**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 H₂O, CO₂, and O₂; 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

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**INTRODUCTION**

Earth today boasts about 4300 known species of minerals, with as many as 50 new types being identified each year (e.g., http://rruff.info/ima). Yet the mineralogical diversity now found at or near Earth’s surface, defined here as micro- or macroscopic solid phases (>1 μm diameter) at crustal depths less than about 3 km (i.e., where direct interaction with microbial life is likely), was not present for much of the planet’s history. Indeed, both the variety and relative abundances of near-surface minerals have changed dramatically over more than 4.5 billion years of Earth history through a variety of physical, chemical, and biological processes.

Our principal objective is to explore the nature of mineral evolution by reviewing significant episodes of change in the diversity and distribution of minerals on Earth (Table 1 and Fig. 1). Thousands of previous publications document specific aspects of Earth’s mineral evolution, from the pre-planetary alteration of