

# Mineral and Energy Resources

## Occurrence, Exploitation, and Environmental Impact

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*For my daughters,  
Laura and Rachel*

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# Preface

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The world community is today cognizant of our precarious situation with regard to both energy and mineral resources. Sophisticated techniques to find elusive mineral deposits and fossil fuels are being developed at an ever increasing pace, although the return seems to be dwindling. How to successfully exploit new discoveries of minerals or energy sources is also given wide attention. Finally, an awareness of the environmental impacts of the exploitation of these resources is widespread, in some countries more so than in others.

The point is well taken that many of our mineral resources, both worldwide as well as in the United States, are in short supply. The United States, which consumes roughly thirty percent of the world total for many substances (iron, copper, fertilizer chemicals, etc.), is becoming more and more reliant on imports as increasing costs and other factors cause shutdowns of many domestic operations. In the future, the per capita consumption of many of these commodities will increase in developing nations to the point that this "endless" supply of imports will be severely taxed. This text takes a careful look at mineral resources, with emphasis on United States supplies, but it also appraises the world resources picture. Environmental concerns about mineral resources exploitation are very real, and both necessary and unnecessary environmental restrictions have been placed on the United States industries involved with mineral resources exploitation.

There are several missions in this book. First, I wish to cover the adequacy of supply of mineral and energy resources, and data are included that allow projections for twenty or more years in most cases. For example, water resources are dwindling, and the Greenhouse Effect will make the United States situation far worse. Soils are being eroded senselessly, and wetlands and other lands are being contaminated on a wide scale. Reasons for our decline in water resources are explored, and the finger of blame points clearly to man's activities.

Second, I wish to cover the environmental impact of mineral and energy resource exploitation, as well as the environmental aspects of chemical and other wastes. There is no "free ride" in today's energy picture. All energy options—coal, nuclear, oil, gas, hydropower, solar, geothermal, and future sources—have associated risks that must all be assessed in terms of environmental impact and potentially adverse public health effects. In this assessment, care is taken to explore aspects of milling and other front end parts of the energy chains, as well as a hard look at disposal of wastes.

The third mission of this book is the most important and the most obvious: education. It is imperative that the world become educated on the issues of mineral and energy exploitation and how to achieve minimal environmental impact and minimal adverse impact on public health. The world faces very hard decisions in the near future on minerals, energy, water supply and use, population control, food availability, and disposal of materials from all aspects of human use. It is hoped that this book will present the reader with enough factual information to help overcome this situation.

Many individuals have contributed their expertise to the development of this book. I particularly want to thank the reviewers for their valuable feedback: Arthur H. Brownlow, Boston University; Peter L. Calengas, Western Illinois University; Peter Crowley, Amherst College; Gregory Eicholz, Georgia Institute of Technology; C. M. Leshner, University of Alabama; Nancy Lindsley-Griffin, University of Nebraska (Lincoln); Paul D. Nelson, St. Louis Community College (Forest Park); Donald B. Potter, Hamilton College; and William C. Rense, Shippensburg University.

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# 1

## Introduction

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The world community is dependent on earth and energy resources, and in order for the world to meet its impending demand for goods and energy, there must be an awareness of how and where earth resources occur and how best to use all energy resources. The assumed goals of every nation are to become industrialized and to promote a healthy society. Although food is abundant throughout the world, it is, like the earth and energy resources, distributed unevenly. So, too, are water resources.

Population growth may be the single most important factor leading to long-term environmental degradation on this planet. At the time of this writing, the world population is steadily creeping, and sometimes almost leaping, toward the 6 billion mark. Further, the world population has been doubling every 33 years or so. Interestingly, due to the herculean efforts of the People's Republic of China, with over one-fifth of the world's people, there is some indication that this doubling period of 33 years may be lengthening. Let us certainly hope so, because in some undeveloped countries the population doubling period is 20 years. The U.S. National Academy of Science has estimated that this planet can produce food to meet the needs of just over 30 billion people—at a starvation level, and assuming worldwide food distribution. This 30 billion figure could be reached roughly half to two-thirds of the way through the twenty-first century, within our children's lifetimes.

There are other factors to consider. Chemicals for the agriculture industry and metals for farm equipment will experience a doubling within the next 10 years or so, but supplies of both are finite and not overly large. So, too, are fossil-fuel energy resources. It is predicted that the world supply of petroleum products will peak early in the next century.

Though this perspective is rather gloomy, all is not as bleak as indicated. In the chapters to follow, resources of water, metals, nonmetals, and energy will be discussed. It will be pointed out that in many instances supplies of various earth

resources may be greater than determined just a few years ago, and that scientific data have revealed intelligent ways to meet our energy demands as well.

However, the response of many nations is an attempt to exploit resources rapidly and often inefficiently. Commonly this goes hand in hand with a blatant disregard for the environmental consequences of poorly harnessing resources and energy.

Therefore, the chapters to follow also focus on the environmental aspects of earth resources and energy sources. In them I discuss mining, milling and other preparatory techniques, then waste disposal, water pollution, and atmospheric pollution. The final chapter focuses entirely on environmental issues. Because this book is not intended to be a text for economic geology, nor is it, an exhaustive look at energy or the environment, additional readings are listed at the end of each chapter.

Any resource from any part of the animal, vegetable, or mineral kingdoms can be called an earth resource. In this book, however, we are concerned with only those commodities that are normally discussed together as *mineral resources*. Wind energy and solar energy are included in this book as well, although they are not “mineral” resources. It is to all of these resources that we owe our existence.

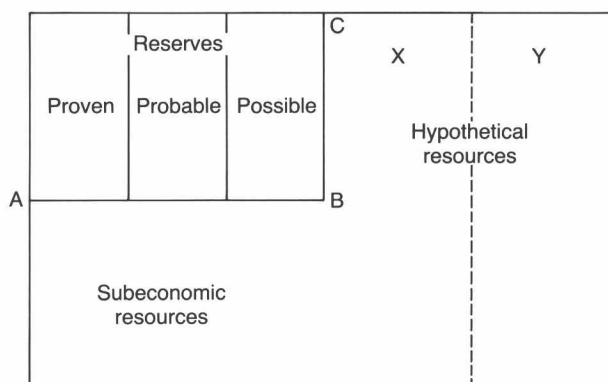
Before proceeding further, a note about units of measurement. There is no worldwide agreement on units for reporting different types of earth resources or environmental problems. Where possible, I have used the International System (S.I.) of units, but the reader will note many instances where measurements are reported in U.S. Customary units. I have felt this necessary so that when reference is made to the original source, the units will be consistent. Further, many metals are reported in ounces, pounds, short tons, long tons, metric tons—even, in the case of mercury, flasks (where one flask equals 76 pounds). Conversion tables are included in the Appendix to help the reader convert one set of units to another.

## RENEWABLE AND NONRENEWABLE RESOURCES

Mineral resources may be classified as renewable or nonrenewable. A *renewable* resource, after use, will eventually be available again. For some resources, such as groundwater, the lag time between initial use and renewal may be so long that for practical purposes the resource becomes nonrenewable. *Nonrenewable* resources include those commodities that, once used, are never again available. For example, burning fossil fuels and splitting atoms remove these substances from use by future generations.

A *reserve* is that part of a resource for which we have precise quality and quantity information (for example, at least a 90 percent probability that a certain amount of rock will yield a specific tonnage of metal). For mineral commodities, such information is best obtained by drilling, assaying the drill core or cuttings, and combining the drill information with geologic data. Depending upon the degree of confidence we have in our estimates, reserves can be classified further as

FIGURE 1-1 Distinguishing between reserves and resources. Reserves are economically recoverable materials from identified deposits, as distinguished from resources of the same material from identified but subeconomic or hypothetical deposits. (Source: From Douglas G. Brookins, *Earth Resources, Energy, and the Environment*, Merrill, 1981.)



*proven, probable, or possible.* These three terms range from a very high level of confidence to a relatively uncertain degree of confidence, but all are still based on firm criteria.

As shown in Figures 1-1 and 1-2, we distinguish reserves from resources. Some resources will be added to or subtracted from reserves as economic conditions change. Other resources are classified as hypothetical, or undiscovered. The assumption is that additions to reserves are more likely from known mining areas and less likely from similar areas of little or no mineral exploitation. In Figure 1-1 the line A-B, representing the limit of profitability, can fluctuate up or down. It merely serves to separate the proven-probable-possible reserves from lower-grade *subeconomic resources*. Should the price of the material rise, the line will move down. For *hypothetical resources*, two categories can be defined: undiscovered ore from known areas of ore occurrence, (X on Figure 1-1), and undiscovered ore from areas where some geologic criteria indicate ore may exist but from which no deposits are known (Y on Figure 1-1). Both hypothetical resources are subject to the same economic considerations as the reserves, as represented by line A-B. Only when sufficient drilling or other techniques have indicated the

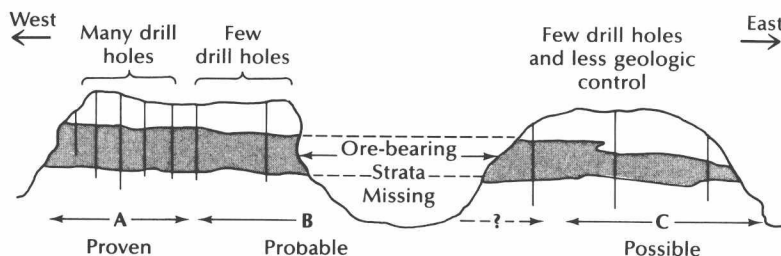


FIGURE 1-2 Classification of reserves. This cross section of ore-bearing strata (from west to east) illustrates proven-probable-possible ore reserves. (Source: From Douglas G. Brookins, *Earth Resources, Energy, and the Environment*, Merrill, 1981.)

presence of some ore can hypothetical resources be properly classified as a reserve.

In Figure 1–2, area A, with its many drill holes (the vertical lines) from which the rock has been assayed, is an area of proven reserves. In area B there are fewer drill holes and thus less certainty, but the grade (tenor) of the ore and its thickness are about the same as for area A, and it is classified as a probable reserve. Further east (area C) the ore horizon thins and the tenor of the ore drops, too. These factors, coupled with lack of drill holes, would dictate that the ore reserves be classified as possible. If the tenor of the ore did not decrease as shown but the thickness of the unit did decrease, then the ore classified as possible might be more properly classified as subeconomic in that too much barren rock would have to be removed to recover the ore profitably.

## MINERALS

Rocks are generally composed of one or more minerals. *Minerals* are naturally occurring inorganic chemical compounds with crystalline structures. Of the 92 naturally occurring elements, nine (oxygen, silicon, aluminum, iron, calcium, magnesium, sodium, potassium, and titanium) make up over 90 percent of all the rocks of the earth's crust. Oxygen and silicon together account for almost 75 percent by weight (47.5 percent and 27.5 percent, respectively). Oxygen bonded in rocks and minerals accounts for 94 percent of their volume.

Of these nine elements, none is an economically recoverable resource in the common rock-forming minerals. This is because all nine elements are found in rocks and minerals as ions, which are bonded together in different ways. *Ions* are merely atoms that have gained or lost electrons. An atom that loses one or more electrons becomes a positive charged ion, called a *cation* because it will be attracted to the cathode in an electrolytic cell. Atoms that gain electrons take on a negative charge and are called *anions* because they would be attracted to the positively charged anode in the same cell. Of the nine elements listed above, only oxygen forms an anion ( $O^{2-}$ ) while the others form cations ( $Si^{4+}$ ,  $Al^{3+}$ ,  $Fe^{2+}$ ,  $Fe^{3+}$ ,  $Mg^{2+}$ ,  $Ca^{2+}$ ,  $Na^{+}$ ,  $K^{+}$ , and  $Ti^{4+}$ ).

Oxygen and silicon commonly combine to form the silica tetrahedron ( $SiO_4^{4-}$ ), a central ion of  $Si^{4+}$  surrounded by four  $O^{2-}$  ions. This structure is possible because the radius for the  $Si^{4+}$  ion is only about one-fourth that of each  $O^{2-}$  ion. The net charge on the silica tetrahedron is  $-4$ , as the four positive charges of the cation only partially offset the eight negative charges of the anions. This negative charge is usually balanced by other elements surrounding the tetrahedron in natural compounds.

A few major rock-forming minerals constitute about 90 percent of the rocks found in the earth's crust. In Table 1–1 they are written in simplest form as compounds. At first glance, this list of minerals looks complex. When we remember that there are more than 2500 minerals found in nature, then the handful listed in Table 1–1 are impressive because they are so much more abundant than all the others.

TABLE 1-1 Major rock-forming minerals.

Mineral	Formula
Olivine	$(\text{Mg,Fe})_2\text{SiO}_4$
Pyroxene	
Enstatite	$\text{MgSiO}_3$
Diopside	$\text{CaMgSi}_2\text{O}_6$
Augite	$(\text{Ca,Na})(\text{Mg,Fe}^{2+},\text{Fe}^{3+},\text{Al})(\text{Al,Si})_2\text{O}_6$
Amphibole	
Hornblende	$(\text{Ca,Na})_{2-3}(\text{Mg,Fe}^{2+},\text{Fe}^{3+},\text{Al})_5(\text{Al,Si})_8\text{O}_{22}(\text{OH})_2$
Potassium feldspars (sanidine, microcline, orthoclase)	$\text{KAlSi}_3\text{O}_8$
Plagioclase—a mixture of	
Albite	$\text{NaAlSi}_3\text{O}_8$
Anorthite	$\text{CaAl}_2\text{Si}_2\text{O}_8$
Micas	
Biotite	$\text{K}(\text{Mg,Fe})_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$
Muscovite	$\text{K}(\text{Al}_2)\text{AlSi}_3\text{O}_{10}(\text{OH})_2$
Quartz	$\text{SiO}_2$

It is noteworthy that titanium (as  $\text{Ti}^{4+}$ ) has not specifically been included in any of the minerals listed so far. This is because titanium is usually hidden in silicate minerals such as augite and hornblende, where due to its similar size (ionic radius) it can substitute for  $\text{Fe}^{3+}$  or, less commonly, for  $\text{Fe}^{2+}$  or  $\text{Mg}^{2+}$ . Owing to its large charge and size relative to  $\text{Si}^{4+}$  and  $\text{Al}^{3+}$ , titanium commonly forms accessory minerals where it is a dominant ion—ilmenite ( $\text{FeTiO}_3$ ) and sphene ( $\text{CaTiSiO}_5$ ), for example. Other important accessory minerals are listed in Table 1-2.

Only in the mineral olivine is the net charge of  $-4$  balanced by a simple charge of  $+4$ . In most other minerals corners of the silica tetrahedron are shared with other tetrahedra to form chains (pyroxenes and amphiboles), sheets (micas and clay minerals), and three-dimensional stacks or frameworks (feldspars and quartz). All minerals with silica tetrahedra are known as silicates. If silicon is absent and only oxygen is present as an anion, then the mineral is called an oxide. Hematite ( $\text{Fe}_2\text{O}_3$ ) and magnetite ( $\text{Fe}_3\text{O}_4$ ) are oxides.

When carbon or phosphorus combines with oxygen to form an anion such as carbonate ion ( $\text{CO}_3^{2-}$ ) or phosphate ion ( $\text{PO}_4^{3-}$ ), then carbonate minerals such as calcite ( $\text{CaCO}_3$ , the main mineral in limestone) or dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ) occur as well as phosphate minerals such as apatite,  $\text{Ca}_5(\text{PO}_4)_3(\text{OH,F})$ . Sulfur usu-

TABLE 1-2 Common accessory minerals.

Mineral	Formula	Comments
Apatite	$\text{Ca}_5(\text{PO}_4)_3(\text{OH}, \text{F})$	Contains phosphorus
Pyrite	$\text{FeS}_2$	Main sulfur-bearing mineral in igneous rocks
Calcite	$\text{CaCO}_3$	Most abundant carbon-bearing mineral (organic carbon not included)
Magnetite	$\text{Fe}_3\text{O}_4$	Common in igneous and metamorphic rocks
Zircon	$\text{ZrSiO}_4$	Common accessory in igneous rocks
Sphene	$\text{CaTiSiO}_5$	Common accessory in granitic rocks
Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	Common sedimentary rock mineral
Clay minerals	Al-silicates with $\text{H}_2\text{O}$ , Fe, Mg, etc.	Common in sedimentary rocks

ally occurs in nature with charges of  $-2$ ,  $0$ , or  $+6$ . In most sulfides the sulfur has a charge of  $-2$  (as in the lead ore galena,  $\text{PbS}$ ). Pyrite ( $\text{FeS}_2$ ) is a notable exception and is the most common accessory sulfide mineral found in common rocks. Native sulfur is common in hot-spring areas near volcanic areas or in other places where hot waters or bacterial action have caused its formation. The ion  $\text{S}^{6+}$  is usually found in combination with oxygen as  $\text{SO}_4^{2-}$ , the sulfate ion. The well-known minerals barite ( $\text{BaSO}_4$ ), and gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) are good examples of sulfate minerals; both are of significant economic importance. Another group of anions in nature is the halides ( $\text{Cl}^-$ ,  $\text{F}^-$ , and  $\text{Br}^-$ ). Chlorides, the first of these, is found in common table salt, the mineral halite ( $\text{NaCl}$ ). Sylvite ( $\text{KCl}$ ), or potassium chloride, is the most important ore for potassium. The most important mineral with the fluoride ion ( $\text{F}^-$ ) is fluorite ( $\text{CaF}_2$ ), or calcium fluoride. Other lesser-known compounds will be mentioned as necessary. Except for iron (which can be  $\text{Fe}^{2+}$  or  $\text{Fe}^{3+}$ ), all of the ions listed in the preceding formulas are assumed to possess their most common charge.

## ROCKS AND THE ROCK CYCLE

Earth is made up of rocks and minerals. The oceans, which cover about two-thirds of the earth's surface, constitute only a very small fraction of the crust and an even smaller fraction of the whole earth. It is easy to introduce the kinds of rocks we find in the earth's crust by use of Figure 1-3, showing the relationships of different rocks as part of a cycle.

Magma, or molten rock formed at depth, crystallizes to form igneous rocks. Magma that reaches the earth's surface is called lava, and it may form either finely crystalline or even noncrystalline, glassy *volcanic* rocks. Magma that crystallizes at depth forms coarse-grained *plutonic* rocks.

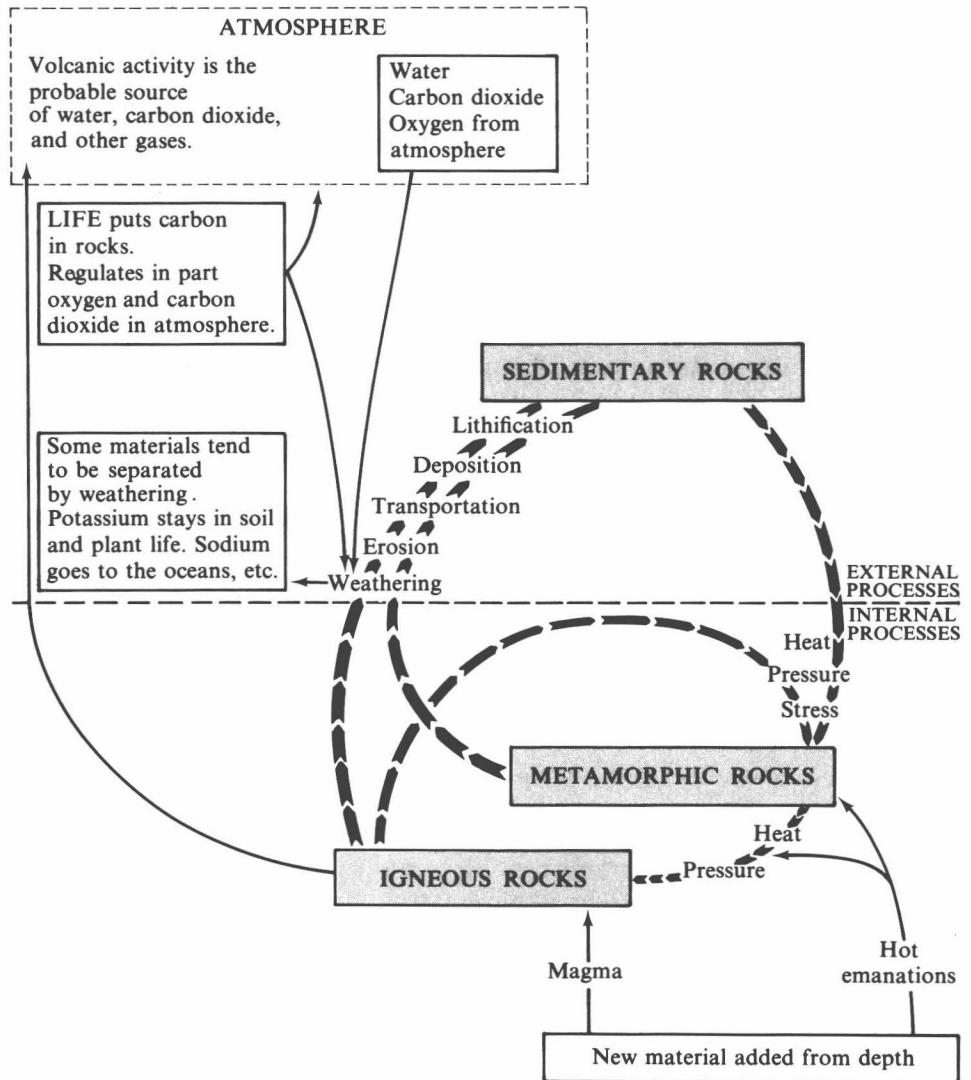


FIGURE 1-3 The middle of this diagram, showing the relationships among igneous, sedimentary, and metamorphic rocks, is what is generally considered the rock cycle. The upper and lower parts of the figure show how material is added to and subtracted from the rock cycle. (Source: From B. Clark Burchfiel, Robert J. Foster, Edward A. Keller, Wilton N. Melhorn, Douglas R. Brookins, Leigh W. Mintz, and Harold Thurman in *Physical Geology*, Merrill, 1982.)



The rocks exposed at the earth's surface to weathering and erosion result in both mechanical and chemical products being added to the oceans and other surface waters. When the mechanically added materials—sediments—settle to the bottom and are compacted, they form *sedimentary* rocks. Chemical precipitates from seawater and inland seas form *evaporites*, *limestones*, and similar rocks.

When any of these types of rocks are buried and subjected to great pressures and temperatures, though not great enough to cause widespread melting, their mineralogies are changed and *metamorphic* rocks form. Metamorphic rocks can be formed from igneous, sedimentary, or older metamorphic rocks.

## IGNEOUS ROCKS

The common types of igneous rocks are given in Table 1–3, a greatly simplified rock chart. Table 1–3 is presented here primarily for readers without a previous geology course. The most abundant rock type on the earth's surface is basalt, which forms most of the oceanic crust (the part of the crust covered by oceans) and is an important rock on the continents as well. If basaltic magma crystallizes at depth, then the rock gabbro forms. Thus Table 1–3 not only lists the igneous rocks in a chemical trend from most silicic (highest  $\text{SiO}_2$  content) to basic (low  $\text{SiO}_2$ ) to ultrabasic (lowest  $\text{SiO}_2$ ), but also notes a difference in rocks due to their formation at depth (plutonic) or at or near the earth's surface (volcanic).

Volcanic rocks include those that reach the surface of the earth and those that are emplaced at very shallow depths. Volcanoes spew out a variety of materials, such as ash (finely divided rock), along with water vapor and other gases. Some of the rocks deposited from volcanic eruptions include tuff, volcanic breccia, perlite, pumice, and scoria.

Plutonic rocks may be very coarse grained, such as pegmatites, and vary widely in grain size within a crystallizing magma chamber. A special type of igneous rock is a *porphyry*. Here crystallization started at depth, forming fairly large crystals. Then the setting of the magma chamber changed so that crystallization proceeded with great rapidity, resulting in a sea of fine-grained crystals (or even glass if the rocks were extruded rapidly) surrounding the large crystals. The large crystals are called phenocrysts, and the fine-grained or glassy matrix, the groundmass. Together they form the rock called porphyry. Porphyritic rocks are important for some metal ore deposits such as copper and molybdenum.

The *Bowen reaction series* is important to igneous rocks for, as shown by Norman L. Bowen in 1929, one can derive many types of major igneous rocks from the same assumed parent magma, one with the composition of a basalt. This is shown in Figure 1–4. Even though the assumed starting magma is basaltic, the first minerals to form as the magma is cooled are high-density olivine and low-density, calcium-rich plagioclase. These minerals have one of two fates: They can settle out of the cooling magma, or they can react with it to form new minerals. Olivine that so reacts with the magma, and thus forms the next highest temperature mineral pyroxene, is said to be resorbed by the magma. Similarly, the cal-