


Mineral Evolution: Mineralogy in the Fourth Dimension

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Dark-colored uranium minerals occur in roll-front ore deposits, formed when U-bearing solutions encounter reducing, organic-rich material in terrestrial sediments. Such deposits formed only in the last 400 million years, since the rise of land plants. Area shown is 3 meters wide.

Mineral evolution, which frames mineralogy in a historical context, is based on the premise that the geosphere and biosphere have coevolved through a sequence of deterministic and stochastic events. Three eras of mineral evolution—planetary accretion, crust and mantle reworking, and biologically mediated mineralogy—each saw dramatic changes in the diversity and distribution of Earth’s near-surface minerals. An important implication of this model is that different terrestrial planets and moons achieve different stages of mineral evolution, depending on the geological, petrological, and biological evolution of the body.

KEYWORDS: mineral evolution, biomineralization, meteorites, plate tectonics

THE FIRST MINERALS

In the beginning, none of the approximately 4400 known minerals existed. Cosmologists estimate that it took perhaps a half million years after the Big Bang before the first atoms of hydrogen and helium (and probably some lithium) condensed from the hot, dense, primordial fireball. It may have taken millions more years for the first stars to form, ignite, and seed space with the initial pulse of heavier, fusion-generated elements (Schatz 2010 this issue).

Only then, as giant stars exploded into the first supernovae, did minute bits of condensed, crystalline matter form in the cooling, expanding, gaseous stellar envelopes. Possibly a dozen micro- and nanoscale mineral species appeared. Diamond and graphite were likely the most abundant crystalline phases in those carbon-rich environments, with a sprinkling of carbides, nitrides, oxides, and magnesium silicates. For perhaps tens of millions of years, these few microscopic primeval “ur-minerals” were the only crystals in the universe.

ERA 1: PLANETARY ACCRETION

The diversification of minerals had to wait for the emergence of planets because planets are the engines of mineral formation (Hazen et al. 2008). Initial pulses of mineralogical novelty came in stellar nebulae, as nascent stars ignited and bathed the nearby concentrations of dust and gas with a refining fire. We define three eras and ten stages of mineral evolution in our own solar system (TABLE 1; FIG. 1). During Stage 1, perhaps 60 different mineral species appeared as primary condensates almost 4.6 billion years

ago, when the Sun entered its intense T-Tauri phase. Among the mineralogical innovations were the first iron–nickel metal phases, sulfides, phosphides, and a host of familiar refractory silicates and oxides like those found in the least-altered chondrite meteorites. These planet-forming materials quickly clumped into planetesimals, some of which became large enough to partially melt, differentiate, and experience a range of thermal and aqueous alteration processes (Stage 2; FIG. 2). The mineralogy of the solar system expanded to about 250 different phases, which are still found today in the diverse suite of meteorites that fall to Earth (McCoy 2010 this issue).

Since the formation of our solar system’s four inner planets and Earth’s moon, three primary mechanisms have driven mineral diversification: (1) the progressive separation and concentration of the elements from their original relatively uniform distribution in the presolar nebula; (2) an increase in the range of combinations of intensive variables, such as pressure, temperature, and the activities of H₂O, CO₂,

TABLE 1 THREE ERAS AND TEN STAGES OF EARTH’S MINERAL EVOLUTION

Era/Stage	Age (Ga)	Cumulative no. of species
Prenebular “Ur-Minerals”	>4.6	12
Era of Planetary Accretion (>4.55 Ga)		
1. Primary chondrite minerals	>4.56 Ga	60
2. Achondrite and planetesimal alteration	>4.56 to 4.55 Ga	250
Era of Crust and Mantle Reworking (4.55 to 2.5 Ga)		
3. Igneous rock evolution	4.55 to 4.0 Ga	350 to 500*
4. Granite and pegmatite formation	4.0 to 3.5 Ga	1000
5. Plate tectonics	>3.0 Ga	1500
Era of Biologically Mediated Mineralogy (>2.5 Ga to Present)		
6. Anoxic biological world	3.9 to 2.5 Ga	1500
7. Great Oxidation Event	2.5 to 1.9 Ga	>4000
8. Intermediate ocean	1.9 to 1.0 Ga	>4000
9. Snowball Earth events	1.0 to 0.542 Ga	>4000
10. Phanerozoic era of biomineralization	0.542 Ga to present	4400+

* Depending on the volatile content of the planet or moon

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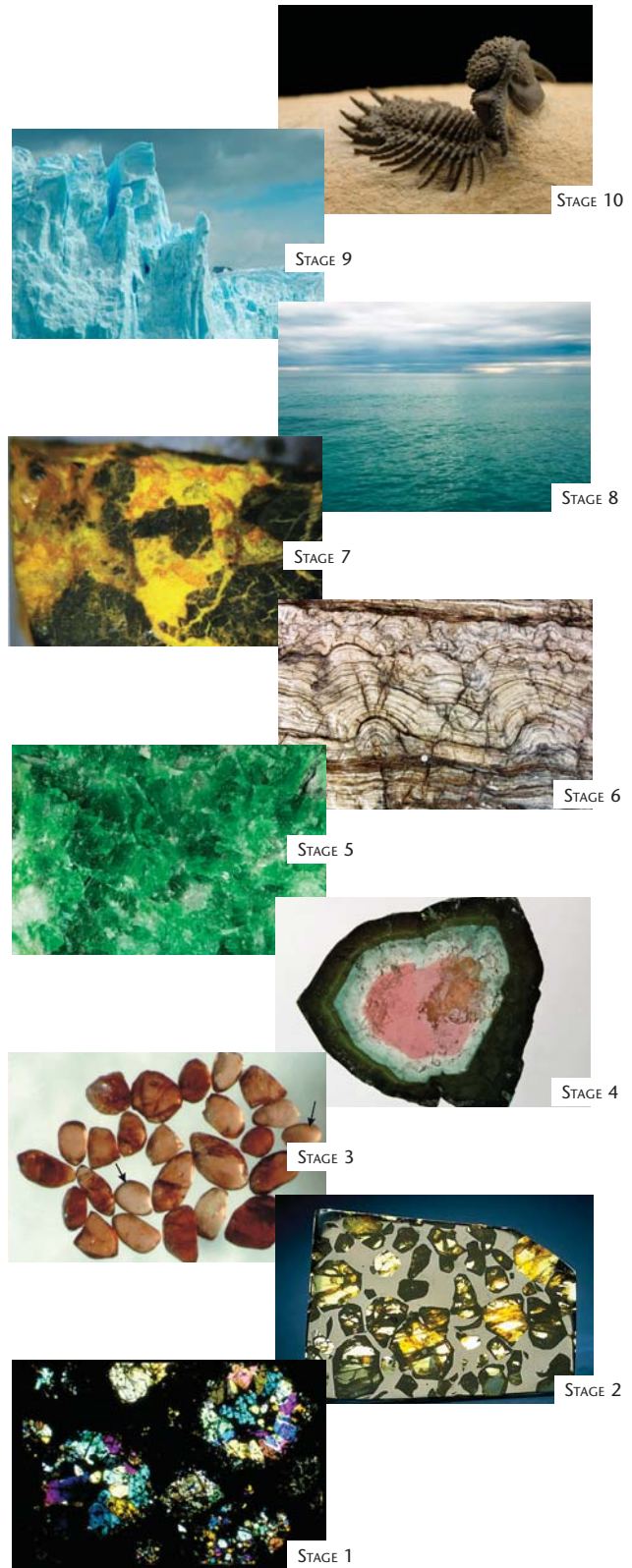
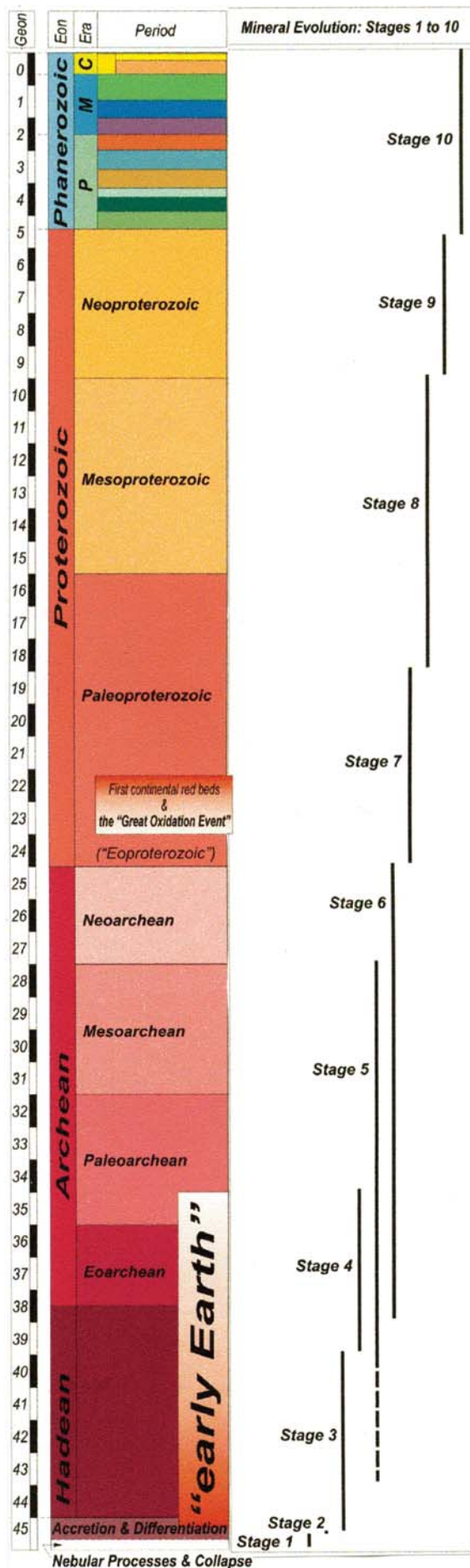


FIGURE 1 Each of the ten stages of mineral evolution saw a change in the diversity and/or surface distribution of mineral species. This timeline is accompanied by photos of near-surface Earth materials illustrative of each stage. **stage 1:** chondrite meteorite, COURTESY OF SMITHSONIAN INSTITUTION; **stage 2:** pallasite meteorite, COURTESY OF SMITHSONIAN; **stage 3:** zircon grains, COURTESY OF JOHN VALLEY; **stage 4:** tourmaline, COURTESY OF ROBERT DOWNS; **stage 5:** jadeite, COURTESY OF ROBERT DOWNS; **stage 6:** stromatolite, COURTESY OF DOMINIC PAPINEAU; **stage 7:** curite, COURTESY OF ROBERT LAUF; **stage 8:** water. MAURO MARZO | DREAMSTIME.COM; **stage 9:** glacier ice. PTEKIEL | DREAMSTIME.COM; **stage 10:** trilobite, Hazen Collection, Smithsonian Institution, PHOTO BY CHIP CLARK



FIGURE 2 Stage 1 of mineral evolution saw the initial diversification of minerals, as represented in primitive meteorites. Pallasite meteorites, an example of which is shown here, contain olivine crystals in an iron–nickel matrix. These phases are products of the differentiation of planetesimals into mantle and core that occurred during Stage 2. PHOTO COURTESY OF THE CROATIAN METEOR NETWORK (WWW.ASTRO.HR/HMM/INDEX.HTML)

and O_2 ; and (3) the generation of far-from-equilibrium conditions by living systems that produce thermodynamically metastable minerals and the ability of their metabolic processes to catalyze mineral-forming reactions that would not occur abiotically. The extent to which these processes act at or near a planet's surface will determine its degree of mineral evolution. On Earth we envision a history with an additional two eras and eight stages, whereas most other planets and moons experienced only the first era.

ERA 2: CRUST AND MANTLE REWORKING

The initial mineral evolution of Earth's crust depended on a sequence of geochemical and petrologic processes, including volcanism and degassing, fractional crystallization, assimilation, regional and contact metamorphism, plate tectonics, and associated large-scale fluid–rock interactions. These processes, which produced the first continents and ultimately resulted in an estimated 1500 different mineral species, can be divided into three evolutionary stages.

All rocky planets and moons experience Stage 3 mineral-forming igneous processes, as outlined in Norman Bowen's classic text, *The Evolution of the Igneous Rocks* (Bowen 1928). Even on a volatile-poor body like Mercury or the Moon, such processes yield as many as 350 different mineral species. If, however, H_2O and other volatiles are abundant, then the mineralogical diversity is enhanced by the development of hydroxides, hydrates, carbonates, and evaporite minerals—a total of approximately 500 mineral species. A once-wet Mars appears to have progressed this far in its mineral evolution.

Stage 4 of mineral evolution requires that a planet possess sufficient inner heat to remelt its initial basaltic crust, resulting in the formation of granitoids. Pulses of mineralogical novelty arise from repeated partial melting and concentration of rare elements to form complex pegmatites and their approximately 500 distinctive minerals of Li, Be, B, Nb, Ta, U, and a dozen other rare elements (FIG. 3). These elements have been present since the time of the ur-minerals, but in concentrations too low for the formation of discrete phases rich in the rarer elements. It takes



FIGURE 3 Granitization and the formation of pegmatites (Stage 4) significantly increased the mineral diversity of Earth's near-surface environment. This image shows a surface exposure of the San Diego gem pegmatite, Mesa Grande, California. FROM LONDON 2008

time—by some estimates more than a billion years—to achieve the required concentrations of these elements in complex pegmatites (London 2008). Venus may have progressed this far, but neither Mars nor Mercury has yet revealed surface evidence of granite formation.

Because of plate tectonics, Earth experienced yet another pulse of mineral evolution (Stage 5; FIG. 4). Subduction of H_2O -rich, chemically diverse crustal materials led to fluid–rock interactions and associated rare element concentration on a vast scale, notably forming massive sulfide deposits with more than 150 new sulfosalts. Dozens more mineral species first appeared at Earth's surface from the uplift and exposure of deeply subducted domains containing a wealth of high-pressure, low-temperature minerals formed along the anomalously low geothermal gradients in subduction zones.



FIGURE 4 In Stages 3 to 5 of mineral evolution, a variety of igneous and metamorphic processes increased the diversity of mineral species. Mount Stromboli (shown here in eruption, October 2007) is an arc volcano formed as the African Plate subducts under the Eurasian Plate. Plate tectonics is an example of mineral-forming processes that first emerged in Stage 5. PHOTO COURTESY OF TOM PFEIFFER (WWW.VOLCANODISCOVERY.COM)

All told, perhaps 1500 different minerals were generated by processes in Earth's dynamic crust and mantle. But mineralogists have catalogued more than 4400 species—an order of magnitude more than on any other nearby world. What makes Earth different?

ERA 3: BIOLOGICALLY MEDIATED MINERALOGY

Abundant and diverse life-forms distinguish Earth from all other planets and moons in the solar system. Life has transformed the near-surface environment—conspicuously the oceans and atmosphere, but rocks as well. Indeed, we argue that fully two-thirds of all known mineral species are the consequence of Earth's transformation by living organisms.

The earliest life on an anoxic Earth had relatively little effect on mineralogical diversity (Stage 6; Papineau 2010 this issue). To be sure, new biologically mediated rock formations appeared, including extensive banded iron formations and localized carbonate reefs. But the land was still barren, surface weathering was slow, and life contributed very little to expand the number or distribution of the approximately 1500 preexisting mineral species.

That situation changed in a geological instant with the remarkable biological innovation of oxygenic photosynthesis and the rise of an oxygen-rich atmosphere (Stage 7). The “Great Oxidation Event” (GOE) (starting ~2.4 Ga), when atmospheric oxygen may have risen to >1% of modern levels, irreversibly transformed Earth's surface mineralogy. More than 2500 minerals are hydrated, oxidized weathering products of other minerals, and these

new minerals are unlikely to have developed in an anoxic environment. Biochemical processes associated with the GOE may thus be responsible, directly or indirectly, for most of Earth's 4400 known mineral species (Sverjensky and Lee 2010 this issue).

The next billion years or so (Stage 8), referred to as the "Intermediate Ocean" (or, more whimsically, the "Boring Billion"), appear to have been a time of relative mineralogical stasis. This period may be considered as a time when the interface in the ocean between an oxic surface layer and anoxic depths gradually got deeper (Anbar and Knoll 2002). However, the "boring" label more likely reflects our ignorance of rock formations that have been relatively little studied compared to much older and much younger ones.

The ninth stage of mineral evolution marks a half-billion-year interval during which at least two global glaciations occurred, commonly referred to as "snowball Earth" episodes (1.0 to 0.542 Ga). Whether ice completely covered the planet is a matter of debate (Hoffman et al. 1998), but ice certainly became the dominant surface mineral for periods in excess of 10 million years. Volcanoes continued to pierce the frozen veneer and contribute to surface mineral diversity, and interglacial periods experienced new pulses of mineral formation, notably the deposition of thick, fast-growing "cap carbonates" with giant crystal fans of aragonite (Pierrehumbert 2004; FIG. 5) and a rapid increase in the generation of clay minerals (Kennedy et al. 2006).

The Phanerozoic mineralogical innovation of bioskeletons of carbonate, phosphate, and silica (FIG. 6) resulted in new mechanisms of mineralization that continue to influence Earth's near-surface mineralogy (Stage 10; Dove 2010 this issue). At the dawn of the Cambrian Period, Earth's subaerial surface was, as it had been for most of the previous 4 billion years, mostly barren rock. The rise of land plants



FIGURE 5 Neoproterozoic "snowball Earth" events (Stage 9) were characterized by alternating episodes of global glaciation and rapid deposition of cap carbonates with giant crystal fans of aragonite. This 100 m section from the Skeleton Coast of Namibia exposes glacial deposits (lower slopes) overlain by carbonates (cliff faces). PHOTO COURTESY OF P. HOFFMAN (WWW.SNOWBALLEARTH.ORG)

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FIGURE 6 Stage 10 of mineral evolution was characterized by the increasing influence of life on mineralization. The trilobite *Hoploichas* (6.5 cm long) from the Ordovician of Russia displays an elaborately sculpted calcitic shell. ROBERT HAZEN COLLECTION, NATIONAL MUSEUM OF NATURAL HISTORY, SMITHSONIAN INSTITUTION

about 400 million years ago not only dramatically altered Earth's surface appearance, but it also led to rapid production of soils, including an order of magnitude increase in the rate of clay mineral production.

IMPLICATIONS OF MINERAL EVOLUTION

The 4.5-billion-year chronicle of mineralogical change underscores the crucial role of time in mineralogy. Every Earth scientist knows that geology is history. It is remarkable, then, that the study of minerals has remained divorced from the dimension of time. Specimens in almost every mineral museum are organized by the Dana system, with composition first, followed by structure type. Each label records a name, chemical formula, locality, and perhaps a crystal class or space group. But with few exceptions, nothing is mentioned about the age of the mineral specimens. Time is not a traditional variable.

There are several good reasons to reframe mineralogy in its historical context. From a planetary perspective, the concept of mineral evolution allows each terrestrial body in the solar system to be placed in a broader mineralogical context. Mineral evolution provides an intellectual framework for identifying mineralogical targets in the search for extraterrestrial life. From the perspective of complex evolving systems, which have often become a lightning rod for debates over biological evolution, mineral evolution provides an excellent example of a nonliving system that diversifies over time through well-known physicochemical mechanisms (Hazen and Eldredge 2010 this issue).

Most importantly, by framing mineralogy as a historical narrative, intimately entwined with the drama of planet formation, plate tectonics, and the origin and evolution of life, mineralogy rightfully claims a central position in the Earth sciences.

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