Nonetheless, the early appearance of eukaryotic attributes directs new attention to the immense interval between the divergence of the Eucarya and their rise to ecological and taxonomic prominence 1200 to 1000 Ma (see diagram) (*11*). Explanations based on biological innovation ("just add sex") have been favored in recent years, but these require careful rethinking, with more attention paid to possible environmental facilitation.

In a now classic model of atmospheric evolution, geochemists have postulated that oxygen concentrations grew from extremely low to nearly modern levels about 2200 to 2300 Ma (*12*). But molecular oxygen is required for sterol synthesis, and independent isotopic evidence connects methanotrophic bacteria that depend on oxygen to late Archean ecosystems (*13*). Thus, regardless of the circumstances of early Archean Earth, biogeochemical observations suggest that by the late Archean, oxygen had begun to accumulate in the atmosphere, perhaps reaching levels sufficient for aerobic respiration by single cells (about 1% of present-day values), although probably not much more (*12*, *14*). Recent models of Proterozoic ocean chemistry also suggest that the partial pressure of oxygen, P_{O_2}, approached modern levels only near the end of the Archean (*1*, *15*), further emphasizing the need to consider a protracted, multistage history of atmospheric chemistry.

Knowledge of Archean life and environments remains sketchy, but the discoveries of Brocks *et al.* bolster confidence that, like the Precambrian-Cambrian boundary before it, the paleontological barrier at the Proterozoic-Archean boundary is destined to fall. This time the advance will be driven by innovative biogeochemistry tied to careful field studies of Archean sedimentary rocks (*16*).

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PERSPECTIVES: MINERALOGY

Mineralogy at a Crossroads

Russell J. Hemley

When Theophrastus described 16 minerals in his textbook "De Lapidibus" around 300 B.C., he laid the foundation for the science of mineralogy and provided the basis for understanding a panoply of natural phenomena. The minerals he described provided the raw material that led to the discovery of many of the chemical elements, and their study was essential in establishing the disciplines of chemistry and physics. Advances within these disciplines in this century brought minerology into the modern era. In particular, the use of x-ray crystallography allowed the structure of all the major rock-forming minerals to be determined on an atomic scale (see the figure). The field has been so successful in these respects that mineralogy in now at a crossroads. New questions cut across the historical boundaries of the field defined in even the most recent textbooks. Recent workshops (*1*–*3*) highlighted both accelerating progress in key areas and expanding opportunities for the coming century.

Dana's System of Mineralogy (*4*) of the last century led to the definition of a mineral as a "naturally occurring crystalline element or compound having definite chemical composition, and formed as a product of inorganic processes." This view is now considered too restrictive: The synthesis of new "minerals" at high pressures and temperatures; the discovery of new amorphous forms; and investigations of nanoscopic to mesoscopic materials, melt structures and fluid-rock interactions, biologically precipitated minerals, and organic-inorganic interactions relevant to the origin of life have considerably broadened the purview of this science. Materials are no longer compartmentalized according to whether they are found naturally in Earth, on other planets, or exclusively as the product of human endeavors. Four themes are emerging from recent developments: an expanded domain of materials and processes, new views of complexity, connections to life, and new roles in advancing fundamental science and technology.

Mineralogy now encompasses a whole-Earth catalog of materials from the planet's atmosphere to its inner core. The study of Earth's deep interior was cast as a problem in mineralogy and solid-state physics by Birch (*5*) and led to the field of mineral physics (*6*, *7*). An array of new techniques allows detailed investigations of Earth materials over the complete range of pressure-temperature conditions that prevail within the planet. The materials of the planet's interior exhibit physical and chemical properties that can be far different from what is observed near the surface. For example, the discovery that hydrogen can be bound in dense silicates and metals has given rise to the possibility of oceans of water locked up within Earth's interior. Minerals and rocks can now be subjected to well-controlled stress conditions, providing critical information for understanding phenomena from deep earthquakes to the movement of continents, the atomic-scale underpinning of plate tectonics (*8*). With a more interdisciplinary outlook, mineral physics is evolving into the wider field of condensed-matter geophysics.

This new scope extends outward to the solar system and beyond, with the discovery of extrasolar system planets. New materials, from fullerenes to dense silicates originally synthesized only in the laboratory, are now documented in extraterrestrial samples, demonstrating the need for laboratory studies and the cross fertilization of chemistry and physics with conventional mineralogy. Future space missions will return samples from other planets, comets, and asteroids; as with the lunar samples of the Apollo era, this presents new opportunities for detailed materials characterization and improved understanding of the processes responsible for planet formation and differentiation. Advances in high pressure temperature experiments provide the prospect for a new experimental mineralogy of ultradense environments at the extreme conditions approaching those found within brown dwarfs and a connection to atmospheric science (*8*).

A distinguishing feature of natural systems is their complexity. Mineral thermo-

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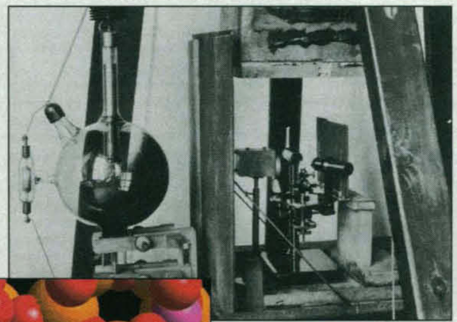
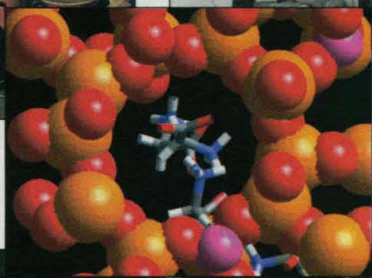
dynamics—its basis developed essentially over a century ago—must now concern itself with surface and interfacial phenomena and thus the "dimensionality" of mineral-containing systems. In situ probes in chemically complex environments reveal the role of surfaces and interfaces in controlling physical and chemical behavior at the nanoscale and the mesoscale (*8*). Moreover, the geologic context requires consideration of the additional coordinate of time, from the time scale of electronic transitions (for example, associated with light absorption at planetary surfaces) to the age of the solar system, spanning no less than 30 orders of magnitude.





From alchemy to accelerators. (Top left) *The Alchemist*, by Stradano. **(Top right)** Apparatus with which W. Friedrich, P. Knipping, and Max von Laue discovered the diffraction of x-rays by crystals on ZnS in 1912. **(Bottom center)** The Advanced Photon Source, a 7-GeV synchroton x-ray facility at Argonne National Laboratory. **(Center)** Atomic framework of the zeolite silicalite/ZSM-5 with amino acids encapsulated in energetically favorable positions.

CREDITS: (CLOCKWISE FROM UPPER LEFT) PALAZZO VECCHIO STUDIOLO, FIRENZE; FROM *OUT OF THE CRYSTAL MAZE*, OXFORD, 1992; ARGONNE NATIONAL LAB; J. V. SMITH *ET AL.* IN (*3*)

Issues of complexity are leading directly to the boundary with biology. It is now recognized that microbes control many geological processes, such as ore deposition and crucial biogeochemical cycles, echoing the connection between biology and geology advanced by Vernadsky (*9*). The implications range from agricultural productivity to climate change and environmental quality (*3*). Indeed, the very existence of life may ultimately be tied to characteristic features of key mineral systems, including the role of mineral catalysis in the origin of life (see the figure). In the prebiotic world, naturally occurring transition metal sulfide minerals may have served as the initiators for the genesis of biochemistry (*8*). Extraterrestrial materials studies may lead to further understanding of fossilization, which is necessary to resolve the current heated discussions about extraterrestrial life.

The continuing role of minerals in science and technology forms a backdrop to these developments. Since Agricola (*10*), the science of mineralogy has been central to both natural resource utilization and materials fabrication. High-pressure experiments have been used to further understand the origin and utilization of potential new energy reserves, such as the large sub-ocean floor deposits of methane clathrates. Minerals provide the raw materials from which silicon chips and lasers are made and for many other materials that humans consume. Mineral studies are also directed at solving fundamental problems in physics and chemistry. Investigations of minerals and mineral analogs are revealing new physics, including high-temperature superconductivity in the perovskite-based cuprates; novel electronic properties in Mott-insulators, giant ferroelectricity, and colossal magnetoresistance in oxides; and photonic band gaps in artificial opals. Theoretical advances help understand phase transitions in complex materials. Computer visualization techniques reveal information on mineral dynamics and transformations not evident from static conventional two-dimensional views. And the principles and techniques of mineralogy continue to be central to the discovery and creation of new technologically important materials, from zeolites to superhard materials (*8*).

Finally, recent developments have resulted in a sea change in the way this science is done. The discovery and application of new radiation probes brought "modern" physics to fin-de-siècle 19th-century mineralogy (*11*); at the turn of this century, mineral sciences have taken the lead in advancing techniques such as high-pressure methods and approaches for examining complex materials, for example, at third-generation synchrotron radiation sources (see the figure). Parallel developments in neutron techniques will allow new classes of experiments at intense spallation neutron sources. A new generation of electron beam instruments permits atomic structure determination with sub-angstrom resolution and analytical examination of natural materials at the single-atom limit. Both ultrafast and ultrahigh pressure-temperature phenomena are being investigated with new laser methods, and new computer architectures allow modeling of increasingly complex systems (*8*) over many length scales.

In view of these developments, this multidisciplinary field of Earth and planetary materials studies requires long-range planning and investment to reach its full potential. The consensus of the recent workshops (*1–3*) indicates funding needs especially for new instruments, scientific manpower, and international training over the next 5 years. Progress both in understanding our corner of the solar system and in maintaining its habitability depends on it.

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