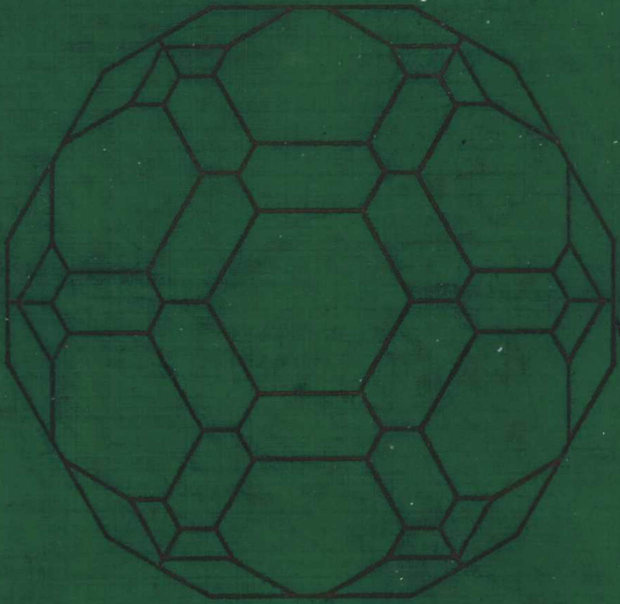
MANUAL OF MINERALOGY
19th. Ed.

CORNELIUS S. HURLBUT, JR.
CORNELIS KLEIN



AFTER J.D. DANA

MANUAL OF MINERALOGY

(*after James D. Dana*)

19th Edition

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The *Manual of Mineralogy* was written by James D. Dana in 1848 and revised by him in 1857, 1878 as the *Manual of Mineralogy and Lithology,* and in 1887 as the *Manual of Mineralogy and Petrography.* An edition number was given to some, but not all reprintings of each revision. For example, the 1887 revision was reprinted in 1891 as the 10th Edition but in 1893, 1895, and 1900 as the 12th Edition.* Subsequent revisions as *Dana's Manual of Mineralogy* have each been given an edition number as follows: *13*, 1912 and *14*, 1929 by William E. Ford. *15*, 1941; *16*, 1952; *17*, 1959; and *18*, 1971 by C. S. Hurlbut, Jr.

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PREFACE

This book, like the preceding edition known as *Dana's Manual of Mineralogy,* is designed for the beginning course in mineralogy and as a permanent mineralogic reference. It is intended for students who will do further work in mineralogy as well as for those for whom this will be their only exposure to the subject. In the nineteenth edition we have expanded the coverage of many mineralogic, and to some extent introductory petrologic, concepts; this expanded coverage should make it easier for students who continue their training in mineralogy and petrology to use effectively more advanced books, references, and journal publications.

The general organization of the present edition, in 12 chapters, allows instructors to select those subjects they consider most essential. It will be impossible in many courses, especially those that are only one semester or one quarter in length, to cover all of the material presented. The order of the various chapters is reasonably logical except for the location of Chapter 11, which deals with introductory aspects of petrology. The material in this chapter should go hand in hand with much of Systematic Mineralogy (Chapters 7, 8, 9, and 10), especially Chapter 10 on Silicates. In our treatment of the various subjects grouped under mineralogy we discuss basic concepts before describing mineral groups and species.

In Chapter 2, Crystallography, the first portion is devoted to various aspects of the symmetry of ordered patterns. Although this discussion is not essential to the subsequent treatment of crystal morphology, it is most helpful in the understanding of the external forms of naturally occurring crystals. In our treatment of crystal morphology we proceed from the crystal system of lowest symmetry to that of the highest symmetry. This arrangement conforms to our discussion of the symmetries of ordered patterns. Within each crystal system, however, the crystal classes are arranged in order of decreasing symmetry. Although this appears illogical with respect to the increasing symmetry of the crystal systems, this sequence of discussion of crystal classes is least cumbersome because the lower symmetry classes can be described as special cases of the highest symmetry class. Moreover, if time does not permit development of all crystal classes, it is those of highest symmetry in each crystal system that are usually discussed.

Chapters 3 (X-ray Crystallography) and 6 (Optical Properties of Crystals) have changed little from the eighteenth edition, except for a short description of the determination of crystal structures by X-ray techniques. Although the contents of these two chapters may be used in only a few introductory mineralogy courses, they are included because in the subsequent treatment on Systematic Mineralogy each mineral species description includes a listing of diagnostic X-ray and optical parameters as well as a discussion of its crystal structure. In other words, if students wish to find out, on their own, by what techniques such information is obtained they can locate it in these two chapters.

Chapter 4, on the crystal chemistry, crystal structure, and chemical composition of minerals, covers bonding forces in crystals, concepts such as polymorphism, polytypism, solid solution and exsolution, the recalculation of mineral analyses, and the graphical representation of mineral compositions. Much of the material in this chapter is essential to a full understanding of the discussion of mineral species under Systematic Mineralogy. This chapter also contains a condensed discussion of laboratory chemical and blowpipe tests for elements found in common minerals.

Chapters 7, 8, 9 and 10 deal with the systematic descriptions of about 200 minerals. The description of each mineral group or major mineral series is preceded by a synopsis of some of the highlights of its chemistry, crystal chemistry, and structure. Each of the approximately 200 descriptions also contains a new section on *Composition and Structure*. The mineral structures are illustrated by some of the best available polyhedral and ball-and-stick representations. In these four chapters use is made of stability diagrams and, under the heading of *Occurrence,* petrologic terms such as facies and assemblage are often used; these concepts are covered in Chapter 11.

Chapter 11 presents a brief and elementary introduction to petrology providing a link between standard mineralogy and petrology books.

At the end of most chapters are selected references which should guide the student to the most relevant literature in the subject. The Determinative Tables (Chapter 12) and Mineral Index, both of which were up-dated wherever necessary, are especially useful in the laboratory for study and identification of unknown minerals.

In short, in writing the nineteenth edition of the *Manual of Mineralogy* our aim was for an introductory mineralogy book that would serve two purposes: (1) to provide the student with an understanding of basic concepts in crystallography, crystal chemistry, chemistry, and introductory petrology—concepts essential to the understanding of the genesis of minerals and rocks; and (2) to provide a reference for quick and unambiguous identification of the common minerals in the field and in the laboratory.

We are grateful to John C. Drake of the University of Vermont for his careful review of the manuscript and to Robert P. Wintsch of Indiana University for his comments on Chapter 11. We thank Mrs. Thea Brown-Fritzinger for her enthusiastic and extraordinarily skillful typing.

Cornelius S. Hurlbut, Jr.
Cornelis Klein

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1
INTRODUCTION

Mineralogy is the study of naturally occurring, crystalline substances—minerals. Everyone has a certain familiarity with minerals for they are present in the rocks of the mountains, the sand of the sea beach, and the soil of the garden. Less familiar, but also composed of minerals, are meteorites and the lunar surface material. A knowledge of what minerals are, how they were formed, and where they occur is basic to an understanding of the materials largely responsible for our present technologic culture. For all inorganic articles of commerce, if not minerals themselves, are mineral in origin.

DEFINITION OF MINERAL

Although it is difficult to formulate a succinct definition for the word mineral, the following is generally accepted:
A mineral is a naturally occurring homogeneous solid with a definite (but generally not fixed) chemical composition and an ordered atomic arrangement. It is usually formed by inorganic processes.

A step-by-step analysis of this defintion will aid in its understanding. The qualification *naturally occurring* distinguishes between substances formed by natural processes and those made in the laboratory. Industrial and research laboratories routinely produce synthetic equivalents of many naturally occurring materials including valuable gemstones such as emeralds, rubies, and diamonds. Since the beginning of the twentieth century, mineralogic studies have relied heavily on the results from synthetic systems in which the products are given the names of their naturally occurring counterparts. Such practice is generally accepted although at variance with the strict interpretation of *naturally occurring.* In this book *mineral* means a naturally occurring substance and its name will be qualified by *synthetic* if purposely produced by laboratory techniques. One might now ask how to refer to $CaCO_3$ (calcite) which sometimes forms in concentric layers in city water mains. The material is precipitated from water by natural processes but in a man-made system. Most mineralogists would refer to it by its mineral name, calcite, since humanity's part in its formation was inadvertent.

The definition further states that a mineral is a *homogeneous solid*. This means that it consists of a single, solid substance that cannot be physically subdivided into simpler chemical compounds. The determination of homogeneity is difficult because it is related to the scale on which it is defined. For example, a specimen that appears homogeneous to the naked eye may prove to be inhomogeneous, made up of several materials, when viewed with a microscope at high magnification. The qualification *solid* excludes gases and liquids. Thus H_2O as ice in a glacier is a mineral, but water is not. Likewise liquid mercury, found in some mercury deposits, must be excluded by a strict interpretation of the definition. However, in a classification of natural materials such substances that otherwise are like minerals in chemistry and occurrence are called *mineraloids* and fall in the domain of the mineralogist.

The statement that a mineral has a *definite chemical composition* implies it can be expressed by a specific chemical formula. For example, the chemical composition of quartz is expressed as SiO_2. Because quartz contains no chemical elements other than silicon and oxygen, its formula is definite. Quartz is, therefore, often referred to as a pure substance. Most minerals, however, do not have such well-defined compositions. Dolomite, $CaMg(CO_3)_2$, is not always a pure Ca-Mg-carbonate. It may contain considerable amounts of Fe and Mn in place of Mg. Because these amounts vary, the composition of dolomite is said to range between certain limits and is, therefore, *not fixed*. Such a compositional range may be expressed by a formula with the same atomic (or more realistically, ionic) ratios as pure $CaMg(CO_3)_2$ in which $Ca:Mg:CO_3 = 1:1:2$. This leads to a more general expression for dolomite as: $Ca(Mg, Fe, Mn)(CO_3)_2$.

An *ordered atomic arrangement* indicates an internal structural framework of atoms (or ions) arranged in a regular geometric pattern. Since this is the criterion of a crystalline solid, minerals are crystalline. Solids, such as glass, that lack an ordered atomic arrangement are called *amorphous*. Several natural solids are amorphous. They, with the liquids water and mercury which also lack internal order, are classified as mineraloids.

According to the traditional definition, a mineral is *formed by inorganic processes*. We prefer to preface this statement with *usually* and thus include in the realm of mineralogy the few organically produced compounds that answer all the other requirements of a mineral. The outstanding example is the calcium carbonate of mollusk shells. The shell of the oyster and the pearl that may be within it are composed in large part of aragonite, identical to the inorganically formed mineral. Other examples are elemental sulfur formed by bacterial action and iron oxide precipitated by iron bacteria. But petroleum and coal, frequently referred to as mineral fuels, are excluded; for, although naturally formed, they have neither a definite chemical composition nor an ordered atomic arrangement. However, in places coal beds have been subjected to high temperatures which have driven off the volatile hydrocarbons and crystallized the remaining carbon. This residue is the mineral, graphite.

HISTORY OF MINERALOGY

Although it is impossible in a few paragraphs to trace systematically the development of mineralogy, some of the highlights of its development can be singled out. The emergence of mineralogy as a science is relatively recent but the practice of mineralogical arts is as old as human civilization. Natural pigments made of red hematite and black manganese oxide were used in cave paintings by early humans, and flint tools were prized possessions during the Stone Age. Tomb paintings in the Nile Valley executed nearly 5000 years ago show busy artificers weighing malachite and precious metals, smelting mineral ores, and making delicate gems of lapis lazuli and emerald. As the Stone Age gave way to the Bronze Age, other minerals were sought from which metals could be extracted.

FIG. 1.1. Prospecting with a forked stick (A) and trenching (B) in the fifteenth century (from: Agricola, *De Re Metallica*, translated into English, Dover Publications, New York, N.Y.).

We are indebted to the Greek philosopher, Theophrastus (372–287 B.C.) for the first written work on minerals and to Pliny, who 400 years later recorded the mineralogical thought of his time. During the following 1300 years, the few works that were published on minerals contained much lore and fable with little factual information. If one were to select a single event signalling the emergence of mineralogy as a science, it would be the publication in 1556 of *De Re Metallica* by the German physician, Georgius Agricola. This work gives a detailed account of the mining practices of the time and includes the first factual account of minerals. The book was translated into English from the Latin in 1912* by the former President of the United States, Herbert Hoover, and his wife, Lou Henry Hoover. In 1669 an important contribution was made to crystallography by Nicholas Steno through his study of quartz crystals. He noted that despite their differences in origin, size, or habit, the angles between corresponding faces were constant. More than a century passed before the next major contributions were made. In 1780 Carangeot invented a device (contact goniometer) for the measurement of interfacial crystal angles. In 1783 Romé de l'Lsle made angular measurements on crystals confirming Steno's work and formulated the law of the constancy of interfacial angle. The following year, 1784, René J. Haüy showed that crystals were built by stacking together tiny identical building blocks, which he called integral molecules. The concept of integral molecules survives almost in its original sense in the unit cells of modern crystallography. Later (1801) Haüy, through his study of hundreds of crystals,

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* Published in 1950 by Dover Publications, Inc., New York.

FIG. 1.2. Portrait of Niels Stensen (Latinized to Nicolaus Steno). Steno was born in Copenhagen, Denmark, in 1638 and died in 1686 (from: G. Scherz, *Steno, Geological Papers*, Odense Univ. Press, 1969).

developed the theory of rational indices for crystal faces.

In the early nineteenth century rapid advances were made in the field of mineralogy. In 1809 Wollaston invented the reflecting goniometer, which permitted highly accurate and precise measurements of the positions of crystal faces. Where the contact goniometer had provided the necessary data for studies on crystal symmetry, the reflecting goniometer would provide extensive, highly accurate measurements on naturally occurring and artificial crystals. These data made crystallography an exact science. Between 1779 and 1848 Berzelius, a Swedish chemist, and his students studied the chemistry of minerals and developed the principles of our present chemical classification of minerals.

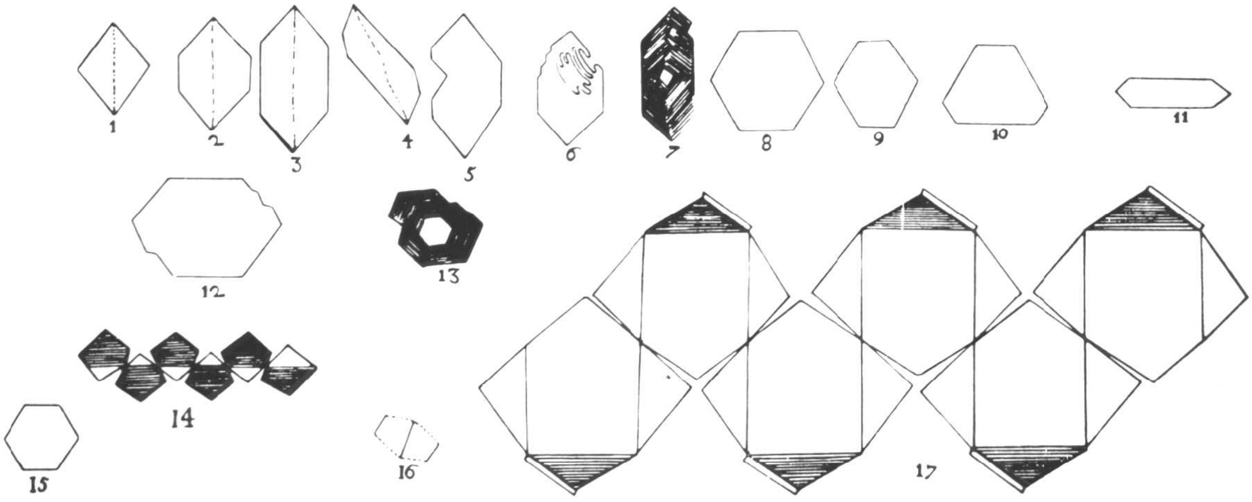

FIG. 1.3. Steno's drawings of various quartz and hematite crystals, illustrating the constancy of angles among crystals of different habits (from: J. J. Schafkranovski, *Die Kristallographischen Entdeckungen N. Stenens,* in *Steno as Geologist,* Odense Univ. Press, 1971).

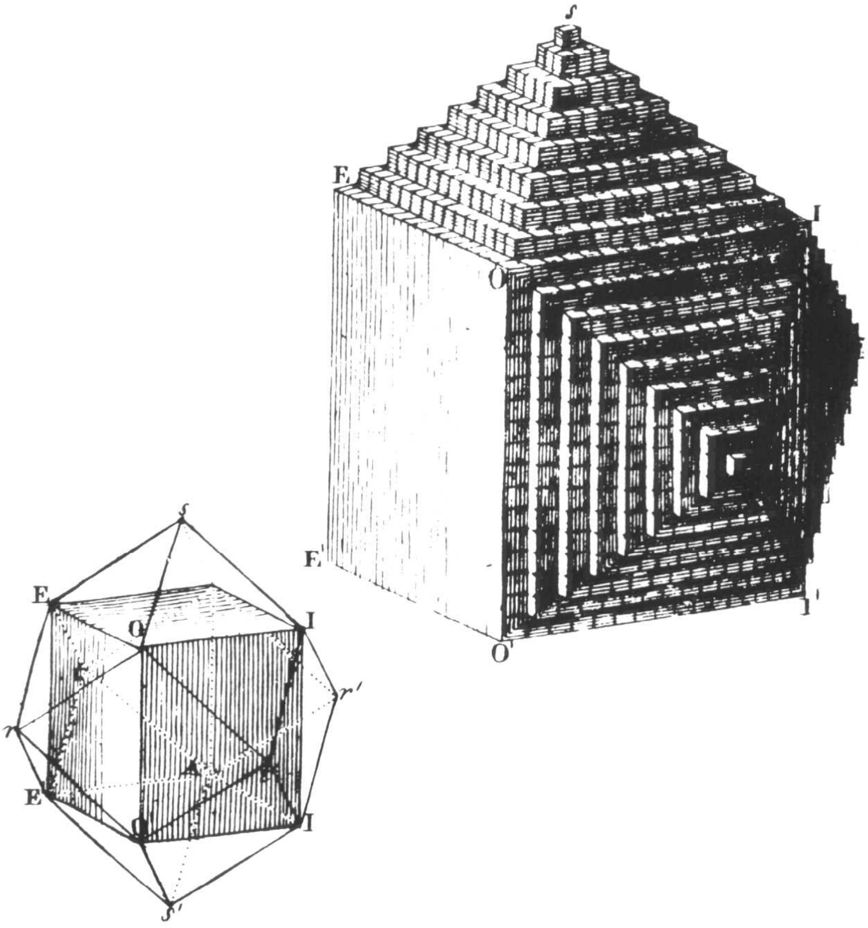

FIG. 1.4. Illustration of the concept developed by R. J. Haüy (1743–1826) of tiny identical building blocks underlying the external form of crystals. In this figure the development of a dodecahedron of garnet is shown (from: G. M. Marr, *Geschichte der Kristallkunde,* reprinted by Sändig, Walluf, West Germany, 1970).

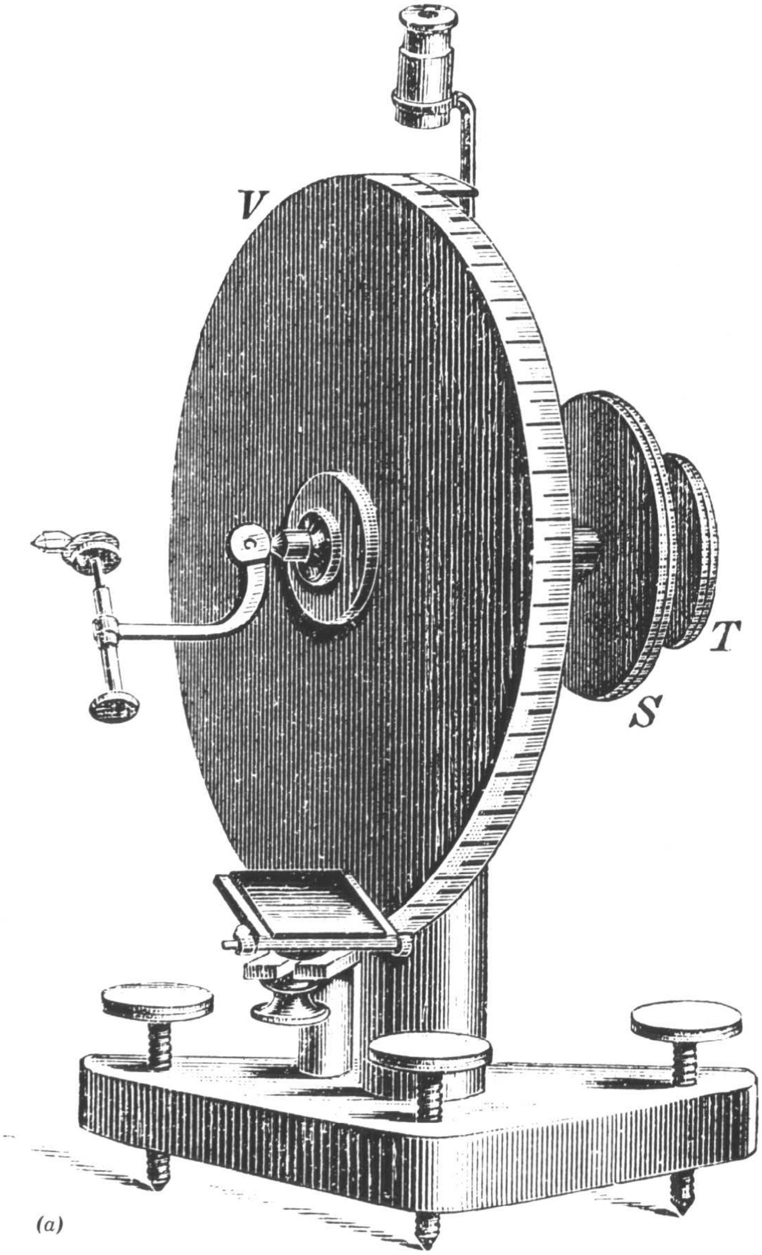

FIG. 1.5. (*a*) Earliest reflecting goniometer as invented by W. H. Wollaston in 1809 (from: G. Tschermak and F. Becke, *Lehrbuch der Mineralogie*, 1921, Hölder-Pichler-Tempsky, Vienna). (*b*) Two-circle reflecting goniometer as developed in the latter part of the nineteenth century (from: P. Groth, *Physikalische Krystallographie*, 1895, Leipzig). Compare with Fig. 2.40.

In 1815, the French naturalist Cordier, whose legacy to mineralogy is honored in the name of the mineral *cordierite,* turned his microscope on crushed mineral fragments immersed in water. He thereby initiated the "immersion method" which others, later in the century, developed into an important technique for the study of the optical properties of mineral fragments. The usefulness of the microscope in the study of minerals was greatly enhanced by the invention in 1828 by the Scotsman, William Nicol, of a polarizing device that permitted the systematic study of the behavior of light in crystalline substances. The polarizing microscope became, and still is, a powerful determinative tool in mineralogical studies. In the latter part of the nineteenth century Fedorov, Schoenflies, and Barlow,

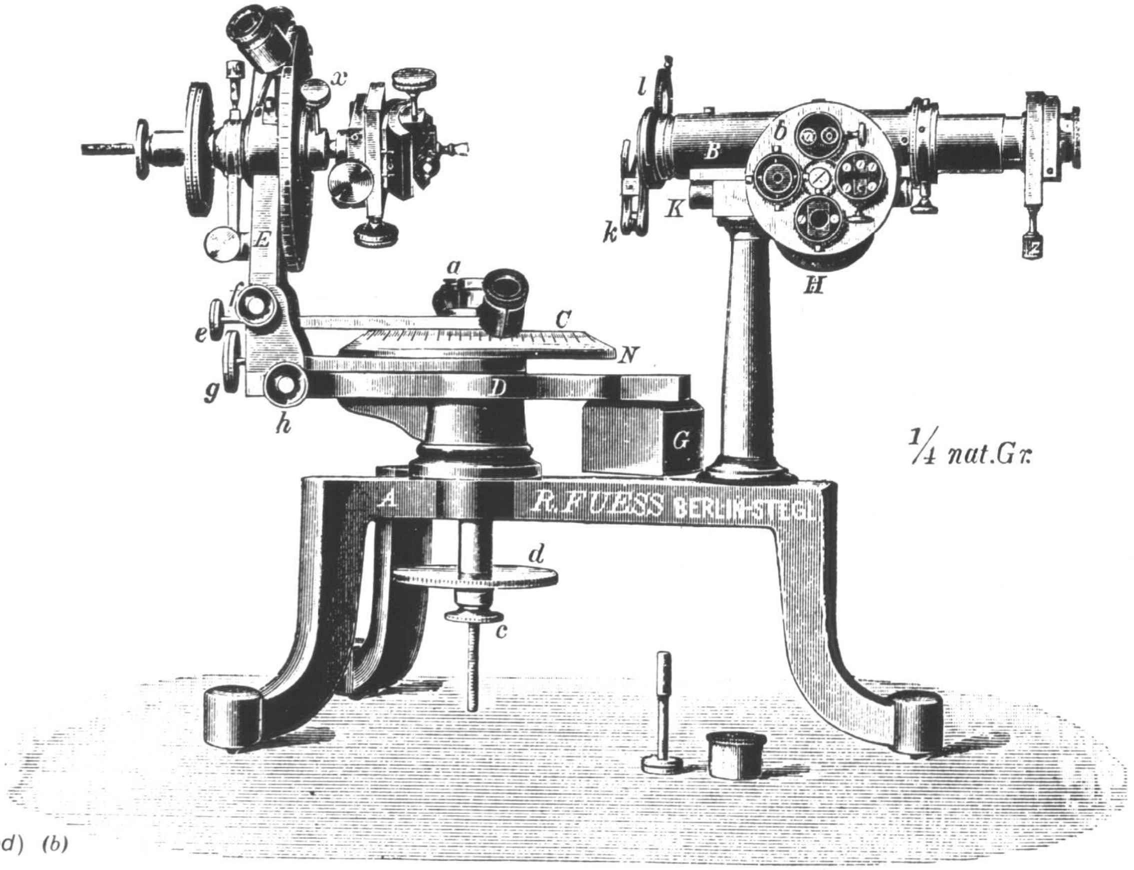

FIG. 1.5 (*Continued*) (*b*)

working independently, almost simultaneously developed theories for the internal symmetry and order within crystals which became the foundations for later work in X-ray crystallography.

The most far-reaching discovery of the twentieth century must be attributed to Max von Laue of the University of Munich. In 1912 in an experiment performed by Friedrich and Knipping at the suggestion of von Laue, it was demonstrated that crystals could diffract X-rays. Thus was proved for the first time the regular and ordered arrangement of atoms in crystalline material. Almost immediately X-ray diffraction became a powerful method for the study of minerals and all other crystalline substances, and in 1914 the earliest crystal structure determinations were published by W. H. Bragg and W. L. Bragg in England. Modern X-ray diffraction equipment with on-line, dedicated computers has made possible the relatively rapid determination of highly complex crystal structures. The advent of the electron microprobe in the early 1960s, for the study of the chemistry of minerals on a microscale has provided yet another powerful tool that is now routinely used for the study of the chemistry of minerals, synthetic compounds, and glasses.

The field of mineralogy now encompasses a wide area of study which includes X-ray crystallography, experimental mineralogy, petrology (the study of rocks), and aspects of metallurgy, crystal physics, and ceramics.

ECONOMIC IMPORTANCE OF MINERALS

Since before historic time, minerals have played a major role in humanity's way of life and standard of living. With each successive century they have be-

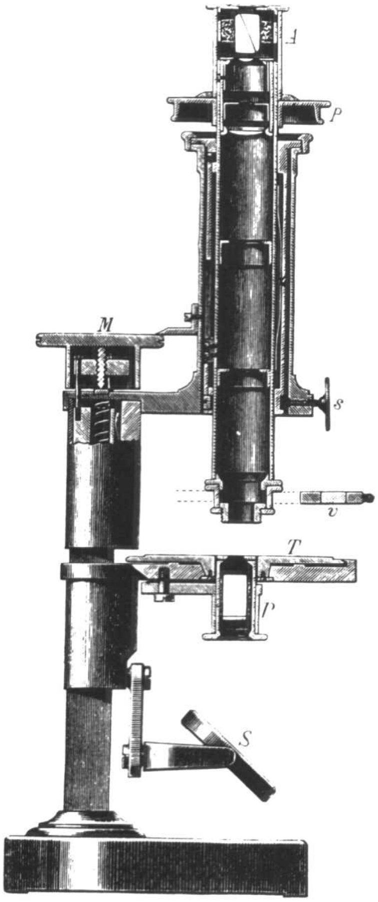

FIG. 1.6. Polarizing microscope as available in the mid-nineteenth century (from: G. Tschermak and F. Becke, *Lehrbuch der Mineralogie*, 1921, Hölder-Pichler-Tempsky, Vienna). Compare with Fig. 6.10.

come increasingly important, and today we depend on them in countless ways—from the construction of skyscrapers to the manufacture of televisions. Modern civilization depends on and necessitates the prodigious use of minerals. A few minerals such as talc, asbestos, and sulfur are used essentially as they come from the ground, but most are first processed to obtain a useable material. Some of the more familiar of these products are: bricks, glass, cement, plaster, and a score of metals ranging from iron to gold. Metallic ores and industrial minerals are mined on every continent wherever specific minerals are sufficiently concentrated to be economically extracted.

The location of mineable metal and industrial mineral deposits, and the study of the origin, size, and ore grade of these deposits is the domain of economic geologists. But a knowledge of the chemistry, occurrence, and physical properties of minerals is basic to pursuits in economic geology.

NAMING OF MINERALS

Minerals are most commonly classified on the basis of the presence of a major chemical component (an anion or anionic complex) into oxides, sulfides, silicates, carbonates, phosphates, and so forth. This is especially convenient because most minerals contain only one major anion. However, the naming of minerals is not based on such a logical chemical scheme.

The careful description and identification of minerals often requires highly specialized techniques such as chemical analysis and measurement of physical properties, among which are the specific gravity, optical properties, and X-ray parameters which relate to the atomic structure of minerals. However, the names of minerals are not arrived at in an analogous scientific manner. Minerals may be given names on the basis of some physical property or chemical aspect, or they may be named after a locality, a public figure, a mineralogist, or almost any other subject considered appropriate. Some examples of mineral names and their derivations are as follows:

Albite ($NaAlSi_3O_8$) from the Latin, *albus* (white), in allusion to its color.

Rhodonite ($MnSiO_3$) from the Greek, *rhodon* (a rose), in allusion to its characteristically pink color.

Chromite ($FeCr_2O_4$) because of the presence of a large amount of chromium in the mineral.

Magnetite (Fe_3O_4) because of its magnetic properties.

Franklinite ($ZnFe_2O_4$) after a locality, Franklin, New Jersey, where it occurs as the dominant zinc mineral.

Sillimanite (Al_2SiO_5) after Professor Benjamin Silliman of Yale University (1779–1864).

An international committee, the Commission on New Minerals and New Mineral Names of the

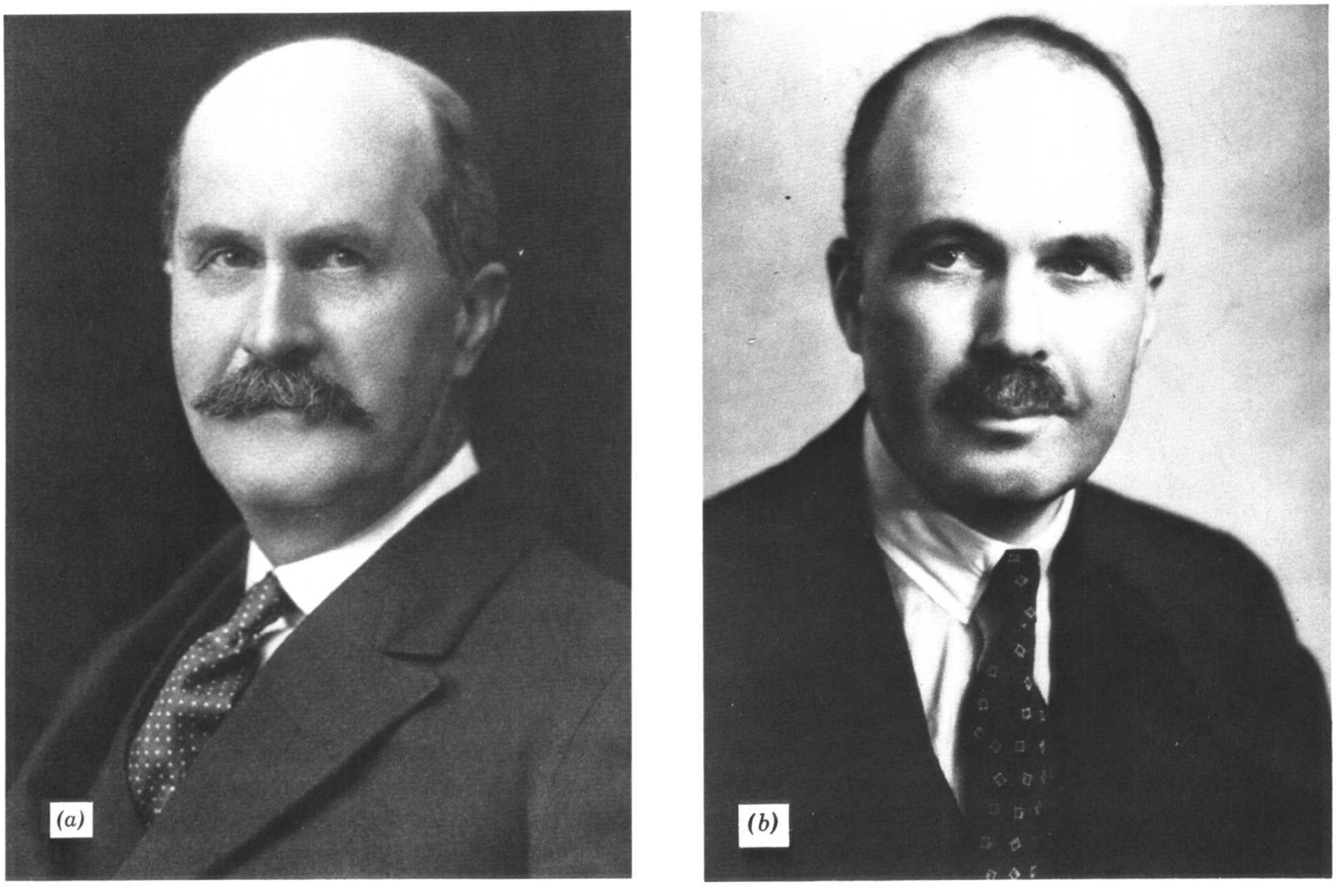

FIG. 1.7 (*a*) Portrait of Sir William Henry Bragg (1862–1942) and (*b*) of his son Sir William Lawrence Bragg (1890–1971). Father and son received the Nobel Prize for Physics in 1915. Both men are eminently known for their researches in the field of crystal structure by X-ray methods (*a* from Godfrey Argent, London, photograph by Walter Stoneman; *b* from Times Newspapers, Ltd., London).

International Mineralogical Association, now reviews all new mineral descriptions and judges the appropriateness of new mineral names as well as the scientific characterization of newly discovered mineral species.

REFERENCES AND LITERATURE OF MINERALOGY

The first comprehensive book on mineralogy in English, *A System of Mineralogy,* was written by James D. Dana in 1837. Since then, through subsequent revisions, it has remained a standard reference work. The last complete edition (the sixth) was published in 1892 with supplements in 1899, 1909, and 1915. Parts of a seventh edition known as *Dana's System of Mineralogy,* have appeared as three separate volumes in 1944, 1951, and 1962. The first two volumes treat the nonsilicate minerals and volume three deals with silica (quartz and its polymorphs). Additional volumes on silicates are in preparation. A more recent reference is the five-volume work, *Rock-Forming Minerals,* by W. A. Deer, R. A. Howie, and J. Zussman. The treatment of the physical properties of all minerals in *Dana's System* is exhaustive. The coverage in *Rock-Forming Minerals,* however, is more topical and expansive in the areas of chemistry, structure, and