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Mine size and the structure of costs

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Abstract

The number of operating mines has fallen sharply for most mineral products, and the average size of mine risen, with the changes gathering momentum during the 1990s. The paper looks at trends in copper, zinc and gold, and then explores the relationship between size and unit costs in copper mining, separately for underground and open-pit mines, in order to ascertain the existence and importance of economies of scale. Changes in mine size have been accompanied by major technological and geographical shifts. There is only a weak relationship between the scale of mines and overall unit costs per tonne of copper produced. The paper discusses the data and explores some of the reasons.

Keywords: Copper; Gold; Zinc; Mine size; Milling capacity; Tonnage milled; Head grades; Economies of scale; Copper-equivalent costs; Leaching; Open-pit mines; Underground mines

Introduction

This paper was developed from a presentation at the PDAC meeting in Toronto in March 2003 (Crowson, 2003) that looked at recent trends in global mine output and in the size of mines in order to assess the implications for future exploration spending. This paper, based on more detailed analysis of basic data, concentrates on changes in the size of mines since the mid-1970s and on the relationship between mine size and production costs. It uses some of the data contained in the earlier paper, but has also drawn heavily on analyses of copper mine size and costs, kindly made available by Rio Tinto.[1]

The first objective of the paper is to show how the size of mines has changed since the mid-1970s, and especially during the 1990s. For most, if not all, mineral products there was a sharp decline in the number of operating mines and a corresponding rise in mine size. The first section of the paper looks at copper, zinc and gold, and the second concentrates in far more detail on different ways of looking at the changing scale of copper mines. Quite apart from the technological improvements that have been common to the mining and processing of all minerals, copper has experienced a significant technological development with the introduction and rapid growth of leaching processes, and particularly of SX-EW production. That has been accompanied by shifts in the geographical centres of production. Changes in mine size have, therefore, been only one of the many influences on production costs The paper examines the relationship between size and unit costs in conventional copper mining, separately for underground and open-pit mines, in order to ascertain the existence and importance of economies of scale. These clearly exist in mining and milling, but they are largely offset by other factors when all costs are taken into account. The relationship between the scale of mines and overall unit costs per tonne of copper produced, allowing for by-products, is weak. The paper discusses some of the factors involved, such as differences in ore grades and by-product contents.

Trends in mine output: copper and zinc

Until the 2001–02 recession global demand for minerals and metals was growing strongly, and much

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[1] Data derived from the Rio Tinto Mine Information System by Michael Bailey, by permission of Dr. David Humphreys. Michael Bailey also kindly assisted with the formulation of the regression equations in the section on mine size and costs.

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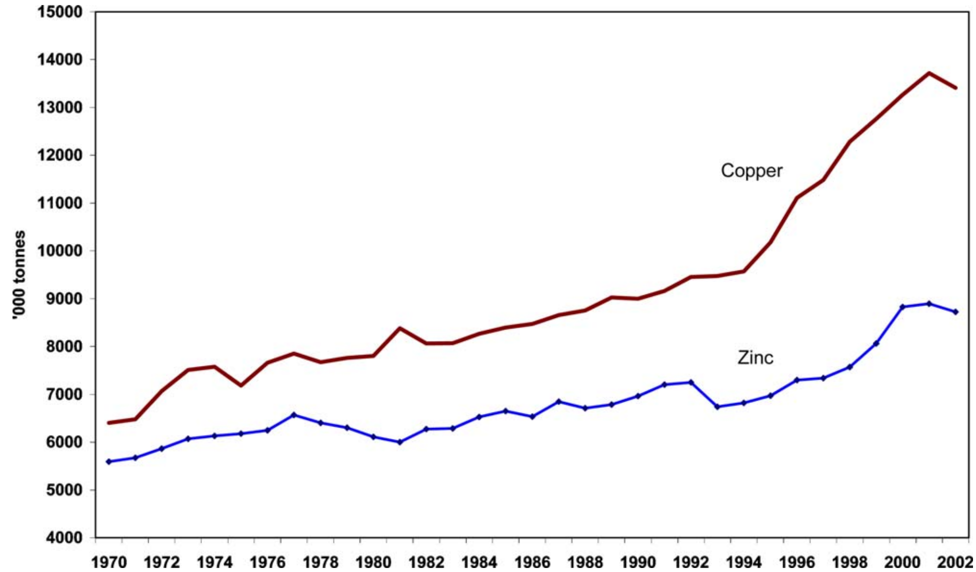

Fig. 1. Global mine output of copper and zinc. *Source*: International Lead and Zinc Study Group and World Bureau of Metal Statistics.

faster in the 1990s than in either of the two previous decades. That comes out of the trends in production shown in Fig. 1.

Even during the 1990s mines were closed because of ore depletion, declining grades, natural disasters, or plain lack of profits, at the same time as new capacity came on stream. The perpetual need for new capacity just to replace closures is an abiding feature of the minerals industry. That need was considerable during the past decade. Between 1992 and 2002 the gross additions to global copper mine capacity exceeded three-fifths of the capacity in place in 1992. For zinc, the proportion was rather less, but still substantial.

Consistent series of capacity on a mine-by-mine basis extending back much more than a decade are not readily available for most products because they were not computerised. We do, however, have more readily available indicators of how capacity has changed. First, we can look at how production has changed on a country-by-country basis. Admittedly changes in mine output do not always precisely track movements in capacity because of shifts in utilization rates, which are largely driven by prevailing economic conditions. Over time, however, output and capacity do move broadly in step with each other, but with a continual erosion of capacity from depleted and uneconomic mines.

Naturally, countries whose output has fallen may have also seen increases in some mines, and those with rising output will probably have had some closures. Both the increases and reductions are, therefore, understated, but even on a broad country-by-country basis the gross additions to copper mine production increased from an annual average 250,000 tonnes during the 1980s to around 550,000 tonnes in the 1990s. Table 1 shows the changes during the 1992–2002 decade. It does not record changes that might have taken place within each decade, but that should not seriously

Table 1
Changes in copper mine output 1992–2002

Increases			Decreases		
	‘000 tonnes	%		‘000 tonnes	%
Chile	2558	65	USA	−611	−15
Indonesia	902	23	Canada	−171	−4
Australia	494	13	Zambia	−126	−3
Peru	473	12	Congo	−112	−3
China	217	5	Philippines	−105	−3
Argentina	203	5			
Kazakhstan	178	5			
Other increases (17 countries)	412	10	Other reductions (22 countries)	−364	−9
Total increase	5437	138	Total reduction	−1489	−38
Net change	3948	100			

Source: World Metal Statistics, Yearbooks and Monthly Bulletin. World Bureau of Metal Statistics.

Table 2
Changes in zinc mine output 1992–2002

Increases			Decreases		
	'000 tonnes	%		'000 tonnes	%
China	707	43	Canada	−422	−26
Peru	619	38	Japan	−88	−5
Australia	454	28	North Korea	−83	−5
USA	243	15			
Mexico	163	10			
Kazakhstan	112	7			
Morocco	101	6			
Other increases (16 countries)	284	17	Other reductions (25 countries)	−442	−27
Total increase	2683	163	Total reduction	−1035	−63
Net change	1648	100			

Source: World Metal Statistics, Yearbooks and Monthly Bulletin. World Bureau of Metal Statistics.

bias the conclusions as the lives of base metal mines usually exceed a decade.

The increases were geographically concentrated. Chile accounted for nearly two-thirds of the gross increase in output, followed by Indonesia. Peru and Argentina were both contributors. Little more than a dozen mines were responsible for much of the increase. Of the 51 countries that mined copper in 1992 no less than 27 saw their output decline during the ensuing decade. In some instances, such as the United States, this was a typical response to weakening prices, with some of the closed mines likely to reopen when conditions improve. In other countries, the closures were probably permanent.

What happened in copper was by no means unique, as we can see from the experience of zinc. The rate of closure of zinc mines, measured on a country-by-country basis, was greater in the 1980s than in the 1990s. That aside, there was a large jump in gross additions to production during the last decade. They rose from an annual average 200,000 tonnes to 275–300,000 tonnes. Closures were running at over 100,000 tonnes per annum throughout the past two decades. As with copper, the changes in the mine output of zinc during the 1990s, shown in Table 2, were geographically concentrated.

Here output fell in 28 countries during the 1990s, with Canada recording the largest percentage decline. China showed the greatest rise amongst the 23 coun-

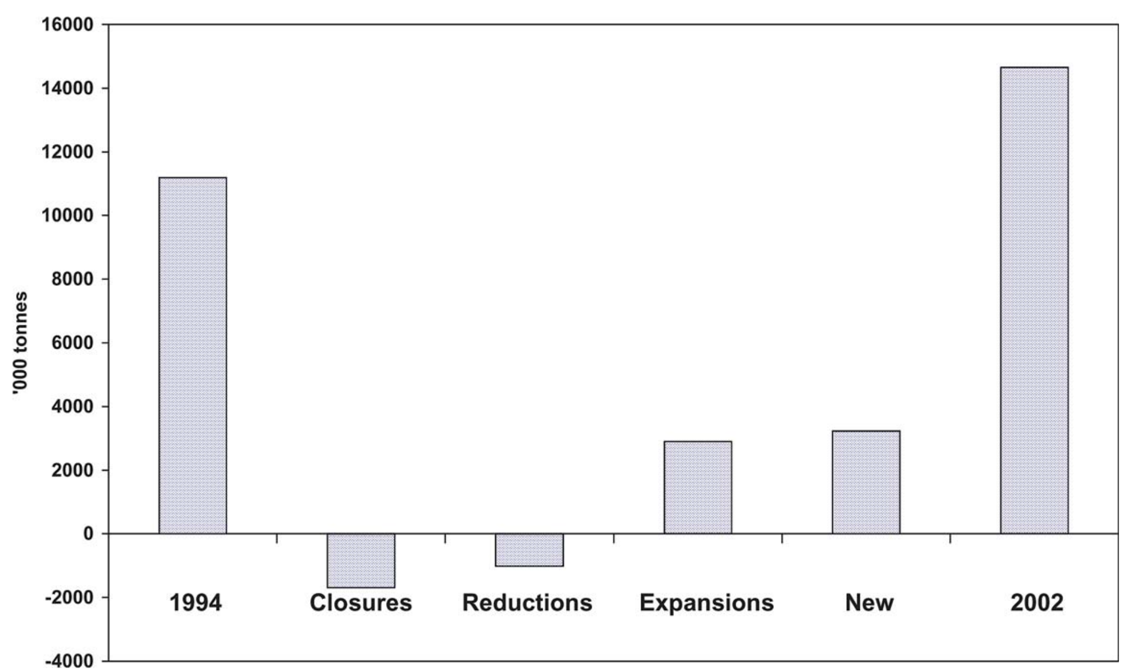

Fig. 2. Changes in global copper mine capacity 1994–2002. *Source*: International Wrought Copper Council. London. Survey of Capacities of Copper Mines, Smelters, Refineries and Copper Wire Rod Plants, IWCC, (2000).

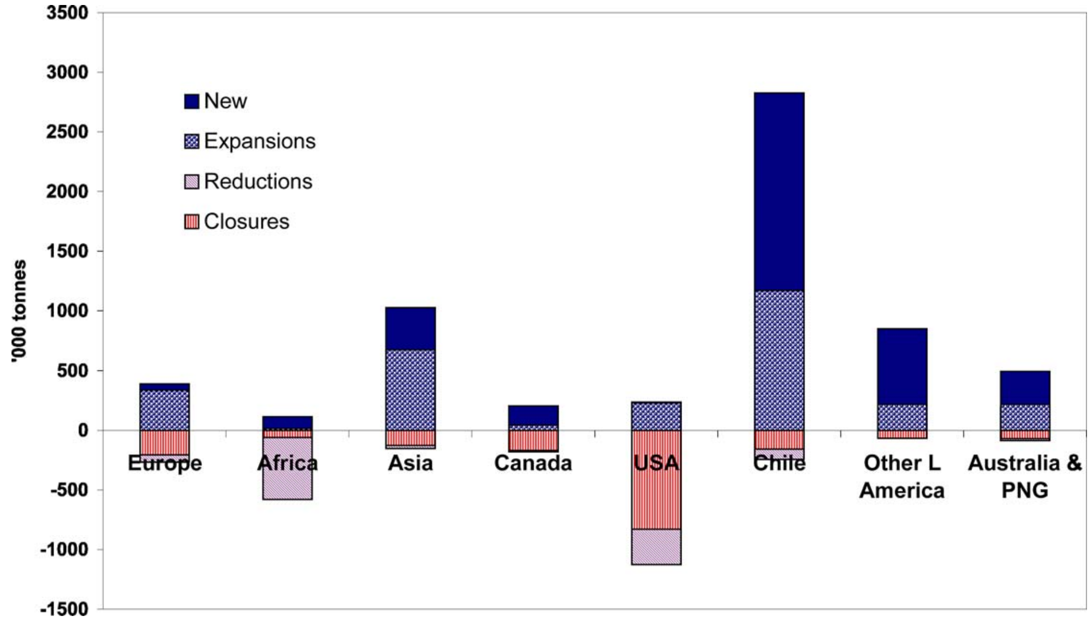

Fig. 3. Changes in global copper mine capacity by region 1994–2002. *Source*: International Wrought Copper Council, London. Survey of Capacities of Copper Mines, Smelters, Refineries and Copper Wire Rod Plants, IWCC (2000).

tries showing increases, followed by Peru, Australia and the United States.

Copper mine capacity

Data on copper mine capacity on a mine-by-mine basis are collected by the International Wrought Copper Council (Survey of Capacities of Copper Mines, Smelters, Refineries and Copper Wire Rod Plants, IWCC (2000)), and circulated within the copper industry. Fig. 2 shows how global mine capacity changed over the much shorter period of 1994–2002.

Global capacity rose from about 11.2 million tonnes in 1994, when it was roughly 86% utilised, to some 14.6 million tonnes in 2002, when the utilization rate was a high 92%. As we have already noted, some of the mines that closed down during the latter part of the period might re-open when market conditions improve, but the longer that prices remain weak relative to costs the lower the likelihood. The net increase is made up of four constituents, outright closures, reductions from mines that were still operating in 2002, expansions to mines that had existed in 1994, and completely new mines. A large share of the expansions came from mines that had relatively recently opened. The geographical distribution of the changes in capacity is summarised in Fig. 3.

This merely reinforces the message of an earlier figure that the changes in mine capacity have been geographically concentrated. Indonesia, which was a major contributor to the increase in capacity, is included with Asia.

Just to round out the picture, the geographical distribution of mine capacity in both 1994 and 2002 is summarised in Fig. 4.

This shows the growing domination of global copper production by Chile and other Latin American countries, and the reducing shares of Africa and North America.

Changes in mine size in summary: copper, zinc and gold

The rise in global mine capacity, especially during the 1990s, was accompanied by a marked increase in the average size of mines. In particular, the relatively high growth rates of the 1990s gave scope for large new mines to start up at, or near to their technical optimum, especially when account is taken of offsetting mine closures. Table 3, based on a variety of sources[2] summarises how the size of copper, zinc and gold mines moved relative to global output over rather different periods.

[2] For copper, the data for 1976 are taken from an internal study by Rio Tinto Economics Department (private communication), and the data for 2000 from the International Wrought Copper Council (IWCC) analysis annotated in (Survey of Capacities of Copper Mines, Smelters, Refineries and Copper Wire Rod Plants above, IWCC (2000)). The data for zinc are derived from the successive World Directories on Lead and Zinc Mines of the International Lead and Zinc Study Group, and especially on analyses of these by the author for the Introduction to the 2001 Edition. For gold the data are from the computerised database of the Raw Materials Group of Stockholm.

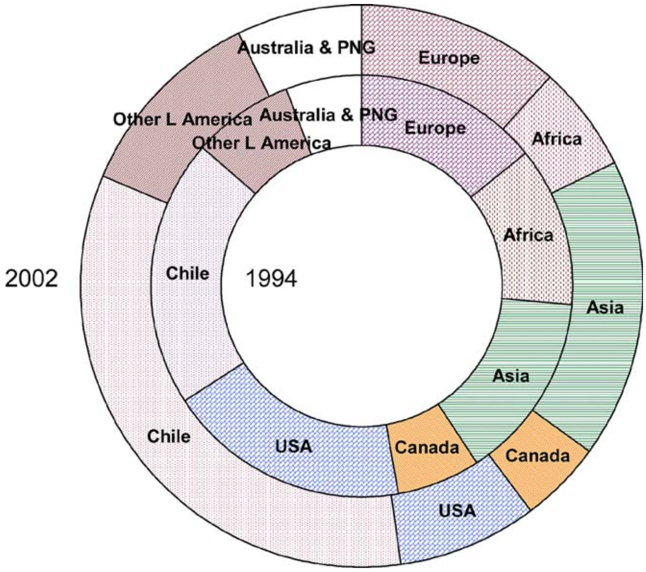

Fig. 4. Global copper mine capacity by region 1994 and 2002. *Source*: International Wrought Copper Council. London. Survey of Capacities of Copper Mines, Smelters, Refineries and Copper Wire Rod Plants, IWCC (2000).

Table 3
Percentage change in global mine output and mine size

	Global output	Mean mine size	Median mine size
Copper 1976–2000	+67	+182	+252
Zinc 1980–2000	+45	+117	+133
Gold 1975–2000	+101	−2	+131

Source: See Footnote [2].

The first column shows the percentage increases in global mine output over the periods covered, such as 1976–2000 in the case of copper. The second column shows the percentage changes in the mean mine size over the same period. This was much greater than the rise in output for both copper and zinc, but not for gold. That is because large South African mines dominated global gold output in the mid-1970s and there was a strong growth in the number of mines in response to the gold price rises of the late 1970s. By contrast, the number of copper and zinc mines has fallen. Since means can be heavily influenced by extreme values, the last column also shows the percentage increase in median mine size. For all three metals, it was greater than both total output and the means.

The changes are best displayed by the full distributions of mine size, first for copper (Fig. 5).

Each column shows the proportion of global output covered by mines in that size range in 1976, 1999, and 2000, respectively. The changes between 1999 and 2000 partly reflect the move towards full capacity working of mines that opened or expanded in the late 1990s, but also temporary cutbacks and closures in response to weak market conditions. Mines that produce at least 200,000 tonnes of copper per annum accounted for over two-fifths of global output in 2000, and mines producing over 150,000 tonnes per annum over one half. Twenty-five years ago such mines accounted for not much more than one-fifth of total output. Certainly, the largest mines took a considerable time to reach their present scale, but many of those in the 150–300,000 t.p.a range started off at such rates.

For zinc, the picture of increasing scale is similar if not as dramatic, as shown in Fig. 6.

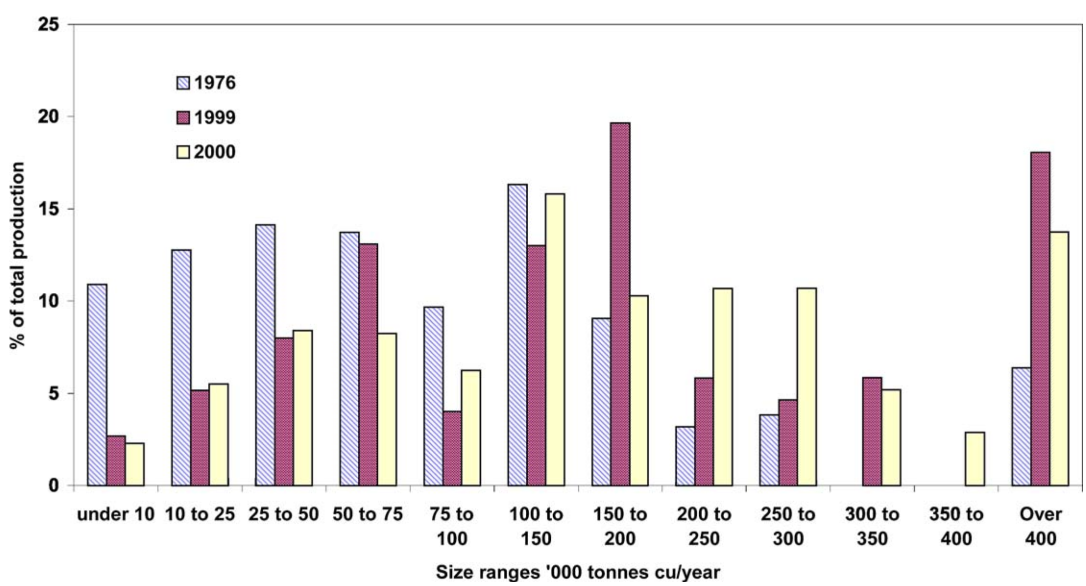

Fig. 5. Size distribution of copper mines. *Sources*: Rio Tinto Mine Information System and International Wrought Copper Council. London. IWCC (2000).

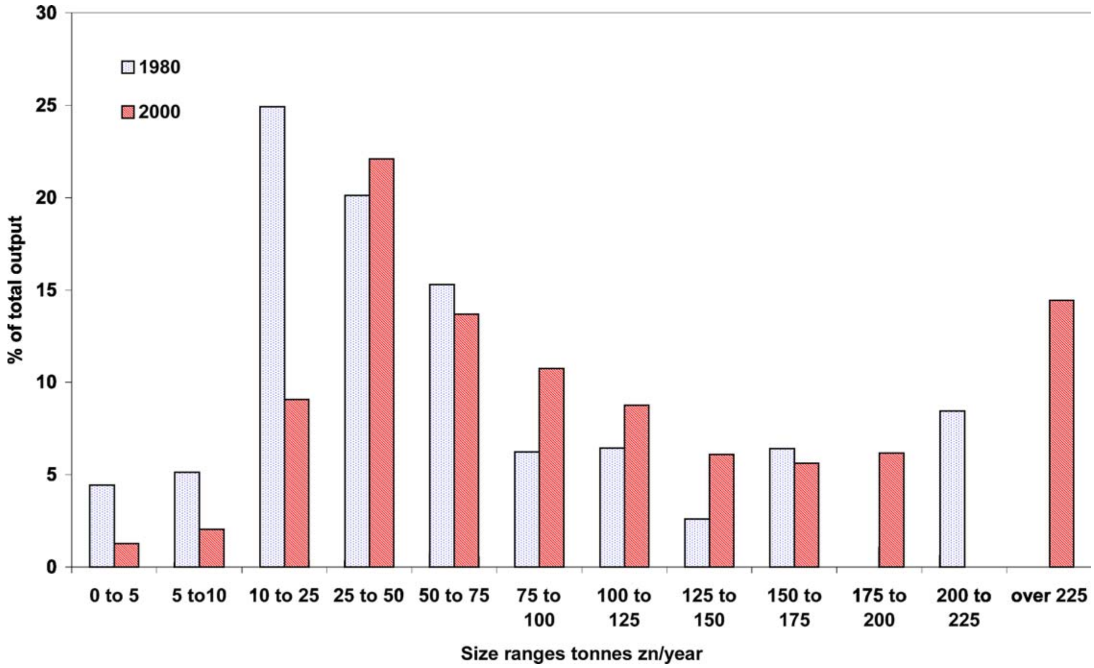

Fig. 6. Size distribution of zinc mines. *Source*: International Lead and Zinc Study Group. See Footnote [2].

Back in 1980, 30% of global output came from mines that produced 100,000 tonnes or more of zinc each year, against 41% in 2000, with 8% coming from mines producing over 200,000 tonnes per annum against 14% in 2000.

As already noted, there were some large gold mines operating in the mid-1970s, but they were nowhere near as important as they are today. Fig. 9 shows that the rise in mine scale was not confined to base metals. Whereas under 19% of gold output came from individual mines producing more than 30 tonnes per annum in 1975, the proportion had risen to some 39% by 2000 (Fig. 7).

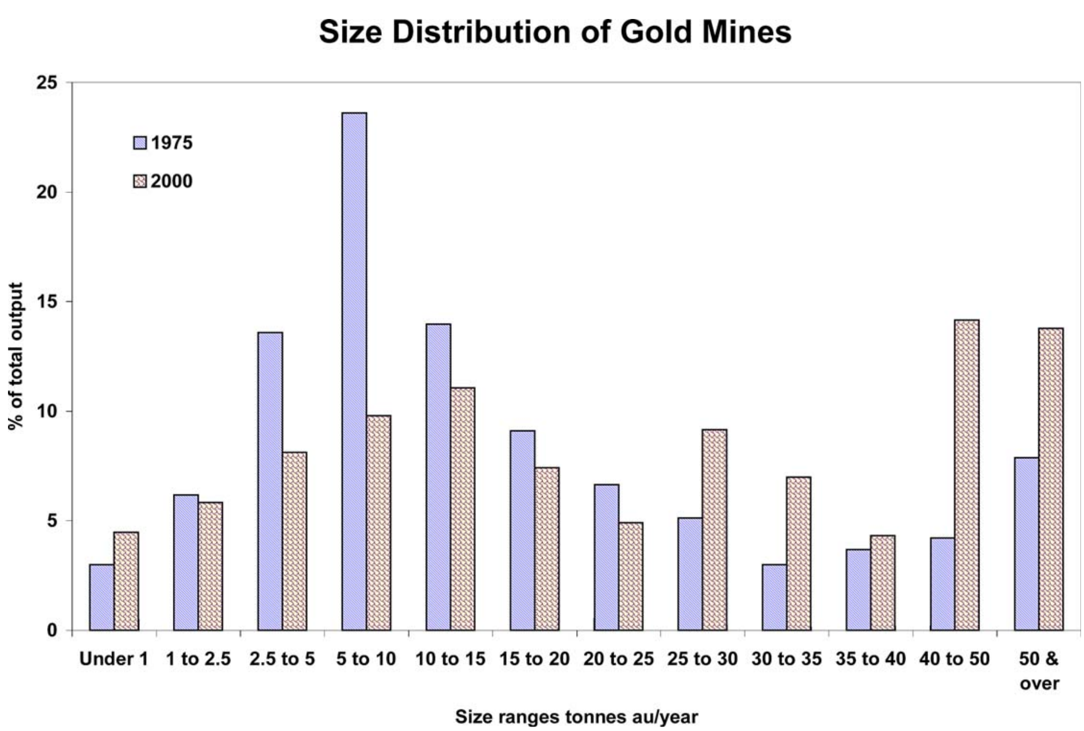

Fig. 7. Size distribution of gold mines. *Source*: Raw Materials Group. Stockholm. Sweden.

Mine size in the copper industry

The growth of the global output of copper and zinc, illustrated in Fig. 1, was considerably higher in the 1990s than in the two preceding decades. This might suggest that the rise in mine scale was concentrated more heavily in the 1990s than in the earlier periods. Strongly rising demand created a need for new mine capacity that was met by increasing scale as well as by the development of large new mines. Data on mine size in the copper industry contained in Rio Tinto's Mine Information ystem (RTMIS) enable us to test these propositions. See footnote [1].

The basic data

RTMIS contains annual information on individual copper mines back to the early 1970s on a reasonably consistent basis. In the 1970s and 1980s, it aimed at complete coverage of all the mines, however small, that produced copper in the Western World. More recently, it has omitted many of the world's smaller mines because the benefits derived from estimating the data were judged to be incommensurate with the costs involved. Table 4 shows how the coverage of mine production, as recorded by the World Bureau of Metal Statistics (WBMS), altered at quinquennial intervals from 1975 onwards. The RTMIS estimates of mine output are shown as percentages of the Western World's total, as conventionally defined. The shares of western world production exceeded 100% in the 1980s because the RTMIS estimates of output were higher for some countries than those recorded by the WBMS.

Table 4
RTMIS coverage of Western World copper mine production

RTMIS as percentages of WBMS	
1975	99.0
1980	101.4
1985	100.5
1990	98.6
1995	94.0
2000	95.5

Sources: Rio Tinto Mine Information System and World Bureau of Metal Statistics.
Note: As the RTMIS does not include data for India in 2000, Indian figures have been excluded throughout to ensure consistency. Data for Polish mines have been included in RTMIS in 1995 and 2000 but are similarly excluded from this paper.

The changes in coverage may overstate the reduction in the number of mines over the period, but Table 4 suggests that estimates of changes in median mine size are unlikely to be greatly biased. More important, the RTMIS data strictly refer to the number of reporting units rather than mines, because mining companies often group data for several mines. Such grouping has become more prevalent during the period covered. The original data have, however, been adjusted as far as practicable to a consistent reporting basis for this paper, in order to eliminate this potential source of bias. The effect of changes in the reporting basis is to understate the true rise in mine size since 1975. Fig. 8 compares the cumulative distribution of copper metal capacity by size of mine as reported in 1975, with the distribution as re-estimated on the reporting basis of 2000. Leaching operations are not included but they were relatively unimportant in 1975 (just over 2% of copper metal capacity). The change in the reporting basis raises the average size of mine (reporting unit) and the share of larger mines in 1975s total capacity.

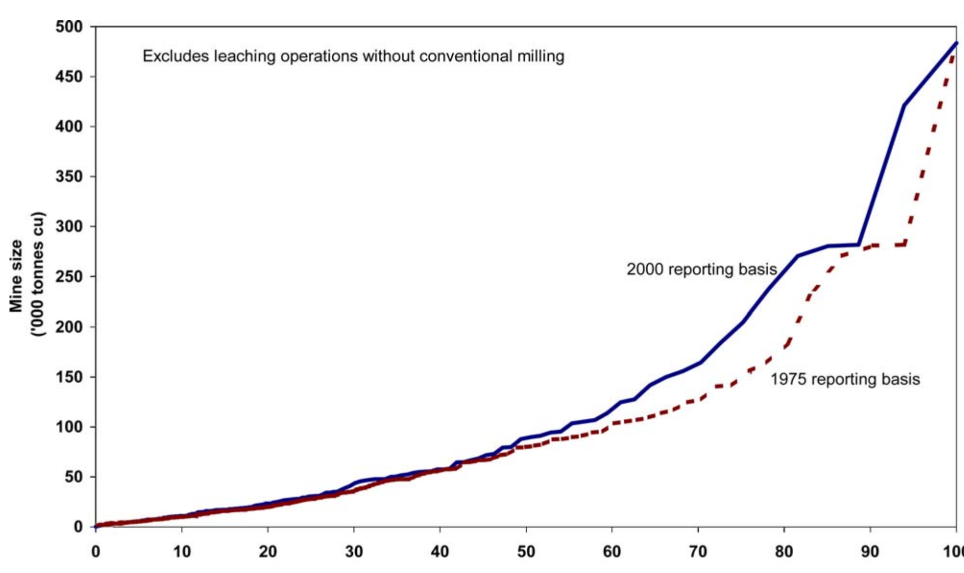

Fig. 8. Cumulative metal capacity by mine size in 1975. *Source*: Rio Tinto Mine Information System.

Table 5
Summary data on copper mines 1975–2000

		1975	1980	1985	1990	1995	2000
Mines with conventional milling							
Number of mines		341	261	223	225	137	101
Tonnes milled	Million t.p.a.	688	797	814	919	959	1106
Mill capacity	000tpd	2481	2762	2848	3136	2997	3474
Metal capacity	000 t.p.a. cu	7955	8018	8100	8814	8681	10,662
Leaching operations (SX-EW)							
Number of mines		19	20	22	32	41	39
Tonnes treated	Million t.p.a.	137[a]	29	33	53	184	641
Metal capacity	000 t.p.a. cu	175	344	449	775	1202	2435
All copper mines							
Number of mines		360	281	245	257	178	140
Tonnes milled/treated	Million t.p.a.	825	826	848	971	1144	1747
Metal capacity	000 t.p.a. cu	8130	8361	8549	9589	9884	13,097
Mine output	000 t.p.a. cu	5645	6123	6474	7109	8103	10,890
Capacity utilisation	%	69.4	73.2	75.7	74.1	82.0	83.1
Leaching operations as % of totals							
Number of mines		5.3	7.1	9.0	12.5	23.0	27.9
Metal capacity		2.1	4.1	5.2	8.1	12.2	18.6

Source: Rio Tinto Mine Information System.
[a] *Note*: The tonnes treated in 1975 included a substantial volume of material from old waste dumps, which is why it is much higher than in subsequent years.

The size of mine at the upper quartile of cumulative capacity was 149,000 tonnes on the 1975 reporting basis but 203,000 tonnes on the basis of 2000. The difference at the median was considerably less.

The main features of the data are summarised in Table 5 below. While the number of mines with conventional milling circuits dropped by some 70% between 1975 and 2000, the total tonnage milled rose by 60%, and there was a 34% increase in the capacity to produce copper metal. The capacity of mines with conventional mills stagnated during the decade from 1975, rose in the late 1980s and dropped in the first half of the 1990s, resuming growth in the second half of that decade. The falls in conventional capacity were offset by the development of SX-EW mines. There was a steady rise in the importance of leaching operations throughout the period. They accounted for roughly 5% of the number of mines and 2% of copper metal capacity in 1975, but for 28% of the number of mines, and nearly 19% of metal capacity in 2000. The data on tonnage milled are rather patchy for leaching operations for the 1980s and 1990s, but the growth shown between 1975 and 2000 is reasonably accurate. Comparison of the growth in tonnage milled or treated with that of metal capacity for all mines over this full period indicates a decline in average ore grades. To an extent the growth in mine capacity, however measured, is rather overstated for the full period as there were many temporary closures in 1975 in response to recession. Even where mines remained open, the capacity utilisation dropped. As shown in the table, utilisation rates were much higher in 1995 and 2000 than in the earlier years.

Copper metal capacity

The nature of the technology employed may affect the balance of the market for copper concentrate, but it is only one aspect of a mine's environmental impact, and it is largely irrelevant to a mine's influence on the overall market for copper metal. Size, as such, is more relevant in both respects. Fig. 9 summarises the cumulative distribution of copper metal capacity by size of mine for all copper-producing mines, including leaching operations, at five-yearly intervals from 1975. It emphasises that the scale of mines changed more in the 1990s than in the preceding 15 years.

The next two figures show the same information about the size distribution of total mine capacity, in terms of potential output of copper metal, in different ways. Fig. 10 contains the size distribution of mines for each fifth year, and Fig. 11 shows how the percentage shares of total metal capacity held by mines in each size range moved over the period.

The proportion of metal capacity coming from mines with annual metal capacity of 250,000 t.p.a. or more jumped from just under 14% in 1990 to nearly 28% in 1995, and to 41% in 2000. The proportion had earlier fallen from 21% in 1975 to 13% in 1980, and to rather below 11% in 1985. The shares of mines with annual

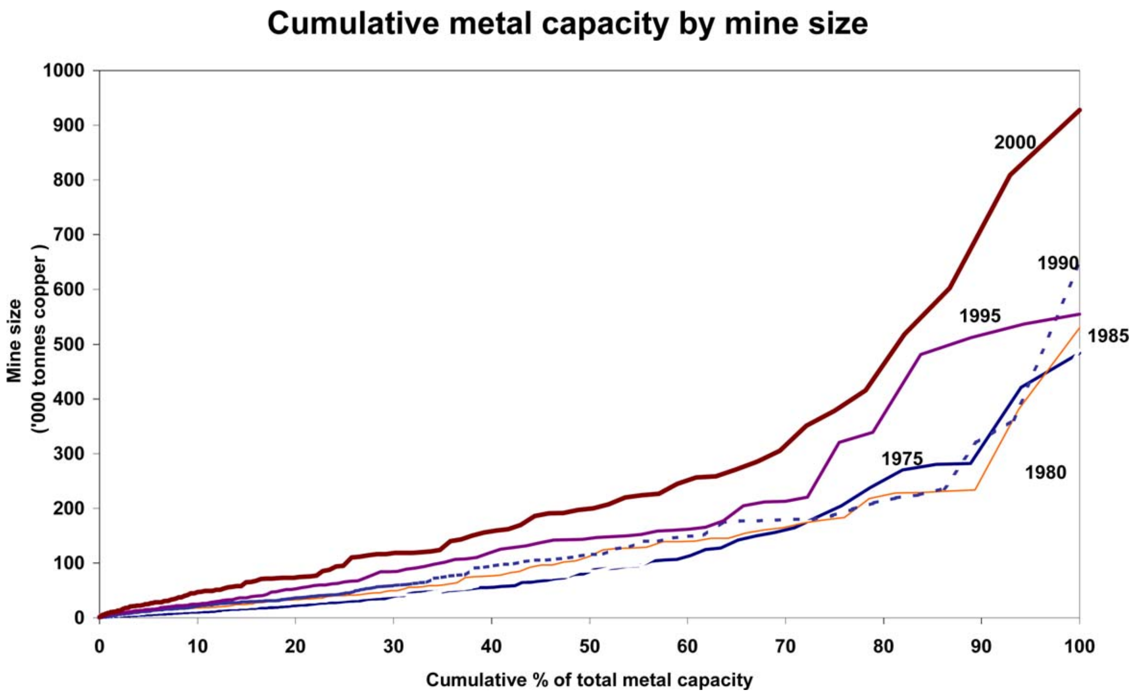

Fig. 9. Cumulative metal capacity by mine size. *Source*: Rio Tinto Mine Information System.

capacities of 50,000 tonnes or less fell throughout the period. Table 6 gives the distribution of mine capacity by mine size in 2000 and the contribution of mines within each size range to the growth of capacity between 1985 and 2000. The increases from mines with an annual capacity to produce 250,000 tonnes or more nearly equalled the increase in total capacity over that period.

The proportion of capacity in mines producing 100–250,000 tonnes per annum is sensitive to changes in only a few mines. In some instances mines may have expanded from one size category to another, whereas in others they might have closed down.

For leaching operations without a conventional milling circuit, the estimates of metal capacity are based on the highest metal output of the preceding five years. For mines with conventional mills, capacity is based on 365 days working of each mill at the year's recovered ore grades. As many mines work rather fewer days the

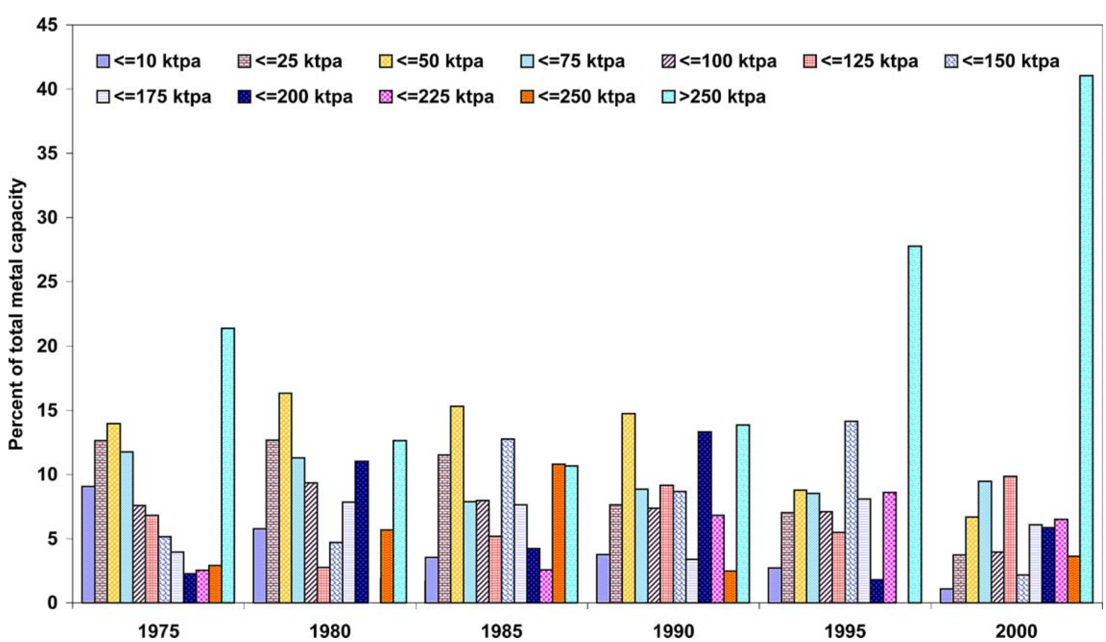

Fig. 10. Copper mines: distribution of metal capacity by mine size.

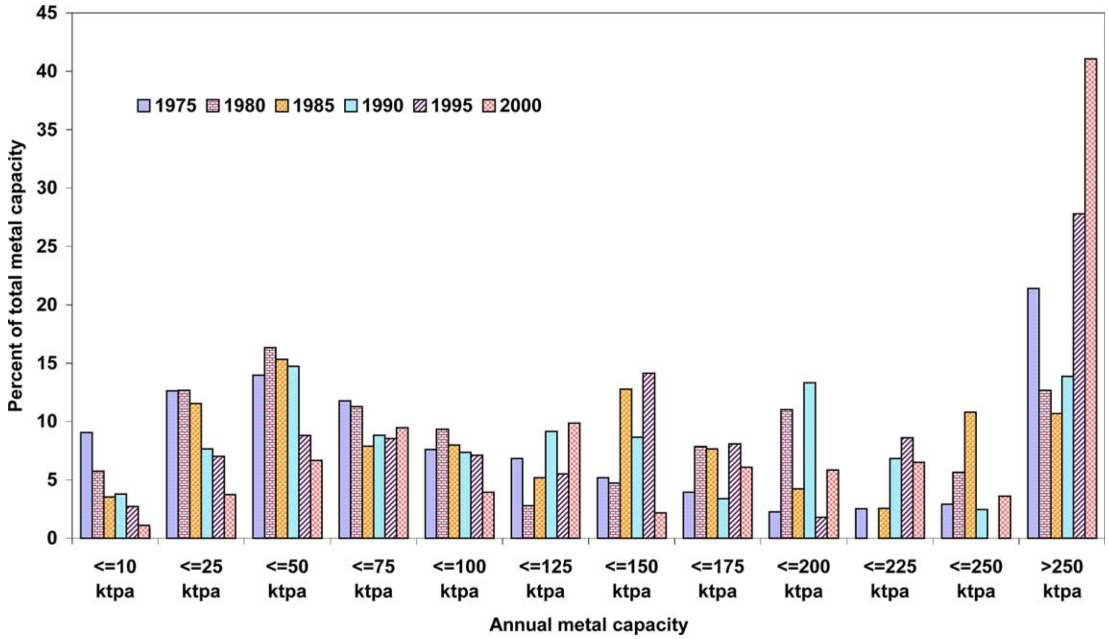

Fig. 11. Copper mines: distribution of metal capacity by mine size. *Sources*: Rio Tinto Mine Information System.

figures may overstate effective capacity, but they have the great merit of consistency across all mines and years. The methodology tends to understate the importance of leaching operations. These accounted for 21.2% of western world mine output in 2000 according to the World Bureau of Metal Statistics, but for only 18.6% of capacity as defined (as shown in Table 5).

Fig. 12 shows the median metal capacity for each year, with the upper and lower quartiles on two bases. All types of mine, including leaching operations, are included in each case. The upper part of the figure is based on the number of mines, whereas the lower portion is based on the cumulative mine capacity. Thus, in the top part half of all mines would have had a capacity greater than the median, whereas in the bottom part half of all capacity existed in mines whose size exceeded the median. Both measures are valid, and both show similar trends. Given the earlier caveats about the coverage of the data, and particularly of small mines in the latter years, the bottom part of the figure is probably more representative.

Both sections of Fig. 12, but especially the lower one contrast the relatively modest change in scale up to 1990 with dramatic change during the 1990s, especially at the upper quartile. In 1975 over half the total capacity was in mines with annual capacities of 84,000 t.p.a. or more, whereas half came from mines of 200,000 t.p.a. or more by 2000, and one quarter from mines with an annual capacity of 378,000 t.p.a. or more. In terms of the number of mines, only one quarter produced more than 18,000 t.p.a. in 1975. The top 25% by number produced 37,000 t.p.a. or more by 1990, but over 115,000 t.p.a. each by 2000.

Table 6
Mine capacity in 2000 and the contributions of each size range to the growth of capacity between 1985 and 2000

Mine size range ('000 t.p.a.)	Total capacity in 2000 ('000 tonnes)	Change in capacity 1985–2000 ('000 tonnes)	% share of 1985–2000 change
≤10	144	−157	−3.5
≤25	490	−495	−10.9
≤50	873	−437	−9.6
≤75	1238	566	12.4
≤100	514	−167	−3.7
≤125	1290	848	18.6
≤150	284	−808	−17.8
≤175	797	144	3.2
≤200	765	404	8.9
≤225	852	634	13.9
≤250	472	−451	−9.9
>250	5378	4467	98.2
Total	13,097	4548	100.0

Source: Rio Tinto Mine Information System.

Milling capacity

Mines extract ore rather than metal, and their capacity is perhaps better measured by the tonnage of ore they treat rather than their metal output. That depends on the grades of ore treated and the recovery rates, which can both vary at the same mine over time, and certainly differ markedly between different mining operations. It also depends on the intensity with which the mine and mill are worked. Two mines of the same nominal milling capacity will have different outputs if one works 24 h per day, every day, whereas the other works only one shift for only five days per week.

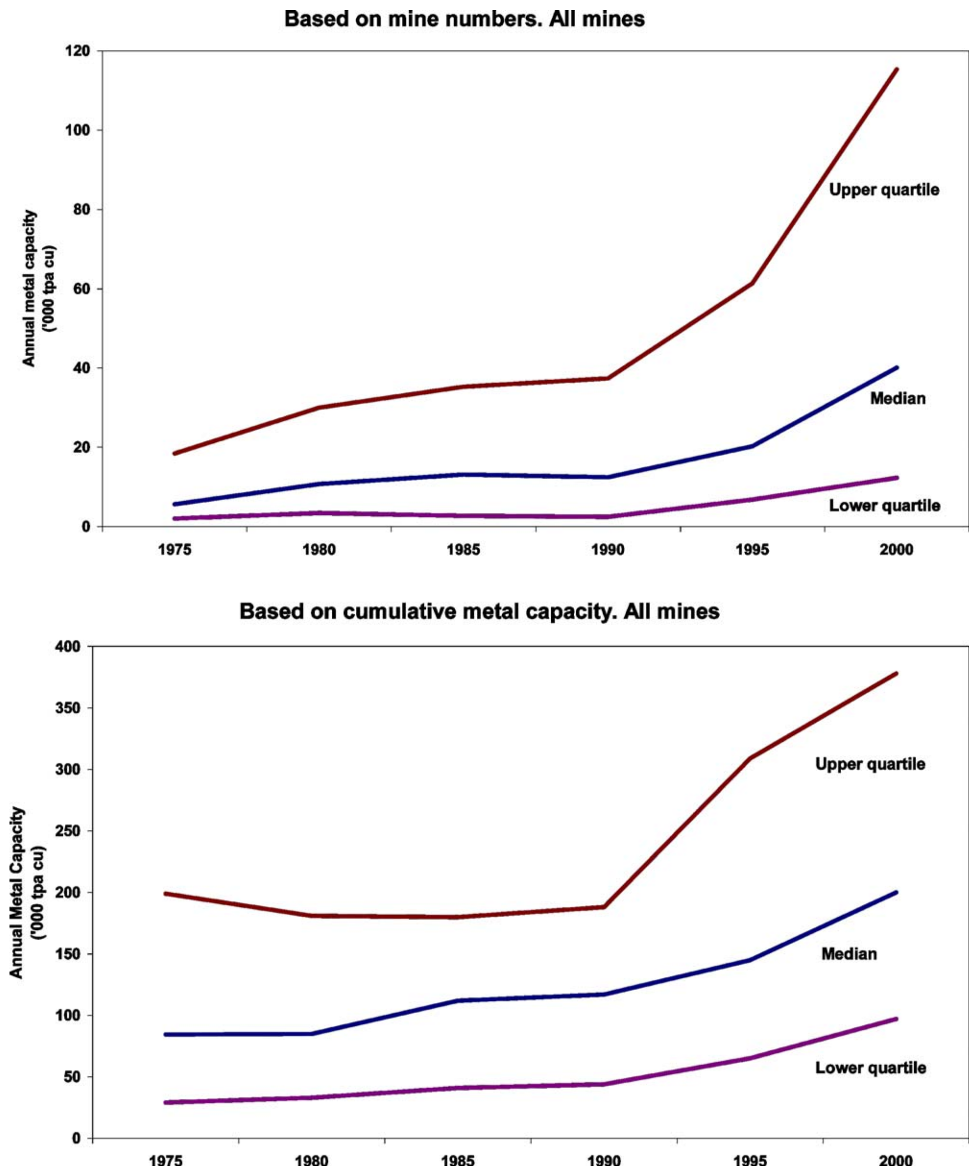

Fig. 12. Average copper mine capacity 1975–2000. *Source*: Rio Tinto Mine Information System.

The environmental footprint of a mine undoubtedly depends far more on the amount of ore treated, plus the waste rock removed, than on its output of products, its nominal milling capacity, or even the processing methods it employs.

Unfortunately, as noted earlier, the data on the tonnage of ore treated in leaching operations are incomplete for some years. The nature of such operations has also changed since 1975, when a sizeable percentage of their copper output came from the re-treatment of old mine dumps rather than newly mined ore. By 2000, the bulk came from newly mined materials. While the average metal output of copper mines based on leaching techniques, mainly SX-EW, is well within the range of the averages of mines with conventional milling circuits, their ore grades fell to much lower levels during the late 1990s. This implies a much greater ore throughput for typical leaching operations than for conventional mines with the same output of metal. Thus, some of the increase in mine scale, based on ore throughput, reflects the change in processing technology that gathered pace during the 1990s. The figures in Table 5 imply that leaching operations accounted for nearly 37% of the copper ore treated in 2000 against 18.6% of metal capacity.

Fig. 13 compares the distribution of the total tonnage milled or treated in 2000 across different size categories for all mines, regardless of their processing technology, with the distribution for mines with conventional milling circuits. It suggests that leaching operations are more prevalent than conventional milling in the 5–20 million tonne per annum range, and also in the largest category

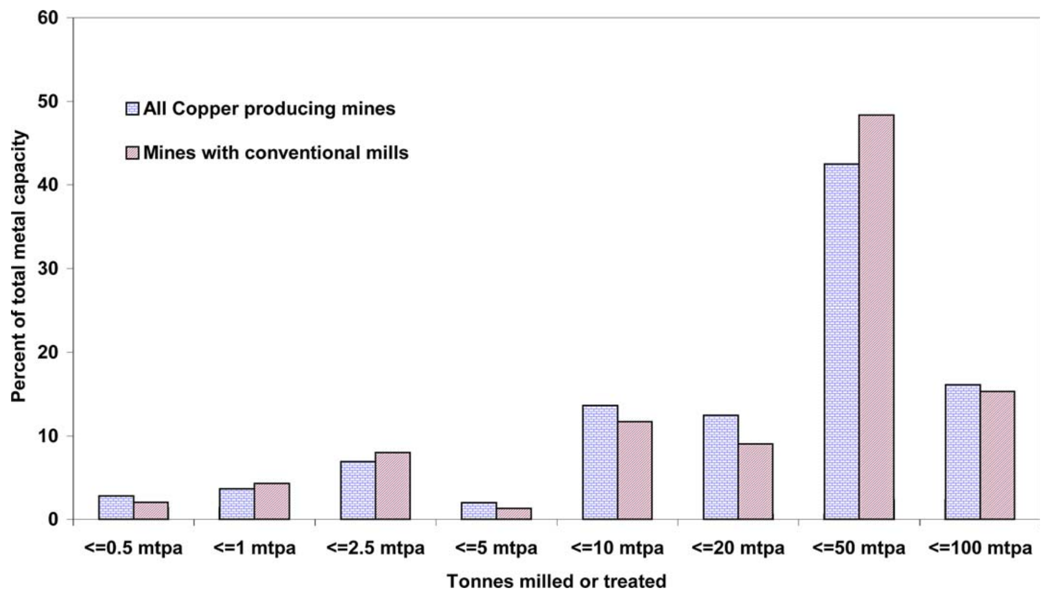

Fig. 13. Size distribution of copper mines in 2000 by tonnage treated. *Source*: Rio Tinto Mine Information System.

shown (over 50 million tonnes of ore per annum). Conversely, conventional mills are more important in the 20–50 million tonne range. The largest mine in 2000, based on ore throughput, was a leaching operation that accounted for almost 2% of copper metal output from over 200 million tonnes of ore. On that basis it was about 2.6 times the size of the next largest mine (with conventional milling).

The remainder of this section concentrates on mines with conventional mills, as the data for these are more complete. Fig. 14 shows the median annual mill throughput for each year, with the upper and lower quartiles, on the basis of cumulative metal capacity. It clearly brings out the marked changes in average scale that took place during the 1990s.

There were no conventional mines milling more than 50 million tonnes of ore in 1975 and 1980, but by 1995 over 9% of metal capacity came from mines treating more than 50 million tonnes of ore per annum. That rose to 16% by 2000. The ore throughput of the mine at the median grew by 51% between 1975 and 1990, with most of that growth in the late 1980s. It increased by 125% in the first half of the 1990s and by 33% in the second half. The increases were still considerable, but smaller, at the upper quartile. Whereas the median ore

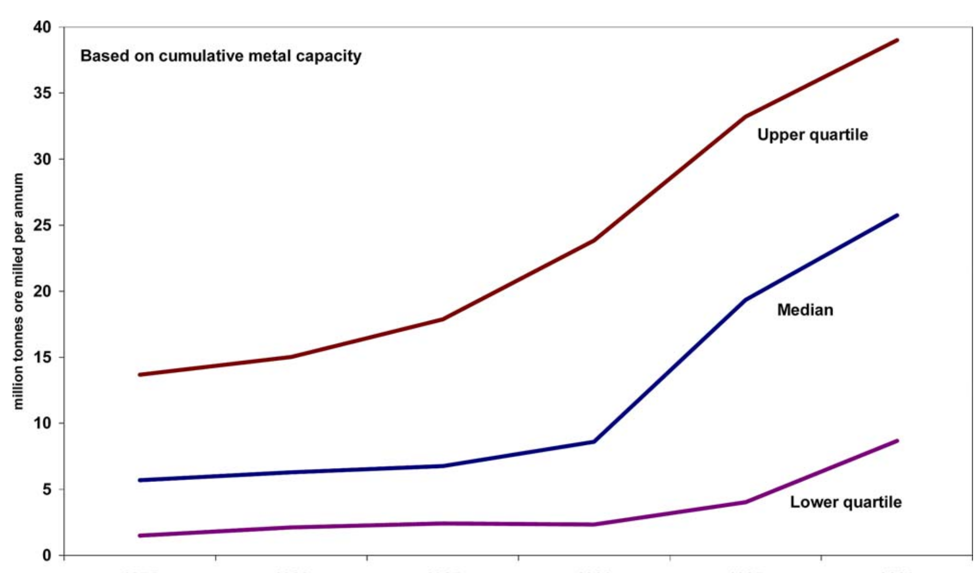

Fig. 14. Average tonnes milled at conventional copper mines 1975–2000. *Source*: Rio Tinto Mine Information System.

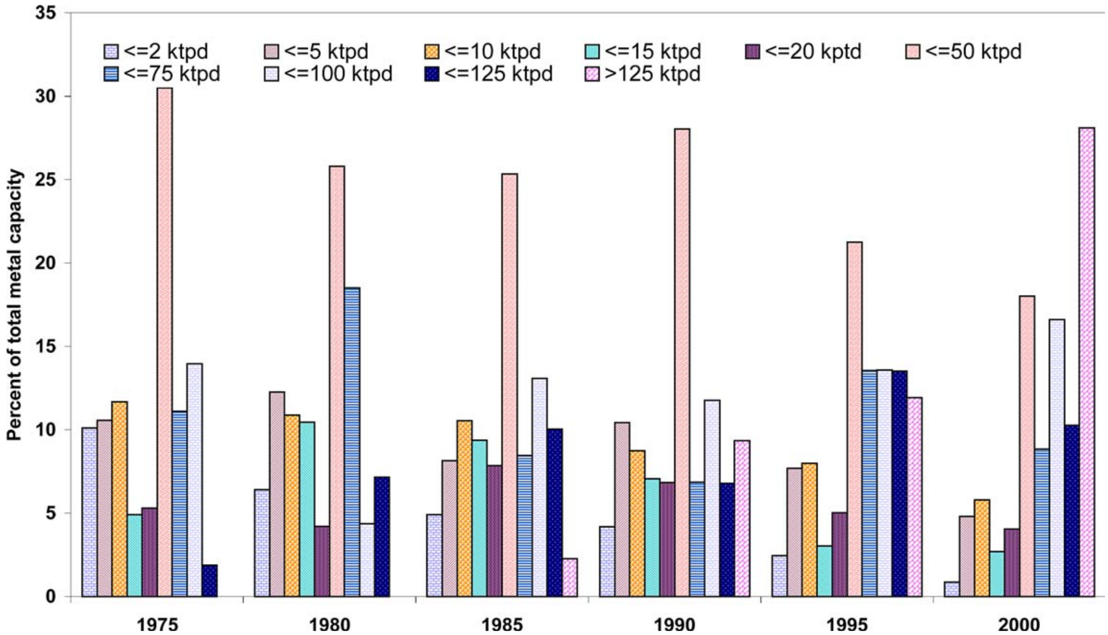

Fig. 15. Conventional copper mines; metal capacity by mill size. *Source*: Rio Tinto Mine Information System.

throughput grew by 4.5 times between 1975 and 2000, the upper quartile rose by a more modest 2.85 times.

Mill throughput depends not only on the daily milling capacity but also on its rate of utilisation. This can vary markedly, both between mines and over the course of the business cycle. Given all the variables involved no measure of capacity is precise and unequivocal. Nonetheless, changes in the size distribution of nominal daily mill capacity do give another indication of shifts in mine scale. Accordingly, Fig. 15 shows the distribution of the metal capacity of mines according to their mill sizes, in terms of daily ore capacity, at the five yearly intervals.

Almost one-third of metal capacity in 1975 was in mines with nominal daily mill capacities of 10,000 tonnes or less, and just under 2% in mines with milling capacities exceeding 100,000 tonnes per day. By 1990, the share of mines with the smaller mills had fallen below one quarter, and almost one-sixth had mill capacities of over 100,000 tonnes per day. In 2000 under one-eighth were in the smaller range against close to two-fifths in the larger.

Fig. 16 shows how the median and quartile mill sizes changed over the period.

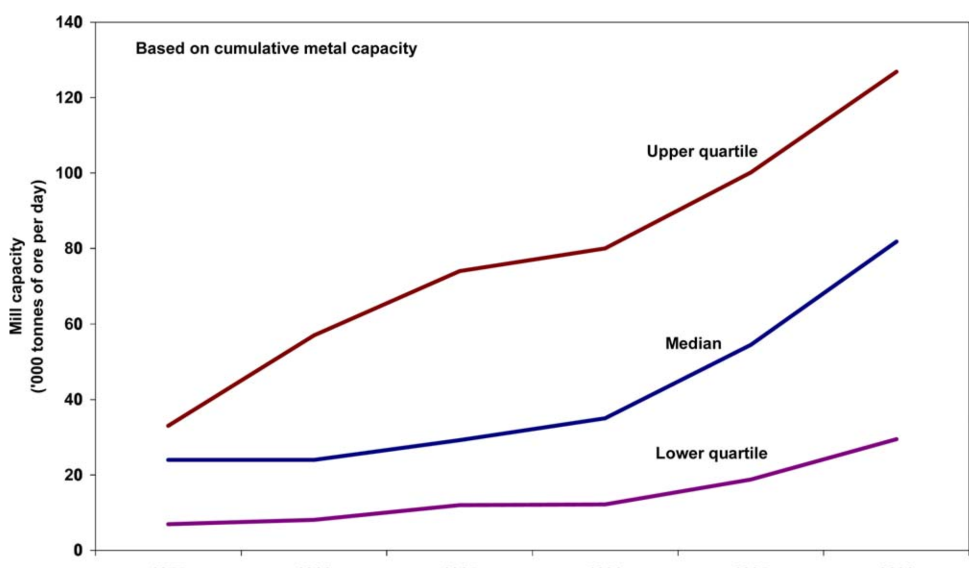

Fig. 16. Average daily mill capacity at conventional copper mines 1975–2000. *Source*: Rio Tinto Mine Information System.

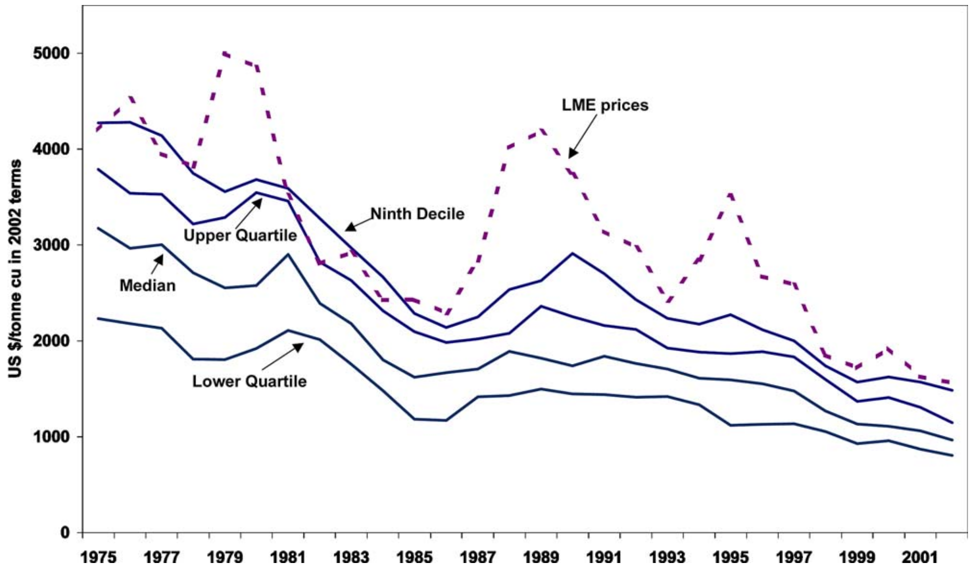

Fig. 17. Copper prices and cash costs. *Source*: Brook Hunt Associates. See Footnote [3].

The median mill capacity, based on cumulative metal capacities rather than mill sizes, grew by 46% from 24,000 tonnes per day in 1975 to 35,000 tonnes per day in 1990. Over the next decade it jumped by 134% to nearly 82,000 tonnes per day in 2000. This, like all the earlier figures, confirms that the scale of copper mines rose strongly in the 1990s. By 2000, the number of mines had fallen to less than one-third of its 1975 level, and to under half the 1990 level, but the amount of ore processed rose throughout. The impact of copper mining, in terms of its environmental footprint, became much less diffuse, in terms of the number of sites involved, but more intense at each remaining site.

Mine size and costs

It is an economic truism that the rising scale of production plants tends to lower unit costs over a wide range of output, before diseconomies of scale possibly set in. The capital costs of larger items of equipment does not rise proportionately to their increased capacity, and fixed costs of all types can be spread across larger outputs. We have demonstrated that the average scale of mines has increased throughout the last 25 years, but particularly in the past decade. The question is whether this growing scale has contributed to the industry's falling production costs.

The decline in both copper prices and production costs in recent years, as summarised in Fig. 17, is well documented.[3] This figure compares cash costs in constant 2002 terms at four points on each year's cumulative cost curve from 1975 to 2002. The points are the median, the lower and upper quartiles and the ninth decile of each year's cumulative production. Both costs and prices moved cyclically around declining trends, and the narrowing gaps between the four levels of costs imply a flattening of the cost curve over the period.

In a series of papers, John Tilton has emphasised the contributions made to falling costs by the growing share of SX-EW operations in total mine output, and by the application of advanced technology across the board.[4] The rising importance of leaching operations has been highlighted above. So too has the changing geographical distribution of global copper output. To the extent that production has risen in low-cost regions and fallen in high-cost regions there would have been a decline in the industry's observed costs. The contribution of economies of scale is separate from these technological and locational effects on costs.

The main impact of rising mine scale in mines with conventional milling circuits is likely to be on mining and milling costs. These are much more closely related to mill throughput than smelting and refining charges, which are often market-determined. This section concentrates on the relationship between mine size, as measured by ore throughput, and mining and milling costs per tonne of ore milled. Ore grades vary widely between individual mines so that there is unlikely to be any close relationship between mining and milling costs per tonne of copper and metal output The subsequent sections examine how the costs of copper produced vary with mine scale.

[3] The data on cash costs in Fig. 17 are from continuing annual surveys carried out by Brook Hunt Associates (defined as C1 costs in the surveys). The prices are annual average LME settlement prices for Grade A copper cathode.

[4] Tilton and Landsberg (1999). Tilton (2003) also summarises a list of references between 1999 and 2003.

Table 7
The relative importance of underground and open-pit copper mines

	Underground mines		Open-pit mines		% Share of U/ground	
	Number of mines	Tonnage milled (mn tonnes)	Number of mines	Tonnage milled (mn tonnes)	Number of mines	Tonnage milled
1975	250	211.4	126	508.3	66.5	29.4
1980	174	223.8	88	574.1	66.4	28.0
1985	155	239.7	67	571.8	69.8	29.5
1990	153	282.0	74	633.2	67.4	30.8
1995	88	175.4	50	756.4	63.8	18.8
2000	59	161.5	44	920.8	57.3	14.9

Source: Rio Tinto Mine Information System.

The relative growth of SX-EW production is not the only change in production techniques that has taken place over the period. Another has been a move in mines with conventional milling away from underground to open-pit mining. This is brought out in Table 7.

Underground mining held its own between 1975 and 1990, but its share of the tonnage milled halved during the 1990s. The fall in the proportion of underground mines was much less pronounced. The change is closely intertwined with the shift in the geographical location of production towards Latin America and Indonesia and away from countries like Canada and Central Africa.

The costs of mining and milling per tonne of ore milled (but not necessarily the total cash costs per tonne of metal produced), tend to be higher in underground than open-pit mining. That is demonstrated by the scatter diagram in Fig. 18, which separately plots the costs of mining and milling for individual underground and open-pit mines in 1975 against their ore throughput. The logarithmic scales of both axes in Fig. 18 illustrate the relationships more clearly than arithmetic scales. The costs have been adjusted to constant 2000 terms to ease comparisons between years. The deflator used here, and throughout the paper, is the United States' Implicit GDP Price Deflator. Alternative measures of inflation are much narrower in scope and do not fully reflect changes in purchasing power, even of individuals. Most of the points for underground mines are higher than those for open-pit mines at given levels of output. The regression lines further demonstrate that economies of scale have been more important for open-pit than for underground mines.

This tendency for costs to decline with mine size in both categories supports the existence of economies of scale, whilst the wide scatter emphasises that scale alone is by no means the only determinant of relative costs. Comparison of the data for 2000, shown in Fig. 19, with those of 1975 given in Fig. 18 suggests

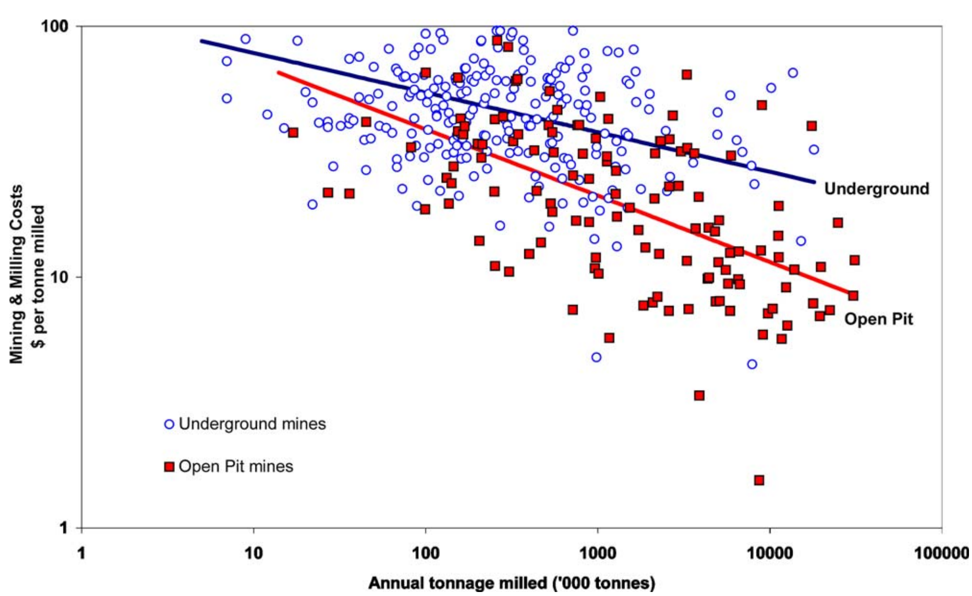

Fig. 18. Mining and milling costs at copper mines 1975 in 2000 terms. *Source*: Rio Tinto Mine Information System. *Note*: Thirteen underground mines, whose costs per tonne milled exceeded US$ 100/tonne in 2000 terms are omitted from the figure, but are included in the regression line.

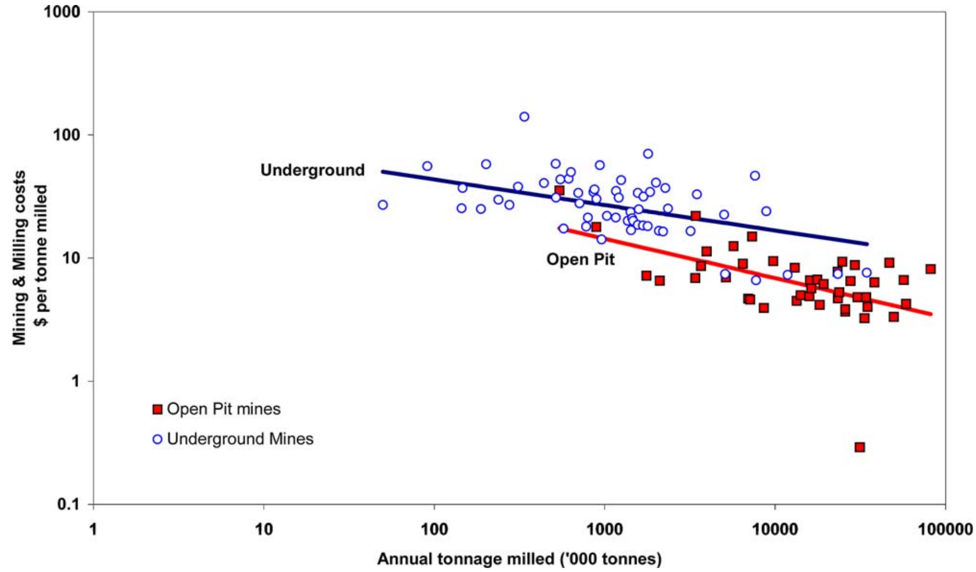

Fig. 19. Mining and milling costs at copper mines 2000. *Source*: Rio Tinto Mine Information System.

that scale economies became more important over the period.

There is a wide variety of possible equations linking costs (Y) and mine size (X). A simple linear arithmetic equation of the form $Y = a + bX$ implies that a given absolute change in mine size would result in the same absolute change in dollar costs, regardless of mine throughput. A slightly more sophisticated formulation relates costs to the logarithm of mine size ($Y = a + b \log X$), implying the same absolute change in costs for a given percentage change in mine output, again regardless of mine size. The effect is that the implied percentage change in costs becomes greater for a given percentage change in mine size the larger the size of the mine. Neither relationship appears plausible, and both equations suffer from a further disadvantage that estimated costs can be negative at levels of output that are well within the range of experience. That problem is avoided by the use of an equation relating the logarithms of costs to logarithms of mine size ($\log Y = a + B \log x$). Such a formulation implies that the percentage change in costs is the same for a given percentage change in output throughout the full range of mine size. In other words it assumes a form of constant returns to scale. This may also be rather simplistic, but comparison of the shifts in the coefficients of such an equation over time can illuminate the changes that have taken place.

Given the massive changes that occurred over the 25 year period, a constant relationship between mill throughput and unit costs through time appears rather unlikely. That would imply that there has been no change in economies of scale throughout the period, and that unit costs fell for other reasons such as productivity improvements, broadly defined. Therefore, we need to specify an equation that makes full use of all the relevant data, and that allows for a changing relationship between the two variables over time. The chosen equation is of the form:

$$\log Y = a + b \log X_{2000} + c \log X_{1990} + d \log X_{1975} + \breve{e}$$

where Y is the costs per tonne milled, X_{2000} is the tonnes milled in 2000, but zero otherwise. X_{1990} is the tonnes milled in 1990, but zero otherwise. X_{1975} is the tonnes milled in 1975, but zero otherwise. a, b, c, and d are constants, $\breve{e}$ is the error

The results are summarised separately for underground and open-pit mines in the next sections.

Underground mines

Between 1975 and 1990, the successive cumulative cost curves (plotting mining and milling costs per tonne milled in constant 2000 terms, against cumulative tonnes milled) generally moved downwards to the right. The trend was uneven, however, to the extent that 1980’s cost curve was above that of 1975 for much of its length. The drop in production from underground mines during the 1990s led to cost curves moving upwards to the left, as displayed in Fig. 20.

This method of presentation does not do proper justice to the changes over the period. Those are better illustrated by the scatter diagram of Fig. 21, which compares the scatters for 1975, 1990, and 2000, all in constant 2000 terms. A relationship between mine size and unit costs exists, but is fairly weak in each year shown. There is a variety of different methods of

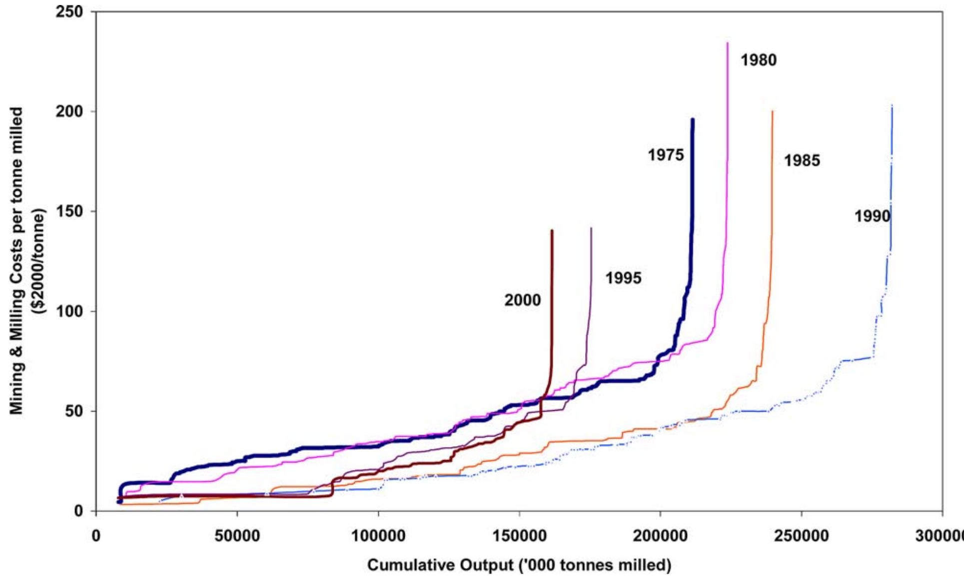

Fig. 20. Cumulative mining and milling costs at underground copper mines. *Source*: Rio Tinto Mine Information System.

underground mining, each suited to particular configurations of the host ore deposit. Each method incurs typical patterns of expenditure that are not brought out in these broad comparisons.

The regression lines shown in Fig. 21 imply that there was virtually no change in economies of scale between 1975 and 1990, but that they became more important during the 1990s. By 2000, a doubling of mine throughput resulted in a 13% reduction in unit costs. The equation underlying the regression lines, which is in the logarithmic form set out above, is summarised in Table 8. Scale is a statistically significant influence on costs, but by no means their only determinant.

Open-pit mines

The relative increase in production from open-pit mines is reflected in the changes in cumulative cost curves over the 1975–2000 period. There was a persistent shift downwards and to the right, as illustrated in Fig. 22.

This figure demonstrates the growth in open-pit production of the 1990s, when a number of large mines was constructed to meet the burgeoning demand for copper metal. Many were based on ore deposits that had been discovered, and even delineated, many years earlier, but whose development had been delayed, either by market conditions, or because of political

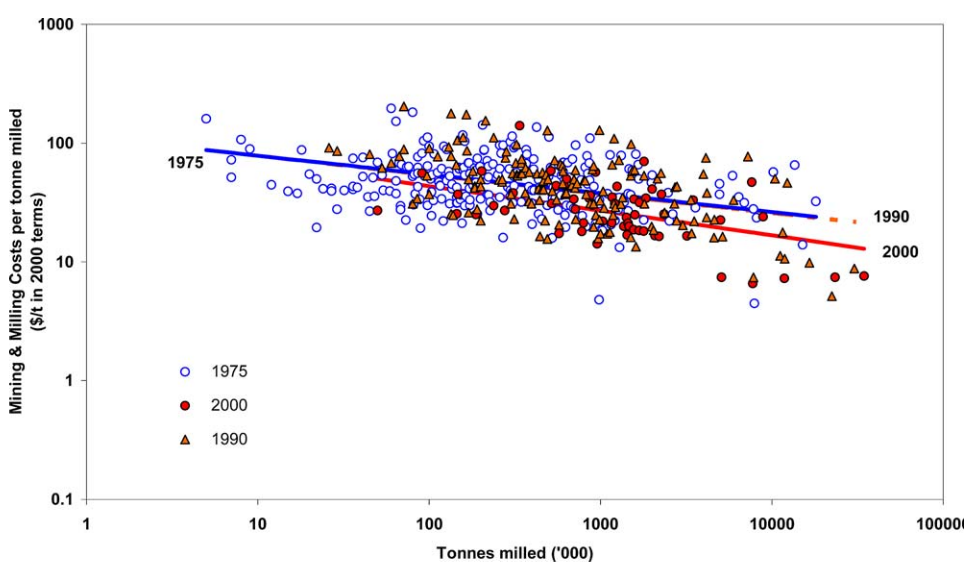

Fig. 21. Mining and milling costs at underground copper mines in 2000 terms. *Source*: Rio Tinto Mine Information System.

Table 8
Regression equation for underground mine size and costs

	Constant *a* (intercept)	Constant *b* (2000)	Constant *c* (1990)	Constant *d* (1975)
Coefficient	2.0522	−0.2071	−0.1599	−0.1581
Standard error	0.046	0.0175	0.0169	0.0188
t Statistic	44.48	−11.86	−9.43	−8.405
Observations	462			
R^2	0.245			
F	49.43			

circumstances. The liberalisation and privatisations of the 1990s gave a strong impetus to investment in previously sterile copper deposits in several Latin American countries.

Fig. 23, which is similar to Fig. 21, shows how the relationship between mine size and costs altered for open-pit mines between 1975, 1990, and 2000. Table 9 sets out the comparable equation for open-pit mines to that given for underground mines in Table 8. Both Table 9 and Fig. 23 support the contention that larger mines have tended to have lower mining and milling costs per tonne milled than smaller mines.

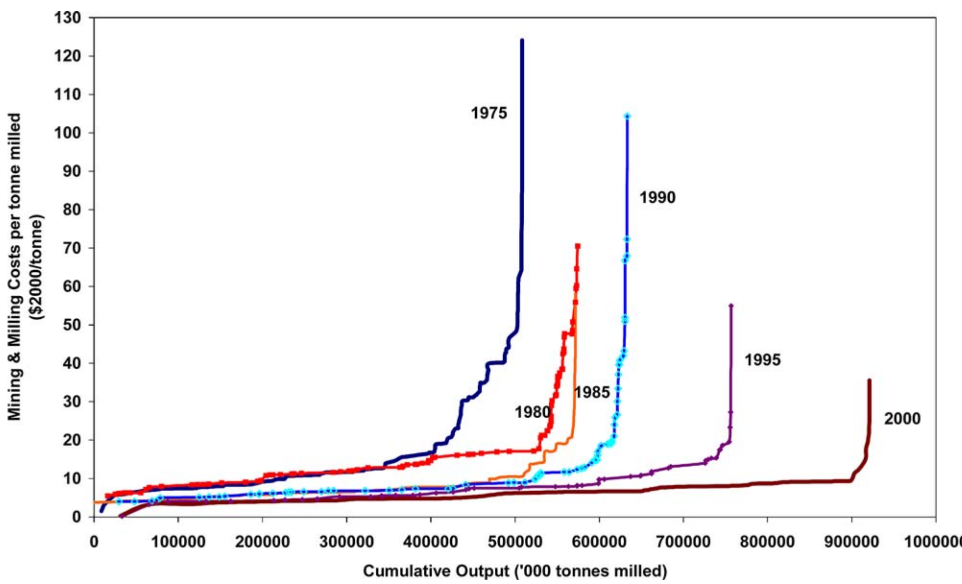

Fig. 22. Cumulative mining and milling costs at open-pit copper mines. *Source*: Rio Tinto Mine Information System.

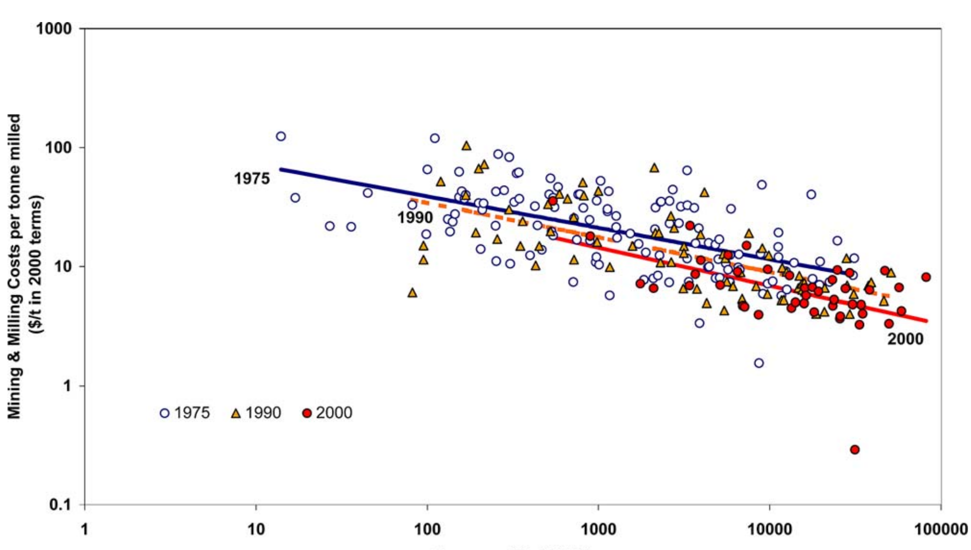

Fig. 23. Mining and milling costs at open-pit copper mines in 2000 terms. *Source*: Rio Tinto Mine Information System.

Table 9
Regression equation for open-pit mine size and costs

	Constant *a* (intercept)	Constant *b* (2000)	Constant *c* (1990)	Constant *d* (1975)
Coefficient	2.1188	−0.320	−0.291	−0.265
Standard error	0.080	0.021	0.024	0.025
t Statistic	26.40	−14.92	−12.21	−10.4
Observations	244			
R^2	0.514			
F	84.57			

The nature of the host rocks, stripping ratios, and geographical conditions differ markedly between open-pit mines, but they all use similar basic techniques. That probably explains why the relationship between mine size and cost has been much stronger throughout the period than for underground mines (an R^2 of 0.51 for open-pit mines against 0.24 for underground mines). In 2000 a doubling of mine size resulted in a 20% reduction in unit costs, against the 13% recorded for underground mines. In all cases costs are partly governed by the political, social and economic conditions of the countries in which the mines are located. These conditions probably vary more for underground than for open-pit mines, an increasing proportion of which are in Latin America. This growing homogeneity of locations may have contributed to a strengthening relationship between the scale of open-pit mines and unit costs throughout the past 25 years. A statistical relationship does not, of itself, establish causation. Many of the larger mines only entered production, or were substantially expanded, during the 1990s. In consequence they had access to the latest available technology that would have probably lowered their unit costs below those of longer established, and possibly smaller, rivals. This is not to deny the existence of economies of scale, which are clearly present, but to emphasise that other influences on relative costs are important.

During the 1990s, open-pit mines showed the same tendency as underground mines for an apparent flattening of the curve relating costs and scale. All the mines use similar processing technology to produce copper concentrates through comminution of the ore, followed by flotation. Leaching operations of all types have been excluded, regardless of their mining method, so that a switch of processing method would not explain this flattening. The 1990s did, however, witness many other technological improvements, and especially those linked to computerisation. These improvements were accessible to all mines, regardless of their scale. They possibly even enabled smaller mines to improve their relative costs and partially offset any disadvantages arising from their smaller scale. This is clearly an area for further research.

Copper output and costs

That mining and milling costs vary inversely with ore throughput does not necessarily imply any similar relationship between scale and the unit cost of production of copper metal. The average copper grade of ore milled varies between mines, and many mines yield a range of metals in addition to copper. The cash breakeven costs of production of copper, shown in Fig. 17 above, are estimated after allowing for by-product credits, the most common method of presentation of costs. That is appropriate when considering the relationship between cost and price, but not when looking at the linkages between costs and scale. Then costs before deducting by- or co-product credits and the total output of metal of all types become relevant. Merely adding the volumes of different metals produced in a mine is invalid as their values vary widely. Accordingly the production of by- and co-products is here converted to copper equivalents. These are calculated by valuing each mine's by-products at each year's prevailing prices and dividing their total value by the year's copper price to give a copper-equivalent tonnage of by-products. This is added to the mine's copper output to give its total copper-equivalent production. Total cash costs of production of copper metal are divided by this copper-equivalent production to give each mine's unit cash costs. Figs. 24–26 show the results for 1975, 1990, and 2000, respectively, for all mines that produced copper, regardless of their production process. The costs have been adjusted to 2000 terms. Fig. 26 is on a different scale to the other two. Each figure includes a regression line. The three years are not shown on one figure because the large number of observations obscures their messages.

Equations relating cash costs per pound of copper-equivalent production to mine size, expressed in terms of copper-equivalent production, are summarised in Table 10. The equations are in the same form as those of Tables 8 and 9.

Mine size has become a much more important influence on the costs of producing copper over the past 25 years. It was relatively insignificant in 1975 (as evidenced by the flatness of the regression line in Fig. 24 and the paltry level of the *t* statistic for constant *d* in Table 10). Scale, as measured by copper-equivalent production, had become a far more important influence by 2000. Economies of scale assumed their prominence during the 1990s, but the wide scatter of observations, even in 2000, shows that the much stronger relationships between mill throughput and the costs per tonne milled are weakened by other influences. That is to be expected, otherwise smaller mines would be forced out of business even more rapidly, and to a greater extent, than has been the case. Conversely, it might be argued that the substantial reductions in mine

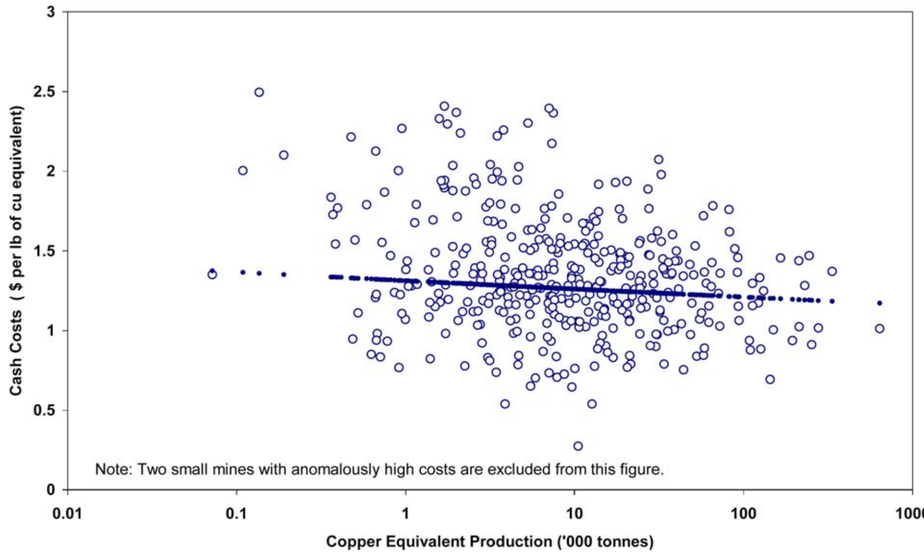

Fig. 24. Cash costs and copper-equivalent production 1975 in 2000 terms. *Source*: Rio Tinto Mine Information System.

numbers and the sharp growth in mine size over the whole period have demonstrated the potency of economies of scale, which may have been pushed near to the limit. That argument may, however, appear rather far fetched.

Individual mine operators often cite prospectively lower unit costs as one motive for expanding the size of their mines and associated facilities. What may possibly apply over time at the level of each individual operation does not, however, show up strongly in the aggregate cross-sectional data. One explanation is that maximising the potential volume of output is sometimes an important managerial objective in its own right, and that cost reductions are incidental benefits that are used as alibis. Another is that most mines have reached their present size through incremental expansion. Each stage uses the latest available technology at the time of the expansion, and does not replace all the existing equipment or working methods. Each mine therefore might have a range of costs associated with technology of different ages. That would tend to attenuate any relationship between size and costs.

Mine size and ore grades

It is not really necessary to seek complicated explanations for the weak correlation between size and

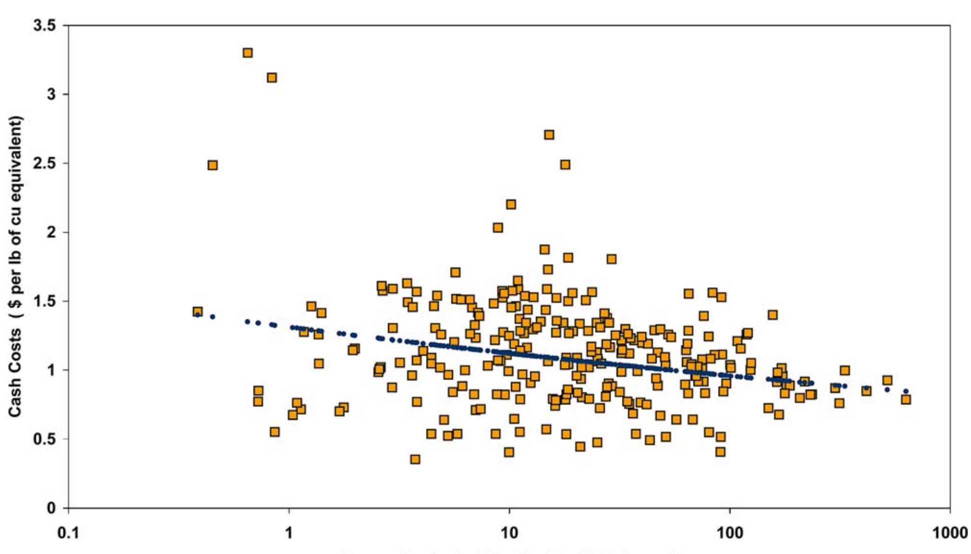

Fig. 25. Cash costs and copper-equivalent production 1990 in 2000 terms. *Source*: Rio Tinto Mine Information System.

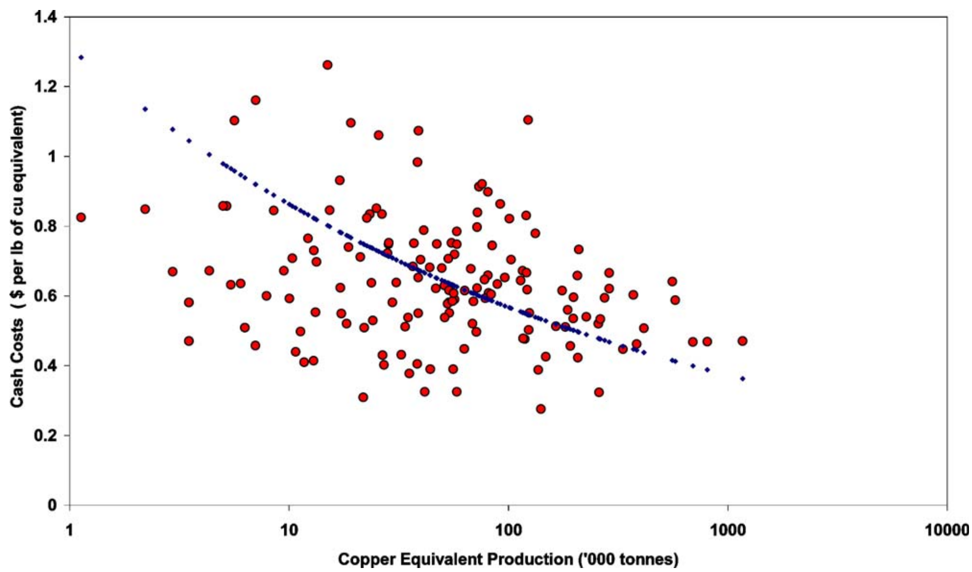

Fig. 26. Cash costs and copper-equivalent production 2000. *Source*: Rio Tinto Mine Information System.

Table 10
Regression equation for mine size and copper-equivalent costs

	Constant *a* (intercept)	Constant *b* (2000)	Constant *c* (1990)	Constant *d* (1975)
Coefficient	0.1180	−0.182	−0.0682	−0.0177
Standard error	0.0098	0.0082	0.086	0.0093
t Statistic	12.09	−22.26	−7.88	−1.9
Observations	814			
R^2	0.428			
F	201.96			

costs. One straightforward reason is that the lower costs of larger mines merely offset their lower grades of ore treated. Fig. 27 contains a scatter diagram relating mine size, as measured by tonnage milled, to copper-equivalent head grades in 1975, 1990, and 2000, respectively. These have been calculated in a similar fashion to the copper-equivalent production of the previous section. The grades of by-product and co-products are converted to copper equivalents using relative prices of the relevant years as weights. This does result in some apparently high copper-equivalent head grades, with 7% copper equivalent, or higher, in about

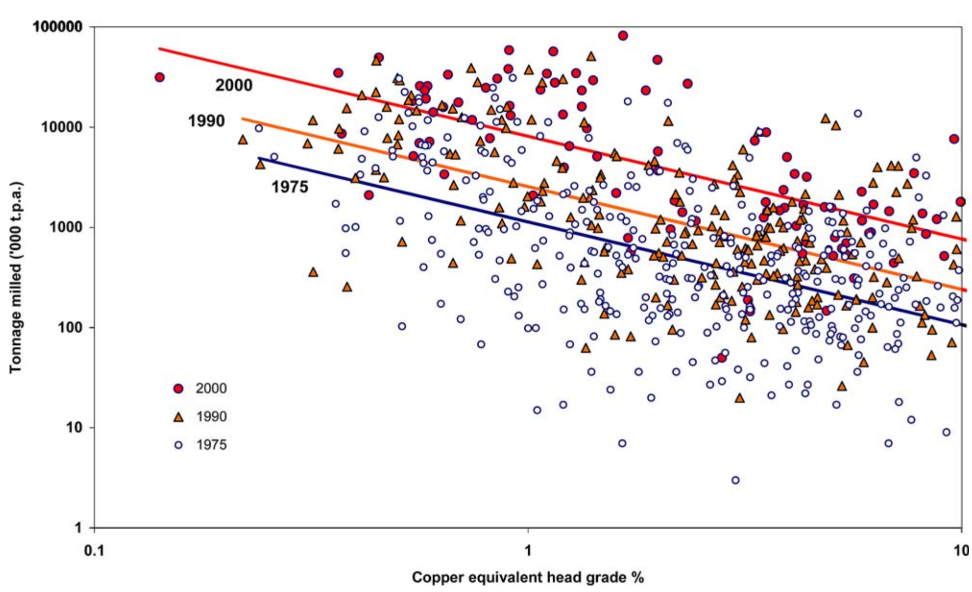

Fig. 27. Copper mine size and head grades. *Source*: Rio Tinto Mine Information System.

Table 11
Regression equation relating mine size and head grades

	Constant e (intercept)	Constant f (ore grade)	Constant g (Dummy 2000)	Constant h (Dummy 1990)
Coefficient	3.0546	−1.0258	0.855	0.352
Standard error	0.040	0.059	0.07	0.053
t Statistic	76.154	−17.38	12.22	6.62
Observations	665			
R^2	0.41			
F	156.25			

10% of the mines. These are mainly lead–zinc mines with good grades of silver and poor grades of copper, often associated with low copper recovery. Such mines also tend to have high costs per tonne of copper equivalent, and are smaller than many copper mines that have limited by-product values.

The figure is drawn on logarithmic scales in order to bring out the relationships between scale and grade. In each year there is a tendency for increasing scale to be associated with lower grades. The regression lines are derived from the equation set out in Table 11 that takes the form:

$$\log T = e + f \log Z + g \text{ Dummy 2000} + h \text{ Dummy 1990}$$

where T is the tonnage milled, Z the copper-equivalent ore grade, and e, f, g, and h are constants. All the variables are statistically significant.

The underlying assumption is that the basic relationship between size and grade is fixed through time and that size has been increasing largely for reasons other than changing ore grades. The mill throughput associated with a given ore grade increased by 125% between 1975 and 1990, and by a further 218% between 1990 and 2000.

The inverse association between mine size and head grades goes a fair way towards explaining why the relationship between mining and milling costs and ore throughput is greatly muted when costs are related to metal production. Other factors include varying recovery rates and the myriad other influences, including national economic conditions and managerial competence that impinge on costs.

Concluding comments

This paper has demonstrated that the size of mines, however measured, has grown over the last 25 years, and especially in the 1990s. It has shown that economies of scale do exist, when looking at mill throughputs, but that these are by no means the only influence on the relative costs of individual mines. There is an inverse relationship between ore grades and mine size, implying that scale is one means of offsetting the disadvantages of lower grades. The analysis suggests that the experiences of the 1990s, when demand was growing strongly, were different from those of the preceding 15 years.

Analysis of the relationship between scale and costs might be improved by going beyond the cross-sectional data used in this paper and tracking the experiences of individual mines. That might allow a disaggregation of the effects of changing scale alone from the many other influences on the trend of cost over time. A wide variety of technological developments have influenced costs throughout the whole range of mine sizes, especially during the 1990s when managerial attention was heavily focussed on methods of cost reduction. Analysis of the type suggested goes beyond the scope of the present paper. So does the construction of any more complex models relating costs, size, grades and other possible explanatory variables. That is another potentially fruitful area for further work.

References

Crowson, Phillip, 2003. Does size matter? Implications for exploration. In: Presentation to the Annual Conference of the Prospectors and Developers Association of Canada. Toronto. March 11th.

Survey of Capacities of Copper Mines, Smelters, Refineries and Copper Wire Rod Plants. Successive editions. International Wrought Copper Council, London, 2000.

Tilton, J.E., 2003. Creating wealth and competitiveness in mining. In Mining Engineering, September 2003. Society for Mining, Metallurgy, and Exploration Inc.

Tilton, J.E., Landsberg, H.H., 1999. Innovation, productivity growth, and the survival of the US copper industry. In: Simpson, R.D. (Ed.), Productivity in Natural Resource Industries: Improvement through Innovation, Resources for the Future, Washington, DC, pp. 109–139.