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On the paragenetic modes of minerals: A mineral evolution perspective

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Abstract

A systematic survey of 57 different paragenetic modes distributed among 5659 mineral species reveals patterns in the diversity and distribution of minerals related to their evolving formational environments. The earliest minerals in stellar, nebular, asteroid, and primitive Earth contexts were dominated by relatively abundant chemical elements, notably H, C, O, Mg, Al, Si, S, Ca, Ti, Cr, and Fe. Significant mineral diversification subsequently occurred via two main processes, first through gradual selection and concentration of rarer elements by fluid-rock interactions (for example, in hydrothermal metal deposits, complex granite pegmatites, and agpaitic rocks), and then through near-surface biologically mediated oxidation and weathering.

We find that 3349 mineral species (59.2%) are known from only one paragenetic context, whereas another 1372 species (24.2%) are associated with two paragenetic modes. Among the most genetically varied minerals are pyrite, albite, hornblende, corundum, magnetite, calcite, hematite, rutile, and baryte, each with 15 or more known modes of formation.

Among the most common paragenetic modes of minerals are near-surface weathering/oxidation (1998 species), subsurface hydrothermal deposition (859 species), and condensation at volcanic fumaroles (459 species). In addition, many species are associated with compositionally extreme environments of highly differentiated igneous lithologies, including agpaitic rocks (726 species), complex granite pegmatites (564 species), and carbonatites and related carbonate-bearing magmas (291 species). Biological processes lead to at least 2707 mineral species, primarily as a consequence of oxidative weathering but also through coal-related and other taphonomic minerals (597 species), as well as anthropogenic minerals, for example as byproducts of mining (603 minerals). However, contrary to previous estimates, we find that only ~34% of mineral species form *exclusively* as a consequence of biological processes. By far the most significant factor in enhancing Earth's mineral diversity has been its dynamic hydrological cycle. At least 4583 minerals—81% of all species—arise through water-rock interactions.

A timeline for mineral-forming events suggests that much of Earth's mineral diversity was established within the first 250 million years. If life is rare in the universe, then this view of a mineralogically diverse early Earth provides many more plausible reactive pathways over a longer timespan than previous models. If, however, life is a cosmic imperative that emerges on any mineral- and water-rich world, then these findings support the hypothesis that life on Earth developed rapidly in the early stages of planetary evolution.

Keywords: Philosophy of mineralogy, classification, mineral evolution, natural kinds, meteorite mineralogy, thermal metamorphism, aqueous alteration, biomineralization