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Highlights and Breakthroughs

Mineral evolution heralds a new era for mineralogy

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In this issue of *American Mineralogist*, Hazen and Morrison (2022) propose that a 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).

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; and (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 work in 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 a distinct difference between geological and chemical research objects in both time and space scales. 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.

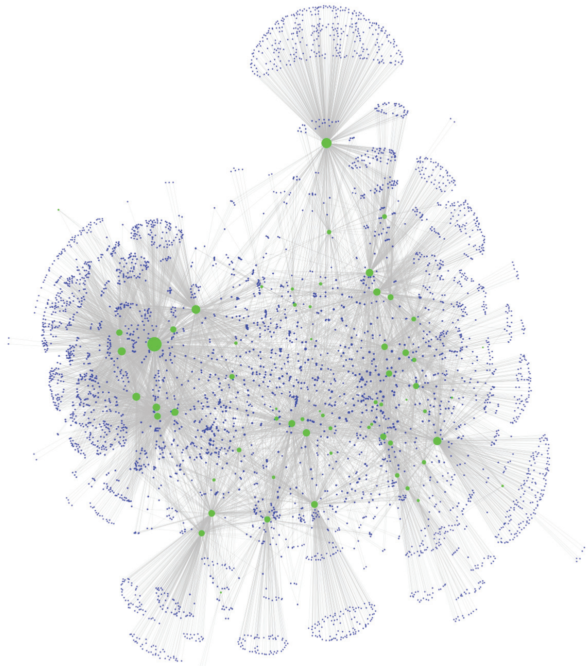

Figure 1. A bipartite network diagram, with 57 green nodes representing different paragenetic modes linked to 5659 different mineral species (denoted by blue dots). Each mineral is linked to one or more paragenetic modes, while each paragenetic mode is linked to multiple minerals. There are ~12 000 links (edges) that show which minerals form by which processes (Hazen et al. 2021). Figure courtesy of Anirudh Prabhu. (Color online.)

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

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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, Soviet mineralogist Yushkin (1987) once proposed that most of the minerals formed on the early Earth belonged to the cubic system while the minerals of the 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 and Chen 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 this 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 a mineral does need to be further developed, though the 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 (Hazen et al. 2016) and later verified (Hummer 2019). Furthermore, as an application of mineral paragenesis theory in today's era of Big Data, the remarkable work of Hazen and Morrison (2022, this issue) 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 paragenetic 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 (2022, this issue), 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 paragenetic association 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 individual minerals with powerful support from Big Data science will certainly become increasingly important to modern mineralogy and beyond.

The new contribution in this work is the first systematic categorization of paragenetic modes. Many of the individual paragenetic modes have been known for decades, but to categorize them into a cohesive system and mark when each mode began operating on Earth is a very meaningful and fundamental contribution both to mineralogy and Earth system science.

Congratulations to Robert M. Hazen, who was honored with the IMA Medal for Excellence in Mineralogical Research 2021, for his outstanding achievements in mineral crystal chemistry, particularly in the field of mineral evolution.

References cited

Haüy, R.J. (1822) Traité de cristallographie: suivi d'une application des principes de cette science à la détermination des espèces minérales, et d'une nouvelle méthode pour mettre les formes cristallines en projection. Bachelier et Huzard.

Hazen, R.M., and Morrison, S.M. (2022) On the paragenetic modes of minerals: A mineral evolution perspective. American Mineralogist, 107, 1262–1287.

Hazen, R.M., Papineau, D., Bleeker, W., Downs, R.T., Ferry, J.M., McCoy, T.J., Sverjensky, D.A., and Yang, H.X. (2008) Mineral evolution. American Mineralogist, 93, 1693–1720.

Hazen, R.M., Hummer, D.R., Hystad, G., Downs, R.T., and Golden, J.J. (2016) Carbon mineral ecology: Predicting the undiscovered minerals of carbon. American Mineralogist, 101, 889–906.

Hazen, R.M., Morrison, S.M., Prabhu, A., Eleish, A., and Fox, P. (2021) Mineral Informatics: Analysis and Visualization of Minerals through Time and Space. American Geophysical Union, Fall Meeting, New Orleans, Abstract IN13A-01.

Hummer, D.R. (2019) The Carbon Mineral Challenge: A worldwide effort to find Earth's missing carbon minerals. Australian Journal of Mineralogy, 20, 55–63.

Lu, A.H., and Chen, G.Y. (1995) Genetic Mineralogy of New subgroup of Chromo-alumino-mica with Emphasis on Genesis and Prospecting for Jiaodong-type Gold Deposits. Geological Press (in Chinese).

Lu, A.H., Li, Y., Ding, H.R., Xu, X.M., Li, Y.Z., Ren, G.P., Liang, J., Liu, Y.W., Hong, H., Chen, N., and others (2019) Photoelectric conversion on Earth's surface via widespread Fe-and Mn-mineral coatings. Proceedings of the National Academy of Sciences, 116, 9741–9746.

Lu, A.H., Li, Y., Liu, F.F., Liu, Y.W., Ye, H., Zhuang, Z.Y., Li, Y.Z., Ding, H.R., and Wang, C.Q. (2021) The photogeochemical cycle of Mn oxides on the Earth's surface. Mineralogical Magazine, 85, 22–38.

Mendeleev, D.I. (1869) Property ratio of atomic weight of elements. The Journal of Russian Chemical Society (Mendeleev Chemistry Journal), 1, 60 (in Russian).

Yushkin, N.P., Shafranovcky, I.I., and Yanulov, K.P. (1987) The law of symmetry in mineralogy. Leningrad: Nauka, 335 (in Russian).

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