The World Copper Industry: Geology, Mining Techniques and Corporate Growth, 1870-1939

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The geological characteristics of the world's copper deposits have always exercised a strong influence on the technology required to exploit them. The resulting technological pressures, in conjunction with the global distribution of copper ores, have also had a marked influence on the forms of economic organization that have arisen to undertake that exploitation. Copper ores of sufficient concentration to merit mining have tended to be located in relatively few locations in the world.[1] Also, particularly since the mid-nineteenth century, new sources of supply have tended to be found in areas increasingly remote from the major centres of consumption in western Europe and the north-eastern United States. At the same time, there has been a marked shift towards mining larger scale and lower grade ore deposits. The broad significance of these changes is that the increasing cost of exploitation, especially in terms of fixed capital requirements, has acted

[1] The level of concentration required to merit exploitation at any given time, in any given location, is subject to a complex equation which includes the prevailing market price for the metal, the relative cost of production (as determined by available technology), the mine location (and therefore transport and other infrastructural costs), together with the mineralogical composition and form of the orebody. Thus, a high grade deposit in a remote region may be a less viable proposition for a mining company than a lower grade deposit nearer settled and developed regions, or a deposit containing valuable by-products like gold or silver may be a better proposition than a higher grade copper deposit with no by-products. Since World War II a general lower cut-off grade of around 0.5 per cent has been assumed in most studies of global copper resource availability; see, for example, Committee on Mineral Resources and the Environment (COMRATE), *Mineral resources and the environment* (Washington DC 1975), pp.130-1.

as a major determinant of the trend towards large-scale enterprise and vertical integration in the copper industry.[2]

Copper mineralization occurs in the earth's crust in a very wide variety of forms, compared with other metals,[3] but can be divided into three major categories: primary (sulphide) ores, altered secondary (sulphide, carbonate, oxide and silicate) ores and native (pure metallic) copper[4] (table 1). The principal copper ore, both in economic terms

TABLE 1. The principal ores of copper

type:	ore:	maximum copper content	chemical formula:
native copper:	-	100.0	Cu
sulphides:	chalcocite	79.8	Cu_2S
	covellite	66.5	CuS
	bornite	63.3	Cu_5FeS_4
	tetrahedrite	52.1	$Cu_8Sb_2S_7$
	enargite	48.0	$3Cu_2S,2As_2S_3$
	chalcopyrite	34.5	$CuFeS_2$
carbonates:	malachite	57.3	$CuCO_3,Cu(OH)_2$
	azurite	55.3	$2CuCO_3,Cu(OH)_2$
oxides:	cuprite	88.8	Cu_2O
	tenorite*	79.8	CuO
silicate:	chrysocolla	36.1	$CuSiO_3,2H_2O$

Sources: E.L. Rhead, *Metallurgy* (London 2nd.ed. 1907), pp.161-3; H. Ries, *Economic Geology* (New York 4th.ed. 1916), pp.168,568; R.F. Mikesell, *The world copper industry* (Baltimore 1979), p.46. The chemical symbol for copper is Cu; others used here are: As arsenic, C carbon, Fe iron, H hydrogen, O oxygen, S sulphur, Sb antimony, Si silicon; * an alternative name for tenorite is melaconite.

[2] This paper extends discussion in, and should be read in conjunction with, my two earlier papers: 'The rise of big business in the world copper industry, 1870-1930' *Economic History Review*, 2nd.ser., 39 (1986), pp.392-410; 'The changing structure of the world copper market, 1870-1939' *Journal of European Economic History*, 26 (1997), pp.295-330. See also, C.J. Schmitz (ed.), *Big business in mining and petroleum* (Aldershot 1995) for a wider review of the literature.

[3] One source notes that '... of all metals it (copper) is the one that forms the largest group of minerals, some 360 of which have been given specific names'; W.R. Jones, *Minerals in industry* (Harmondsworth 3rd.ed. 1955), p.68. However, few of these minerals have been of any economic importance.

[4] Copper, together with gold, is almost unique amongst metals in being found in its pure form in nature, although only in limited quantities and locations. The most notable example of native copper deposits is that found in the Lake Superior district of Michigan, in the USA.

and in relation to forming the basic source material for other ores, is chalcopyrite (a sulphide). This has a theoretical maximum copper content of 34.5 per cent by weight although its frequent combination with iron pyrite (FeS_2) may reduce this to less than 12 per cent. Where chalcopyrite veins have been subject to weathering, in particular the downward percolation of rainwater (a weak form of carbonic acid) over a period of time, the copper is dissolved and redeposited near the water-table, as a range of altered and enriched ores, such as chalcocite, malachite and cuprite.

Secondary ores (in particular carbonates) were more easily concentrated and smelted than sulphides, with the available technology, until the early twentieth century,[5] and being bright green or blue in colour were often noticed and mined at an earlier stage than deeper, harder-won sulphides, for instance in Chile during the nineteenth century.[6] Sulphides, on the other hand, have been far more important in the longer term as a source of newly-won copper. In Australia, for example, whilst most copper mined until 1900 was won from rich oxidized ores, by around 1920 it was almost entirely extracted from sulphide ores.[7] An analysis of world copper production in 1909 suggested between 66 and 72 per cent came from sulphides, 15 to 20 per cent from carbonates and oxides, together with 12 per cent from native copper deposits.[8] During the twentieth century the proportion of copper won from sulphide ores has continued to rise on trend and by the 1970s was estimated to account for some 90 per cent of newly-won metal.[9]

Despite considerable complexity in the field of ore genesis theory and classification, economic geologists recognise three main forms of copper orebody: massive sulphide,[10] strata-bound and porphyry

[5] Sulphide ores generally require preliminary roasting to release excess sulphur, prior to smelting. With secondary carbonate ores this process is achieved naturally in the weathering process, at the same time that the copper content is considerably enhanced.
[6] W.H. Weed, *Copper mines of the world* (New York 1907), pp.184-6.
[7] R. Allen, *Copper ores* (London 1923), p.76.
[8] F. Beyschlag and J.H.L. Vogt, *Deposits of the useful minerals* II (London 1916), p.872.
[9] A.K. Biswas and W.G. Davenport, *Extractive metallurgy of copper* (Oxford 1980), p.1.
[10] Massive, not in the sense of large scale, but in the strict geological sense of discrete mineral aggregations, as opposed to diffused, small-scale particles.

deposits.[11] To these, some studies have added two significant sub-groupings: nickel-copper ore complexes (as found at Sudbury, Ontario, Canada)[12] and native copper of the Keweenaw variety (Michigan, USA).[13] Each of these types tends to display certain characteristics, in terms of prevailing copper grade, size and form of the deposit and mineralogical composition (including potential by- and co-products).[14] These characteristics, in turn, have had a marked influence on the methods adopted to exploit the orebodies and, ultimately, upon the forms of industrial organization embraced by copper-producing firms.

Massive sulphide deposits, created by copper-bearing vapours ascending through lines of weakness in the earth's crust, exhibit a wide variety of forms but are usually found in veins or disseminated infillings in sedimentary strata (eg sandstones or shales) and in volcanic rocks. They typically have a high-grade metal content, around four to 25 per cent copper in the period up to 1939, but with a few exceptions are relatively limited in extent, containing from a few thousand to around fifty million tonnes of ore. They also invariably display a well defined cut-off point where they meet the non ore-bearing, or host rock. Due to their accessibility and ease of working, especially where subject to secondary enrichment and oxidization, vein deposits of this type provided one of the major sources of copper

[11] This classification is based on the geological environment in which orebodies are located and is adopted, amongst others, by R.F. Mikesell, *The world copper industry* (Baltimore 1979), pp.47-8, and by COMRATE, *Mineral resources* (1975), pp.132,151. Other classifications used by geologists and based on ore genesis (eg hydrothermal, mesothermal, epithermal and telethermal deposits) are outlined in A.M. Evans, *Introduction to ore geology* (Oxford 1987), pp.95-8.

[12] Some systems of classification define nickel-copper deposits as a sub-set of the massive sulphide type, eg Mikesell, *World copper industry* (1979), p.48, however it is probably more useful to adopt the US Geological Survey definition of the Sudbury type deposits as a distinct grouping; D.P. Cox *et al.*, *The nature and use of copper reserve and resource data* (Washington DC 1981), p.F2.

[13] D.P. Cox *et al.*, 'Copper' in D.A. Brobst and W.P. Pratt (eds.), *United States mineral resources* (Washington DC 1973), pp.169-80.

[14] The distinction between by- and co-products is not precise; in rough terms a by-product (such as gold) is worth considerably less than the copper in an orebody, while co-products are more equally matched in terms of relative value of production.

mined until the early twentieth century. The most common copper mineral contained is chalcopyrite, but they also typically include chalcocite, bornite and a range of carbonate alteration minerals.[15] Common bi-product minerals include lead, zinc and arsenic ores plus varying quantities of gold and silver. The vast majority of the mines in the major producing region of Britain, the counties of Cornwall and Devon, were exploiting vein-form massive sulphide deposits during the nineteenth century,[16] as were most mines in Chile (prior to around 1910),[17] a number of mines in South Australia (for example Wallaroo-Moonta)[18] and Southern Africa (including O'Okiep and Nababeep)[19]. In these areas, the individual veins would typically be from a few centimetres to three or four metres in width, with workable lengths of up to a thousand metres or so and depths of a thousand metres or more from surface. Particularly rich mines might work veins with larger dimensions. Devon Great Consols, the leading producer in south-west England during the middle decades of the nineteenth century, exploited a main lode of mixed copper and arsenic sulphides, over a length of four kilometres, to a depth of 550 metres, with the vein averaging between two and ten metres in width.[20]

Many massive sulphide-type deposits display non vein-like structures, instead being formed in irregular, disseminated masses. Important examples are the Noranda and Flin Flon mines in Canada. Noranda Mines Ltd. opened up a complex of thick masses of gold-copper sulphide ores in its Horne mine, in Quebec province, between 1922 and 1930.[21] The

[15] Cox *et al.*, 'Copper' (1973), p.168.

[16] H.G. Dines, *Metalliferous mining region of south-west England* (London 1956), I pp.10-19.

[17] Beyschlag and Vogt, *Deposits of the useful minerals* II (1916), pp.891-6.

[18] H.Y.L. Brown, *Record of the mines of South Australia* (Adelaide 4th.ed. 1908), pp.139-44; A.B. Edwards (ed.), *Geology of Australian ore deposits* (Melbourne 1953), pp.487-504.

[19] S.H. Haughton, *Geology of some ore deposits in South Africa* (Johannesburg 1964), II pp.281-95.

[20] Dines, *Mining region of south-west England* (1956), II pp.655-61; J.C. Goodridge, 'Devon Great Consols: a study of Victorian mining enterprise' *Transactions of the Devonshire Association*, XCVI (1964), 231-2.

[21] G.A. Young, *Geology and economic minerals of Canada* (Ottawa 3rd.ed. 1947), pp.66-9; *The Canadian mineral industry in 1937* (Ottawa 1938), pp.6-7.

Flin Flon mine (Hudson Bay Mining and Smelting Co.), on the Manitoba-Saskatchewan border, developed a series of steeply dipping, irregular copper-zinc sulphide lenses, between 1927 and 1939.[22] Where large-scale oxidization and secondary enrichment of sulphide deposits takes place, irregular shaped orebodies may result, for example in the Burra Burra mine in South Australia. There, a large concentration of copper carbonates and oxides occured within fifty metres of the surface. Upwards of fifty thousand tonnes of copper was produced in underground mining operations between 1845 and 1869, followed by opencast extraction between 1870 and 1877.[23] Similar secondary enrichment was of great importance in a number of mining districts world-wide, including Chile where mining operations until the early twentieth century were largely confined to relatively accessible, high-grade oxide and carbonate ores.[24]

There are two other types of orebody which are usually assigned to the massive sulphide group, but which present some problems of classification. The immense orebodies at Butte, Montana, one of the two largest historic agglomerations of copper

[22] Canadian Institute of Mining and Metallurgy, *Structural geology of Canadian ore deposits* (Montreal 1948), I pp.295-301.

[23] J.F. Drexel, *Mining in South Australia* (Adelaide 1982), pp.34-48; Edwards, *Geology of Australian ore deposits* (1953), pp.437,476-8. The latter source comments (p.437): 'In fact most of South Australia's copper deposits have contained bodies of oxidized ore much richer and larger than.. the primary orebodies at depth'. The same could be said of the majority of copper mineralization in Queensland, Australia, where Edwards (p.389) comments 'Primary copper ore has been exploited profitably in only three deposits - Mount Isa, Duchess and Trekelano. Elsewhere profitable mining ceased with the termination in depth of the secondarily enriched copper ore...'.

[24] Allen, *Copper ores* (1923), pp.182-3, which notes 'In few cases in Chile have the primary ores been mined, so that they are usually unknown'. This parallels the experience of the naturalist Charles Darwin who, visiting Chile in 1834, commented that 'the Chilean miners were so convinced that copper pyrites [the primary ore] contained not a particle of copper, that they laughed at the Englishmen for their ignorance, who laughed in turn, and bought their richest veins for a few dollars'; *Journal of researches.. during the voyage of H.M.S. Beagle round the world* (London 11th.ed. 1892), p.255. During the XIXth century Chilean ores averaged 10-15 per cent copper, and ranged up to 50 per cent: as a result 'Chilean copper miners throughout this period took little or no interest in the abundant low grade ores'; J. Mayo, *British merchants and Chilean development 1851-1886* (Boulder 1987), pp.147,156.

in the United States,[25] are rather more complex in nature, currently being regarded as something of a cross between a massive sulphide vein type and a disseminated porphyry.[26] However, until 1950, underground mining of vein-type orebodies was the rule at Butte; only after 1955 did opencast extraction of the extensive lower grade, porphyry-type orebodies commence.[27] Other orebodies which present a problem of definition are the large-scale pyritic deposits of Spain, Portugal, Norway, Russia and Tasmania. At mines like Rio Tinto, Tharsis, Kyshtim and Mount Lyell, large masses of mixed iron and copper pyrite,[28] with gold and silver by-products, have generally been classified as a sub-set of the massive sulphide type.[29] However, the opencast working of these deposits, for their sulphur and iron content as well as their non-ferrous metals, has had much more in common with the extraction technology undertaken in the copper porphyries than with traditional lode mining.

Strata-bound deposits are less widely distributed through the world than massive sulphides. As a result of having been deposited in past shallow marine or river delta environments, they tend to form beds of

[25] In 1976 the total copper content of the Butte complex of orebodies (past production plus estimated reserves to a cut-off grade of 0.72 per cent) was put at around 18.3 million tonnes. In 1970 the past production and recoverable reserves (to a cut-off grade of 0.71 per cent) of the Bingham porphyry deposit, in Utah, was estimated as 18.8 million tonnes; Cox *et al.*, *Copper reserve and resource data* (1981), p.55; Comrate, *Mineral resources* (1975), pp.153-4; C. Meyer *et al.*, 'Ore deposits at Butte, Montana' in J.D. Ridge (ed.), *Ore deposits of the United States 1933-1967* (New York 1968), II, pp.1376-92. In a global context the Chuquicamata porphyry in Chile, and possibly also the Rhokana-Nchanga stratiform deposit in Northern Rhodesia-Zambia, have been larger.

[26] Cox *et al.*, 'Copper' (1973), pp.171-2; Meyer *et al.*, 'Ore deposits at Butte' (1968), pp.1376-92. The latter source notes (p.1392) that the general width of Anaconda veins was 6-9 metres, but locally they were up to 30 metres wide, containing rich chalcocite ores in the upper levels.

[27] Evans, *Ore geology* (1987), pp.220-3.

[28] Analysis of the Rio Tinto, Tharsis and Mason and Barry ores just before World War I gave the following average contents: 48 per cent sulphur, 41.7 per cent iron, 2.5 per cent copper, 0.04 per cent silver; Beyschlag & Vogt, *Deposits of the useful minerals* I (1914), pp.321-4.

[29] Mikesell, *World copper industry* (1979), pp.47-8; Allen, *Copper ores* (1923), p.8. For more detailed discussion of the genesis and morphology of one pyritic deposit see S.G. Checkland, *The mines of Tharsis* (London 1967), pp.24-8.

copper-bearing shales or sandstones of varying thickness and richness, alternating with beds of barren sedimentary rocks. Like massive sulphides, they tend to display a fairly well defined cut-off point where they come into contact with non ore-bearing strata. They generally constitute medium to large orebodies, ranging from around a million to 250 million tonnes of ore and commonly averaging three to six per cent copper, in the period up to 1939. Whilst stratiform deposits may vary in width from a few centimetres to several metres, their lateral extent may be vast. The Kupferschiefer (or copper shale) of the north German plain, is the classic geological example of this type of deposit. Formed in the shallow Zechstein Sea of the upper Permian epoch (about 250 million years ago), this consists of a number of thin beds of ore-bearing sediment, extending over an area of about 600,000 square kilometres, from Warsaw in the east to the Netherlands in the west.[30] It has generally proved too low in grade for economic exploitation but was mined in a few locations where the copper content rose above two or three per cent, most notably in the Mansfeld mines, at the eastern end of the Harz mountains in Germany.[31] The Boleo orebody in Mexico, Perm (Bogoslovsk) in Russia,[32] and Kapunda in South Australia are also normally regarded as being of the stratiform variety.[33]

During the twentieth century the most important stratiform deposits to be developed were those located in the central African copperbelt, straddling the border between the Belgian Congo (Democratic Republic of Congo) and Northern Rhodesia (Zambia). Between 1892 and 1906 geological surveys in the Katanga province of the Belgian Congo indicated the presence of massive beds of copper-bearing sediments up to 60 metres in width, containing seven to thirty per cent copper and

[30] Evans, *Ore geology* (1987), pp.195-8.

[31] The Mansfeld mine commenced operations around the year 1199 and by 1880 was the third largest producer in the world, with an output of 10,000 tonnes of smelted copper; W.P. Jervis, 'The Mansfeld copper-slate mines.. their past and present state..' *Journal of the Society of Arts*, IX (1861), 592-632; *Mineral resources of the United States 1885* (Washington DC 1886), pp.228-9.

[32] Allen, *Copper ores* (1923), p.9.

[33] Classification of the Kapunda orebody is made difficult because it was worked as a series of vein-like structures within the confines of a bed of mixed sandstones and shales; Edwards, *Geology of Australian ore deposits* (1953), pp.478-83.

extending over an area of about 20,000 square kilometres.[34] From 1906 these were worked in a combination of underground and open-cast mining techniques by the Anglo-Belgian financed Union Minière company.[35] The adjacent deposits of Northern Rhodesia were delineated by geological survey work undertaken between 1902 and the late 1920s. This revealed copper-bearing strata of lower grade than Katanga, at about three to six per cent,[36] although the Rhodesian deposits eventually proved larger in extent.[37] The most common copper minerals in stratiform deposits are the sulphides covellite (particularly in the African copperbelt), chalcocite and chalcopyrite, together with varying quantities of disseminated native copper.[38] Typical by-products include lead and zinc (as at Mansfeld), silver, nickel, bismuth and cobalt,[39] the latter being particularly significant in the African copperbelt.[40]

The third major group, porphyry deposits, tend to be lower-grade than either massive sulphide or stratabound deposits, typically running

[34] Union Minière, *Evolution des techniques et des activités sociales* (Brussels 1957), pp.15-22,75-88; *Union Minière du Haut Katanga 1906-1956* (Brussels 1957), pp.36-61.

[35] *Union Minière 1906-1956* (1957) pp.67-76; S. Katzenellenbogen, *Railways and the copper mines of Katanga* (Oxford 1973), pp.21-73.

[36] J.A. Bancroft, *Mining in Northern Rhodesia* (London 1961), pp.54-78; F.L. Coleman, *The Northern Rhodesia copperbelt 1899-1962* (Manchester 1971), pp.6-77; M. Joll, 'The geology and origin of the copper deposit at Roan Antelope, Northern Rhodesia' *Camborne School of Mines Journal*, LXIV (1964), 40.

[37] At 30 June 1936, estimated reserves in Northern Rhodesia (Rhokana-Nchanga, Roan Antelope and Mufulira mines) amounted to some 19.0 million tonnes of contained copper, whilst at Union Minière the figure on 31 Dec. 1935 was 4.6 million tonnes; *Mines Register 1937*, (New York) pp.1093-4,1097,1104.

[38] Cox *et al.*, 'Copper' (1973), p.168.

[39] D.A. Singer *et al.*, *Grade and tonnage relationships among copper deposits* (Washington DC 1975), p.A2.

[40] In the period 1934-8, the Belgian Congo was the world's largest producer of cobalt ores (about 34 per cent of the total) whilst Northern Rhodesia was the second producer (about 28 per cent); Jones, *Minerals in industry*, pp.63-6. Such has been the value of cobalt production in the African copperbelt, in relation to the value of copper output, that it merits the label co-product rather than by-product. It also means that copper output in this region has been rather less responsive to changes in world copper prices than that from countries more purely dependent on copper. Despite the catastrophic international copper price collapse between 1929 and 1930, Union Minière increased its sales in absolute terms and as a percentage of world output (from 6.7 to 9.1); C.J. Schmitz, *World non-ferrous metal production and prices 1700-1976* (London 1979), p.76.

at about 0.45 to 2.5 per cent copper and in relative terms are often very large - from 100 to 2,000 million tonnes of ore in the 1920s and 1930s. Broadly speaking, these huge low-grade, disseminated orebodies are believed by geologists to have formed deep in the earth's crust, beneath areas of volcanic activity, near destructive continental plate margins.[41] This explains their concentration around the Pacific coastlines of Canada, the United States, Peru and Chile, an arc of particularly intense volcanic and earthquake activity.[42] Copper minerals in porphyries are usually confined to sulphides, mainly chalcopyrite, enargite and chalcocite (the latter formed by secondary enrichment). Typical by- and co-product minerals include molybdenum, gold and silver.[43] Significantly, these deposits are not usually distinguished by a sharp cut-off between payable ore and barren rock, but instead large tracts of ground in which there is a gradation from relatively high-grade

[41] This theory of porphyry genesis is surveyed in: F. Aprahamian (ed.), *Porphyry copper case study* (Milton Keynes 1976), pp.56-69 and Evans, *Ore geology* (1987), pp.171-94. This theory assumes the earth's crust is divided into a number of continental 'plates' which are moving in relation to one another. At points where they meet, one may be forced under another, causing profound heating and pressure effects at depths of up to 300 km. beneath the surface, in turn promoting earthquakes, volcanic activity and the release of upward-moving pockets of mineralization (including copper, molybdenum and other minerals). One such subduction zone (or destructive continental plate margin) is that running down virtually the entire Pacific margin of North and South America - hence its position as one the major metallogenic provinces in the world. Porphyry deposits tend, on the whole, to have been formed more recently in earth history than other types of orebody. Although there is some variation, most porphyries appear to have been emplaced about 30 to 130 million years ago, whilst most stratabound deposits date from 500 to 1,800 million years ago and the majority of massive sulphides from 1,800 to 3,200 million years ago; COMRATE, *Mineral resources* (1975), p.151.

[42] Since the 1970s, porphyries have also been developed in a similar geological environment in Papua New Guinea, Indonesia and the Philippines (on the western Pacific plate margin).

[43] Cox *et al.*, 'Copper' (1973), pp.168,170. Molybdenum is a steel-hardening metal used increasingly from about 1917 onwards; Jones, *Minerals in industry* (1955), pp.133-5. Between 1905 and 1953, sales revenue from by-products at the Bingham Canyon mine, Utah, was as follows: gold $197.8 million, molybdenum (only recovered from 1937 onwards) $130.0 million and silver $40.6 million (compared with total copper revenue of $1,980.1 million). By the early 1950s Bingham was regarded as the seventh or eighth largest gold mine in the world and the second largest molybdenum producer (after the Climax mine, in Colorado); A.B. Parsons, *The porphyry coppers in 1956* (New York 1957), pp.29,43.

mineralization to material well below the economic definition of payable ore. During the 1930s this represented a cut-off point of about 0.75 per cent copper.[44] The gradation from economic to sub-economic ore displayed by porphyries is of great importance both in respect of theories concerning the relationship between ore grade and size of orebodies and in the technology required to exploit these deposits.

Of all the major types of orebody, the porphyries made the most significant contribution to the rise of large-scale mining technology in the period under review. Unlike massive sulphide or stratiform deposits, they were effectively unknown as sources of payable copper ores before about 1899. They thus necessitated the rapid acceptance, amongst geologists, mining engineers and company executives, of novel conceptual frameworks regarding their form, as well as the required methods and financial implications of exploitation.

The first copper porphyries to be identified and developed were located in the south-western United States, in Utah and Arizona. Exploration work undertaken between 1899 and 1904 in the Bingham Canyon district of Utah, an area of previous small-scale gold, silver and copper mining, indicated the presence of extensive low-grade ore deposits. In a careful study of the costs of open-cast extraction, milling, smelting and refining, a number of prominent mining engineers including Daniel Jackling, John Hays Hammond, Alfred Chester Beatty and Henry Krumb, confirmed the view that these deposits could be worked at a profit by utilizing large-scale extraction methods. Following these reports, the Utah Copper Co. commenced operations in August 1904, becoming the first large-scale copper porphyry producer.[45] Within three years, limited extraction of a porphyry-type orebody was also being undertaken at Morenci in Arizona, by the

[44] Simple consideration of the grade-tonnage equation, at any given price, is not sufficient to determine the economic viability of an orebody. This will also depend on a complex interplay of such factors as the mineralogical composition of the ore (and hence its ease of concentration and smelting), the location and disposition of the orebody (and therefore its method and cost of working, and cost of access to market), and the possible presence of by- or co-products such as molybdenum, cobalt or gold, which may enhance the viability of the project.

[45] A.B. Parsons, *The porphyry coppers* (New York 1933), pp.4-7,48-77.

Scottish-financed Arizona Copper Co. Ltd.[46] Between 1904 and 1918 ten copper porphyry mines came into operation in the United States and

TABLE 2. Porphyry copper mines, 1904-1939
Output and control

Mine:	Location:	Controlling corporation:	Year started:	Output to 1939:
Bingham	Utah	Kennecott	1904	2,326.1
Morenci	Arizona	Phelps Dodge	1907	598.2
Nevada Consolidated	Nevada	Kennecott	1908	900.0
Braden (El Teniente)	Chile	Kennecott	1910	1,770.8
Miami	Arizona	Miami C.Co.	1911	617.6
Ray	Arizona	Kennecott	1911	559.2
Chino	New Mexico	Kennecott	1912	626.0
Inspiration	Arizona	Anaconda	1915	720.8
Chuquicamata	Chile	Anaconda	1915	2,076.9
New Cornelia	Arizona	Phelps Dodge	1917	564.1
Copper Queen	Arizona	Phelps Dodge	1923	198.0
Andes (Potrerillos)	Chile	Anaconda	1927	495.1
Consolidated Coppermines	Nevada	Cons. Copper	1932	52.3
Bagdad	Arizona	Bagdad C.Corp	1937	0.7

Total production (recovered copper) to the end of 1939 in thousands of tonnes. Source: A.B. Parsons, *The porphyry coppers in 1956* (New York 1957), pp.5,10-11. The year started refers to first working by large-scale porphyry methods: in many cases these mines were exploiting relatively high-grade ores by selective methods prior to these dates, as in the case of the Arizona Copper Co. at Morenci. Details of controlling interests refer principally to the period c.1937-39. Morenci was controlled by the Arizona Copper Co. Ltd. to 1921; Inspiration was owned by the Inspiration Consolidated Copper Co. but this was effectively controlled by the Anaconda Co. from 1911; Chuquicamata was controlled by the Guggenheim Exploration Co. to 1923; Consolidated Coppermines Corp. was subject to a minority (non-controlling) shareholding by the American Metal Company in the later 1930s; *Mines Register* 1937, (New York) pp.59,246,728.

[46] W. Turrentine Jackson, *The enterprising Scot: investors in the American west after 1873* (Edinburgh 1968), pp.179-83; Parsons, *Porphyry coppers* (1933), pp.97-113. In his book, *The story of the birth of the porphyry coppers* (London 1933) pp.1-31, James Colquhoun argues that the earliest working of copper porphyries occurred around 1901-04, in the Humboldt and Longfellow orebodies of the Arizona Copper Co., of which he was general manager. However, Parsons, *Porphyry coppers in 1956* (1957), pp.49-50, argues that while the Arizona Co. was successfully mining and milling typical porphyry ores before Utah commenced operations in 1904, the Scottish company was still concentrating on the selective underground mining of richer ores in its Morenci mines, on average around 3 per cent or more in grade. The nearby low-grade Clay orebody lay effectively unexploited until developed as a true open-pit porphyry working by Phelps Dodge in 1937, the latter firm having purchased the Scottish company's assets in 1921; Parsons (1957), pp.56-66; R.G. Cleland, *History of Phelps Dodge 1834-1950* (New York 1952), pp.244-60.

Chile: by 1939 the figure had risen to fourteen, although two of these were relatively unimportant as producers prior to World War II (table 2).[47] After 1905 the porphyry mines, as a group, made an increasingly important contribution to global mine output of copper (table 3), with

Table 3. Porphyry copper mines, 1905-1939
Number in operation and mean annual total output as a percentage of world mine production

	Number:	Percentage:
1905-6	1	0.3
1907	2	3.3
1908-9	3	7.3
1910	4	10.8
1911	6	13.4
1912-14	7	17.3
1915-16	9	22.7
1917-22	10	26.4
1923-6	11	36.3
1927-31	12	35.0
1932	11	20.1
1933	6	21.2
1934-6	7	26.6
1937	13	34.7
1938-9	12	30.1

The above figures exclude a number of porphyry copper mines which suspended operations during the period 1932-9: 1932 (1), 1933 (6), 1934-6 (5), 1937 (1), 1938-9 (2). Source: 1905-31, A.B. Parsons, *The porphyry coppers* (New York 1933), p.6; 1932-9, A.B. Parsons, *The porphyry coppers in 1956* (New York 1957), pp.10-11.

[47] In addition to these 14 mines, a few porphyry-type deposits in Mexico and Canada were exploited prior to 1939 but not on the same scale or technological basis as those listed by Parsons. In Mexico, the Cananea and Moctezuma mines (in the state of Sonora) were exploiting the richer portions of porphyry deposits by underground methods from about 1900 onwards: open-pit working of the lower grade ores did not commence until after 1939; Allen, *Copper ores* (1923), pp.9.153-4; Beyschlag & Vogt, *Deposits of the useful minerals* II (1916), pp.890-1; I.F. Marcosson, *Anaconda* (New York 1957), pp.251-65. The Canadian porphyries were primarily located in the Boundary District of British Columbia but also tended to be mined along traditional lines until after 1939; Weed, *Copper mines of the world* (1907), pp.217-20; Canada, Department of Mines, *Report on the mining and metallurgical industries of Canada 1907-8* (Ottawa 1908), pp.136-157; H. Ries, *Economic Geology* (New York 4th.ed. 1916), pp.590-2.

their share of world production reaching a pre-1939 peak of 39.5 per cent in 1928.

Nickel-copper deposits are restricted geographically, having only been commercially exploited prior to 1939 in parts of Canada and Norway.[48] By far the most productive group of deposits in this class is that situated at Sudbury, Ontario.[49] First located by workmen cutting a route for the Canadian Pacific Railway in 1883, this extensive zone of copper-nickel-iron orebodies extends over an area of 60 km by 25 km and to a proven depth of over 3 km.[50] A number of important mines were opened in the area after 1886: the Copper Cliff, Frood and Creighton (owned by the Canadian Copper Co., reconstructed as the International Nickel Co. in 1902); the Murray (owned between 1889 and 1912 by the Swansea copper-smelting firm of H.H. Vivian & Co.), and the Victoria mine (operated from 1901 by the British-financed Mond Nickel Co. Ltd., which merged with International Nickel in 1929).[51] Most were worked as underground mines, although open-pit working occurred on the two largest orebodies, the Frood and Creighton. These were particularly large deposits, producing sixty million and thirty million tonnes of nickel-copper ores respectively, up to the end of World War II.[52] Virtually all the Sudbury copper ore was chalcopyrite and was closely intermixed with the nickel ores,

[48] The most productive of the numerous Norwegian copper-nickel deposits was the Flaad mine, 230 km SW of Oslo, which between 1872 and 1908 produced 75 thousand tonnes of ore averaging 1.07 per cent copper and 1.8 per cent nickel; Beyshchlag & Vogt, *Deposits of the useful minerals* I (1914), p.297.

[49] The Sudbury district was responsible for around 80 per cent of global nickel production, as well as 2.45 million tonnes of copper, in the period up to 1945; Canadian Institute of Mining and Metallurgy Symposium, *Structural geology of Canadian ore deposits* (1948), I p.596; Young, *Geology and economic minerals of Canada*, p.65.

[50] Some controversy surrounds the geological origins of the Sudbury deposit but one influential school favours the view that it resulted from a huge meteoric impact; Evans, *Ore geology* (1987), pp.150-5.

[51] A.P. Coleman, *The nickel industry, with special reference to the Sudbury region, Ontario* (Ottawa 1913), pp.13-17; O.W. Main, 'International Nickel: the first fifty years' in D.S. Macmillan (ed), *Canadian business history* (Toronto 1972), pp.255-61.

[52] Containing approximately 1.2 and 0.6 million tonnes of copper, respectively; Canadian Institute of Mining and Metallurgy, *Canadian ore deposits* (1948), I pp.608-11; Canada, Department of Mines, *Mining and metallurgical industries* (1908), pp.385-6.

inhibiting separate production of the two metals. In the early years of working, the ores tended to contain more copper than nickel.[53] Between about 1900 and 1930, however, the mean copper grade fell to around two per cent whilst the mean nickel grade was about 3.5 per cent: by the early 1940s both fell to lower and more even levels, at about 1.0-1.25 per cent.[54] Taking into consideration the higher prevailing prices for nickel throughout the period under review, copper was generally regarded as a bi-product by International Nickel and the other major producers.[55]

The final type of deposit, native (or pure metallic) copper, is fairly widespread throughout the world in small quantities but has only been exploited commercially in a few locations, for example in Cornwall[56], the Corocoro mines of Bolivia[57] and, most notably, in the Lake Superior district of Michigan. The earliest workings in the Keweenaw Peninsula of northern Michigan, between 1844 and 1856,[58] concentrated on extracting shallow masses of pure copper, several of which were up to 500 tonnes in weight.[59] From the later 1850s,

[53] In the period 1893-98 the mean copper grade of Sudbury ores was 2.85 per cent while the nickel grade averaged 2.47 per cent; *Mineral industry 1898* (1899), p.524.

[54] Young, *Geology and economic minerals* (1947), p.64.

[55] Between 1920 and 1939 the mean New York prices for electrolytic copper and nickel were 11.9 and 35.7 cents/lb. ($262, $787 a tonne) respectively; Metallgesellschaft, *Comparative statistics* (Frankfurt-am-Main 1953) pp.210-11; S.H. Schurr and E.K. Vogely, *Historical statistics of minerals in the United States* (Washington DC 1960), p.19. As a result of the price differential, copper formed a relatively marginal part of Sudbury producers' incomes and therefore their copper output was rather insensitive to price changes in the market, at the same time as their copper output levels were effectively tied to their level of nickel output.

[56] Between 1741 and 1852 the Wheal Unity mine at Mullion, on the Lizard Peninsula of Cornwall, yielded a considerable quantity of native copper. One slab of pure copper raised in 1848, weighing 711 kg, was presented to the Geological Museum in London, where it is still on display; A.K. Hamilton Jenkin, *Mines and miners of Cornwall*, XIII (Truro 1967), pp.7-13.

[57] Allen, *Copper ores* (1923), p.9; Beyschlag and Vogt, *Deposits of the useful minerals* II (1916), pp.938-9.

[58] A substantial period of shallow mining by native Americans, prior to European settlement, should be noted; see T.A. Rickard, *A history of American Mining* (New York 1932), pp.1-2,222-8.

[59] B.S. Butler and W.S. Burbank, *The copper deposits of Michigan* (Washington DC 1929), p.63.

however, larger deposits of disseminated native copper (or amygdaloid lodes), with overall grades of only 0.75 to four per cent, were being worked in deeper mines like the Pewabic and Quincy.[60] In 1864 the largest Michigan deposit was located, the Calumet and Hecla conglomerate, in which the pure metal occurred between quartz pebbles in a massive 'puddingstone' stratum four to eight metres thick, at depths of up to 1.7 km from surface.[61] In general terms, the larger Michigan deposits tended to contain higher grades of copper: the Calumet and Hecla conglomerate, which produced some two million tonnes of copper up to 1946, averaged around 2.5 per cent, while the much smaller Atlantic amygdaloid lode, for example, produced just under 65 thousand tonnes of copper, from ores with a mean grade of 0.68 per cent.[62] On the eve of the copper porphyry era, around 1905-07, the Lake Superior mines were working some of the lowest grade ores in the United States, from the deepest mine shafts in the world.[63]

The metallurgical purity of the Lake Superior ores had three major consequences for the companies mining them. First, the technology of milling and smelting the copper was much more straightforward than

[60] The amygdaloid lodes mainly consisted of pre-Cambrian (c.580-590 million year old) lava flows in which the vesicles (or gas bubbles) had been wholly or partly filled with native copper and smaller quantities of native silver and other minerals: Weed, *Copper mines of the world* (1907), p.311; E.P. Rathbone, 'On copper mining in the Lake Superior district' *Proc. Institute of Mechanical Engineers*, LXXIX (1887), 86-8.

[61] Weed, *Copper mines of the world* (1907), pp.313-4; W.B. Gates, *Michigan copper and Boston Dollars* (Cambridge MA 1951), pp.12-13.

[62] Butler and Burbank, *Copper deposits of Michigan* (1929), pp.98,146-7; Gates, *Michigan copper* (1951), p.232.

[63] In 1907, for example, the mean copper content of Michigan ores was 1.11 per cent, compared with 3.01 per cent in Montana and 4.02 per cent in Arizona; *Mineral resources of the United States 1907* (1908), pp.584,588. By 1912 the figures were: Michigan 0.96 per cent, Montana 2.51 per cent and Arizona 1.53 per cent; *Mineral resources of the United States 1912* (1913), p.292. The Red Jacket shaft at the Calumet and Hecla mine was sunk to a vertical depth of 1500 metres by 1902: in 1910, the deepest workings in the Calumet & Hecla, Tamarack and Quincy mines were 1601, 1635 and 1222 metres respectively. In contrast, the deepest workings at the Anaconda mine in Montana reached only 884 metres and the deepest gold mines on the Rand in South Africa 1200 metres by 1910-11: in 1906 a shaft on the Bendigo goldfield in Australia had reached almost 1400 metres; *Mineral industry 1902* (1903), p.168; Beyschlag and Vogt, *Deposits of the useful minerals* II (1916), pp.613,886,933,1155.

in other mining areas of the world.[64] Secondly, smelted Lake copper, which normally required no further refining, was of such a high grade of purity that it commanded a price premium over other grades, including electrolytic copper, until about 1913, and was quoted as the standard price in United States markets until 1900.[65] Thirdly, there were no significant bi-products in the Michigan lodes, apart from a little native silver. As a consequence, unlike Montana or Arizona producers, Michigan mining companies could not rely on income from gold or silver in their ores and thus they tended to find themselves having to respond much more closely to short-term fluctuations in copper prices.[66]

During the twentieth century the strata-bound and porphyry deposits have been of profound importance both in terms of increments to the world's reserves of copper ores and the increasing scale of operations in the copper industry. Between 1870 and 1939 other classes of deposit, like the pyritic orebodies of Spain and the nickel-copper

[64] Rathbone, 'Copper mining in the Lake Superior district' (1887), *op. cit.* 100-106,121-3; *Mineral resources of the United States 1907* (1908), pp.623-9. The purity of their ores and the fairly simple methods required to process them into metal helped the Michigan mines compete in the copper market, despite increasing costs from deeper working and the move to lower grade ores. However, the adoption in the western states of the Bessemer process at the matte production stage, helped reduce this advantage from the mid-1880s. Gates also suggests that the Lake Superior mines benefited from lower labour costs than the producers in Montana and Arizona; *Michigan copper* (1951), pp.92-115.

[65] Quotations for electrolytic copper were not established on the New York market until 1899, in which year Lake copper commanded a premium of 6.7 per cent over the former, which was regarded with some continuing suspicion by consumers. Between 1900 and 1913, Lake copper's premium over electrolytic on the New York market varied between 0.7 per cent and 3.3 per cent (with a mean of 2.04 per cent); Metallgesellschaft, *Comparative statistics* (1914), p.95. By about 1906-07 electrolytic copper had effectively superseded Lake copper as the standard market quotation and the latter was not generally quoted after 1914. On the growing consumer acceptance of electrolytic copper and its market relationship with Lake copper, see Gates, *Michigan copper* (1951), pp.91-2.

[66] Some Michigan mines sold small quantities of silver: 1878-84 the Osceola's income from the precious metal equalled 0.53 per cent of its revenue from copper while the proportion at the Quincy mine, 1894-8, was 0.85 per cent; Butler and Burbank, *Copper deposits of Michigan* (1929), pp.92,94. On a broader front, in 1912, total Michigan revenue from precious metals in cupreous ores represented 0.82 per cent of copper sales: in Arizona the figure was 4.05 per cent, Montana 13.2 per cent and Utah 16.2 per cent; *Mineral resources of the United States 1912* (1913), p.292.

orebodies of Canada, made major contributions to rising world output and the increasing scale of operations in the industry. However, in the longer run, the massive size of the former two types ensured that they dominated any calculations of world copper reserves.[67] The technological innovations and increased scale of finance required to exploit the porphyries of Utah, Arizona and Chile, as well as the central African stratiform deposits, with firms increasingly utilizing highly capital-intensive and vertically-integrated plant, also necessitated new forms of corporate organization within the industry.[68]

Shifts in the major types of orebody being exploited have been paralleled by a general decline in mean ore grades. The economic exploitation of copper minerals over at least the past two centuries has followed a broad pattern of mining progressively leaner ores from increasingly large individual deposits. This has arisen through a combination of shallow, relatively easily won vein-deposits, such as those in Cornwall, effectively becoming exhausted by the later nineteenth century and the contemporaneous development of cost-cutting technology in mining, concentrating, and smelting processes. Data are presented in table 4 for two leading copper producing regions from the late eighteenth to mid-twentieth centuries, Cornwall and Devon, and the United States, and for a number of leading mines in those regions and elsewhere. Although there are periodic deviations from the downward trend in ore grades, for example the United States during the early 1930s, on the whole the downward trend appears clear.

In general terms it is apparent that there is a reasonably significant negative correlation between ore grade and size of deposit. Data relating to 127 leading copper mines/prospects operating between the 1770s and 1939 have been assembled and the average grade plotted against total copper content, defined as total production plus, in the case of mines/prospects in operation after 1939, projected reserves (see

[67] A 1972 estimate of global copper reserves suggested 52.4 per cent of the total was contained in porphyries, 26.9 per cent in stratiform deposits and only 9.9 per cent in massive sulphides (the residue was allocated to miscellaneous types); COMRATE, *Mineral resources* (1975), p.151.

[68] See my paper 'Rise of big business' (1986).

appendix).[69] This indicates that certain broad groupings of mines/orebodies were exploited in the period up to World War II.[70] First, the Cornwall and Devon group consisted of relatively small but high grade mines, working principally between about 1770 and 1870, within the overall limits of about 4.5 to 12 per cent copper, in orebodies containing up to 75 thousand tonnes of copper. The next group is a high-grade Australian-Southern African group, worked mainly between the 1840s and World War I, at about 11 to 27 per cent copper and containing 10 to 120 thousand tonnes of copper.[71] A scattering of plots trending towards lower grades and higher volume deposits then represents mines working into the early twentieth century. Two major groupings dominate the higher tonnage range of the plot: the stratiform

[69] Regression analysis of the data (where G = average percentage grade and T = copper tonnage in orebody; standard error terms in brackets) yielded the following results:

$$\log.T = 3.128 - 2.094 \log.G \qquad r^2 = 0.479$$
$$(0.150) \quad (0.195)$$

A non-log form yielded notably weaker results with $r^2 = 0.066$. Excluding six relatively low grade/low tonnage Michigan orebodies (Ahmeek-Mohawk, Quincy-Pewabic, Champion-Baltic, Osceola, Isle Royale and Atlantic) improved the coefficient of determination in the log linear form to $r^2 = 0.523$.
From this data set, reproduced in an appendix, it is also possible to tabulate the total share of past output/reserves for mines (or mine groups) working different ranges of ore grades in the period c.1770-1939:

Grade (%):	**No of mines:**	**Total tonnage:**	**Mean tonnage:**
- 2.99	35	77 160 000	2 205 000
3 – 5.99	24	29 368 000	1 224 000
6 +	67	1 046 000	15 600

The 12 porphyries (0.95-2.18% grade) accounted for 56.6 million tonnes (or a mean 4.7 million), while the four copperbelt deposits (3.3-5.8%) amounted to 25.1 million tonnes (mean 6.3 million); together these two groups represented just over 76% of the total tonnage for all deposits. Amongst other things, the shift to leaner grades necessitated higher inputs of energy to extract each tonne of metal.
[70] For a graphic representation of the broad features of the historical relationship between grade and tonnage in the major mining districts, see my 'Rise of big business in the world copper industry', p.401.
[71] Mount Oxide, Peak Downs, Mount Perry, Duchess and Trekelano in Queensland, Kapunda and Burra in South Australia, Whim Well in Western Australia, O'Okiep in Cape Colony (South Africa) and Otavi in German South-West Africa (Namibia).

African copperbelt deposits, being opened up between 1907 and 1930, with grades of from 3.3 to 7.5 per cent and reserves of around 2.3 to 14 million tonnes of copper, and the important porphyry group, represented by 12 mines in 1931 (nine in the United States and three in Chile). These ranged in grade from 0.95 per cent (Miami, Arizona) to 2.18 per cent (El Teniente, Chile) and in terms of deposit size at 1931, from 450 thousand tonnes (Copper Queen, Arizona) to 22.5 million tonnes (Chuquicamata, Chile). Completing the pattern are two other

Table 4. Copper ore grades, 1797-1957

Major producing areas and mines, mean percentage grades

	CORNWALL & DEVON [average,	UNITED STATES all mines]	Devon Consols [UK]	Calumet & Hecla [US]	Utah Copper [US]	Great Cobar [AU]	Rio Tinto [SP]
1797-99	10.5						
1800-09	9.1						
1810-19	8.6						
1820-29	8.1						
1830-39	8.1						
1840-49	7.6		9.9				
1850-59	6.9		6.8				
1860-69	6.5		6.2				
1870-79	6.8		5.3	4.5		13.7	2.4
1880-89	5.9		4.6	4.2		10.6	3.0
1890-99				3.3		3.7	2.8
1900-09		2.2		2.2	1.85	2.6	2.4
1910-19		1.7		1.15	1.39		2.0
1920-29		1.55		1.87	1.01		1.44
1930-39		1.61			0.97		1.69
1940-49		1.01			0.97		
1950-57		0.84			0.89		

In general, data appear to refer to mean grades of ore before milling. Mine locations: UK United Kingdom, US United States, AU Australia, SP Spain. Incomplete periodic averages are: Cornwall and Devon 1880-3, United States 1906-9, Devon Great Consols 1848-9,1880-3, Calumet & Hecla 1874-9,1920-5, Utah 1905-9,1950-5, Great Cobar 1876-9,1895-9,1900-7, Rio Tinto 1876-9. Data sources: Cornwall & Devon: R. Hunt, *British mining* (London 1887) p.892; United States: *Mineral resources of the United States* (Washington DC 1918) pt.1 p.897, (1922) pt.1 p.267, (1930) pt.1 p.714, *Minerals yearbook* (Washington DC 1936) pt.1 p.118, (1940) pt.1 p.85, (1942) pt.1 p.129, (1947) pt.1 p.410, (1957) pt.1 p.418; Devon Great Consols: R. Burt et.al., *Devon and Somerset mines* (Exeter 1984) pp.39-40; Calumet & Hecla 1874-1925: B.S. Butler et.al., *Copper deposits of Michigan* (Washington DC 1929) pp.80,92,94-5; Utah: A.B. Parsons, *The porphyry coppers in 1956* (New York 1957), p.42 (estimated from graph); Great Cobar: J.E. Carne, *The copper mining industry in New South Wales* (Sydney 1908) p.243; Rio Tinto: C.E. Harvey, *The Rio Tinto Company: an economic history* (Penzance 1981) pp.332-3.

clusters. There is a pyritic sub-group, represented by large, low-grade deposits in Iberia, Norway and at Mount Lyell in Tasmania, which which contained on average less than three per cent copper (in orebodies containing between 190 thousand and 2.8 million tonnes of copper).[72] Finally, there is a rather anomalous sub-grouping of relatively low-grade and low-tonnage producers in the Lake Superior district of the United States, ranging between 0.68 and 1.22 per cent copper content and from 65 to 396 thousand tonnes in size.[73]

Although there are localised exceptions to this model, such as the copper district of northern Michigan, where the larger deposits tended to exhibit higher grades,[74] in general, as mining companies have moved towards exploiting lower grade ores (as they have increasingly been forced to do), then they have encountered disproportionately larger scale orebodies. This is particularly true of the porphyry coppers where a geological proposition known as Lasky's Law suggests that where there is a gradation from relatively rich to relatively low-grade material in a deposit, the tonnage of ore increases geometrically as grade decreases arithmetically.[75] This is illustrated by the example of Bingham mine in Utah, which during the period 1899 to 1970, moved towards a lower grade and exponentially higher tonnage. Amongst non-porphyries, where there is a sharper cut-off from ore to barren rock, the relationship appears to be less clear although in general it would

[72] Rio Tinto and Tharsis in Spain, San Domingo (Mason & Barry) in Portugal, Lokken and Sulitjelma in Norway, and Mount Lyell in Tasmania.

[73] Champion-Baltic, Quincy-Pewabic, Ahmeek-Mohawk, Osceola, Isle Royale and Atlantic mines.

[74] W.S. White, 'The native-copper deposits of northern Michigan', in J.D. Ridge (ed.), *Ore deposits in the United States, 1933-1967* (1968), I, pp.306-7.

[75] S.G. Lasky, 'How tonnage and grade relations help predict ore reserves' *Engineering & Mining Journal* (April 1950), pp.81-5. There is some evidence that the relationship is not a pure log. linear one, as suggested by Lasky, but more a 'bell-shaped' curve, with a peak at about 0.7 per cent, below which grade, decreasing increments to tonnage occur; see Aprahamian, *Porphyry copper case study*, p.75 and J. Blunden, *Mineral resources and their management* (London 1985), pp.271-2. Lasky's general proposition would seem to be a reasonable one, if only because the concentration factor required to raise the mean crustal abundance of copper (around 0.0058 per cent) to that of a low-grade orebody (0.7- 2.0 per cent Cu) is likely to occur over larger areas than that required for higher grades.

appear to hold true, for example with the Anaconda mine at Butte from 1907 to 1964. A major consequence of this trend towards larger, lower-grade ore deposits, was that the world-wide industry was propelled towards a regime of increasingly large-scale business activity, as a response to a mix of resultant technological, financial and marketing pressures.[76]

The global geographical distribution of economic copper deposits also exercised a powerful influence on the development of corporate structures within the industry. Copper is a relatively widespread element in the earth's crust[77] but is only present in sufficient concentration for economic exploitation in a limited number of locations. Recent geological research suggests that around 98 per cent of the global economic resource[78] is concentrated in eleven discrete regions of relatively high-level mineralization. Two of these regions, or metallogenic provinces,[79] were only effectively exploited after 1939.[80] The remaining nine, containing 92.7 percent of global resources, include: [1] the Andean province, running down the western margin of South America through Peru and Chile (28.8 per cent of estimated global resources); [2] the North American Cordilleran province, running down the western margin of Canada and the United States (22.7 per cent); [3] South central Africa, including the Congo-Rhodesia copperbelt (19.3 per cent); [4] Northern Europe, including Germany, Poland, Britain, Norway, Sweden and Finland (8.5 per cent); [5] the North American Great Lakes province, including the Lake Superior

[76] See my 'Rise of big business in the world copper industry'.

[77] The mean crustal abundance of copper is estimated to be in the region of 0.0058 per cent, which suggests that the top 4.5 kilometres of the earth, excluding that under the sea, contains about 140,000 billion tonnes of the metal. However, various constraints, including a minimum exploitable grade of around 0.5 per cent, problems with mining at extreme depth and under certain terrains, such as urban areas, reduce this figure considerably. By the early 1970s, the size of the world's economically exploitable copper deposits (past production and projected reserves) was estimated to be in the region of 390-396 million tonnes; COMRATE, *Mineral resources* (1975), pp.128-131.

[78] Defined as past production plus reserves exploitable within the limits of prevailing technology and price levels during 1970; COMRATE, *Mineral resources* (1975), p.156.

[79] On the concept of metallogenic provinces, see Evans, *Ore geology* (1987), p.86.

[80] The Ural-Kazakstan (USSR) and Phillipines provinces.

mines of the USA and the nickel-copper producers of Ontario, Canada (8.2 per cent); [6] the East Mediterranean province, mainly located in Cyprus (2.2 per cent); [7] Huelva, Spain, including the Rio Tinto and Tharsis mines (1.8 per cent); [8] Japan (1.9 per cent) and [9] the Eastern Australian province, including Tasmania (1.2 per cent). A marked feature of mining developments both within these longer-established metallogenic provinces, and within the newer-developed ones, is that they have increasingly taken place within remote and harsh environments, such as desert or arctic tundra, which has increased both labour and infrastructural costs. This, in turn, has strongly reinforced the trend towards business concentration within the industry.

Between the mid-nineteenth and mid-twentieth centuries, as the frontier of mineral exploration and mining development spread through the Americas, Asia and Africa, there grew an increasing remoteness between major ore deposits and the principal centres of processing and consumption in western Europe and the north-eastern United States. The approximate distances from the mines of Cornwall and Devon, to London or Birmingham, or from the Mansfeld mines in Germany, to Hamburg, was around 300 to 400 kilometres, while from the Michigan mines to New York was about 1,400 kilometres. Against this, the journey from the south-western United States mines, in Arizona or Utah, to New York was around 3,500 kilometres, and from Chile or the African copperbelt to either London or New York, the distances were in the range 11,000 to 15,000 kilometres. Despite cost-cutting innovations in transportation, there remained an increasing burden of costs associated with shipping ores or semi-processed metal, quite apart from the higher costs mentioned above, and this also helped encourage an increasing degree of vertical integration within copper firms.[81]

This evidence drawn from the shifting structure and location of world copper production since the mid-nineteenth century suggests that the underlying geology of the ore deposits exercised a profound

[81] As discussed in my 'Rise of big business in the world copper industry', especially pp.402-5.

influence on both technological change and corporate organizational evolution within the industry. At the heart of these changes lay major shifts in the mineralogical composition, morphology and size of the orebodies which increasingly came to constitute the world's leading resources of copper into the middle decades of the twentieth century, as well as their location in relation to the chief areas of consumption. This is not to deny that there were wider forces at play in the trend towards larger-scale enterprise and vertical integration in the industry, such as desire for monopoly profits, the influence of governments, of capital markets and individual entrepreneurs.[82] Nevertheless, it is important to redress the imbalance in many of the previous discussions of business concentration in the minerals sector, where the geological basis of the industry is frequently overlooked, or regarded as relatively unimportant.

[82] For an alternative viewpoint, emphasing market control motives rather than geological and technological factors with respect to business concentration in the mineral industry, see: I.R. Phimister, 'The Chrome Trust: the creation of an international cartel, 1908-38' *Business History*, 38 (1996), pp. 77-89.

APPENDIX

Major world copper deposits, c.1770-1930/39: grade and tonnage

Mine/deposit	Area	Tonnage (thou.tonnes)	Grade
Chuquicamata <P>	Chile	22500.0	2.12
Rhokana-Nchanga	N Rhodesia	14100.0	5.1
Bingham <P>	USA	9980.0	1.07
Sudbury	Canada	9300.0	1.0
Braden (El Teniente) <P>	Chile	6260.0	2.18
Union Minière	Belgian Congo	6070.0	5.8
Mufulira	N Rhodesia	4570.0	4.5
Morenci <P>	USA	4490.0	1.02
Roan Antelope	N Rhodesia	3350.0	3.3
Rio Tinto	Spain	2800.0	1.44
Chino <P>	USA	2200.0	1.4
New Cornelia <P>	USA	2000.0	1.25
Anaconda (1907)	USA	1970.0	3.0
Ray <P>	USA	1950.0	1.65
Andes (Potrerillos) <P>	Chile	1900.0	1.51
Inspiration <P>	USA	1800.0	1.4
Nevada <P>	USA	1770.0	1.48
Horne Mine (Noranda)	Canada	1390.0	2.4
Miami <P>	USA	1320.0	0.95
Calumet & Hecla (1925) [1]	USA	1295.0	2.45
Mount Lyell (1950) [2]	Australia	1100.0	1.7
Tharsis [3]	Spain	600.0	1.7
Mansfeld (1907)	Germany	590.0	3.0
Boleo (1947)	Mexico	540.0	3.97
Falun	Sweden	500.0	3.5
Ahmeek/Mohawk [1]	USA	534.0	0.96
Copper Queen <P>	USA	450.0	1.63
Lokken (1974)	Norway	400.0	2.0
Quincy/Pewabic [1]	USA	396.0	1.16
Champion/Baltic [1]	USA	396.0	1.22
Sulitjelma (1974)	Norway	370.0	1.85
Wallaroo & Moonta	Australia	339.0	5.3
Flin Flon	Canada	300.0	1.9
Hidden Creek	Canada	250.0	2.24
Besshi	Japan	210.0	3.8
Messina	South Africa	205.0	2.34

Mine/deposit	Area	Tonnage (thou.tonnes)	Grade
Kosaka	Japan	200.0	2.0
San Domingo (Mason & Barry)	Portugal	190.0	2.5
Osceola [1]	USA	189.0	0.84
Mount Isa (1949)	Australia	157.0	4.1
Lo Aguirre (Santiago)	Chile	156.0	2.6
O'okiep	South Africa	119.0	19.5
Great Cobar	Australia	116.0	2.79
Caucasus Copper (1908)	Russia	114.0	3.1
Mount Elliott	Australia	110.0	5.2
Parys & Mona mines [4]	UK	100.0	4.0
Isle Royale [1]	USA	95.6	0.82
Röros (1907) [5]	Norway	90.0	5.0
Kyshtim	Russia	79.0	2.75
Clifford Amalgamated [6]	UK	74.4	7.7
Atlantic [1]	USA	64.8	0.68
Spassky	Russia	63.0	10.8
Perm (Bogoslovsk)	Russia	55.0	5.5
Tilt Cove	Newfoundland	55.0	4.1
Burra Burra	Australia	52.0	22.0
Otavi (1907)	SW Africa	50.0	16.0
Devon Great Consols	UK	49.8	6.5
Bor	Yugoslavia	34.0	13.0
Fowey Consols	UK	30.3	7.8
Carn Brea & Tincroft	UK	25.9	7.1
Duchess	Australia	25.1	12.3
Dolcoath	UK	24.0	6.75
Wheal Buller	UK	23.9	9.6
Mount Perry	Australia	23.8	17.0
Basset Mines	UK	23.4	7.9
Kvarzhana	Russia	22.5	4.5
South Caradon	UK	22.1	10.0
Trekelano	Australia	20.5	10.9
Tresavean	UK	20.0	6.8
Lloyd (Burraga)	Australia	18.9	4.03
Peak Downs	Australia	17.0	17.0
Wheal Friendship	UK	14.5	9.25
Kapunda	Australia	13.7	20.0
North Roskear	UK	13.6	8.0
Kadford (Alta)	Norway	13.0	6.0
Betts Cove	Newfoundland	13.0	9.5

Mine/deposit	Area	Tonnage (thou.tonnes)	Grade
Levant	UK	13.0	10.0
Alfred Consols	UK	13.0	7.3
Mount Garnet	Australia	12.0	6.0
Hampden-Cloncurry	Australia	11.9	6.9
Par Consols	UK	11.2	9.0
West Seton	UK	10.5	8.25
Whim Well	Australia	10.1	13.2
Mount Oxide	Australia	9.6	26.7
Ecton (Staffordshire)	UK	9.1	15.0
Great Wheal Busy [7]	UK	8.7	6.5
Einasleigh	Australia	8.2	6.04
West Caradon	UK	8.1	9.2
East Crinnis	UK	8.1	10.0
Crenver & Wheal Abraham	UK	8.0	7.0
North & East Crofty	UK	7.7	6.9
Tolgus mines [8]	UK	7.7	8.4
Wheal Seton	UK	7.5	6.5
North Pool	UK	7.1	7.3
Pembroke	UK	7.0	7.9
Perran St George & Droskyn	UK	7.0	6.5
Poldice	UK	6.9	6.25
Marke Valley	UK	6.8	5.25
Hingston Down [9]	UK	6.0	6.0
Cadia	Australia	5.9	5.8
Phoenix United	UK	5.8	6.8
East Pool & Agar	UK	5.6	6.0
Marazion Mines (Prosper Utd)	UK	5.5	6.7
Tywarnhayle	UK	5.5	5.9
Michilla (Antofagasta)	Chile	5.5	5.5
Wheal Jewell	UK	5.3	9.0
Treskerby	UK	4.7	9.0
Bedford United	UK	4.5	6.75
Mellanear	UK	4.0	6.0
Callington United [10]	UK	4.0	6.7
Unity Wood (West Poldice)	UK	3.9	6.9
East Caradon	UK	3.9	7.0
Mount Molloy	Australia	3.6	8.45
Rosewarne (Gwinnear)	UK	3.5	10.3
Ting Tang (St Day)	UK	3.5	8.5
Wheal Damsel (St Day)	UK	3.3	8.75

Mine/deposit	Area	Tonnage (thou.tonnes)	Grade
Wheal Gorland (St Day)	UK	3.1	7.5
Camborne Vean	UK	2.8	7.5
Wheal Crebor	UK	2.7	6.5
Penstruthal	UK	2.7	4.5
Botallack	UK	2.7	11.8
Glasgow Caradon	UK	2.6	7.0
Tremayne (Gwinnear)	UK	2.4	8.2
Little North Downs (Scorrier)	UK	2.4	8.0
Cook's Kitchen	UK	2.3	5.5
South Roskear	UK	2.2	7.75
Crinnis (Par)	UK	2.0	5.25

<P> denotes porphyry type deposit.

Tonnage represents estimated copper content of 127 mines/orebodies to 1939, except where noted. In each case, as far as can be ascertained, orebody tonnage equals the sum of recorded output plus estimated reserves by the given date. Orebodies discovered after 1939 are not included here.

Grade represents either the estimated mean tenor of orebodies, following exploration programmes (eg the Northern Rhodesian figures), or the mean copper content of ores mined (or a combination of the two). Data representing copper content of mined ore are subject to some variation of definition. In some cases they may refer to metal recovered from smelted ores, in others the estimated content of ores as mined (before or after varying degrees of sorting or concentration). The original sources rarely make these distinctions clear, although in general it appears that mined ore estimates are based on run-of-mill grades, that is the mean copper content of ores before concentration (but possibly after preliminary hand sorting).

Data taken from Dines (1956), for mines in Cornwall and Devon, in some cases represent total tonnage and weighted mean grades from a group of mines, where they were either worked by the same company for a part of their history, or appear to have exploited the same orebodies or a related group of mineral veins. The weighted mean grade is obtained by multiplying the ore output of each mine in a group by its mean grade, summing these and dividing by total group ore output. Data are included for all mines in Cornwall and Devon recorded by Dines as having produced more than two thousand tonnes of copper-in-ores.

The data for tonnage and ore grades in United Kingdom mines are subject to a particular degree of error. As one source warns, most recorded output figures only cover the period from 1815 up to the 1890s, when copper mining had effectively ceased in south-west England (D.B. Barton, A *history of copper mining in Cornwall and Devon* (Truro 2nd.ed. 1968) p.97). This consequently ignores earlier output, which goes back to the first decade of the 18th century and in some cases was quite considerable after the 1750s. However, within the parameters of the present analysis, this makes little significant difference to the overall statistical results. Even allowing for considerable copper produced at the Gwennap United and Great Consolidated mines between the 1750s and 1815/1819 (when the above data respectively start), the total outputs for these mines could hardly have been more than about forty and fifty thousand tonnes respectively. Also, extension of coverage to this earlier period, if possible, would almost certainly raise mean grade at the same time and produce similarly good fits on the log-log trend line for these and other data-deficient mines.

[1] Represents overall tonnage and grade in the seven major lodes/ore-bearing formations in the Lake Superior district from 1845 to 1925. The Calumet & Hecla figure includes 1284.2 thou. tonnes from the Calumet & Hecla Company, the remainder coming from the mines of the Centennial, Osceola and Tamarack companies. Together these seven ore-bearing formations yielded 94 percent of total Lake Superior copper production up to the end of 1925.

[2] Includes orebodies in Mount Lyell, Lyell Comstock, Crown Lyell, North Lyell, Lyell Blocks, Lyell Tharsis, Royal Tharsis and South Lyell, and West Lyell mines.
[3] Tharsis tonnage is the estimated copper content of pyrites output 1857-1939, grade being interpolated from average copper content, which declined on trend from around 2.6-2.7 percent in the 1870s and 1880s, to just under 1.0 percent by the 1920s.
[4] Parys and Mona ore is recorded as averaging 3 to 5 percent copper.
[5] Röros ore contained from 4 to 6 percent copper.
[6] Clifford Amalgamated was a re-working of the Great Consolidated and United Mines, of Gwennap Cornwall, each representing groupings of smaller mines which had been operating from the 1750s onwards. Separate tonnage and grade figures for these groupings are: Great Consolidated (1819-57) 39.8 thousand tonnes at 8.4 percent, United Mines (1815-61) 28.8 at 7.1 percent, Clifford Amalgamated (1861-70) 5.8 at 6.0 percent.
[7] Includes Hallenbeagle.
[8] Tolgus, South Tolgus and Great South Tolgus mines.
[9] Includes Gunnislake Clitters.
[10] Holmbush, Redmoor and Kelly Bray mines.

Sources:

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