Mineral resources appraisal

Mineral endowment, resources, and potential supply: concepts, methods, and cases

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PREFACE

This book results primarily from the need for an account of quantitative methods for the estimation of mineral and energy resources. In a larger sense, it reflects an interest which initially was fostered by my reading of the seminal work of Maurice Allais and subsequently intensified by exposure to the ideas of John C. Griffiths on geostatistics and operations research. This interest led directly to my own doctoral research and to a continuing interest in the development of this relatively new field of inquiry and analysis.

My first attempt at a book, which was completed in 1977, was basically an extension of a survey and critique of appraisal methods for the US Energy Research and Development Administration. The political and economic events at that time had created a keen interest in energy and resource issues; as a result of that interest, I received requests from all quarters of the world for the 1977 document. Satisfying these requests soon exhausted the limited stock. In recognition of the very rapid evolution of ideas and appraisal methodologies during the period from 1975 to 1981, the 1977 document was updated and extensively rewritten to form the manuscript for this book.

Paramount among considerations of content and style of this book is the identification and description of a conceptual framework that defines the field and enriches understanding of the highly varied contributions, most of which are applications of one or more quantitative methods. By virtue of the compound nature of mineral and energy resources, this framework must bring together elements from economics, geology, and technology. Furthermore, because of uncertainty about the existence and characteristics of undiscovered mineral deposits, appraisal of mineral resources involves issues of statistical estimation. Consequently, the sweep of topics covered in this book is very broad. Accordingly, some sections of the book will be of interest primarily to geologists, others to economists, and still others to statisticians and systems analysts. The reader, regardless of his major discipline, will I hope be rewarded for his effort.

DV.P.H.

Arizona
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Special acknowledgement is made of the contribution of Alice Yelverton, who not only typed the manuscript in all its stages of evolution but also supervised the proofing and coordinating of the manuscript. The magnitude of her effort is exceeded only by its quality.

I am indebted to Professor Brian Skinner of Yale University for the suggestion that an earlier manuscript be reworked and published as a book, and I am grateful to the Oxford University Press for undertaking the publication of a book dealing with a subject as specialized as mineral resource appraisal.

Finally, I am indebted to my wife, Sandra, for sustenance and encouragement during the preparation of this book.

CONTENTS

1 INTRODUCTION: MINERAL RESOURCES AND MINERAL RESOURCE ANALYSIS

1.1. Perspective on mineral resources

The term 'mineral resources', which is in the title of this book, conveys little information without additional qualification; at best, it identifies the general subject to be materials that are sources of one or more minerals. In this book, 'mineral' is used in a loose sense to include metals, nonmetallics, and hydrocarbons. Accordingly, a mineral resource is a material from which a metal, a nonmetallic element, or a hydrocarbon can be extracted. Where greater specificity is required, one of these classes of minerals will be employed as a qualifier of resources, e.g. metal resources or oil resources. When no distinction is desired and the statement could apply to metals, nonmetallics, or hydrocarbons, the term mineral is used as a qualifier, e.g. mineral resources, mineral supply, or mineral endowment.

Mineral resources exist only with respect to an economic and technological framework. A useful statement on mineral resources must also be a statement on specific *economic conditions, technological capabilities*, and the *state of nature*.

The term 'mineral' resources includes reserves, those accumulations of a mineral that are known and have been explored to the extent that there is reasonable assurance that the mineral could be produced from them economically, and minerals in known deposits that cannot be exploited economically. Together, these two kinds of mineral resources comprise the category of known resources. Most of our study and analysis traditionally has been devoted to this category of resources, for these are the resources that we know most about and for which we have an immediate interest because of their support of current and near-future economic activities.

Appraisal of *unknown resources*, the category of resources that we know *least* about, is the subject of this book. These resources consist of both economic and subeconomic unknown resources. Obviously, the motivation for the appraisal of unknown resources must stem from issues that relate to a moderate- or long-term time frame. Such issues may include resource adequacy and mineral policy, issues that recently have received considerable attention and, in the case of oil, have become topics of household conversation. While these issues may be of primary concern to governments, because of the time lag from exploration to production, the large mineral firm also may be motivated to examine the long-term outlook for mineral consumption and potential mineral supply, hence mineral resources.

There is no elegant nor ultimately definitive means for estimating unknown mineral resources short of direct sampling of the earth's crust, e.g. drilling at a spacing sufficient to locate and delineate the mineral deposits. While such a programme would most assuredly provide the best possible data for the appraisal of resources, it has not been demonstrated to be the most efficient means for appraisal, although some scholars urge its implementation (Ridge 1974). Arguments justifying such a programme on the basis of economics have so far been superficial. At present, and probably in the future, unknown resources are inferred by models, hopefully founded on fact, of aspects of the economic–physical system within which resources are defined.

The conceptual framework and the resource terms of the following section are developed and stated with respect to only one of the major classes of minerals, metals. While in general, mineral can be substituted for metal without violation of concepts that are developed in this chapter, some of the terms employed are appropriate only for metal resources. This conceptual framework and the definitions of resource terms could have been generalized to apply to metal, nonmetallics, and hydrocarbons simply by considering any member of these three classes of mineral substances to be a chemical compound. Then, grade would be the concentration of the particular chemical compound within the rock, irrespective of whether the compound is a hydrocarbon or a metal sulphide. Following such a general scheme would lead to the statement of the quantity of resources either in terms of an element of the chemical compound, such as copper contained in chalcopyrite ($CuFeS_2$), or in terms of the chemical compound. Adoption of one of these alternatives violates practice in either the metals industry or the hydrocarbons industries. For example, metal resources are generally stated in terms of the quantity of metal, but oil resources are stated in terms of the quantity of the basic hydrocarbon compound.

An alternative to the general development is a separate development of the conceptual framework and definitions of terms for metals, nonmetallics, and hydrocarbons. But, since much of the conceptual framework is identical for each of these classes of minerals and many of the terms are similar, such a presentation would be repetitive and monotonous. Consequently, the decision was made to develop the conceptual framework and definitions of terms on only one of the classes of minerals, metals.

1.2. A conceptual framework for resources and resource analysis

1.2.1. *Definitions of resource terms and identification of useful concepts*

The earth's crust can be considered as one large deposit of metal, a deposit having an average grade (concentration of metal) equivalent to the measure of crustal abundance but possessing considerable variation in grade. Of course, the tonnage of a given metal in this deposit is extremely large. The term *resource base* (Schurr, Netschert, with Eliasberg, Lerner, and Landsberg 1960) has been used to refer to the totality of a metal in the earth's crust. While resource base is useful as a concept, the term has little use in actual resource analysis, for concentrations many times that of crustal abundance are available in smaller quantities and constitute the deposits that are exploited and provide our supply of metal. Fortunately, we have not yet had to turn to extremely low-grade deposits.

Our experience has shown that the ultimate deposit of a metal consists of many smaller deposits occurring in varied geological environments and possessing various characteristics of grade, size, shape, chemical combinations, depth, host rock, etc. The entire collection of such deposits (known plus unknown) is referred to as *RB*. Suppose that for specified factor price and product price and for currently feasible or near-feasible technology of production (exploration, mining, and processing) those deposits of a metal in *RB* that could be produced profitably could be identified. The sum of the amount of the metal that could be recovered from these deposits is referred to as resources *rs*. Critical in the definition of resources is that resources exist for *specified economic* conditions and *currently feasible* or *near-feasible* technology of production. The economic conditions need not be those that currently prevail.

Specification of economic conditions and technology of production equal to those that currently exist identifies a subset of deposits that could be mined at a profit. The sum of the metal that could be recovered from these deposits is referred to as economic resources *rs'*.

At any given time, man has only partial knowledge of resources and economic resources. Qualifiers of these two terms are needed to convey the degree of knowledge. Correct and liberal use of these qualifiers is imperative for proper communication.

Known economic resources
Known subeconomic resources } Known resources

Unknown economic resources
Unknown subeconomic resources } Unknown resources

When the term resources is used without a qualifier, it is to be interpreted as referring in total to all of the above categories of resources.

Known economic resources are commonly referred to as ore reserves. This general category of resources is subdivided into classes, e.g. proved, probable, and possible, to indicate degree of certainty about the estimated quantity and grade of ores. Such refinement is not needed for the subject matter of this book; therefore ore reserve terminology will not be discussed here. A comprehensive treatment of ore reserve and resources terminology has been provided by Schanz (1975).

The relations of economics, technology, and degree of knowledge to categories of resources were summarized in a tableau (see Table 1.1) by Schurr *et al.* [1] (1960). This tableau captures the important dynamics of resources: a change in product or factor prices or an improvement in technology of production causes a change in resources. Although resource base conceptually is an absolute, resources are not absolute; they are a function of economics and technology.

The most widely cited resource classification scheme is attributed to Vincent E. McKelvey (1973), past director of the US Geological Survey (see Fig. 1.1). The diagram of this classification has become known as the 'McKelvey box'. While the 'McKelvey box' is a refinement of the Schurr–Netschert tableau in that it defines a greater number of categories of resources, it is a less complete representation of resource relations than is the tableau. For example, technology, factor prices, and product price are all

TABLE 1.1. *A tabulation of reserve–resource terminology.* (*Source*: *Schurr* et al. *1960*, p. 298.)

	Aspects		
Terms	Occurrence	Economic	Technological
Reserves	Known	Present cost level	Currently feasible
Resources	Known and unknown	Any cost level specified	Currently feasible and probable future feasibility
Resource base	Known and unknown	Irrelevant	Feasible and infeasible

lumped into one effect, economics. Furthermore, closing the box at the base of submarginal resources leaves out of this classification some of the material referred to by Schurr and Netschert. For example, material which has a sufficient concentration of the element or compound sought but for which there is no existing or near-feasible technology for production is not a resource according to the definition of resources provided by Schurr and Netschert, but it is a part of the resource base. Since the McKelvey box does not specify a nonresource category, it does not include this material. Finally, there is some question as to what is included in submarginal resources.

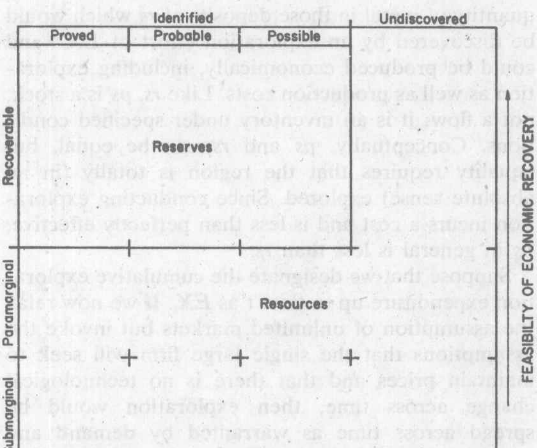

Fig. 1.1. Classification of mineral reserves and resources. Degree of certainty increases from right to left, and feasibility of economic recovery increases from bottom to top. (Source: McKelvey 1973.)

The foregoing discussion stressed the importance of economics and technology in the concept of resources. These factors impart a special character to resources, for the economic structure and the employable or near-feasible technology of a nation are dynamic—they change with time. Consequently, that which today is a non-economic resource may be an economic resource five years from now. Such a result can be due to increased demand and higher prices, a cheapening of the real cost of labour and capital for a given technology, the adoption of newly conceived technology, or all of the foregoing. In a sense, resources can be created by man's economic activities and his scientific and engineering genius. Similarly, they can be destroyed by unfavourable economics, which includes the availability of low-cost, foreign supplies and policies on taxation, trade, environmental protection, mineral leasing, etc. As the identity of economic resources changes with economic conditions and technological improvement, the conditions of interest for the identification and appraisal of resources change.

An additional term, metal endowment, is used in this book. A definition of this term is provided here. Consider each occurrence of the metal in *RB*, the collection of occurrences that constitute the resource base, to have *NC* characteristics, such as concentration, size, chemical combination, mineral assemblage, host material, depth, geometric form, geological association, etc. In theory, *NC* is large, for it is the number of all characteristics of the occurrences of the metal. Suppose that only a few *NCM* of these *NC* characteristics are selected as classification criteria, such as concentration, size, and depth, and that a minimum acceptable level for each of the *NCM* characteristics is identified. The collection of all occurrences having levels of the *NCM* characteristics at least as good as those identified is referred