

**EXORCIZING THE RESOURCE CURSE:
MINERALS AS A KNOWLEDGE INDUSTRY, PAST AND PRESENT**

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July 2002**

Abstract

Recent literature argues that natural resource abundance is likely to be bad for economic growth. This paper provides a counterargument by highlighting examples of successful resource-based development. The first is historical: the United States from the mid-nineteenth century to the mid-twentieth. We show that U.S. mineral abundance was an endogenous historical phenomenon driven by collective learning, increasing returns, and an accommodating legal environment. Recent instances of successful resource-based growth affirm that so-called “nonrenewable” resources can be progressively extended through exploration, technological progress, and investments in appropriate knowledge. Indeed, minerals constitute a high-tech knowledge industry in many countries.

Keywords – mining, technology, resources, dutch disease

Introduction

Resource-based economic growth has had a bad press for some time. Adam Smith wrote:

“Projects of mining, instead of replacing the capital employed in them, together with the ordinary profits of stock, commonly absorb both capital and stock. They are the projects, therefore, to which of all others a prudent law-giver, who desired to increase the capital of his nation, would least chuse to give any extraordinary encouragement...” (1776, p. 562).

Perhaps abetted by the intuition associating “primary” products with “primitive” modes of production, coupled with the Ricardian-Malthusian premise that nonrenewable resources are fated to diminish over time (since as gifts of nature they cannot be replenished), the impression has been prevalent for at least two centuries that economic progress entails moving away from natural resources into sectors based on knowledge, skills, capital and technology.

Recent studies in development economics seem to add quantitative rigor to this impression. Richard M. Auty writes: “Since the 1960s the resource-rich developing countries have underperformed compared with the resource-deficient economies” (1998, p. viii). Sachs and Warner (1997) report that the adverse effect of a natural resource environment on per capita GDP growth is robust in the face controls for institutional quality, the share of investment in GDP, changes in relative prices, and other variables. The inverse association between resource abundance and growth has been widely accepted as one of the stylized facts of our times (Auty and Mikesell 1998, p. 6.) Although dissenting studies have appeared (such as Davis 1995), recent restatements by Sachs and Warner (2001) and Auty (2001) are virtually unchanged from the original. This “resource curse” hypothesis is often encountered and uncritically accepted in the popular press. (See James Surowiecki’s article in The New Yorker, “The Real Price of Oil.”)

Can it really be true that less equals more, that like King Midas, developing countries would be better off with smaller endowments of natural resources? Although models that generate this result have been developed, most researchers acknowledge that they do not know the underlying reasons for the reported econometric associations. There are good reasons to question whether these associations are true structural relationships inherent in resource-based activity. Cross-country regressions are notoriously subject to bias. If countries fail to build upon their resource base productively, then measures of “resource dependence” (such as the share of

resources in exports) may serve primarily as proxies for development failure, for any number of reasons that may have little to do with the character of the resources themselves.¹ When greater care is given to defining and measuring “resource abundance,” the results are quite different.²

The literature occasionally recognizes that there are exceptions to the general rule, countries well endowed with minerals whose economies have in fact performed successfully in recent decades. If there are prominent exceptions, can it then be true that “the problems of mineral economies [are] inherent to the production function of mining...” (Auty 1998, p. 46)? Since most treatments of the phenomenon culminate sooner or later in a discussion of politics, it would seem that (to quote the same author) “the staple trap is a less deterministic outcome than Sachs assumes and owes more to policy choice” (Auty 1998, p. 40). What we may have, in other words, is a set of countries whose political structures and institutions have failed to support sustained economic development. One can well imagine that in a setting of fragile institutions and factionalized politics, windfall resource gains may be a mixed blessing. But on this reading, the underlying problems are not inherent in the resources themselves, and the successfully managed resource economies surveyed in this paper are the exceptions that prove this rule.

The present paper develops this perspective by highlighting cases of successful resource based development. The first is historical: the United States from the mid-nineteenth century to the mid-twentieth. Not only was the USA the world’s leading mineral economy in the very historical period during which the country became the world leader in manufacturing (roughly from 1890 to 1910); but linkages and complementarities to the resource sector were vital in the broader story of American economic success. Subsequent sections describe successful modern development of the minerals sector in South American countries (Chile, Peru and Brazil) and in Canada, leading up to a more detailed look the remarkable rejuvenation of minerals in Australia – a country that had earlier consigned the resource-based phase of its development to history.

The broad lesson that emerges is that what matters most for resource-based development is not the inherent character of the resources, but the nature of the learning process through which their economic potential is achieved. The main failing of the recent literature is to regard natural resources as “endowments” whose economic essence is fixed by nature. This characterization does not fit US history, and it is no more appropriate for the resource-based economies of today.

The United States as a Resource-Based Economy

According to the figures of Angus Maddison, the United States overtook the United Kingdom in GDP per Worker-Hour as of 1890, and moved into a decisive position of world productivity leadership by 1913 (1991, Chapter 2 and Table C.11). Perhaps surprisingly, in the same historical phase the US also overtook the previous world leader in GDP per Worker-Hour, Australia. In a neglected footnote, Maddison writes: “In defining productivity leadership, I have ignored the special case of Australia, whose impressive achievements before the First World War were due largely to natural resource advantages rather than to technical achievements and the stock of man-made capital” (p. 45, note 1). Resource-based leadership, it seems, is a second-class variety, not to be confused with the real thing.

How unexpected it is, therefore, to find that in 1913 the United States was the world’s dominant producer of virtually every one of the major industrial minerals of that era. Here and there a country rivaled the US in one or another mineral – France in bauxite, for example – but no other nation was remotely close to the United States in the depth and range of its overall mineral abundance. Furthermore, there is reason to believe that the condition of abundant resources was a significant factor in shaping if not propelling the US path to world leadership in manufacturing. The coefficient of relative mineral intensity in US manufacturing exports actually increased sharply between 1879 and 1914, the very period in which the country became the manufacturing leader (Wright 1990, pp. 464-468). Cain and Paterson (1986) find a significant materials-using bias in technological change in nine of twenty US manufacturing industries between 1850 and 1919, including many of the largest and most successful cases. A study of the world steel industry in 1907-09 put the US at a par with Germany in total factor productivity (15 percent ahead of Britain), but the ratio of horsepower to worker was twice as large in America as in either of the other two contenders (Allen 1979, p. 919). Resource abundance was evidently a distinguishing feature of the American economy; yet economists do not seem inclined to downgrade US performance on this account.

There are good reasons not to. The American economy may have been resource abundant, but Americans were not rentiers living passively off of their mineral royalties. Clearly the American economy *made* something of its abundant resources. Nearly all major US

manufactured goods were closely linked to the resource economy in one way or another: petroleum products, primary copper, meat packing and poultry, steel works and rolling mills, coal mining, vegetable oils, grain mill products, sawmill products, and so on. The only items not conspicuously resource-oriented were various categories of machinery. Even here, however, some types of machinery serviced the resource economy (such as farm equipment), while virtually all were beneficiaries in that they were made of metal. These observations by no means diminish the country's industrial achievement, but they confirm that American industrialization was built upon natural resources.

The Endogeneity of American Mineral Resources

There is a deeper reason to reject the notion that American industrialization should be somehow downgraded because it emerged from a setting of unique resource abundance: On closer examination, the abundance of American mineral resources should not be seen as merely a fortunate natural endowment, but is more appropriately understood as a form of collective learning, a return on large-scale investments in exploration, transportation, geological knowledge, and the technologies of mineral extraction, refining, and utilization. This case is set out in detail by David and Wright (1997), and may be briefly summarized here.

For one thing, the United States was not always considered minerals-rich. Writing in 1790, Benjamin Franklin declared: "Gold and silver are not the produce of North America, which has no mines." (In 18th century, "mine" referred to an outcropping or deposit of a mineral.) Harvey and Press note that prior to 1870, Britain was self-sufficient in iron ore, copper, lead and tin, and "Britain was easily the most important mining nation in the world" (1990, p. 65). US lead mine production did not surpass that of Britain until the late 1870s. Leadership in coal came even later. Despite a vastly larger area, US coal production did not pass Germany's until 1880, and Britain's only in 1900. Leadership or near-leadership in copper, iron ore, antimony, magnesite, mercury, nickel, silver and zinc all occurred between 1870 and 1910. Surely this correspondence in timing among so many different minerals cannot have been coincidental.

In direct contrast to the notion of mineral deposits as a nonrenewable "resource endowment" in fixed supply, new deposits were continually discovered, and production of nearly all major minerals continued to rise well into the twentieth century – for the country as a whole,

if not for every mining area considered separately. To be sure, this growth was to some extent a function of the size of the country and its relatively unexplored condition prior to the westward migration of the nineteenth century. But mineral discoveries were not mere byproducts of territorial expansion. Some of the most dramatic production growth occurred not in the Far West but in older parts of the country: copper in Michigan, coal in Pennsylvania and Illinois, oil in Pennsylvania and Indiana. Many other countries of the world were large, and (as we now know) well endowed with minerals. But no other country exploited its geological potential to the same extent. Using modern geological estimates, David and Wright show that the US share of world mineral production in 1913 was far in excess of its share of world reserves (Table 1). Mineral development was thus an integral part of the broader process of national development.

David and Wright identify the following elements in the rise of the American minerals economy: (1) an accommodating legal environment; (2) investment in the infrastructure of public knowledge; (3) education in mining, minerals, and metallurgy.

US mineral law was novel, in that the government claimed no ultimate legal title to the nation's minerals, not even on the public domain. All other mining systems retained the influence of the ancient tradition whereby minerals were the personal property of the lord or ruler, who granted users rights as concessions if he so chose. This liberality was not entirely intentional, but emerged from the collapse of federal leasing efforts in lead mines between 1807 and 1846, and from the de facto nonintervention policy during the great California gold rush that began in 1848. The federal mining laws of 1866, 1870 and 1872 codified what was by then an established tradition of minimal federal engagement: open access for exploration; exclusive rights to mine a specific site upon proof of discovery; and the requirement that the claim be worked at some frequency or be subject to forfeit. Although the fuel minerals coal and oil have received separate treatment in the twentieth century, most US mining activity has been governed by the Mining Law of 1872, among the most liberal in the world.

It would be mistaken to view the encouragement to mining as flowing exclusively from a simple well-specified system of rights and incentives, because much of the best US mineral land was transferred into private hands outside of the procedures set down by federal law. Nearly six million acres of coal lands were privatized between 1873 and 1906, for example, mostly

disguised as farmland. Most of the iron lands of northern Minnesota and Wisconsin were fraudulently acquired under the provisions of the Homestead Act. Nevertheless, whether through official or unofficial procedures, the posture of American legal authority towards mining was permissive and even encouraging well into the twentieth century.

This discussion may convey the impression that the rise of US mineral production was primarily an exercise in rapid exhaustion of a nonrenewable resource in a common-property setting. Although elements of such a scenario were sometimes on display during periodic mineral “rushes,” resource extraction in the US was more fundamentally associated with ongoing processes of learning, investment, technological progress and cost reduction, generating a many-fold expansion rather than depletion of the nation’s resource base. A prime illustration is the United States Geological Survey. Established in 1879, the USGS was the most ambitious and productive governmental science project of the nineteenth century. The agency was successor to numerous state-sponsored surveys and to a number of more narrowly focused federal efforts. It proved to be highly responsive to the concerns of western mining interests, and the practical value of its detailed mineral maps gave the USGS, in turn, a powerful constituency in support of its scientific research. The early twentieth-century successes of the USGS in petroleum were instrumental in transforming attitudes within the oil industry toward trained geologists and applied geological science.

The third factor was education. By the late nineteenth century, the US emerged as the world’s leading educator in mining engineering and metallurgy. The early leader was the Columbia School of Mines, opened in 1864; some twenty schools granted degrees in mining by 1890. After a surge in enrollment during the decades bracketing the turn of the twentieth century, the University of California at Berkeley became the largest mining college in the world. The most famous American mining engineer, Herbert Hoover – an early graduate of Cal’s arch cross-bay rival, Stanford – maintained that the increasing assignment of trained engineers to positions of combined financial and managerial, as well as technical responsibility, was a distinctive contributing factor to US leadership in this sector. A manpower survey for military purposes in 1917 identified 7,500 mining engineers in the country, with a remarkably broad range of professional experience, domestic and foreign.

Technology and Increasing Returns: The Case of Copper²

Between 1900 and 1914, the copper mines in the United States produced more than ten times as much copper as did the mines of Chile; but this vast differential was not based on superior geological endowment. Figure 1 shows that Chilean copper production exceeded that of the USA until the 1880s, and nearly recovered its relative standing by the 1930s. During the 1880-1920 era of US ascendancy, however, there was no comparison. The rapid growth of US copper production illustrates the ways in which investment and technology can expand a country's resource base, effectively creating new natural resources from an economic standpoint.

The pure native coppers of the Great Lake region were indeed a remarkable gift of nature, but the capital requirements for profitable exploitation of this potential were immense. Along with the railroads, the copper companies of Michigan pioneered in the organization of the giant integrated business enterprise. Advances in the 1870s and 1880s reflected technological developments in drilling and blasting such as the use of nitroglycerine dynamite and rock drilling machines powered by compressed air. Steam engines were adapted to hoist ore from the deepest mines in the country, as well as in stamping and other surface operations. Beginning in the 1870s, national totals were augmented by production from newly discovered deposits in Arizona and Montana, but Michigan copper continued to grow absolutely until the 1920s.

What truly propelled the copper industry into the twentieth century was a revolution in metallurgy, overwhelmingly an American technological achievement. In the 1880s and 1890s, the major breakthroughs were the adaptation of the Bessemer process to copper converting and the introduction of electrolysis on a commercial scale for the final refining of copper. These advances made possible a nearly complete recovery of metal content from the ore. The dramatic new development of the first decade of the twentieth century was the successful application of the Jackling method of large-scale, non-selective mining using highly mechanized techniques to remove all material from the mineralized area – waste as well as metal-bearing ore.

Complementary to these techniques, indeed essential to their commercial success, was the use of the oil flotation process in concentrating the ore. Oil floatation called for and made possible extremely fine grinding, which reduced milling losses sufficiently to make exploitation of low-grade “porphyry” coppers commercially feasible.³

Together these technological developments made possible a steady reduction in the average grade of American copper ore, as shown in Table 2. By contrast, in copper-rich Chile – where output was stagnant – yields averaged 10-13 percent between 1890 and 1910 (Przeworski 1980, pp. 26, 183, 197). From these facts alone, one might infer that the US had simply pressed its internal margin of extraction further than Chile, into higher-cost ores. But Figure 1 makes it evident that the real price of copper was *declining* during this period, confirming that the fall in yields was an indicator of technological progress. Indeed, the linkage between yield reduction and the expansion of ore reserves was exponential, because of the inverse relationship between the grade of ore and the size of deposits (Lasky 1950). Advances in technology thus led directly to an expansion of American mineral wealth.

Capital requirements and the need for long time horizons made copper an industry for corporate giants, an organizational form in which the USA may also have had a comparative advantage. Large enterprises internalized many of the complementarities and spillovers in copper technology, but they also drew extensively on the national infrastructure of geological knowledge and on the training of mining engineers and metallurgists. Although the initial impact was primarily within US territory, ultimately these techniques and organizations were transportable internationally, and by the 1920s Chile's copper production was on its way back to world leadership, largely through American technology, expertise, and corporate organization.

Historians differ on the reasons for the Chilean lag. In the mid-nineteenth century, the Chilean industry was comparable to and probably superior to that of the US in its technological sophistication. But the supply of high-grade ores began to decline in the 1880s, and in contrast to the US, Chile did not respond to this deterioration with either new discoveries or technological adaptation. Political historians stress the lack of national consensus in support of the industry, and the predominance of revenue motives in government policy. Economists tend to emphasize the obstacles posed by large fixed capital requirements in transportation and other forms of infrastructure, as well as in mining and processing facilities. One might attribute the comparative performance to economies of scale at the national level, since the US had a much larger territorial area, and American copper benefited from engineering skills, geological knowledge, and transport facilities that were developed to support many other resources besides copper. Scale

economies were not independent of the legal and political regime, however; in Chile, for example, the mining code discouraged the consolidation of individual mining claims.⁴

Whatever the precise mixture of explanation, the important point is that Chile's problem was not its mineral endowment, but delay in developing its resource potential. The barriers were real, but large US companies found profitable what the Chileans did not, and investments by Guggenheim and Anaconda after the turn of the century began the long-term reversal of the industry's fortunes. Through massive investments in railroads, roads, steamships, water and housing, these private firms in effect created their own infrastructure.

Resource-Rich Underachievers

What was true of Chilean copper was also true of other areas of the world that are now known to be richly endowed with mineral resources: Latin America, Russia, Canada, even Australia – a country whose economic performance has been impugned for its excessive reliance on natural resources. European settlement of Latin America was largely motivated by the search for precious metals; but the Spanish and Portuguese rulers had little interest in possible spillover benefits from gold and silver mining to broader mineral development. Table 3 deploys the same methodology as Table 1 to show that as of 1913, the countries of Latin America had barely made a beginning at exploiting their potential in zinc, lead, bauxite, iron ore, phosphate rock and petroleum. Contemporaries and historians have found many rationalizations for this pattern of underachievement. But the proximate impediment seems to have been a lack of accurate knowledge about the extent and distribution of mineral deposits. A 1913 report by Orville A. Darby, calling attention to enormous undeveloped deposits of high-grade iron ore in Brazil, attracted great interest in that country. Yet even in the 1930s experts cautioned that “a belief that South America is a vast reservoir of untouched mineral wealth is wholly illusory” (Bain and Read 1934, p. 358). Somehow the illusions metamorphosed into real resource endowments within sixty years, as mining investments blossomed throughout Latin America in the 1990s.

Australia was a leading gold-mining country in the nineteenth century, but Table 4 shows that Australia was an under-achiever in virtually every other mineral, particularly coal, iron ore and bauxite. In a nation with a strong mining sector and a cultural heritage similar to that of the US, why should this have been so?

Here too it is easy to identify adverse factors that may have discouraged resource exploitation. The population of Australia has been small relative to its area, and the harsh climate of the large desert areas has discouraged migration from the coast. But similar conditions prevailed in much of the western USA. States like Montana, Utah and Arizona are not famous for their gentle climates. Australia did invest in institutions of learning related to mining (such as geological surveys, mining schools, and museums) and indications are that "a viable and independent technological system did develop in the years approximately 1850 to 1914" (Inkster, 1990, p. 43). Yet Australia lagged well behind other developed countries in engineers per capita (Edelstein, 1988, p. 14), and was heavily dependent upon foreign science. Into the 1880s, most large Australian mines were managed by Cornishmen, who had much practical experience but were untrained in metallurgy and resistant to new technology. The emerging Australian technological system was distinctly informal, reliant upon outside science, and lacking in scale economies relative to the U.S. In the early twentieth century, as Britain fell behind in minerals education and research, and as protectionist policies inhibited inflows of knowledge embodied in goods and people, the relative pace of learning in the Australian minerals sector decreased substantially. In a 1977 lecture at the University of Queensland, Raymond J. Stalker (a Professor of Mechanical Engineering) stated that "on the eve of the Second World War, the 'self-image' of Australia was that of a relatively unsophisticated and technologically dependent dominion of the British Empire" (as quoted in Magee, 1996).

Above all, what seems to have been missing in Australia was an atmosphere of buoyant expectations about the prospects for major new discoveries. Arguably as a result of the above factors in conjunction with low mineral prices, by the 1930s Australians had become pessimistic about the possibilities for further expansion of their natural resources. Sinclair (1976, p. 201) speaks of "a greatly reduced willingness to underwrite a process of development based primarily on the exploitation of natural resources." In parallel with growing concerns in other countries about the extent of natural resource supplies, Australians deemed it prudent to conserve minerals for domestic industries.

Pessimism led to misguided policies and lack of survey effort. In 1938, when Australia had recently begun to export iron ore on a small scale and gave promise of expanding this traffic,

the government imposed an embargo on all iron ore shipments in an effort to conserve the remaining supply – effectively raising a barrier to exploration that remained in place for the next 25 years. The policy was justified by a report to the Commonwealth in May 1938: “it is certain that if the known supplies of high grade ore are not conserved Australia will in little more than a generation become an importer rather than a producer of iron ore” (quoted in Blainey 1993, p. 337). As late as the 1950s, the accepted view was that Australian minerals were fated to diminish over time. A 1951 report stated:

We have been utilizing several of our basic metals at an ever-increasing rate and, with the development of many of the so-called backward nations, it appears likely that that rate will not diminish in the future; demand is likely to increase. We have not an unlimited supply of these metals available to us by economic processes as known today, nor is there any indication that sources other than the kind of ore-deposits worked today will become available to us. The capacity for production of some metals cannot be increased indefinitely...Periods of shortage such as we have experienced will recur more frequently. [Australian Bureau of Mineral Resources, Geology and Geophysics (1951)]

However, when the policy regime changed in the 1960s, lifting the embargo and offering state encouragement to exploration and construction of new ore terminals, a rapid series of new discoveries opened up previously unknown deposits, not only of iron ore but of copper, nickel, bauxite, uranium, phosphate rock and petroleum. By 1967 proved reserves of high-grade iron ore were already more than 40 times the level of 10 years earlier (Warren 1973, p. 215).

Prior to the 1960s, Australians accepted any number of unscientific rationalizations for the absence of important minerals such as petroleum: oil could not be found south of the equator; Australia’s rocks were too old to contain oil; the country had been so thoroughly scoured by prospectors that surely nothing valuable could remain to be found. But this very attitude could lead to lethargic and therefore self-confirming search behaviors. Geologist Harry Evans recalled his own classic “rational expectations” reaction when a search party from the Weipa mission on the Cape York Peninsula found extensive outbreaks of bauxite in 1955: “As the journey down the coast revealed miles of bauxite cliffs, I kept thinking that, if all this is bauxite, then there must be something the matter with it; otherwise it would have been discovered and appreciated long ago.” Indeed there was nothing wrong with it: by 1964 Weipa held about one-quarter of the known potential bauxite in the world (Blainey 1993, p. 332).

The outlines of Canada's mineral history are similar if less extreme. The Geological Survey of Canada was organized by Act of Parliament only in 1877, and did not issue a complete set of statistical returns until 1886. Nickel first appeared on the scene as a contaminating factor in copper refining. But after the discovery and commercial production of nickel-steel in France in 1885, the value of nickel as a mineral was recognized, and the area around Sudbury, Ontario, quickly became the world's largest producer.

Nonetheless, at the time of the world survey of iron ore resources conducted by the International Geological Congress in 1910, the Canadian correspondent reported that "in Canada comparatively little work of investigation has been carried on yet, and with the information at our disposal it would be impossible to venture to afford figures which could give even an approximate idea of what might be called iron ore reserves" (1910, p. 31). In its tabular summary, the Congress Report listed actual Canadian ore supplies as "Considerable" and potential ore supplies as "probably enormous." The report for the Yukon, Alberta and Saskatchewan frankly acknowledged "how difficult it is to come to any definite conclusions as to the available supplies of iron ores in such a large country as Canada, the greater part of which is practically unexplored" (p. 732). But failure to explore can often lead to the assumption that the resources are not there. As late as 1966, a distinguished Canadian economist wrote that Canada is not "rich in natural resources" relative to the United States (Dales 1966, p. 164).

Such relative assessments are questionable, because they depend upon on the extent of exploration, the technological sophistication with which exploration is carried out, and relative demand for various minerals. In the twentieth century, Canadians have been responsible for path-breaking innovations in metallurgy that significantly expanded the range of commercially exploitable ores (Dow 1985, pp. 214-223). In the year 2000, private-sector expenditures for mineral exploration in Canada were fifty percent larger than those in the United States, and significant new discoveries are regularly reported. Because of their experience and expertise, Canadian mining firms are now highly visible around the world. In 1999 there were over 3,000 mineral properties in more than 100 countries where Canadian companies were active; they accounted for 30 percent of large-company programs worldwide.

The Rise of Petroleum: Causes and Implications

The leading global mineral story of the twentieth century has been petroleum. In its origins and growth as an American specialty, petroleum illustrates the themes of this essay very well: mineral development as a knowledge industry; evolving institutional relationships among government agencies, academic institutions, and private corporations; and national economic strength emerging from a resource base. The usefulness of the liquid mineral originally known as “rock oil” was first recognized in the United States, which dominated world production for more than a century. New discoveries led to an ever-widening range of uses in the twentieth century. Oil-using technologies spread around the world under American influence. It would seem to be a classic example of a nation building comparative advantage around its resource base. Yet we now know that from a world perspective, the United States was not particularly well endowed with petroleum. Paradoxically, American technology launched a worldwide, century-long movement away from the use of a mineral for which the United States has enormous reserves (coal) in favor of a liquid mineral in which the domestic supply is drying up, and for which geographic linkages between resources and industry have been substantially weakened.

Before petroleum, the role of applied science in industry was negligible. When the first oil well was put down at Titusville, Pennsylvania, in 1859, the techniques used were well known from centuries of drilling deep wells for brine and water. As discoveries moved on to more difficult terrain, drilling was facilitated by technological improvements, such as the replacement of the cable drill by the rotary drill. The rotary drill was first applied to petroleum 1900, and was responsible for bringing in the Spindletop gusher of 1901. In addition to advances in machinery, the application of petroleum geology was critical. The increasing use of oil as an energy source, and the expanding range of petroleum byproducts with market potential, provided the “demand push” for the systematic deployment of scientific knowledge. At the Columbia School of Mines, the curriculum included instruction in the drilling of artesian, brine and oil wells, while Charles F. Chandler, its dean and professor of applied chemistry, devised the flash-point test for kerosene, and was the foremost chemical consultant for the industry at the time. During the 1880s and 1890s several pioneer American geologists were employed as consultants by oil operators to help locate deposits in the Appalachian fields (Williamson et al 1963, p. 441).

The major breakthroughs for petroleum geology came in the two decades after the turn of the century. At least forty professional geologists and geological engineers were employed in California between 1900 and 1911, probably more than in any other oil region of the world at the time. Working with reliable field data published by the U.S. Geological Survey, these early graduates of the University of California and Stanford were influential in popularizing the anticlinal theory of the structure of oil-bearing strata. While the major elements of the theory had been worked out before 1900, the discovery in 1911 of the rich Cushing pool in Oklahoma dramatically demonstrated that anticlines were favorable places to find oil. In 1914 the Oklahoma Geological Survey published a structure-contour map of the Cushing field clearly indicating that the line separating oil from water was parallel to the surface structure contours. For the next 15 years most new crude discoveries were based on the surface mapping of anticlines. Prior to the 1920s, oil development outside of the US and Canada was almost entirely based on surface seepage. Because of the absence of detailed structural maps, major potential fields in other parts of the world had been passed over (Owen 1975, p. 437).

It was not geology but this investment in geological knowledge that explains the long American domination of world oil production. Other producing centers did eventually emerge, most notably in the Middle East, which collectively passed the United States in 1960. The rich oil potential of the Middle East had long been suspected, but its exploitation was delayed by political turmoil and international rivalries. Informed people were aware even during World War II that the center of gravity of world production would shift to the Persian Gulf. But as late as 1948, estimated reserves in North America and the Middle East were closely matched. By the 1980s, total world reserves surpassed anything dreamed of in 1948. The Middle East held by far the largest share, but oil reserves in virtually every other continent have come to surpass those of North America. To some extent this trend towards globalization reflects the many years of depletion of the US stock. But the more important influence has been the spread of exploration around the world, using advanced science-based techniques for detection, and with drilling capabilities that make even deep offshore wells commercially viable. If all the oil extracted in the US since 1859 were put back in the ground, North America would still be a minor player in the world oil production picture today.

Oil and Economic Development

The historical American specialization in petroleum was thus not primarily a matter of endowment but of learning. One might well question, however, just what contribution this historical path has made to American economic development in general. Many modern analysts believe that the advent of petroleum has led to economic deterioration if not ruin for “petro-states” such as Venezuela (e.g., Karl 1997). Does the extended American love affair with oil have any lessons to offer on this score?

The discoveries of oil in the San Joaquin Valley, at Signal Hill, Santa Fe Springs and Huntington Beach did not bring economic ruin to southern California.⁵ Before 1900, California was a small, remote, peripheral economy, experiencing a long period of sluggish development. Between 1900 and 1930, California (not Texas) became the leading oil state in the nation, and the result was a “sudden awakening” of the regional economy. Spurred not just by jobs in the oil industry but also by the dramatic fall in the cost of energy, California’s share of national income nearly doubled; contrary to Dutch disease models, the size of the state’s manufacturing sector quadrupled. One clear lesson of the California oil history: do not restrict the indicators of progress to per capita income. With the rush of population, California’s level of per capita income continued its slow downward convergence toward the national average. But the state was launched on its modern course of leadership in technology and economic organization.

The transition from coal to oil entailed learning of many kinds, as California became the world’s first oil-fueled economy. Potential users had to “learn to burn” the new fuel, convert burners and establish fuel supply networks. The Southern Pacific Railroad began using fuel oil on a permanent basis after 1895, and switched over completely after 1900. The state’s electric utilities and sugar refining led the way, as virtually all of the large fuel consumers switched. With oil came a commitment to the gasoline-powered automobile, as California came to symbolize the high-mobility American lifestyle of the twentieth century. Although opinions are undoubtedly divided about the value of this lifestyle for humanity, one cannot deny that the institutions of higher learning that petroleum geology helped to put on the map – Berkeley and Stanford to name only the two most prominent – have evolved into world-class research universities.

The developmental contribution of oil was not limited to California. With the rise of

petrochemicals in the 1920s, one may say that petroleum was instrumental in the transition of American manufacturing from traditional mass production to science-based technologies. Prior to 1920, there was little contact between oil companies and the chemical industry. The rise of the US to world stature in chemicals was associated with a shift of the feedstock from coal tar to petroleum. Working in close partnership with M.I.T., New Jersey Standard's research organization in Baton Rouge, Louisiana, produced such important process innovations as hydroforming, fluid flex coking, and fluid catalytic cracking. As the chemical engineer Peter Spitz has written: "regardless of the fact that Europe's chemical industry was for a long time more advanced than that in the United States, the future of organic chemicals was going to be related to petroleum, not coal, as soon as the companies such as Union Carbide, Standard Oil (New Jersey), Shell, and Dow turned their attention to the production of petrochemicals" (Spitz 1988, p. xiii). Progress in petrochemicals is an example of new technology built on a resource-based heritage. It may also be considered a return to scale at the industry level, because the search for by-products was an outgrowth of the vast American enterprise of petroleum refining.

The Case of Norway

The reader may accept this analysis as history, and yet protest that it has little relevance for the newer oil-producing nations of the world. How could such newcomers expect to contribute to what is now an extremely advanced science-based world petroleum technology? In rebuttal, consider the example of Norway, in which the first commercial discoveries of oil occurred only in 1969. In many ways the Norwegian experience parallels that of California. Though not poor by world standards, Norway in the 1960s was remote and structurally underdeveloped. Yet in fairly short order, the country was able to reorient its traditional engineering skills from shipbuilding, to become a full partner in the adaptation of oil exploration and drilling technologies to Norwegian conditions. Virtually from the start, negotiations with international oil companies emphasized the transfer of competence and control to Norway. With the establishment of a state-owned company (Statoil) in 1973, and investment in the training of petroleum engineers at the Norwegian Technical University and Rogaland Regional College, "recipient competence" was transformed into "participant competence," making it possible to

speak of an independent Norwegian oil industry. The industry became expert at producing deepwater drilling platforms; initially designed to overcome immediate production bottlenecks, the platforms came to be export goods, as they proved useful for offshore drilling in other parts of the world. A distinctive approach to exploration developed at the University of Oslo's Department of Geology, focusing on the properties of different types of sandstone as reservoir rock and the flow of water and oil in sediment basins, has come to be known as the "Norwegian school of thought" regarding oil exploration. As a result, forecasts of impending depletion have been repeatedly overturned and reserve estimates adjusted upward. In effect, these advances in technology and in the infrastructure of knowledge have effectively extended the quantity of Norway's petroleum reserves, and they have allowed Norwegians to participate in the process as well-paid professionals, not just as passive recipients of windfall economic rents.⁶

Granted, Norway sets a high standard for national administrative competence and open and participatory democracy. As Karl notes, the Norwegian civil-service state was "the complete antithesis of Venezuela" (1997, p. 217), where intra-governmental political conflict and rent-seeking repeatedly disrupted the work of the state-owned oil development agency (PDVSA). Yet even in Venezuela, the PDVSA has been able to maintain a relatively high level of efficiency and expertise, with considerable success in developing technologies appropriate for the unusual concentration of heavy oil in the Orinoco Belt. Country-specific advances in heavy-oil technology led to a significant upward jump in Venezuela's oil reserves in the 1980s. Building on a legacy of professionalism from the international affiliates prior to nationalization in 1976, and aided by collaborative research agreements with BP Petroleum (a company with Canadian experience in heavy oil), PDVSA developed a new fuel (Orimulsion) for use by power utilities and heavy industry. Orimulsion is considered to have great potential, because it has a potential for gasification, can be used in a combined fuel cycle, and is environmentally friendly (Brossard 1993, pp. 170-177). Because of it, Venezuela is now in position to make full use of its previously uneconomic "sleeping whale."

Minerals and Economic Development: Modern Success Stories

Are mineral resources a sensible basis for economic development in today's world? One must acknowledge that certain things have changed over the past century. The rise of oil-based transportation was the first major crack in the breakup of the huge industrial concentrations that were dominant on the basis of locational economics, such as the "American Manufacturing Belt" in the northeast and midwest. Daniel Yergin portrays World War I as a metaphorical contest between the locomotive and the truck, the rigid technology of the past versus the high-mobility wave of the future (Yergin 1991, Chapter 9). The process of geographic dispersion was further advanced by electrification, the chief advantages of which were the speed at which power could be transmitted over long distances and the flexibility with which it could be deployed. Indicators of geographic concentration in manufacturing within the United States show a steady decline since World War II from the peaks of the 1920-1940 era, an indicator of underlying tendencies in a setting unconstrained by national boundaries (Kim 1995, Figures I and II). With the liberalization of world trade and the decline in world transportation costs, international differences in the costs of industrial inputs such as iron ore and coking coal fell to insignificance by the 1960s. For all of these reasons, industrialization behind the "natural protective barrier of distance" ceased to be a viable strategy for resource-producing countries. On the whole, these trends are favorable from a global perspective, because they have expanded opportunities for successful industrialization in countries with few natural resources on which to build. But does this imply that countries should not develop the resources they do possess?

The operational question is not whether countries should attempt to reinvent themselves as entirely different historical and geographic entities than they are in actuality – such things are not matters of choice. The practical policy issue is whether countries with resource potential should encourage investment, exploration, and research for the purpose of developing that potential to its maximum. Even skeptics about resource-based development concede that policies to restrict exports in order to "conserve" nonrenewable resources have had disastrous consequences (Auty and Mikesell 1998, p. 47). But such writers continue to base their analysis on the erroneous assumption that "natural resources, in contrast to assets produced by capital and labor, represent an endowment to society" (*ibid.*, p. 45); or that natural resource industries,

“which rely on exhaustible factors of production, cannot expand at the same rate as other industries” (Rodriguez and Sachs 1999, p. 278).

In reality, so-called “natural” resources require extensive investments before they are valuable – perhaps more so today than in the past – and the required investments include not just physical capital and transportation, but also the acquisition of knowledge about the resource base and the development of technologies that increase the value of that resource base. The fact that “information” can be disseminated costlessly and instantaneously around the world by no means implies that location-specific knowledge is no longer valuable. If anything, the opposite is true. Because extending the “knowledge frontier” can extend a country’s effective resource base, it is entirely possible for resource sectors to lead an economy’s growth for extended periods of time.

To be sure, there are risks associated with resource-based growth. Sudden windfalls or unexpected “natural resource booms” may disrupt otherwise healthy industries, calling for a level of policy restraint that may be difficult to achieve. Still worse, resource booms that channel profits directly to the state may constitute irresistible temptations for corruption and rent-seeking activity. It may even be, as Ascher (1999) has argued, that resource sectors are peculiarly vulnerable to such policy failures. One should note, however, that the essence of the policy failures described by Ascher was not the excessive expansion of resource-based activity, but political interference with incentives to develop these resources more fully. At times of fiscal crisis, cash-poor governments in both Mexico and Venezuela chose to raid the investment budgets of the state-owned oil companies, crippling development programs for a decade if not longer (Ascher 1999, Chapter 6). Statistical analysis of such episodes may tell us much about the pitfalls of resource management, but they do not justify a conclusion that resource development itself is mistaken as a national policy. By pointing instead to the successes of well-managed resource-based regimes, we can illustrate what is possible in today’s world

Latin America

Having neglected their resources for generations, and having stifled incipient expansion in more recent decades through misguided state policies, many Latin American countries turned the corner in the 1990s. The turnaround was fostered by reforms encouraging foreign investment in mining and increasing the security of mining investments – sometimes including privatization of mining companies, but also with strong roles for state geological agencies (World Bank 1996). Latin America is now the world's fastest growing mining region, well ahead of Australia, Canada, Africa and the US in its share of spending on exploration (Engineering and Mining Journal, January 2002, p. 29). The business press regularly reports new discoveries, new investment projects to develop existing deposits, and new technological developments that extend the mining potential of particular areas. The leaders in this burgeoning new minerals growth are Chile, Peru and Brazil. Argentina has yet to experience major minerals success, but maintains a high level of exploration activity, knowing that “the country as a whole is underexplored compared to its neighbors” (Mining Journal, April 20, 2001).

Chile

During the 1990s, the Chilean economy grew at a remarkable 8.5 percent per year. The mining industry has been central to this growth, accounting for 8.5 percent of GDP and 47 percent of all exports during the decade. Copper is still Chile's most important mineral; Chilean mined copper accounted for 35 percent of world production and 40.5 percent of Chile's export earnings in the year 2000. Chile also produces and exports substantial quantities of potassium nitrate, sodium nitrate, lithium, iodine, and molybdenum.

The Engineering and Mining Journal notes that “investment plans are...coming into the pipeline at a higher-than-average rate in Chile;” planned mine projects rose to US\$10.7 billion in 2001 (January 2002, pp. 29-30). As the Mining Journal comments: “Without successful exploration, many such projects would not have come to fruition.” The state mineral development company (Codelco) has been very active in exploration activity. Typical reported projects include: \$7 million “to continue delineating the Gaby Sur porphyry copper deposit located in Region II;” “Codelco plans to spend US\$20 million during 2001 quantifying reserves

at the Mina project in the north;” “Codelco was also active in a number of exploration joint ventures;” “Codelco is in talks to form a partnership with Ventanas, the copper smelter and refinery complex owned by another state body, Enami” (Mining Journal May 1, 2001). The relationship between ore grade and reserve quantity is illustrated by reports such as the one stating that “estimated resources at Escondida, which include resources used to define ore reserves, have increased significantly due to the release for the first time of low grade ore which is below the current concentrator cut-off grade but above the *economic* cut-off grade” (*ibid.*). Investments in exploration and processing continue to expand for an array of other minerals, even as production of almost every Chilean mineral continues to rise. In early 2002, Couer d’Alene Mines Corp. announced the discovery of high-grade gold and silver deposits on its Cerro Bayo property in southern Chile but noted that “only a small portion of the Cerro Bayo property has been explored” (Skilling’s Mining Review, February 2, 2002, p. 15).

Peru

Peruvian mining is considered the region’s “greatest success story.” After the privatization program started in 1992, mining exports doubled to \$3.01 billion by 1999. As of the end of 2001, Peru ranked second in the world in production of silver and tin, fourth in zinc and lead, seventh in copper and eighth in gold. Mining Magazine reports: “There is a determination that the mining sector should play an even larger role in the economy and a number of legal instruments are now in place aimed at promoting foreign investment...As mining regimes go, Peru’s can be fairly described as possessing an enabling environment” (May 1, 2001). The president of Codelco, Juan Villarzu, “liken(s) the country to Chile in the early 1990s” (Mining Magazine, January 2002, p. 12). That present development is far below potential is confirmed by such reports as: “Iscaycruz is one of the world’s highest-grade zinc mines, but at present operates on only 1,000 ha of the 52,000 ha it holds in concessions” (*ibid.*).

Yet Peru appears to be on its way to reaching this potential. For instance, “Roque Benavides, chief executive of Compania de Minas Buenaventura,...is forecasting that by 2008, output will have climbed to 1.38Mt for copper, 1.16 Mt for zinc, and 146 Mt for gold” (Mining Magazine January 2002, p. 6; these figures represent increases relative to 2000 of 145, 28, and 11

percent, respectively; note that this prediction was made before the Barrick gold discovery, discussed below). A US\$3.2 billion project began production at Antamina in 2001 and is expected to yield 675 million lbs. of copper over the first ten years (Mining Engineering December 2002, p. 21). In Yanacocha, "exploration efforts (by Minera Yanacocha, Latin America's largest gold producer) indicated major copper sulfide deposits under the gold deposits...Yanacocha may someday become a major copper producer in addition to gold" (*ibid.*, p. 21). In May of 2002, Barrick Gold Corp. announced the discovery of an estimated 3.5 million ounces of gold at its Alta Chicama property in southern Peru (Skillings Mining Review May 4, 2002, p. 8). Substantial investments in mineral processing facilities are also underway (Mining Engineering December 2001, p. 21).

Brazil

Brazil is the leading industrial nation of the region, though the share of the mining sector is low relative to its neighbors. Following an intensive government investment program in prospecting, exploration and basic geologic research (highlighted by the Radar Survey of the Amazon Region Project), mineral production grew at more than 10 percent per year in the 1980s. Exploration was interrupted between 1988 and 1994, because of restrictions imposed by the Constitution of 1988 on foreign participation in mining. These restrictions were lifted in 1995, and the government mining company (CVRD) was privatized in 1997 (US Geological Survey 1999). Mineral exploration activities expanded significantly in the 1990s, increasing both production and Brazil's reserves of most minerals. Currently Brazil produces more than 60 mineral commodities and is the world's largest exporter of iron ore.

At present, Brazil has only one copper mine and imports substantial amounts of copper. Because of a number of major discoveries in the Carajas region in Para State, however, Brazil expects "to occupy a prominent position in world copper production beginning in the period 2003-2005" (Mining Journal April 20, 2001). Production capacity for bauxite, which has already risen dramatically over the past two decades, is expected to increase further, with Brazil's largest bauxite producer planning to finish a \$200US million expansion by the end of 2002 (Mining Engineering, March 2002, p. 10).

Canada

Canada is at the forefront of high-technology research in mineral exploration technologies. Federal/provincial Mineral Development Agreements support geoscience, extraction and processing technology, but many initiatives are by the provinces. A program sponsored by Ontario is known as "Operation Treasure Hunt," the goal of which is to help identify new high-priority mineral targets of interest to the private sector. Its track record thus far illustrates the continuing importance of the "infrastructure of public knowledge." For example, discoveries by the Ontario Geological Survey of petalite-bearing pegmatites, beryl and spodumene in southeastern Ontario have led to aggressive exploration programs by several companies (Canadian Mining Journal January 1, 2001). The role of complementarities in search is illustrated by the nickel-copper-cobalt belt in Voisey's Bay, Labrador, (known as "Discovery Hill"), found while exploring for diamonds (Mining Journal March 30, 2001).

Canadian mining engineers and firms are leaders in automated mining techniques, such as automated rock monitoring with lasar, sonar, geophysical, and image-producing technology, and automated explosives handling, including the use of robotic arms to load blastholes (McAllister and Alexander 1997). Much of Canada's mining knowledge and technology have been applied to foreign soils, generating concerns about the future of the national industry itself. Investments in exploration and development seem to have reversed the trend in the mid-1990s, especially for diamonds, copper, and magnesium. Quebec and Ontario ranked at the top of an "Investment Attractiveness Index" based on the survey responses of 162 mining companies (Engineering and Mining Journal February 2002, p. 13). Planned mine project investments in Canada increased to US\$6.4 billion in 2001, with Canada moving up one place to fifth in the world in terms of this statistic (Engineering and Mining Journal January 2002, p. 30).

Australia

The most striking success story is Australia. Beginning in the 1960s, Australia witnessed a simultaneous resurgence of successful minerals search and economic growth. Figure 2 showcases a few of the dramatic increases in Australian minerals production that have occurred in recent decades. Contrary to earlier fears, increased production has not diminished mineral reserves. From 1989 to 1999, Australian mineral reserves expanded alongside production for 22 out of 32 minerals and for all but one (bauxite) of the seven major minerals in Figure 2 (Table 5). As the Mining Journal reports, "There have been 136 gold discoveries since 1970...In other mineral sectors and against a background of difficult commodity prices, (more) recent Australian successes include an entirely new mineral sands province, the Murray Basin; the development of lateritic nickel deposits such as Murrin Murrin, Cawse and Bulong, and sulphide nickel deposits such as Black Swan, Cosmos and RAV 8; and major zinc and copper discoveries such as Century, Cannington and Ernst Henry" (April 5, 2002, p. 244). The Australian minerals sector has created much more wealth than it has depleted; the real value of Australia's subsoil assets increased by almost 150 percent from 1990 to 1998, while the real value of the mining sector's capital stock increased by 40 percent over the same period, almost twice the rate for all other industries (Stoeckel 1999, pp. 18-19).

The case of Australia demonstrates that expansion of a country's minerals base can go hand in hand with economic growth *and* technological progress. The Australian minerals sector's share of GDP expanded through the mid-1980s (Figure 3) as Australia reversed more than a century of relatively slow GDP growth in reaching its current rank as the sixth wealthiest country. The surge in production of mineral inputs has carried a number of new and old industries along in its wake. In the decades following the onset of Australia's most recent minerals boom, leading manufacturing industries had obvious connections to minerals: metal and steel products, autos, industrial equipment, petroleum products, ships, and chemicals.

The Australian minerals sector is knowledge intensive. In the past ten years, income from Australian intellectual property in mining has grown from \$40 million a year to \$1.9 billion a year, a larger sum than that earned by the wine export industry. R&D expenditures by the mining sector accounted for almost 20 percent of R&D expenditure by all industries in 1995-96

(Stoeckel 1999, p. 17), a disproportionate contribution relative to the sector's share of GDP. The mining sector's contributions to Australia's human capital are also relatively large. From July to September of 1996, the mining sector spent an average of \$896 per employee on training, while the average for all industries was \$185; over the same period, the proportion of payroll spent on training was 5.8 percent for mining and 2.5 percent for all industries (Stoeckel 1999, p. 18).

As Australia's mineral production has flourished since the abandonment of the passive conservation policies of the 1930s, the country has emerged as one of the world's leaders in mineral exploration and development technology. "Australia leads the world in mining software and now supplies 60 to 70 per cent of mining software worldwide" (Stoeckel 1999, p. 25). Australia's unique geology calls for unique science; for example, World Geoscience, an Australian company, is a leader in the development of airborne geophysical survey techniques. Industry leaders have put forward an ambitious technological vision known as the "glass Earth project," a complex of six new technologies that would allow analysts to peer into the top kilometer of the Earth's crust to locate valuable mineral deposits. One executive stated: "The discovery of another Mt. Isa or Broken Hill – and we think they are out there – would lift us to fifth [place in the world]" (Cave 2001). Yet many of the technologies coming out of Australia's particular geological conditions find applications in other parts of the world and "Australian mining companies search the world for minerals, (with) the bigger Australian companies now spending 30-40 per cent of their exploration budgets offshore" (Stoeckel 1999, p. 31).

As environmental concerns increase, Australians also see promising opportunities to market the country's know-how and technology in cleaning up air, water and soil, recycling waste and eliminating pollution. According to the CEO of an environmental industry "venture catalyst:" "It is lovely that the environment benefits, but I'm really more interested in the business case and how it either saves costs or generates revenue. This field isn't recognized as a sector yet and Australia is well placed to take up a leading position" (Cave 2001).

The Development Potential of Minerals

Economists have known for some time that Harold Hotelling's theoretical prediction, that the scarcity and relative prices of nonrenewable resources would rise inexorably over time, has not been borne out by the facts of history. Jeffrey Krautkraemer's recent comprehensive survey of the evidence reaches the following conclusions:

For the most part, the implications of this basic Hotelling model have not been consistent with empirical studies of nonrenewable resource prices and *in situ* values. There has not been a persistent increase in nonrenewable resource prices over the past 125 years... Economic indicators of nonrenewable resource scarcity do not provide evidence that nonrenewable resources are becoming significantly more scarce. Instead, they suggest that other factors of nonrenewable resource supply, particularly the discovery of new deposits, technological progress in extraction technology, and the development of resource substitutes, have mitigated the scarcity effect of depleting existing deposits. (1998, pp. 2066, 2091).

But Krautkraemer's analysis, like virtually all economic writing on this subject, is conducted at the level of the entire market for a commodity, which is to say the world as a whole. Although this may be appropriate for testing the Hotelling thesis, these conclusions leave open the possibility that the spectre of depletion has only been staved off at the global level – i.e., in large part through the opening up of new or previously underexplored territories. What has not been appreciated is that the process of ongoing renewal of nonrenewable resources has operated within individual countries as well as across continents.

Table 6 displays average annual growth rates of mine production for eight major minerals in six relatively well-managed mineral-producing nations. The strong positive growth rates for the world as a whole reinforce Krautkraemer's point. But equally striking is the vigorous production growth of nearly every mineral in nearly every country. The one notable exception (among the minerals displayed in Table 6) is lead mining, for which production has declined in the world as a whole. This decline is presumably related to lead's unique position as a recyclable; two-thirds of consumption consists of scrap recovery, thus reducing demand for the newly mined mineral. For a true mineral economic success story like Australia, however, production growth has continued for every one of the minerals on the list, lead included. For the group taken as a whole, it is remarkable that production has expanded country by country across a twenty-year period during which real minerals prices have drifted steadily downward.

The error in most of the “resource curse” literature is not just the assumption that nonrenewables are fixed in quantity and therefore cannot grow, but the failure to differentiate between demand-side fluctuations and the determinants of long-run supply. Typical titles feature keywords such as “windfall” or “boom,” and the analysis concerns itself with optimal resource allocation in the presence of (to cite one recent work) “mineral deposits that could reasonably be expected to run out in the not too distant future” (Hannesson 2001, p. 6). Despite its hopeful title (Investing for Sustainability: The Management of Mineral Wealth), Hannesson’s book presents time graphs of mineral revenues (in various countries and in Alaska) that do not separate price from quantity effects, and thus convey a misleading impression that the declines since the 1970s are associated with resource exhaustion. The book never considers the possibility that a country’s resource base might be extended by investments in knowledge and relevant technology.

Many economists are aware of the global historical evidence but remain in the grip of the intuition that because minerals are nonrenewable, eventually they must grow scarcer -- these forms of advance serve only to “mitigate” the Hotelling forecast, so that “finite availability...has not *yet* led to increasing economic scarcity of nonrenewable resources” (Krautkraemer 1998, p. 2103, emphasis added). But if examples of successful country-specific mineral development are so numerous, the question arises whether common underlying processes in such countries may exist, and this possibility in turn leads to reconsideration of the sustainability of nonrenewable resources as a base for economic development.

Certainly we are not qualified to make pronouncements about the geographical distribution of minerals in the earth’s crust, much less within particular countries. But a cursory reading of the geological literature on mineral stocks convinces us that most geologists would not be surprised by the patterns we have described. DeVerle P. Harris, for example, notes in a recent survey article that “ore deposits of a specific kind, e.g., massive sulfide copper, are created from common crustal material by earth processes that are characteristic of that deposit type. Consequently, such deposits exhibit some common characteristics irrespective of where they occur, e.g., in the African or North American continents” (1993, p. 1035).

Among these characteristics are deposit size; average grade; intradeposit grade variation; and depth to deposit. Mapping the statistical properties of these distributions is now the object of

sophisticated, large-scale computer modeling, such as the Minerals Availability System (MAS) of the U.S. Bureau of Mines. The broad picture that emerges from such investigations is that the underlying elasticities of mineral supply are very high with respect to any number of physical and economic margins. The more that is learned about the effects of deposit features on “discoverability,” and the information gain that occurs from continued exploration within regions, the more it is evident that the potential for expansion of the resource base – the economically meaningful concept of mineral resource endowment – is vast if not unlimited.

In the important case of copper, an example of a geophysical relationship that would underlie open-ended progress is the proposition that there is an inverse relationship between the average grade of deposits and the mineral tonnage available at that grade. Harris and Skinner report that a belief in such a relationship is strongly held among specialists (1982, pp. 312-313). Although Harris (1993) suggests that the available statistical evidence may suffer from sampling and truncation biases (i.e., the contamination of geologic data by economics), it nonetheless seems that the long-term decline in the average yield of copper ore (depicted in Table 2) has continued through the twentieth century, supporting an ongoing increase in copper production, even while the real price of the mineral has fallen. If similar relationships are common, it is not difficult to imagine a future in which extension of the minerals frontier can continue indefinitely.

From the standpoint of development policy, a crucial aspect of the process is the role of country-specific knowledge. Although the deep scientific bases for progress in minerals are undoubtedly global, it is in the nature of geology that location-specific knowledge continues to be important. Sometimes this has to do with unique features of the terrain, affecting the challenge of extraction. At other times, heterogeneity in the mineral itself calls for country-specific investments in the technologies of manufacture and consumption. The petroleum industries of Norway and Venezuela, respectively, provide examples of these two possibilities. More generally, in virtually all the countries we have examined, the public-good aspects of the infrastructure of geologic knowledge have justified state-sponsored or subsidized exploration activities, often with significant payoffs to provincial or national economies.

Perhaps the clearest recent example of the importance of country-specific knowledge comes from the United States, a country that has extracted more minerals for a longer time period

than any other nation on earth, and yet is still among the world's mining leaders. Tilton and Landsberg (1999) recount the technological breakthroughs that have served to revive American copper mining in the 1980s and 1990s, after it had been pronounced dead by observers in the mid 1980s. The primary vehicle was not new discoveries and newly opened mines, but development and application of the solvent extraction-electrowinning (SX-EW) process, which separates the mineral from the ore more effectively and is especially useful for the leaching of mine dumps from past operations. Although this technology will ultimately become global, its near-term impact has been most significant in countries like the United States, which have substantial accumulated waste piles of oxide copper minerals, and where copper deposits are located largely in arid regions. The SX-EW process is also best suited for countries with stringent environmental regulations, which require recovery of sulfur emissions from smelting operations, thus providing a low-cost source of sulfuric acid for the SX-EW process. Thus there is a symbiotic relationship between the new SX-EW process and traditional technology (*ibid.*, p. 131).

Conclusion

This paper argues that the mineral abundance of the United States was an endogenous historical phenomenon, a forerunner for the many modern examples of successful resource-based growth. Contrary to long-entrenched intuition, so-called “nonrenewables” can be progressively extended through exploration, technological progress, and investments in appropriate knowledge. We suggest that such processes operate within countries as well as for the world as a whole. The countries we have reviewed are by no means representative, but they are far from homogeneous, and together they refute the allegation that resource-based development is “cursed.”

The resource price escalation of the 1970s did indeed constitute an exogenous unanticipated windfall boom from the perspective of many minerals-based economies. It is obvious in retrospect that those boom times were destined to end, and perhaps one can make the case that even in the midst of those turbulent times, countries should have been more aware of the ephemeral character of the boom and planned accordingly. Without doubt, many countries made poor use of these one-time gains. Nothing in this paper offers any guarantees against corruption, rent-seeking, and mismanagement of mineral and other natural resources. Our point is, however, that the experience of the 1970s stands in marked contrast to the 1990s, when mineral production steadily expanded primarily as a result of purposeful exploration and ongoing advances in the technologies of search, extraction, refining, and utilization; in other words, by a process of learning. It would be a major error to take the decade of the 1970s as the prototype for minerals-based development.

To state the obvious, we have no way of knowing *ex ante* whether all of the major minerals-based economies have comparable potential. But surely investing in such knowledge should be seen as a legitimate component of a forward-looking economic development program. The danger of the resource-curse thesis is that countries may be discouraged from pursuing this reasonable and potentially fruitful avenue for economic progress.

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Tables and Figures

Table 1: U.S. Share of World Totals (%)

	1913 output	1989 reserves	1989 reserves plus cumulative production	1989 reserve base plus cumulative 1913-1989 production
Petroleum	65	3.0	19.8	
Copper	56	16.4	19.9	18.5
Phosphate	43	9.8	36.3	15.4
Coal	39	23.0	23.3	
Bauxite	37	0.2	0.5	0.5
Zinc	37	13.9	14.0	15.6
Iron ore	36	10.5	11.6	7.4
Lead	34	15.7	18.1	18.8
Gold	20	11.5	8.6	8.4
Silver	30	11.7	16.3	17.6

Sources: David and Wright (1997), using data from: *Minerals Yearbook; The Mineral Industry--Its Statistics, Technology and Trade* (supplement to *Engineering and Mining Journal*); American Petroleum Institute, *Basic Petroleum Data Book*, Vol. X (September 1990); National Coal Association, *International Coal*; COE/EIA, *Annual Prospects for World Coal Trade* (1991).

Table 2: Average Yields of Copper Ore (%)

1800	English	9.27
1850	English	7.84
1870-1885	English	6.56
1880	American	3.00
1889	American	3.32
1902	American	2.73
1906	American	2.50
1907	American	2.11
1908	American	2.07
1909	American	1.98
1910	American	1.88
1911-1920	American	1.66
1921-1930	American	1.53

Sources: David and Wright (1997), using data from W. Y. Elliot *et al.* (1884), 'International Control in the Non-Ferrous Metals,' in R. Hunt, *British Mining and Metalliferous Metals*, p. 374; Y. S. Leong *et al.* (1940) 'Technology, Employment and Output per Man in Copper Mining,' WPA National Research Project Report No. E-12.

Table 3: Latin American¹ Share of World Totals (%)

	1913 output	1989 reserves	1989 reserves plus cumulative production	1989 reserve base plus cumulative production
Petroleum	7.4	13.4	21.8	
Copper	12.6	32.1	26.5	28.9
Phosphate	0.0	5.2		
Coal	0.2	1.1	1.0	
Bauxite	0.0	27.2	29.4	30.0
Zinc	0.6	11.1	12.1	10.2
Iron ore	0.02	12.5	12.0	9.7
Lead	4.8	10.7	13.2	11.8
Gold	5.6	4.4	4.4	4.3
Silver	38.6	30.3	30.3	27.8

¹South America plus Mexico and Caribbean.

Sources: David and Wright (1997), using data from: *Minerals Yearbook; The Mineral Industry--Its Statistics, Technology and Trade* (supplement to *Engineering and Mining Journal*); American Petroleum Institute, *Basic Petroleum Data Book*, Vol. X (September 1990); National Coal Association, *International Coal*; COE/EIA, *Annual Prospects for World Coal Trade* (1991); C. J. Schmitz (1979), *World Non-Ferrous Metal Production and Prices 1700-1976*, London: Frank Cass; B. R. Mitchell (1983), *International Historical Statistics: The Americas and Australia*, Detroit, MI: Gale Research Co.

Table 4: Australian Share of World Totals (%)

	1913 output	1989 reserves	1989 reserves plus cumulative production	1989 reserve base plus cumulative production
Copper	4.7	5.1	3.8	5.5
Coal	0.9	8.6	8.9	
Bauxite	0.0	20.2	20.5	20.5
Zinc	21.8	13.2	11.1	13.5
Iron ore	0.06	9.9	9.1	14.5
Lead	21.8	20.0	15.3	16.8
Gold	9.9	4.3	3.4	3.6
Silver	7.5	10.0	7.5	7.8

Sources: David and Wright (1997), using data from: *Minerals Yearbook, The Mineral Industry--Its Statistics, Technology and Trade* (supplement to *Engineering and Mining Journal*); American Petroleum Institute, *Basic Petroleum Data Book*, Vol. X (September 1990); National Coal Association, *International Coal*; COE/EIA, *Annual Prospects for World Coal Trade* (1991); C. J. Schmitz (1979), *World Non-Ferrous Metal Production and Prices 1700-1976*, London: Frank Cass; B. R. Mitchell (1983), *International Historical Statistics: The Americas and Australia*, Detroit, MI: Gale Research Co.

Table 5: Average Annual Percentage Growth Rates of Australian Mineral Reserves, 1989-1999

Mineral	Growth Rate (%)	Mineral	Growth Rate (%)
Antimony	17.84	Mineral Sands:	
Bauxite	-3.80	Ilmenite	10.92
Black Coal (in situ)	-0.92	Rutile	7.73
Black Coal (recoverable)	-1.34	Zircon	5.64
Brown Coal (in situ)	-1.01	Nickel	25.43
Brown Coal (recoverable)	-1.03	Petroleum:	
Cadmium	6.42	Condensate	4.64
Cobalt	47.51	Crude	0.42
Columbium	10.75	Liquid Petrol. Gas	3.54
Copper	13.07	Natural Gas	3.76
Diamond (gem)	-7.46	Silver	3.65
Diamond (industrial)	-8.77	Tantalum	8.04
Gold	12.94	Tin	-6.20
Iron Ore	0.81	Tungsten	-25.31
Lead	2.42	Uranium	1.88
Lithium	-8.00	Vanadium	33.51
Manganese	1.30	Zinc	4.60

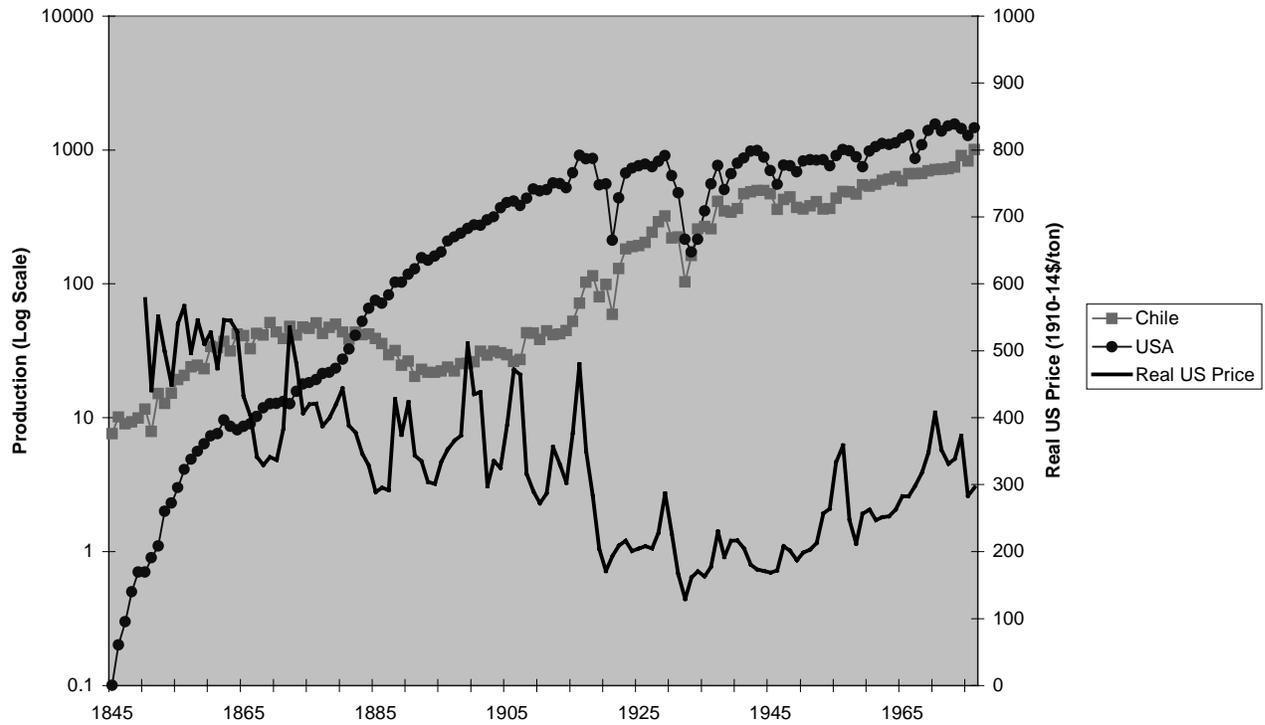
Sources: *Minerals Yearbooks* for 1989 and 1999.

Table 6: Average Annual Percentage Growth Rates of Mine Production for Selected Mineral/Country Pairs, 1978-1998

	Australia	Brazil	Canada	Chile	Mexico	Peru	World
Bauxite	3.0892	12.2992					2.0396
Cobalt	4.6849		8.4070				0.8472
Copper	5.1299	34.6073	0.3360	6.5619	7.9620	1.2379	2.1754
Gold	13.5510	10.0202	4.7462	12.8975	6.1938	16.7184	2.1278
Lead	1.8864	-4.3570	-3.2390	-1.4280	-0.2060	1.7171	-0.7870
Nickel	2.5485	9.1635	2.4511				2.7566
Silver	4.0146	12.6557	0.5891	9.6929	2.6175	3.8155	3.0069
Zinc	3.8370	4.7570	-0.7890	10.8042	2.1335	3.2539	0.8354

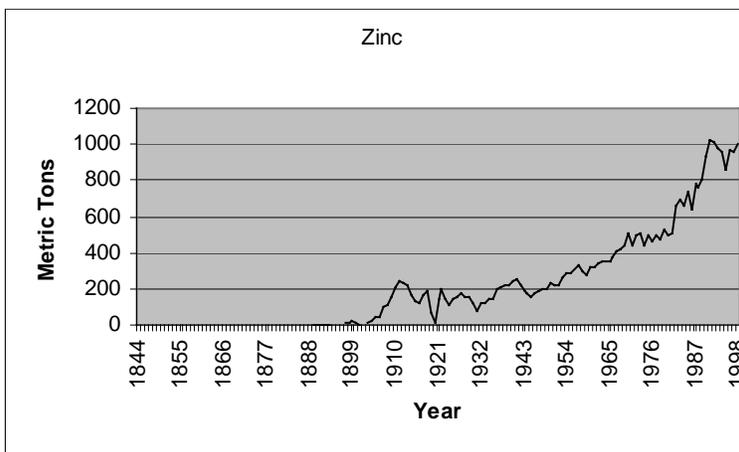
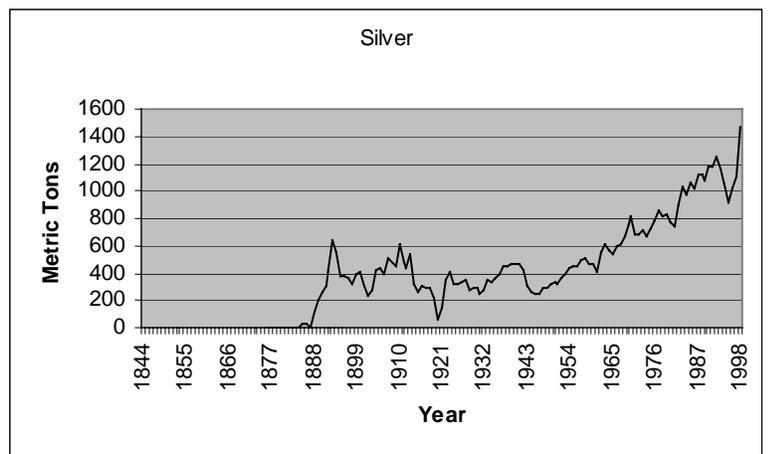
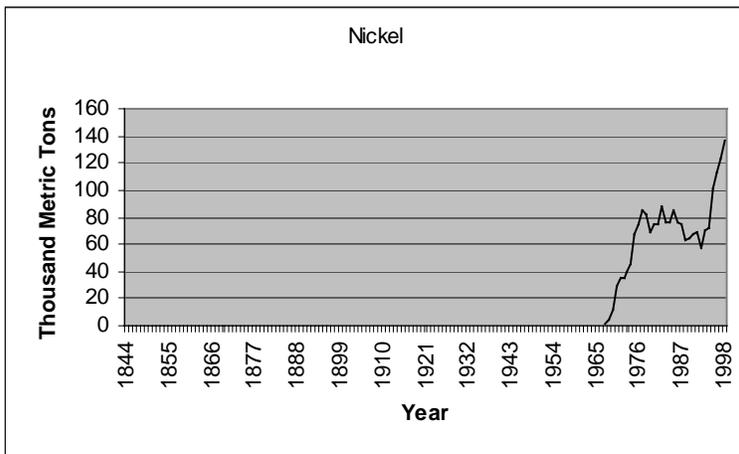
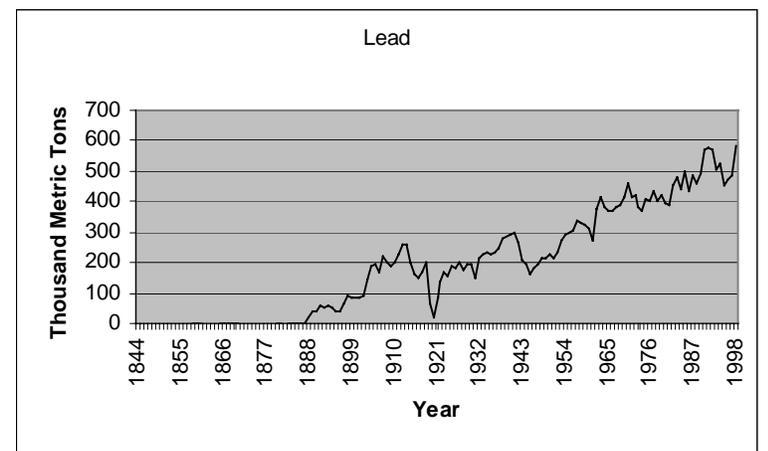
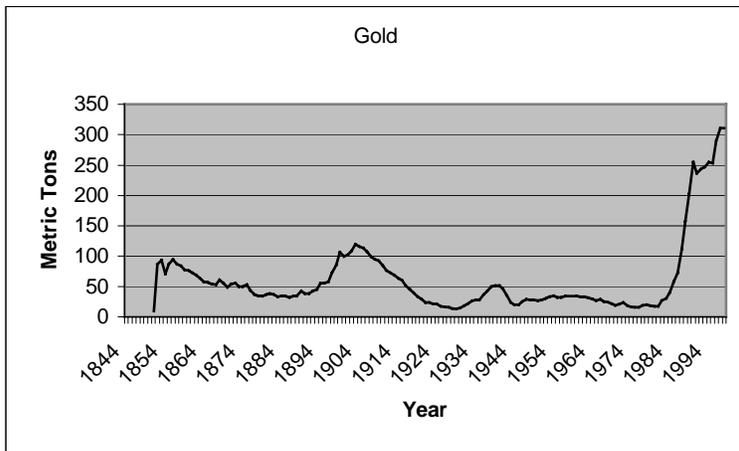
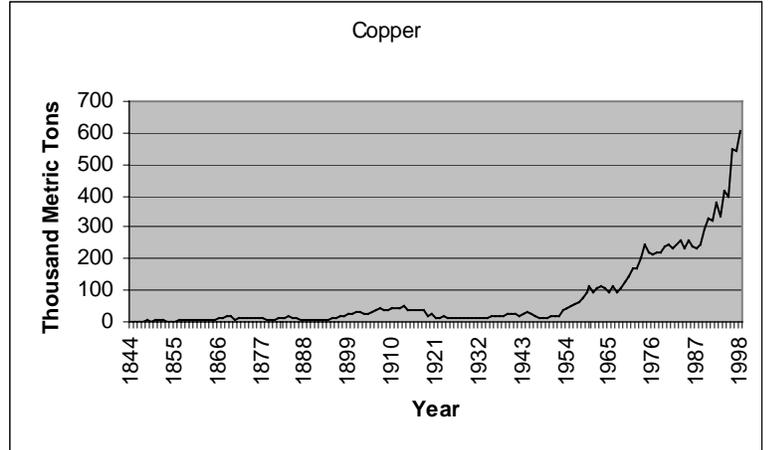
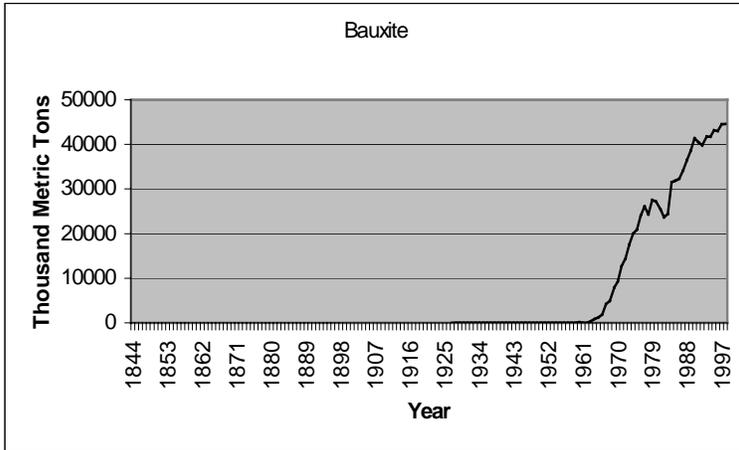
Sources: *Non-Ferrous Metals Yearbooks* (selected years from 1978 to 1998).

Figure 1: Copper mine production, United States and Chile, and real U.S. price of copper, 1845-1976

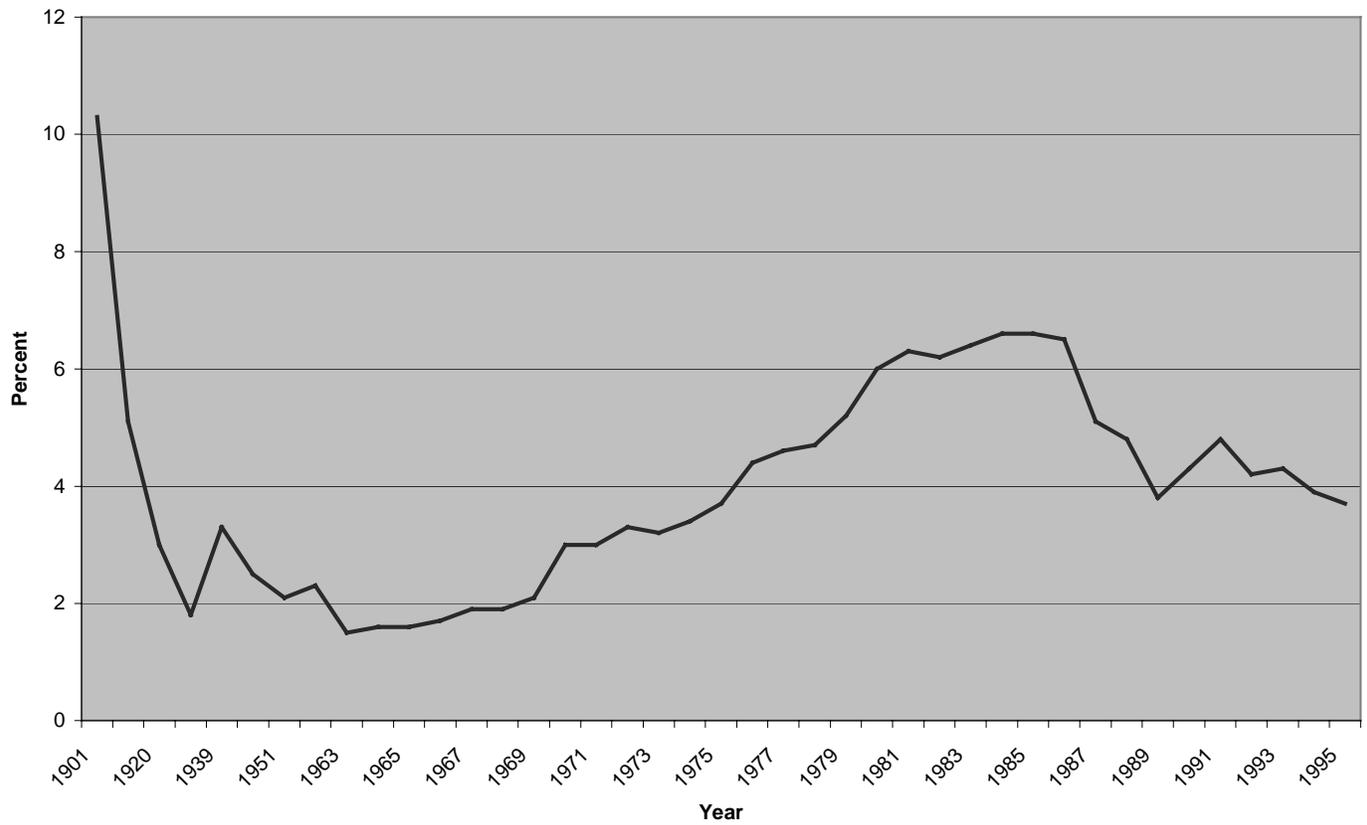


Sources: Wright (1999), using data from C. J. Schmitz (1979), World Non-Ferrous Metal Production and Prices, 1700-1976, London: Frank Cass, pp. 63-78 and 270-72.

Figure 2: Australian Mine Production, Selected Minerals, 1844-1998



Sources: Schmitz (1979) and American Bureau of Metal Statistics, *Non-Ferrous Metal Yearbook*, various years.

Figure 3: Australian Mining's Share of GDP at Current Prices

Sources: 1900-1963: Boehm (1979), pp. 10-11. 1963-1995: *Australian Commodity Statistics 1996*.

Notes

¹ This concern is especially acute in those studies for which resource-based sectors are taken to include crop-growing agriculture. The inverse relationships between resources and economic performance seem stronger for agriculture than for minerals and forest products. See Auty (1998, p. 7; Leamer et al [1999], pp. 38-39). Sachs and Warner assert, however, that variation in mineral exports accounts for a large fraction of the overall variation in their natural resource variable (2001, p. 831).

² See particularly the forthcoming dissertation at the University of California, Berkeley, by Stijns (2001).

³ This account of copper technology draws upon Parsons (1933), Schmitz (1986, pp. 403-405), and Lankton (1991, chs. 2-4).

⁴ Accounts of the contrasting histories of the Chilean and US copper industries include Przeworski (1980) and Culver and Reinhart (1985, 1989).

⁵ The discussion of oil in California draws on Rhode (1990).

⁶ There is little published literature in English on Norway's contribution to petroleum technology. The discussion here is drawn from unpublished research by Ole Andreas Engen, Odd Einar Olsen and Martin Gjelsvik of the Rogaland Research Institute in Stavanger, Norway. The reference to the "Norwegian School of Thought" comes from Appolon 2000: Research Magazine from the University of Oslo, pp. 28-29. Andersen (1993) presents some relevant material. Karl (1997) notes that Norway is an exception to her generalizations about the adverse effects of petroleum, but she does not discuss technological developments (pp. 213-220). Remarkably in light of this record, the most recent Norwegian study bemoans the general public's lack of appreciation for the nonsustainability of oil wealth, neglecting knowledge investments entirely [Hanneson (2001), especially p. 83].