

# Mineralogy: A Historical Review

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Mineralogy is the study of the naturally occurring elements and compounds that comprise the solid portions of the universe. Mineralogy has developed simultaneously in several different fields because of the broad significance and varied applications of minerals. As the principal source of inorganic chemicals, minerals provide the essential raw materials for technological development and economic productivity. As crystals of great diversity and perfection of form, minerals yield insights into the nature of atomic structure and bonding. As complex products of earth processes at various temperatures and pressures, minerals offer a key to understanding the origin and evolution of the earth and planets. The beauty, utility, and scientific significance of minerals have been analyzed in more than two thousand years of mineralogical writings.

Four questions have provided a focus for much of the research and speculation about minerals:

1. What are the origins of minerals?
2. What are the characteristic chemical, physical, and structural properties of minerals?
3. How should minerals be classified?
4. What are the economic applications of minerals?

The objective of this brief history of mineralogy is to review changing concepts of the origins, properties, and classification of minerals. Emphasis is placed on developments of the eighteenth and nineteenth centuries, during which time the interwoven advances of chemistry, physics, crystallography, and high-temperature, high-pressure studies transformed mineralogy from a qualitative to a quantitative science. The development of applied mineralogy, though an essential impetus to the scientific study of minerals, will be mentioned only in passing.

## THE ORIGIN OF MINERALS

Perhaps the most fundamental question asked about minerals concerns their origin. In ancient and medieval times minerals were grouped with a variety of inanimate natural objects, including what are now recognized as fossils, rocks, and soils. The great majority of these objects were found in an inert state and their origins were thus difficult to deduce. However, a few types of "fossils," such as cave formations, salt from evaporating sea water, and the urinary concretions of men and animals, were observed to "grow" and thus gave clues to the origins of other types of minerals. All of these natural products solidified in the presence of water, and it was assumed by many that fluids play an important role in the formation of these and other "fossils." Most pre-eighteenth-century theories of mineral generation incorporated the concept of "lapidifying juices" or fluids, which cause solidification under the influence of heat, cold, or other stimulus. The evolution of these early theories and speculations is detailed by Adams (1954).

A more quantitative understanding of the origin of minerals resulted from studies on glass and ceramics (Yoder, 1980). In an effort to duplicate the unknown composition of delicate Chinese porcelain, the distinguished French scientist and mathematician René-Antoine Ferchault de Réaumur (1683-1757) conducted melting experiments on a variety of minerals and rocks.

His research on glass devitrification clearly demonstrated the growth of mineral crystals, and thus established one mode of mineral formation. Similar experiments by fellow countryman Jean D'Arcet (1725-1801), who performed many experiments on the effects of heating minerals, demonstrated that mixtures of minerals have lower melting temperatures than the pure phases.

Most minerals form at combined high temperature and high pressure. The formidable experimental challenge of reproducing such an environment in the laboratory was first met by Sir James Hall (1761-1832), a Scottish geologist, who demonstrated that pressure prevents the thermal decomposition of calcite. Hall's discovery was crucial in James Hutton's (1726-1797) defense of the plutonic theory of basalt formation; were it not for the high-pressure stability of calcite, limestone that was observed to be interbedded with basalt would have decomposed. Hutton cited Hall's experimental data to counter successfully this objection of the Neptunists.

Hall's experimental design served as the basis for subsequent investigations of mineral synthesis which occupied the efforts of many workers in the nineteenth century. By the 1870s, most major groups of rock-forming minerals had been synthesized. This progress in the understanding of mineral origins was summarized in two important monographs: *Études Synthétiques de Géologie Expérimentale* by Gabriel-Auguste Daubrée (1814-1896), and *Synthese des Minéraux et des Roches* by Ferdinand André Fouqué (1828-1904) and Auguste Michel-Lévy (1844-1911). These studies confirmed the igneous origin of many minerals, and helped explain relationships between minerals and their host rocks. American petrologist Joseph Paxton Iddings (1857-1920), for example, relied on such experiments in his explanation of the origin of phenocrysts in volcanic lavas.

By the third quarter of the nineteenth century the emphasis of experimental mineralogy had gradually shifted from synthesis of individual phases to studies of mineral assemblages. Genetic relationships between coexisting minerals were demonstrated in rock thin sections by petrographers, notably Ferdinand Zirkel (1838-1912), who examined thousands of sections in the preparation of his *Die Mikroskopische Beschaffenheit der Mineralien und Gesteine* and as microscopical petrographer to the United States Geological Exploration of the 40th Parallel (1867-1877; commonly known as the King Survey). Thermodynamic generalizations relating to coexisting phases, including the "phase rule," were elucidated by Josiah Willard Gibbs (1839-1903), Professor of Mathematical Physics at Yale University. Gibbs provided a basis for future mineralogical studies in heterogeneous equilibrium. Thin-section techniques and thermodynamic theory were complemented by a variety of high-temperature, high-pressure synthesis devices, including solid-media "squeezers" capable of pressures exceeding 50,000 atmospheres and 1750 degrees C (Yoder, 1980).

Microscopical petrography, the theory of phase equilibria, and laboratory experiments were combined by twentieth-century petrologists to provide a detailed quantitative model of rock- and mineral-forming processes in the crust and upper mantle. Norman Levi Bowen (1887-1956), for example, achieved such a synthesis in his classic work, *The Evolution of the Igneous Rocks*, which was first published in 1928. This research philosophy has been continued by recent high-temperature, high-pressure

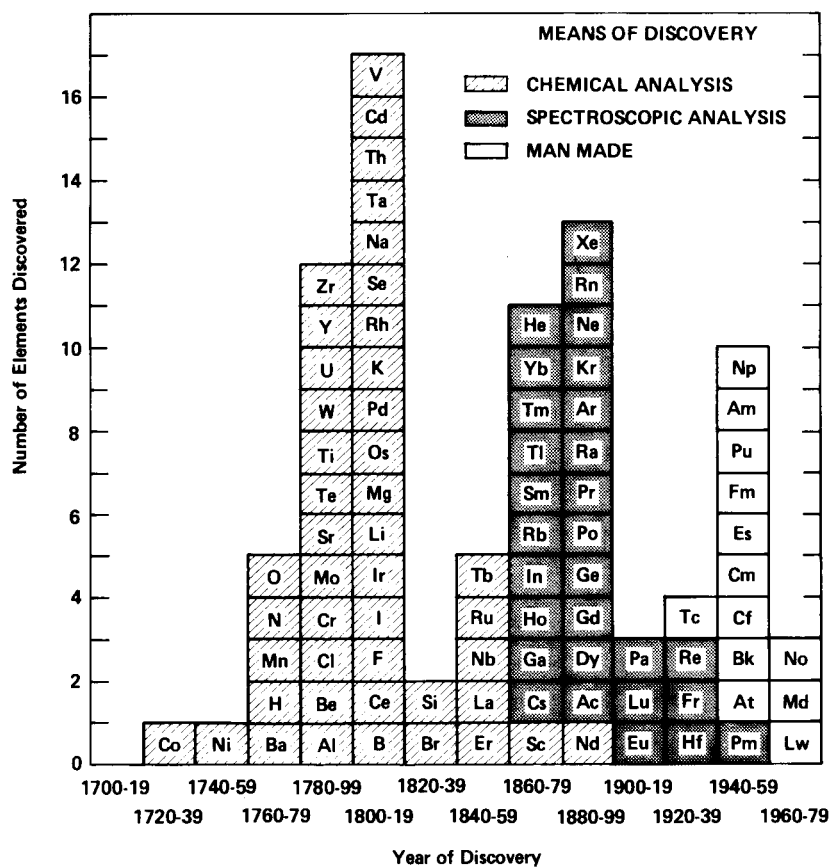


Figure 1. Chronological record of the discovery of the chemical elements. Prior to 1860 new elements were discovered by chemical analysis. Between about 1870 and 1930 more than two dozen new elements were identified by spectroscopic analysis.

studies with laser-heated, diamond-anvil pressure cells, which hold the promise of duplicating conditions of mineral formation in the deepest interior of the earth.

### PROPERTIES OF MINERALS

Interest in mineralogy, whether it be for economic, aesthetic, or scientific reasons, stems from the distinctive chemical, physical, and crystallographic properties of minerals. Progress in the description of these properties, especially in regard to the gradual transition from qualitative to quantitative parameters, closely parallels developments in chemistry and physics.

#### Chemistry of Minerals

Minerals, the source of most inorganic chemicals and all metals, are essential to chemical science and industry. The history of mineral chemistry is thus entwined with the development of qualitative and quantitative chemical analysis, the formulation of atomic theory, and the discovery of periodic element properties. The Aristotelian concept of four elements did little to elucidate the distinctive chemical characteristics of different minerals, but ancient miners and smelters were, nevertheless, successful in separating copper, iron, lead, mercury, tin, and other metals from their ores. By the sixteenth century, Georgius Agricola (1494-1555) was able to describe procedures for the manufacture of sulfur, alum, copperas (iron sulfate), soluble salts, and several other chemicals from minerals. There was little correlation, however, between these empirical processes and chemical theory.

Robert Boyle's (1627-1691) rejection of the doctrine of four elements was an essential step in the chemical

description of minerals. In *The Sceptical Chymist* he presented perhaps the earliest modern definition of an element:

I now mean by elements . . . certain Primitive and Simple, or perfectly unmingled bodies; which not being made of any other bodies, or of one another, are the Ingredients of which all those call'd perfectly mixt bodies are immediately compounded, and into which they are ultimately resolved (Boyle, 1661, p. 354).

Given this definition, several elements were quickly recognized. Ancient metals, including gold, silver, copper, iron, tin, lead, zinc, and mercury, as well as antimony, arsenic, bismuth, and platinum, were all identified as elements. Carbon, sulfur, and phosphorus, which were known in their native state, and calcium, in its oxide form of lime, were also added to the list.

The science and art of qualitative and quantitative chemical analysis developed in the eighteenth and nineteenth centuries largely as a result of the recognition of chemical elements. Analytical techniques served both to define chemicals in terms of known elements and to lead to the discovery of new ones. Minerals were the most intensively studied compounds in the search for new elements; between 1735 and 1860 forty-three new elements were discovered, of which thirty-eight were isolated by mineral analysis (Figure 1). Prominent among the analytical chemists of this period were the Frenchman Antoine-Laurent Lavoisier (1743-1794), who proposed the modern definition of a chemical element, and the German Martin Heinrich Klaproth (1743-1817), discoverer of uranium, zirconium, and cerium. Klaproth,

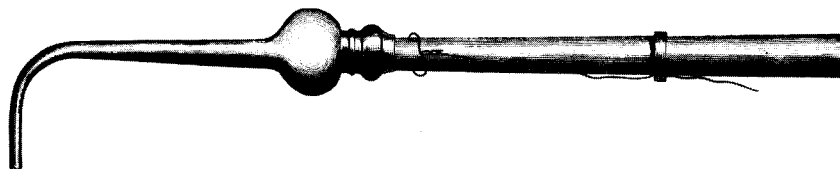


Figure 2. The blowpipe of Axel Cronstedt (from Kobell, 1864, p. 119).

who was recognized as "the most eminent analytical chemist of his time" (Brush, 1883, p. 7), analyzed hundreds of minerals during his distinguished career. Another noted German chemist, Justus von Liebig (1803-1873), successfully isolated several elements and was the first to chemically analyze many rock-forming silicates. But the most remarkable group of mineral chemists worked in Sweden, where between 1735 and 1843, no fewer than 19 elements, including cobalt, nickel, fluorine, oxygen, manganese, and tungsten, were identified for the first time.

Of the many analytical techniques devised by this group of Swedish chemists, the blowpipe had perhaps the greatest influence on mineralogy. The blowpipe in its simplest form (Figure 2) was a tapered tube by which air could be directed at a fine, hot flame, which was thus focused on a sample. The response of a mineral to this flame, including fusibility, flame coloration, and nature of the fusion products, provided a rapid and distinctive chemical test for the identification of many minerals. Blowpipe analysis was well known to early eighteenth-century metal workers, and was adapted to the qualitative study of minerals by several Swedish scientists, notably Axel Fredrik Cronstedt (1722-1765), who devised a mineral classification based in part on blowpipe response. The use of the blowpipe was elevated from an art to a science by Cronstedt's pupil, Johan Gottlieb Gahn (1745-1818), who excelled in the field identification of mineral species. Although Gahn did not detail these methods in his own writings, his techniques were championed in the publications of Jöns Jacob Berzelius (1779-1848), the most famous of the Swedish mineral chemists. In addition to his discovery of cerium (independently and nearly simultaneously to that of Klaproth), selenium, and thorium, Berzelius made numerous other contributions to chemistry and mineralogy. His treatise on the use of the blowpipe was translated into German, French, English, Russian, and Italian, and had a profound influence on descriptive mineralogy for more than a century.

Chemical analysis of minerals and other inorganic compounds gradually led to two important empirical "laws." The "law of definite proportions," according to which elements combine in exact ratios when forming compounds, was stated effectively by Joseph Louis Proust (1754-1826) in several papers. Proust recognized the important distinction between chemical compounds, with their precise ratios of elements, and chemical mixtures. The "law of equivalents" and the related concepts of stoichiometry and equivalent weights were developed by Jeremias Benjamin Richter (1762-1807). Richter deduced that if a compound AB reacts with compound CD to form AC, then B and D will also combine exactly. By measuring the difference in weights of AB, AC, CD, and BD, the relative weights of the different elements were then derived. These concepts were essential to the development of chemical formulae of minerals and other substances.

The atomic theory of English chemist John Dalton (1766-1844) provided the necessary theoretical framework for the empirical laws of Proust and Richter. The concept that particulate atoms combine in certain ratios

explains the laws of definite proportions and equivalents and provides a basis for chemical nomenclature. Dalton's cumbersome chemical symbols were soon replaced by the simplified Berzelius notation, which is the basis for modern chemical formulae.

Quantitative understanding of the combination of elements to form compounds led to more precise quantitative chemical analysis. These analyses, in turn, led to the recognition by Eilhard Mitscherlich (1794-1863) of the phenomena of isomorphism and polymorphism, which are crucial to the classification of minerals. Mitscherlich, observing the crystal form and properties of a number of sulfates, phosphates, and arsenates, discovered that certain element substitutions result in the formation of compounds of nearly identical form and properties. He concluded that these elements can substitute for each other without altering the atomic arrangement. The concept of isomorphism was extended by Gustav Tschermak (1836-1927), who developed the principles of mineral solid solution and coupled-element substitution. His observations resolved one of the most puzzling aspects of mineral classification in that they revealed how certain closely related groups of minerals, such as micas, pyroxenes, or feldspars can have a wide range of chemical compositions.

A second important discovery by Mitscherlich was that some compounds such as sulfur exist in more than one crystal form. Mineralogists, using this concept of polymorphism, were able to explain the differing character of chemically identical mineral sets, such as pyrite-marcasite, calcite-aragonite, and kyanite-andalusite-sillimanite.

The recognition of isomorphism was an important step in the identification of similarities in the chemical properties of certain elements. Subsequent work by Johann Wolfgang Döbereiner (1780-1849) and others established systematic relationships between the weights of substituting elements, such as fluorine, chlorine, and bromine or magnesium, calcium, and strontium, and led to the concept of "triads" of related elements. The ultimate statement of these systematic element properties was the periodic law, as set forth in the famous table of Dmitry Ivanovich Mendeleev (1834-1907). His periodic table of the elements (Figure 3) provides a theoretical framework for understanding the relationships between mineral composition and chemical properties and placed the chemical classification of minerals on a firm quantitative basis.

An important consequence of atomic periodicity was the prediction of the existence of many "missing" elements. Robert Wilhelm Bunsen (1811-1899) and Gustav Robert Kirchhoff (1824-1887) were instrumental in "filling out" the periodic table by their development of spectroscopic analysis in the late 1850s. The application of this technique to the study of minerals led to the identification of more than two-dozen new elements between 1860 and 1920 (Figure 1). Of special significance was Wilhelm Conrad Roentgen's (1845-1923) discovery in 1895 of x-rays, which led to the discovery of radioactivity by Henri Becquerel (1852-1908), and Marie Curie's



distinctive behavior of isotropic, uniaxial, and biaxial materials. These observations, however, were not directly applied to the routine identification and classification of minerals.

The polarizing microscope provided a means for quantifying optical properties of minerals and thus represented a method for the rapid identification of the tiny constituents of rocks. The Scottish natural philosopher William Nicol (c.1768-1851) is credited with the attachment of crossed polarizers to a microscope and, with his co-workers, the recognition of a number of diagnostic optical characteristics of minerals. The properties of mean refractive index and color could be measured without a polarizer, and pleochroism and axial refractive indices could be determined with a single polarizer. It was with the crossed polarizers of Nicol, however, that such critical and diagnostic optical properties as birefringence, extinction angle, interference colors, optic sign, and optical-axis angle could be determined with precision.

The petrographic microscope was first employed in the study of small grains of minerals. The microscope did not achieve a major impact on mineralogy, however, until the use of thin-sections was developed. Although rock thin sections may have been prepared as early as the first decades of the nineteenth century, it was not until 1831 that Nicol presented the initial brief description of the process as applied to the investigation of microstructures in fossil wood. It was another two decades before Henry Clifton Sorby (1826-1908) published an account of the technique as applied to rocks. The microscope revealed a number of mineral properties that were not otherwise evident, including compositional zoning, exsolution, fluid inclusions, and complex textural relations. These inter- and intra-granular features soon became important factors in mineral identification. Microscopical petrography also provided new insights to the origin of rocks and led Harry Rosenbusch (1836-1914), a leading German petrographer of the nineteenth century, to devise his genetic classification of igneous rocks.

Optical techniques were further refined in the first half of the twentieth century, and the identification of both nonopaque minerals and opaque minerals (by reflected light microscopy) became routine aspects of mineralogy. The decades following World War II were characterized by the introduction of a variety of sophisticated spectroscopic methods for the analysis of electronic, elastic, magnetic, and vibrational mineral properties. Optical absorption, infrared, Mössbauer, Raman, Brillouin, and nuclear magnetic resonance are but a few of the spectroscopic techniques that revolutionized mineral physics in the second half of the twentieth century.

### Crystallography and Mineral Structure

Unlike members of the plant and animal kingdoms, most minerals have no obvious internal structures. Yet the perfect regularity of mineral crystals and cleavage fragments led many natural philosophers to the conclusion that minerals have characteristic internal structures (see Burke, 1966, for a detailed history of these developments).

Two distinct theories on the internal structure of crystals were supported in the second half of the seventeenth century. The first of these theories, known as the "corpuscular hypothesis," was elucidated by Robert Hooke (1635-1702), whose ideas were presented in 1665 in *Micrographia*. Hooke believed that atoms combine to form molecules or "corpuscles," which in turn combine as crystals. Hooke supported the view, proposed half a century earlier by Johannes Kepler (1571-1630), that molecules are spherical. Arrangements of spherical corpuscles, for example, gave rise to the regular 90 degree angles of salt and the 120 degree angles of quartz.

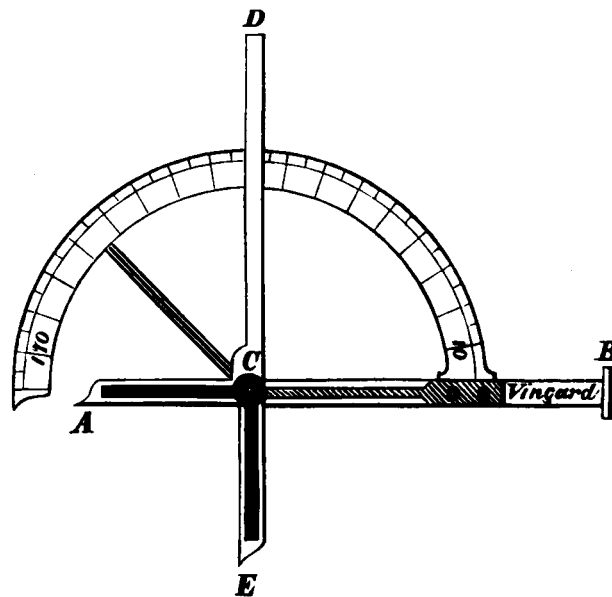


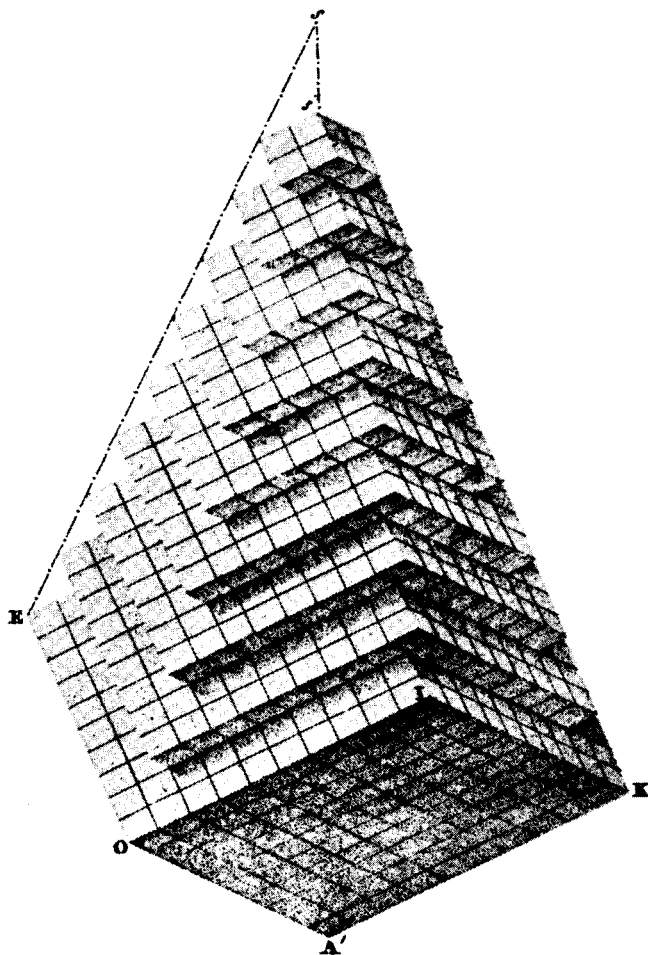
Figure 4. The contact goniometer of Arnould Carangeot (from Kobell, 1864, p. 103).

An alternative theory of mineral structure was proposed in *De Solido intra Solidum Naturaliter Conteno Dissertationis Prodromus*, written by Niels Stensen, also known as Nicolaus Steno (1638-1686), and published in 1669. Steno recognized that the angles between specific pairs of crystal faces, in both quartz and hematite, are the same from specimen to specimen. These angles, furthermore, are not constrained to be 90 degrees or 120 degrees. The constancy of interfacial angles, one of the fundamental observations of crystallographic mineralogy, is inconsistent with Hooke's model of regularly stacked spheres. Rather than speculate on unseen molecules, Steno proposed that matter is infinitely divisible and that external form is a consequence of internal forces. Steno's "polar hypothesis," therefore, may be viewed as the more empirical approach to the science of crystals (Schneer, 1983).

The hypotheses of Hooke and Steno served as frameworks for many subsequent workers. Christiaan Huygens (1629-1695) elaborated on the corpuscular model by proposing an ellipsoidal rather than a spherical shape for the calcite molecule, in order to explain that mineral's distinctive cleavage and crystal forms. Several eighteenth-century naturalists, including Domenico Guglielmini (1655-1710) and Maurice Cappeller (1685-1769), abandoned the spherical and ellipsoidal molecule in favor of polygonal shapes. The view that all crystals could be derived from a few simple polyhedra — the cube, the rhombus, or octahedron, for example — persisted well into the nineteenth century.

The empirical approach, reflected in Steno's observations, was adopted by a number of eighteenth-century mineralogists who observed the characteristic forms, and in some cases the angles, of mineral species. The measurement of interfacial angles was greatly simplified by Arnould Carangeot's (1742-1806) invention of the contact goniometer (Figure 4). More precise measurements, even on tiny crystals, were made possible by William Hyde Wollaston's (1766-1828) reflecting goniometer.

Several mineralogists attempted to relate complex crystal forms to the shape of the simple polyhedral molecule. Swedish naturalist Torbern Olof Bergman (1735-1784), for example, demonstrated the derivation of complex calcite crystal forms from the simple cleavage



**Figure 5.** The scalenohedral ("dog-tooth") form of calcite as derived from Haüy's "molecules intégrent" (from Haüy, 1801, v. 5, Plate III, Figure 17).

rhombus (Figure 5). These studies, combined with Jean-Baptiste Louis Romé de l'Isle's (1736-1790) explicit statement of the constancy of interfacial angles, paved the way for a quantitative understanding of crystal form.

René-Just Haüy (1743-1822) was the first scientist to demonstrate clearly that external crystal form is a manifestation of internal order. Haüy's interest in the structure of crystals is said to have stemmed from an unfortunate incident at a mineral museum where the eager student dropped and shattered a group of calcite crystals. He was surprised to discover that hexagonal prismatic crystals of calcite yield rhombohedral cleavage fragments when they are broken. Haüy subsequently smashed several calcite crystals of differing shape from his own collection and found that all of them broke into the same rhombohedral shaped cleavage fragments. Haüy's first publications are similar to those of Bergman, both in concept and content; each author demonstrated the development of external form by the stacking of simple polyhedra. Haüy's major original contribution came as a result of detailed study of the systematics of interfacial angles. It was from these data that he was able to derive the law of rational indices and thus establish a mathematical basis for the description of crystal form.

The analysis of crystal forms and the measurement of interfacial angles remained an integral part of descriptive mineralogy for more than a century and a half (see Kraus, 1941, and Frondel, 1983). The one-circle reflecting goniometer of Wollaston was replaced by the more versatile 2-circle model in the 1890s. Crystal data were

recorded on thousands of compounds, and were prominently featured, for example, in *Zeitschrift für Kristallographie*, founded and edited by Paul Heinrich von Groth (1843-1927), who was instrumental in establishing relationships between crystal form and structure. The observation of interfacial angles was undertaken much as it had been in the first decades of the nineteenth century, but concepts of the integrant molecule and structure underwent great changes. The optical discoveries of Brewster and Biot, in particular the recognition of the distinct optical behavior of isotropic, uniaxial, and biaxial crystals, led to studies of crystal symmetry. Mathematical analysis of the symmetry of periodic arrangements led Christian Samuel Weiss (1780-1856) to propose the six crystal systems. Soon thereafter Johann Friedrich Christian Hessel (1796-1872) and Auguste Bravais (1811-1863) independently derived the 32 point groups. Bravais also demonstrated the fourteen distinct ways of filling space by simple translations, now known as the Bravais lattices. These systematics of crystal symmetry provided, for the first time, a sound basis for a structural classification of minerals.

Details of atomic arrangement were unknown, but it was possible to enumerate all of the ways in which the 32 point groups could be combined with the 14 Bravais lattices to generate periodic arrangements of atoms. Derivation of the 230 space groups was accomplished independently and almost simultaneously by the Russian crystallographer Evgraf Stepanovich Fyodorov (1853-1919), the German mathematician Arthur Moritz Schoenflies (1853-1928), and the remarkable English amateur scientist William Barlow (1845-1934). In spite of the elegant mathematical framework provided by the enumeration of space groups, not one detailed crystal structure had been determined by 1900.

The great breakthrough in crystallography came as a result of Max von Laue's (1879-1960) brilliant realization that the newly discovered x-rays might have a wavelength similar to that of atomic spacings and thus crystals might diffract x-rays. Laue's speculation was a spectacular success, and within a few years the father-and-son team of William Henry Bragg (1862-1942) and William Lawrence Bragg (1890-1971) had documented the atomic arrangements in calcite, pyrite, halite, and fluorite. In 1937, just a quarter century after the first x-ray diffraction experiments, the younger Bragg wrote his classic *Atomic Structures of Minerals*, which represented a culmination of more than three centuries of crystallographic effort. By the second half of the twentieth century, single-crystal x-ray diffraction had been used to determine the structures of most rock-forming minerals, and powder x-ray diffraction was employed in the routine identification of unknown samples.

Transmission electron microscopy, developed in the 1940s, provided the mineralogist and crystallographer with a new technique for examining mineral structures. The great resolving power of the electron microscope, almost to the atomic level, has revealed a wealth of new information on nonperiodic aspects of mineral structure, including dislocations, stacking faults, exsolution, anti-phase domains, and other features not resolvable by x-ray diffraction (Figure 6).

### THE CLASSIFICATION OF MINERALS

The desire to classify — to place objects or people into related groups — is an instinctive human characteristic. Classification systems may be based on physical characteristics such as color, on size or shape, on response to external influences, on locality or mode of occurrence, or on some combination of these and other criteria. A system of classification, which may be in large measure a reflection of current theory, "must remain just as primitive or as imperfect as the theories upon which the classification is founded" (Burke, 1969, p.



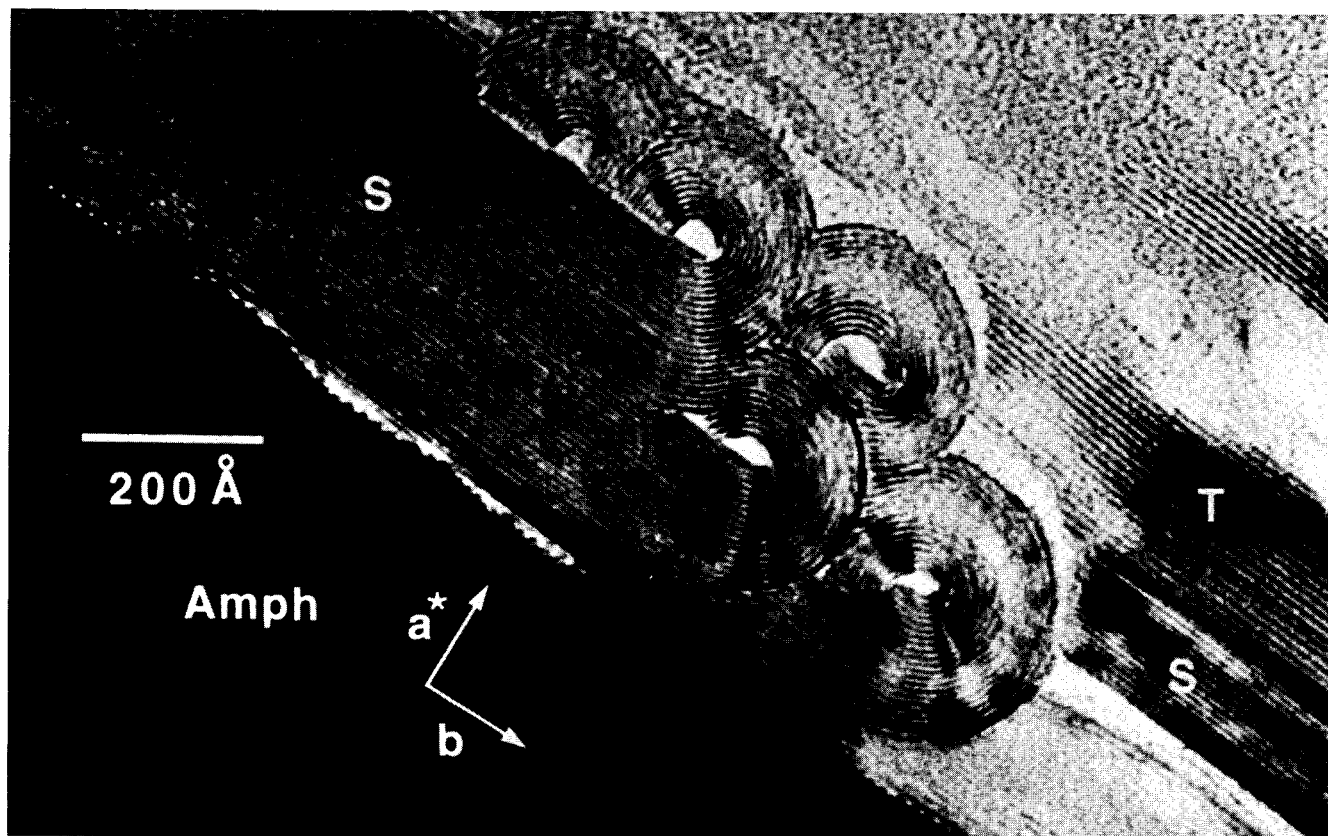


Figure 6. High-resolution transmission electron micrograph of serpentine (from Veblen, 1979, p. 1399). The regions designated "S," "T," and "AMPH" are the minerals serpentine, talc, and amphibole, respectively. Electron microscopy has provided insights to the nonperiodic structures of minerals.

77). The evolution of mineralogical classification, therefore, closely parallels developments in chemistry, physics, and crystallography, upon which most systems of mineralogy eventually were based.

Minerals, with their great diversity of chemical composition, physical properties, crystal structure, and modes of occurrence, have challenged the taxonomic abilities of philosophers and naturalists for more than 2,000 years. The key to the success of any classification scheme is the nature of the unit of description that defines a species; that is, what makes one mineral different from another and worthy of separate recognition and a separate name. An important aspect of mineralogical classification, therefore, has been the establishment of reference collections of rocks and minerals. Large collections gathered by individuals and institutions, particularly those assembled in the eighteenth and nineteenth centuries, were instrumental in these developments.

Table 1 is a list of just a few of the hundreds of mineralogical classifications that have been devised during the past two millennia. The earliest known arrangement of minerals, that of the peripatetic school of Aristotle as set down in the writings of Theophrastus (c.371-287 B.C.), employed a tripartite mineral classification scheme based on response to fire and water. Such a scheme reflected the Athenian's belief that all matter is composed of a combination of four elements: earth, air, fire, and water. Mineral properties such as solubility in water or resistance to fire thus were related closely to the perceived composition of minerals.

Little progress in mineral classification was achieved during the Middle Ages. Tabulations of minerals from the eleventh through the fifteenth centuries were usually presented alphabetically with no attempt at subdivision. The sixteenth century, however, saw several attempts to group minerals on the basis of external properties (Table

1). Erasmus Stella (fl.1515), for example, arranged minerals according to their color, and Anselmus Boetius de Boodt (c. 1550-1632), who was particularly interested in gemstones, included the subjective properties of rarity and beauty along with size, color, and hardness. Two sixteenth-century mineral classifications, worthy of special note, were based on more philosophical criteria and were influential in subsequent taxonomic attempts.

Agricola's *De Natura Fossilium* employed physical properties as the basis of mineral-species identification; inorganic nature was first split into "fluids and vapors" and "fossils," and the latter were further divided into "simple fossils," composed of one kind of material (i.e., gems, metals, earths, and stones) and "compound fossils," composed of two or more kinds of materials (e.g. metal ores, conglomerates). Individual species were identified and defined by their distinctive properties.

Konrad Gesner (1516-1565) proposed an alternative mineral classification in his *De Rerum Fossilium*. Gesner divided all fossils into fifteen classes on the basis of external shape. The first class included all euhedral geometrical shapes such as pyrite cubes and other regular crystals. The second class was comprised of "forms like heavenly bodies," such as star-shaped crinoid columnals. Other classes included "like things from the sea," "like parts of trees," and "like parts of animals." Given the varied forms of many minerals such a classification proved difficult to implement, but it was one of the first systems to emphasize the importance of mineral form.

The debate over the true or "natural" basis for mineral classification developed in the eighteenth century and was to pervade much of mineralogical literature for more than a century. Some naturalists, including Georges-Louis Leclerc, Comte de Buffon (1707-1788), observed the great variety of forms exhibited by individual species and so rejected crystal form as a basis of

AUTHOR (DATES)	DATE	SHORT TITLE	BASIS OF CLASSIFICATION AND COMMENTS
Theophrastus (c.371-287 B.C.) Greek philosopher	c.314 B.C.	<i>Peri Lithon</i>	Two classes, "stones" and "earths," divided on the basis of reaction to fire and water. This is the Aristotelian system.
Pliny The Elder (c.23-79 A.D.) Roman savant	c.77 A.D.	<i>Natural History</i>	Five books on "fossils" are divided in part economically: Book 33 = gold and silver; Book 34 = copper and iron; Book 37 = gems.
Avicenna, or Ibn Sinā (980-1037) Arabic philosopher	1021-1023	<i>De Mineralibus et Rebus Metallicis</i>	Adheres closely to the Aristotelian classification as given by Theophrastus.
Albertus Magnus (1193-1280) German philosopher	c.1260	<i>De Mineralibus</i>	Albertus Magnus and other authors of "lapidaries" of the eleventh through fifteenth centuries arranged minerals alphabetically.
Erasmus Stella (fl.1515)	1517	<i>Interpraetamenti Gemmarum Libellus</i>	Four classes of minerals based on color.
Georgius Agricola (1494-1555) German scholar	1546	<i>De Natura Fossilium</i>	Classification based on a combination of external characteristics, including color, density, luster, taste, odor, transparency, shape, and texture.
Konrad Gesner (1516-1565) German/Swiss naturalist	1565	<i>De Rerum Fossilium, Lapidum et Gemmarum</i>	Fifteen classes arranged according to external form, including "geometrical forms," "like things from the sea," and others.
Anselmus Boetius de Boodt (c.1550-1632) Hanoverian naturalist	1609	<i>Gemmarum et Lapidum Historia</i>	Two classes, "gems" and "stones," based on size of deposit; subdivided according to hardness, color, transparency, beauty, and rarity.
John Woodward (1665-1728) English naturalist	1695	<i>Essay Toward a Natural History of the Earth</i>	Six classes of minerals are earths, stones, salts, bitumina, metallik minerals, and metals. He attempted to separate what we now distinguish as fossils and minerals.
	1728	<i>Fossils of all Kinds Digested into a Method</i>	
Maurice Cappeller (1685-1769) French crystallographer	1723	<i>Prodromus Crystallographiae</i>	Crystals classified primarily on the basis of crystal form.
Carl Linneaus (1707-1778) Swedish naturalist	1735	<i>Systema Naturae</i>	Linneaus held "the extreme position that crystal form and only crystal form should be used for the classification of minerals." (Schneer, 1983, p. 262).
Johan Gottschalk Wallerius (1709-1785) Swedish mineralogist	1747 1768	<i>Mineralogia De Systematibus Mineralogicis</i>	More emphasis on chemical composition in classification than in previous systems. Translated into many languages.
Axel Fredrik Cronstedt (1722-1765) Swedish chemist	1758 1760 1770 1794	<i>För sök til Mineralogie</i> German edition English edition American edition	One of the first true chemical classifications. Four classes based on effects of heat, water, and oil; blowpipe analysis used effectively; Cronstedt distinguished simple minerals from rocks.
Jean-Baptiste Louis Romé de l'Isle (1736-1790) French crystallographer	1772	<i>Essai de Cristallographie</i>	Four divisions of minerals based on effects of heat and water; subdivided by external crystal form.
Abraham Gottlob Werner (1749-1817) German geologist	1774 1789	<i>Von den Ausserlichen Kennzeichen der Fossilien Mineralsystem</i>	Classification based on chemical composition; identification based on unique combination of physical properties. Crystal form is just one of many diagnostic properties.
Georges-Louis Leclerc, Comte de Buffon (1707-1788) French naturalist	1779	<i>Époques de la Nature</i>	Physical properties rather than crystal forms are valid basis for mineral classification.



AUTHOR (DATES)	DATE	SHORT TITLE	BASIS OF CLASSIFICATION AND COMMENTS
Richard Kirwan (1733-1812) Irish mineralogist	1784 1794/96 1810	<i>Elements of Mineralogy</i> <i>Elements</i> , 2nd edition <i>Elements</i> , 3rd edition	Classification, following Cronstedt, based on qualitative chemical tests.
William Babington (1756-1833) English mineralogist	1795	<i>Systematic Arrangement of Minerals</i>	Mineral classification based on chemical composition, with subdivisions by crystal form.
René-Just Haüy (1743-1822) French crystallographer	1801 1822	<i>Traité of Minéralogie</i> <i>Traité</i> , 2nd edition	Major divisions are chemical, with subdivisions based on crystal form. Each distinctive form was given a separate name (e.g., 150 names for calcite).
Robert Jameson (1774-1854) Scottish naturalist	1804/08 1816 1820	<i>System of Mineralogy</i> <i>System</i> , 2nd edition <i>System</i> , 3rd edition	Followed Werner's system, termed the "natural history" system.
Alexandre Brongniart (1770-1847) French mineralogist	1807	<i>Traité Élémentaire de Minéralogie</i>	Classification based on a combination of chemical, physical, and crystallographic properties. The division "silicates" used; divided by electronegative element.
Jacques-Louis, Comte de Bournon (1751-1825) French mineralogist	1808 1813	<i>Traité de Minéralogie</i> <i>Catalogue de la Collection Minéralogique</i>	Followed Haüy's system. Influenced British views through lecture tours in England.
John Kidd (1755-1851) English naturalist	1809	<i>Outlines of Mineralogy</i>	Generally followed Kirwan with four classes; recognized Haüy's use of form.
Richard Chenevix (1774-1830) French naturalist	1811	<i>Observations on Mineral Systems</i>	Followed Haüy's system. Chenevix was a vocal critic of Werner's system.
Jöns Jacob Berzelius (1779-1848) Swedish chemist	1814	<i>System of Mineralogy</i>	Chemical classification based on the most electronegative element. Berzelius recognized polymorphism and isomorphism. He also promoted the use of the blowpipe.
Parker Cleaveland (1780-1858) American geologist	1816	<i>Elementary Treatise on Mineralogy</i>	Cleaveland followed Brongniart in combining chemical composition and crystal form as grounds for classification.
Friedrich Mohs (1773-1839) German mineralogist	1820 1820	<i>Grundriss der Mineralogie</i> <i>Natural History System of Minerals</i>	Followed Werner's natural history system. He incorporated the six crystal systems of Weiss and introduced a ten-point hardness scale.
Johann Friedrich August Breithaupt (1791-1873) German mineralogist	1820 1836-47	<i>Kurze Charakteristik der Mineral-Systems</i> <i>Handbuch der Mineralogie</i>	Wernerian natural history system with new Latin nomenclature. He resisted the change to chemical and crystallochemical classifications after most others had switched.
Francois-Sulpice Beudant (1787-1850) Finnish mineralogist	1824 1830/32	<i>Traite Elementaire de Mineralogie</i> <i>Traite</i> , 2nd edition	Classification in first edition based on volatility and color of oxidized products. In second edition isomorphs grouped together. Beudant used a type of chemical formula.
Nils Gustaf Nordenskiöld (1792-1866) Finnish mineralogist	1827 1848	<i>Mineralsystem</i> <i>Atomistisch-chemische Mineral System</i>	An ambitious chemical classification of minerals with such groups as "haploites" (elements), "diploites" (binary compounds), "bidiploites" and so on.
Christian Samuel Weiss (1780-1856) German crystallographer	1822/24	<i>Grundriss der Mineralogie</i>	Minerals divided in part by crystal system.
Robert Allan (1806-1863) Scottish mineralogist	1834	<i>Manual of Mineralogy</i>	Followed Werner's system in this widely distributed text. In the introduction 42 pages are devoted to physical properties and only 1 to chemical composition.

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James Dwight Dana (1813-1895) American geologist	1837 1844 1850	<i>System of Mineralogy</i> <i>System</i> , 2nd edition <i>System</i> , 3rd edition	In first edition used a Wernerian-type system with complex binomial Latin names; second edition similar; third edition has new chemical classification with "elements," "halides," "silicates" as divisions and new simplified nomenclature.
Karl Friedrich Rammelsberg (1813-1899) German mineralogist	1841	<i>Handwörterbuch des Chemischen Theils Mineralogie</i>	Based in large part on Weiss' division into crystal classes and on chemical composition.
Ours Pierre Armand Petit Dufrénoy (1792-1857) French geologist	1844/47	<i>Traité de Minéralogie</i>	A combined chemical, physical, and crystallographic classification. Isomorphous species grouped together. Ten dimorphous species are distinguished.
Gustav Rose (1798-1873) German mineralogist	1852	<i>Das Krystallo-Chemische Mineralsystem</i>	Advocated a crystallo-chemical classification, much like that in the third edition of Dana's system. Rose noted that species definition is arbitrary in cases of solid solution.
Frank Rutley (1842-1904) English economic geologist	1874	<i>Elements of Mineralogy</i>	An economic classification, with minerals grouped according to the most valuable essential element. The 26th edition was published in 1970.
Victor Moritz Goldschmidt (1888-1947) German geochemist	1927	<i>Geochemische Verteilungsgesetz der Elemente</i>	Classification of minerals based on structure type.
Ralph Walter Greystone Wyckoff (1897-) American crystallographer	1948	<i>Crystal Structures</i>	Ambitious structural classification, based first on the form of chemical formula (i.e., $A_2B_3$ or $ABO_4$ ), and then on structure type. This classification was applied to all inorganic compounds.

Table 1. Mineral classification systems.

classification in favor of chemical or physical properties. Other scientists, notably Carl Linnaeus (1707-1778), took the opposite view that "form and only form should be used for the classification of minerals" (Schneer, 1983, p. 262). This crystallographic view was adopted by Romé de l'Isle, Haüy, and others.

Abraham Werner, in the most influential of all eighteenth-century mineral classification systems, enumerated four essential types of mineral properties: external characteristics observable by the five senses, internal or chemical properties, physical characteristics (such as optical and electric properties), and "empirical" properties relating to characteristic geological position or associated minerals. Werner's system, which placed composition as the true basis for division of minerals into species, relegated external form to a relatively minor role as but one of many factors useful in mineral identification. Among the supporters of the Wernerian classification system, which was popularly termed the "natural history" system, were the German Friedrich Mohs, the Scot Robert Jameson (1774-1854), and the American Charles Upham Shepard (1804-1886).

Werner's system was opposed, quite naturally, by followers of the crystallographic approach, whose philosophy was stated in Haüy's *Traité de Minéralogie*. Haüy's followers included fellow countrymen Jacques-Louis, Comte de Bournon (1751-1825), who lectured extensively in England, and Richard Chenevix (1774-1830), an outspoken critic of Werner. Mineralogy could never achieve the status of a science, Haüy's proponents argued, as long as qualitative external properties were used as a basis of species division. In spite of the evident interrelationships among chemistry, physical properties, and crystal form, the supporters of Werner and those of Haüy tended to polarize the debate over mineral classification. Each

group labelled the others' system as "artificial," that is based on arbitrary, nonessential characteristics of minerals. Given the lack of agreement on one system, numerous mineral classification systems were proposed in the first half of the nineteenth century (see, for example, Kobell, 1864, and Orceel, 1963). Some workers supported the extreme crystallographic or natural history positions, while others attempted more balanced intermediate schemes, with combinations of chemical, physical and crystallographic properties employed in mineral arrangement and identification. Furthermore, each author proposed his own favored mineral names, and as a result mineralogical nomenclature grew almost ten times faster than the discovery of new species. Many adopted the inappropriate Linnaean binomial nomenclature, which further confused and cluttered the mineralogical literature with a multiplicity of generic as well as specific names.

Mineralogists soon recognized the folly of adopting such polarized views of classification and such multiplicity of mineral names. One mineralogist observed that "an intelligent student in mineralogy, having set before him in various text-books the two rival methods, could not fail to be impressed by the radical opposition between them, and to ask whether some mode of reconciliation might not be found" (Hunt, 1892, p. xiv).

The system of mineral classification that was eventually adopted by most mineralogists was first proposed by James Dwight Dana (1813-1895) in the 1850 third edition of his *System of Mineralogy*. Dana's major divisions of minerals were based on chemistry; elements, halides, sulfides, silicates, carbonates, and other chemical groupings were used. Within each of these categories further subdivisions were largely based on structure; Dana grouped together all carbonates with the calcite structure, for example. Physical properties, as in Werner's

system, were reviewed in great detail and provided the basis for mineral identification. The classification and description of minerals continued to occupy much of the effort of mineralogists in the second half of the nineteenth century as the systems of Dana and Gustav Rose (1798-1873), in particular, were expanded and refined. Alternative classifications were advanced in the late nineteenth and twentieth centuries, primarily on the basis of economic or structural considerations, but the crystal-chemical method has remained the most widely employed basis for mineral classification.

#### CONCLUDING STATEMENT

For most of the history of mineralogical investigation researchers were concerned with equilibrium properties of minerals. With the introduction of the electron microprobe, spectroscopic techniques, transmission electron microscopy, and other procedures that resolve mineral composition and structure on a small scale, it has become evident that most minerals are not in equilibrium. Minerals, which in general change extremely sluggishly below temperatures of a few hundred degrees, preserve structural and compositional patterns that are characteristic of their particular pressure-temperature histories. The study of minerals as indicators of geological history gained prominence in the early 1970s as a result of the intensive study of Lunar samples. This new aspect of mineralogy, combined with the ongoing study of chemical, physical, and structural properties of minerals, holds the promise for a rich future in mineralogical research.

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#### FOOD FOR THOUGHT

The modern perspective of earth history owes little to Scottish geology. Huttonian uniformitarianism was fundamentally uncongenial to historical geology. Its vision of a permanent present made James Hutton object to invertebrate extinction. It also caused Charles Lyell to reject the evidence for the progressive succession of fossils. The common notion that modern geology originated with uniformitarianism is a hindrance to the unencumbered study of the origin of the new geology. The distinctive nature of English geology was in fact accentuated by the conscious manner in which it set itself apart from the Scottish tradition.

Nicholaas A. Rupke, 1983, *The great chain of history, William Buckland and the English school of geology (1814-1849)*: Oxford, Clarendon Press, 322 p. (from p. 5)