used; otherwise, a number of price references have been consulted, including "Metals Week" (1969–99), Robertson (1986), and USBM (1993).

Conclusions drawn in this study are based on broad trends in exploration and production and are not thought to be particularly sensitive to minor inconsistencies in the series of data. All money values presented are in constant 1999 U.S. dollars.

50-Year Trends in Base-Metal and Gold Exploration Costs

Table 1 presents exploration expenditure trends in gold and base metals on a decade-by-decade basis for the period 1950–99. Overall, approximately $76 billion has been spent on the search for new economic deposits. The results indicate that exploration expenditure levels have been increasing significantly in real terms over time. Exploration increased from $3.5 billion in the 1950s to $12 billion in the 1970s and to approximately $28 billion in the 1990s. Taken on its own, this trend suggests that discovery costs have been increasing over time. More generally, changing discovery costs over time should provide a measure of the tradeoff between depletion and technological advances.

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Table 1. Global base-metal and gold exploration expenditures.

[All money values in 1999 U.S. dollars, in billions]

Years	Base metals	Gold	Total
1950s	$3.0	$0.5	$3.5
1960s	$7.2	$1.3	$8.5
1970s	$9.3	$2.7	$12.0
1980s	$7.3	$16.7	$24.0
1990s	$10.0	$18.0	$28.0
Total	$36.8	$39.2	$76.0

A more detailed analysis of the exploration expenditure series presented in table 1 shows that the overall trend is disguising the two distinct trends for gold and base metals. While gold and base-metal expenditures each accounted for about half of the total expenditure, base-metal expenditures increased in the early decades and then decreased in the 1980s before increasing again to end the study period at approximately $10 billion during the 1990s. Gold has shown a steadily increasing trend over the past 50 years and peaked at approximately $18 billion in the 1990s.

As we look ahead to the coming decades, exploration expenditures for base metals are likely to continue within the range indicated by the past three decades. Expenditures for gold, on the other hand, are not likely to continue to increase at the same rate in the future. Indeed, it is highly likely that a decrease in the level of gold exploration expenditures from the peak 1990s value will occur over the next decade, as expenditure levels in 2000 and 2001 are projected to be significantly below those in the latter years of the 1990s.

50-Year Trends in Base-Metal and Gold Production Amounts

To more fully evaluate the importance of the trends in exploration expenditure, comparisons are made with the output of the various metals being considered. Table 2 illustrates the amounts of metals produced over the five decades. Overall base-metal production increased by more than 200 percent over the study timeframe, while gold and silver production increased by more than 100 percent.

Table 2. Global base-metal and gold and silver production.

[Base metals in millions of metric tons; precious metals gold and silver in millions of ounces. For this table only, silver is treated as a precious metal; in the rest of this paper, it is grouped with the base metals]

Years	Cu	Pb	Mo	Ni	Zn	Total base metals	Au	Ag
1950s	34	23	0.3	2	31	90	305	2,200
1960s	54	30	0.5	4	46	135	435	2,500
1970s	75	37	0.9	7	61	181	420	3,150
1980s	81	34	1.0	8	65	189	412	4,150
1990s	104	30	1.3	10	73	218	735	4,950
Total	348	154	4.0	31	276	813	2,307	16,950

50-Year Trends in Base-Metal and Gold Discovery Costs

An exact picture of discovery costs over time would measure the amount of metal discovered per dollar of exploration expenditure. Because we do not have a record of the metals contained in discoveries over the past 50 years, the production of metals has been used as a proxy. Thus, exploration expenditure is measured as a function of the metal produced. Table 3 shows this ratio on a decade-by-decade basis for base metals and gold. These results have been calculated by dividing exploration expenditures from table 1 by metal production from table 2. The results indicate that exploration costs for base-metal output have fluctuated between 1.5 and 2.4 cents per pound over time, with an average for the entire period of 2.1 cents per pound. These values do not support the notion that discovery costs are increasing with time. With respect to gold exploration, the cost per ounce increased substantially, to more than $40 per ounce in the 1980s, as exploration expenditures increased rapidly. The large jump in gold production during the 1990s resulted from increased exploration in the 1980s and pushed the discovery cost back down to under $25 per ounce.

50-Year Trends in Base-Metal and Gold Production Values

Table 4 illustrates the value of production for base metals and gold over the past five decades. The values are expressed in 1999 U.S. dollar equivalents and represent gross value measured by the average annual price times total production for each metal for each year. Several interesting trends emerge from the data. First, the overall trend in value of mineral production increased sharply in the 1960s and 1970s and then leveled off during the 1980s and 1990s. This trend suggests that the increases in production illustrated in table 2 essentially have been offset by decreases in metal prices. Thus, over the past three decades, there has been little overall growth in the sector. This finding has important implications for corporate planning, as most companies have a stated objective of year-over-year growth. Notwithstanding more efficient production and focus on cost cutting, it is highly unlikely that most companies can grow in an industry where the overall value of production has remained essentially flat over a long period.

The other important trend concerns the relative values of base-metal and gold production. Overall, base metals have accounted for roughly two-thirds of the total value, but gold has increased its percentage share in recent decades. Furthermore, gold has increased in value of production each decade, while base metals increased sharply until the 1970s and then decreased during the 1980s and 1990s. The total value of base-metal production in the 1990s in real terms was approximately 22 percent less than in the 1970s in spite of an overall 20 percent increase in the amount of metal produced.

Exploration Expenditure as a Function of Value of Production

Results from table 3 suggest that exploration expenditure per unit of metal production has remained relatively flat for base metals and increased, then decreased, for gold. Values of production as shown in table 4, however, have generally decreased for base metals and increased for gold in later decades of the study period. We now want to consider the relation between exploration expenditures and value of production. This ratio provides a measure of the percentage of gross value of production that is being reinvested in exploration. Table 5 presents exploration expenditure per unit of value of production for base-metal and gold production. Overall, the percentage of value of production reinvested in exploration has increased from 1.1 percent to 3.6 percent over the five decades. By commodity grouping, we see that the major increase has been for gold where about 6 percent of value has been reinvested in exploration during the 1980s and 1990s. Given generally low profit levels in the gold sector in recent years, it is unlikely that this ratio is sustainable. For base metals, exploration as a percentage of value of production has remained relatively constant in the 1–2 percent range, with only the 1990s value exceeding 2 percent.

Table 3. Global discovery costs per unit of production for base metals and gold.

Years	Base metals (cents per pound)	Gold (dollars per ounce)
1950s	1.5	1.6
1960s	2.4	3.0
1970s	2.3	6.4
1980s	1.8	40.5
1990s	2.1	24.5
Average	2.1	17.0

Table 4. Value of global production for base metals and gold.

[All money values in 1999 U.S. dollars, in billions]

Years	Base metals	Gold	Total
1950s	$250	$60	$310
1960s	$400	$75	$475
1970s	$625	$125	$750
1980s	$520	$270	$790
1990s	$485	$300	$785
Total	$2,280	$830	$3,110

Table 5. Exploration expenditures as a function of value of global production, in percent.

Years	Base metals	Gold	Total
1950s	1.2	0.8	1.1
1960s	1.8	1.7	1.8
1970s	1.5	2.2	1.6
1980s	1.4	6.2	2.9
1990s	2.1	6.0	3.6
Average	1.6	4.6	2.4

Depletion Versus Technology—Case Study Involving Copper

As shown by the evidence presented above, trends in discovery costs, metal prices, and value of production suggest that technology has been able to more than offset any depletion effects during the past 50 years. Can it be assumed that these same trends will continue for the foreseeable future, or are new external factors at play that will fundamentally alter the depletion-technology balance? To address this question, it is necessary to consider the trends in production and the technology factors underlying the trends in costs, prices, and output. While there have been important technological advances at all stages of the mineral supply process from exploration to development to production to reclamation, those having the greatest impact have been in one way or another related either to scale of operation or to processing and metallurgy. To examine these technology factors, consider the case of copper production over the period 1978 to 2000.

Historical Production of Copper

Table 6 presents the breakdown of total copper production until the end of 1999 (USBM, 1956, 1980; Natural Resources Canada, 1963–2000; Mikesell, 1979). More than 430 million metric tons of copper have been produced. Of this total, 43 percent has been produced in the past 20 years, and 24 percent in the past 10 years. When viewed in this way, the depletion of copper resources has accelerated to the point where nearly one-quarter of all of the copper ever produced was supplied in the 1990s. This raises the important question of whether copper resources can continue to meet this increasing trend as we move into the new century.

Table 6. Historical global copper supply.

[Data from U.S. Bureau of Mines, 1956, 1980; Natural Resources Canada, 1963–2000; Mikesell, 1979]

Period	Production (millions of metric tons)	Percent of total
Pre-1900	10	2
1900–50	70	16
1950–99	[1]>350	82
1980–99	184	43
1990–99	104	24
Total	[1]>430	100

[1] The greater than sign (>) was used to allow for uncounted production in parts of the Communist world.

Scale of Copper Production, 1978–2000

With respect to scale of copper operations, much of the increased output of metals on a worldwide basis has resulted from the development of huge open-pit operations. Technological advances in mining and processing equipment have enabled enormous increases in mine capacity with resulting decreases in unit operating costs and cutoff grades. A survey of copper mines provides a good example of the staggering increases in capacity. The 10 largest copper mines in terms of annual capacity in 1978 (Mackenzie, 1979) are shown in table 7. The total productive capacity of these mines was 2.145 million metric tons of copper. The single largest mine was Chuquicamata, which had a capacity of 475,000 metric tons of copper. Capacities of the other nine mines ranged from 125,000 to 275,000 metric tons.

Table 7. Annual capacity of the 10 largest copper mines in the world in 1978.

[Capacity in thousands of metric tons. Data from Mackenzie, 1979]

Mine, country	Capacity
Chuquicamata, Chile	475
El Teniente, Chile	275
Chingola, Zambia	240
Bingham, U.S.A.	204
Bougainville, Papua New Guinea	184
Cuajone, Peru	180
Kamoto Pit, Congo (D.R.C.)	172
Mount Isa, Australia	150
Mufulira, Zambia	140
Palabora, South Africa	125
Total	2,145

Table 8 shows the projected annual capacities of the 10 largest copper mines in 2000 (International Copper Study Group, 1999). The total productive capacity of the 10 mines is 4.895 million metric tons—230 percent higher than comparable production in 1978. This total represents one-third of the productive copper capacity of all operating mines in 2000. In terms of the size of individual producers, 8 of the 10 now have capacities exceeding 300,000 metric tons per year. These huge increases in copper production capacity have been achieved in spite of the lowering of average grade of production in most cases, suggesting that physical mining capacity has increased at an even higher rate. From the perspective of depletion, 3 of the top 10 mines in 1978 are still in the top 10 in 2000, and only 1 of the 10 largest mines in 1978 has been depleted of ore reserves.

Table 8. Projected annual capacity of the 10 largest copper mines in the world in 2000.

[Capacity in thousands of metric tons. Data from International Copper Study Group, 1999]

Mine, country	Capacity
Escondida, Chile	905
Grasberg, Indonesia	730
Chuquicamata, Chile	680
Morenci, U.S.A.	490
Noril'sk, Russia	450
Colluhuasi, Chile	450
El Teniente, Chile	350
Bingham, U.S.A.	310
Los Pelambres, Chile	280
Andina, Chile	250
Total	4,895

Another interesting factor is the geographic distribution of the largest mines. In 1978, 4 of the 10 were located in Africa, 3 in South America, 2 in Australia and Papua New Guinea, and 1 in North America. In 2000, 6 of the 10 largest mines were located in South America, 2 in North America, 1 in Russia, and 1 in Asia. This changing distribution reflects not only geological endowment but also political factors, particularly in Africa and South America.

Advent of Solvent Extraction Electrowinning Technology

The second major technological advance affecting copper supply, and ultimately the copper cost curve and copper price, is improved metallurgy. The introduction of hydrometallurgical techniques (such as solvent extraction electrowinning) for the production of copper metal at the mine site, rather than producing a concentrate to ship to a smelter and refinery, has resulted in the reduction of costs for individual producers. The direct production of copper cathode increased from essentially zero in 1978 to approximately 20 percent of total copper supply by the year 2000.

Future Production Trends for Copper

Table 9 illustrates a possible future trend in copper supply calculated by assuming a 1.8 percent annual increase over the next 50 years. Total copper supply by the year 2050, under this scenario, would reach approximately 34 million metric tons per year. Comparing future production levels at this rate of growth in copper supply reveals that copper production from 2000 to 2010 would amount to 38 percent of

Table 9. Projected future global copper supply.

Period	Production (millions of metric tons)	Percent of pre-2000 total
2000–2010	165	38
2000–2025	350	81
2000–2050	1,200	280

all copper produced before the year 2000 (430 million metric tons; see table 6). Similarly, by the year 2025, 81 percent of total pre-2000 production would be achieved, and by 2050, copper production would be 280 percent of the pre-2000 total.

How would this level of copper supply be attained? How much exploration expenditure would be required to find the required deposits? Is it possible for technology to allow for this enormous increase in supply while continuing to lower costs and prices? To address some of these points, consider the two major technological factors discussed above—scale of operations and metallurgical improvements.

Scale of Operations

How large can individual copper mines become to meet future needs? Consider the hypothetical case outlined above of a 1.8 percent annual growth in copper supply over the next half century. If the 10 largest mines were to account for one-third of total production as they do today, they would need to produce more than 11 million metric tons of copper on an annual basis. Thus, the average production of the 10 largest mines would be more than 1 million metric tons of copper per year, which is larger than the single largest producer at present. Another important implication of the need for ever-larger producers is the environmental impact of huge open-pit mines. As environmental regulations become ever-more stringent around the world, it is difficult to imagine a scenario where mines are permitted to become large enough to meet this expanded production. Thus, it is unlikely that such increases in capacity will be accomplished by increases in scale of operations like those seen over the past two decades.

Metallurgical Advances

The other major area of technological advance that is likely to affect future supply of gold and base metals is improved metallurgical processing techniques. As indicated above for copper, hydrometallurgical processing has begun to replace pyrometallurgy. To date, these gains have been made by processing those ores most susceptible to leaching processes—oxide and supergene ores. Future breakthroughs in mineral processing are likely to include treating sulfide ores through leaching or pressure leaching, or even in-place leaching, to produce metals at the mine site. We are at the early stages of this technology, which gradually will replace pyrometallurgical processing over the next 50 years. Thus, unlike the scale-of-operations question discussed above, there is considerable opportunity for advances in processing technology to provide an increased supply of metal by promoting a lower cost structure for processing primary ores.

Conclusions

- Technology has won the battle with depletion in the past 50 years, primarily by increasing scales of operation and improving processing efficiencies.
- At even moderate rates of increase in demand, metal production in the next 50 years will dwarf all-time historical totals.
- It is unlikely that the rate of increase in scale of operations can be sustained in the longer term because of growing environmental concerns.
- Major metallurgical improvements in the processing of primary ores have only just begun.
- Depletion-driven increases in metal prices may prevail eventually, but technological innovations are expected to keep prices low for at least the next 50 years.

References Cited

Australian Bureau of Statistics, 1965–91, Mineral exploration, Australia [issued annually]: Canberra, Australian Bureau of Statistics publication with catalog number 8407.0 and ABS reference number 10.41.

Cranstone, Donald, Mackenzie, B.W., and Doggett, M.D., 1987, Long-term breakeven price for Canadian gold supply, *in* Long-term prospects for gold mining; Proceedings of the seventeenth CRS Policy Discussion Seminar, October 6–8, 1986, Kingston, Ontario: (Kingston, Ontario) Queen's University, Centre for Resource Studies, Proceedings no. 20.

Doggett, M.D., 1994, Incorporating exploration in the economic theory of mineral supply: Kingston, Ontario, Queen's University, unpublished Ph.D. thesis, 195 p.

Doggett, M.D., and Mackenzie, B.W., 1987, Economic trends in Canadian gold supply: (Kingston, Ontario) Queen's University, Centre for Resource Studies, Working Paper no. 41, 77 p.

International Copper Study Group, 1999, Directory of copper mines and plants: Lisbon, Portugal, International Copper Study Group, July, 82 p.

Mackenzie, B.W., 1979, Canada's competitive position in copper and zinc markets: (Kingston, Ontario) Queen's University, Centre for Resource Studies, Working Paper no. 16, 43 p.

Mackenzie, B.W., and Doggett, M.D., 1989, Economic aspects of gold exploration—How much is too much?: (Kingston, Ontario) Queen's University, Centre for Resource Studies, Working Paper no. 44, 26 p.

Mackenzie, B.W., and Doggett, M.D., 1992, Worldwide trends in gold exploration: (Kingston, Ontario) Queen's University, Centre for Resource Studies, Working Paper no. 49.

Mackenzie, B.W., Doggett, M.D., and Ortiz, F.J., 1997, Economic potential of mineral exploration in Chile—Evidence from the historical record: (Kingston, Ontario) Queen's Unversity, Centre for Resource Studies, Technical Paper 15, 221 p.

Mackenzie, B.W., Doggett, M.D., and Thompson, Mickey, 1997, Economic potential of mineral exploration in Australia—Evidence from the historical record, 1955–91: (Kingston, Ontario) Queen's University, Centre for Resource Studies, Technical Paper 16.

Metals Week, 1969–99: New York, McGraw Hill, v. 40–63.

Mikesell, Raymond, 1979, The world copper industry; Structure and economic analysis: Baltimore, The Johns Hopkins University Press, 393 p.

Natural Resources Canada [and its predecessor agencies], 1963–2000, Canadian minerals yearbook 1960–99: Ottawa, Natural Resources Canada, variously paged. (Also available online at http://www.nrcan.gc.ca/mms/cmy/pref_e.htm.)

Robertson, Neil, 1986, Mineral commodity prices—Computer database assembly and preliminary analysis: (Kingston, Ontario) Queen's University, unpublished B.Sc. thesis.

Statistics Canada, 1946–98 [various periodicals on mining]: Ottawa, Statistics Canada catalog numbers 26–201 (General Review of the Mineral Industries, Mines, Quarries and Sand Pits), 26–202 (Canada's Mineral Production, Preliminary Estimates), 26–209, 26–223 (Metal Ore Mining), 26–224 (Non-metal Mines), 61–205 (Private and Public Investment in Canada, Intentions), 61–206 (Private and Public Investment in Canada, Revised Intentions).

U.S. Bureau of Mines, 1956 and 1980, Mineral facts and problems: U.S. Bureau of Mines Bulletins 556 (1042 p.) and 671 (1060 p.).

U.S. Bureau of Mines, 1993, Metal prices in the United States through 1991: Washington, D.C., U.S. Bureau of Mines, 201 p.