

Evolution of Minerals

BY ROBERT M. HAZEN

Looking at the mineral kingdom through the lens of deep time leads to a startling conclusion: most mineral species owe their existence to life

KEY CONCEPTS

- Only a dozen minerals (crystalline compounds) are known to have existed among the ingredients that formed the solar system 4.6 billion years ago, but today Earth has more than 4,400 mineral species.
- Earth's diverse mineralogy developed over the eons, as new mineral-generating processes came into play.
- Remarkably, more than half of the mineral species on Earth owe their existence to life, which began transforming the planet's geology more than two billion years ago.

—The Editors

Once upon a time there were no minerals anywhere in the cosmos. No solids of any kind could have formed, much less survived, in the superheated maelstrom following the big bang. It took half a million years before the first atoms—hydrogen, helium and a bit of lithium—emerged from the cauldron of creation. Millions more years passed while gravity coaxed these primordial gases into the first nebulae and then collapsed the nebulae into the first hot, dense, incandescent stars.

Only then, when some giant stars exploded to become the first supernovas, were all the other chemical elements synthesized and blasted into space. Only then, in the expanding, cooling gaseous stellar envelopes, could the first solid pieces of minerals have formed. But even then, most of the elements and their compounds were too rare and dispersed, or too volatile, to exist as anything but sporadic atoms and molecules among the newly minted gas and dust. By not forming crystals, with distinct chemical compositions and atoms organized in an orderly array of repeating units, such disordered material fails to qualify as minerals.

Microscopic crystals of diamond and graph-

ite, both pure forms of the abundant element carbon, were likely the first minerals. They were soon joined by a dozen or so other hardy microcrystals, including moissanite (silicon carbide), osbornite (titanium nitride), and some oxides and silicates. For perhaps tens of millions of years, these earliest few species—"ur-minerals"—were the only crystals in the universe.

Earth today, in contrast, boasts more than 4,400 known mineral species, with many more yet to be discovered. What caused that remarkable diversification, from a mere dozen to thousands of crystalline forms? Seven colleagues and I recently presented a new framework of "mineral evolution" for answering that question. Mineral evolution differs from the more traditional, centuries-old approach to mineralogy, which treats minerals as valued objects with distinctive chemical and physical properties, but curiously unrelated to time—the critical fourth dimension of geology. Instead our approach uses Earth's history as a frame for understanding minerals and the processes that created them.

We quickly realized that the story of mineral evolution began with the emergence of rocky planets, because planets are the engines of min-



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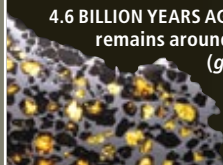
Snapshots of Mineral Genesis

In the 4.6 billion years since the solar system formed, the suite of minerals present has evolved from modest beginnings—about a dozen minerals in the presolar nebula—to better than 4,400 minerals found on Earth today. The planet has passed through a series of stages, represented at the right and in the following pages by five snapshots, involving a variety of mineral-forming processes. Some of these processes generated completely new minerals, whereas others transformed the face of the planet by turning former rarities into the commonplace.



Making Earth

4.6 BILLION YEARS AGO: Millions of planetesimals form in the disk of dust and gas that remains around the recently ignited sun (in background) and collide to form Earth (glowing planet). More than 200 minerals, including olivine and zircon, develop in the planetesimals, thanks to melting of their material, shocks from collisions, and reactions with water. Many of these minerals are found in ancient chondritic meteorites.



◀ Olivine crystals in pallasite (meteorite)



◀ Zircon

▶ Chondrite (meteorite)



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eral formation. We saw that over the past four and a half billion years Earth has passed through a series of stages, with novel phenomena emerging at each stage to dramatically alter and enrich the mineralogy of our planet's surface.

Some details of this story are matters of intense debate and will doubtless change with future discoveries, but the overall sweep of mineral evolution is well-established science. My colleagues and I are not presenting controversial new data or radical new theories about what occurred at each stage of Earth's history. We are, rather, recasting the larger story of that history in the light of mineral evolution as a guiding concept.

I do, however, want to emphasize one intriguing insight: most of Earth's thousands of minerals owe their existence to the development of life on the planet. If you think of all the nonliving world as a stage on which life plays out its evolutionary drama, think again. The actors renovated their theater along the way. This observation also has implications for the quest to find signs of life on other worlds. Sturdy minerals rather than fragile organic remains may provide the most robust and lasting signs of biology.

Making Earth

Planets form in stellar nebulas that have been seeded with matter from supernovas. Most of a nebula's mass rapidly falls inward, producing the central star, but remnant material forms a

vast rotating disk around the star. These leftovers progressively clump into larger and larger bits: sand-, pebble- and fist-size fluff balls of primordial dust harboring a limited repertoire of a dozen or so ur-minerals, along with other miscellaneous atoms and molecules.

Dramatic changes occur when the nascent star ignites and bathes the nearby concentrations of dust and gas with a refining fire. In our own solar system, stellar ignition occurred almost 4.6 billion years ago. Pulses of heat coming from the infant sun melted and remixed elements and produced crystals representing scores of new minerals. Among the crystalline novelties of this earliest stage of mineral evolution were the first iron-nickel alloys, sulfides, phosphides, and a host of oxides and silicates. Many of these minerals are found in the most primitive meteorites as "chondrules": chilled droplets of once molten rock. (These ancient chondritic meteorites also provide the evidence for the ur-minerals that predated chondrules. Mineralogists find the ur-minerals in the form of nanoscopic and microscopic grains in the meteorites.)

In the ancient solar nebula, chondrules quickly clumped into planetesimals, some of which grew to more than 100 miles in diameter—large enough to partially melt and differentiate into onionlike layers of distinctive minerals, includ-

COURTESY OF THE TEACHING COMPANY (Hazen); RON MILLER (illustrations); NATURAL HISTORY MUSEUM, LONDON (pallasite); SCIENTIFICA Getty Images (Zircon); MASSIMO BREGA Photo Researchers, Inc. (chondrite)



Black Earth

4.4 BILLION YEARS AGO: The surface of lifeless Hadean Earth is largely black basalt, a rock formed from molten magma and lava. The next two billion years see about 1,500 minerals produced. Repeated partial melting of rock concentrates scarce, dispersed elements such as lithium (found in lepidolite), beryllium (in beryl) and boron (in tourmaline). Chemical reactions and weathering by the early oceans and the anoxic atmosphere also contribute. Minerals formed under high pressure, such as jadeite, are brought to the surface by plate tectonics.



ing a dense, metal-rich core. Frequent collisions in the crowded solar suburbs introduced intense shocks and additional heat, further altering the minerals in the largest planetesimals. Water also played a role; it had been around from the beginning, as ice particles in the presolar nebula, and in the planetesimals these melted and aggregated in cracks and fissures. Chemical reactions with the resulting water generated new minerals.

Perhaps 250 different mineral species arose as a consequence of these dynamic planet-forming processes. Those 250 minerals are the raw materials from which every rocky planet must form, and all of them are still found today in the diverse suites of meteorites that fall to Earth.

Black Earth

Primordial Earth grew ever larger. Big planetesimals swallowed smaller ones by the thousands until only two major rivals remained in our orbital zip code, the proto-Earth and a much smaller Mars-size body sometimes known as Theia, after the mother of the Greek goddess of the moon. In a final paroxysm of unimaginable violence, Theia sideswiped the proto-Earth, vaporizing its outer layers and blasting 100 million trillion tons of incandescent rock vapors into space to become the moon. This scenario explains the high angular momentum of the Earth-moon system and many unusual features of the moon, including why its bulk composition matches that of Earth's



Repeated partial melting of granites concentrated rare "incompatible" elements.

mantle (the nearly 2,000-mile-thick layer that extends from Earth's iron-nickel core to the three- to 30-mile-thick crust at Earth's surface).

Following this moon-spawning collision about 4.5 billion years ago, the molten Earth began the cooling that continues to this day. Although Earth's primitive surface included dozens of rare elements—uranium, beryllium, gold, arsenic, lead and many more—that were capable of forming a diverse assortment of minerals, Theia's impact had served as a cosmic "reset." It left Earth's outer layers thoroughly mixed, with these less common elements far too dispersed to form separate crystals. Our planet was a desolate, hostile world, incessantly bombarded by nebular debris and largely covered by a veneer of black basalt, a kind of rock that is formed even in modern times when lava solidifies.

Earth's mineralogical diversity gradually increased through the aptly named Hadean eon (prior to about four billion years ago), primarily from repeated melting and solidifying of the rocky crust, as well as from weathering reactions with the early oceans and atmosphere. Over countless cycles, this partial melting and resolidifying of volumes of rock, and interactions between rock and water such as the dissolution of selected compounds, gradually concentrated uncommon elements enough to form new generations of exotic minerals.

Not every planet possesses this great mineral-



Red Earth

2 BILLION YEARS AGO: Photosynthetic living organisms have given Earth's atmosphere a small percentage of oxygen, dramatically altering its chemical action. Ferrous (Fe²⁺) iron minerals common in black basalt are oxidized to rust-red ferric (Fe³⁺) compounds. This "Great Oxidation Event" paves the way for more than 2,500 new minerals, including rhodonite (found in manganese mines) and turquoise. Microorganisms (*green*) lay down sheets of material called stromatolites, made of minerals such as calcium carbonate.



◀ Fossil stromatolite cross section



▶ Turquoise

▼ Rhodonite



In a geologic instant, photosynthesis by new kinds of algae brought about the Great Oxidation Event.

forming potential. Tiny, dehydrated Mercury and Earth's equally dry moon became frozen before much melting could occur. Consequently, we estimate that no more than about 350 different mineral species will be found on those worlds. Mars, with a modest water budget, might have fared a little better as a result of hydrous species such as clays and evaporite minerals that form when oceans dry up. We estimate that NASA probes might eventually identify as many as 500 different minerals on the Red Planet.

Earth is bigger, hotter and wetter and thus has a few other mineral-forming tricks to play. All the rocky planets experienced volcanism that poured basalt across their surfaces, but Earth (and maybe Venus, which is about equal in size) had enough inner heat to remelt some of that basalt to form a suite of igneous rocks called granitoids, including the familiar tan and gray granites of curbstones and countertops. Granites are coarse-grained blends of minerals, including quartz (the most ubiquitous grains of sand at the beach), feldspar (the commonest of all minerals in Earth's crust), and mica (which forms shiny, sheetlike mineral layers). All these minerals were produced earlier in very small quantities in large planetesimals, but they first appear in great abundance in Earth's geologic record thanks to the planet's granite-forming processes.

On Earth, repeated partial melting of gran-

ites concentrated rare "incompatible" elements that are unable to find a comfortable crystallographic home in common minerals. The resulting rocks feature more than 500 distinctive minerals, including giant crystals of species rich in lithium, beryllium, boron, cesium, tantalum, uranium, and a dozen other rare elements. It takes time—some scientists estimate more than a billion years—for these elements to achieve mineral-forming concentrations. Earth's planetary twin, Venus, may have been sufficiently active for long enough to progress this far, but neither Mars nor Mercury has yet revealed significant surface signs of granitization.

Earth gained even more mineral diversity through the planetary-scale process of plate tectonics, which generates fresh crust along chains of volcanoes, while old crust is swallowed up in subduction zones, where one plate slips under another and is returned to the mantle. Immense quantities of wet, chemically diverse rocks subducted from the crust were partially melted, causing further concentration of scarce elements. Hundreds of new minerals were produced in massive sulfide deposits, which today provide some of Earth's richest bodies of metal ore. Hundreds more mineral species first appeared at Earth's surface when tectonic forces uplifted and exposed deep rock domains with their hoard of distinctive minerals that form under high pres-

RON MILLER (Illustrations); SCIENTIFICA/Getty Images (rhodonite); TED KINSMAN/Photo Researchers, Inc. (stromatolite); E. R. DEGGINGER/Photo Researchers, Inc. (turquoise)



White Earth

700 MILLION YEARS AGO: Climate change covers the entire planet surface with one mineral—ice—for millions of years. Eventually carbon dioxide from volcanoes triggers runaway global warming, and the planet cycles between hothouse and snowball. In the hothouse phases, weathering adds large quantities of fine-grained clay minerals such as kaolinite to the landscape. Distinctive “cap carbonate” layers deposited in shallow, warming oceans include crystals six feet tall.

▲ Kaolinite

▶ Ice

sure, such as jadeite (one of two minerals better known as the gemstone jade).

All told, perhaps 1,500 different minerals found on or near Earth’s surface might have been generated by dynamic crust and mantle processes during Earth’s first two billion years. But mineralogists have catalogued more than 4,400 different mineral species. What happened to triple Earth’s mineralogical diversity?

Red Earth

The answer is life. The biosphere distinguishes Earth from all other known planets and moons, and it has irrevocably transformed the near-surface environment—most conspicuously the oceans and atmosphere but also the rocks and the minerals.

Life’s earliest manifestations—primitive single-celled organisms that “fed” on the chemical energy of rocks—cannot have had much effect on Earth’s mineralogical diversity. To be sure, geologists have found biologically mediated rock formations dating back to 3.5 billion years ago, including reefs made of calcium carbonate and so-called banded iron formations (in which iron oxides apparently lock away the first oxygen produced by life). But the land was still barren, the atmosphere at large still lacked oxygen, surface weathering was slow, and the earliest life contributed almost nothing to alter the number of minerals present or their distribution.



▲ Cap carbonate

That situation changed in a geologic instant with the rapid rise of oxygen in the atmosphere, thanks to the innovation of oxygen-producing photosynthesis by new kinds of algae. Debate still rages about this transition, called the Great Oxidation Event. In particular, researchers have not settled exactly when and how rapidly it began. But by 2.2 billion years ago atmospheric oxygen had risen to greater than 1 percent of modern levels—a small amount but enough to forever transform Earth’s surface mineralogy.

Chemical modeling by my colleagues and me suggests that the Great Oxidation Event paved the way for more than 2,500 new minerals, many of which are hydrated, oxidized weathering products of other minerals. These species of crystals are unlikely to form in an anoxic environment, so Earth’s biochemical processes appear to be responsible, directly or indirectly, for the majority of Earth’s 4,400 known mineral species.

Most of these new minerals occurred as thin coatings and rinds of altered material on existing rocks. Many rare mineral species are known from only a handful of precious crystals that weigh less than a gram. But the Great Oxidation Event had global mineralogical consequences as well. Most notably, the planet rusted—across the globe, the black basalt that previously dominated the landscape turned red as the ferrous iron (Fe^{2+}) of common basalt minerals oxidized to hematite and other rust-red ferric iron (Fe^{3+}) com-

COURTESY OF ALAN JAY KAUFMAN (cap carbonate); TED KINSMAN (photo researchers, Inc. (kaolinite)); SCIENCE SOURCE (photo researchers, Inc. (snow crystal))



Green Earth

400 MILLION YEARS AGO: Multicellular organisms have emerged, and plants have colonized the land, followed by animals. Biochemical breakdown by plants and fungi increases the weathering of rock and production of clays (mixtures of hydrated minerals) by orders of magnitude. Earth's surface takes on its modern appearance for the first time—and its modern distribution of minerals. Life directly produces minerals such as aragonite and calcite (found in everything from trilobites to human skeletons), as well as extreme rarities such as hazenite, laid down by microbes.



▲ Aragonite



▶ Fossil trilobite

pounds. From space, Earth's continents two billion years ago might have looked something like Mars, albeit with blue oceans and white clouds providing dramatically colorful contrasts.

The red color of Mars is also caused by oxidation, but its oxygen was produced by sunlight dissociating water high in the atmosphere, with the hydrogen escaping to space. That process made enough oxygen to somewhat rust the small planet's surface, though not enough to create the thousands of minerals possible on the highly oxidized, more geologically active Earth.



▲ Hazenite

White Earth

For the billion years or so after the Great Oxidation Event, little of mineralogical interest seems to have happened. This interval, dubbed the Intermediate Ocean or, more whimsically, the Boring Billion, appears to have been a time of relative biological and mineralogical stasis. The “intermediate” of the name refers to oxygen levels: ocean waters near the surface were oxygenated, yet the depths remained anoxic. The interface between these two realms gradually got deeper, but no fundamentally new life-forms emerged, nor did many new mineral species arise.

In sharp contrast to the Boring Billion, the next few 100 million years saw remarkable changes at Earth's surface. About 800 million years ago most of the planet's continents were

located in a single grand cluster near the equator, called Rodinia. Then plate tectonic forces broke up this large landmass, resulting in more coastline, greater rainfall and more rapid rock erosion—processes that sucked heat-trapping carbon dioxide from the atmosphere. As the greenhouse effect weakened and the climate cooled, the extent of polar ice grew.

The growing expanses of ice and snow reflected more sunlight back into space, reducing the sun's heating effect. The more the ice spread, the colder things got. For 10 million years or more Earth was a giant snowball, with only a few active volcanoes poking through the white veneer. By some estimates global average temperatures plunged to -50 degrees Celsius.

But Earth could not remain locked in ice forever. Volcanoes continued to belch carbon dioxide, and with no rainfall and little weathering to remove this greenhouse gas, its levels rose ever so slowly to hundreds of times modern levels, ultimately triggering a cycle of greenhouse warming. As equatorial ice melted, the runaway warming episode may have taken only a few hundred years to transform Earth from icebox to hothouse.

For the next 200 million years Earth cycled between these extremes perhaps two to four times. Although apparently few if any fresh mineral species arose during this tumultuous period, the distribution of surface minerals changed drastically with each new glacial cycle. During

RON MILLER (Illustration); E. R. DEGGINGER Photo Researchers, Inc. (Aragonite); COURTESY OF CHIP CLARK Smithsonian Institution, National Museum of Natural History (Trilobite); COURTESY OF HEXIANG TANG (Hazenite)

the hothouse phases, production of fine-grained clay minerals and other weathering products increased sharply in the barren, eroding, rocky landscape. In shallow areas of the warming oceans, carbonate minerals precipitated in giant crystal fans.

The snowball/hothouse cycles had profound consequences for life. The ice ages shut down almost every ecosystem, whereas the warming periods saw abrupt increases in biological productivity. In particular, at the end of the last big glaciation, atmospheric oxygen rose sharply from no more than a few percent to about 15 percent, produced in part by vigorous and widespread coastal algal blooms. Many biologists suggest that such high levels of oxygen were an essential prelude to the origin and evolution of large animals, with their increased metabolic demands. Indeed, the earliest known multicellular organisms appear in the fossil record just five million years after the last great global glaciation.

The geosphere and biosphere have continued to co-evolve, especially as diverse microbes and animals learned to grow their own protective mineral shells. The innovation of carbonate skeletons led to deposition of massive limestone reefs, which punctuate the world's landscapes in countless cliffs and canyons. Such minerals were not new, but their prevalence was unprecedented.

Green Earth

For almost all of Earth's history, the land was uninhabitable. Ultraviolet radiation from the sun destroys essential biomolecules and kills most cells. With higher levels of atmospheric oxygen, a protective stratospheric ozone layer developed, shielding the land below from ultraviolet rays, enough to harbor a terrestrial biosphere.

Life on land took time to thrive. Algal mats may have lived in swampy terrains following the snowball Earth, but the biggest terrestrial transformation had to await the development of mosses—the first true land plants—about 460 million years ago. Widespread colonization of the land took another 10 million years, with the rise of vascular plants, whose roots penetrate rocky ground to provide an anchor and gather water.

Plants and fungi brought with them rapid modes of biochemical breakdown of rock, increasing weathering rates of surface rocks such as basalt, granite and limestone by an order of magnitude. The abundance of clay minerals and the rate of formation of soils increased vastly, providing an ever expanding habitat for more and larger plants and fungi.

By perhaps 400 million years ago, in the Devonian period, Earth's surface had for the first time evolved to a strikingly modern appearance—green forests thrived, populated with an ever widening cast of insects, tetrapods and other creatures. And thanks to the profound influence of life, Earth's near-surface mineralogy had also achieved its modern state of diversity and distribution.

The Future of Mineral Evolution

The view of Earth's mineralogy as a dynamic, changing story points to some exciting opportunities for research. For example, different planets achieve different stages of mineral evolution. Small, dry worlds like Mercury and the moon possess simple surfaces of low mineral diversity. Small, wet Mars fared a little better. Bigger planets like Earth and Venus, with their greater stores of volatiles and inner heat, can progress further through the formation of granitoids.

But the origin of life, and the resulting co-evolution of biology and minerals, sets Earth apart. As I noted earlier, minerals may be as valuable as organic remains for identifying the signature of life on other worlds. Only those with life would likely be extensively oxidized, for instance.

Worlds with different compositions may also undergo very different mineral evolutions. Jupiter's moon Io, which is rich in sulfur, and Saturn's frigid moon Titan, replete with hydrocarbons, will have quite distinct repertoires of minerals. The same is likely true of Europa and Enceladus (moons of Jupiter and Saturn, respectively), both believed to harbor liquid oceans of water below their icy surfaces and thus to be prime sites for possible extraterrestrial life.

Viewing minerals in an evolutionary context also elucidates a more general theme of evolving systems throughout the cosmos. Simple states evolve into increasingly complicated states in many contexts: the evolution of chemical elements in stars, mineral evolution in planets, the molecular evolution that leads to the origin of life, and the familiar biological evolution through Darwinian natural selection.

Thus, we live in a universe primed for complexification: hydrogen atoms form stars, stars form the elements of the periodic table, those elements form planets, which in turn form minerals abundantly. Minerals catalyze the formation of biomolecules, which on Earth led to life. In this sweeping scenario, minerals represent but one inexorable step in the evolution of a cosmos that is learning to know itself. ■

Minerals may be as valuable as organic remains for identifying the signature of life on other worlds.

MORE TO EXPLORE

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