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Chapter 12

Copper Mining and Ore Dressing

FROM IRON ORE we pass to another important metal mining industry, that producing copper. Today copper comes chiefly from the mountain states (especially Arizona, Utah, Montana and Nevada), although considerable quantities of the metal are still produced from Michigan ores. Like iron mining, the extraction of copper has increasingly become an open pit enterprise. A peculiarity of the industry is that most copper mines yield small amounts of other nonferrous metals—especially gold and silver—as byproducts. The process of bringing metallic copper to market usually involves four distinct operations: (1) mining; (2) ore dressing; (3) smelting; and (4) refining. Customarily the first two of these operations are regarded as nonmanufacturing, and the last two as manufacturing, processes. In our treatment the customary definition is employed: the indexes presented in this study refer to the mining and dressing of ores by establishments whose output is valued chiefly for its copper content.

The copper industry, thus defined, has two types of final product: ores and concentrates. Ores are, of course, produced by all copper mines, but in most cases the ores as taken from the earth are not sufficiently rich in metal or simple in mineralogy to be smelted directly. Hence most ores are subjected to a preliminary treatment designed to expedite the subsequent extraction of their metallic content. This treatment, variously known as ore dressing, concentrating, milling or beneficiating, involves, essentially, reducing the amount of barren rock in which the metal is imbedded and, when the ore contains metals other than copper, separating the important metallic constituents of the ore into products in each of which one metal predominates. The products resulting from this treatment are known as concentrates because, basically, they consist of ore that has been concentrated into smaller bulk through the removal of waste.[1]

[1] The development and significance of ore dressing techniques were discussed above in Chapter 7.

Not all ores are concentrated; some may be smelted without any preliminary treatment. Such ores are known as direct smelting ores. They are to be distinguished from the far more important class of concentrating ores, for they appear as a final product of the copper mining industry in the form of ore, while the others appear as concentrates.[2]

Neither direct smelting ores nor concentrates constitute a homogeneous grouping. Within each category there are broad variations in type and quality. These comprise differences in grade (metal content per ton); differences in the form in which the metal occurs (ease with which it can be smelted); differences in the amount of other metals, such as gold and silver, associated with the copper (which in some ores may mean that a metal other than copper is of chief value), etc. Defined precisely, therefore, the output of the copper industry consists of direct smelting ores and concentrates of varying qualities and types which, when smelted and refined, will yield metallic copper and perhaps several other metals.[3] We measure this output (Chart 45 and Appendix Table A-5) in terms of the recoverable content of copper, gold and silver in the ores and concentrates the industry produces, with each metal weighted by its price.[4] This index of course differs from the index of output for the commodity copper (Chart 4 and Appendix Table A-7), for it includes those amounts of gold and silver which come from copper ores.

We chose not to base our measure of output upon tonnage of ore chiefly because quality of ore varies within rather wide limits. If quantity and value data for both ores and concentrates were available in sufficient detail to be classified into fairly homogeneous categories and suitably weighted, an adequate index based upon such statistics could be constructed. Unfortunately such data are not available.[5] The data we have are of two kinds: (1) tonnage

[2] For a discussion of concentrates and direct smelting ores—regarded as the two commodities produced by the copper mining industry—see Appendix D.

[3] The metals these ores contain, in addition to copper, are mainly gold, silver, lead, zinc and molybdenum. See "Copper Ore," preliminary release of the Census of Mineral Industries, 1939 (March 1941).

[4] The construction of our indexes of output for the various nonferrous metal mining industries is described in greater detail in Appendix B.

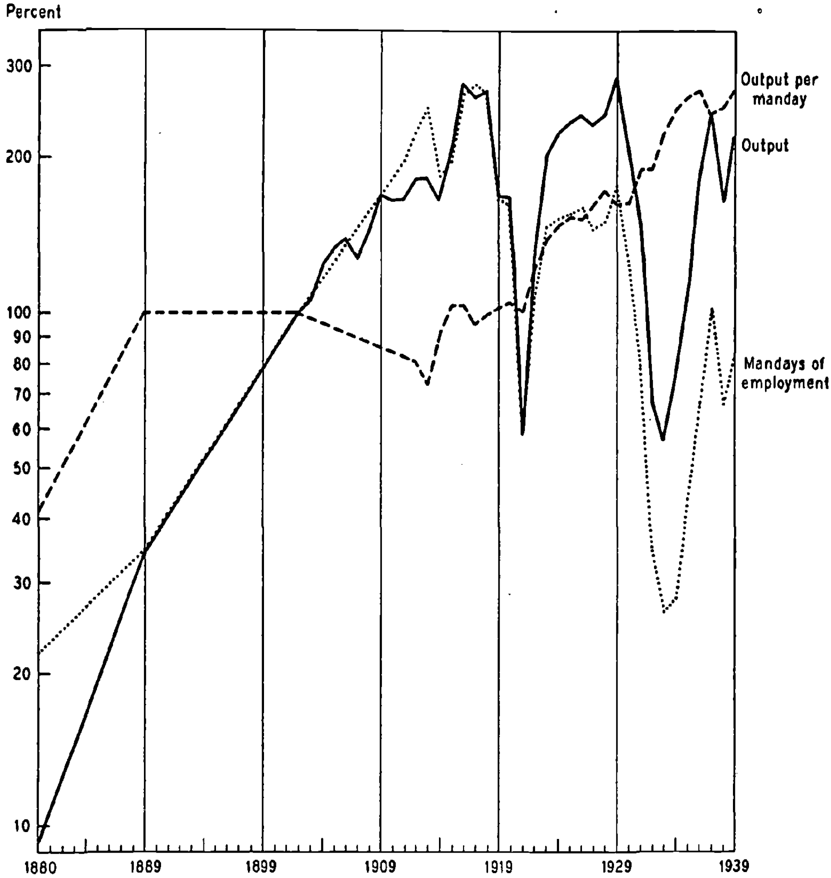
[5] It is, indeed, doubtful that such data could be collected, if only because the almost infinite variety of cupriferous ores and concentrates would hardly allow for a simple system of classification into which ores and concentrates would conveniently fall. The most convenient classification would be based on metal content, as in manganese ore, but so many factors other than content of copper determine quality

Chart 45

COPPER MINING AND ORE DRESSING

Output, Employment and Productivity, 1880 – 1939

(1902 : 100)



Ratio scale

For source and notes see Appendix E

that a very large number of classifications and subclassifications would undoubtedly be needed in this case. In addition, the marketing of metalliferous ores and concentrates—as epitomized in the bewildering smelter contract with its system of deductions, bonuses, and penalties, in which value is determined not only by the amount of metal contained, but also by the presence or absence (above a certain percentage) of various constituents deemed necessary to efficient smelting—is of such a nature that the values per ton of certain ores and concentrates that might conceivably fall into the same classification would vary within rather wide limits. For a comprehensive treatment of the marketing of ores and concentrates see A. B. Parsons, "Metalliferous Ores and Concentrates," in *The Marketing of Metals and Minerals,* ed. by J. E. Spurr and F. E. Wormser (McGraw-Hill, 1925), pp. 583-626.

of copper ore (in the case of milling ores, before concentration); and (2) recoverable metallic content of ores and concentrates produced. Data of the first kind take no account of the changing composition of total tonnage: because of the persistent downward trend in the copper content of ore (Table 22) an average ton of ore in 1939 is a quite different commodity from an average ton in 1899. Nor is metallic content of ore a perfect measure of physical output. Only if grade or quality of ore and concentrates were uniquely determined by metallic content or, more specifically, if an ore containing twice as much copper per ton were worth twice as much per ton, would an index based on these data be equivalent to one based on a detailed breakdown of ores and concentrates. Although this is not exactly the case, metallic content is undoubtedly the chief factor determining value per ton, and we may, therefore, assume that an index based on metallic content is a fairly close approximation to an ideal measure of output.[6] For this reason we have employed metallic content rather than ore tonnage to measure the physical output of copper mining, as of other nonferrous metal mining industries.

THE RELATION BETWEEN OUTPUT AND EMPLOYMENT

Between 1902 and 1939 output more than doubled, whereas in the latter year manday employment stood slightly lower than in the former. In other words, output per manday rose by about the same amount as production over the 37-year period. Both output and employment appear to exhibit first a rising and then a falling trend, but peaks in the two series are separated by a twelve-year

[6] While superior concentrating techniques appear to have raised the grade of material leaving the mining industry (see Appendix Table D-3), high grade concentrates tend to have a disproportionately high value per ton. To this extent the use of series for recoverable content may understate the rise which would be reported by an index of ore production weighted by the prices of different grades of ore, could this be computed. Besides this weakness there is the added difficulty that the measure relates to metal recoverable at a stage in the production process one or two steps removed from mining. If an increase in the efficiency of smelting and refining were to result in the extraction of more metal than formerly, the index would suffer from an upward bias. However, it seems that the improvement in smelter recovery has been slight (see Appendix Table D-1). It is obvious that to some extent these considerations cancel each other. The adequacy of our index, based upon recoverable content, is appraised from these and other viewpoints in Appendix D.

interval. In employment the high point was reached in 1917 (or, at least, during the years 1916–18), but the peak in production did not occur until 1929. It is noticeable, however, that the 1929 peak in output is only slightly above the level reached in 1916, and that 1929 is in fact the sole year in which the 1916 level was surpassed.

The increase in manday productivity from 1902 to 1939 was 168 percent. This is only about one half of the percentage gain in iron mining, and is about equal to the increase for the entire metals group. In terms of manhours the comparison offers much the same picture. Output per manhour in copper rose by 200 percent over the entire period, a net gain similar to that in metal mining as a whole, in which output per manhour jumped 196 percent. In iron mining during the same period manhour output increased by 346 percent, or nearly twice as much as in copper (see Table 11 above). Productivity in iron mining, although subject to sharp fluctuations from year to year for reasons discussed in Chapter 11, rose rather continuously over the period: in copper mining practically no advance in productivity occurred between the turn of the century and the close of the first World War.

Both output and employment rose substantially between 1902 and 1916–18. Chart 45, in which data for 1880 and 1889 are plotted also, reveals that the rise in these two series during this period is merely a continuation of the general upward movement before the turn of the century. The rise in output per manday was more uneven. During the earliest decade (1880–89) production rose considerably faster than employment, but from 1889 to 1916 output per manday failed to rise appreciably, even though the industry was passing through its period of most rapid expansion. The relative stagnation of productivity in copper mining during these years contrasts sharply with the experience of iron mining, the other principal metal mining industry, discussed in the preceding chapter.

After the World War both output and employment fell to a low level in 1921. Once again it is noteworthy that the net change from 1916–18 in the two series was approximately the same: the productivity index did not change appreciably. Not until the period of the 1920's did the movements of the two series begin to diverge once more, and output per manday resume its rise. In the next decade the divergence widened, and by 1937 employment had fallen 42 percent from the 1929 level while production had declined by 14 percent.

Thus the year 1921 seems to mark a dividing point in the behavior of productivity in copper mining. Output per worker in that year was roughly the same as it had been in 1889. After 1921 the productivity index rose rapidly and the period of the 1920's and 1930's saw a persistent gain in the efficiency with which the industry used its labor input. The comparative stagnation of output per worker during the 32 years 1889–1921 deserves further comment. Copper mining underwent at least as great a technological change as, perhaps an even greater one than, any other metal mining industry. This suggests that other factors besides technological change were at work. In the last analysis industrial productivity is the net result of the interplay of technology and resource conditions. The role of each of these two elements will now be considered.

RESOURCE CONDITIONS

Probably in few other mineral industries have increasing natural difficulties been as important as in copper mining, which has been beset both by increasing difficulties in gaining access to ore,[7] and by declining grade of ore. Of the two the latter has probably exerted the greater influence.

The drain upon productivity in copper mining exerted by the decline in grade of ore is not easily determined. In fact, it is doubtful that in principle a decline in grade must affect productivity adversely, for low grade ores are mined and treated according to a technique quite different from that applied to high grade ores. For the entire industry, average grade, measured by yield of copper, declined from about 60 pounds per ton in 1880 to about 25 pounds in 1939. These figures, however, give an exaggerated impression of the increased difficulty of obtaining the metal, as we shall now explain.

We have mentioned that United States copper mines produce both direct smelting ores and concentrating ores. Although the latter group is by far the more important of the two, it is evident from Table 22 that the relative importance of the two types of

[7] For instance, from 1905 to 1935 the average depth of shafts in underground copper mines in Arizona, Montana and Michigan increased by 50 to 100 percent. (Y. S. Leong and others, *Copper Mining*, National Research Project, Philadelphia, 1940, p. 84.)

TABLE 22

PRODUCTION AND YIELD OF DIRECT SMELTING AND MILLING COPPER ORES, 1902–39[a]

Year	*Total*[b]		*Smelting Ores*		*Milling Ores*	
	(Th. s.t.)	Yield of Copper (Percent)	(Th. s.t.)	Yield of Copper (Percent)	(Th. s.t.)	Yield of Copper (Percent)
1902	11,465	2.73	4,905	4.19	6,559	1.68
1907	20,253	2.11	3,958	4.05	16,296	1.41
1908	22,291	2.07	4,387	4.27	17,761	1.49
1909	27,933	1.98	5,268	4.15	22,665	1.47
1910	28,497	1.88	5,001	4.14	23,496	1.40
1911	29,988	1.82	4,356	4.66	25,633	1.34
1912	35,656	1.71	5,014	4.45	30,642	1.26
1913	36,337	1.67	5,290	4.22	31,046	1.22
1914	35,176	1.60	4,597	4.23	30,478	1.20
1915	43,404	1.66	5,434	4.60	37,970	1.26
1916	57,863	1.70	6,928	4.72	50,935	1.28
1917	58,483	1.60	7,438	4.39	51,045	1.19
1918	62,289	1.51	6,224	4.51	53,938	1.18
1919	36,122	1.65	3,466	4.64	30,770	1.35
1920	36,765	1.63	3,201	4.89	31,348	1.34
1921	13,396	1.70	1,236	4.77	11,023	1.44
1922	26,893	1.74	2,278	5.36	23,259	1.43
1923	45,519	1.58	3,497	5.12	40,210	1.29
1924	49,178	1.59	3,555	5.08	44,427	1.33
1925	53,103	1.54	3,877	4.90	48,187	1.28
1926	57,182	1.46	3,768	4.75	52,084	1.24
1927	56,725	1.41	3,408	4.67	49,179	1.23
1928	62,097	1.41	3,766	4.44	54,214	1.24
1929	68,422	1.41	4,235	4.60	59,728	1.22
1930	47,382	1.43	2,984	4.57	41,327	1.23
1931	34,051	1.50	1,520	5.38	30,057	1.33
1932	12,320	1.83	759	6.98	10,965	1.51
1933	8,388	2.11	872	6.30	7,476	1.63
1934	11,724	1.92	977	6.21	10,682	1.53
1935	19,112	1.89	1,612	5.42	17,065	1.57
1936	38,514	1.54	2,389	5.05	36,117	1.31
1937	61,513	1.29	2,763	4.30	58,738	1.15
1938	37,795	1.34	2,028	4.49	34,374	1.17
1939	55,239	1.25	2,396	4.61	50,710	1.09

[a] For 1902–36 data are from Y. S. Leong and others, *Copper Mining* (National Research Project, Philadelphia, 1940), Table A-4, p. 220; for 1937–39 from *Minerals Yearbook*. In some years small amounts of copper ore were produced in Alaska, and these are generally included.

[b] Includes ores that were leached and other ores not reported as smelted or milled. Figures for earlier years read: 1889—3,323 th. s.t. yielding 3.32 percent copper; and 1880—1,007 th. s.t. yielding 3.00 percent copper. Data for 1889 cover Michigan, Montana, Arizona and New Mexico only, but production from other states was negligible.

ores has undergone a considerable change since 1902. Whereas 95 percent of the ore mined in 1939 was concentrated, only 57 percent of the ore produced in 1902 required (or at least received) such treatment. (In terms of metallic copper produced the percentages are 84 in 1939 and 35 in 1902.) Since the average smelting ore ordinarily contains between 3 and 4 times as much copper as does concentrating ore, it is evident that the increase in the relative importance of concentrating ores must have exerted a depressing influence on average grade. For the industry as a whole a large part of the decline in average grade since 1902 can be traced to this shift.

The fact that decline in average grade has resulted partly from a shift from one type of ore to another has mitigated its adverse effect upon productivity. For the concentrating ores, as a class, or at least the porphyry ores within the group, are produced—especially in the open pit mines of the West—under conditions strikingly different from those obtaining in mines turning out direct smelting ores. And because of wide differences in method of production, output per worker in mines producing the former type of ore is generally higher than in mines that provide the much higher grade, direct smelting ores (in this context output is measured, of course, in terms of metal content). This situation arises, however, not so much because the low grade ore mines are more advanced in the application of technological innovations, as because the ores of low grade often lend themselves to certain highly productive methods of exploitation which cannot be utilized with ores of superior grade. [8] The important consideration, then, is that the utilization of such ores does not necessarily mean that productivity has risen less rapidly than it would have if the same technological advances had been applied to ore bodies of a considerably higher grade, because the technological advances are often of such a nature that they cannot be utilized except with relatively low grade ores.

How, then, does the decline in grade of ore operate to lessen

[8] In particular, large scale open pit mining and caving methods of underground mining, used in conjunction with rather elaborate concentration techniques: see Chapters 5 and 7 above. It can, of course, be argued that, because of differences in mining methods, grade of ore should not be interpreted to mean merely metallic content. Certainly, in the valuation of an ore body, possible methods of exploitation are as important a factor as metallic content per ton of ore. However, such factors as method of exploitation cannot be consolidated into a single simple measure to indicate the grade of the resources.

the increase in productivity which might otherwise have followed the technological changes in copper mining and ore dressing? Obviously this question must be answered cautiously, yet it seems certain that major importance must be attached to the decline in grade within the categories of direct smelting and concentrating ores, rather than to the shift in their relative importance. If, for instance, the grade of porphyry ores had not declined, the mines producing such ores must almost certainly have experienced a greater increase in output per worker, in view of progressing technology, than was actually the case. In other words, it is not in the large decline in the average grade of copper ore as a whole between 1902 and 1939 that we can find an explanation of the relative moderation of the rise in the copper productivity index, but rather in the (much smaller) changes in grade within the two categories of ore produced in the industry. The concentrating ores, in particular, have grown leaner during the period under review, and we may surmise that the benefits derived from technological advances in producing them have to some extent been swallowed up by the decline in their grade.

Unfortunately we can do little more than indicate the manner in which declining grade of ore operates to affect industrial productivity. To go beyond this point and attempt to measure the downward pressure exercised upon productivity by declining grade would require data we do not possess. There are, however, certain figures which have at least suggestive value.

In the concentrating ores, which since 1902 have become an ever more important segment of the industry's output, copper yield (in pounds per ton) has declined about 35 percent (see Table 22). If yield has dropped by this much, the original content of the ore (before milling) must have fallen off by a still higher percentage, for mill recovery has increased substantially during this period.[9] According to some authorities mill recovery rose from about 60 to 75 percent of content in the early 1900's to about 90 percent in the 1930's.[10] If these figures are correct the 35 per-

[9] This is well illustrated by the data in Appendix D. Among several important porphyry operations the yield of copper (in the form of concentrates) in pounds per ton of ore declined by 11 percent from 1913 to 1929. Yet between the same two years the original content of copper (before milling) per ton of ore declined by 30 percent, almost 3 times as much as yield.

[10] Andrew V. Corry and O. E. Kiessling, *Grade of Ore* (National Research Project, Philadelphia, 1939), p. 50; see also Appendix Table D-3.

cent drop in yield is actually equivalent to a decline in content of between 45 percent and 60 percent.[11] This means that if all other factors (including technology) had remained constant, output per worker engaged in producing concentrating ores (and concentrates therefrom) could be expected to fall between 45 percent and 60 percent from 1902 to 1939—a rough measure of the handicap with which technology in the predominating sector of this industry has been burdened over the long run.

The inclusion of direct smelting ores in the output index for the industry probably tends to mitigate this disadvantage somewhat. For in the case of these ores there is no evidence of a secular decline in grade. Indeed, over the entire period yield of copper per ton of direct smelting ore rose by about 10 percent. Of course, this may merely be a reflection of the increasing effectiveness with which the smelters recover metal from these ores, and their content may actually have declined. But even if this is so, the additional effort which was required to maintain and even increase yield was not exerted within the mining end of the industry, and hence productivity could not have been adversely affected.[12] It seems likely, however, that increasing difficulties of access played a more important role with this group of ores than with the milling ores, since milling ores occur largely in deposits near the surface, whereas direct smelting ores come from deep mines. Unfortunately, we are not able to evaluate the importance of this factor.

[11] Provided, of course, that there has been no important secular change in the percentage of copper recovered from concentrates by smelters and refiners. If improved recoveries have also characterized this branch of the industry, the actual decline in content would be even greater. However, the evidence at hand suggests that smelter recovery has not changed greatly (see Appendix Table D-1).

[12] The case of direct smelting ores illustrates the ambiguity inherent in an index of production not based on the original metallic content of mine output. For if our index were based on the latter rather than recoverable content, any decline that occurred in the grade of mine output would have affected physical output directly, and have affected productivity through the index of physical output. The same is true also of milling ores, so far as the index of physical output is concerned. However, in the case of milling ores the additional effort required to maintain yield in the face of a decline in content is to be traced (for the most part) to the nonmanufacturing end of the industry, whereas with direct smelting ores it is, as we have noted, expended in the manufacturing end, i.e., in smelting. It should be noted that our estimate of the decline in the content of concentrating ores does not (as noted in the preceding footnote) take into account possible improvements in smelter and refinery recovery of metal from concentrates. It may thus be an incorrect measure of the decline in grade. Yet even if it is incorrect, it is the best way to estimate the handicap with which mining technology has been burdened, for the "correct" measure of decline in grade would have included that part of the handicap (if any) which manufacturing has overcome.

TECHNOLOGY

It should be sufficiently clear from references in the preceding section that technological advance has been instrumental in facilitating the utilization of ores of a considerably lower grade than those commonly exploited at the end of the last century. This influence has been exerted in two ways: (1) new mining methods, based on the large scale extraction of very low grade ore, have been devised; and (2) existing techniques have been improved so that productivity has increased even in the face of the growing natural difficulties associated with each method of mining. The first category comprises open cut mining, together with caving methods of underground mining, both essentially nonselective in character, and inapplicable to the winning of rich deposits.[13] In the second category we count such factors as the mechanization of the mining process and the elaboration of milling techniques.[14] Most of these innovations are common to other metal mining industries, but they have played a particularly important role in copper. Nor, within the copper mining industry, do they represent independent lines of development. Improved milling, for instance, was of great value in the working out of new mining techniques and, even within new mining methods, mechanization has been of considerable importance. However, it is best to treat these two types of technological change separately, if only for convenience in presentation. In Part Two the nature of these changes was examined in some detail. Here we are concerned primarily with the contribution of such technological innovations to increasing productivity in the industry.

The trend of output per manday at underground and open pit mines and in all copper mining (excluding employment in milling) is shown in Chart 46. A comparison of output per manhour in open pit and in various underground methods of mining is offered in Table 23. Among the several methods utilized in mining copper ore, the open cut ranks highest in output per manhour. This is demonstrated by data from the National Research Project's report on copper (reproduced in Table 23) which indicate that in 1929 output per manhour in open cut mining was more than twice the average for all methods of underground

[13] For a description of these and other mining methods, see Chapter 5 above.

[14] Current practice in the milling of nonferrous ores was described in Chapter 7.

TABLE 23
COPPER MINING, 1917–36
Output per Manhour According to Mining Method[a]
Copper plus copper equivalent of accessory metals in pounds[b]

		Underground Methods					
Year	*Open Cut*	All Methods	Block Caving	Open Stope	Square Set	Cut and Fill	Shrinkage
1917	34.1	13.8	18.3	8.2	13.6	16.0	21.6
1918	34.1	13.2	19.9	6.9	13.3	14.6	18.8
1919	31.2	13.9	22.3	8.6	13.5	14.9	18.0
1920	32.9	15.7	20.6	10.3	15.0	16.0	24.7
1921	45.0	15.8	30.5	11.1	14.5	9.9	34.0
1922	57.8	16.4	22.8	9.4	15.8	14.4	30.8
1923	38.8	17.6	20.3	12.0	16.1	19.3	28.1
1924	39.1	18.8	21.6	12.1	18.3	19.1	28.5
1925	35.0	19.6	23.8	13.1	18.1	21.7	27.6
1926	39.2	18.9	22.9	11.8	17.8	23.3	25.1
1927	45.5	18.7	24.1	12.2	16.4	25.1	24.3
1928	48.9	19.6	24.9	13.0	18.2	24.3	21.9
1929	43.8	18.8	23.6	12.2	17.8	24.7	18.3
1930	42.4	20.0	29.1	12.1	21.0	22.7	19.0
1931	53.0	23.1	40.2	13.6	23.6	21.6	24.8
1932	47.5	25.2	48.4	10.7	29.7	30.4	34.3
1933	56.9	29.1	24.1	20.8	30.1	34.9	10.6
1934	60.7	29.8	106.4	21.3	25.8	36.8	13.6
1935	74.8	33.3	60.3	25.5	28.8	38.8	47.9
1936	82.7	31.3	58.0	26.8	23.3	37.6	43.5

[a] Y. S. Leong and others, *Copper Mining* (National Research Project, Philadelphia, 1940), Table A-7, pp. 224-37. In line with the procedure adopted in that report, the ratios here are based on employment figures which exclude employment in ore dressing. The data relate only to those mines whose output of copper in 1929 was more than 2,000,000 lbs. Mines were classified according to the mining method predominating over the entire period 1917–36. Thus, to the extent that mines used more than one method, the categories are not definitive. The various methods named were described in Chapter 5: see also Glossary at end of volume.

[b] Accessory metals have been converted to copper equivalent as follows: the quantity of each metal is multiplied by a constant price for that metal, the values are aggregated, and the sum is divided by a constant price for copper to yield the number of pounds of copper equivalent.

mining.[15] The high productivity associated with the open cut technique assumes significance in the light of the pronounced shift toward this method of mining following its introduction in

[15] We use 1929 rather than later years since the 1930's witnessed a revival of "selective" mining (because of the slump in the copper market) which made for higher levels of productivity in some methods than would have been the case under more normal conditions. In its present context the term "selective" mining refers to the deliberate exploitation of the richer portions of an ore deposit (see discussion in Chapter 5 above). This may occur even in a mine in which nonselective methods are normally employed. Data on output per manday for open cut and underground methods from 1914 to 1936 will be found in Appendix Table A-10; these are reproduced in Chart 46.

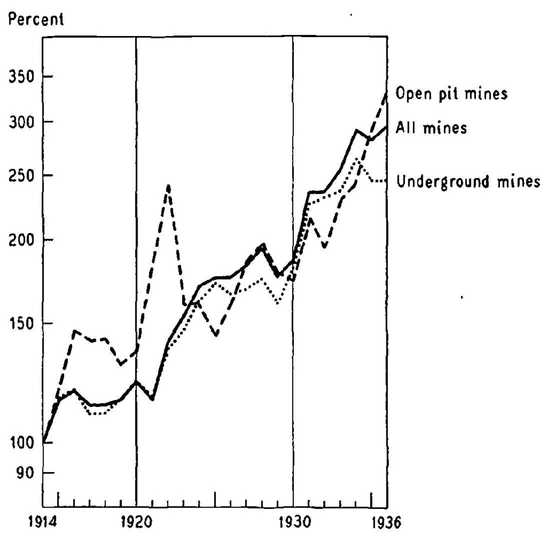
1906. In 1907, the first year for which data covering output by the several methods are available, open cut mines accounted for only 2 percent of the recoverable copper content of ores produced, whereas in 1936, the last year covered by the NRP report, open cut mines produced 44 percent of the recoverable copper content

Chart 46

COPPER MINING

Output per Manday at Underground and Open Pit Mines, 1914–36

(1914 : 100)



Ratio scale

For source and notes see Appendix E

of ores,[16] or 39 percent of the copper industry's output if allowance is made for other metals (Table 24).

In underground mining, caving methods increased their relative importance, accounting for 5.8 percent of recoverable copper in 1907 and for 10 percent in 1936.[17] According to the breakdown reproduced in Table 24, however, it appears that block caving and

[16] Leong and others, *Copper Mining*, Table A-2, p. 216. According to Appendix Table A-10, output per manday in copper mining rose from 88 lb. (recoverable content) in 1914 to 259 lb. in 1936, or by 171 lb. Using the method of Table 13 (reading pounds of copper for dollars, and mandays for manhours), we may associate 139 lb. of the increase with changes in underground and open pit productivity as such, and 32 lb. with the shift from the former to the latter method of mining. The relative contribution of this shift in mining method to the rise in productivity during the last 20 or 25 years appears to have been slightly less in copper than in iron mining: see Chapter 11, footnote 18.

[17] *Ibid.*

shrinkage—the two underground methods which we may broadly class as large scale and nonselective in character, and which employ gravity loading—had attained their greatest extension by the early 1920's, and during the thirties suffered a temporary eclipse. (Data for years since 1936 are not available; but the importance of the methods in question has probably revived since then with the current expansion in copper output.) The decline in the relative importance of caving and shrinkage during the 1930's coincided with a low level of copper mining activity, and with a return, in the case of underground mining, to more selective methods of exploitation. Thus in underground copper mining large scale methods appear to be marginal, in the sense that, when the market for copper deteriorates, mines using them will close down before mines using traditional cut-and-fill or stoping methods. In view of the apparent high efficiency of caving and shrinkage among underground methods of copper mining (Table 23), this finding presents something of a paradox. The matter seems worth pursuing. Let us assume, which is not strictly accurate, that unit cost of production varies inversely with output per manhour. It may be that the greater efficiency shown by the newer methods in Table 23, where data are calculated from figures which exclude mill employment, is absorbed by relatively higher milling costs; [18] in this case, mines using caving and shrinkage are not really more efficient than mines using the traditional methods. That is to say, we should have to conclude that the advantages of scale and the use made of gravity in these mines are offset, or more than offset, by poverty of the ore: otherwise the lack of competitive power shown by large scale methods in a period of depression such as the early 1930's is hard to explain.[19]

[18] Both block caving and shrinkage are nonselective in character, and produce chiefly milling ores. The grade of ore from shrinkage mines does not differ greatly from the average for all underground mines; ores produced by block caving are below average in grade (Leong and others, *Copper Mining,* Table A-11, p. 254).

[19] It may be argued that the proposition, that nonselective methods of underground copper mining are marginal in the sense indicated, is negated by the relatively large contributions which block caving and shrinkage methods made to copper output in 1921. But the depression of that year, though intense, was of short duration. A feature of nonselective methods of underground metal mining is the elaborate planning, and substantial maintenance activities, which are necessary: for this reason their exploitation is probably not very sensitive to short run changes in the demand for the product, and the depression of the 1930's, which lasted longer, is a better test of competitive power.

As an alternative explanation of the lack of competitive power shown by large scale methods of underground mining, at least in the depression of the 1930's, we

If the hypothesis advanced in relation to block caving and shrinkage is plausible, it may be worth while to apply it to the interpretation of the figures for open cut mining in Tables 23 and 24. Typically this method produces ores of very low grade. Although by 1921 open cut mining had already become more efficient than any other method shown in Table 23, its contribution to output suffered a sharp decline in that year (Table 24). We may suppose that greater costs of concentration outweighed the higher manhour output in mining; moreover, the method is very flexible and shutdown costs are low. But during the depression of the 1930's, by contrast, the share of open cut mining increased rather steadily to an all-time high (for the period shown) in 1936: during these years its behavior is quite dissimilar to that exhibited by the two nonselective underground methods for which we have data. We may suppose that advances in milling, especially of porphyry ores, were sufficient, despite the slump in the copper market, to offset the low grade of the open cut product; just as we must infer that the need to handle and process low grade ores offered disadvantages which many underground mines using block caving and shrinkage methods were unable, during these years, to overcome.[20]

The light cast by the figures in Tables 23 and 24 upon the rela-

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may hazard the guess that caving and shrinkage methods are more efficient than other methods of underground mining only when the mine using them is working at or near capacity. (If true, this might also explain the low level of manhour output for block caving and shrinkage reported for 1933: see Table 23.) If this is the case, it is conceivable that imperfections in the market for copper concentrates might prevent mines which use the methods discussed from pressing home the advantage which would otherwise accrue to them in periods of depression. To most readers this explanation will probably appear less plausible than that advanced in the text.

It is sometimes said that mines which do not employ large scale methods derive a competitive advantage in periods of depression from their ability to return to more selective methods of mining, and that during such periods their costs are lowered by the rise in the grade of ore which results. We think it will be found that this suggestion leads, according to the assumptions chosen, either (1) to the explanation advanced in the text (i.e., that the costs of large scale nonselective underground mines are not really lower than those of mines using traditional methods); or (2) to the explanation of the preceding paragraph of this note (i.e., that large scale mining is more efficient than the traditional methods, but that the market is imperfect); or (3) to the conclusion that the richer ores obtained from selective mining are not adequately assessed with depletion costs, and that the advantage apparently enjoyed by the older methods during depression periods is illusory.

[20] Advances in the milling of low grade ores are discussed in Chapter 7, above, and in Appendix D. Since the data in Table 23 are based upon recovered metal, they reflect improvements in mill recovery; but they take no account of changes in the amount of metal processed per mill employee.

tive advantages of different mining methods, from one period to another, is at best uncertain. The categories are not definitive, for some mines use more than one method or a combination of several; and year to year changes in manhour output are of doubtful significance. But the rise in productivity in the copper mining industry as a whole (Charts 45 and 46) is well established. In part it has been caused by the substitution of open cut for underground methods, but mainly by the rise in manhour output recorded for each of the methods shown in Table 23.

Let us recall the peculiar behavior of productivity in copper

TABLE 24

COPPER MINING, 1917–36
Percentage Contributions of Different Mining Methods to Total Output[a]

		Underground Methods					
Year	*Open Cut*	Total	Block Caving	Open Stope	Square Set	Cut and Fill	Shrinkage
1917	23.6	76.4	14.5	11.1	30.3	12.9	7.6
1918	23.7	76.3	16.4	9.9	31.8	11.7	6.5
1919	20.9	79.1	17.4	13.1	28.5	13.1	7.0
1920	20.9	79.1	15.8	11.4	30.4	13.1	8.5
1921	14.2	85.8	17.1	13.7	23.2	15.5	16.3
1922	17.1	82.9	18.5	10.0	31.9	11.7	10.8
1923	24.7	75.3	16.9	8.2	28.9	12.9	8.3
1924	26.8	73.2	16.9	7.4	28.5	13.1	7.3
1925	26.1	73.9	16.4	8.3	28.6	13.4	7.2
1926	28.4	71.6	16.1	9.2	26.5	13.2	6.6
1927	28.7	71.3	17.1	9.8	24.9	13.1	6.4
1928	31.6	68.4	15.6	9.1	24.7	13.8	5.3
1929	29.2	70.8	15.5	9.1	27.0	14.4	4.8
1930	25.2	74.8	17.5	12.4	25.9	13.5	5.6
1931	28.3	71.7	17.8	11.2	28.4	9.9	4.4
1932	26.7	73.3	14.1	10.8	26.9	19.0	2.6
1933	32.7	67.3	.8	12.2	27.8	26.3	.1
1934	37.6	62.4	3.0	10.8	20.3	28.2	.1
1935	34.5	65.5	4.9	8.3	25.0	24.9	2.3
1936	38.7	61.3	8.9	7.8	20.8	19.9	4.1

[a] Y. S. Leong and others, *Copper Mining* (National Research Project, Philadelphia, 1940), Table A-7, pp. 224-37. The data relate only to those mines whose output of copper in 1929 was more than 2,000,000 lbs. Mines were classified according to the mining method predominating over the entire period 1917–36. Thus, to the extent that mines used more than one method, the categories are not definitive. The various methods named were described in Chapter 5; see also Glossary, at the end of this volume.

Total output is measured as copper plus copper equivalent of accessory metals. The latter have been converted to copper equivalent as follows: the quantity of each metal is multiplied by a constant price for that metal, the values are aggregated, and the sum is divided by a constant price for copper to yield their amount as copper equivalent.

mining over the long run—several decades of stability, apparently preceded and certainly followed by periods of sharp increase in output per manday. It is evident that these movements can be explained only in terms of the reaction between technological change and resource conditions. On the one hand, depletion has led to a decline in grade of ore, and in some underground mines to greater inaccessibility of the deposits; on the other, there have occurred important technological developments. A conflict of this kind may lead to decisive results, or it may end in a draw. Evidently a draw would mean unchanging productivity, whereas a victory for technology would mean rising productivity—just as we may interpret declining productivity as a triumph of nature. Between, say, 1890 and 1920 the contest between these forces seems, in the copper industry, to have been indecisive. After 1920 technological developments apparently outweighed the effects of depletion.

Nevertheless, we should beware of assuming that these conflicting tendencies are independent of one another in their operation. Few industries have encountered such natural handicaps, or have been forced to revise so drastically their conceptions of what was, and what was not, workable mineral. And yet the rise in productivity over the period as a whole has been substantial, as we have seen. It is not unreasonable to suppose that the deterioration of resources acted as a stimulus to technological development. We may notice, especially, that the lean ores of the western states, developed during the last three decades, required an entirely new technique for their exploitation—a technique whose efficiency no doubt astonished those who were prone to judge commercial possibilities mainly in terms of grade of ore mined. What seems to have happened, in part at least, is that the very process of continuing combat against natural difficulties led to such important changes that the level of productivity was, in the end, higher than before the deterioration of resources had begun.[21]

[21] This suggestion is not new. Simon Kuznets (*Secular Movements in Production and Prices,* Houghton Mifflin, 1930, Ch. 1) offers the hypothesis that impoverishment of raw materials in the extractive industries provides a constant stimulus to technical progress. Hence the slackening in the introduction of innovations, which he observes in manufacturing, is not found in mining. Kuznets argues, however, that output per worker tends to react less and less to such innovations because of the very factor of increasing natural difficulties. He offers some statistical evidence of this tendency, but is fearful lest the presentation of such proof appear in the

Why the increase in productivity did not begin until after 1920 it is difficult to say. A more thorough investigation of the dates at which technological changes were generally adopted, and at which shifts from one type of mining to another occurred, would doubtless be necessary.[22] At any rate it is clear that the renewed growth in productivity cannot have been due to a reversal of the trend toward increasing natural difficulty; for we know that the grade of ore continued to decline, and it is obvious that the large output of the 1920's must have continued the pressure on available resources. To be sure, a return to more selective methods produced a recovery in grade of ore mined during the early 1930's, but this proved to be a temporary phenomenon. Unless new deposits of copper should be discovered in this country, or invention have surcease, the struggle will continue, and upon its outcome the future level of productivity in copper mining will depend.

We have examined the history of two important metal mining industries—iron and copper—in each of which the development of techniques of open pit exploitation played an important role in the rise of productivity levels. We turn briefly in the next and final chapter of Part Three to the prototype of all open pit operations—the quarrying of stone.

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nature of supererogation, since increasing difficulties of production must obviously produce effects of this sort sooner or later.

Yet, as the copper industry illustrates, it is difficult to say at what point the slackening in productivity growth, or its actual decline, becomes inevitable. Certainly an investigation of copper productivity that ended in the early 1920's would have led to the conclusion that in copper that stage had already been reached. But copper productivity began to rise thereafter, and the investigator would find that he had failed (perhaps inevitably) to take full cognizance of the magnitude of certain innovations which had already evolved (or might in the future appear) in the course of adjustment to an unfavorable environment. Eventually, of course, a resource may be entirely exhausted, but with most minerals depletion still occurs only in a relative sense, in that grade declines and natural conditions become more difficult, but absolute exhaustion rarely takes place. And as long as this remains true, the possibility of a rise in productivity following even a prolonged decline exists, provided, of course, that technological advance does not come to a standstill.

[22] A possible explanation lies in the fact that the flotation process of ore concentration (see Chapter 7), which had been developed around 1912, was the subject of litigation for most of the succeeding decade. Hence the improved recoveries associated with this technique were not realized until it came into general use about 1922 (see A. B. Parsons, *The Porphyry Coppers,* American Institute of Mining and Metallurgical Engineers, 1933, p. 452).