Part Three

Resources and Technology

Chapter 5

World Copper Resources

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World Copper Resources

A copper ore deposit is a localized zone in the earth's crust that contains copper-bearing minerals in unusually large quantities. On average, the continental crust contains about 0.0058 percent copper, or 58 parts per million. A deposit of copper-bearing minerals is classed as an ore reserve if there are sufficient quantities and concentrations of minerals to be extracted at a profit. Commercial copper ore deposits today contain from 0.5 to 6 percent copper, or between 100 and 1000 times the crustal average. In contrast, iron and aluminum constitute around 5.8 percent and 8 percent of the earth's crust, respectively, and their commercial deposits need to be only 3 to 10 times as concentrated as the crustal average. Thus, copper may be considered a relatively scarce element geochemically.[1]

This chapter begins with a description of the geology of copper–the kinds of copper minerals, how they formed, and where they are found. The chapter then discusses current world copper resources, and the copper content (or ore grade) of current mine production. The relations between ore grades, tonnages, and production costs are discussed in chapter 9.

[1] Brian J. Skinner, "A Second Iron Age Ahead?" *American Scientist*, vol. 65 (May/June 1976), pp. 258-269.

THE GEOLOGY OF COPPER

Copper occurs in three different mineral groups (see table 5-1). In sulfide mineral deposits, the copper is linked with sulfur. In carbonate deposits, the copper occurs with carbon and oxygen. In silicate mineral deposits, the copper is linked with silicon and oxygen. The latter two groups are also termed oxide ores. Copper is more easily extracted from the sulfide and carbonate minerals.

Classes of Copper Deposits

Copper deposits are classified by general geologic setting, including the type of rock in which the copper deposit formed. Rocks belong to three main categories: igneous, sedimentary, and metamorphic. Each category is further subdivided on the basis of distinguishing characteristics such as mineralogical composition and texture. Igneous rocks generally form from a molten mass such as lava; sedimentary rocks form by the accumulation of material transported and deposited by water or wind, from chemical precipitation, or from the buildup of organic substances; and metamorphic rocks come from the effect of heat and pressure on other rocks.[2]

[2] Floyd F. Sabins, Jr., *Remote Sensing: Principles and Interpretation* (New York, NY: W.H. Freeman & Co., 1986).

Table 5-1.—Most Commonly Occurring Copper Minerals

Mineral	Elemental Components (weight percent)					
	Cu	Fe	S	CO2	SiO2	H2O
Sulfides:						
Chalcopyrite	34.5	30.5	35.0	—	—	—
Bornite	63.3	11.2	25.5	—	—	—
Chalcocite	79.8	—	20.2	—	—	—
Covellite	66.4	—	33.6	—	—	—
Carbonates:						
Azurite	55.3	—	—	25.6	—	5.2
Malachite	57.4	—	—	19.9	—	8.2
Silicates:						
Chwsocolla	36.1	—	—	—	34.3	20.5

SOURCE Cornellus S Hurl but (cd.), *Dana's L4anua/ of M/nera/ogy (New* York, NY Wiley, 17th ed , 1966)

The three main categories of copper deposits are porphyry type deposits, strata-bound deposits, and massive sulfide deposits. **Porphyry deposits are the most common. They account** for about 45 percent of the world's total copper reserves, including the largest portion of the ore reserves in the western United States. q These deposits are associated with bodies of igneous intrusive rocks with copper sulfide minerals disseminated in them.

Porphyry deposits tend to occur **in discontinu**ous belts. The best known is the belt that runs from Canada down through the southwestern United States, northern Mexico, Central America, and South America through Peru, Chile, and western Argentina. Another porphyry belt runs through Papua New Guinea, Indonesia, and the Philippines and on up into China and parts of Siberia; and a third through southeastern Europe, Iran, and Pakistan (see figure 5-1).

The grade and size of porphyry deposits varies. Typical deposits in Chile and Peru contain 1.0 to 2.0 percent copper and 500 million to 1 **bil**lion tonnes of ore, although the largest deposits may contain 4 to 5 billion tonnes. The deposits in the southwestern United States and northern Mexico contain 200 to 500 million tonnes of 0.4 to 0.8 percent copper ore. Those in the Philippines and Canada contain from 0.3 to 0.5 percent copper and from sO to 200 million tonnes of ore.

Strata-bound deposits, the second most important in terms of metal reserves, are less common and smaller than porphyry deposits (1 million to 100 million tonnes of ore per deposit). Copper-bearing silicates, carbonates, and sulfides, occur in old marine sediments, such as shales and sandstones. Strata-bound copper reserves are found in Zambia and Zaire, as well as Europe and the north central United States (figure 5-1). The **Zambian deposits commonly contain 2.o to 4.o percent copper in sulfide minerals, and the Zairian deposits 4.0 to 6.0 percent copper in carbonate and silicate minerals.**

[3]United Nations Industrial Development Organization (UN IDO), *Technological Alternatives for Copper, Lead, Zinc and Tin in Developing Countries,* Report prepared for the First Consultation on the Non-ferrous Metals Industry, Budapest, Hungary, July 1987.

Massive sulfide deposits are large concentrations of mixed sulfide minerals (copper, nickel, lead, or zinc) occurring as veins and massive replacements in limestone, and as large bodies in volcanic rock sequences. Massive sulfide deposits are important in eastern Canada and the eastern United States, Australia, South Africa, the Philippines, and Cyprus. These deposits typically are small with well-defined boundaries and commonly have a copper content from 1.0 to 5.0 percent. Copper often is produced as a valuable byproduct of the other minerals in these deposits. The volume of ore reserves ranges from several hundred thousand to several million tonnes.

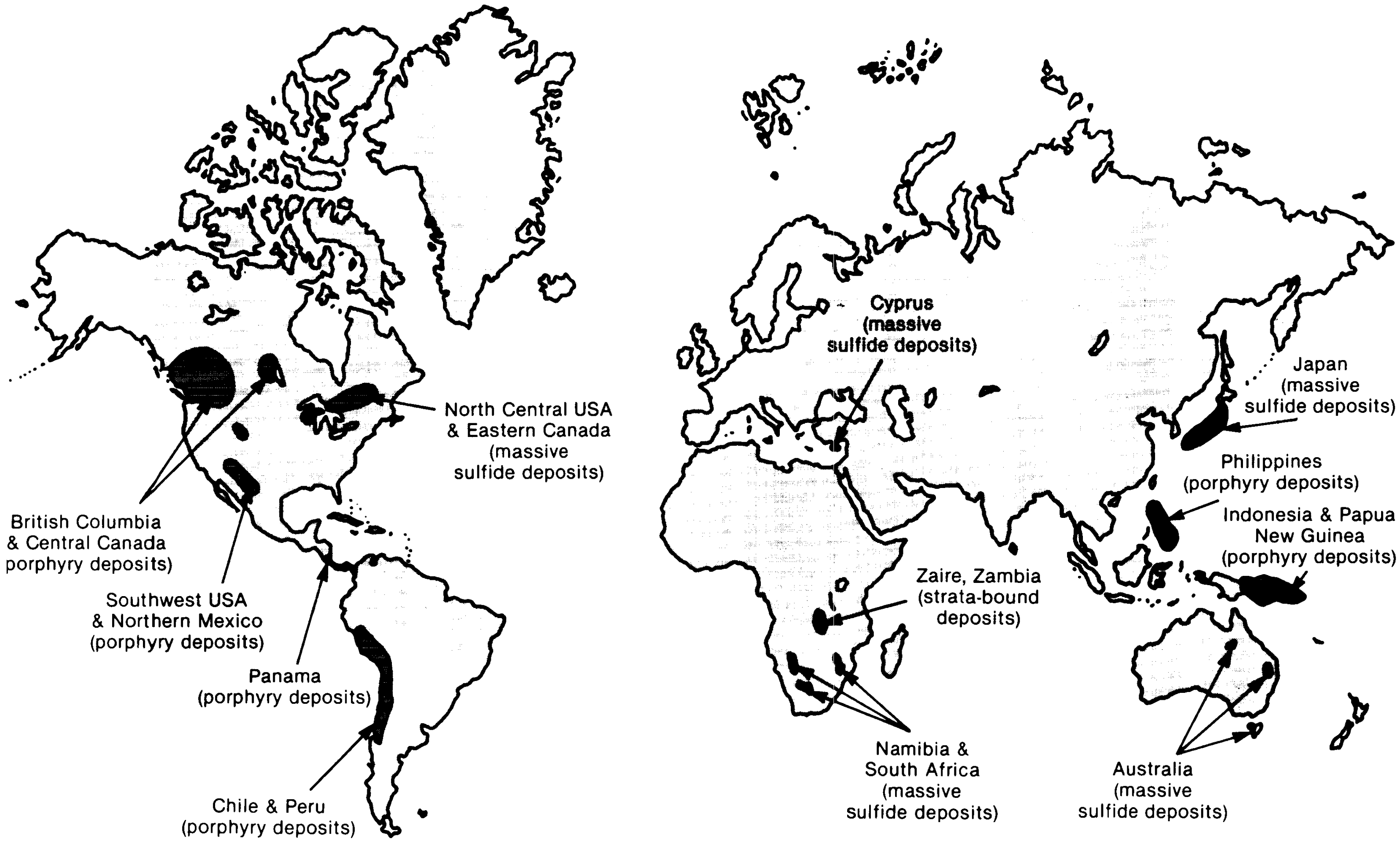
Most copper mineral deposits have definable boundaries; in some these are gradational and in others sharply defined (as in veins), Deposits with gradational boundaries, such as porphyrins, often contain zones that are subeconomic in ore grade, which may become ore if either the price of copper increases or the cost of extracting the copper from the ore declines enough to make mining profitable. Thus, significant changes **in perceived ore reserves may occur for such** de**posits as a result of cost or price changes.**

Other Metals Occurring With Copper

Many copper deposits contain **more than one** valuable metal. The other metals are classed as coproducts or byproducts, depending on their relative value. If the deposit is economically viable on the basis of copper production alone, then copper is the main product and any other metals are byproducts. If the economic viability of the deposit depends on the production of both copper and one or more additional metals, then copper and the other metal(s) are coproducts. Depending on current metal prices, the status of a metal occurring with copper can change from byproduct to coproduct and vice versa.

Each class of copper deposit is characterized by a different set of coproduct and byproduct metals. Important byproducts in porphyry deposits are molybdenum, silver, and gold. Molybdenum is a byproduct in some of the North and South American deposits, and is actually a coproduct for some of the Canadian deposits and U.S. deposits. Roughly 60 percent of world molybdenum

Figure 5-1.—Important Copper-Producing Areas in the Market Economy Countries



SOURCE: Raymond F. Mikesell, *The World Copper Industry* (Washington DC: Resources for he Future, 1979).

production is a result of copper mining.[4] The Bougainvillea and Ok Tedi deposits in Papua New Guinea, Ertsberg in Indonesia, and some Philippine deposits all have an unusually high gold content, but without any molybdenum.

The strata-bound deposits in Central Africa commonly have cobalt as a byproduct, with the Zairian deposits having a higher cobalt content. These deposits are the Western world's most important source of cobalt. s

The massive sulfide deposits contain significant amounts of nickel, or of lead and zinc. other metals of less importance in massive sulfide deposits are silver, gold, bismuth, cadmium, and cobalt.

[4]1 bid.

[5]U.S. Congress, Office of Technology Assessment (OTA), *Strategic Materials: Technologies To Reduce U.S. Import Vulnerability,* OTA-ITE-249 (Washington, DC: U.S. Government Printing Off Ice, January 1985)

COPPER RESOURCES AND RESERVES

A general classification for describing the status of mineral occurrences was developed by the U.S. Geological Survey and the U.S. Bureau of Mines in 1976.[6] The so-called "McKelvey Box" (named after the then director of the U.S. Bureau of Mines, Vincent McKelvey) simplified the understanding of the economic relationships of the mineral resource classification system (see figure **5-2). This system is based on a judgmental determination of present or anticipated future value of the minerals. The economic definitions on which the resource classification system is based are:**

- **Resource: A** concentration of a naturally-occurring mineral in a form and amount such that economic extraction of a commodity is currently or potentially feasible.
- **Identified Resource: Resources whose location, grade, quality, and quantity are known or reliably estimated.**
- **Demonstrated Resource: Resources whose location and characteristics have been measured directly with some certainty *(measured)*** or estimated with less certainty (indicated).
- Inferred Resource: Resources estimated from assumptions and evidence that minerals occur beyond where measured or indicated resources have been located.
- **Reserve Base: That part of an *identified resource*** that meets the economic, chemical, and physical criteria for current mining and production practices, includ ng that which is estimated from geological k nowledge (in***ferred reserve base).***
- **Reserves: That part** of the ***reserve base*** that could be economically extracted at the time of determination.
- **Marginal Reserves:** That part of the ***reserve base*** that at the time of determination borders on being economically producible.
- **Undiscovered Resources: Resources whose** existence is only postulated.

These categories indicate different degrees of knowledge about the quantity of reserves in an ore body. For example, determination of measured reserves requires extensive drilling of the ore body (see ch. 6). However, only the existence of a minimum volume of ore must be proven in order to justify preparation of a feasibility study for a potential mine or mine expansion. Thus, indicated and inferred reserves may be a far larger figure because extensive drilling is costly and companies may not undertake drilling beyond what is required for the feasibility study. Nevertheless, many published figures on reserves use the broad sense of the term and include not only measured reserves, but also indicated and inferred reserves. z

The criteria for measuring reserves have not been standardized, so that totalling or comparing reserve estimates for different companies can be like adding or comparing apples and oranges.

[6]U.S. Department of the Interior, Bureau of Mines and Geological Survey, *Principles of a Resource/Reserve Classification for Minerals* (Washington, DC: Geological Survey Circular 831, 1980).

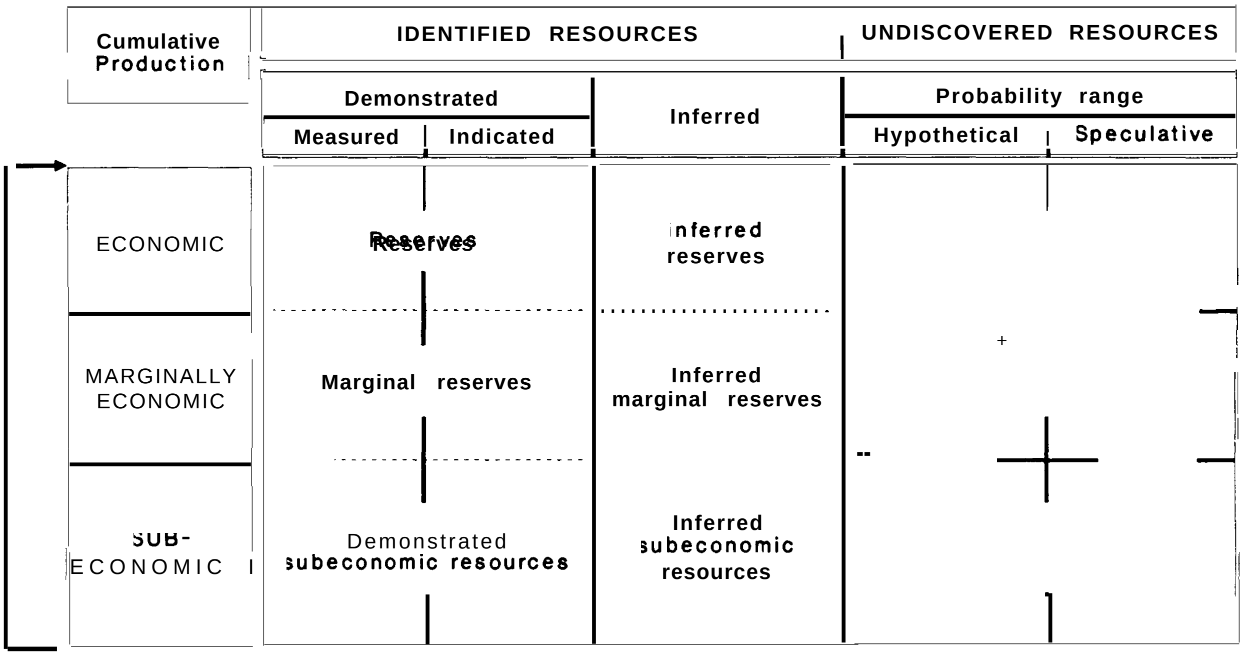
[7]Raymond F. Mikesell, *The World Copper Industry: Structure and Economic Analysis* (Baltimore, MD: The Johns Hopkins Press, 1979).

Figure 5-2.—McKelvey Box

RESOURCES OF *(commodity name)*

(A part of reserves or any resource category may be restricted from extract ion by laws or regulations)

AREA: *(mine, district, field, State, etc.)* UNITS: *(tons, barrels, ounces, etc.)*



SOURCE U S Department of the Interior, Bureau of Mines and Geological Survey, "Principles of a Resource/Reserve Classification for Minerals, " Geological Survey Circular 831, 1980.

The amount of perceived reserves in an ore body is a function of price and of extraction costs, and assumes that the net return on production will be sufficient to attract the required investment, including an allowance for risk. However, minimum acceptable rates of return or discounted cash flow rates will differ among companies, and between government enterprises and private companies. The potentially minable material in a deposit also varies with available technology and economic conditions. Resource estimates are revised periodically to account for changes i n these factors.

Recognizing these uncertainties, the U.S. Bureau of Mines and the U.S. Geological Survey regularly develop estimates of world copper resources and reserves. Table 5-2 shows the Bureau of Mines 1985 copper resource and reserve estimates for 241 deposits in the market economy countries. The U.S. Geological Survey estimates that total land-based copper resources (the reserve base plus a larger body of less well characterized resources) are around 1.6 billion tonnes, of which 35 percent are in the market economy countries.[8]

In 1985, demonstrated resources of recoverable copper[9] in the market economy countries were estimated at 333.4 million tonnes for 241 deposits. The Bureau of Mines estimates the total world reserve base at 566 million tonnes contained copper in ore.[10] Regionally, Latin America has the most abundant resources, with around

[8] Janice L.W. jolly, "Copper, " *Mineral Facts and Problems* (Washington, DC: U.S. Government Printing Office, 1985).

[9] Contained copper less mining and processing losses; includes oxide and leach material.

[10] Janice L.W. Jolly, "Copper," 1985 *Bureau of Mines Minerals Yearbook* (Washington, DC: U.S. Department of the Interior, Bureau of Mines, 1985).

Table 5-2.—Summary of Demonstrated Market Economy Country Copper Resources in 1985[a]
(million metric tons unless otherwise specified)

	Number of deposits	In situ resource: Ore tonnage	In situ grade (% Cu)	Contained copper	Minable resource: Ore tonnage	Feed grade (% Cu)	Contained copper	Recoverable copper
North America:								
Canada	35	4,195	0.50	20.9	4,069	0.50	20.4	17.6
Mexico	6	4,468	0.68	29.1	4,103	0.65	26.5	20.5
United States[b]	62	16,204	0.53	85.7	15,753	0.51	80.8	57.4
Total or average[c]	103	24,867	0.55	35.7	23,924	0.53	27.7	95.5
Central and South America:								
Chile	16	11,969	1.00	119.9	11,877	1.00	118.1	112.2
Peru	12	3,082	0.83	25.7	3,022	0.82	24.9	21.2
Other	8	3,098	0.66	20.6	3,014	0.66	19.9	17.3
Total or average[c]	36	18,149	0.92	166.2	17,913	0.91	162.9	150.7
Europe	12	929	0.84	7.8	837	0.79	6.6	5.5
Middle East	10	586	1.33	7.8	551	1.30	7.1	6.3
Asia:								
India	6	458	1.28	5.8	439	1.23	5.4	4.7
Philippines	22	3,211	0.47	5.0	2,660	0.47	12.5	10.4
Other	6	522	0.67	3.5	524	0.65	3.4	2.9
Total or average[c]	34	4,191	0.58	24.3	3,624	0.59	21.3	18.0
Africa:								
South Africa, Republic of	5	423	0.65	2.7	425	0.64	2.7	2.2
Zaire	8	677	4.04	27.3	614	4.09	25.1	20.7
Zambia[d]	9	621	2.58	16.0	635	1.97	12.5	10.2
Other	10	116	1.98	2.3	116	1.87	2.2	1.7
Total or average[c]	32	1,837	2.63	48.4	1,790	2.38	42.5	34.7
Oceania:								
Australia	9	2,261	1.69	38.3	1,746	2.00	30.0	26.0
Papua New Guinea[e]	5	3,639	0.47	17.2	3,122	NA	15.0	12.0
Grand total or average[c]	241	56,462	0.79	445.7	53,511	1.00	413.0	348.6

[a]Based on January 1985 resource estimates [illegible] producing and [illegible] idle, developing, or explored deposits in market economy countries, representing nearly 80 percent of the world reserve base. Excludes copper available from byproduct mines. Total world reserve base is estimated at 566 million tonnes contained copper in ore.
[b]Tonnage and grade figures include 4,989 million tonnes oxide and silicate material at 0.29 pct Cu. Sulfide resources and mill feed averaged 0.65 and 0.62 Cu, respectively.
[c]Data may not add to totals shown because of independent rounding.
[d]Tonnage and grade figures include 135 million tonnes oxide material at 0.70 pct Cu in Nchanga Stage III leach project. Primary resources and mill feed averaged 3.10 pct and 2.32 pct Cu respectively.
[e]Includes Namosi deposit in Fiji.

SOURCE: "Copper," *An Appraisal of Minerals Availability for 34 Commodities* (Washington, DC: U.S. Department of the Interior, Bureau of Mines, Bulletin 692, 1987).

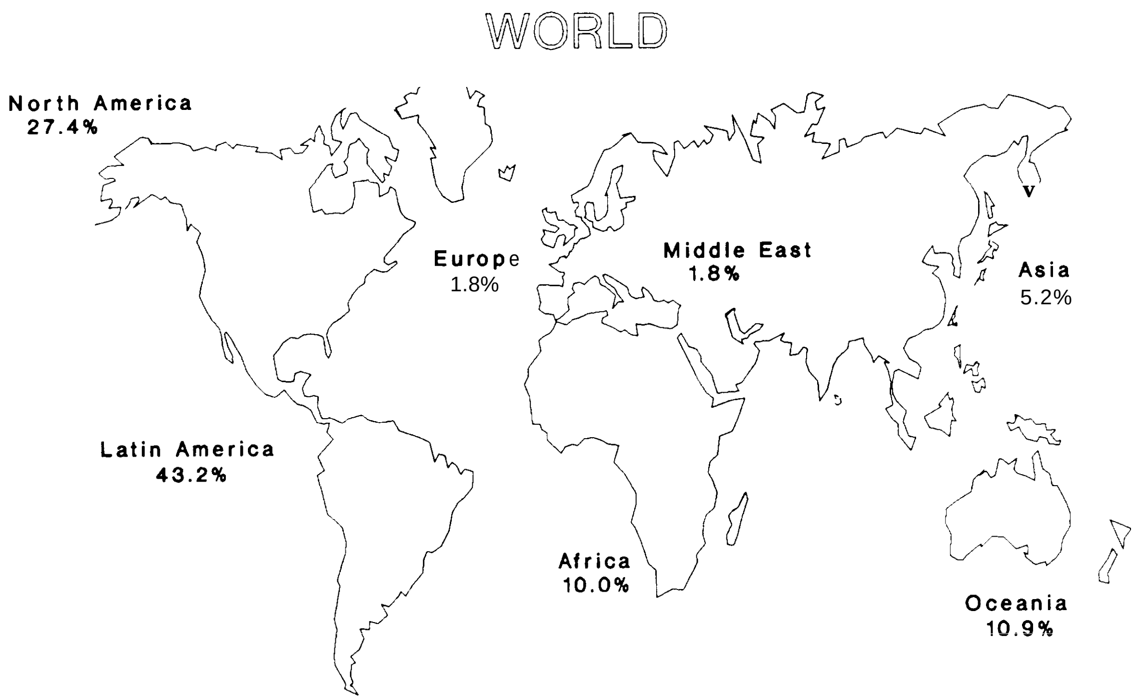
43 percent of the western world's demonstrated resources of recoverable copper (see figure 5-3). North America ranks second with around 27 percent of the total. About 11 percent of demonstrated resources are located in Oceania and Australia, followed by Africa with around 10 percent, and Asia with 5 percent. The remaining 3 percent are located in Europe and the Middle East.

In terms of individual countries, nearly half of the market economy countries' copper resources are located in Chile and the United States, with approximately 32 and 17 percent of the total, respectively. **Australia ranks third** in copper resources with **7 percent, and Peru, Mexico, and Zaire each have around 6 percent. The remain**ing 26 percent are located in approximately 33 other countries.[11]

More than 90 percent of U.S. copper reserves are located in five States: Arizona, Utah, New Mexico, Montana, and Michigan. Nearly all of the reserves are in mines for which copper is the

[11] "Copper," *An Appraisal of Minerals Availability for 34 Commodities* (Washington, DC: U.S. Department of the Interior, Bureau of Mines, Bulletin 692, 1987).

Figure 5-3.—Market Economy Country Copper Resources (1985)



SOURCE" U S Bureau of Mines data

principal product; small quantities are in base or precious metal mines where copper is a byproduct. Resources in Alaska and Minnesota also are sizable, and may hold promise for future exploration.[12]

[12] Jolly, Supra note 8.

ORE GRADES

Grade is the relative quantity or percentage of mineral content in an orebody. As discussed above, different types of copper deposits yield different amounts of ore, with strata-bound deposits generally having the highest grades, and porphyrins the lowest. The ore grade determines how many tonnes of ore must be mined in order to produce a tonne of copper. For example, a mine with an ore grade of 0.5 percent must extract 200 tonnes of ore to produce 1 tonne of metal, but an ore running 2.0 percent copper only requires 50 tonnes to produce 1 tonne of metal. Similarly, to maintain copper production, the company mining 0.5 percent ore must discover 200 tonnes of new reserves for each tonne of metal produced.

The yield of copper ore from domestic and foreign mines has declined over time, both with the exhaustion of high-grade deposits and with technological changes that permitted profitable mining of lower ore grades.[13] For example, the initial discovery of copper in Butte, Montana was a 50-foot wide seam of rich "copper glance" (lustrous chalcocite) ore that ran 30 percent copper. As the copper glance was mined out and methods for processing lower grade ores were developed, mining at Butte moved into porphyry ores. Today, the average ore grade at Butte is closer to 0.5 percent copper. Box 5-A illustrates the relation between technological advances and resources, reserves, and ore grades using the Bingham Canyon, Utah mine as an example.

Currently, most of the world's copper production comes from ores with an average yield of around 0.79 percent copper. Individual countries' resources vary in average ore grade from a low of about 0.46 percent copper in Papua New Guinea and the Philippines to a high of around 4 percent copper in Zaire (see table 5-2). The United States has an average ore grade of 0.51 percent copper for all types of copper minerals, including low-grade leachable deposits, and an average feed grade of 0.62 percent copper for sulfide resources.[14]

[13] The history of technological development and its relation to ore grade is discussed in ch. 6.

[14] U.S. Bureau of Mines, supra note 11.

Box 5-A.—Illustration of Expanding Reserves

The Bingham Pit is a classic example of how mineral reserves expand as mining and exploration proceed, and as technology and economics permit the mining of ever lower ore grades. The original prospectus for the Bingham Canyon Mine, issued in 1899, estimated that the deposit contained reserves of 12.4 million short tons of copper ore with an average grade of 2 percent. At that time, 2 percent was an extremely low-grade copper ore. In the early 1900s, financing for the mine was sought from the Guggenheim interests, who undertook an independent examination. That report, prepared around 1905, estimated the property to contain 40 million short tons of ore assaying 1.98 percent copper. In 1910, as development of the open pit proceeded, an adjacent property was merged with Bingham, By 1929, the reserve estimates had increased to 640 million tons of 1.07 percent ore, and by 1931 to 1 billion tons of 1.1 percent ore. The mine operated continuously until 1985, when it closed temporarily due to adverse conditions and for modernization. During the 80 years that the Bingham Pit has been in operation, it produced over 13 million tons of copper from 1.7 billion tons of ore. When it resumed operation after modernization, its production capacity was scheduled to be 185,000 tons of refined copper per year, or 110,000 tons of ore per day, with an average ore grade of 0.748 percent.[1]

[1] Adapted from A. B, Parson s., The *Porphyry Coppers* (New York, NY The American Institute ot' Mining and Metallurgical Engineers, 1933), and Simon D Strauss, *Trouble in the Third Kingdom* (London: Mining Journal Books Ltd , 1986)

The minimum grade that can be mined profitably from a deposit is termed the cut-off grade. The yield and tonnage of ore above the cut-off grade are critical both in estimating ore reserves and determining mine profitability. For example, although Africa is one of the least abundant regions of copper resources in terms of ore tonnage, it ranks third in recoverable copper as a result of its richer ore, which averages 2.38 percent copper. Central and South America, on the other hand, have only slightly better than average ore grades (0.91 percent), but rank first in recoverable copper due to the abundant tonnage. Similarly, North America has lower than average ore grades, but, because of the huge amount of ore, ranks second in recoverable copper.

Cut-off grade, in turn, is a function of the type of ore and mining operation. For example, a near-surface deposit may have a slightly lower cut-off grade than a deeper one, because the costs of removing the overlying waste rock and hauling the ore are lower. A mine with significant byproduct or coproduct minerals (e.g., lots **of gold)** may have a lower cut-off grade than a mine where copper is the only mineral, because the ore's extra value "pays" for the more costly handling and processing.[15] Indeed, at mines **where** copper is a byproduct, the principal minerals may cover the full production cost and the copper represents profit.

In formulating a mine plan and determining the cut-off grade, there is a trade-off between deeper mines with higher grade ore, and wider mines that exploit the lower grades surrounding the main ore body. A copper producer must mine, crush/grind, and concentrate the total amount of ore. These processes consume large amounts of energy—both human and mechanical or electrical. Thus, the more material that has to be handled, the higher the cost tends to be. For example, with 1975 technology, producing cathode copper from 0.5 percent ore was estimated to require more than 3 times as much direct and indirect energy than producing lead from 4 percent ore.[16] Recovery rates[17] also tend to drop as the ore grade decreases (see table 5-3).

Ore grade and mineralization thus play a critical role in determining the competitiveness of a mining operation. The low grade of domestic copper resources often was cited as a critical factor in the poor competitive position of the U.S. industry **during the early 1980s.** Yet U.S. copper producers have actually increased ore yields in recent years (see figure 5-4). Improvements in metal recovery technology have meant less copper lost during processing. Mine plans have been adjusted to take advantage of lower-grade areas when prices are high, and higher grades when prices are low.[18] Also, because cut-off grades

[15] The role of byproduct credits and ore grades in production costs are discussed further in ch. 9.

[16] William C. Peters, *Exploration and Mining Geology* (New York, NY: John Wiley & Sons, 1978)

[17] The recovery rate is the amount of metal actually produced from the ore and not lost in tailings and other wastes, expressed as a percentage ot' the total available amount of ore.

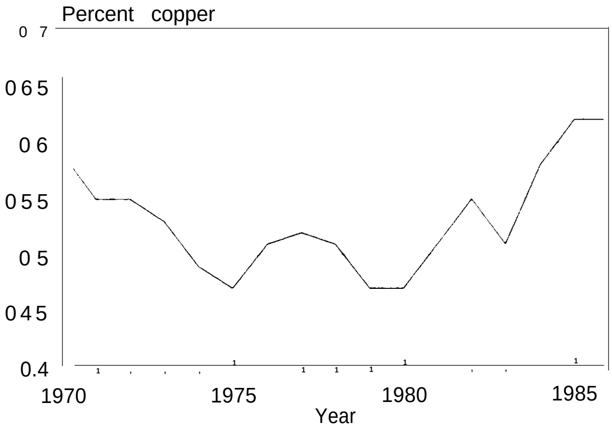
[18] Note that this is not the same as high-grading, which is removing the higher grade ore from a deposit in such a way as to preclude future mining of the lower grade material. Over time, however, selective mining ot the higher grade ores in a deposit will reduce the average grade ot the remaining ore

Table 5.3.—Overall Effect of Varying Cut-off Grade

Cut-off grade (% Cu)	0	.22	.29	.34	.40	.45
Tons milled (x 10')	26.60	23.52	21.07	19.09	17,44	16.06
Mill head grade (% Cu)	0.45	0.50	0.55	0.60	C.65	0.70
Cu produced (tons)	106.3	100,000	100,000	100,000	100,000	100,000
Btu/ton Cu (x 10^8)		101.0	97.9	95.9	95.1	95.7
Tons leached (x 10^6)	0	4.15	9.03	13.82	18.90	25.12
Dump grade (o/o Cu)	0	0.17	0.22	0.24	0.27	0.29
Cu produced (tons)	0	2,351	6,662	11,056	17,007	24,284
Btu/ton Cu (x 10^6)	0	93.7	93.7	93.7	93.7	93.7
Total tons treated (x 10')	26.60	27.67	30.10	32.91	36.34	41.18
Total Cu produced (tons)	100,000	102,351	106,622	111,056	117,007	124,284
Average Btu/ton Cu (x 10')	106.3	100.8	97.6	95.7	94.9	95.3
Percent resource recovery	0.835	0.822	0.787	0.750	0.751	0.671

SOURCE Charles H. Pitt and Milton E Wadsworth, *An Assessment of Energy Requirements in Proven and New Copper Processes,* report prepared for the U S. Department of Energy, contract No EM-78 -S-07-1 743, Dec 31 1980

Figure 5-4.—Average Ore Yields From U.S. Mines



SOURCE: U.S. Bureau of Mines, Minerals Yearbook, various years

have declined so much in the last century, waste dumps contain significant copper resources; what was waste when the cut-off grade was 2 percent is now valuable ore. Waste-dump leaching (see ch. 6) exploits a tremendous in-place resource at a very low cost because the mining cost is already "off the books."[19]

[19] Jon K. Ahlness and Michael G. Pojar, *In Situ Copper Leaching in the United States: Case Histories of Operations* (Washington DC: U.S. Department of the Interior, Bureau of Mines, Circular No. 8961, 1983).