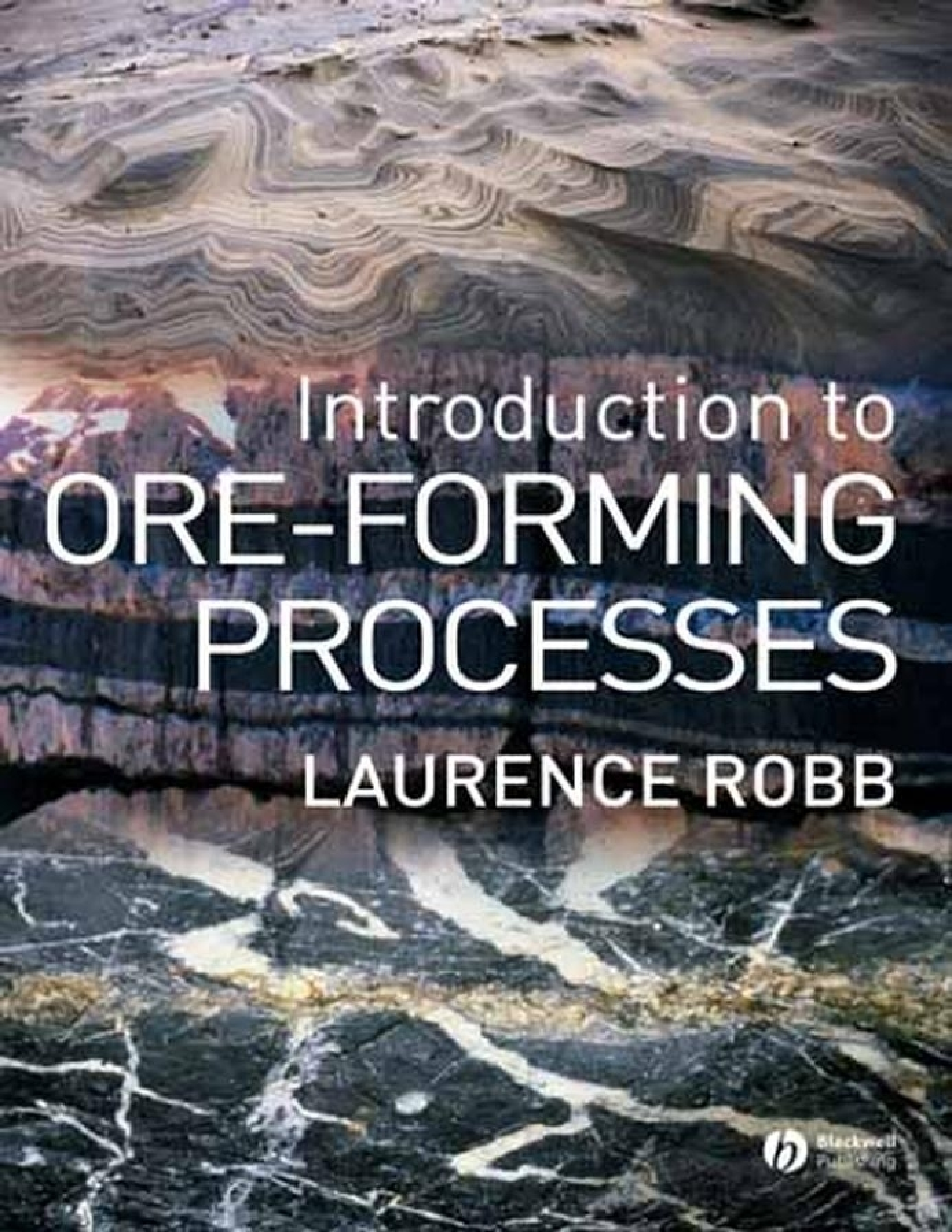

Introduction to ORE-FORMING PROCESSES

LAURENCE ROBB

Blackwell Publishing

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Introduction to Ore-Forming Processes

LAURENCE ROBB

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Preface

There are many excellent texts, available at both introductory and advanced levels, that describe the Earth's mineral deposits. Several describe the deposits themselves and others do so in combination with explanations that provide an understanding of how such mineral occurrences form. Few are dedicated entirely to the multitude of processes that give rise to the ore deposits of the world. The main purpose of this book is to provide a better understanding of the processes, as well as the nature and origin, of mineral occurrences and how they fit into the Earth system. It is intended for use at a senior undergraduate level (third and fourth year levels), or graduate level (North America), and assumes a basic knowledge in a wide range of core earth science disciplines, as well as in chemistry and physics. Although meant to be introductory, it is reasonably comprehensive in its treatment of topics, and it is hoped that practicing geologists in the minerals and related industries will also find the book useful as a summary and update of ore-forming processes. To this end the text is punctuated by a number of boxed case studies in which actual ore deposits, selected as classic examples from around the world, are briefly described to give context and relevance to processes being discussed in the main text.

Metallogeny, or the study of the genesis of ore deposits in relation to the global tectonic paradigm, is a topic that traditionally has been, and should remain, a core component of the university earth science curriculum. It is also the discipline that underpins the training of professional earth scientists working in the minerals and related industries of the world. A tendency in the past has been to treat economic geology as a vocational topic and to provide instruction only to those individuals who wished to specialize in the discipline or to follow a career in the minerals industries. In more recent years, changes in earth science curricula have resulted in a trend, at least in a good many parts of the world, in which economic geology has been sidelined. A more holistic, process-orientated approach (earth systems science) has led to a wider appreciation of the Earth as a complex interrelated system. Another aim of this book, therefore, is to emphasize the range of processes responsible for the formation of the enormously diverse ore deposit types found on Earth and to integrate these into a description of Earth evolution and global tectonics. In so doing it is hoped that metallogenic studies will increasingly be reintegrated into the university earth science curricula. Teaching the processes involved in the formation of the world’s diminishing resource inventory is necessary, not only because of its practical relevance to the real world, but also because such processes form an integral and informative part of the Earth system.

This book was written mainly while on a protracted sabbatical in the Department of Earth Sciences at the University of Oxford. I am very grateful to John Woodhouse and the departmental staff who accommodated me and helped to provide the combination of academic rigor and quietitude that made writing this book such a pleasure. In particular Jenny Colls, Earth Science Librarian, was a tower of support in locating reference material. The “tea club” at the Banbury Road annexe provided both stimulation and the requisite libations to break the monotony. The staff at Blackwell managed to combine being really nice people with a truly professional attitude, and Ian Francis, Delia Sandford, Rosie Hayden, and Cee Pike were all a pleasure to work with. Dave Coles drafted all the diagrams and I am extremely grateful for his forebearance in dealing amiably with a list of figures that seemingly did not end. Several

people took time to read through the manuscript for me and in so doing greatly improved both the style and content. They include John Taylor (copy-editing), Judith Kinnaird and Dave Waters (Introduction), Grant Cawthorn (Chapter 1), Philip Candela (Chapter 2), Franco Pirajno (Chapter 3), Michael Meyer (Chapter 4), John Parnell and Harold Reading (Chapter 5), and Mark Barley, Kevin Burke, and John Dewey (Chapter 6). The deficiencies that remain, though, are entirely my own. A particularly debt of gratitude is owed to David Rickard, who undertook the onerous task of reviewing the entire manuscript; his lucid comments helped to eliminate a number of flaws and omissions. Financial support for this project came from BHP Billiton in London and the Geological Society of South Africa Trust. My colleagues at Wits were extremely supportive during my long absences, and I am very grateful to Spike McCarthy, Paul Dirks, Carl Anhauesser, Johan Kruger, and Judith Kinnaird for their input in so many ways. Finally, my family, Vicki, Nicole, and Brendan, were subjected to a life-style that involved making personal sacrifices for the fruition of this project – there is no way of saying thank you and it is to them that I dedicate this book.

Laurence Robb

Johannesburg

Introduction: mineral resources

TOPICS

GENERAL INTRODUCTION AND AIMS OF THE BOOK

A SIMPLE CLASSIFICATION SCHEME FOR MINERAL DEPOSITS

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sustainability

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INTRODUCTION AND AIMS

Given the unprecedented growth of human population over the past century, as well as the related increase in demand for and production of natural resources, it is evident that understanding the nature, origin and distribution of the world's mineral deposits remains a strategic topic. The discipline of "economic geology," which covers all aspects pertaining to the description and understanding of mineral resources, is, therefore, one which traditionally has been, and should remain, a core component of the university earth science curriculum. It is also the discipline that underpins the training of professional earth scientists working in the minerals and related industries of the world. A tendency in the past has been to treat economic geology as a vocational topic and to provide instruction only to those individuals who wished to specialize in the discipline or to follow a career in the minerals industry. In more recent years, changes in earth science curricula have resulted in a trend, at least in a good many parts of the world, in which economic geology has been sidelined.

The conceptual development of earth systems science, also a feature of the latter years of the twentieth century, has led to dramatic shifts in the way in which the earth sciences are taught. A more holistic, process-orientated approach has led to a much wider appreciation of the Earth as a complex interrelated system. The understanding of feedback mechanisms has brought an appreciation that the solid Earth, its oceans and atmosphere, and the organic life forms that occupy niches above, at and below its surface, are intimately connected and can only be understood properly in terms of an interplay of processes. Examples include the links between global tectonics and climate patterns, and also between the evolution of unicellular organisms and the formation of certain types of ore deposits. In this context the teaching of many of the traditional geological disciplines assumes new relevance and the challenge to successfully teaching earth system science is how best to integrate the wide range of topics into a curriculum that provides understanding of the entity. Teaching the processes involved in the formation of the enormously diverse ore deposit types found on Earth is necessary, not only because of its practical relevance to the real world, but also because such processes form an integral and informative part of the Earth’s evolution.

The purpose of this process-orientated book is to provide a better understanding of the nature and origin of mineral occurrences and how they fit into the Earth system. It is intended for use at a senior undergraduate level (third and fourth year levels), or a graduate level, and assumes a basic knowledge in a wide range of core earth science disciplines, as well as in chemistry and physics. It is also hoped that practicing geologists in the minerals and related industries will find the book useful as a summary and update of ore-forming processes. To this end the text is punctuated by a number of boxed case studies in which actual ore deposits, selected as classic examples from around the world, are briefly described to give context and relevance to processes being discussed in the main text.

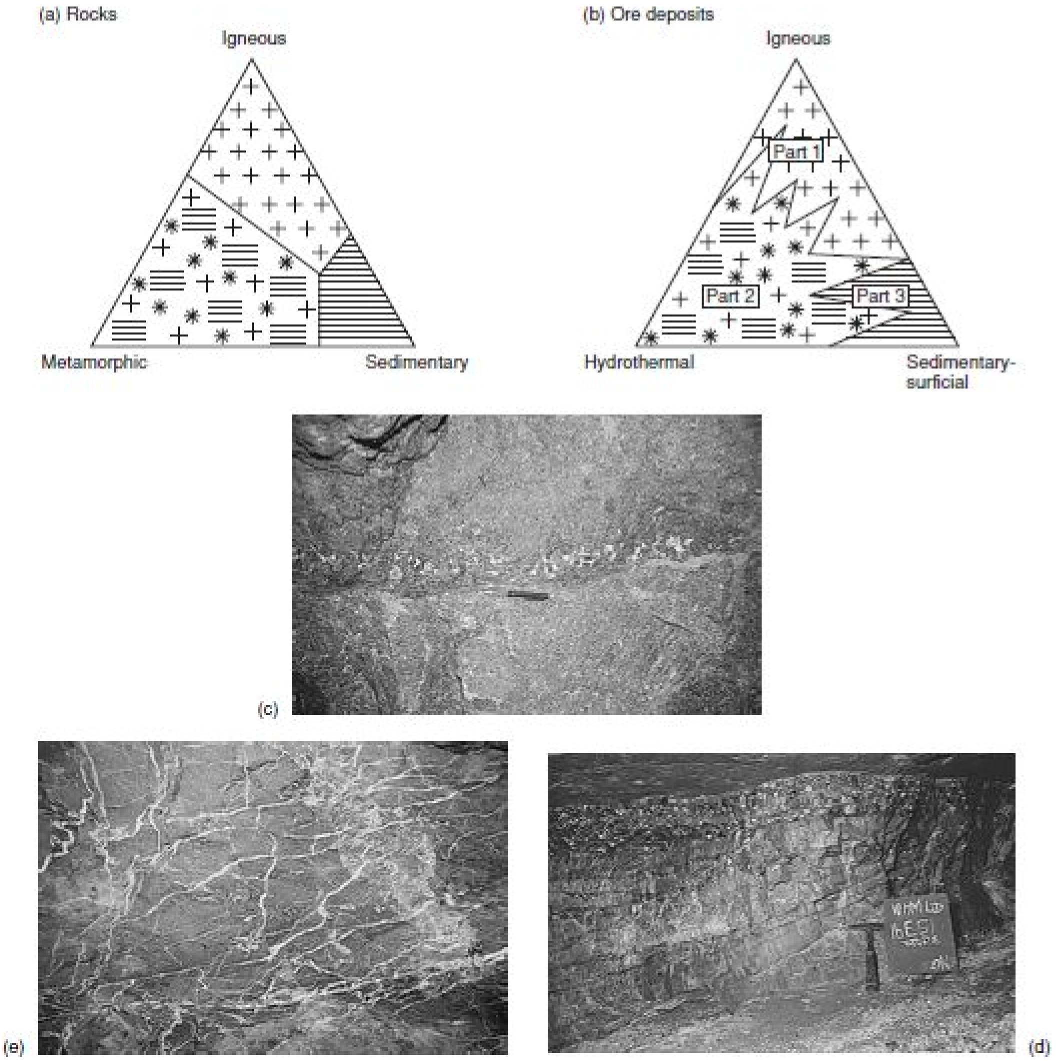
A CLASSIFICATION SCHEME FOR ORE DEPOSITS

There are many different ways of categorizing ore deposits. Most people who have written about and described ore deposits have either unwittingly or deliberately been involved in their classification. This is especially true of textbooks where the task of providing order and structure to a set of descriptions invariably involves some form of classification. The best classification schemes are probably those that remain as independent of genetic linkages as possible, thereby minimizing the scope for mistakes and controversy. Nevertheless, genetic classification schemes are ultimately desirable, as there is considerable advantage to having processes of ore formation reflected in a set of descriptive categories. Guilbert and Park (1986) discuss the problem of ore deposit classification at some length in Chapters 1 and 9 of their seminal book on the geology of ore deposits. They show how classification schemes reflect the development of theory and techniques, as well as the level of understanding, in the discipline. Given the dramatic improvements in the level of understanding in economic geology over the past few years, the Guilbert and Park (1986) classification scheme, modified after Lindgren's

(1933) scheme, is both detailed and complex, and befits the comprehensive coverage of the subject matter provided by their book. In a more recent, but equally comprehensive, coverage of ore deposits, Misra (2000) has opted for a categorization based essentially on genetic type and rock association, similar to a scheme by Meyer (1981). It is the association between ore deposits and host rock that is particularly appealing for its simplicity, and that has been selected as the framework within which the processes described in this book are placed.

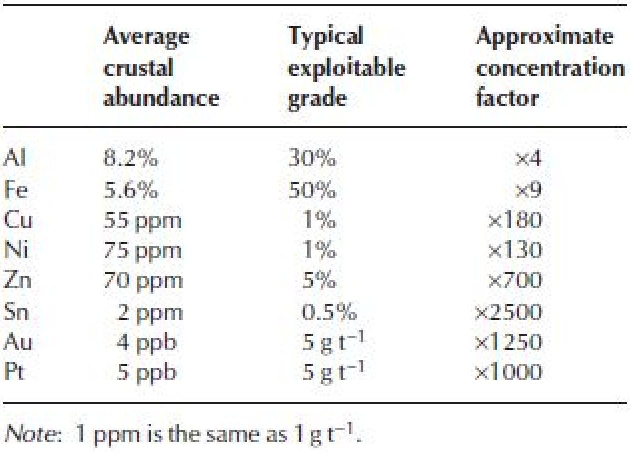
Rocks are classified universally in terms of a threefold subdivision, namely igneous, sedimentary and metamorphic, that reflects the fundamental processes active in the Earth's crust (Figure 1a). The scheme is universal because rocks are (generally!) recognizably either igneous or sedimentary, or, in the case of both precursors, have been substantially modified to form a metamorphic rock. Likewise, ores are rocks and can often be relatively easily attributed to an igneous or sedimentary/surficial origin, a feature that represents a good basis for classification. Such a classification also reflects the genetic process involved in ore formation, since igneous and sedimentary deposits are often syngenetic and formed at the same time as the host rock itself. Although many ores are metamorphosed, and whereas pressure and temperature increases can substantially modify the original nature of ore deposits, it is evident that metamorphism does not itself represent a fundamental process whereby ore deposits are created. Hydrothermalism, however, is a viable analogue in ore-forming processes for metamorphism and also involves modification of either igneous or sedimentary rocks, as well as heat (and mass) transfer and pressure fluctuation. A very simple classification of ores is, therefore, achieved on the basis of igneous, sedimentary/ surficial and hydrothermal categories (Figure 1b), and this forms the basis for the structure and layout of this book. This subdivision is very similar to one used by Einaudi (2000), who stated that all mineral deposits can be classified into three types based on process, namely magmatic deposits, hydro-thermal deposits and surficial deposits formed by surface and groundwaters. One drawback of this type of classification, however, is that ore-forming processes are complex and episodic. Ore formation also involves processes that evolve, sometimes over significant periods of geologic time. For example, igneous processes become magmatic-hydrothermal as the intrusion cools and crystallizes, and sediments undergo diagenesis and metamorphism as they are progressively buried, with accompanying fluid flow and alteration. In addition, deformation of the Earth's crust introduces new conduits that also facilitate fluid flow and promote the potential for mineralization in virtually any rock type. Ore-forming processes can, therefore, span more than one of the three categories, and there is considerable overlap between igneous and hydrothermal and between sedimentary and hydrothermal, as illustrated diagrammatically in Figure 1b, and also in the accompanying photographs of the three major categories of ore types.

Figure 1 Classification of the principal rock types (a) and an analogous, but much simplified, classification of ore deposit types (b). Photographs show the interplay between ore forming processes. (c) Igneous ore type: the PGE-bearing Merensky Reef, Bushveld Complex, South Africa. This unit and the ores within it can be altered and redistributed by hydrothermal solutions. (d) Sedimentary ore type: Au- and U-bearing conglomerate from the Witwatersrand Basin, South Africa. Quartz veins cutting this unit attest to the action of later hydrothermal fluids in the sequence. (e) Hydrothermal ore type: quartz-carbonate vein network in an Archean orogenic or lode-gold deposit from the Abitibi greenstone belt in Canada. The deposit is associated with igneous (lamprophyre) intrusions that may be implicated in the mineralization process.



The main part of this book is subdivided into three sections termed Igneous (Part 1), Hydrothermal (Part 2), and Sedimentary/surficial (Part 3). Part 1 comprises Chapters 1 and 2, which deal with igneous and magmatic-hydrothermal ore-forming processes respectively. Part 2 contains Chapter 3 and covers the large and diverse range of hydrothermal processes not covered in Part 1. Part 3 comprises Chapter 4 on surficial and supergene processes, as well as Chapter 5, which covers sedimentary ore deposits, including a short section on the fossil fuels. The final chapter of the book, Chapter 6, is effectively an addendum to this threefold subdivision and is an attempt to describe the distribution of ore deposits, both spatially in the context of global tectonics and temporally in terms of crustal evolution through Earth history. This chapter is considered relevant in this day and age because the plate tectonic paradigm, which has so pervasively influenced geological thought since the early 1970s, provides another conceptual basis within which to classify ore deposits. In fact, modern economic geology, and the scientific exploration of mineral deposits, is now firmly conceptualized in terms of global tectonics and crustal evolution. Although there is still a great deal to be learnt, the links between plate tectonics and ore genesis are now sufficiently well established that studies of ore deposits are starting to contribute to a better understanding of the Earth system.

Table 1 Average crustal abundances for selected metals and typical concentration factors that need to be achieved in order to produce a viable ore deposit



	Average crustal abundance	Typical exploitable grade	Approximate concentration factor
Al	8.2%	30%	×4
Fe	5.6%	50%	×9
Cu	55 ppm	1%	×180
Ni	75 ppm	1%	×130
Zn	70 ppm	5%	×700
Sn	2 ppm	0.5%	×2500
Au	4 ppb	5 g t^{-1}	×1250
Pt	5 ppb	5 g t^{-1}	×1000

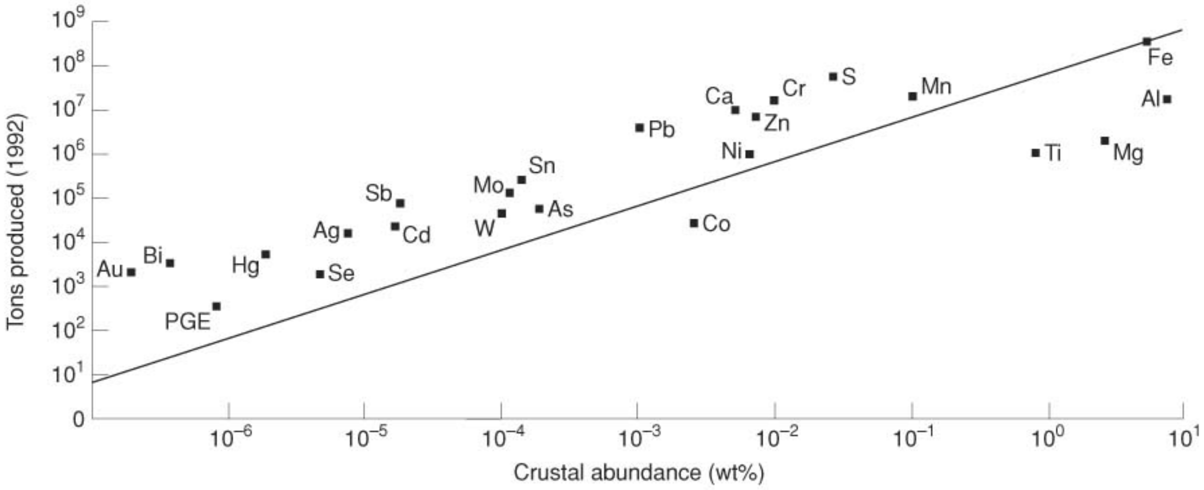
Note: 1 ppm is the same as 1 g t^{-1}.

WHAT MAKES A VIABLE MINERAL DEPOSIT?

Ore deposits form when a useful commodity is sufficiently concentrated in an accessible part of the Earth's crust so that it can be profitably extracted. The processes by which this concentration occurs are the topic of this book. As an introduction it is pertinent to consider the range of concentration factors that characterize the formation of different ore deposit types. Some of the strategically important metals, such as Fe, Al, Mg, Ti, and Mn, are abundantly distributed in the Earth's crust (i.e. between about 0.5 and 10%) and only require a relatively small degree of enrichment in order to make a viable deposit. Table 1 shows that Fe and Al, for example, need to be concentrated by factors of 9 and 4 respectively, relative to average crustal abundances, in order to form potentially viable deposits.

By contrast, base metals such as Cu, Zn, and Ni are much more sparsely distributed and average crustal abundances are only in the range 55-75 parts per million (ppm). The economics of mining dictate that these metals need to be concentrated by factors in the hundreds in order to form potentially viable deposits, degrees of enrichment that are an order of magnitude higher than those applicable to the more abundant metals. The degree of concentration required for the precious metals is even more demanding, where the required enrichment factors are in the thousands. Table 1 shows that average crustal abundances for Au and Pt are in the range 4–5 parts per billion (ppb) and even though ore deposits routinely extract these metals at grades of around 5g t^{-1}, the enrichment factors involved are between 1000 and 1250 times.

Figure 2 Plot of crustal abundances against global production for an number of metal commodities (after Einaudi, 2000). The line through Fe can be regarded as a datum against which the rates of production of the other metals can be compared in the context of crustal abundances.



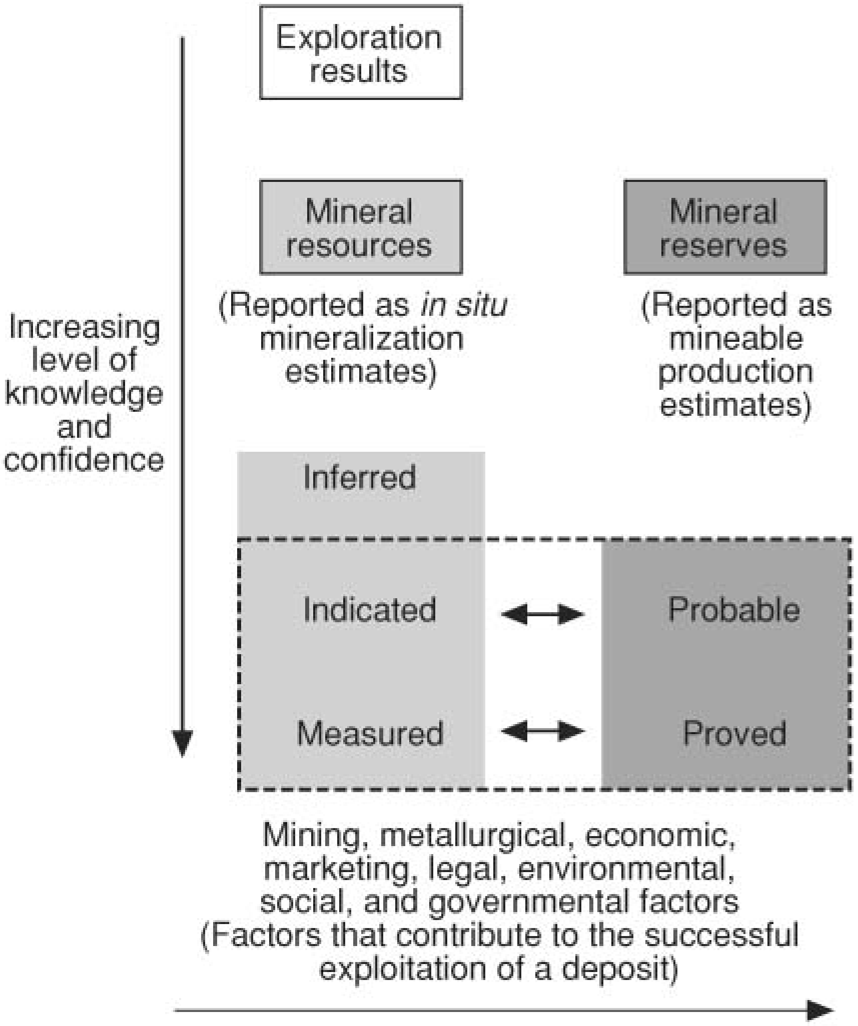
Another useful way to distinguish between the geochemically abundant and scarce metals is to plot average crustal abundances against production estimates. This type of analysis was first carried out by Skinner (1976), who used a plot like that in Figure 2 to confirm that crustal abundance is a reasonable measure of the availability of a given resource. It is by design and of necessity that we use more of the geochemically abundant metals than we do the scarce ones. The nature of our technologies and the materials we use to manufacture mechanical items depend in large measure on the availability of raw materials. As an example, the technologies (geological and metallurgical) that resulted in the dramatic increase in global aluminum production over the latter part of the twentieth century allowed iron to be replaced by aluminum in many products such as motor vehicles. More importantly, though, Figure 2 allows estimates to be made of the relative rates of depletion of certain metals relative to others. These trends are discussed again below.

Mineral resources and ore reserves

In the course of this book reference is made to the term “ore deposit” with little or no consideration of whether such occurrences might be economically viable. Although such considerations might seem irrelevant in the present context it is necessary to emphasize that professional institutions now insist on the correct definition and usage of terminology pertaining to exploration results, mineral resources, and ore reserves. Such terminology should be widely used and applied, as it would help in reducing the irresponsible, and sometimes even fraudulent, usage of terminology, especially with respect to the investor public. Correct terminology can also assist in the description and identification of genuine ore deposits from zones of marginal economic interest or simply anomalous concentrations of a given commodity.

Although the legislation that governs the public reporting of mineral occurrences obviously varies from one country to the next, there is now reasonable agreement as to the definition of terms. In general it is agreed that different terms should apply to mineral occurrences depending on the level of knowledge and degree of confidence that is associated with the measurement of its quantity. Figure 3 is a matrix that reflects the terminology associated with an increased level of geological knowledge and confidence, and modifying factors such as those related to mining techniques, metallurgical extraction, marketing, and environmental reclamation. Exploration results can be translated into a *mineral resource* once it is clear that an occurrence of intrinsic economic interest exists in such form and quantity that there are reasonable prospects for its eventual exploitation. Such a resource can only be referred to as an *ore reserve* if it is a part of an economically extractable measured or indicated mineral resource. One problem with this terminology is that what is economically extractable in a Third World artisinal operation may not of course be viable in a technically developed First World economy, and vice versa. The term “ore deposit” has no significance in the professional description of a mineral occurrence and is best used as a simply descriptive or generic term.

Figure 3 Simplified scheme illustrating the conceptual difference between mineral resources and ore reserves as applied to mineral occurrences. The scheme forms the basis for the professional description of ore deposits as defined by the Australian and South African Institutes of Mining and Metallurgy.



SOME USEFUL DEFINITIONS AND COMPILATIONS

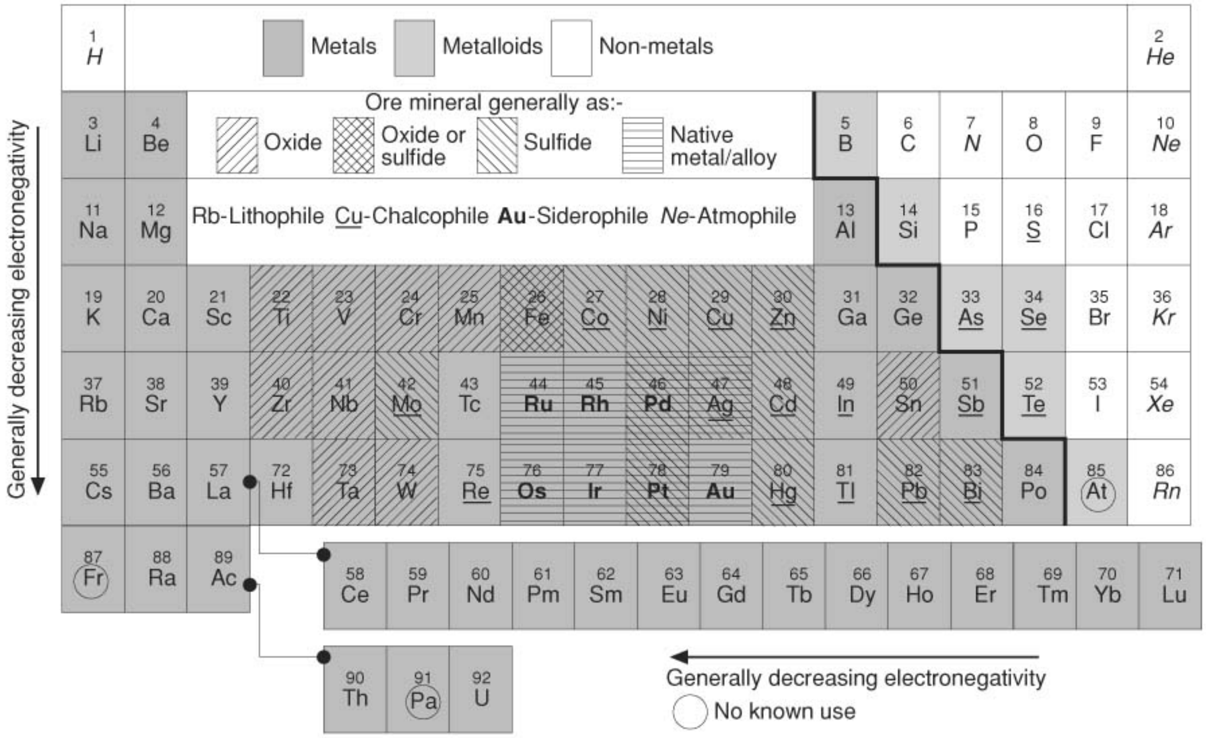
Some general definitions

This section is not intended to provide a comprehensive glossary of terms used in this book. There are, however, several terms that are used throughout the text where a definition is either useful or necessary in order to avoid ambiguity. The following definitions are consistent with those provided in the *Glossary of Geology* (Bates and Jackson, 1987) and *The Encyclopedia of the Solid Earth Sciences* (Kearey, 1993).

- *Ore:* any naturally occurring material from which a mineral or aggregate of value can be extracted at a profit. In this book the concept extends to coal (a combustible rock comprising more than 50% by weight carbonaceous material) and petroleum (naturally occurring hydrocarbon in gaseous, liquid, or solid state).
- *Syngenetic:* refers to ore deposits that form at the same time as their host rocks. In this book this includes deposits that form during the early stages of sediment diagenesis.
- *Epigenetic:* refers to ore deposits that form after their host rocks.
- *Hypogene:* refers to mineralization caused by ascending hydrothermal solutions.
- *Supergene:* refers to mineralization caused by descending solutions. Generally refers to the enrichment processes accompanying the weathering and oxidation of sulfide and oxide ores at or near the surface.

- *Metallogeny:* the study of the genesis of mineral deposits, with emphasis on their relationships in space and time to geological features of the Earth’s crust.
- *Metallotect:* any geological, tectonic, lithological, or geochemical feature that has played a role in the concentration of one or more elements in the Earth’s crust.
- *Metallogenic Epoch:* a unit of geologic time favorable for the deposition of ores or characterized by a particular assemblage of deposit types.
- *Metallogenic Province:* a region characterized by a particular assemblage of mineral deposit types.
- *Epithermal:* hydrothermal ore deposits formed at shallow depths (less than 1500 meters) and fairly low temperatures (50–200 °C).
- *Mesothermal:* hydrothermal ore deposits formed at intermediate depths (1500–4500 meters) and temperatures (200–400 °C).
- *Hypothermal:* hydrothermal ore deposits formed at substantial depths (greater than 4500 meters) and elevated temperatures (400–600 °C).

Figure 4 Periodic table showing the 92 geologically relevant elements classified on the basis of their rock and mineral associations.



Periodic table of the elements

The question of the number of elements present on Earth is a difficult one to answer. Most of the element compilations relevant to the earth sciences show that there are 92 elements, the majority of which occur in readily detectable amounts in the Earth’s crust. Figure 4 shows a periodic table in which these elements are presented in ascending atomic number and also categorized into groupings that are relevant to metallogenesis. There are in fact as many as 118 elements known to man, but those with atomic numbers greater than 92 (U: uranium) either occur in vanishingly small amounts as unstable isotopes that are the products of various natural radioactive decay reactions or are synthetically created in nuclear reactors. The heaviest known element, ununoctium (Uuo, atomic number 118), has been only transiently detected in a nuclear reactor and its actual existence is still conjectural. Some of the heavy, unstable elements are, however, manufactured synthetically and serve a variety of uses. Plutonium (Pu, atomic number 94), for example, is manufactured in fast breeder reactors and is used as a nuclear fuel and in weapons manufacture. Americium (Am, atomic number 95) is also manufactured in reactors and is widely used as the active agent in smoke detectors.

Of the 92 elements shown in Figure 4, almost all have some use in our modern technologically driven societies. Some of the elements (iron and aluminum) are required in copious quantities as raw materials for the manufacture of vehicles and in construction, whereas others (the rare earths, for example) are needed in very much smaller amounts for use in the alloys and electronics industries. Only three elements appear at this stage to have little or no use at all (Figure 4). These are astatine (At, atomic number 85), francium (Fr, atomic number 87), and protactinium (Pa, atomic number 91). Francium is radioactive and so shortlived that only some 20–30 g exists in the entire Earth’s crust at any one time! Astatine, likewise, is very unstable and exists in vanishingly small amounts in the crust, or is manufactured synthetically. Radon (Rn, atomic number 86) is an inert or noble gas that is formed as a radioactive decay product of radium. It has limited use in medical applications, but, conversely, if allowed to accumulate can represent a serious health hazard in certain environments.

The useful elements can be broadly subdivided in a number of different ways. Most of the elements can be classified as metals (Figure 4), with a smaller fraction being non-metals. The elements B, Si, As, Se, Te, and At have intermediate properties and are referred to as metalloids. Another classification of elements, attributed to the pioneering geochemist Goldschmidt, is based on their rock associations and forms the basis for distinguishing between lithophile (associated with silicates and concentrated in the crust), chalco-phile (associated with sulfides), siderophile (occur as the native metal and concentrated in the core), and atmophile (occur as gases in the atmosphere) elements. It is also useful to consider elements in terms of their ore mineral associations, with some preferentially occurring as sulfides and others as oxides (see Figure 4). Some elements have properties that enable them to be classified in more than one way and iron is a good example, in that it occurs readily as both an oxide and sulfide.

Common ore and gangue minerals

It is estimated that there are about 3800 known minerals that have been identified and classified (Battey and Pring, 1997). Only a very small proportion of these make up the bulk of the rocks of the Earth’s crust, as the common rock forming minerals. Likewise, a relatively small number of minerals make up most of the economically viable ore deposits of the world. The following compilation is a breakdown of the more common ore minerals in terms of chemical classes based essentially on the anionic part of the mineral formula. Also included are some of the more common “gangue,” which are those minerals that form part of the ore body, but do not contribute to the economically extractable part of the deposit. Most of these are alteration assemblages formed during hydrother-mal processes. The compilation, including ideal chemical formulae, is subdivided into six sections, namely native elements, halides, sulfides and sulfo-salts, oxides and hydroxides, oxy-salts (such as carbonates, phosphates, tungstates, sulfates), and silicates. More detailed descriptions of both ore and gangue minerals can be found in a variety of mineralogical texts, such as Deer *et al.* (1982), Berry *et al.* (1983), and Battey and Pring (1997). More information on ore mineral textures and occurrences can be found in Craig and Vaughan (1994) and Ixer (1990).

1 Native elements

Both metals and non-metals exist in nature in the native form, where essentially only one element exists in the structure. Copper, silver, gold, and platinum are all characterized by cubic close packing of atoms, have high densities, and are malleable and soft. The carbon atoms in diamond are linked in tetrahedral groups forming well cleaved, very hard, translucent crystals. Sulfur occurs as rings of eight atoms and forms bipyramids or is amorphous.

Metals

Gold – Au
Silver – Ag
Platinum – Pt
Palladium – Pd
Copper – Cu

Non-metals

Sulfur – S
Diamond – C
Graphite – C

2 Halides

The halide mineral group comprises compounds made up by ionic bonding. Minerals such as halite and sylvite are cubic, have simple chemical formulae, and are highly soluble in water. Halides sometimes form as ore minerals, such as chlorar-gyrite and atacamite.

Halite – NaCl
Sylvite – KCl
Chlorargyrite – AgCl