Introduction to Ore-Forming Processes

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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
- Some important definitions
  - metallogeny, syngenetic, epigenetic, mesothermal, epithermal, supergene, hypogene, etc.
- Some relevant compilations
  - periodic table of the elements
  - tables of the main ore and gangue minerals
  - geological time scale
- Factors that make a viable mineral deposit
  - enrichment factors required to make ore deposits
  - how are mineral resources and ore reserves defined?
- Natural resources and their future exploitation
  - sustainability
  - environmental responsibility

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, hydrothermal deposits and surficial deposits formed by

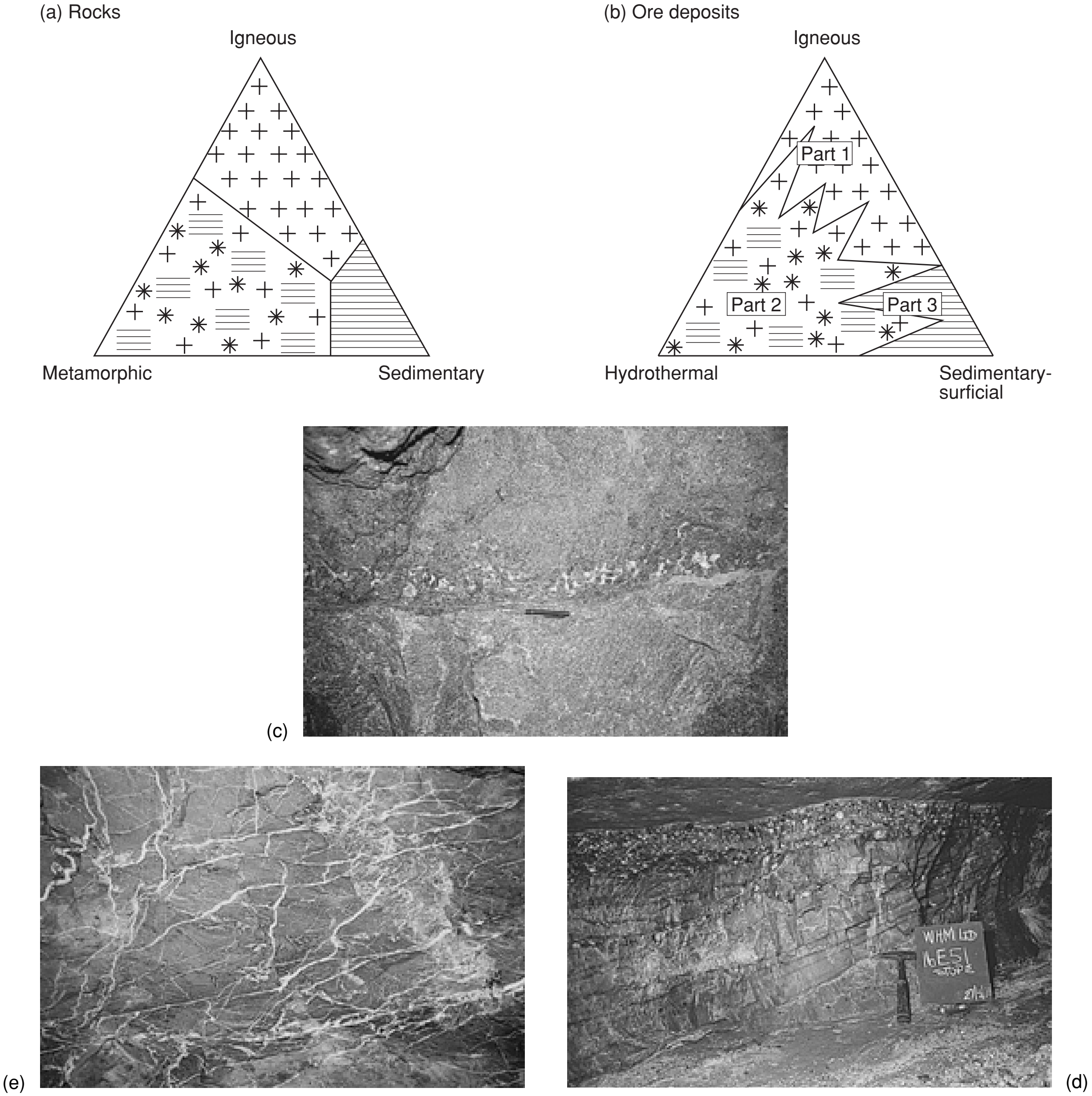

Figure 1 Classification of the principal rock types (a) and an analogous, but much simplified, classification of ore deposit types (b). Photographs show the interplay between ore forming processes. (c) Igneous ore type: the PGE-bearing Merensky Reef, Bushveld Complex, South Africa. This unit and the 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.

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.

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 poten-

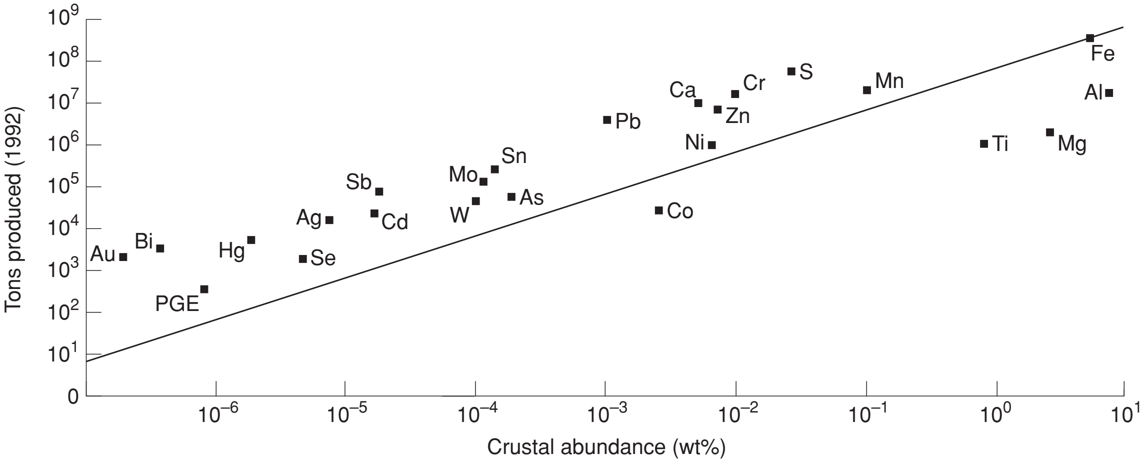

Figure 2 Plot of crustal abundances against global production for an number of metal commodities (after Einaudi, 2000). The line through Fe can be regarded as a datum against which the rates of production of the other metals can be compared in the context of crustal abundances.

tially 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 5 g t^{-1}, the enrichment factors involved are between 1000 and 1250 times.

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

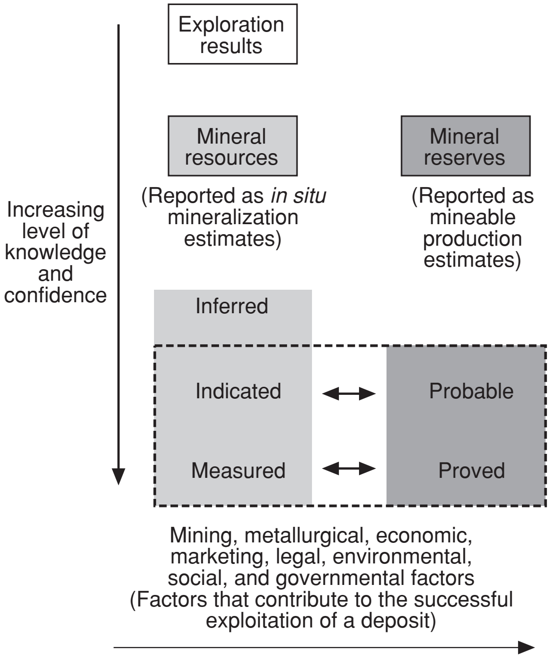

Figure 3 Simplified scheme illustrating the conceptual difference between mineral resources and ore reserves as applied to mineral occurrences. The scheme forms the basis for the professional description of ore deposits as defined by the Australian and South African Institutes of Mining and Metallurgy.

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.

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

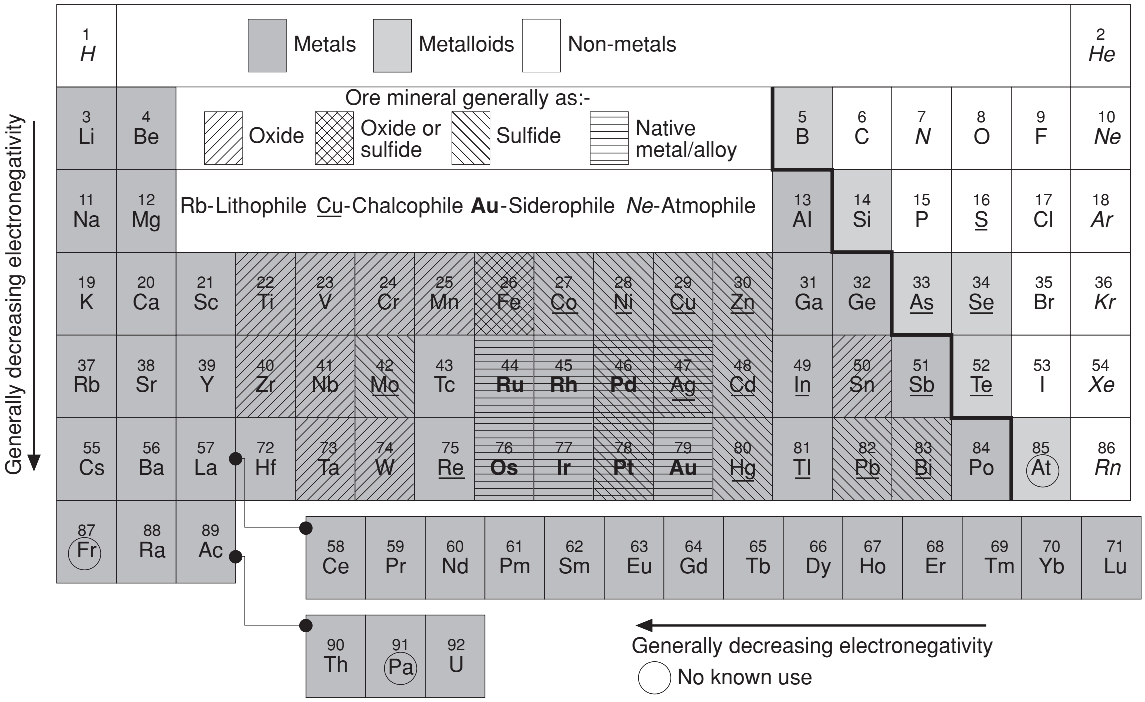

Figure 4 Periodic table showing the 92 geologically relevant elements classified on the basis of their rock and mineral associations.

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).

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 short-lived 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), chalcophile (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 hydrothermal 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 chlorargyrite and atacamite.

Halite – NaCl
Sylvite – KCl
Chlorargyrite – AgCl
Fluorite – CaF_2
Atacamite – $Cu_2Cl(OH)_3$

3 Sulfides and sulfo-salts

This is a large and complex group of minerals in which bonding is both ionic and covalent in character. The sulfide group has the general formula A_MX_P, where X, the larger atom, is typically S but can be As, Sb, Te, Bi, or Se, and A is one or more metals. The sulfo-salts, which are much rarer than sulfides, have the general formula $A_MB_NX_P$, where A is commonly Ag, Cu, or Pb, B is commonly As, Sb, or Bi, and X is S. The sulfide and sulfo-salt minerals are generally opaque, heavy and have a metallic to sub-metallic lustre.

Sulfides
Chalcocite – Cu_2S
Bornite – Cu_5FeS_4
Galena – PbS
Sphalerite – ZnS
Chalcopyrite – $CuFeS_2$
Pyrrhotite – $Fe_{1-x}S$
Pentlandite – $(Fe,Ni)_9S_8$
Millerite – NiS
Covellite – CuS
Cinnabar – HgS
Skutterudite – $(Co,Ni)As_3$
Sperrylite – $PtAs_2$
Braggite/cooperite – (Pt,Pd,Ni)S
Moncheite – $(Pt,Pd)(Te,Bi)_2$
Cobaltite – CoAsS
Gersdorffite – NiAsS
Loellingite – $FeAs_2$
Molybdenite – MoS_2
Realgar – AsS
Orpiment – As_2S_3
Stibnite – Sb_2S_3
Bismuthinite – Bi_2S_3
Argentite – Ag_2S
Calaverite – $AuTe_2$
Pyrite – FeS_2
Laurite – RuS_2

Sulfo-salts
Tetrahedrite – $(Cu,Ag)_{12}Sb_4S_{13}$
Tennantite – $(Cu,Ag)_{12}As_4S_{13}$
Enargite – Cu_3AsS_4

4 Oxides and hydroxides

This group of minerals is variable in its properties, but is characterized by one or more metal in combination with oxygen or a hydroxyl group. The oxides and hydroxides typically exhibit ionic bonding. The oxide minerals can be hard, dense, and refractory in nature (magnetite, cassiterite) but can also be softer and less dense, forming as products of hydrothermal alteration and weathering (hematite, anatase, pyrolucite). Hydroxides, such as goethite and gibbsite, are typically the products of extreme weathering and alteration.

Oxides
Cuprite – Cu_2O
Hematite – Fe_2O_3
Ilmenite – $FeTiO_3$
Hercynite – $FeAl_2O_4$
Gahnite – $ZnAl_2O_4$
Magnetite – Fe_3O_4
Chromite – $FeCr_2O_4$
Rutile – TiO_2
Anatase – TiO_2
Pyrolucite – MnO_2
Cassiterite – SnO_2
Uraninite – UO_2

Thorianite – ThO_2
Columbite-tantalite – $(Fe,Mn)(Nb,Ta)_2O_6$

Hydroxides (or oxyhydroxides)
Goethite – $FeO(OH)$
Gibbsite – $Al(OH)_3$
Boehmite – $AlO(OH)$
Manganite – $MnO(OH)$

5 *Oxy-salts*

The carbonate group of minerals form when anionic carbonate groups (CO_3^{2-}) are linked by intermediate cations such as Ca, Mg, and Fe. Hydroxyl bearing and hydrated carbonates can also form, usually as a result of weathering and alteration. The other oxy-salts, such as the tungstates, sulfates, phosphates, and vanadates, are analogous to the carbonates, but are built around an anionic group of the form XO_4^{n-}.

Carbonates
Calcite – $CaCO_3$
Dolomite – $CaMg(CO_3)_2$
Ankerite – $CaFe(CO_3)_2$
Siderite – $FeCO_3$
Rhodochrosite – $MnCO_3$
Smithsonite – $ZnCO_3$
Cerussite – $PbCO_3$
Azurite – $Cu_3(OH)_2(CO_3)_2$
Malachite – $Cu_2(OH)_2CO_3$

Tungstates
Scheelite – $CaWO_4$
Wolframite – $(Fe,Mn)WO_4$

Sulfates
Baryte(s) – $BaSO_4$
Anhydrite – $CaSO_4$
Alunite – $KAl_3(OH)_6(SO_4)_2$
Gypsum – $CaSO_4.2H_2O$
Epsomite – $MgSO_4.7H_2O$

Phosphates
Xenotime – YPO_4
Monazite – $(Ce,La,Th)PO_4$
Apatite – $Ca_5(PO_4)_3(F,Cl,OH)$

Vanadates
Carnotite – $K_2(UO_2)(VO_4)_2.3H_2O$

6 *Silicates*

The bulk of the Earth's crust and mantle is made up of silicate minerals that can be subdivided into several mineral series based on the structure and coordination of the tetrahedral SiO_4^{4-} anionic group. Silicate minerals are generally hard, refractory and translucent. Most of them cannot be regarded as ore minerals in that they do not represent the extractable part of an ore body, and the list provided below shows only some of the silicates more commonly associated with mineral occurrences as gangue or alteration products. Some silicate minerals, such as zircon and spodumene, are ore minerals and represent important sources of metals such as zirconium and lithium, respectively. Others, such as kaolinite, are mined for their intrinsic properties (i.e. as a clay for the ceramics industry).

Tekto (framework)
Quartz – SiO_2
Orthoclase – $(K,Na)AlSi_3O_8$
Albite – $(Na,Ca)AlSi_3O_8$
Scapolite – $(Na,Ca)_4[(Al,Si)_4O_8)]_3$ (Cl, CO_3)
Zeolite (analcime) – $NaAlSi_2O_6.H_2O$

Neso (ortho)
Zircon – $Zr(SiO_4)$
Garnet (almandine) – $Fe_3Al_2(SiO_4)_3$
Garnet (grossular) – $Ca_3Al_2(SiO_4)_3$
Sillimanite – Al_2SiO_5
Topaz – $Al_2SiO_4(F,OH)_2$
Chloritoid – $(Fe,Mg,Mn)_2(Al,Fe)Al_3O_2(SiO_4)_2(OH)_4$

Cyclo (ring)
Beryl – $Be_3Al_2Si_6O_{18}$
Tourmaline – $(Na,Ca)(Mg,Fe,Mn,Al)_3(Al,Mg,Fe)_6Si_6O_{18}(BO_3)_3(OH,F)_4$

Soro (di)
Lawsonite – $CaAl_2Si_2O_7(OH)_2.H_2O$
Epidote – $Ca_2(Al,Fe)_3Si_3O_{12}(OH)$

Phyllo (sheet)
Kaolinite – $Al_4Si_4O_{10}(OH)_8$
Montmorillonite – $(Na,Ca)_{0.3}(Al,Mg)_2Si_4O_{10}(OH)_2.nH_2O$
Illite – $KAl_2(Si,Al)_4O_{10}(H_2O)(OH)_2$
Pyrophyllite – $Al_2Si_4O_{10}(OH)_2$
Talc – $Mg_3Si_4O_{10}(OH)_2$
Muscovite – $KAl_2(AlSi_3O_{10})(OH)_2$
Biotite – $K(Fe,Mg)_3(Al,Fe)Si_3O_{10}(OH,F)_2$
Lepidolite – $K(Li,Al)_3(Si,Al)_4O_{10}(OH,F)_2$
Chlorite – $(Fe,Mg,Al)_{5-6}(Si,Al)_4O_{10}(OH)_8$

Ino (chain)
Tremolite-actinolite – $Ca_2(Fe,Mg)_5Si_8O_{22}(OH)_2$
Spodumene – $LiAlSi_2O_6$
Wollastonite – $CaSiO_3$

Unknown structure
Chrysocolla – $(Cu,Al)_2H_2Si_2O_5(OH)_4.nH_2O$

Geological time scale

The development of a geological time scale has been the subject of a considerable amount of thought and research over the past few decades and continues to occupy the minds and activities of a large number of earth scientists around the world. The definition of a framework within which to describe the secular evolution of rocks, and hence the Earth, has been, and continues to be, a contentious exercise. The International Commission on Stratigraphy (ICS is a working group of the International Union of Geological Sciences: IUGS) has been given the task of formalizing the geological time scale and this work is ongoing (www.micropress.org/stratigraphy/). In this book reference is often made to the timing of various events and processes and the provision of a time scale to which the reader can refer is, therefore, useful. Figure 5 is a time scale based on the 2000 edition of the International Stratigraphic Chart published and sanctioned by the ICS and IUGS. In this diagram global chronostratigraphic terms are presented in terms of eons, eras, periods, and epochs, and defined by absolute ages in millions of years before present (Ma). Also shown are the positions on the time scale of many of the ore deposits or metallogenic provinces referred to in the text.

NATURAL RESOURCES, SUSTAINABILITY, AND ENVIRONMENTAL RESPONSIBILITY

One of the major issues that characterized social and economic development toward the end of the twentieth century revolved around the widespread acceptance that the Earth's natural resources are finite, and that their exploitation should be carried out in a manner that will not detrimentally affect future generations. The concept of "sustainable development" in terms of the exploitation of mineral occurrences implies that future social and economic practice should endeavor not to deplete natural resources to the point where the needs of the future cannot be met. This would seem to be an impossible goal given the unprecedented population growth over the past century and the fact that many commodities will become depleted within the next 100 years. The challenge for commodity supply over the next century is a multifaceted one and will require a better understanding of the earth system, improved incentives to promote more efficient recycling of existing resources, and the means to find alternative sources for commodities that are in danger of serious depletion.

There has been a dramatic rise in global population over the past 150 years. The number of humans on Earth has risen from 1 billion in 1830 to 6 billion at the end of the twentieth century. Most predictions suggest that the populations of most countries will start to level off over the next 30 years and that global numbers will stabilize at around 11 billion people by the end of the twenty-first century. Societies in the next 100 years are, nevertheless, facing a scenario in which the demand for, and utilization of, natural resources continues to increase and certain commodities might well become depleted in this interval. Production trends for commodities such as oil, bauxite, copper, and gold (Figure 6) confirm that demand for resources mirrors population growth and is likely to continue to do so over the next few

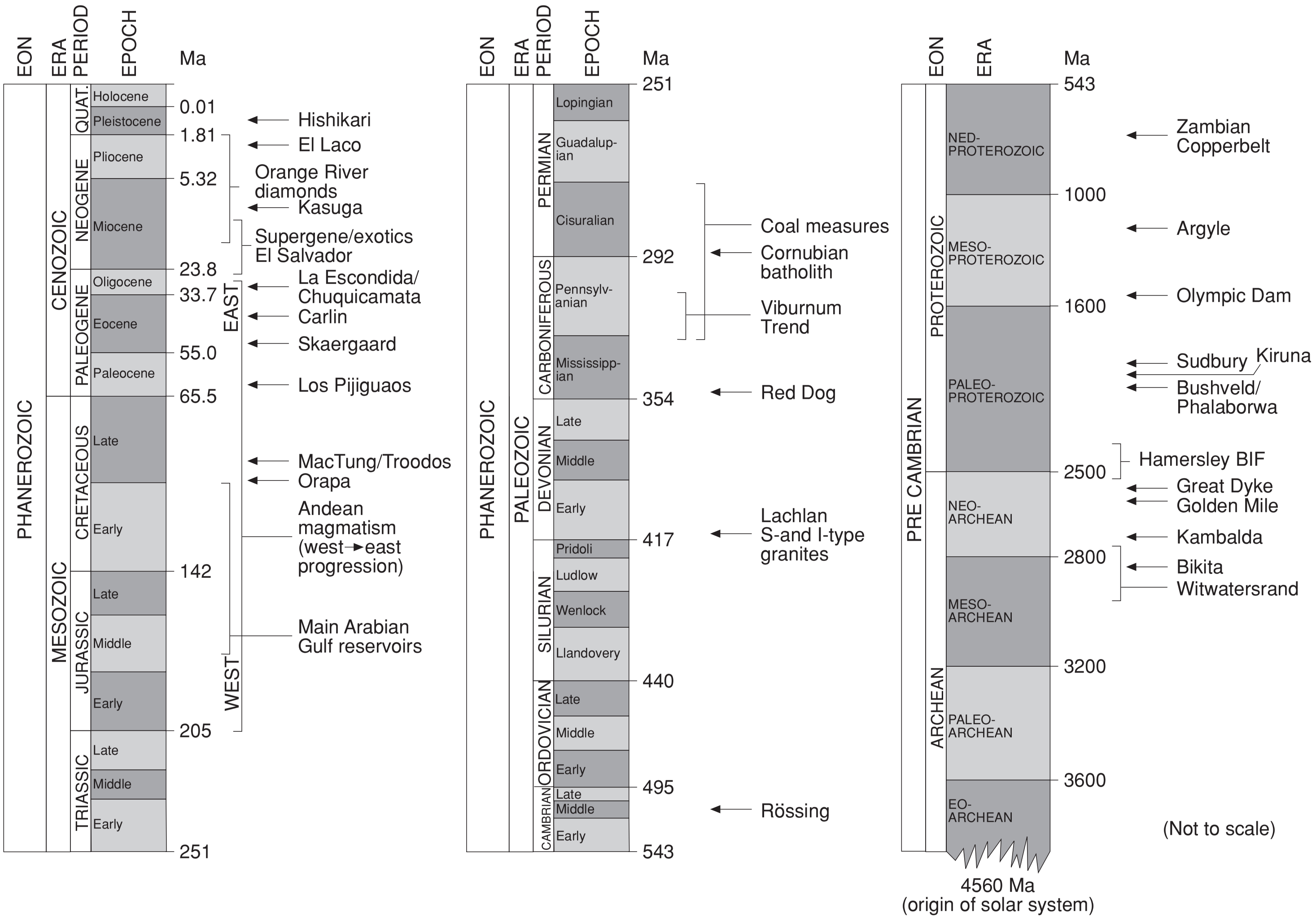

Figure 5 Geological time scale after the ICS (2000). Also shown are the ages of the various deposits and metallogenic provinces mentioned in the book.

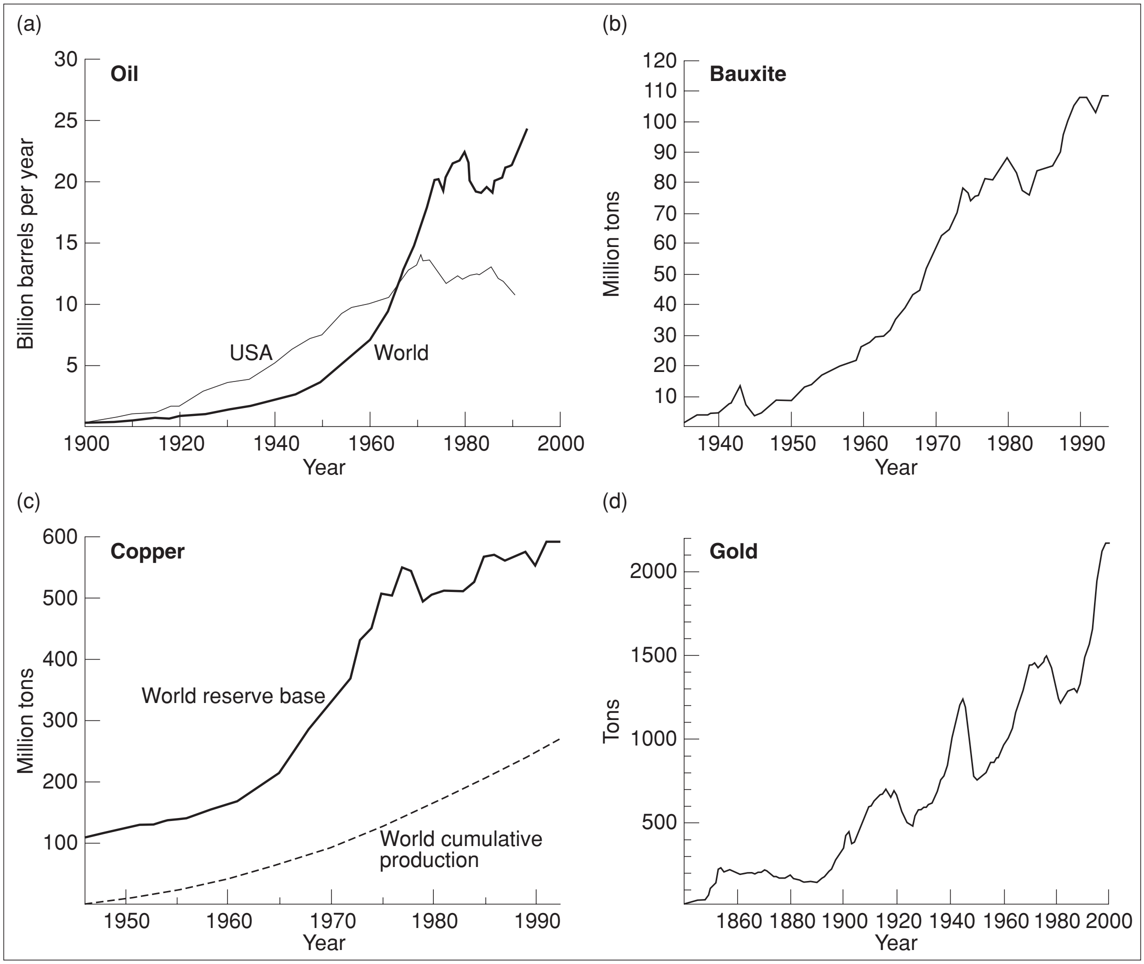

Figure 6 Global production trends for oil (a), bauxite (b), copper (c), and gold (d) over the twentieth century (after compilations in Craig *et al.*, 1996).

decades. World oil production increased precipitously until the late 1970s, but since then a variety of political and economic factors have contributed to tempering production (Figure 6a), thereby ensuring a longer-term reserve base. A similar levelling of production is evident for bauxite (Figure 6b) but such a trend is not yet evident for the precious metals such as gold or platinum. For some commodities, such as copper (Figure 6c), the world reserve base is also levelling off, a feature that in part also reflects fewer new and large discoveries. Critical shortages of most natural commodities are not likely to present a problem during the early part of the twenty-first century (Einaudi, 2000), but this situation will deteriorate unless strategies for sustainability are put into place immediately.

The depletion of commodities in the Earth's crust is particularly serious for those metals that are already scarce in terms of crustal abundances and for which high degrees of enrichment are required in order to make viable ore deposits. Figure 2 illustrates the point by referring to the production of iron as a baseline measure against which extraction of other metals can be compared (Skinner, 1976). Those elements which fall above the Fe production line (notably Au, Ag, Bi, Sb, Sn, Cu, Pb, and Zn) are being extracted or depleted at faster rates, relative to their crustal abundances, than Fe. It is these metals that are in most danger of depletion in the next 50 years or so unless production is ameliorated or the reserve base is replaced. Conversely, those metals that plot beneath the Fe production line (such as Ti, Mg, and Al) are being extracted at slower rates than Fe and are in less danger of serious depletion during this century.

One of the ways in which metallogeny can assist in the creation of a sustainable pattern of resource utilization is to better understand the processes by which ores are concentrated in the Earth's crust. The replacement of the global commodity reserve base is obviously dependent on exploration success and the ability to find new ore deposits that can replace those that are being depleted. It is, of course, increasingly difficult to find new and large deposits of conventional ores, since most of the accessible parts of the globe have been extensively surveyed and assessed for their mineral potential. The search for deeper deposits is an option but this is dependent to a large extent on the availability of technologies that will enable mining to take place safely and profitably at depths in excess of 4000 meters (currently the deepest level of mining in South African gold mines). Another option is to extract material from inaccessible parts of the globe, such as the ocean floor, a proposal that has received serious consideration with respect to metals such as Mn and Cu. Again, there are technological barriers to such processes at present, but these can be overcome, as demonstrated by the now widespread exploration for, and extraction of, oil and gas from the sea floor. A third option to improve the sustainability of resource exploitation is to extract useful commodities from rocks that traditionally have not been thought of as viable ores. Such a development can only be achieved if the so-called "mineralogical barrier" (Skinner, 1976) is overcome. This concept can be described in terms of the amount of energy (or cost) required to extract a commodity from its ore. It is, for example, considerably cheaper to extract Fe from a banded iron-formation than it is from olivine or orthopyroxene in an igneous rock, even though both rock types might contain significant amounts of the metal. The economics of mining and the widespread availability of banded iron-formation dictate that extraction of Fe from silicate minerals is essentially not feasible. The same is not true of nickel. Although it is cheaper and easier to extract Ni from sulfide ore minerals (such as pentlandite) there is now widespread extraction of the metal from nickeliferous silicate minerals (garnierite) that form during the lateritic weathering of ultramafic rocks. Even though Ni is more difficult and expensive to extract from laterite than from sulfide ores, the high tonnages and grades, as well as the widespread development and ease of access of the former, mean that they represent viable mining propositions despite the extractive difficulties. Ultimately, it may also become desirable to consider mining iron laterites, but this would only happen if conventional banded iron-formation hosted deposits were depleted, or if the economics of the whole operation favored laterites over iron-formations. This is not likely to happen in the short term, but, if planned for, the scenario does offer hope for sustainability in the long term. In short, sustainable production of mineral resources requires a thorough understanding of ore-forming processes and the means to apply these to the discovery of new mineral occurrences. It also requires the timely development of technologies, both in the earth sciences and in related fields of mining and extractive metallurgy, that will enable alternative supplies of mineral resources to be economically exploited in the future.

Mining and environmental responsibility

A global population of 11 billion by the end of the century presents a major problem in terms of the supply of most of the world's mineral resources. What is even more serious, though, is the enormous strain it will place on the Earth's fragile environment arising from the justifiable expectation that future technologically advanced societies will provide an adequate standard of living, in terms of food, water, housing, recreation, and material benefits, to all their peoples. In addition to commodity supply problems, the twenty-first century will be also be characterized by unprecedented depletion of even more critical resources in the form of soil, water, and clean air (Fyfe, 2000). Legislation that is aimed at dealing with issues such as atmospheric pollution and greenhouse gas emissions, factory waste and acid drainage, the burning and destruction of forests, the protection of endangered species, overgrazing, and erosion is highly desirable but far from globally applicable because it is perceived as a luxury that only the developed world can afford.

The study of ore-forming processes is occasionally viewed as an undesirable topic that ultimately contributes to the exploitation of the world's precious natural resources. Nothing could be further from the truth. An understanding of the processes by which metals are concentrated in the Earth's crust is essential knowledge for anyone concerned with the preservation and remediation of the environment. The principles that underpin the natural concentration of ores in the crust are the same as those that can be utilized in issues such as the control of acid mine drainage, and soil and erosion management. Mining operations around the world are increasingly having to assume responsibility for reclamation of the landscape once the resource has been depleted. The industry now encompasses a range of activities extending from geological exploration and evaluation, through mining and beneficiation, and eventually to environmental reclamation. This is the mining cycle and its effective management in the future will be a multidisciplinary exercise carried out by highly skilled scientists and engineers. Earth systems science, and in particular the geological processes that gave rise to the natural concentration of the ore in the first place, will be central to this entire operation.

SUMMARY

The discipline of "economic geology" and in particular the field of metallogeny (the study of the genesis of ore deposits) remains critical to the teaching of earth systems science. A holistic approach involving the integration of knowledge relevant to the atmosphere, biosphere, and lithosphere is now regarded as essential to understanding the complexities of the earth system. The development of environmentally responsible and sustainable policies with respect to the future supply of all natural resources will demand a thorough knowledge of the nature and workings of the earth system. Central to this is an understanding of metallogeny and the nature and origin of the entire spectrum of mineral resources, including the fossil fuels. The classification of mineral deposits in terms of process can be simply and effectively achieved in terms of rock associations, namely igneous, hydrothermal, and sedimentary. This breakdown forms the basis for the layout of this book.

FURTHER READING

Blunden, J. (1983) *Mineral Resources and Their Management*. Harlow: Longman, 302 pp.

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PART ONE

Igneous Processes

CHAPTER ONE

Igneous ore-forming processes

TOPICS

- Metallogeny of oceanic and continental crust
- Fundamental magma types and their metal endowment
- The relative fertility of magmas and the "inheritance factor"
  - "late-veneer" hypothesis
  - diamonds and kimberlite/lamproite
  - metal concentrations in metasomatized mantle
  - S- and I-type granites
- Partial melting and crystal fractionation as ore-forming processes
- Trace element distribution during partial melting
- Trace element distribution during fractional crystallization
- Monomineralic chromitite layers
- Liquid immiscibility as an ore-forming process
- Special emphasis on mineralization processes in layered mafic intrusions
  - sulfide solubility
  - sulfide–silicate partition coefficients
  - the R factor
  - PGE clusters and hiatus models

CASE STUDIES

Box 1.1 Diamondiferous kimberlites and lamproites: the Orapa (Botswana) and the Argyle (Western Australia) diamond mines
Box 1.2 Partial melting and concentration of incompatible elements: the Rössing uranium deposit
Box 1.3 Boundary layer differentiation in granites and incompatible element concentration: the Zaaiplaats tin deposit, Bushveld Complex
Box 1.4 Crystal fractionation and formation of monomineralic chromitite layers: the UG1 chromitite seam, Bushveld Complex
Box 1.5 Silicate–sulfide immiscibility: the komatiite hosted Ni–Cu deposits at Kambalda, Western Australia
Box 1.6 New magma injection and magma mixing: the Merensky Reef, Bushveld Complex
Box 1.7 Magma contamination and sulfide immiscibility: the Sudbury Ni–Cu deposits

1.1 Introduction

Igneous rocks host a large number of different ore deposit types. Both mafic and felsic rocks are linked to mineral deposits, examples of which range from the chromite ores resulting from crystal fractionation of mafic magmas to tin deposits associated with certain types of granites. The processes described in this chapter relate to properties that are intrinsic to the magma itself and can be linked genetically to its cooling and solidification. Discussion of related processes, whereby an aqueous fluid phase forms or "exsolves" from the magma as it crystallizes, is placed in Chapter 2. The topics discussed under the banners of igneous and magmatic–hydrothermal ore-forming processes are intimately linked and form Part 1 of this book.

A measure of the economic importance of ore deposits hosted in igneous rocks can be obtained from a compilation of mineral production data as a function of host rock type. A country like South Africa, for example, is underlain dominantly by sedimentary rocks and these undoubtedly host many of the valuable mineral resources (especially

Table 1.1 A comparison of the value of mineral production from igneous and sedimentary rocks in South Africa

Mineralization hosted in	Area (km^2)	Value of sales, 1971 (10^6 US$)	% of total area	% of total value	Unit value (US$/km^2)
Granites	163 100	1973	13.3	3.4	12 000
Mafic layered complexes	36 400	7288	3.0	12.5	200 200
Total (igneous)	199 500	9261	16.3	15.9	46 400
Sedimentary rocks	1 023 900	49 137	83.7	84.1	47 900

Source: after Pretorius (1976).

if the fossil fuels are taken into consideration). Nevertheless, the value of ores hosted in igneous rocks *per unit area of outcrop* can be comparable with that for sedimentary rocks, as indicated in Table 1.1. Although South Africa is characterized by a rather special endowment of mineral wealth related to the huge Bushveld Complex, the importance of igneous-hosted ore deposits is nevertheless apparent.

1.2 MAGMAS AND METALLOGENY

It is well known that different igneous rocks host ore deposits with different metal associations, and that this must be related somehow to the environments in which magmas are generated and the resulting compositional characteristics they inherit from their various settings. It is widely recognized, for example, that many of the chalcophile and siderophile elements (such as Ni, Co, Pt, Pd, and Au) are more likely to be associated with mafic rock types, whereas concentrations of many lithophile elements (such as Li, Sn, Zr, U, and W) are typically found in association with felsic or alkaline rock types. This has implications for understanding ore genesis and, consequently, some of the factors related to these differences are discussed below.

1.2.1 Crustal architecture and mineral wealth

Although the greatest concentrations of siderophile and chalcophile elements almost certainly reside in the mantle and core of the Earth, these are generally inaccessible due to their very great depths. In fact, most of the world's economically exploitable mineral wealth effectively lies on the surface or just below the surface of the Earth. The world's deepest mine, the Western Deep Levels gold mine near Johannesburg, South Africa, extends to just over 4000 m depth and this places an effective limit on ore body exploitation, at least in terms of present technologies. Nevertheless, many mineral commodities are formed much deeper in the crust than 4 km, with some even being derived from the mantle. Diamonds, for example, are hosted in kimberlite magmas that have been brought to exploitable depths by a variety of igneous or tectonic mechanisms. Understanding ore genesis processes, therefore, requires a knowledge of lithospheric (i.e. crust and upper mantle) architecture, and also of the origin and nature of the igneous rocks in this section of the Earth.

The oceanic crust, which covers some two-thirds of the Earth surface, is thin (less than 10 km) and, compared to the continents, has a composition and structure that is relatively simple and consistent over its entire extent. The upper layer, on average only 0.4 km thick (Kearey and Vine, 1996), comprises a combination of terrigenous and pelagic sediments that are distributed mainly by turbidity currents. They are often highly reduced and metal charged. This is underlain by a layer, typically 1–2.5 km thick, that is both extrusive and intrusive in character and dominantly basaltic in composition. The basalts are, in turn, underlain by the main body of oceanic crust that is plutonic in character and formed by crystallization and fractionation of basaltic magma. This cumulate assemblage comprises mainly gabbro, pyroxenite, and peridotite. Sections of tectonized and meta-