GEOLOGICAL SURVEY CIRCULAR 682

Summary of United States Mineral Resources

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By Donald A. Brobst, Walden P. Pratt, and V. E. McKelvey

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This circular is an excerpt from Professional Paper 820, United States Mineral Resources, and consists of its first two chapters. These chapters summarize our resources and provide the basic guidelines under which the individual commodities were evaluated in greater detail in that report.

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United States Department of the Interior
ROGERS C. B. MORTON, *Secretary*

Geological Survey
V. E. McKelvey, *Director*

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SUMMARY OF UNITED STATES MINERAL RESOURCES

INTRODUCTION

By DONALD A. BROBST and WALDEN P. PRATT

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THE PURPOSE OF THIS BOOK

Our civilization is dependent on minerals. Few people living in the United States and other developed nations pass through a single day without using raw or manufactured materials that have been made from, processed by, fertilized with, or in some other way affected by minerals or mineral products. Without a steady supply of minerals our civilization could not survive.

Unlike most other natural resources, minerals are not renewable. They are formed in the earth's crust by infinitesimally slow natural geologic processes acting for thousands or millions of years. Once removed and used, they cannot be grown again. The vital question, then, is this: Is our supply of minerals running out?

To answer this question, as it applies to nearly all the mineral commodities in use today, is the general aim of this book. More specifically, the book attempts to provide answers to three basic questions about each mineral commodity: (1) How important is it to our present industrial civilization and standard of living? (2) how much of it do we have and to what extent is it economically and technologically available? and (3) how and where can we find more? The emphasis here is on domestic resources, but many chapters include information on foreign resources, generally most complete for those commodities for which we are most dependent upon sources abroad.

The answers to the above questions are matters that should be of concern not only to geologists (both professional and student), but also to exploration managers, research administrators, economists and economic analysts, legislators, lawyers, planners, magazine and newspaper editors, and indeed many segments of the public at large. The book has been written with this varied audience in mind. The descriptions of the geology and origin of mineral deposits in each chapter necessarily involve some scientific jargon, but discussions of the uses, importance, history of exploitation, resources, and problems needing research are cast largely in nontechnical language so that they may be of use to scientist and nonscientist alike.

RESOURCES OR RESERVES?

A fundamental concept in the evaluation of mineral resources is the distinction between *resources* and *reserves*. Detailed definitions vary (the entire problem of resource terminology is currently being studied by the National Commission on Materials Policy), but the principal distinction is based on current economic availability: *reserves* are *known, identified deposits* of mineral-bearing rock from which the mineral or minerals can be extracted *profitably with existing technology and under present economic conditions*; whereas *resources* include not only reserves but also other mineral deposits that may eventually become available—either known deposits that are not economically or technologically recoverable at present, or unknown deposits, rich or lean, that may be inferred to exist but have not yet been discovered. A simple analogy from the field of personal finance, suggested by our colleague J. E. Gair, may be helpful in clarifying this important distinction: *Reserves* are represented by the funds in one's bank account and by other liquid assets; *resources* then include, in addition, all other assets and, more importantly, all income one may expect to receive, from whatever source, through the duration of one's lifetime. We will discuss various categories of resources and their relation to reserves later in this introduction, but for the present we would emphasize that because reserves are the only part of the total resource that is *immediately available*, they are of paramount concern to the mineral industry, and reserve estimates for most mineral commodities are generally available and are undergoing constant revision. For most minerals, however, current reserves are only a small part of the total resource. The remainder of the total—the *potential resources*—are by far the most important for the long term, and they receive major emphasis in this book. Mineral resources, whether real or potential, are geologic entities—concentrations of one or more elements in the earth's crust. Because such concentrations occur as the result of geologic processes, the question of how and where to find more of them can ultimately be resolved only through the understanding of geologic principles and the application of geologic insight; accordingly, the chapters of this volume deal with predictions based on geologic reasoning, and have been written by geologists.

A WARNING

Implicit in the distinction between reserves and resources is a serious danger, which we state now and will reiterate throughout this volume: Potential resources are *not* reserves; they are "birds in the bush," or to return to the analogy already used, they are frozen assets and next year's income, and *cannot* be used to pay this month's bills. No matter how optimistic an outlook is engendered by estimates of vast resources, such resources cannot be mined, much less used, until they have been converted into the category of reserves, whether by discovery (of undiscovered resources of minable quality), or by improvements in technology (for recovering identified subeconomic resources), or by both. For nearly all minerals, the estimates of potential resources indicate quantities that may become available *only if we vigorously pursue geologic and technologic research* to discover new mineral deposits in regions and geologic environments that are known to be favorable, to discover new favorable regions and environments, to discover new kinds of mineral deposits not previously recognized, to improve existing exploration techniques and develop new ones, and to improve extractive technology for processing low-grade ores that are not now economically recoverable. Readers of this volume must therefore be cautioned that the resource estimates contained herein are indeed estimates, not measurements; and they present an optimistic outlook for many commodities *only in the context that they represent a potential, not a reality.* Using these estimates in any effort to optimize our domestic resource outlook may only defeat the purpose if they are removed from this context or are quoted without adequate qualification. We have attempted to insure against such misinterpretation by repeating definitions of the appropriate resource terminology on all tables of resource estimates in this volume.

Even with these qualifiers, some may criticize this volume for its articulation of a philosophy that they may consider to be unrealistic. We can only offer the response that in the fairly recent past, each of the kinds of geologic and technologic research enumerated in the preceding paragraph *has in fact resulted in the conversion of potential resources into minable reserves*—"rock in the box," in mining parlance; a few examples are the discoveries of the huge Kidd Creek zinc-copper-silver ore deposit in Ontario and the disseminated gold deposits of Carlin and Cortez in Nevada, and the development of technology for processing taconite iron ores.

Indeed the events of the last 20 years are the best reason for optimism. In 1952, the recoverable reserves of lead were estimated to be 7.1 million tons, of which only about 1 million tons was called proved reserve. These figures were quoted on page 41 of volume 2 of "Resources for Freedom" (President's Materials Policy Commission, 1952), better known as the Paley report. Farther down on that page we find the following statement, "The poor discovery record of the past few decades provides little basis for optimism that the equivalent of the southeast

Missouri district can be expected to turn up in the future; the major hope lies in the development of some new methods of prospecting, as, for example, methods that would indicate the probability of deposits in the absence of surface ontcrops." Drilling in the mid-1950's on the west side of the Southeast Missouri district resulted in the discovery of the large unexposed deposits of lead ore known as the Viburnum Trend. By 1970, half a dozen mines were operating, and the reserves of lead in Missouri alone had increased to 30 million tons. (See the chapter on "Lead" in this volume.) The Viburnum Trend will yield more lead than the total production of the old part of the district. With the phoenixlike rejuvenation of the Southeast Missouri district, the Viburnum Trend becomes the perfect example of a potential resource converted to a reserve.

We see no reason why such discoveries and developments cannot be expected to continue in the future. To point the direction to potential resources and to attempt to evaluate them are the objectives of this book.

OUR DEPENDENCE ON MINERALS

Few people are fully aware of their daily dependence upon minerals. An awareness is growing as the fragilities of modern civilization, stemming from population growth and economic expansion, become recognizable not only as world and national problems, but also as personal problems. The availability of mineral resources to meet the projected demands will critically affect future events.

It is important, therefore, to be able to predict the occurrence of minerals, with some degree of realism, on several different scales of both time and space; we must know not only in which direction a particular mine opening should be extended to continue in an ore body, but over a longer time period, we must know where prospecting and exploration should be concentrated to discover new deposits of each kind of mineral—and the likelihood of success. In other words, where are our potential mineral resources and how large are they? How long will they last? For which minerals, if any, are we "in good shape"? Is our supply of any minerals unlimited? Of which ones do we have very little, or are we likely to run out in the near future? For these, is there a geologic probability that more can be discovered in the United States?—that is, are there geologic environments in which such minerals are likely to occur? If so, where? And what problems are likely to be encountered in finding and extracting them? If domestic resources are not likely to be sufficient, then to which parts of the globe must we look for adequate resources in the future? These are the questions to which the authors of this volume have addressed themselves.

CLASSIFICATION OF RESOURCES

What, then, is a mineral resource? To begin with, we may define a mineral resource as a concentration of elements in a particular location in or on the earth's crust (or, now, also in the oceans), in such a form that a usable mineral commodity—whether it be an element (such as iron or aluminum), a chemical compound (such as salt or borax), a mineral (such as emerald or asbestos), or a rock (such as marble, coal, or gypsum)—can be extracted from it. The perceptive reader will recognize that such a definition has little practical value if the particular mineral commodity cannot be extracted at a profit. As already suggested, this feasibility of profitable extraction, or economic availability, is one of two parameters that distinguish between resources and reserves; the other parameter is the degree of certainty of existence. These two parameters were originally formulated into a classification of resources by V. E. McKelvey (1972), whose presentation of these concepts is so vital to the philosophy of resources, and whose classification is so important as the cornerstone of the present volume, that we have included his article as the second chapter of this volume. We will summarize McKelvey's resource classification by stating merely that he defines *reserves* as economically recoverable material in identified deposits, and applies the term *resources* to include "deposits not yet discovered as well as identified deposits that cannot be recovered now." The terms *recoverable, paramarginal,* and *submarginal* designate successively lower degrees of economic recoverability; paramarginal resources are defined as low-grade resources that are recoverable at prices as much as 1.5 times those prevailing now, and submarginal resources are those of still lower grade. (See fig. 4, p. 12.)

In this volume we use a similar classification of resources; but because of our conviction that the long-range potential lies in resources that have not yet been discovered, our classification places less emphasis on the definition of various levels of economic recoverability, and more emphasis on evaluating the undiscovered—defining the various degrees of certainty. For the purpose of this volume, we distinguish three different such degrees (fig. 1). *Identified resources* are specific bodies of mineral-bearing rock *whose existence and location are known.* They may or may not be evaluated as to extent and grade. Identified resources include

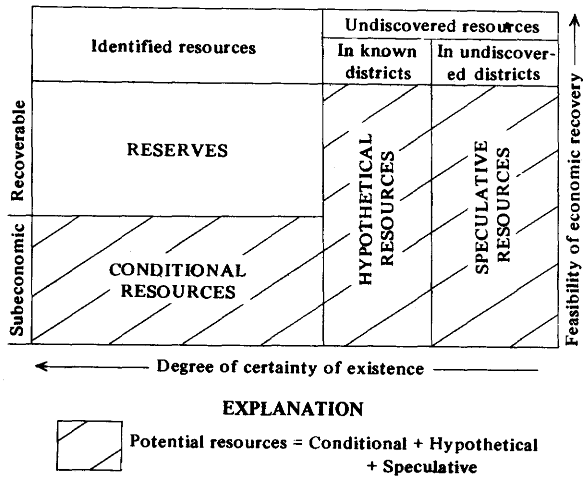

FIGURE 1.—Classification of mineral resources used in this volume.

reserves—masses of rock whose extent and grade are known to a greater or lesser degree and whose grade and physical nature are such that they may be extracted at a profit with existing technology and at present price levels. These last constraints of technology and economics exclude from the category of reserves many mineral deposits that are known and evaluated but are not profitably or technologically minable at present, and to this important category of identified but subeconomic resources we apply the informal term *conditional resources*—resources that may eventually become reserves when conditions of economics or technology are met. Conditional resources have an immediate potential, because they are *known*, and their assessment provides a target for technologic research. This term is used in the volume primarily as a convenience, because most authors were unable to distinguish the paramarginal and submarginal categories in McKelvey's classification.

We divide the remaining potential resources, all undiscovered, into two informally designated categories. *Hypothetical resources* are here defined as undiscovered resources that we may still reasonably expect to find *in known districts; speculative resources* are defined as undiscovered resources that may exist elsewhere—either conventional types of deposits in broad geologic terranes in which as yet there are no discoveries, or else unconventional types of resources that have only recently been recognized (or are yet to be recognized) as having some potential.

The utility of this distinction can be demonstrated by a few examples. In evaluating sandstone-type uranium deposits, for instance, we would consider as *hypothetical resources* the deposits that have so far eluded discovery in the known districts of New Mexico or Wyoming; our geologic knowledge tells us that there is good reason to expect we will find more deposits in those areas similar to the deposits already known, and our estimate of hypothetical resources is, in this case, an attempt to quantify the potential of these undiscovered resources, mainly on the basis of the extent of unexplored but favorable ground. A different kind of geologic perspective, on the other hand, suggests that there is still some likelihood of finding not just new deposits, but new major uranium districts. Our estimate of these *speculative resources*, even though it may be only an order of magnitude, is an attempt to quantify the resource potential of sedimentary basins that are known to exist but have not been sufficiently tested for uranium.

Resources of copper can be used as another example of the distinction between hypothetical and speculative resources. We are justified in *hypothesizing*, for instance, that porphyry copper deposits are concealed under basin fill in and near the known copper districts of the southwest, whereas the discovery in recent years of porphyry-type copper deposits of Paleozoic and Precambrian age in Eastern North America permits us to *speculate* that whole new regions have some potential for new discoveries.

Yet another example of the distinction between hypothetical and speculative resources involves the black bedded deposits of barite such as those currently being mined principally in Nevada and Arkansas. The known deposits are scattered over wide areas of both States, and chances are excellent that new deposits — hypothetical resources — will be found. But recent geologic studies of these deposits suggest that they are related more to sedimentary processes than was formerly believed. If this is true, then the potential for the discovery of new deposits and districts in other sedimentary basins—speculative resources—is likewise excellent. This example is an indication of how the reexamination and study of basic geologic principles can help to open new areas and environments favorable for exploration.

One further aspect of the value of such a distinction is that it has forced us to realize that the speculative resources of some commodities are relatively low. From a worldwide geologic perspective, we can say that the regions with significant potential for discovery of iron, or phosphorite, or marine evaporites, are largely known; thus, the significant undiscovered resources fall under the heading of "hypothetical," rather than "speculative." For some commodities, this may simply reflect insufficient knowledge of regional geology to identifiy other promising areas, but for others it is an expression of confidence that the favorable terranes have all been identified.

The entire field in the diagram of figure 1 represents our total primary resources (as distinct from secondary resources, such as recycled scrap, which are not considered in this volume)—identified reserves, plus potential resources, which consist of conditional, hypothetical, and speculative resources. Conversions of potential resources into reserves are made by discovery, technologic advance, or changes in economic conditions. The same processes may lead to similar conversions from outside the field—to make potential resources from materials at present inconceivable as resources.

A corollary of the emphasis of this volume on geologic rather than economic factors is that our classification is less concerned with the degrees of feasibility of recovery defined by McKelvey. We recognize that the concepts of paramarginal and submarginal resources are valid, but because of the broader objectives of this volume, nearly all our authors found that a single degree of distinction based on economic recoverability was difficult enough to obtain for identified resources, let alone for undiscovered resources, without the further complication of another degree defined by a specific price factor. Thus, nearly all the chapters of this volume differentiate three major categories of resources—identified, hypothetical, and speculative; within the first category, most chapters differentiate between recoverable identified resources (reserves), and subeconomic identified resources (conditional resources). In only a few chapters have the authors attempted to extend the levels of economic recoverability into the hypothetical and speculative fields, and where this has been done, it is generally in terms of "recoverable" versus "subeconomic"—for example, "subeconomic hypothetical resources."

Special problems are posed in classifying the resources found in sea-floor manganese nodules, in metal-bearing muds of the Red Sea, and in the recently discovered metal-bearing sedimentary rocks of the Belt Supergroup in Idaho and Montana. Some authors were reluctant to characterize the deposits in these three environments as identified resources. We see no question that they are identified, in that they broadly fit the criteria of being known as to existence and location; but we well realize that they are not fully evaluated. Our decision to classify these resources as "identified," for consistency of treatment within this volume, may therefore be regarded as arbitrary and is in no way binding on our authors or on our readers. We note, however, that officials of two major U.S. mining companies were recently reported to have said they "expect to be selling metal made from the [sea-floor] nodules by the end of the decade" (Faltermayer, 1972, p. 170). Such expectations, in our view, are not likely to have been predicated on resources that are undiscovered.

PUBLIC AWARENESS, RESOURCE ESTIMATES, AND GEOLOGIC AVAILABILITY

Public awareness of our dependence on mineral resources appears to be growing. With this growth in awareness—and indeed responsible for some of it—is a growth in the number of magazine and newspaper articles, and even books, that attempt to evaluate our supply of mineral resources and in some cases to forecast economic or cultural trends that are dependent on this supply. (See, for example, Faltermayer, 1972; Meadows and others, 1972; U.S. News and World Report, 1972.) The almost universal tendency of such articles is to discuss mineral resources principally from the perspective of economic availability under a given set of conditions, thereby overlooking the vital fact that reserves are but a part of resources. The results are, we feel, disturbing. Evaluations predicated only on knowledge (or estimates) of current reserves can easily lead to forecasts of the death of the industrial society in a short time. On the other hand, evaluations based on another kind of assumption suggest that a rise in prices will increase the reserves and bring much more material to market economically from lower and lower grade material in larger and larger deposits. This reasoning too is fallacious because elements are available in the earth's crust in very finite amounts. But in both instances, the reasoning leads to serious misinterpretations because it does not give adequate consideration to the single factor that ultimately determines all levels and degrees of mineral potential: *geologic availability*. Geologic availability concerns the existence and concentration of certain elements or combinations of elements and is the most fundamental characteristic of a mineral commodity that governs its commercial use.

Assessment of geologic availability of a commodity requires basic knowledge of the geology, mineralogy, and geochemistry of that material, the geologic environments in which it occurs, and its concentration in those environments. The technology of exploration, mining, beneficiation, recovery, and use is founded upon this information. Studies of geologic availability are indispensable—at all levels of commerce, industry, and government—for any economic planning that considers the available supply or use of primary mineral commodities and their byproducts.

Generally, however, public concepts of the magnitude of mineral resources are based on evaluations of economic rather than geologic availability, and even these are subject to numerous problems. Sound, accurate estimates of reserves for large regions are highly difficult to compile, for many reasons. Reserve data from industrial deposits may not be available because of the problems of competition and taxes. Managements of many companies believe that in the competitive atmosphere of business they should not release information about their reserves. Some States tax the reserves in the ground held by mining companies, making it economically advantageous, and in some cases necessary, to produce at capacity for years from deposits that are continually reported to be nearly exhausted. Definition of tonnages of mineral resources of sufficiently high grade to be minable at current prices is difficult enough without trying to distinguish grades minable at 1.5 or more times greater than the current price. Economic evaluations of a specific mineral deposit have become a complex task for a team of specialists, including not only geologists but also mining engineers, ore dressers, metallurgists, and economists. So many complex factors govern price at any given time that it would seem foolhardy to estimate resources in each of the economic categories and expect the results to be meaningful for very long.

At some time, however, the pressures of both economic and geologic factors will meet in crisis. Economic factors may be altered rapidly. Changes in demand and use alter patterns of production and consumption; new deposits are sought elsewhere; substitutes will be sought; and new technology will be developed as the ingenuity of man is focused on solving the problems. But there is no economic availability if there is no geologic availability. Of the two factors, geologic availability is the more fundamental because without it economic availability is not pertinent. Just as no biological miracle can make it possible to extract blood from a turnip, neither technological magic nor astronomic dollar value can make it possible to extract gold or aluminum or borax or mica from rocks in which they are not present. *Geologic availability, therefore, is the ultimate determinant of mineral potential,* and it is geologic availability that is stressed in the evaluations of potential mineral resources in this volume. Few chapters in the volume attempt to distinguish between tonnages now recoverable and those available only at subeconomic levels of the three "certainty-of-existence" categories shown in figure 1, but virtually every chapter offers a quantitative evaluation in numbers or words for the resources in each of the three categories, and the use of the threefold terminology has been applied as rigorously and uniformly as practical in each chapter.

GENERAL CONCLUSIONS

We realize that this book lacks a plot sufficient to induce its readers into proceeding through it from cover to cover. Therefore, we offer here some general conclusions on several aspects of the Nation's mineral-resource position, which have emerged from our editorial overview of the chapters as a whole. Of first importance is a summary answer to the principal question to which the volume is directed: Where do we stand with regard to resources of each commodity? Other conclusions pertain to the increasing importance, as resources, of large volumes of low-grade rocks, and attendant environmental problems; the problem of enormous quantities of potential mineral byproducts that are now literally being wasted; the factor of energy in the extraction of minerals; and finally, the pressing need for vigorous research along many lines.

MINERAL POTENTIAL: WHERE DO WE STAND?

Each chapter of the volume has its own calculation or other evaluation of resources governed by those factors deemed by the authors to be important to the respective commodity. There is no way to make the data in each chapter absolutely comparable. We would prefer that users of the volume read the chapters of interest to them in order to obtain the best possible understanding of the authors' presentation of resource data, and then formulate their own conclusions. We have, however, compiled a table that shows resource appraisals on a numerical scale, for commodities of major importance, put into perspective in terms of the *minimum* anticipated cumulative demand [1] for the period 1968–2000 as compiled by the U.S. Bureau of Mines (1970). Once again we emphasize that the resources indicated here are for the most part *potential,* and that their eventual availability as reserves is entirely dependent on continued geologic and technologic research as well as economic factors.

[1] In using "demand" values for purposes of comparison we do not represent them as being specific goals to be reached. This volume presents no social or political judgments; its sole purpose is to make available reliable geologic resource facts and assessments for public policy decision as well as for use by the minerals industry.

TABLE 1.—*Potential U.S. resources of some important mineral commodities, in relation to minimum anticipated cumulative demand to year 2000 A.D.*

ST=short tons. lb=pounds.
LT=long tons. Tr oz=troy ounces.
Identified resources: Includes reserves, and materials other than reserves that are reasonably well known as to location, extent, and grade, that may be exploitable in the future under more favorable economic conditions or with improvements in technology.
Hypothetical resources: Undiscovered but geologically predictable deposits of materials similar to present identified resources.
I. Domestic resources (of the category shown) are greater than 10 times the minimum anticipated cumulative demand 1968–2000.
II. Domestic resources are 2 to 10 times the MACD.
III. Domestic resources are approximately 75 percent to 2 times the MACD.
IV. Domestic resources are approximately 35–75 percent the MACD.
V. Domestic resources are approximately 10–35 percent the MACD.
VI. Domestic resources are less than 10 percent of the MACD.

Commodity	Minimum anticipated cumulative demand, 1968–2000 [1]	Identified resources	Hypothetical resources
Aluminum	290,000,000 ST	II	Not estimated.
Asbestos	32,700,000 ST	V	VI
Barite	25,300,000 ST	II	II
Chromium	20,100,000 ST	VI	VI
Clay	2,813,500,000 ST	III	II
Copper	96,400,000 ST	III	III
Fluorine	37,600,000 ST	V	V
Gold	372,000,000 Tr oz	III	Not estimated.
Gypsum	719,800,000 ST	I	I
Iron	3,280,000,000 ST	II	I
Lead	37,000,000 ST	III	IV
Manganese	47,000,000 ST	III	Not estimated.
Mercury	2,600,000 flasks	V	Not estimated.
Mica, scrap	6,000,000 ST	II	I
Molybdenum	3,100,000,000 lbs	I	I
Nickel	16,200,000,000 lbs	III	Not estimated.
Phosphate	190,000,000 ST	II	I
Sand and gravel	56,800,000,000 ST	III	Not estimated.
Silver	3,700,000,000 Tr oz	III	III
Sulfur	473,000,000 LT	I	I
Thorium	27,500 ST [2]	II	Not estimated.
Titanium (TiO_2)	38,000,000 ST	II	II
Tungsten	1,100,000,000 lbs	IV	IV
Uranium	1,190,000 ST	II	III
Vanadium	420,000 ST	II	Not estimated.
Zinc	57,000,000 ST	II	II

[1] As estimated by U.S. Bureau of Mines, 1970.
[2] For thorium, *maximum* anticipated cumulative demand 1968-2000, which assumes commercial development of economically attractive thorium reactors by 1980.

Careful study of both this table and the volume in its entirety leads to the conclusion that only a few commodities are readily available to the United States in quantities adequate to last for hundreds of years. By no means is it too early to become concerned about future mineral supplies—and to start planning. Charles F. Park (1968) wrote of the decrease in mineral supplies that is placing modern American affluence in jeopardy. The real extent of our dependence on mineral resources places in jeopardy not merely affluence, but world civilization.

LOW-GRADE ORES AND THE ENVIRONMENT

The impelling need for minerals poses environmental problems of concern to all. Probably foremost among these is the fact that for many minerals future production will depend on mining enormous volumes of low-grade ores, with necessarily strong environmental impact. The problem can be temporary, and can be solved, as witness the utilization of the manganese deposits in the Nikopol region, U.S.S.R., described in the chapter on "Manganese." But in most areas the opposing factions of industry and environmentalist are still just facing off. We believe the problem must be met squarely, realistically, and soon, by frank and objective exchange—not merely between small groups representing the mining industry on the one hand and outdoor enthusiasts on the other but between industry and the public at large. The environment is far bigger then any small interest group. Ultimately, a concerned public must decide in which order to place its priorities, and each faction of that public is entitled to basic information on the need for and availability of mineral resources as a foundation on which to base its decisions. Thus, as only two examples of such factions, the enthusiastic hiker—whether fisherman, Scout leader, or vacationing city dweller—must realize that his dacron-covered aluminum-frame backpack, his nylon fishing line, his polyurethane foam pad, and even his dehydrated foods are either made of or processed by mineral products, which continue to be used up and must continue to be made available. Conversely, the miner must realize that his assertion of need to develop a new copper deposit, when the technology of extraction may leave not only important potential byproducts but half the copper itself in the ground, may sound more like expediency than need.

It is beyond the scope of this volume to attempt a comprehensive review or evaluation of the mineral-environmental problem in general. Our purpose here is simply to indicate that the chapters of this volume provide some of the basic information on which such reviews or evaluations should be based.

ECONOMICS AND WASTE

A major aspect of resources that appears in many of these chapters is the extent to which many potential byproducts or coproducts are literally being *wasted*—lost forever—because there is no apparent economic incentive for recovering them. Some minerals go into slurry ponds, some into slags, some up the flue. Examples of such commodities are the vanadium in magnetite deposits; selenium, tellurium, and gold lost through in-place leaching of porphyry copper deposits; fluorine, vanadium, uranium, scandium, and rare earths in marine phosphorites; cadmium, bismuth, and cobalt in lead ores; and several metals in coal ash. Strictly speaking, these resources belong in the category of conditional resources, but we believe there is a significant distinction between resources that are not economically minable under present conditions and those that either are not recovered because of selective mining, or are discarded because of selective processing. In many cases the perspective of geologic availability makes possible the view that what may seem economical for the short term is not necessarily so for the long term, and these potential resources should not be overlooked or misused.

THE ENERGY FACTOR

Extraction and processing of all minerals requires some form of energy, and it is a safe generalization to say that to produce a fixed amount of any given commodity, the lower the grade of ore, the greater is the quantity of energy required. Although this volume contains individual chapters on mineral energy resources, a comprehensive evaluation of energy resources in the context of their specific relation to extraction of minerals is far beyond the scope of the book. The reader should bear in mind that as the mining industry turns to lower and lower grades of many ores, the cost and availability of the required energy are probably the single most important factors that will ultimately determine whether or not a particular mineral deposit can be worked economically.

THE NEED FOR RESEARCH

Potential resources are transformed into reserves not by moving rock, but by expanding the artificial boundaries of geologic knowledge and economic availability that delimit "reserves" from "resources"; hence, the potential of most of the resources discussed in this volume can be realized only as a result of applied research. Development of new technologies will make economic extraction of conditional resources feasible; innovative application of old geologic theory and the creation of new concepts of ore formation can be expected to lead to the discovery of conventional mineral deposits in favorable regions (hypothetical resources); research and exploration can be counted on to discover some new types of deposits and some new ore environments and regions that we do not know about now (speculative resources).

Clearly, to these factors of geologic and economic availability we must also add the factor of human ingenuity. W. E. Pratt (1943), vice president of Standard Oil Co., in speaking some years ago of petroleum exploration, cogently expressed a viewpoint that is equally pertinent for mineral exploration: "* * * physical conditions in the earth's crust impose fewer and less formidable obstacles to the development of commercial oil fields over the earth than do some of our mental and social habits * * * . Whatever the geological conditions may be and whatever technique we employ, we find oil in the earth very rarely unless we have first acquired an appropriate mental attitude * * *. Where oil really is, then, in the final analysis, is in our own heads!"

The chapters of this volume constitute a beginning effort to cultivate the "appropriate mental attitude" and to articulate the resulting ideas in terms of where and in what magnitudes our future mineral resources might be found. Only by continuing this effort, through vigorous pursuit of exploration, research, and technologic development, can we confidently expect to locate these potential resources and convert them into usable reserves.

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MINERAL RESOURCE ESTIMATES AND PUBLIC POLICY

By V. E. McKelvey

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TABLE

INTRODUCTION

Not many people, I have found, realize the extent of our dependence on minerals. It was both a surprise and a pleasure, therefore, to come across the observations of George Orwell in his book "The Road to Wigan Pier." When describing the working conditions of English miners in the 1930's, he evidently was led to reflect on the significance of coal:

Our civilization . . . is founded on coal, more completely than one realizes until one stops to think about it. The machines that keep us alive, and the machines that make the machines are all directly or indirectly dependent upon coal . . . . Practically everything we do, from eating an ice to crossing the Atlantic, and from baking a loaf to writing a novel, involves the use of coal, directly or indirectly. For all the arts of peace coal is needed; if war breaks out it is needed all the more. In time of revolution the miner must go on working or the revolution must stop, for revolution as much as reaction needs coal . . . In order that Hitler may march the goosestep, that the Pope may denounce Bolshevism, that the cricket crowds may assemble at Lords, that the Nancy poets may scratch one another's backs, coal has got to be forthcoming.

To make Orwell's statement entirely accurate—and ruin its force with complications—we should speak of mineral *fuels*, instead of coal, and of other minerals also, for it is true that minerals and mineral fuels are the resources that make the industrial society possible. The essential role of minerals and mineral fuels in human life may be illustrated by a simple equation

$$L=\frac{R\times E\times I}{P}$$

in which the society's average level of living (L), measured in its useful consumption of goods and services, is seen to be a function of its useful consumption of all kinds of raw materials (R), including metals, nonmetals, water, soil minerals, biologic produce, and so on; times its useful consumption of all forms of energy (E); times its useful consumption of all forms of ingenuity (I), including political and socio-economic as well as technologic ingenuity; divided by the number of people (P) who share in the total product.

This is a restatement of the classical economists' equation in which national output is considered to be a function of its use of capital and labor, but it shows what capital and labor really are. Far from being mere money, which is what it is popularly thought to mean, capital represents accumulated usable raw materials and things made from them, usable energy, and especially accumulated knowledge. And the muscle power expended in mere physical toil, which is what labor is often thought to mean, is a trivial contribution to national output compared to that supplied by people in the form of skills and ingenuity.

This is only a conceptual equation, of course, for numerical values cannot be assigned to some of its components, and no doubt some of them—ingenuity in particular—should receive far more weight than others. Moreover, its components are highly interrelated and interdependent. It is the development and use of a high degree of ingenuity that makes possible the high consumption of minerals and fuels, and the use of minerals and fuels are each essential to the availability and use of the other. Nevertheless, the expression serves to emphasize that level of living is a function of our intelligent use of natural resources, and it brings out the importance of the use of energy and minerals in the industrial society. As shown in figure 2, per capital Gross National Product among the countries of the world is, in fact, closely related to their per capita consumption of energy. Steel consumption also shows a close relation to per capita GNP (fig. 3), as does the consumption of many other minerals.

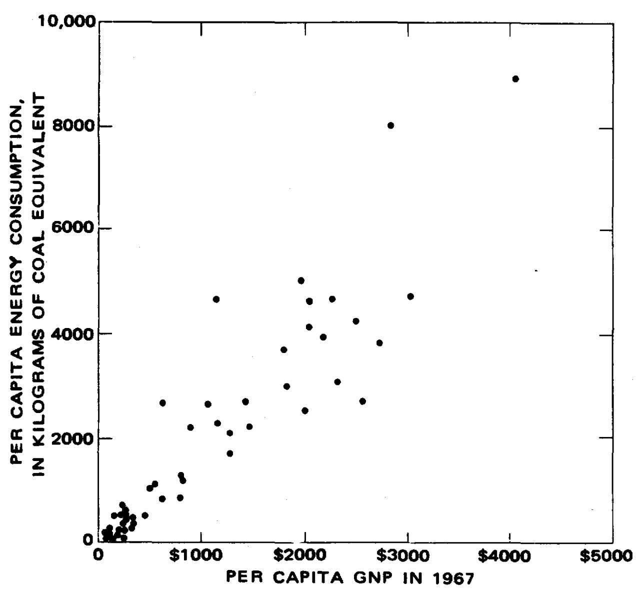

FIGURE 2.—Per capita energy consumption compared to per capita Gross National Product (GNP) in countries for which statistics are available in the United Nations "Statistical Yearbook" for 1967.

Because of the key role that minerals and fuels play in economic growth and in economic and military security, the extent of their resources is a matter of great importance to government, and questions concerning the magnitude of resources arise in conjunction with many public problems. To cite some recent examples, the magnitude of low-cost coal and uranium reserves has been at the heart of the question as to when to press the development of the breeder reactor—which requires a research-and-development program involving such an enormous outlay of public capital that it would be unwise to make the investment until absolutely necessary.

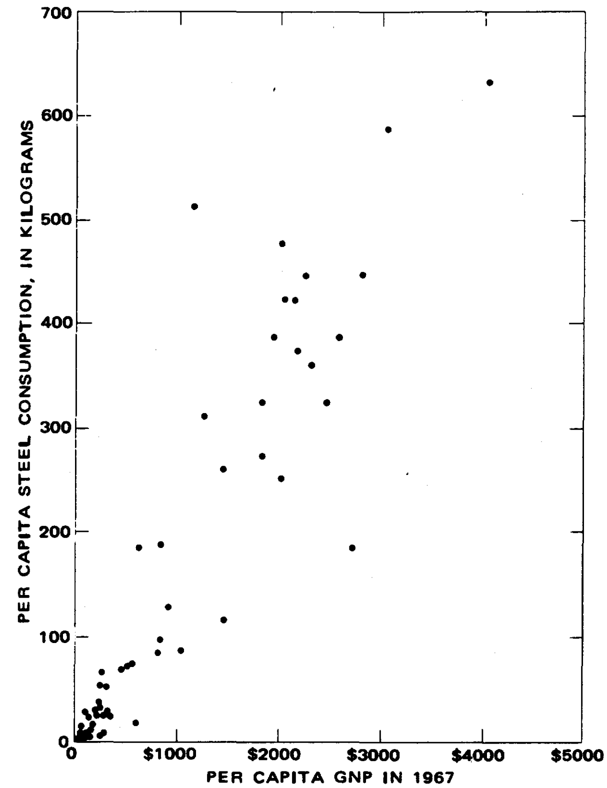

FIGURE 3.—Per capita steel consumption compared to per capita Gross National Product (GNP) in countries for which statistics are available in the United Nations "Statistical Yearbook" for 1967.

Similarly, estimates of potential oil and gas resources are needed for policy decisions related to the development of oil shale and coal as commercial sources of hydrocarbons, and estimates are needed also as the basis for decisions concerning prices and import controls.

Faced with a developing shortage of natural gas, the Federal Power Commission is presently much interested in knowing whether or not reserves reported by industry are an accurate indication of the amount of natural gas actually on hand; it also wants to know the extent of potential resources and the effect of price on their exploration and development. At the regional or local level, decisions with respect to the designation of wilderness areas and parks, the construction of dams, and other matters related to land use involve appraisal of the distribution and amount of the resources in the area. The questions of the need for an international regime governing the development of seabed resources, the character such arrangement should have, the definition of the area to which it should apply also involve, among other considerations, analysis of the probable character, distribtuion, and magnitude of subsea mineral resources.

And coming to the forefront is the most serious question of all—namely, whether or not resources are adequate to support the continued existence of the world's population and indeed our own. The possibility to consider here goes much beyond Malthus' gloomy observations concerning the propensity of a population to grow to the limit of its food supply, for both population and level of living have grown as the result of the consumption of nonrenewable resources, and both are already far too high to maintain without industrialized, high-energy, and high mineral-consuming agriculture, transportation, and manufacturing. I will say more about this question later, but to indicate something of the magnitude of the problem let me point out that, in attaining our high level of living in the United States, we have used more minerals and mineral fuels during the last 30 years than all the people of the world used previously. This enormous consumption will have to be doubled just to meet the needs of the people now living in the United States through the remainder of their lifetimes, to say nothing about the needs of succeeding generations, or the increased consumption that will have to take place in the lesser developed countries if they are to attain a similar level of living.

CONCEPTS OF RESERVES AND RESOURCES

The focus of most of industry's concern over the extent of mineral resources is on the magnitude of the supplies that exist now or that can be developed in the near term, and this is of public interest also. Many other policy decisions, however, relate to the much more difficult question of potential supplies, a question that to be answered properly must take account both of the extent of undiscovered deposits as well as deposits that cannot be produced profitably now but may become workable in the future. Unfortunately, the need to take account of such deposits is often overlooked, and there is a widespread tendency to think of potential resources as consisting merely of materials in known deposits producible under present economic and technologic conditions.

In connection with my own involvement in resource appraisal, I have been developing over the last several years a system of resource classification and terminology that brings out the classes of resources that need to be taken into account in appraising future supplies, which I believe helps to put the supply problem into a useful perspective. Before describing it, however, I want to emphasize that the problem of estimating potential resources has several built-in uncertainties that make an accurate and complete resource inventory impossible, no matter how comprehensive its scope.

One such uncertainty results from the nature of the occurrence of mineral deposits, for most of them lie hidden beneath the earth's surface and are difficult to locate and to examine in a way that yields accurate knowledge of their extent and quality. Another source of uncertainty is that the specifications of recoverable materials are constantly changing as the advance of technology permits us to mine or process minerals that were once too low in grade, too inaccessible, or too refractory to recovery profitably. Still another results from advances that make it possible to utilize materials not previously visualized as usable at all.

For these reasons the quantity of usable resources is not fixed but changes with progress in science, technology, and exploration and with shifts in economic conditions. We must expect to revise our estimates periodically to take account of new developments. Even incomplete and provisional estimates are better than none at all, and if they differentiate known, undiscovered, and presently uneconomic resources they will help to define the supply problem and provide a basis for policy decisions relating to it.

The need to differentiate the known and the recoverable from the undiscovered and the uneconomic requires that a resource classification system convey two prime elements of information: the degree of certainty about the existence of the materials and the economic feasibility of recovering them. These two elements have been recognized in existing terminology, but only incompletely. Thus as used by both the mining and the petroleum industries, the term **reserves** generally refers to economically recoverable material in identified deposits, and the term **resources** includes in addition deposits not yet discovered as well as identified deposits that cannot be recovered now (for example, Blondel and Lasky, 1956).

The degree of certainty about the existence of the materials is described by terms such as **proved, probable**, and **possible**, the terms traditionally used by industry, and **measured, indicated**, and **inferred**, the terms devised during World War II by the Geological Survey and the Bureau of Mines to serve better the broader purpose of national resource appraisal. Usage of these degree-of-certainty terms is by no means standard, but all their definitions show that they refer only to deposits or structures known to exist.

Thus, one of the generally accepted definitions of **possible** ore states that it is to apply to deposits whose existence is known from at least one exposure, and another definition refers to an ore body sampled only on one side. The definition of **inferred** reserves agreed to by the Survey and the Bureau of Mines permits inclusion of completely concealed deposits for which there is specific geologic evidence and for which the specific location can be described, but it makes no allowance for ore in unknown structures of undiscovered districts. The previous definitions of both sets of terms also link them to deposits minable at a profit; the classification system comprised of these terms has thus neglected deposits that might become minable as the result of technologic or economic developments.

To remedy these defects, I have suggested that existing terminology be expanded into the broader framework shown in figure 4, in which degree of certainty increases from right to left and feasibility of economic recovery increases from bottom to top. Either of the series of terms already used to describe degree of certainty may be used with reference to identified deposits and applied not only to presently minable deposits but to others that have been identified with the same degree of certainty. Feasibility-of-recovery categories are designated by the terms **recoverable, paramarginal**, and **submarginal.**

Paramarginal resources are defined here as those that are recoverable at prices as much as 1.5 times those prevailing now. (I am indebted to S. P. Schweinfurth for suggesting the prefix **para** to indicate that the materials described are not only those just on the margin of economic recoverability, the common economic meaning of the term **marginal.**) At first thought this price factor may seem to be unrealistic. The fact is, however, that prices of many mineral commodities vary within such a range from place to place at any given time, and a price elasticity of this order of magnitude is not uncommon for many commodities over a space of a few years or even months, as shown by recent variations in prices of copper, mercury, silver, sulfur, and coal. Deposits in this category thus become commercially available at price increases that can be borne without serious economic effects, and chances are that improvements in existing technology will make them available at prices little or no higher than those prevailing now.

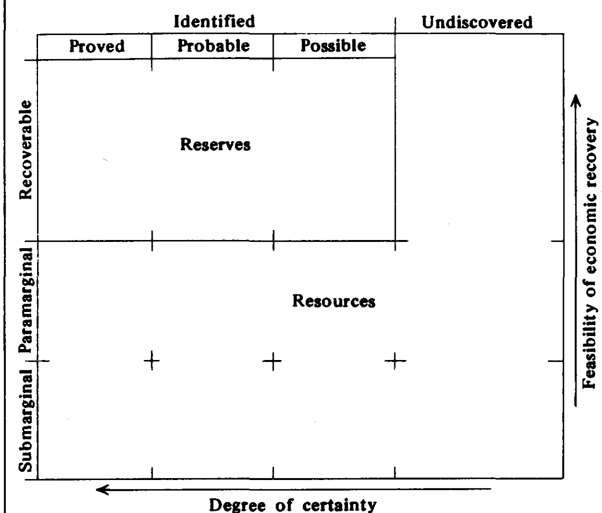

FIGURE 4.—Classification of mineral reserves and resources. Degree of certainty increases from right to left, and feasibility of economic recovery increases from bottom to top.

Over the longer period, we can expect that technologic advances will make it profitable to mine resources that would be much too costly to produce now, and, of course, that is the reason for trying to take account of submarginal resources. Again, it might seem ridiculous to consider resources that cost two or three times more than those produced now as having any future value at all. But keep in mind, as one of many examples, that the cutoff grade for copper has been reduced progressively not just by a factor of two or three but by a factor of 10 since the turn of the century and by a factor of about 250 over the history of mining. Many of the fuels and minerals being produced today would once have been classed as submarginal under this definition, and it is reasonable to believe that continued technologic progress will create recoverable reserves from this category.

EXAMPLES OF ESTIMATES OF POTENTIAL RESOURCES

For most minerals, the chief value of this classification at present is to call attention to the information needed for a comprehensive appraisal of their potential, for we haven't developed the knowledge and the methods necessary to make meaningful estimates of the magnitude of undiscovered deposits, and we don't know enough about the cost of producing most presently noncommercial deposits to separate paramarginal from submarginal resources. Enough information is available for the mineral fuels, however, to see their potential in such a framework.

The fuel for which the most complete information is available is the newest one—uranium. As a result of extensive research sponsored by the Atomic Energy Commission, uranium reserves and resources are reported in several cost-of-recovery categories, from less than $8 to more than $100 per pound of U_3O_8. For the lower cost ores, the AEC makes periodic estimates in two degree-of-certainty categories, one that it calls **reasonably assured reserves** and the other it calls **additional resources**, defined as uranium surmised to occur in unexplored extensions of known deposits or in undiscovered deposits in known uranium districts. Both the AEC and the Geological Survey have made estimates from time to time of resources in other degree-of-certainty and cost-of-recovery categories.

Ore in the less-than-$8-per-pound class is minable now, and the AEC estimates reasonably assured reserves to be 143,000 tons and additional resources to be 167,000 tons of U_3O_8—just about enough to supply the lifetime needs of reactors in use or ordered in 1968 and only half that required for reactors expected to be in use by 1980. The Geological Survey, however, estimates that undiscovered resources of presently minable quality may amount to 750,000 tons, or about 2.5 times that in identified deposits and districts. Resources in the $8- to $30-a-pound category in identified and undiscovered deposits add only about 600,000 tons of U_3O_8 and thus do not significantly increase potential reserves.

But tens of millions of tons come into prospect in the price range of $30 to $100 per pound. Uranium at such prices would be usable in the breeder reactor. The breeder, of course, would utilize not only U^{235} but also U^{238}, which is 140 times more abundant than U^{235}. Plainly the significance of uranium as a commercial fuel lies in its use in the breeder reactor, and one may question, as a number of critics have (for example, Inglis, 1971), the advisability of enlarging nuclear generating capacity until the breeder is ready for commercial use.

Until recently the only information available about petroleum resources consisted of estimates of proved reserves prepared annually by the American Petroleum Institute and the American Gas Association, plus a few estimates of what has been called ultimate production, that is, the total likely to be eventually recovered. A few years ago, however, the API began to report estimates of total oil in place in proved acreage, and the Potential Gas Committee began to estimate possible and probable reserves of natural gas, defining them as consisting of gas expected to be found in extensions of identified fields and in new discoveries in presently productive strata in producing provinces. It also introduced another category, **speculative resources**—equivalent to what I have called "undiscovered"—to represent gas to be found in nonproducing provinces and in presently unproductive strata in producing provinces.

In 1970 the National Petroleum Council released a summary of a report on "Future Petroleum Provinces of the United States," prepared at the request of the Department of the Interior, in which it reported estimates of crude oil in the combined probable-possible class and in the speculative category. In addition, NPC estimated the amounts that would be available under two assumptions as to the percent of the oil originally in place that might be recovered in the future (table 2). NPC did not assess the cost of such recovery, but the average recovery is now about 30 percent of the oil in place, and NPC expects it to increase gradually to about 42 percent in the year 2000 and to 60 percent eventually. The NPC estimates do not cover all potentially favorable areas either on land or offshore but, even so, in the sum of these various categories NPC sees about 12 times as much oil remaining to be discovered and produced as exists in proved reserves alone.

The Potential Gas Committee's estimates of potential gas resources similarly do not cover all favorable areas, but they indicate that resources in the probable, possible, and speculative categories are about twice that of proved reserves and past production. Because about 80 percent of the gas originally in place is now recovered, paramarginal and submarginal resources in ordinary gas reservoirs are not as large as for crude oil. Paramarginal and submarginal gas resources may be significant, however, in kinds of rocks from which gas is not now recovered, namely impermeable strata and coal. In the Rocky Mountain province, for instance, Haun, Barlow, and Hallinger (1970) recently estimated

TABLE 2.—*Some estimates of U.S. crude-oil reserves and resources, in billion barrels*

[API, American Petroleum Institute; NPC, National Petroleum Council]

	In identified fields or stuctures		In undiscovered fields and structures (speculative)
	Proved	Probable-possible	
Recoverable at present rate[1]	31 (API)	74 (NPC)	67 (NPC)
Additional at 42 percent recovery	47 (NPC)	22 (NPC)	21 (NPC)
Additional at 60 percent recovery	69 (NPC)	40 (NPC)	37 (NPC)
Oil originally in place	388 (API)[2]	227 (NPC)	209 (NPC)
Total oil originally in place	2200 (Hendricks and Schweinfurth, 1968).		
Ultimate production[2]	190 (Hubbert, 1969); 353 (Moore, 1966); 433 (Weeks)[3]; 450 (Elliott and Linden, 1968); 432–495 (NPC); 550 (Hendricks and Schweinfurth, 1968).		

[1] Average recovery is 30 percent of oil in place.
[2] Includes past production of 86 billion barrels.
[3] See McKelvey (1968, Table II, p. 18).

potential gas resources in ordinary reservoirs to be in the range of 100 to 200 trillion cubic feet, but pointed out that gas in impermeable strata which might be released by nuclear stimulation would be several times that amount. Gas occluded in coal—now only a menace in this country as a cause of explosions—is already recovered in some European mines and is also a potentially large resource.

The uncertainties concerning potential coal resources center not on their total magnitude, as they do for oil and gas, but on the amounts available at present prices. Because coal beds have great lateral continuity, geologic mapping and stratigraphic studies make it possible to project them long distances from their outcrops and to categorize them in terms of thickness of beds, thickness of overburden, rank of coal, and other features that affect cost. The Geological Survey has prepared such estimates, but the cost of recovering coal in the various categories has yet to be determined. Coal in beds more than 14 inches thick totals at least 3.3 trillion tons in the United States, but estimates of the amounts minable at present prices have ranged from 20 to 220 billion tons. (See U.S. Office of Science and Technology, "Energy R and D and National Progress.") Because 20 billion tons represents nearly a 40-year supply at present rates of consumption, it is easy to see why the studies needed to determine how much would be available at various costs have not been undertaken. The question is by no means only of academic interest, for the nuclear power development program was justified in part in its early years on the assumption that reserves of low-cost coal were extremely limited, and part of the continued growth of the nuclear power industry is said to be the result of the difficulty power companies are having in acquiring low-cost reserves.

QUANTIFYING THE UNDISCOVERED

Considering potential resources in the degree-of-certainty, cost-of-recovery framework brings out the joint role that geologists, engineers, mineral technologists, and economists must play in estimating their magnitude. Having emphasized the importance of the economic and technologic side of the problem, I want now to turn to the geological side and consider the problem of how to appraise the extent of undiscovered reserves and resources.

It is difficult enough to estimate the extent of unexplored resources of the inferred or possible class. In fact, it is even difficult to estimate measured or proved reserves with a high degree of accuracy until they have been largely mined out. Thus, estimates of proved reserves prepared in advance of appreciable production commonly have an error of about 25 percent, and the error in estimates of incompletely explored deposits is usually much larger. Generally the combination of the geologist's inherent conservatism and the lack of information on the geology of concealed areas leads to estimates that err in being too low rather than too high.

One eminent mining geologist reported that, having recognized these effects, he once arbitrarily tripled his calculations to arrive at an estimate of the ore remaining in a producing district; twice the amount of his inflated estimate, however, was found and mined over the next 20 years, and more was in prospect. To match many such stories are at least a few prematurely deserted mills and mine installations built on the expectation of finding ore that did not materialize. Both kinds of experiences emphasize the difficulty of appraising the extent of mineral deposits even in partly explored areas. In the light of such experiences one is justified in asking—as many well-informed people have—whether estimates of the magnitude of undiscovered deposits can have enough reliability to make them worthwhile.

The fact that new districts are still being discovered for nearly every commodity and that large areas favorable for the occurrence of minerals of all kinds are covered by alluvium, volcanics, glacial drift, seawater, or other materials that conceal possible mineral-bearing rocks or structures assures us that undiscovered deposits are still to be found. Qualitatively, at least, we know something about the distribution of minerals with respect to other geologic phenomena and, if this is so, we have a chance of developing quantitative relations that will give us at least a start.

Two principal approaches to the problem have been taken thus far. One is to extrapolate observations related to rate of industrial activity, such as annual production of the commodity; the other is to extrapolate observations that relate to the abundance of the mineral in the geologic environment in which it is found.

The first of these methods has been utilized by M. K. Hubbert (1969), C. L. Moore (1966), and M. A. Elliott and H. R. Linden (1968) in estimating ultimate reserves of petroleum. The essential features of this approach are to analyze the growth in production, proved reserves, and discovery per foot of drilling over time and to project these rate phenomena to terminal values in order to predict ultimate production. Hubbert has used the logistic curve for his projections, and Moore has utilized the Gompertz curve, with results more than twice as high as those of Hubbert. As Hubbert has pointed out, these methods utilize the most reliable information collected on the petroleum industry; modern records on production, proved reserves, number of wells drilled, and similar activities are both relatively complete and accurate, at least as compared with quantitative knowledge about geologic features that affect the distribution of petroleum.

The rate methods, however, have an inherent weakness in that the phenomena they analyze reflect human activities that are strongly influenced by economic, political, and other factors that bear no relation to the amount of oil or other material that lies in the ground. Moreover, they make no allowance for major breakthroughs that might transform extensive paramarginal or submarginal resources into recoverable reserves, nor do they provide a means of estimating the potential resources of unexplored regions. Such projections have some value in indicating what will happen over the short term if recent trends continue, but they can have only limited success in appraising potential resources.

Even the goal of such projections, namely the prediction of ultimate production, is not a useful one. Not only is it impossible to predict the quantitative effects of man's future activities but the concept implies that the activities of the past are a part of an inexorable process with only one possible outcome. Far more useful, in my opinion, are estimates of the amounts of various kinds of materials that are in the ground in various environments; such estimates establish targets for both the explorer and the technologist, and they give us a basis for choosing among alternative ways of meeting our needs for mineral supplies.

The second principal approach taken thus far to the estimation of undiscovered resources involves the extrapolation of data on the abundance of mineral deposits from explored to unexplored ground on the basis of either the area or the volume of broadly favorable rocks. In the field of metalliferous deposits, Nolan (1950) pioneered in extrapolation on the basis of area in his study of the spatial and size distribution of mineral deposits in the Boulder Dam region and in his conclusion that a similar distribution should prevail in adjacent concealed and unexplored areas. Weeks (1958, 1965) and Pratt (1950) played similar roles with respect to the estimation of petroleum resources—Weeks extrapolating on the basis of oil per unit volume of sediment and Pratt on the basis of oil per unit area. Many of the estimates of crude oil that went into the NPC study were made by the volumetric method, utilizing locally appropriate factors on the amount of oil expected per cubic mile of sediment. Olson and Overstreet (1964) have since used the area method to estimate the magnitude of world thorium resources as a function of the size of areas of igneous and metamorphic rocks as compared with India and the United States, and A. P. Butler (written commun., 1958) used the magnitude of sandstone uranium ore reserves exposed in outcrop as a basis for estimating the area in back of the outcrop that is similarly mineralized.

Several years ago, Zapp (1962) and Hendricks (1965) introduced another approach, based on the amount of drilling required to explore adequately the ground favorable for exploration and the reserves discovered by the footage already drilled—a procedure usable in combination with either the volumetric or areal approach. Recently J. B. Zimmerman and F. L. Long (cited in "Oil and Gas Journal, 1969") applied this approach to the estimation of gas resources in the Delaware–Val Verde basins of west Texas and southeastern New Mexico; and Haun, Barlow, and Hallinger (1970) used it to estimate potential natural gas resources in the Rocky Mountain region. In the field of metals, Lowell (1970) has estimated the number of undiscovered porphyry copper deposits in the southwestern United States, Chile and Peru, and British Columbia as a function of the proportion of the favorable pre-ore surface adequately explored by drilling, and Armstrong (1970) has similarly estimated undiscovered uranium reserves in the Gas Hills area of Wyoming on the basis of the ratios between explored and unexplored favorable areas.

I have suggested another variant of the areal method for estimating reserves of nonfuel minerals which is based on the fact that the tonnage of minable reserves of the well-explored elements in the United States is roughly equal to their crustal abundance in percent times a billion or 10 billion (fig. 5). Obviously this relation is influenced by the

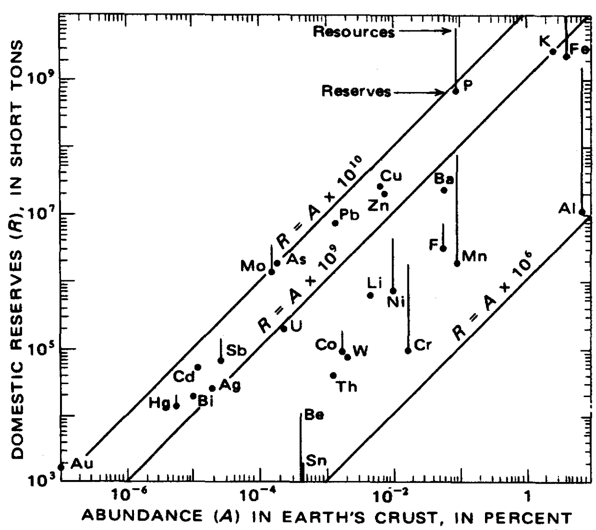

FIGURE 5.—Domestic reserves of elements compared to their abundance in the earth's crust. Tonnage of ore minable now is shown by a dot; tonnage of lowergrade ores whose exploitation depends upon future technological advances or higher prices is shown by a bar.

extent of exploration, for it is only reserves of the long-sought and well-explored minerals that display the relation to abundance. But it is this feature that gives the method its greatest usefulness, for it makes it possible to estimate potential resources of elements, such as uranium and thorium, that have been prospected for only a short period. Sekine (1963) tested this method for Japan and found it applicable there, which surprised me a little, for I would not have thought Japan to be a large enough sample of the continental crust to bring out this relationship.

The relation between reserves and abundance, of course, can at best be only an approximate one, useful mainly in order-of-magnitude estimates, for obviously crustal abundance of an element is only one of its properties that lead to its concentration. That it is an important factor, however, may be seen not only in its influence on the magnitude of reserves but also in other expressions of its influence on the concentrations of the elements. For example, of the 18 or so elements with crustal abundances greater than about 200 parts per million, all but fluorine and strontium are rock forming in the sense that some extensive rocks are composed chiefly of minerals of which each of these elements is a major constituent. Of the less abundant elements, only chromium, nitrogen, and boron have this distinction. Only a few other elements, such as copper, lead, and zinc, even form ore bodies composed mainly of minerals of which the valuable element is a major constituent, and in a general way the grade of minable ores decreases with decreasing crustal abundance. A similar gross correlation exists between abundance of the elements and the number of minerals in which they are a significant constituent.

Members of a committee of the Geology and the Conservation of Mineral Resources Board of the Soviet Union have described a somewhat similar method for the quantitative evaluation of what they call predicted reserves of oil and gas, based on estimates of the total amount of hydrocarbons in the source rock and of the fraction that has migrated into commercial reservoirs—estimates that would be much more difficult to obtain for petroleum than for the elements. Probably for this reason not much use has been made of this method, but it seems likely that quantitative studies of the effects of the natural fractionation of the elements might be of some value in estimating total resources in various size and grade categories.

Some studies of the grade-frequency distribution of the elements have, in fact, been undertaken by geochemists in the last couple of decades, and, taking off from Nolan's work, several investigators have studied the areal and size-frequency distribution of mineral deposits in conjunction with attempts to apply the methods of operations research to exploration (for example, Allais, 1957; Slichter, 1960; Griffiths, 1964; DeGeoffroy and Wu, 1970, and Harris and Euresty, 1969). None of these studies has been concerned with the estimation of undiscovered reserves, but they have identified two features about the distribution of mineral deposits that may be applicable to the problem.

One is that the size distribution of both metalliferous deposits, expressed in dollar value of production, and of oil and gas, expressed in volumetric units, has been found to be log normal, which means that of a large population of deposits, a few contain most of the ore (for example, Slichter, 1960; Kaufman, 1963). In the Boulder Dam area, for example, 4 percent of the districts produced 80 percent of the total value of recorded production. The petroleum industry in the United States has a rule of thumb that 5 percent of the fields account for 50 percent of the reserves and 50 percent of fields, for 95 percent. And in the USSR, about 5 percent of the oil fields contain about 75 percent of the oil, and 10 percent of the gas fields have 85 percent of the gas reserves.

The other feature of interest is that in many deposits the grade-tonnage distribution is also log normal, and the geochemists have found this to be the case also with the frequency distribution of minor elements.

These patterns of size- and grade-frequency distribution will not in themselves provide information on the magnitude of potential resources, for they describe only how minerals are distributed and not how much is present. But if these patterns are combined with quantitative data on the incidence of congeneric deposits in various kinds of environments, the volume or area of favorable ground, and the extent to which it has been explored, they might yield more useful estimates of potential resources than are obtainable by any of the procedures so far applied. Thus, estimates of total resources described in terms of their size- and grade-frequency distributions could be further analyzed in the light of economic criteria defining the size, grade, and accessibility of deposits workable at various costs, and then partitioned into feasibility-of-recovery and degree-of-certainty categories to provide targets for exploration and technologic development as well as guidance for policy decisions.

Essential for such estimates, of course, is better knowledge than is now in hand for many minerals on the volume of ore per unit of favorable ground and on the characteristics of favorable ground itself. For petroleum the development of such knowledge is already well advanced. For example, whereas most estimates of resources have been based on an assumed average petroleum content of about 50,000 barrels per cubic mile of sediment, varied a little perhaps to reflect judgments of favorability, the range in various basins is from 10,000 to more than 2,000,000 barrels per cubic mile. As shown by the recent analysis by Halbouty and his colleagues (1970) of the factors affecting the formation of giant fields, the geologic criteria are developing that make it possible to classify sedimentary basins in terms of their petroleum potential. Knowledge of the mode of occurrence and genesis of many metalliferous minerals and of the geology of the terranes in which they occur is not sufficient to support comprehensive estimates prepared in this way. But for many kinds of deposits enough is known to utilize this kind of approach on a district or regional basis, and I hope a start can soon be made in this direction.

NEED FOR REVIEW OF RESOURCE ADEQUACY

Let me return now to the question of whether or not resources are adequate to maintain our present level of living. This is not a new question by any means. In 1908 it was raised as a national policy issue at the famous Governors' Conference on Resources, and it has been the subject of rather extensive inquiry by several national and international bodies since then. In spite of some of the dire predictions about the future made by various people in the course of these inquiries, they did not lead to any major change in our full-speed-ahead policy of economic development. Some of these inquiries, in fact, led to immediate investigations that revealed a greater resource potential for certain minerals than had been thought to exist, and the net effect was to alleviate rather than heighten concern.

Now, however, concern about resource adequacy is mounting again. The overall tone of the recent National Academy of Sciences' report on "Resources and Man" was cautionary if not pessimistic about continued expansion in the production and use of mineral resources, and many scientists, including some eminent geologists, have expressed grave doubts about our ability to continue on our present course. The question is also being raised internationally, particularly in developing countries where concern is being expressed that our disproportionate use of minerals to support our high level of living may be depriving them of their own future.

Personally, I am confident that for millennia to come we can continue to develop the mineral supplies needed to maintain a high level of living for those who now enjoy it and raise it for the impoverished people of our own country and the world. My reasons for thinking so are that there is a visible undeveloped potential of substantial proportions in each of the processes by which we create resources and that our experience justifies the belief that these processes have dimensions beyond our knowledge and even beyond our imagination at any given time.

Setting aside the unimaginable, I will mention some examples of the believable. I am sure all geologists would agree that minable undiscovered deposits remain in explored as well as unexplored areas and that progress in our knowledge of regional geology and in exploration will lead to the discovery of many of them. With respect to unexplored areas, the mineral potential of the continental margins and ocean basins deserves particular emphasis, for the technology that will give us access to it is clearly now in sight. For many critical minerals, we already know of substantial paramarginal and submarginal resources that experience tells us should be brought within economic reach by technological advance. The process of substituting an abundant for a scarce material has also been pursued successfully, thus far not out of need but out of economic opportunity, and plainly has much potential as a means of enlarging usable resources.

Extending our supplies by increasing the efficiency of recovery and use of raw materials has also been significant. For example, a unit weight of today's steel provides 43 percent more structural support than it did only 10 years ago, reducing proportionately the amount required for a given purpose. Similarly, we make as much electric power from 1 ton of coal now as we were able to make from 7 tons around the turn of the century. Our rising awareness of pollution and its effects surely will force us to pay even more attention to increasing the efficiency of mineral recovery and use as a means of reducing the release of contaminants to the environment. For similar reasons, we are likely to pursue more diligently processes of recovery, reuse, and recycling of mineral materials than we have in the past.

Most important to secure our future is an abundant and cheap supply of energy, for if that is available we can obtain materials from low-quality sources, perhaps even country rocks, as Harrison Brown (1954, p. 174–175) has suggested. Again. I am personally optimistic on this matter, with respect to the fossil fuels and particularly to the nuclear fuels. Not only does the breeder reactor appear to be near enough to practical reality to justify the belief that it will permit the use of extremely low-grade sources of uranium and thorium that will carry us far into the future, but during the last couple of years there have been exciting new developments in the prospects for commercial energy from fusion. Gothermal energy has a large unexploited potential, and new concepts are also being developed to permit the commercial use of solar energy.

But many others do not share these views, and it seems likely that soon there will be a demand for a confrontation with the full-speed-ahead philosophy that will have to be answered by a deep review of resource adequacy. I myself think that such a review is necessary, simply because the stakes have become so high. Our own population, to say nothing of the world's, is already too large to exist without industrialized, high energy- and mineral-consuming agriculture, transportation, and manufacturing. If our supply of critical materials is enough to meet our needs for only a few decades, a mere tapering off in the rate of increase of their use, or even a modest cutback, would stretch out these supplies for only a trivial period. If resource adequacy cannot be assured into the far-distant future, a major reorientation of our philosophy, goals, and way of life will be necessary. And if we do need to revert to a low resource-consuming economy, we will have to begin the process as quickly as possible in order to avoid chaos and catastrophe.

Comprehensive resource estimates will be essential for this critical examination of resource adequacy, and they will have to be made by techniques of accepted reliability. The techniques I have described for making such estimates have thus far been applied to only a few minerals, and none of them have been developed to the point of general acceptance. Better methods need to be devised and applied more widely, and I hope that others can be enlisted in the effort necessary to do both.

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