

# Mineral Evolution Heralds a New Era for Mineralogy

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In a recent publication in *American Mineralogist*, Hazen and Morrison (2021) proposed that mineral paragenetic mode can be defined as “a natural process by which a collection of atoms in solid and/or fluid form are reconfigured into one or more new solid forms”. The definition is based on a systematic summary of their research that spanned the last 15 years. By conducting “a systematic survey of 57 different paragenetic modes distributed among 5659 mineral species”, it was revealed that “patterns in the diversity and distribution of minerals related to their evolving formational environments” (Fig.1).

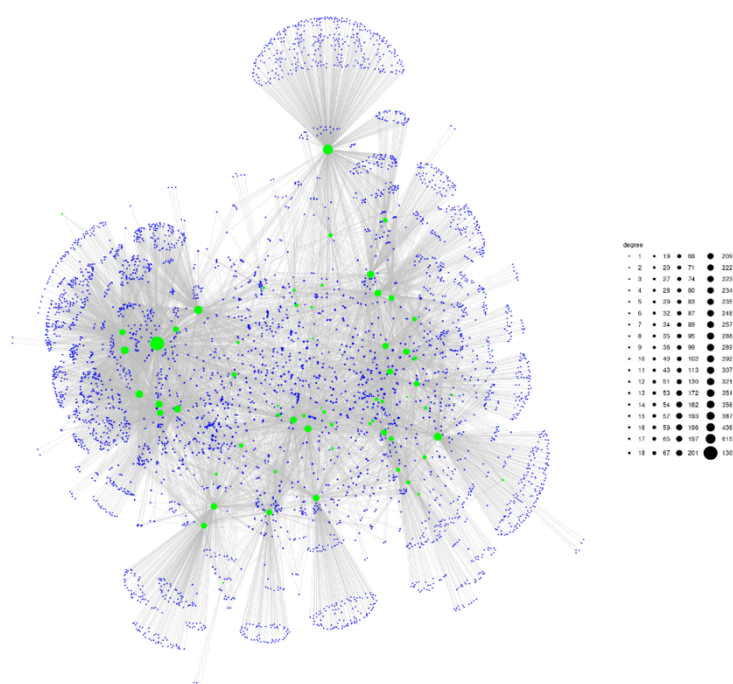


Fig.1 A bipartite network diagram, with 57 green nodes representing different paragenetic modes linked to 5659 different mineral species. Each mineral is linked to one or more paragenetic modes, while each paragenetic mode is linked to multiple minerals. There are ~12,000 links (edges) that show which minerals form by which processes.

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Important conclusions drawn from this research are as follows: 1) Water plays a dominant role in the mineral diversity of Earth and is involved in the formation of more than 80% of mineral species; 2) Life plays a direct or indirect role in the formation of ~50% of known mineral species while a third of known minerals form exclusively as a consequence of biological activities. 3) Pyrite has the most different modes of formation of any mineral species. 4) 41 rare chemical elements, which collectively account for only 1 in every 10,000 crustal atoms, are essential constituents of 42% of known minerals; i.e., rare elements play a disproportionate role in Earth's mineral diversity.

The methods and theories presented in this research serve as the basis for important advances in the field of mineral crystal chemistry and reflect the development and integration of systematicity, integrity, and evolvability in geosciences.

Research on crystal chemistry emerged from the flourishing of conventional mineralogy. Mineralogists have accumulated abundant mineralogical knowledge through a long exploration history of chemical composition, crystal structure, physical properties, and occurrence and utilization of individual minerals over the past centuries. Case analyses, scientific summaries, and phenomena descriptions of inherent features constitute the fundamental methodologies for traditional mineralogy and geology. For example, French mineralogist Haüy (1822) did pioneering works on crystallography and discovered the periodic structure inside a crystal while examining the perfect rhombohedral shapes of broken calcite specimens. Mineral crystal chemistry, including research on crystal structure and chemical composition, is largely driven by advanced physical and chemical theories, methods, and techniques. Conversely, it is crystal chemistry that contributes greatly to the development of conventional mineralogy and even to that of physics and chemistry. A classic example is provided by Russian chemist Mendeleev (1869), who formulated the Periodic Law of elements as a result of his studies on mineral crystal chemistry.

Mineral evolution research (Hazen et al., 2008), to some extent, has enriched mineral crystal chemistry. There is distinct difference between geological and chemical research objects in both time and space scale. Chemists tend to focus on microscopic reactions that occur tens of thousands of times in a second, while

geoscientists pay more attention to natural processes that occur once in tens of thousands of years on a macro level. Therefore, a systematic, integrated, and evolutionary methodology is critical for geology research. It can be said the new requirements of the burgeoning Earth system science have given rise to mineral evolution research. After accumulating a large amount of data, it is necessary not only to establish an overall cognition of the Earth, but also to reveal the general laws of complex natural systems from multiple perspectives and, more importantly, to explore geological processes and evolution over the course of more than 4.6 billion years.

In addition to the currently emphasized evolution of mineral assemblages and species, the chemical composition and crystal structure, as well as the resulting mineral properties, have evolved throughout geological history as well. A better understanding of these evolution modes would serve as a major theoretical advance in geosciences. When studying crystal structure evolution in the 1980s, Soviet mineralogist Yushkin once proposed that most of the minerals formed on the early Earth belonged to cubic system while the minerals of triclinic system, such as microcline, were almost absent before the formation of granites. In our study on the regional geology of Jiaodong, China, the evolution pattern of Cr-containing minerals from Precambrian crystalline basement, Mesozoic granites, and gold deposits supported mineral evolution as a tracer of geological processes (Lu et al., 1995). Moreover, the evolution of Mn-bearing minerals, possibly involving the Great Oxidation Event, exerts potential oxygen production and solar energy conversion functions on Earth's surface (Lu et al., 2019, 2021). During the evolution, the mineral assemblages, mineral species, chemical composition, crystal structure, trace elements, and isotopic features can be linked to specific stages of the lithosphere as well as constitute a fingerprint of mineral evolution through deep time that warrants further investigation.

The current definition of minerals does need to be further developed, though IMA has expanded the mineral formation cause from "geological process" to "natural process" in 1997. Now the solid materials formed in media such as organisms and mine dumps can be classified as new minerals. Whether or not naturally occurring particles, i.e., nanominerals, and metallic clusters with defined chemical composition, specific local structure, and relatively independent function in organisms can be

defined as minerals is discussed. There is no denying that some of the new minerals can be predicted by the characteristics of crystal chemistry, yet most new minerals were discovered passively in the past through fortune and serendipity. Therefore, as an application of mineral paragenesis theory in today's era of Big Data, the remarkable work of Hazen and Morrison (2021) provides a potential way to predictably discover possible minerals in nature.

The development from the static research of mineral crystal chemistry to the developing research of mineral evolution, especially the comprehensive consideration of the physical, chemical, and biological processes responsible for mineral formation, will bring about significant progress for mineralogy while simultaneously laying a solid foundation for modern mineralogy to remain as a basic subject of Earth system science. Nowadays, we mostly do research on the "present life" of minerals; however, the "past life" of minerals should also be addressed by mineralogical research. Usually, the "past life" of minerals is closely related to the geological process, in the way that the process of Earth evolution is often recorded in the history of mineral ontogeny and phylogeny of occurrence, development, and change. Thus, minerals can be key to reconstructing the entire "past life" and predicting the "future life" of Earth.

The study of mineral symbiosis assemblages by the method of association can also reveal principal rules closely related to mineral assemblages. The relationship between minerals and physics and chemistry is well known with emerging connections to biology. The evolution of life is closely associated with the evolution of minerals. Minerals have fundamental impacts on biological processes. For example, basic biometric symmetry is thought to be influenced by the secondary axisymmetry characteristic of early minerals. Therefore, the roles of minerals in the origin of life should also be explored as well as corresponding biological activities. As proposed by Hazen and Morrison (2021), along with the emergence of organisms, the number of mineral species boomed to over 4000. The underlying regulatory factors and formation mechanisms have become major tasks in the field of mineral evolution, the understanding of which will offer a novel path for us to be able to explore deep space and search for extraterrestrial life and habitable planets in the future.

Natural processes have been evolving from less to more, single to plural, individual to system, basic to advanced, and simple to complex, etc.. Mineral

symbiosis assemblage is the product of mineral evolution to an advanced stage, in which one mineral symbiotic assemblage may correspond to one or more natural processes. In short, the research of mineral evolution to reflect the characteristics of geological processes, based on the crystal chemistry of single mineral with powerful support from Big Data science, will certainly become increasingly important to modern mineralogy and beyond.

Congratulations to Hazen, who is honored with the 2021 IMA Medal (<https://www.ima-mineralogy.org>) for his outstanding achievements in mineral crystal chemistry, particularly in the field of mineral evolution.

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