American Mineralogist, Volume 93, pages 1693–1720, 2008

Review Paper

Mineral evolution

Robert M. Hazen,[1,*] Dominic Papineau,[1] Wouter Bleeker,[2] Robert T. Downs,[3] John M. Ferry,[4] Timothy J. McCoy,[5] Dimitri A. Sverjensky,[4] and Hexiong Yang[3]

[1]Geophysical Laboratory, Carnegie Institution, 5251 Broad Branch Road NW, Washington, D.C. 20015, U.S.A.
[2]Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A OE8, Canada
[3]Department of Geosciences, University of Arizona, 1040 East 4th Street, Tucson, Arizona 85721-0077, U.S.A.
[4]Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, Maryland 21218, U.S.A.
[5]Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, D.C. 20560, U.S.A.

Abstract

The mineralogy of terrestrial planets evolves as a consequence of a range of physical, chemical, and biological processes. In pre-stellar molecular clouds, widely dispersed microscopic dust particles contain approximately a dozen refractory minerals that represent the starting point of planetary mineral evolution. Gravitational clumping into a protoplanetary disk, star formation, and the resultant heating in the stellar nebula produce primary refractory constituents of chondritic meteorites, including chondrules and calcium-aluminum inclusions, with ~60 different mineral phases. Subsequent aqueous and thermal alteration of chondrites, asteroidal accretion and differentiation, and the consequent formation of achondrites results in a mineralogical repertoire limited to ~250 different minerals found in unweathered meteorite samples.

Following planetary accretion and differentiation, the initial mineral evolution of Earth's crust depended on a sequence of geochemical and petrologic processes, including volcanism and degassing, fractional crystallization, crystal settling, assimilation reactions, regional and contact metamorphism, plate tectonics, and associated large-scale fluid-rock interactions. These processes produced the first continents with their associated granitoids and pegmatites, hydrothermal ore deposits, metamorphic terrains, evaporites, and zones of surface weathering, and resulted in an estimated 1500 different mineral species. According to some origin-of-life scenarios, a planet must progress through at least some of these stages of chemical processing as a prerequisite for life.

Biological processes began to affect Earth's surface mineralogy by the Eoarchean Era (~3.85–3.6 Ga), when large-scale surface mineral deposits, including banded iron formations, were precipitated under the influences of changing atmospheric and ocean chemistry. The Paleoproterozoic "Great Oxidation Event" (~2.2 to 2.0 Ga), when atmospheric oxygen may have risen to >1% of modern levels, and the Neoproterozoic increase in atmospheric oxygen, which followed several major glaciation events, ultimately gave rise to multicellular life and skeletal biomineralization and irreversibly transformed Earth's surface mineralogy. Biochemical processes may thus be responsible, directly or indirectly, for most of Earth's 4300 known mineral species.

The stages of mineral evolution arise from three primary mechanisms: (1) the progressive separation and concentration of the elements from their original relatively uniform distribution in the pre-solar nebula; (2) an increase in range of intensive variables such as pressure, temperature, and the activities of H_2O, CO_2, and O_2; and (3) the generation of far-from-equilibrium conditions by living systems. The sequential evolution of Earth's mineralogy from chondritic simplicity to Phanerozoic complexity introduces the dimension of geologic time to mineralogy and thus provides a dynamic alternate approach to framing, and to teaching, the mineral sciences.

Keywords: Pre-solar minerals, meteorite minerals, biominerals, organominerals, teaching mineralogy