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PLANNING AND SUCCESS OF MINERAL EXPLORATION IN THE UNITED STATES

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FOREWORD

In December 1983, the Mineral Trade and Markets Project sponsored a task force meeting on the Economics of Mineral Exploration in an effort to add to the limited literature available on this topic. The eleven papers prepared for this meeting focus on two important questions: First, what are the important factors influencing the overall level of exploration, as well as its allocation by geographic area and mineral target type? How important are mineral prices, political risk, new developments in exploration techniques, and other factors in this regard? Second, has the productivity of exploration been declining over time? Has it become more difficult and costly to find new mineral reserves because the easier to find deposits generally are discovered first? The papers are now being revised, and will eventually be submitted in an edited volume for publication.

An earlier version of this study on Planning and Success of Mineral Exploration in the United States was among the papers presented at the task force meeting. It was prepared by Arthur W. Rose, Professor of Geochemistry at the Pennsylvania State University, and Roderick G. Eggert, a Research Scholar at IIASA with a Ph.D. in Mineral Economics from the Pennsylvania State University.

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ABSTRACT

This paper examines three areas related to metallic mineral exploration in the United States: exploration success over time, the episodic nature of exploration activity for specific minerals, and exploration planning within large corporations.

The gross value of metallic mineral discoveries, excluding uranium and iron, exhibits no clear upward or downward trend from 1955 to 1980 in the United States, although large short-term fluctuations in discovery values make discernment of a trend difficult. When exploration costs are compared with these discovery values, the success ratio (gross value of discoveries/exploration costs) appears to decrease over time. Nevertheless, these calculations are fraught with uncertainty. Gross values for recent mineral discoveries are difficult to estimate, because it is unclear how many will actually come into production and because initial reserve figures are usually much lower than what ultimately is mined. Moreover, the expenditure data are drawn from a number of sources and must be viewed as estimates, not precise figures.

Exploration for copper, molybdenum, iron, gold, and uranium has been episodic over the last 80 years. Surges of activity, lasting for 5 to 15 years, are followed by periods of little exploration. The surges are often caused by increases in demand for a particular metal due to new uses, technologic changes in methods or mineral processing that permit different ore types to be used, and new geologic models of mineral occurrence that are used to guide exploration for specific types of deposits. Periods of inactivity result from mineral discoveries that significantly alter the supply of a metal (frequently due to successful exploitation of a new geologic or exploration model), and decreases in demand for a metal due to obsolescence.

A range of exploration management and planning styles exists in large companies, ranging from a "strong manager" to a "team management" approach. Although "team managements" have become more prevalent in recent years, some of the most successful exploration groups are organized around "strong managers."

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Planning and Success of Mineral Exploration in the United States

by

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Introduction

Short-term activities in U.S. mineral exploration are determined by the planning and decisions of mining companies. Longer term activities are strongly affected by the success rate in finding deposits and the costs of discovery. Although both these topics are of considerable importance, very little has been published on them.

In this paper, we report and discuss data bearing on the following questions:

1. How successful has metallic mineral exploration been in the U.S., and how much has been spent for exploration?

2. Is the success rate decreasing with time?

3. How has the success been distributed between major old-line mining companies, small mining companies, oil companies, individuals, and other organizations?

4. Does exploration and discovery occur at a uniform rate with time, or is it episodic, with booms interspersed with periods of activity, and what are the controls of this behavior?

5. What is the nature of exploration management in large U.S. companies and how does this relate to success?

6. To what extent have inflation, international instability, new methods of economic analysis and other recent developments changed the decision-making procedures in mineral exploration?

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Exploration Success

Economists might measure exploration success as the discounted net value of exploration activities, by comparing total exploration costs to the the net financial returns from mineral deposits discovered and brought into production. Mackenzie and Woodall (1983) have made this type of calculation for mineral exploration in Australia and Canada. Unfortunately, the data are completely lacking for the United States. This study, therefore, presents two simpler measures of exploration success in the United States since World War II: gross discovery values by five-year intervals, and success ratios (gross discovery value/cost of exploration). It is an extension of Rose (1982), which included a listing of mineral discoveries in the U.S. up to about 1980. The literature has been searched up through 1983 for additional discoveries and production decisions, and a few discoveries that were overlooked have been added.

In this paper, a discovery is defined as used by Cranstone (1983) as "a mineral deposit sufficiently attractive to have warranted the expenditure necessary to establish its tonnage and grade." The list therefore includes some deposits that are not now orebodies in the sense of current profitability, but all are at least major resources that could come into production under improved economic conditions. In general, deposits with a gross value less than $100,000,000 have not been included except for some minor metals. The main reason for excluding such deposits is two-fold: the smaller deposits are much more difficult to obtain data on, and they appear to be of little or no significance in evaluating the overall success of metallic mineral exploration. In other words, most of the value is accounted for by the large deposits. Because of this size exclusion, the list is not equivalent to lists for Canada, where the government has collected more detailed data over the years.

The list includes metallic deposits except uranium and iron. There is good data already available for uranium exploration success (Lieberman, 1976; U.S. Dept. of Energy Data). Iron is excluded mainly because it is not clear how to assign a value to iron deposits in the absence of a clear market price, but the discoveries since 1940 do not appear large enough to affect the results seriously.

The discovery date is also intended to follow the usage of Cranstone (1983), as "the year in which a drillhole intersected a mineral zone that was recognized within a relatively short period of time as being part of a mineral deposit so that its tonnage and grade were established." Because the table is based mainly on published data, it is likely that the true discovery date is earlier than that quoted for many deposits, but it seems unlikely that the dates are wrong by more than a year or two. The table is intended to include all large discoveries from 1940 through 1982.

A major question is the inclusion of announced "discoveries" that are not currently minable at a profit. Some of these discoveries are extremely large (Duluth gabbro Cu-Ni, Stillwater Pt.), and it is not clear whether these will be produced in the next 10 years or so. They have been included on the basis that they represent very large accumulations of metal that undoubtedly help to define an upper limit on the production costs of future deposits of economic interest; in addition these deposits may become major producers at some future date. A related question is the profitability of many of the producing deposits. Cook (1983) suggests that only 21 U.S. discoveries of non-uranium deposits since 1953 have been highly profitable, and represent the real goal of exploration. Limitation of the listing to only these highly profitable discoveries would considerably decrease the gross value of discoveries but only slightly decrease the profit, which is the real return.

The value listed is the gross value of contained metal at prices prevailing in 1981 (Table 1 footnote), based on announced information or estimates of the size of the deposits. These data are also subject to considerable error, because the ultimate size of some deposits is undoubtedly underestimated, and because some mineralized material may never be profitable to recover or because of decreased relative metal prices, not all of the quoted values will be recovered. These factors should partly cancel each other. The relative prices of various commodities have changed since 1981, and will undoubtedly change in the future. Nevertheless, the general nature of the figures should be valid.

One important problem is the success rate and cost of success in mineral exploration. Figure 1 shows the value of discoveries in the interval 1940-1982, classified into 5-year intervals. If only producing deposits are counted, the value of discoveries appears to have reached a peak in 1960-64 and then declined. However, it is almost certain that some discoveries from the 1970-80 period will come into production in the next few years (Thompson Cr., Id. and Red Dog, Wulik, and Green Creek, Alaska seem the best candidates, and others are likely). If half of the discoveries in 1975-79 come into production in the near future, as for 1960-64 and 1970-74, then the value of 1975-79 discoveries would about equal the value for 1960-64, the highest period. Based on this inference, it appears that the value of discoveries from 1955 to 1980 has averaged about $\$30 \times 10^9$ per 5-year period, with no clear trend upward or downward with time.

Evaluation of the cost side of exploration economics requires data on exploration expenditures. There are no good data on exploration expenses for minerals in the U.S. Data in Minerals Yearbook (U.S. Bur. of Mines) that purport to be "exploration drilling" actually appear to include all non-blasthole drilling at U.S. mines, including a great deal of percussion drilling for short-term mine planning as well as diamond drilling to allow medium-term development planning. Also, the data on feet of diamond and rotary drilling tend to decrease in the late 1970's whereas all other data show a large increase in exploration expenditures. This inconsistency suggests that the data may be less complete in recent years.

Data on "Census of the Mineral Industries" for 1977 do not allow separation of capitalized successful exploration from capitalized development at operating mines, but the 1977 figures in Table 2 probably include some expensed development at operating mines. Data for 1967 and 1972 involve similar ambiguities, as indicated by the footnotes to Table 2.

We have used the various estimates and reports listed in Table 2 and illustrated in Figure 2 to make estimates for exploration to the stage of discovery. The intent is to estimate exploration for metallic ores (except uranium) within the U.S. to compare with the discovery data. Unfortunately, it is not possible to separate uranium easily, though much of the U exploration is by companies not doing metals exploration. In some cases the numbers probably include foreign exploration by U.S. companies. For 1979-81, Barber (1981) showed that 35-40% of total expenditures by 12 large companies were foreign. Some of the data include only large companies. As can be seen, there are significant differences between the estimates, but none larger than a factor of two. For the early period, estimates made by AMAX are used. According to Pierce Parker (personal communication) these estimates were based at least partly on counts of identified exploration personnel in the AIME, multiplied by factors of dollars per explorationist. For the later periods, various surveys made by industry pesonnel are used. However, our own incomplete data suggest that the higher estimates must include a large component of foreign exploration and uranium, so we have used estimates for U.S. metals exploration near the lower estimates.

The estimates adopted are listed in Table 3, along with values corrected for inflation.

Data on uranium exploration expenditures have been collected since 1966 by the Atomic Energy Commission and its successors (Table 4 and Figure 3). It is apparent that in the late 1970's, uranium exploration expenditures exceeded other metals. The inclusion of part of these expenditures in some estimates of Table 2 is believed to account for the major discrepancies.

Using the above estimates, Figure 4 shows the trend of the exploration success ratio (value discovered /deflated cost of exploration) plotted against deflated cumulative cost (in 1981 dollars and 1981 metal prices).

The existence and steepness of any trend on Figure 4 clearly depends on how one evaluates the deposits not yet in production. Taking only deposits in production, the success ratio decreases with time by more than a factor of 10 in 25 years. A decrease of this magnitude is similar to that observed for oil (Menard and Sharman, 1975) and uranium (Lieberman, 1976). However, as noted previously, at least some of the non-producing discoveries are almost certain to be produced in the next 5 years or so. If the proportion is similar to that estimated for Figure 1 ($25 x 10^9 for 1970-74; $47 x 10^9 for 1975-79), then the success ratio decreases at a somewhat lower rate. Even less of a decrease is possible if a larger proportion of the non-producing discoveries are to be counted. In summary, the success ratio for minerals appears to decrease with time, but the decrease is not as large as for oil and uranium.

The absolute value of the success ratio ranges from about 20 to 60 if it is assumed that at least half the discoveries will eventually produce. These ratios imply that the cost of discovering metallic minerals is 2 to 5% of their gross value. Similarly, Brown (1983) indicates that the cost of finding gold in the United States in the period 1960-1980 has been \$8 to \$30/oz., or about 2 to 8% of its value. As noted by Brown (1983) and others, the success ratio for different companies ranges widely, and some companies have been much more fortunate or less fortunate than the averages. This topic will be discussed further in a later section.

The discoveries have been classified by type of company in Table 5. The bulk of the discoveries in both number and value have been made by the major metallic mining companies, but medium-sized mining companies have been relatively successful, as have non-metallics companies that have entered the metallic field. Oil companies appear to have been relatively unsuccessful, especially in finding deposits that can be put into production promptly. Small mining companies, stock promotions and individuals have also been very successful for their size, though this segment does not appear to be nearly as important as in Canada, where securities laws make raising capital on the stock market much easier. In Canada, 62% of the discoveries in 1951 to 1974 are reported to have been made by small mining companies (Snow and MacKenzie, 1981). In the U.S., many additional discoveries with size below \$100 x 10^6 gross value are certain, probably with a considerable proportion by small companies, but it seems unlikely they would account for 60% of all successes in the U.S. The nature of some of these small companies is not clear, but comments on several of the most successful may be instructive.

Banner Mining started with a small underground copper mine and a 300 ton per day mill near Lordsburg, N.M. The acquisition of claims, starting in

1950, on part or all of 3 major porphyry copper deposits, 2 of which are developed and producing, has been described by Bowman (1963). The cash flow from the one operating mine plus shrewd acquisition of mining claims on promising small copper mines and one government development loan were used to prove, develop and mine progressively larger deposits, largely under gravel-covered areas, until the major properties were finally sold to Anaconda-Amax in the 1960's, reportedly for about $20,000,000, to become the Twin Buttes mine plus portions of the Pima-Mission mines and undeveloped resources at Helvetia.

Another outstanding success was the discovery of the Kalamazoo orebody by Quintana Minerals. This orebody is actually the faulted half of the San Manuel porphyry copper orebody but owing to complex geology and extensive cover in the area, the deposit was not apparent to geologists working in the district. A consultant, J.D. Lowell, was responsible for recognizing the correct geology and pressing for drilling of the 3000-4000 ft. drillholes needed to discover the orebody, which has since been sold to San Manuel Copper for a reported $27,000,000.

Inspection of Table 1 suggests that small companies may be making a higher proportion of discoveries in recent years than previously. In part this results from more complete data for recent years, but it is also believed to be a real trend. The small gold deposits that are a major focus of U.S. exploration since the late 1970's can be discovered and developed with relatively small expenditure and pay back their investment in 1 to 2 years. The relatively small size of these gold deposits compared to the deposits discovered in previous years leaves questions as to whether exploration by very large major exploration companies will be viable in the future, although the Carlin district and surroundings, which are the best of the districts, continue to be very profitable for Newmont.

Table 6 summarizes the discovery history and value by geological deposit types. As can be seen, porphyry copper, porphyry molydenum and magmatic copper-nickel-platinum deposits are the largest classes by far. The high value for magmatic sulfides is based completely on unmined discoveries so this class is of uncertain economic significance. Discovery of the porphyry deposits reached a peak in the 1960's and early 1970's and declined thereafter. The Mississippi Valley lead-zinc, exhalative lead-zinc-silver, and sediment-hosted gold are also important types. Mississippi Valley lead-zinc deposits have been a continuing target with considerable success in Missouri and Tennessee. The exhalative lead-zinc, sediment-hosted gold, and epithermal gold only became popular targets in the 1970's, but are currently a major focus of exploration because of their precious metal content, and in the case of the exhalative deposits, high grade coupled with significant tonnages. Volcanogenic massive sulfides, a major target in Canada from the 1950's to the present, received increased attention in the U.S. during the 1970's, with some success.

Beginning in the 1950's and increasingly in the 1960's and 1970's, exploration has been to be increasingly oriented toward these specific geologic deposit types. Geologic models of idealized deposit geology were developed as the basis for reconnaissance exploration and follow-up of favorable indications. Previously, mineral occurrences found by general prospecting tended to be evaluated on an individual basis, with comparison to other deposits made only after the occurrence was found and was being evaluated for followup.

As an example, the model for porphyry copper deposits includes the following components:

1. Occurrence in a granitic porphyry stock and in adjacent sedimentary and igneous country rocks.

2. Association with andesitic volcanics, developed in a subduction-zone environment.

3. Metals include Cu, Mo (richest within deposits formed in continental environments), Au (richest in deposits formed in island arc environments), and Ag; these byproducts may be useful geochemical guides as well as being economically important. In addition, Pb, Zn, Ag, Mn and other metals may occur in small deposits or geochemical anomalies around the periphery of the copper deposits.

4. The Cu sulfides and accompanying pyrite are disseminated in very large volumes of rock, and the pyritized rock can extend to several kilometers from the deposit, forming a halo that increases the target size. In addition to visual observations, the sulfides can be detected by the induced polarization (I.P.) geophysical method, a new technique developed to help exploration for these deposits, especially where a cover of younger rocks conceals the sulfides.

5. Extensive alteration of the host rocks to clay, mica, feldspar, and other minerals extends out as much as several kilometers from the deposit. The alteration is zoned, forming a "bulls-eye" in many cases that can guide exploration to the ore. Accessory magnetite is destroyed in most alteration, but is added in skarn zones if limestones are present, leading to magnetic anomalies.

6. The host rock is extensively shattered, commonly in one or two preferred directions that coincide with regional lineaments and swarms of igneous dikes that may assist in locating favorable targets.

The application of this model allows detection and efficient exploration of deposits that are concealed by younger rocks, which cover 2/3 of the favorable region in southwestern U.S., thus providing much greater potential for discovery. Similar models now exist for all the deposit types of Table 6, as well as other types (Ohle and Bates, 1981; Cox, 1983). The development and refinement of these models is now a major focus of effort in exploration by major companies (Wilson, 1982).

Time Aspects of Exploration for Specific Metals

A closer look at exploration and discovery suggests that exploration may be episodic in nature, at least during some stages of the process. This behavior is well illustrated for copper in Figure 5.

Initial deposits of native copper discovered in about 1845 in northern Michigan required only simple crushing and gravity separation to obtain the metal. Grades were apparently several percent Cu. The ores occurred in geologically relatively simple flow tops and thin conglomerates. No further major discoveries were made until 1870, when Butte, Montana was found. The Butte ores (at this period) were in very high grade veins (5 to 20% Cu with significant silver and some gold. The veins had complex structural relations that spurred development of geological techniques for predicting extensions, but the grade was high enough to support relatively expensive underground mining.

In 1899, Daniel Jackling recognized the potential for low-cost open pit mass mining of relatively low grade "porphyry copper" ore at Bingham, Utah (Parsons, 1957). The ore had a grade of 2% Cu but copper minerals were relatively uniformly distributed through a large mass of "porphyry", a granitic igneous rock. Jackling was initially ridiculed because the grade was similar to the tailings (waste after processing) at Butte, but by mining and processing large tonnages by new methods, Jackling achieved competitive costs. The age of electricity had started, furnishing an increased demand for copper. The success at Bingham, coupled with increased demand, spurred discovery and development of seven other porphyry copper deposits in western U.S. and two in Chile in the period 1900-1915. The extremely high-grade non-porphyry deposit at Kennecott, Alaska was also discovered in 1900 and put into production in 1911.

Although production at Bingham was started on the basis of about 12 million tons of 2% copper ore, it was readily apparent that very much larger tonnages of lower grade ore were present. By increasing the scale of operations and by applying the new process of flotation to separate the copper minerals from useless gangue, profitable grades dropped to about 1% in 1925 and 0.8% in 1960. The total production of Bingham to 1972 was 1.24×10^9 tons of 0.91% Cu, plus valuable byproducts of 0.036% Mo, 0.0064 oz/T Au and 0.058 oz/T Ag, with a total value of $\$35 \times 10^9$ at the prices of Table 1; in addition, 1.7×10^9 tons with 0.71% Cu still remained in 1972 (Gilmour, 1982). Similar decreases in profitable grade were accomplished at other deposits, though tonnages of ore are generally smaller, in the hundreds of millions of tons, as illustrated on Figure 6. The major copper companies (Kennecott, Phelps Dodge, Anaconda, Miami Copper) were organized by consolidations of ownership in 1910-1925. Porphyry copper deposits have accounted for about 80% of U.S. copper production and 40% of world copper production.

By this process of technological improvement and expansion the demand for copper was satisfied until about 1950. Very little exploration for copper was carried out in the period 1915-1945, and of the few deposits that were found, only the Bagdad deposit in Arizona was put into production, by an independent company. The large consumption during World War II probably accelerated the development of tighter supplies. In the early 1950's, several new companies (ASARCO, Pima Mining, Copper Range, Newmont) responded to increasing demand by discovering and opening new mines, mostly of the porphyry copper type, and the major copper producers greatly stepped up exploration. Governmental loans and price support agreements during the Korean War also promoted development. This exploration "boom" for porphyry copper deposits lasted until about 1974 and resulted in discovery of about 30 porphyry copper deposits in western U.S., and many others in Canada, Mexico, Panama, Ecuador, Peru, Chile, Argentina, Phillipines, New Guinea, Yugoslavia, Iran, and elsewhere.

This period of exploration success ended in the early 1970's because the price of copper no longer justified the very high capital expense of constructing the large mining and processing facilities, reflecting the fact that an adequate supply of copper was available from the existing deposits, the world economy had slowed its growth, and exploration had been extremely successful. Exploration for copper is now largely limited to search for the smaller but higher grade massive sulfide deposits which tend to contain high values in zinc and precious metals as well as copper.

A major question is whether exploration for copper will recover in the near future when the economy improves or will remain at a low ebb. Table 1 and the equivalent table in Rose (1982) indicate that non-producing discoveries contain about 50 x 10^6 tons of Cu. At least 40 x 10^6 tons remain in producing deposits. Given the consumption of about 2 x 10^6 tons of copper per year in the U.S. and questionable growth in consumption, this reserve will last for about 45 years. These data suggest that another period of limited exploration for copper is at hand, unless the world demand and price increase to an extent that the U.S. becomes a major exporter of copper. I.. the meantime, discussions with managers of exploration companies suggest that they are interested only in deposits of markedly higher grade and lower production cost than the classical porphyry copper.

Similar conclusions appear valid for other metals. The discovery of Climax in about 1915 supplied the molybdenum market until about 1957, when Questa, N.M. was found. As indicated in Table 1, six very major discoveries were made in 1965 to 1981. The total reserves of Mo in these deposits amount to about 5 x 10^6 tons of MoS_2, which would supply the U.S. consumption for 50 years, even without the continuing supply of byproduct Mo from porphyry copper deposits, and the remaining reserves at the 4 producing deposits.

For iron, a major worldwide period of exploration in 1946-1960 was so successful that little or no exploration is now being done for this commodity. The technological developments in taconite mining and processing were an important part of this success, as was the recognition of a very large type of deposit, the Superior-type ores of middle Precambrian age. Since 1970 the major iron companies have largely diversified their mineral exploration staffs to ferro-alloys.

For gold, a similar pattern of episodic exploration is evident, though in this case it reflects abrupt changes in price. We are presently in the midst of an exploration boom, after a period of negligible exploration from 1940-1970.

For uranium, exploration from 1940 to 1957 supplied adequate reserves for nuclear weapons (Figure 3). Development of nuclear power plants led to another boom in 1967-80, largely terminated by major high-grade discoveries in Canada and Australia, along with decreases in demand. Exploration is now dormant.

The existence of this episodic behavior for other metals is not so evident, but suggestions exist for these also. The episodes appear to be caused by several factors:

1. The very large size of some discoveries or deposit types (Superior-type iron formations, porphyry copper and molybdenum deposits, unconformity uranium deposits) resulting in drastic changes in supply from one or a few discoveries.

2. The successful exploitation of exploration models and resulting discovery of many deposits once a new ore-type is identified; the porphyry copper and porphyry molybdenum models are good examples, but many others are in use in recent years (Cox, 1983).

3. Increases in demand and price created by new uses plus recognition of tight supply conditions; decreases in demand and price resulting from obsolescence of uses and excess supply.

4. Technologic changes, such as the development of flotation, and heap leaching of low-grade gold, which open up a new class of deposits; in a few cases technologic improvements in exploration have had a major impact, such as airborne magnetic methods for iron ore in the 1950's.

The episodic behavior for metals contrasts greatly with the Gaussian pattern of petroleum discovery proposed by Hubbert (1974). However, the

Hubbert curve deals with reserves rather than exploration for new fields. Even in oil, episodic periods of surplus can be recognized; for example during the 1930-1960 period when the Texas Railroad Commission limited production to avoid sharp decreases in price resulting from major Texas discoveries. It appears that oil discovery within the U.S. is also episodic if the total reserves in supergiant fields are counted in the year of their discovery, as done here for metals, rather than during development of the fields.

If the stock of reserves declines to the point that it is inadequate or is perceived to be inadequate to supply consumption, and the real metal price increases markedly, the history of exploration suggests that explorationists are stimulated to find new deposits and to search for and find new types of deposits. The discovery of porphyry coppers, porphyry molybdenum, Carlin gold, sandstone and unconformity uranium, and Cu-Ni-Co-bearing Mn nodules in the deep sea appear to illustrate this pattern. Exploitation of the ideas generated by a new deposit-type may lead to a glut of reserves and near cessation of exploration. The price of the commodity may increase initially, but the eventual price is likely to depend on production technology as well as supply-demand relations.

In the past it seems to have been assumed that increasing demand for mineral commodities would lead to constantly increasing levels of mineral exploration. The historical record does not appear to justify this assumption. It appears more likely that the rate of mineral exploration for individual commodities is inherently unstable, especially if we are mining concentrations of relatively small dimensions with a grade tens to hundreds of times that of average rocks, the discovery of which involves a large component of qualitative geologic knowledge and risk capital. The total metallic exploration effort is the sum of efforts for individual commodities, and may smooth some of the peaks and valleys, but large fluctuations appear to remain. This conclusion appears to have major implications for long-range resource planning, exploration, research and education.

Exploration Planning

The year to year exploration activities of mining companies reflect the decisions and style of their exploration managers and the interactions of these individuals both within and outside their company. In 1982, we conducted interviews of several hours duration with exploration managers of 3 large companies and found some distinctive and unexpected responses. This outcome led to telephone interviews with 6 other managers to investigate the extent to which the initial 3 were representative. The following discussion is qualitative, but is believed to be relevant to an understanding of exploration.

The interviews indicate two end-member styles of operation. In one end-member, the exploration manager is a strong individual leader, and he tends to dominate the planning of exploration. At the other end, the planning is conducted by a team, which may have the manager as a coordinator or leader, but with only slightly more impact than other participants. These two styles are obviously generalized and do not exactly fit any one company, but are useful in understanding the range of behavior.

In companies with strong managers, the selection of commodities is likely to be done by the leader on a largely qualitative basis, with only incidental input from formal commodity and market analysts. These individuals tend to have a wide range of acquaintances in the minerals industry, and to rely on informal news and highly competent consultants and friends, plus their own ideas, for recognizing new possibilities and trends. The geologic potential for discovery and development of new types of deposits is given strong weight in selection of commodities, and market analyses tend to be informal or to follow the geologic idea. The strong manager tends to have and use access to the company president or chairman to ratify his decisions when necessary. He also has strong ideas on how exploration should be done, and makes these known. This type of management exists in several companies with annual exploration budgets exceeding $15,000,000, in oil companies as well as mining companies. This expenditure level appears to exceed the proposed level of efficient exploration (3 to 8 million dollars) within a "hunting group" (Snow and Mackenzie, 1981). However, each of these organizations does allow a significant creative role to explorationists below the exploration manager. perhaps counterbalancing the problems of size.

In contrast, the "team" management relies more on organized groups of specialists to study and recommend commodities. These specialists are commonly attached to a planning group in company headquarters, rather than to the exploration department, though this is not always true. In some instances the exploration manager may suggest a list of commodities for study, but the staff report is the key to action. The commodity appraisal is commonly made prior to development of geologic ideas for types of deposits and countries to be explored. A long-range plan (5 or even 10 years) may be developed and updated by a planning group. The exploration manager does not generally have or use as much access to top company officers to make or confirm decisions. This type of management exists in both oil and mining companies, but obviously tends to be more common in large companies.

Similarly, in terms of choosing and evaluating countries in which to explore, the strong managers tend to make decisions based on their own experience in the countries, or by ad hoc consultation with friends, consultants, and company personnel with experience in the country. The team management tends to assemble a team of specialists to evaluate and report on countries, or to have a permanent group organized in the company.

The companies with strong exploration managers also tended to have strong leaders as president or chairman of the company. These leaders generally provided more input to the exploration department than in group management companies, though it was appropriately broad in most instances. In several companies, the top officials suggested new commodities and countries. In contrast, the top management in team managements seemed to be willing to let their exploration department and evaluation groups choose the commodities and countries, and to exercise only financial management.

There appears to be a trend toward the group management style. Several companies had initiated organized evaluation groups in the last 1 to 3 years. The large oil companies that have entered the minerals business or purchased mining companies tend to have group management, but this is not universal; one of the oil companies, a moderate sized one, was most clearly in the strong manager group. The old-line mining companies were more likely to have strong managers, but several were intermediate, with neither a strong manager nor a well developed team. In several companies, the group management was adopted as part of a plan to diversify, but two of the strong-manager companies were diversifying as well.

It would be of interest to evaluate the success of the two types of management. Unfortunately, we have detailed data on discoveries and exploration expenditures mainly for the strong manager type of company, probably because these companies were more willing to be interviewed. It is apparent that both types of management have made multiple discoveries and can be successful. However, a tentative conclusion is that the strong-manager companies are probably more successful; certainly they are quite successful, because all of them have made at least 2 major discoveries since 1970 that have come into production or seem likely to do so within a few years. the success of these exploration groups appears attributable to being potentially quicker to seize new opportunities, more entrepreneurial, and better able to satisfy most other characteristics of successful exploration groups expressed by Snow and Mackenzie (1981) and Bailly (1979). The disadvantage appears to be that if the strong-manager is not competent enough, the whole effort may fail. In contrast, although all of the team management companies have made discoveries since 1970, the number likely to come into production soon appears to be 0 or 1 per company, even though several of these companies have exploration budgets similar to the larger strong-manager companies.

Another trend that has important implications for future exploration is a tendency to evaluate discoveries primarily by comparison of their cost of production with the existing array of deposits, rather than by return on investment. The recent severe inflation, and unusually depressed metal prices relative to long-term averages have obviously impressed these managements with the difficulty of estimating meaningful future prices for minerals. As a result, return on investment cannot be calculated with any assurance. The planning of exploration to discover deposits with relatively low cost of production relative to existing deposits was noted as a company goal by all managers interviewed in depth and by several others. Similarly, when they found a deposit, this criterion was given heavy weight in deciding on development.

A related change in recent years has been the re-orientation of exploration into geologic types of deposits that will produce higher and more certain profit, even though these are smaller than other types. For example, volcanogenic massive sulfides are preferred as a target compared to larger but lower grade porphyry copper deposits, and the low-grade gold deposits in Nevada commonly have short pay-out times and low capital cost.

Conclusions

The main results of this study may be summarized as follows:

1. Very little useful data exists on expenditures for and success of exploration in the U.S.; companies do not tend to release explicit data and the figures collected by the U.S. government are incomplete and inappropriate for evaluation of exploration.

2. The gross value of metallic mineral discoveries in the U.S. has averaged about \$6 x 10^9 per year between 1955 and 1980, with no clear trend with time, but large short-term fluctuations make discernment of a trend very difficult.

3. Expenditures for metallic mineral exploration in the U.S. have increased by a factor of about 2.5 in real dollars over the period 1955-1983. There is a probable decrease in 1983 compared to 1982.

4. The success ratio (gross value of discoveries/cost of discovery) is difficult to evaluate for the last 10 years, because of uncertainty as to how many recent discoveries will really come into production. The ratio appears to decrease with time, but by less of a factor than for oil and uranium.

5. Oil companies entering metallic mineral exploration appear to have been less successful than major metallic and non-metallic mining companies, and small companies.

6. Planning of exploration in recent years has been organized around search for specific geologic types of deposits, which are considered to have favorable economic and exploration characteristics. An idealized set of geologic and exploration attributes is developed for each type and used to guide exploration. This approach has been responsible for groups of discoveries over periods of 10 years or so, and considerable increases in reserves.

7. Exploration for copper, molybdenum, iron, uranium and gold has been episodic over the past 80 years, with spurts of activity for 5-15 years followed by periods of little activity. The assumption of constantly increasing future exploration is not justified.

Causes for episodic exploration include discovery of one or a few very large deposits that drastically change the reserves and costs of production, successful exploitation of exploration models to discover many deposits over a short period, changes in demand caused by new uses of metals, decreases in demand caused by obsolescence, and technologic change in methods mineral processing.

8. A range of management and planning styles exists in exploration groups; these can be categorized as ranging from a "strong manager" to a "team management" approach. There is a trend toward "team management", but some of the most successful exploration groups have a strong manager organization.

9. New discoveries now tend to be evaluated more on cost relative to existing producers than on return on investment, because of inflation and rapid changes in metal prices and production costs. There is also a trend toward exploration for high-profit deposits rather than large low-grade deposits requiring major capital investment and slow payback.

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TABLE 1

Discoveries of metallic mineral deposits in the U.S. since 1940.

Deposit	Company	Date	Metal	Type of Deposit	Value of metal ($\$10^9$)	5-yr sums ($\$10^9$)
Lucky Friday, Id.	Hecla	1940	Pb,Ag,Zn	VR	1.0*	
Yellow Pine, Id.	Bradley (U.S. Geol. Surv.)	1941	W,Sb, Au	VR	0.8*	
Castle Dome, Ariz.	Miami(U.S.G.S.)	1942	Cu	PC	0.5*	
San Manuel, Ariz.	Newmont (U.S. Bur. Mines)	1943	Cu	PC	10.0*	11.5*
Indian Creek, Mo.	St. Joe	1947	Pb	MV	1.2*	
Shullsburg, Wisc.		1947	Zn	MV	?*	
Copper Cities,Ariz.	Miami	1949	Cu	PC	0.9*	2.1*
Jefferson City, Tn.	NJZinc	1950	Zn	MV	0.3*	
Silver Bell,Ariz.	Asarco	1950	Cu	PC	1.4*	
White Pine,Mich.	Copper Range	1950	Cu	SC	5.0*	
Yerington,Nev.	Anaconda	1951	Cu	PC	1.8*	
Pima-Mission,Ariz.	Pima-Asarco	1951	Cu	PC	8.1*	
Flat Gap, Tn.	NJZinc	1952	Zn	MV	0.2?*	
New Market, Tn.	Asarco	1952	Zn	MV	1.0*	
Immel, Tn.	Asarco	1954	Zn	MV	0.8*	18.6*
Esperanza,Ariz.	Duval	1955	Cu	PC	0.95*	
Viburnum, Mo.	St. Joe	1955	Pb	MV	3.0*	
San Xavier,Ariz.	Asarco	1957	Cu	PC	1.74*	
Questa, N.M.	Molycorp	1957	Mo	PM	12. *	
Continental,N.M.	U.S. Smelting	1958	Cu	SK	1.1*	
Tyrone, N.M.	Phelps Dodge	1958	Cu	PC	4.0*	
Safford(KCC),Ariz.	Kennecott	1958	Cu	PC	8.0	
Fletcher, Mo.	St. Joe	1958	Pb	MV	3.0*	
Palo Verde, Ariz.	Banner	1959	Cu	PC	1.5*	
Glacier Peak, Wash.	Kennecott	1959	Cu,W	PC	0.4	
Burgin, Utah	Kennecott	1959	Pb,Ag,Zn	VR	0.5*	
Young, Tn.	Asarco	1959	Zn	MV	0.8*	37.0(28.6*)
Christmas, Ariz.	Inspiration	1960	Cu	SK	1.2*	
Mineral Park, Ariz.	Duval	1960	Cu	PC	1.8*	
Brushy Creek, Mo.	St. Joe	1960	Pb	MV	2.0*	
Buick, Mo.	Amax	1960	Pb,Zn	MV	4.0*	
Ruby Creek, Alaska	Kennecott	1960	Cu,Co	VR	2.4	
Safford(PD),Ariz.	Phelps Dodge	1961	Cu	PC	5.8	
Duluth gabbro, Minn.	Inco	1961	Ni,Cu	MS	33.0	
Sierrita, Ariz.	Duval	1962	Cu,Mo	PC	8.1*	
Carlin, Nev.	Newmont	1962	Au	SG	2.1*	
Ozark Pb,Mo.	Kennecott	1962	Pb	MV	1.9*	
Magmont, Mo.	Cominco	1962	Pb	MV	2.0*	
Hall Mo, Nev.	Anaconda	1962?	Mo	PM	2.6*	
Brady Glacier, Al.	Freeport	1962	Ni,Cu	MS	5.	
Sacaton, Ariz.	Asarco	1963	Cu	PC	0.9*	
Blue Hill, Me.	Kerr Addison	1963	Cu,Zn	VS	0.07*	
Troy, Mont.	Kenn.-Asarco	1963	Ag,Cu	SC	1.6*	

TABLE 1 (continued)

Twin Buttes, Ariz.	Banner	1964	Cu,Mo	PC	15. *	89.5(43.3*)
Bluebird, Ariz.	Ranchers	1965	Cu	PC	0.7*	
Kalamazoo, Ariz.	Quintana	1965	Cu,Mo	PC	6.7*	
Copper Canyon, Nev.	Duval	1965	Cu,Au	SK-PC	2.6*	
Henderson, Colo.	Amax	1965	Mo	PM	17. *	
Cortez, Nev.	Amex	1966	Au	SG	0.5*	
Sanchez, Ariz.	Inspiration	1968	Cu	PC	0.6	
Taylor, Nev.	Silver King	1969	Ag	VR	0.2*	
Elmwood, Tn.	NJZinc	1969	Zn	MV	0.76*	
Nacimiento, N.M.	Earth Res.	1969	Cu	SC	0.2*	29.[illegible]6*
Helvetia, Ariz.	Banner-Anaconda	1970	Cu	PC	4.	
Copper Creek,Ariz.	Newmont	1970	Cu	PC	2.	
Vekol, Ariz.	Newmont	1970	Cu	PC	1.2	
Red Mtn., Ariz.	Kerr McGee	1970	Cu	PC	6.	
Lakeshore, Ariz.	Hecla	1970	Cu	PC	7.85*	
Florence, Ariz.	Conoco	1970	Cu	PC	6.4	
Metcalf, Ariz.	Phelps Dodge	1970	Cu	PC	5.6*	
Pinson, Nev.	Cordex-Rayrock	1971	Au	SG	0.2*	
Flambeau, Wisc.	Kennecott	1971	Cu	VS	0.4	
Stillwater, Mont.	Anac.(Amax)	1971	Ni,Cu	MS	7.5	
Pinto Valley, Ariz.	Cities Serv.	1973	Cu	PC	3.5*	
Copper Basin, Ariz.	Phelps Dodge	1973	Cu	PC	2.	
Cyprus-Johnson,Ariz.	Bagdad	1974	Cu	SK	0.2*	
Pinos Altos, N.M.	Exxon	1974	Cu,Zn	SK	0.4	
Sultan, Wash.	Brenmac	1974	Cu,Mo	PC	1.0	
Alamo, Nev.	Union Carb.	1974	W	SK	?	
Delamar, Id.	Earth Res.	1974	Ag	EG	0.75*	
McDermitt, Nev.	Placer	1974	Hg	EG	0.06*	
Cornucopia, Nev.	Std. Silver	1974	Ag,Au	EG	0.5*	
Round Mtn., Nev.	Copper Range	1974	Au	IG	4.4*	53.6(23.1*)
Rhinelander, Wisc.	Noranda	1975	Cu,Zn	VS	0.1	
Thompson Cr., Id.	Cyprus	1975	Mo	PM	6.5	
Red Dog, Alaska	Cominco (U.S.B.M)	1975	Pb,Zn	EP	18.	
Arctic, Alaska	Kennecott	1975?	Cu	VS	9.	
Ambler R., Alaska	Anaconda	1975	Cu	VS	?	
Stillwater Pt.	Johns Man.-Anac.	1975	Pt,Pd	MS	14.0?	
Green Creek, Alaska	Noranda	1975	Zn,Pb,Ag	VS	1.	
Rochester, Nev.	Asarco	1976	Ag	EG	1.6	
Quartz Hill, Alas.	U.S. Borax	1976	Mo	PM	8.2	
Ashland, Me.	Superior-La.Land	1976	Cu,Zn	VS	1.5	
Jerritt Cyn.,Nev.	FMC-Freeport	1976	Au	SG	1.7*	
Crandon, Wisc.	Exxon	1976	Cu,Zn	VS	5.	
Oracle Ridge,Ariz.	Continental	1976	Cu	VR?	0.4	
Casa Grande,Ariz.	Hanna-Getty	1976	Cu	PC	7.	
Ortiz, N.M.	Goldfields	1976	Au	Eg	0.2*	
Stonewall, Tn.	NJZinc	1977	Zn	MV	0.25	
Gordonsville, Tn.	NJZinc	1977	Zn	MV	0.7*	
Pine Grove, Utah	Phelps Dodge	1977	Mo	PM	6.0	
Mt. Emmons, Colo.	Amax	1977	Mo	PM	12.	
Beaver Cr., Tn.	NJZinc	1977	Zn	MV	0.12	
Carthage, Tn.	St.Joe-Freep.	1977	Zn	MV	2.0	

TABLE 1 (continued)

Wulik, Alaska	Houston	1978	Pb,Zn,Ag	EP	2.4	
Kearsarge, Cal.	Pickands-Math.	1978	Au,Ag	EG	0.4	
Nye Co., Nev.	UV Ind.	1978	Mo	EP	0.7	
Alligator Ridge,Nev.	Amselco	1978	Au	SG	3.0*	
Bald Mtn., Me.	Superior	1979	Cu,Zn	VS	0.3	102.5(5.6*)
Blackbird, Id.	Hanna-Noranda	1980	Co,Cu	O	0.6	
Pierrepont, N.Y.	St. Joe	1980	Zn	EP?	0.35*	
Maggie Cr., Nev.	Newmont	1980	Au	SG	0.25*	
Hillsboro,N.M.	Quintana	1980	Cu	PC	0.5*	
West Fork, Mo.	Asarco	1980	Pb	MV	0.9	
McLaughlin	Homestake	1980	Au	EG	1.6	
West End, Id.	Superior	1980	Au	EG	0.1*	
Silver Peak, Id.	Sunshine	1980	Ag	EG	0.1	
Borealis, Nev.	Houston	1980	Au	EG	0.1*	
Mercur, Utah	Getty	1981	Au	SG	0.45*	
Mt. Hope, Nev.	Exxon	1981	Mo	PM	5.	
Golden Sunlight, Mont.	Placer Amex	1981	Au	EG	0.6	
Escalante Ag, Utah	Ranchers	1981	Ag	EG	0.4*	
Gold Quarry, Nev.	Newmont	1982	Au	SG	4.	
Rain, Nev.	Newmont	1982	Au	SG	0.5	
Zaca, Cal.	Calif. Silver	1982	Au,Ag	EG	0.1	
Boulder Cr., Nev.	Rayrock	1982	Au	SG	0.15	
Horse Canyon, Nev.	Placer Amex	1982	Au	SG	0.1	15.8(2.75*)

*Deposit that has produced.

Notes:

Value of deposits is based on estimated total production plus reserves, evaluated at the following prices: Cu, $1/lb.; Pb, $0.40/lb.; Zn, $0.40/lb.; MoS_2, $9/lb.; Ni, $3/lb.; Au, $500/oz.; Ag, $12/oz.; Pt, $600/oz.; Pd, $200/oz.; Sn, $8/lb.; Co, $10/lb.; W, $100/STU; Sb, $1/lb.

For 5-year totals, values in parentheses are totals for produced deposits, if different from total.

Source of data: Rose, 1982; Subsequent mining journals and Minerals Yearbooks, Company annual reports, Gilmour (1982) and other sources.

In general, deposits with value less than $\$0.1 \times 10^9$ are not included.

Types of deposits: VR, vein and replacement hydrothermal; PC, porphyry copper; PM, porphyry molybdenum; MV, Mississippi Valley type lead-zinc; SC, sedimentary copper; SK, skarn; MS, magmatic Cu-Ni-Pt sulfide; SG, sediment hosted disseminated gold; VS, volcanogenic massive sulfide; EG, epithermal gold and silver (and mercury) except sediment-hosted disseminated gold; EP, exhalative Pb-Zn-Ag; O, other.

Table 2. Estimates of Mineral Exploration Expenditures for the U.S.

Period	Exploration Expenses per year, 10^6 \$	Includes Foreign	Includes Uranium, Nonmetals	Source
1955-59	35	No	Yes?	AMAX in National Acad. Science (1975)
1960-64	55	"	"	
1965-69	90	"	"	
1968-71	110			Wargo (1973) sum of 21 companies
1972	100	Yes	Yes	Barber (1981) 12 major U.S companies
1973	130	"	"	
1974	150	"	"	"
1975	170	"	"	"
1976	180	"	"	"
1977	190	"	"	"
1978	210	"	"	"
1979	310	"	"	"
1980	410	"	"	"
1979	200	No	"	"
1980	240	"	"	"
1977	75-110	No?	Yes	U.S. Gov't(1979)
1961	60	"	"	Brown (1983) 30 U.S. companies based on published data, inquiries and estimates.
1965	80	"	"	
1970	140	"	"	
1975	210	"	"	
1980	390	"	"	
1954	14.9	No?	No	Preston (1960) from Census of Min.Ind. Non-producing sites only
1954	15	No	No?	Preston (1960, p. 106), 7 cos., includes development.
1967	27[1]	No?	No	Census of the Minerals Industry (1967,1972,1977)
1972	116[2]	"	"	
1977	264[3]	"	"	
1980	190	In part	In part	Unpublished data on U.S. metals exploration for 6 companies, and published total mineral exploration data for 6 others.

Table 2. (continued)

Period	Exploration Expenses per year, 10^6 $	Includes Foreign	Includes Uranium,Nonmetals	Source
1981	260	In part	In part	Extrapolation of 1980 estimate (190×10^6) based on trend of data for 6-12 companies
1982	275	"	"	
1983	180	"	"	

[1]Total capitalized and expensed mineral development and exploration plus minerals rights and geological expenditures at non-producing establishments for Cu, Pb and Zn, plus same for all establishments for other metals except uranium.

[2]Expensed mineral development and exploration expenditures plus mineral rights and geological expenditures, minus uranium. Does not include capitalized successful exploration; probably includes some development at producing mines.

[3]Expensed mineral exploration and development, including land and rights, plus capitalized land and mineral rights, minus uranium. This accounts for unsuccessful exploration and probably includes some expensed development at operating mines, does not include successful projects, except land costs.

Table 3. Estimated exploration expenditures in the U.S., and success ratios

Period	Av. Expenditures per year (10^6\$)[1]	Av. Expend. (10^6 1981 \$)[2]	Cum. Expend. (10^6 1981 \$)[3]	Success Ratio[4]
1955-59	35	108	540	43 (58)
1960-64	55	156	1320	58 (110)
1965-69	90	226	2450	26 (26)
1970-74	140	278	3645	17 (38)(19*)
1975-79	210	290	5095	4 (64)(32*)
1980-83	260	263	6147	2.1 (12)(6*)

[1]Based on data from Rose (1982) plus estimates discussed in the text.

[2]Data of the preceding column converted to 1981 dollars using the GNP implicit deflator (U.S. Dept. of Commerce, 1966, 1979, 1981, 1983).

[3]Cumulation of data for yearly deflated expenditures.

[4]Value of metal discovered (Table 1) divided by exploration expenditure for period. First value for producing deposits, value in parentheses for all discoveries and values with * for deposits likely to be producing in the next few years.

Table 4. Exploration expenditures for uranium in the United States.

Year	Expenditures	Feet of Drilling
1948		0.17×10^6 ft.
1949		0.36
1950		1.10
1951		1.08
1952		1.36
1953		3.65
1954		4.05
1955		5.27
1956		7.29
1957		7.35
1958		3.76
1959		2.36
1960		1.40
1961		1.32
1962		1.48
1963		0.88
1964		0.97
1965		1.16
1966	$\$8.4 \times 10^6$	1.80
1967	24.8	5.44
1968	53.4	16.2
1969	58.7	20.5
1970	52.2	18.0
1971	41.2	11.4
1972	32.4	11.8
1973	49.5	11.7
1974	79.1	14.7
1975	122.0	15.7
1976	170.7	20.4
1977	258.1	28.0
1978	314.3	29.0
1979	315.9	28.1
1980	267.0	19.6
1981	175(est.)	15.2
1982	157(est.)	13.4

Source: Chenoweth (1979, p. 178), Sanders (1981, Table 1 and Fig. 1). About 15% of this expenditure appears to be for development activities.

Table 5. Discoveries by type of company

Type	No. of Companies	No. of Discoveries	Value, All Discoveries	Value, Produced Discoveries
Major metallic mining cos.	18	64	$\$205.1 \times 10^9$	$\$80.01 \times 10^9$
Medium metallic mining cos.	10	14	50.35	40.67
Non-metallic mining cos.	5	8	42.35	15.15
Oil Cos.	6	9	26.05	0.55
Small mining, stock cos.	10	15	32.2	26.6
Unclassified		6		

Definitions

A major metallic mining company had sales exceeding $400,000,000 in 1980 and a long-time position in U.S. metallic mining.
A medium metallic mining company had sales less than $400,000,000 in 1980, and a prior history of U.S. metallic mining.
A small mining or stock company had sales less than 10,000,000 and little or no previous mineral production.
A non-metallic mining company had its major interests in non-metallics, including sulfur, prior to a metallics discovery.
An oil company had its major interest in oil, gas, and possibly uranium prior to entry into the metallic minerals field.

Table 6. Classification of discoveries by deposit type.

Number of Discoveries

Type of Deposit	Key	1940's	1950's	1960's	1970's	1980's	Total Disc.	Value
Porphyry Cu	PC	3	9	8	11	1	31	$\$125.7 \times 10^9$
Porphyry Mo	PM		1	2	4	1	8	64.
Skarn	SK		1	2	3		6	5.5
Vein-replacement	VR	2	1	2	1		6	.3
Volcanogenic Cu-Zn	VS			1	8		9	17.9
Exhalative Pb-Zn-Ag	EP				3	1	4	21.
Mississippi Valley Pb-Zn	MV	2	7	6	4	1	20	25.
Sedimentary Cu	SC		1	2			3	6.8
Magmatic Cu-Ni-Pt	MS			2	1		3	60.
Sediment-hosted Au	SG			2	3	6	10	12.8
Epithermal Au-Ag-Hg	EG				7	7	14	10.9

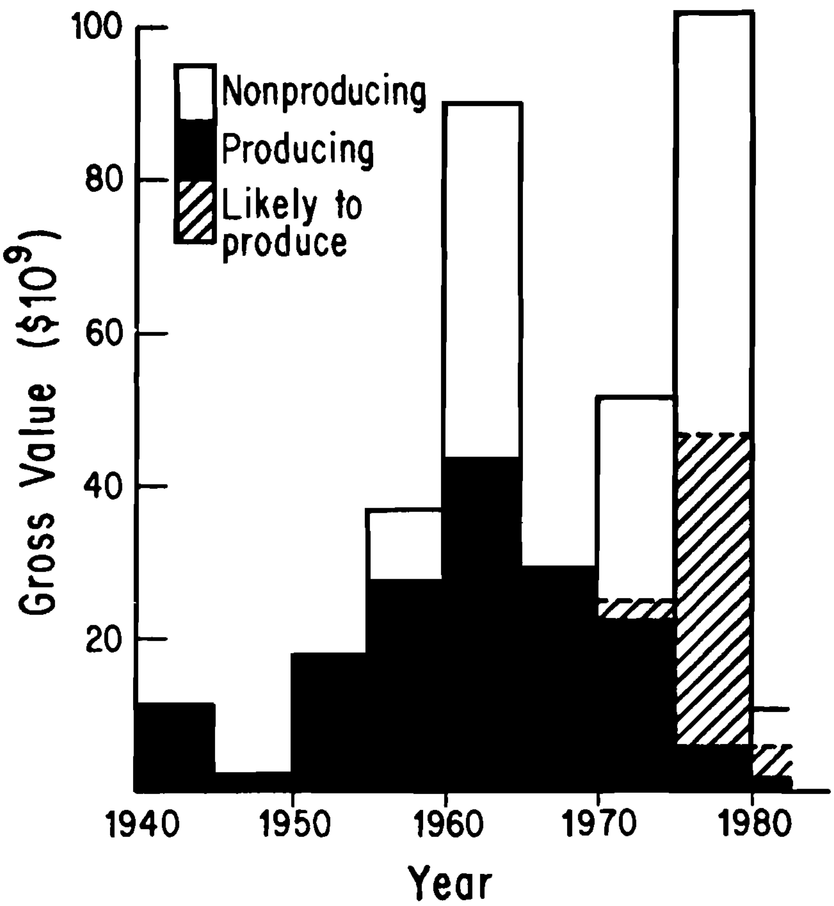


Figure 1. Gross value of mineral discoveries in the U.S. by 5-year intervals, 1940-1982. Dashed lines indicate inferred value for producing deposits a few years in the future, assuming 50% of total discoveries will be producing.

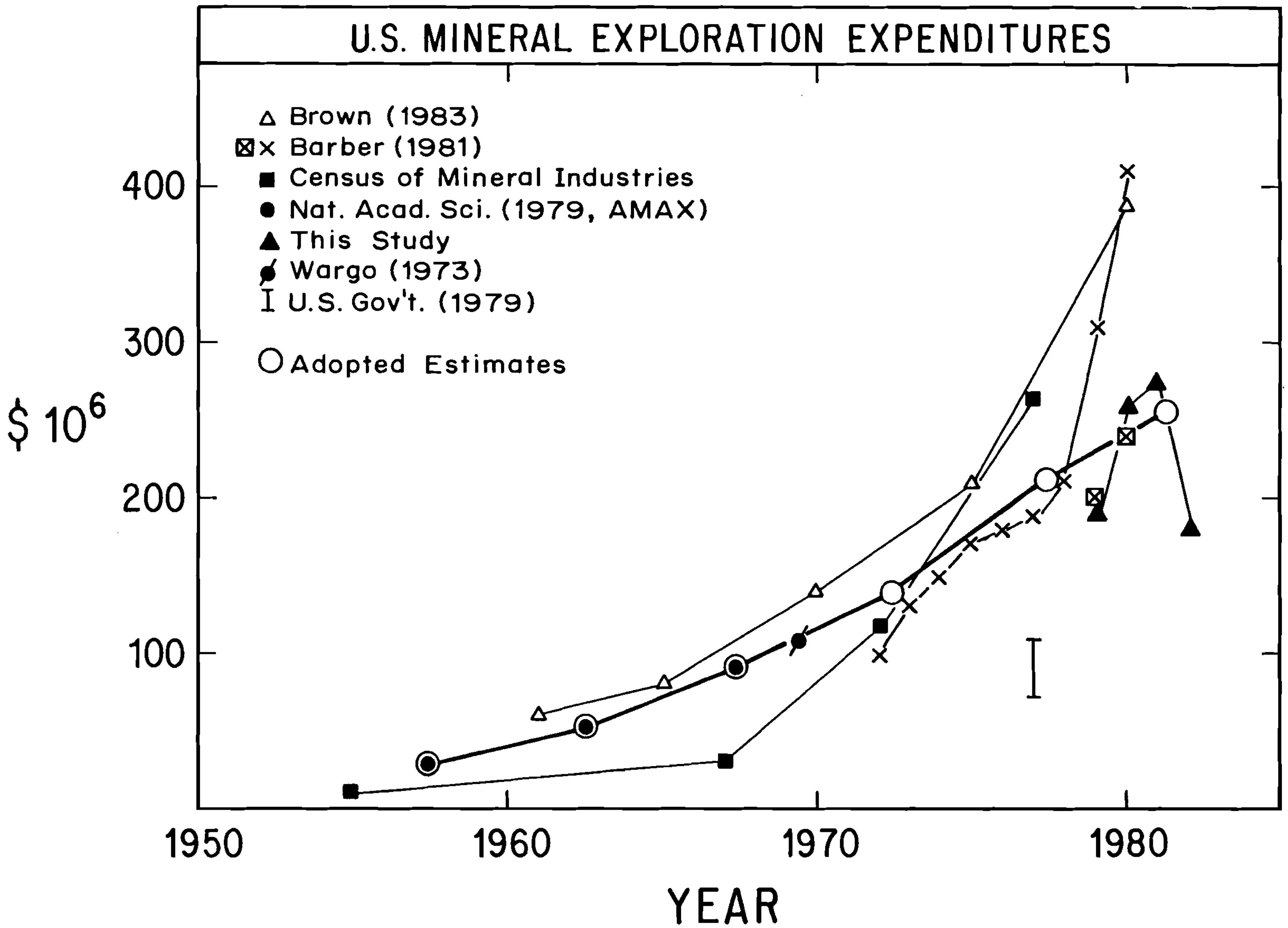
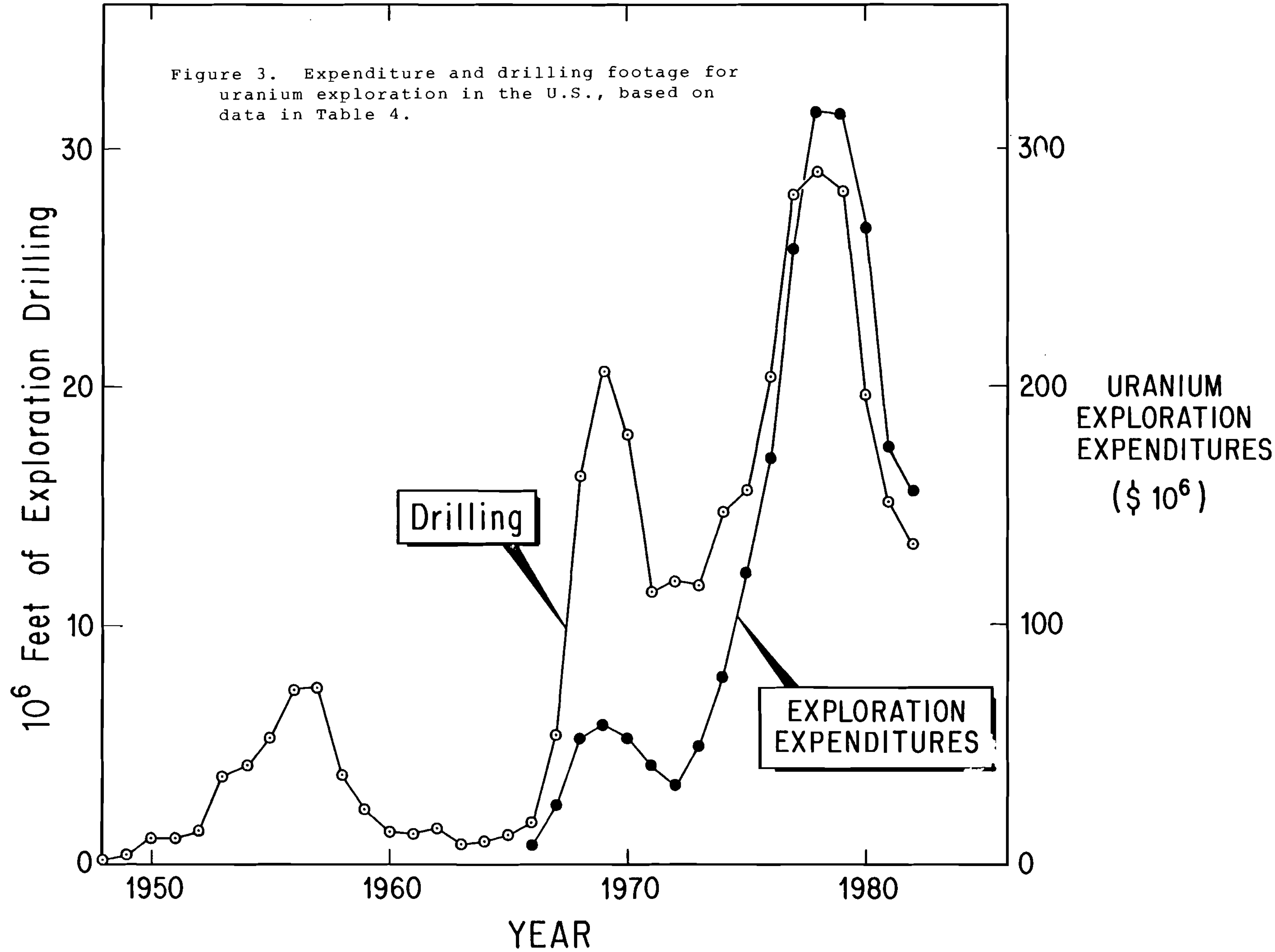


Figure 2. Expenditures for mineral exploration versus time. The adopted estimates represent the inferred expenditure for metallic minerals except uranium in the U.S., through the stage of discovery but not including development. See Tables 2 and 3 for further information.

Figure 3. Expenditure and drilling footage for uranium exploration in the U.S., based on data in Table 4.



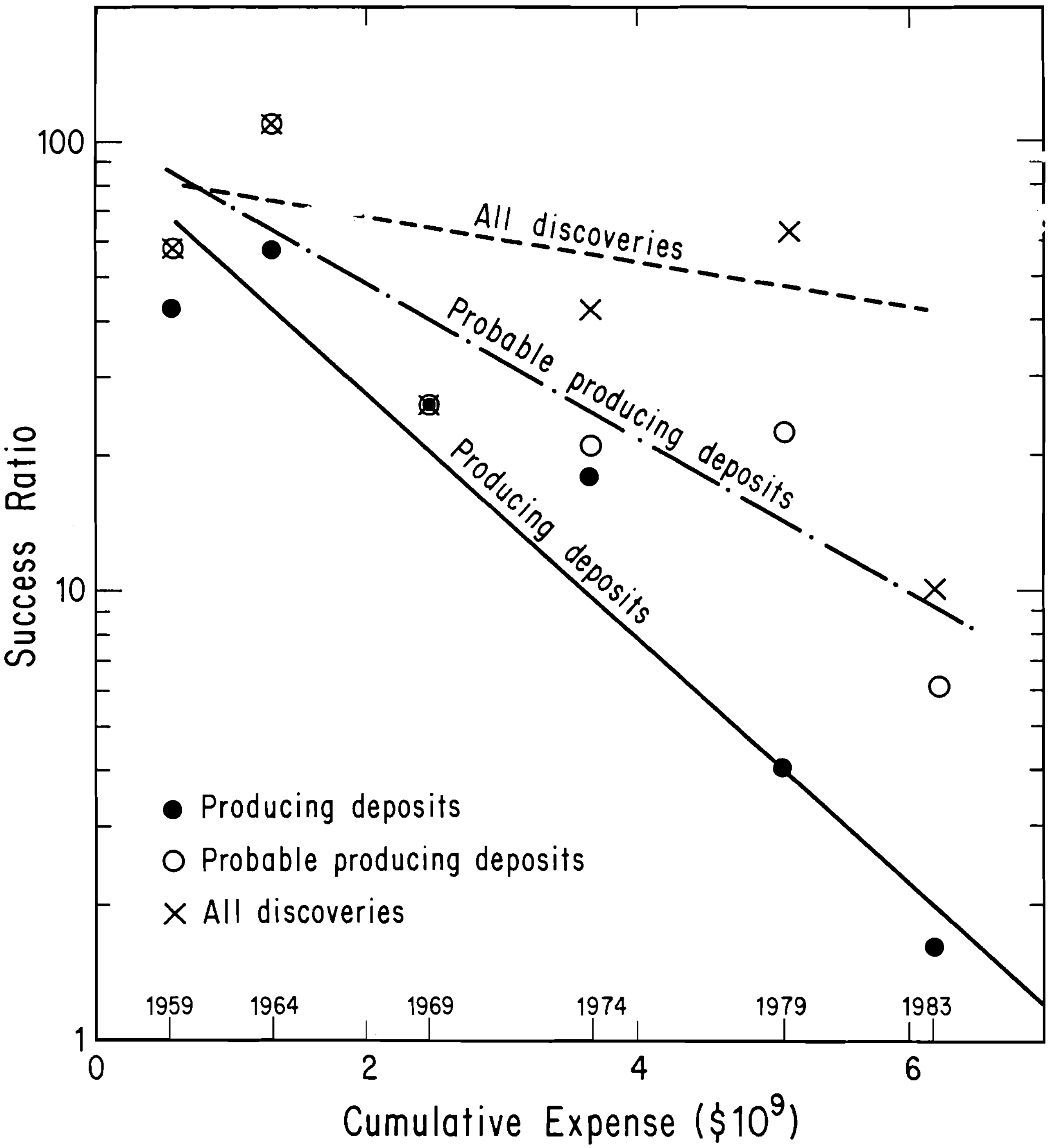


Figure 4. Sucess ratios (value of discoveries/deflated cost of exploration in 1981 dollars) versus cumulative exploration expense for metallic minerals in the U.S., 1955-1983, showing inferred trends with time; 1983 point not considered in estimating trend.

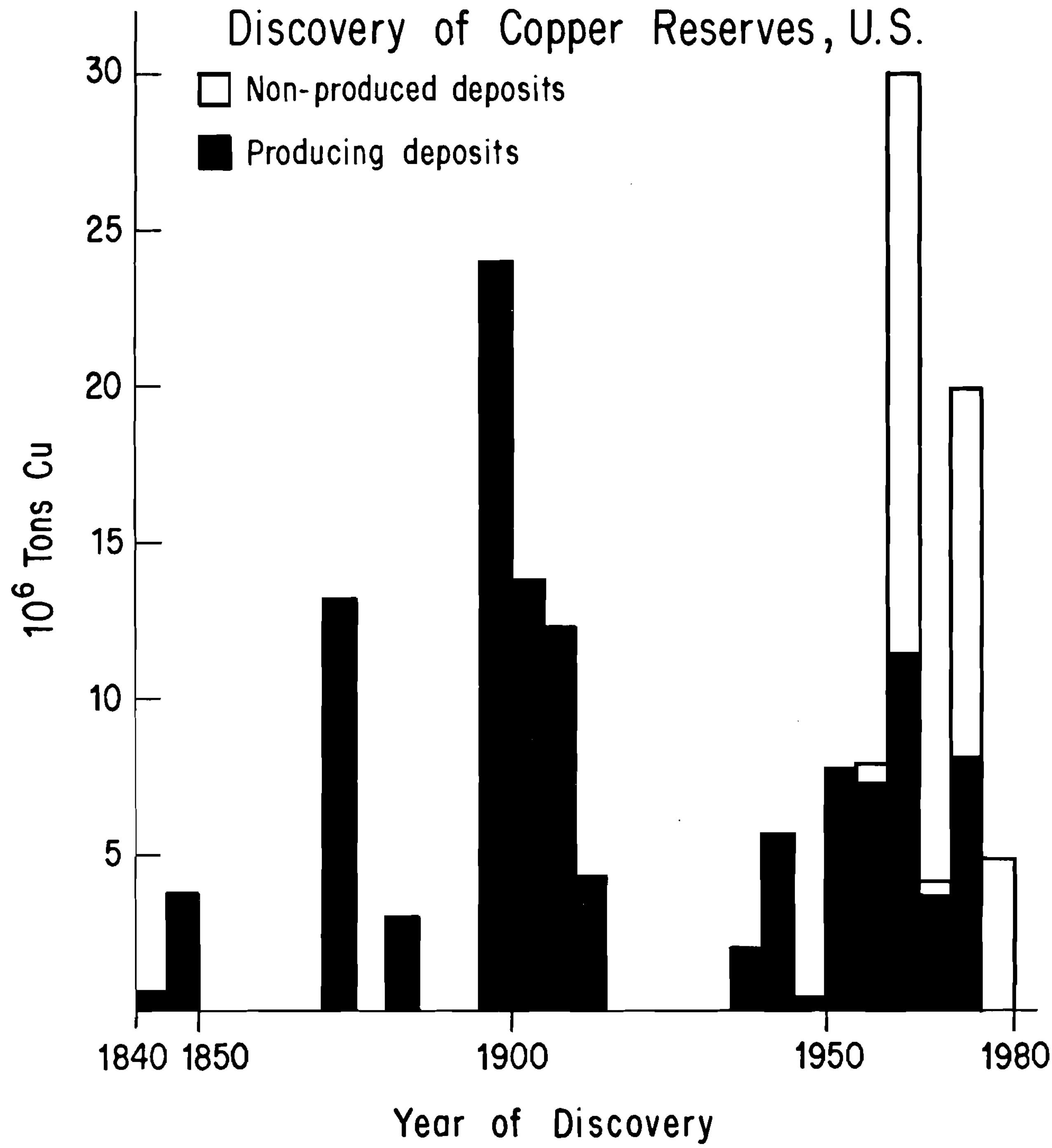


Figure 5. Discovery of major copper resources in the U.S., showing episodic character. Data from Rose (1982) with minor additions.

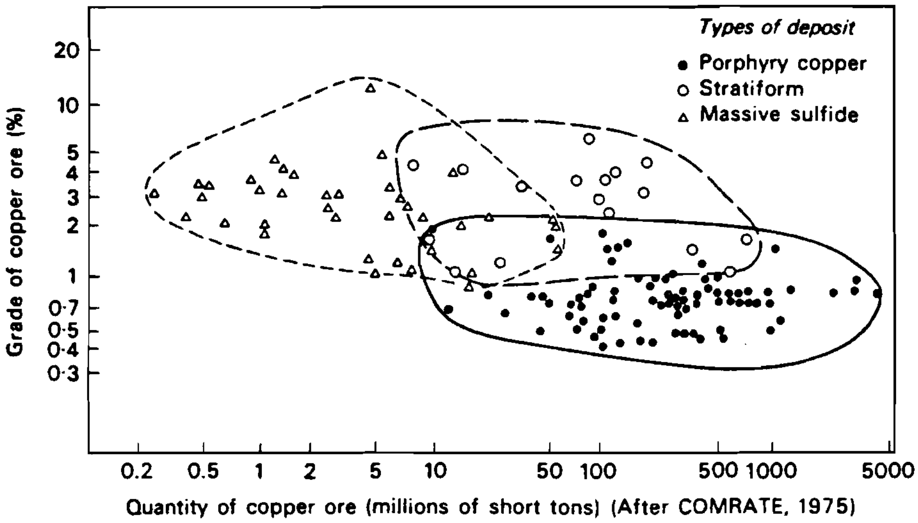


Figure 6. Tonnage and grade of major types of copper deposits in the world (after National Academy of Sciences, 1975).