This is a preproof accepted article for *Mineralogical Magazine*
This version may be subject to change during the production process
DOI: 10.1180/mgm.2026.10245

Revision #1 for *Mineralogical Magazine*—150th Anniversary Contribution—02 July 2026

Deep-Time Mineralogical Metaphors:

Arrows, Cycles, Trees, and Networks

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"My interest in scientific metaphor focuses on its role in charting our search for knowledge of a world not yet known. How else is one to seek understanding of the new, of the not yet intelligible, if not by comparison with what is already familiar? But comparison is hardly enough; a useful guide to the unknown must also keep us mindful of the strangeness, the incomparability, of novelty." Evelyn Fox Keller (2020)

Abstract

The 4.6-billion-year history of Earth's changing mineral diversity and distribution provides a robust, comprehensively documented example of an abiotic evolving system. As in evolution of other domains, including elements, organic molecules, life, and social and technological systems, minerals began simply—in this instance with a score of refractory stellar minerals. New minerals emerged through a sequence of physical, chemical, and ultimately biological processes. Stage by stage, minerals diversified through a congruent path, each stage adding complexity to what came before—a history that has led to today's inventory of more than 6200 approved mineral species.

Concepts of mineral and rock evolution have been framed using a range of metaphors, each of which captures an aspect of change through time. The unidirectional increase in diversity of

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https://doi.org/10.1180/mgm.2026.10245 Published online by Cambridge University Press

Earth's minerals through geological history suggests an "arrow of time"—a characteristic of many evolving systems that begin simply and exhibit an inexorable increase in structural and chemical complexity. Rocks and minerals also display cycles in time as they evolve—a metaphor championed by James Hutton in his transformational *Theory of the Earth*. From daily and seasonal hot/cold and wet/dry cycles to longer-term effects of gradual glaciation/deglaciation, episodic bolide impacts, and plate tectonics, many minerals form, degrade, and form anew.

Superimposed on the arrows and cycles of mineral evolution is a tree-like organization of diversifying mineral species—a hierarchical framing based on chemistry and structure that is embedded in the Dana chemical and structural system of mineral classification. In the recently proposed "Evolutionary System of Mineralogy," network analyses of the evolution and co-occurrence of minerals provide quantitative, multi-dimensional visual metaphors that emphasize the "social" aspects of mineral systems—their diverse patterns of communities and outliers, associations and antipathies—while simultaneously incorporating arrows, cycles, and trees.

Keywords: Metaphor; Mineral Evolution; Network Analysis; Rock Cycle; Classification; Deep Time

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https://doi.org/10.1180/mgm.2026.10245 Published online by Cambridge University Press

Introduction

Scientists often face the challenge of describing and explaining complex concepts and counterintuitive natural processes, both to their peers and to non-scientists. Everyday experience cannot prepare us to comprehend the universe's vast extremes of space, time, mass, and energy. Familiar vocabulary fails to capture quantum behaviors, the scale of subatomic matter, the energetics of exploding stars, or the vastness of intergalactic space. We are surrounded by mysterious, invisible phenomena—gravity, electromagnetic waves, radioactivity, dark matter, and more. Little wonder, then, that important scientific concepts often seem abstract and impenetrable to students and the general public.

Faced with this recurrent challenge, scientific metaphors and analogies provide a powerful strategy for explaining that which is "not yet intelligible … by comparison with what is already familiar" (Keller 2020; see also Hesse 1963; Keller 1995). In this regard, metaphors have long played a central, essential role in public dissemination of scientific discovery (Knudson 2003, 2005; Humar 2021; Steele et al. 2022; Beger and Smith 2023; Hilliard 2023; Smedinga et al. 2023). Examples occur in virtually every facet of science, including biology (Keller 1995), ecology (Olson et al. 2019), oncology (Camus et al. 2009), physics (Wernecke et al. 2017), Earth science (Cuadrado and Durán 2013), climate science (Deignan et al. 2019), materials science (Gruber 2023), and data science (Mitchell 2024).

As important as metaphors have become in science education and public engagement, they have proven equally vital in scientific discovery, because apt metaphors provide a powerful illustrative framework for conceptualizing, exploring, and extending scientific theories (Hesse 1963; Tourangeau and Sternberg 1982; Loettgers 2013; Haack 2019; Beger and Smith 2023).

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https://doi.org/10.1180/mgm.2026.10245 Published online by Cambridge University Press

Concepts such as genetic "code," electron "orbitals," stellar "nurseries," and ecosystem "collapse" shape scientists' views of the natural world and lead to new insights regarding nature's complex behaviors (Keller 2020).

At the same time, while metaphors and analogies may help to transform nonintuitive concepts into familiar and comprehensible patterns, they also have the potential to mislead. Associated with the advantages of timely and compelling metaphors to explain such diverse concepts as atomic "architecture," chemical "bonds," and living "cells," there is also the danger that any metaphor is not only inherently incomplete, but also ladened with potentially false implications. Such familiar descriptions as electron "clouds," bond "sharing," and cell "engines" are instructive in some ways but potentially misleading in others (Taylor and Dewsbury 2018; Sullivan-Clarke 2019; Keller 2020).

An important case in point from the geosciences relates to deeply entrenched metaphors of plate tectonics. This revolution in our conception of the dynamic Earth has played an outsized role in the past half-century of geological discovery. However, invocation of concepts such as conveyor belts, jigsaw puzzles, and rigid plates obscure critical details (Dolphin and Benoit 2016). Furthermore, the familiar associated rhetoric of "colliding" continents, "thrusting" faults, and subduction "factories" not only provide potentially misleading conceptualizations of what are, on a human scale, very gradual processes (Boroditsky 2011), but also represent "masculine-coded narratives" that have long pervaded the geosciences (Pico 2019).

In this context, while fully recognizing the potential benefits and risks of timely metaphors, we ask what is the most apt framing of mineral evolution and Earth's changing mineralogy through deep time? Several mineralogical metaphors continue to vie for that distinction.

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Deep-Time Mineralogical Metaphors

Geoscientists have long recognized that Earth's near-surface mineralogy, petrology, and geochemistry have changed dramatically through billions of years of Earth history (Bowen 1928; Goldschmidt 1937; Gastil 1960; Zhabin 1979, 1981; Yushkin 1982; Hazen et al. 2008, 2023a; Hazen and Ferry 2010; Krivovichev 2010; Liu et al. 2016). In particular, mineral diversity has increased significantly from the earliest modest inventory of ~25 minerals condensed in the expanding and cooling atmospheres of stars (Hazen and Morrison 2020), to the thousands of species produced through multiple stages of nebular and planetary processes (Morrison and Hazen 2020, 2021; Hazen and Morrison 2021; Hazen et al. 2021, 2023b; Morrison et al. 2023a, 2024; see https://rruff.net, accessed 10 March 2026). A sequence of new physical, chemical, and ultimately biological processes leads to mineral evolution on Earth and other worlds.

This evolution of minerals can be framed using a range of metaphors, each of which captures an aspect of change through deep time (Heaney 2016; Hazen 2025). In this contribution we compare four contrasting examples: arrows, cycles, trees, and networks.

Arrows: The unidirectional increase in diversity of Earth's minerals through geological history suggests an "arrow of time"—a characteristic of many evolving systems that begin simply and exhibit an inexorable increase in structural and chemical complexity (Wong et al. 2023a; Hazen and Wong 2024; Hazen and Wong 2026). The metaphor of an arrow is also widely applicable in mineralogy for any sequence of species that forms as a consequence of changing temperature, pressure, and/or composition.

Metamorphism provides familiar examples of directed mineral formation. The Barrovian sequence of index minerals is based on the appearance of new phases with increasing

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temperature and pressure: *chlorite* → *biotite* → *garnet* → *staurolite* → *kyanite* → *sillimanite*, as first outlined by Barrow (1893). In a similar vein, Bowen (1940) listed 10 calc-silicate minerals common in skarn zones in order of increasing formation temperature: *tremolite* → *forsterite* → *diopside* → *periclase* → *wollastonite* → *monticellite* → *åkermanite* → *spurrite* → *merwinite* → *larnite.*

Bowen (1928) proposed a similar kind of mineralogical sequence for igneous silicates formed under conditions of decreasing temperature, with arrows representing both mafic and feldspathic components (Figure 1). In these instances, the simplicity of the one-dimensional arrow metaphor mirrors the unidirectional evolution of a mineral sequence.

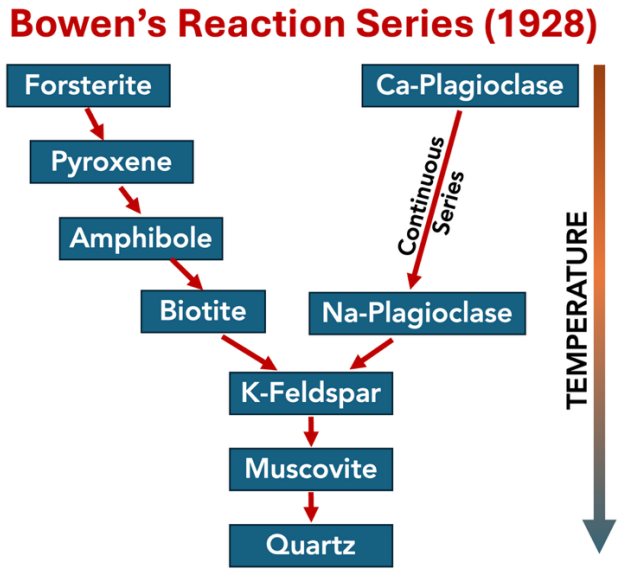


Figure 1. Norman Bowen's (1928) reaction series embeds arrows as metaphors for changes in both mafic (upper left) and feldspar (right) mineralogy in a cooling igneous melt.

Cycles: Minerals also display cycles in time as they evolve. From daily and seasonal hot/cold and wet/dry cycles to longer-term effects of gradual glaciation/deglaciation, sea level changes, and episodic bolide impacts, many minerals repeatedly form, degrade, and form anew (Ronov et al. 1969; Rubin 2018).

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The concept of the "rock cycle," introduced by James Hutton in his transformational *Theory of the Earth* (Hutton 1795) and elaborated and clarified by Charles Lyell (1830, 1832, 1833), provides a vivid visual metaphor for transitions among igneous, metamorphic, and sedimentary rocks (e.g., Figure 2). An important feature of this cycle is that it can proceed either clockwise or counterclockwise, depending on the sequence of mineralogical change.

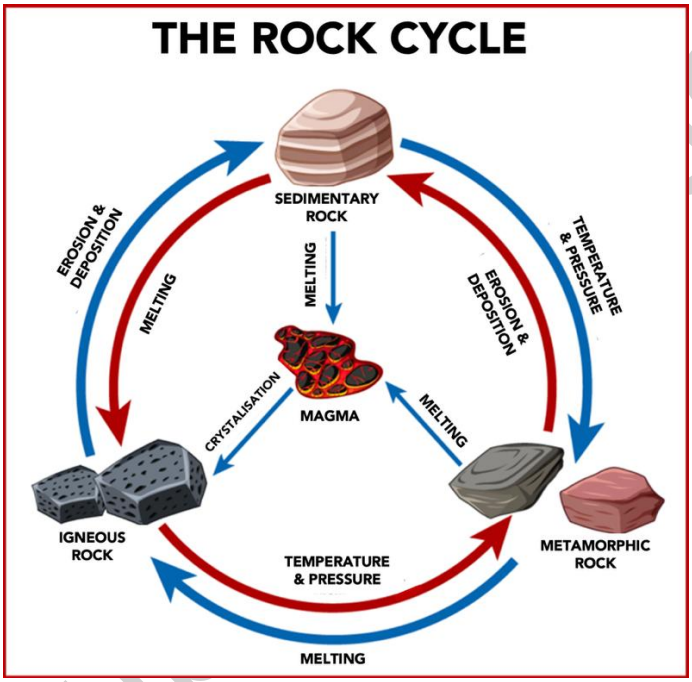


Figure 2. The rock "cycle," a familiar metaphor for the evolution of crustal rocks, illustrates the continuous transitions observed among igneous, metamorphic, and sedimentary rocks.

At a grander scale in space and time, Earth has experienced at least five supercontinent cycles, each of which was an extended period of converging continents assembled into a dominant single landmass (with associated mineralization processes) followed by the breakup, divergence, and dispersal into separate ocean-bounded continents (Barley and Groves 1992; Bozhko 2009; Bradley 2011; Hazen et al. 2014; Nance et al. 2014). In the process, supercontinent cycles have expanded Earth's mineral inventory by more than a thousand new species (Hazen and Morrison 2022; Hazen et al. 2023a). Furthermore, the cyclic formation of

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rocks and minerals via subduction of surface lithologies hundreds of kilometers into the mantle, with subsequent melting and volcanism, not only resurfaces Earth with new layers of rock, but also cycles nutrients (e.g., C, N, and S) that are essential for our planet's biosphere.

Trees: Complementing the familiar arrows and cycles of mineral evolution, Heaney (2016) also recognized a tree-like organization of diversifying mineral species—a hierarchical framing based on chemistry and structure that reflects the organization of James Dwight Dana's system of mineral classification (Dana 1850; Figure 3). In this instance, chemical and structural relationships, as opposed to changes over time, provide the basis for a branching visual metaphor of mineral diversity. As in the phylogenetic trees of biology, minerals with similar attributes (in this case chemical composition and crystal structure) are positioned most closely together in the branching tree.

However, in contrast to biological species, two mineral species that are closely related by their chemistries and structures need not also be linked through their modes of formation. Minerals do not evolve by common descent. For example, Ca-Mg-Fe-bearing members of the garnet group—phases closely associated in a mineral classification tree—have arisen through billions of years of Earth history in widely separated environments, as both primary igneous and secondary metamorphic phases. Similarly, Ca-bearing carbonates that are closely related by chemistry and structure occur variously as igneous, metamorphic, and sedimentary minerals formed in a wide range of pressure and temperature regimes, as well as via biological processes.

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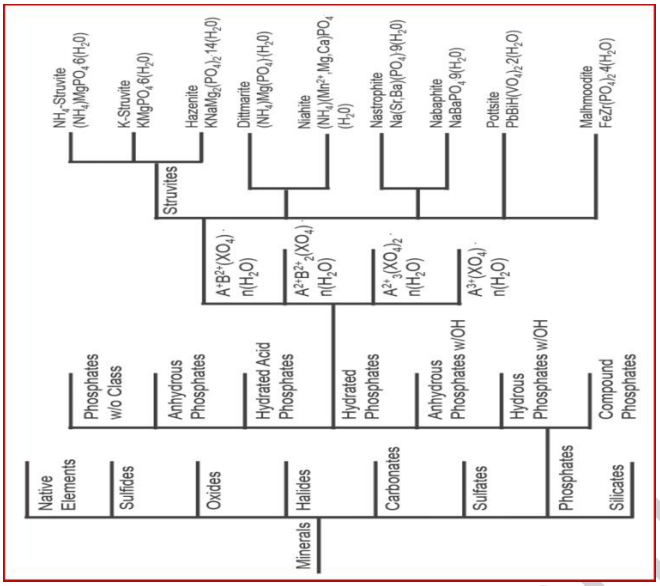


Figure 3. Dana's *System of Mineralogy* (Dana 1850) employed a hierarchical, treelike structure, not unlike Darwin's (1859) tree of life. After Heaney (2016).

Networks as Metaphors for Mineral Evolution

In their "Evolutionary System of Mineralogy," which is complementary to the standard system of classification championed by the International Mineralogical Association (Burke 2006; Mills et al. 2009; Schertl et al. 2018; Cleland et al. 2021), Hazen, Morrison, and colleagues have employed network analyses of the evolution and co-occurrence of minerals to provide multi-dimensional visualizations that simultaneously incorporate arrows, cycles, and trees (Morrison et al. 2017; Hazen et al. 2019, 2021, 2023a,b). A unipartite mineral network (e.g., Figure 4) typically features two visual elements: circular *nodes*, each of which represents a mineral species, and linear *edges* that link pairs of nodes based on mineral co-occurrence. Mineral attributes, such as abundance, chemistry, symmetry, locality, age, or hardness, can be indicated by varying the sizes, shapes, colors, and/or textures of the nodes. Because the network visualizes the relationship of each mineral species to all others, a unipartite network with *N* mineral nodes is a projection of an (*N-1*)-dimensional graph. In many network algorithms, for

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example force-directed graphs (Fruchterman and Reingold 1991; Csardi and Nepusz 2006; Bostock et al. 2011), network visualizations are interactive, allowing the user to vary the projection while interrogating the identity and connectivity of each node. The power of mineral network representations therefore lies in their ability to reveal high-dimensional associations and attributes of complex rock and mineral systems.

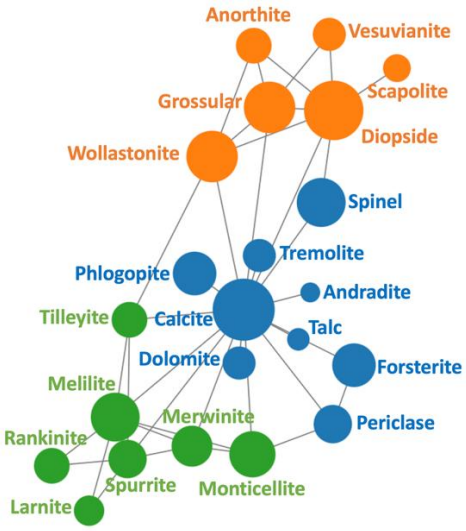


Figure 4. This unipartite network displays 22 metamorphic minerals from calc-silicate lithologies. Node sizes correspond to relative abundances, while node colors reveal three "communities" of closely associated minerals. Edges indicate pairs of minerals that commonly co-occur. This graph is derived from algorithms in Morison et al. (2024).

Not surprisingly, network science has embraced its own array of vivid metaphors related to relationships among individual nodes and their connections to the larger topology. Networks are often quantified by metrics such as "distance," "diameter," and "density." Concepts such as "communities," "associations," "landscapes," "webs," and "maps"—indeed, "network" itself—are metaphors that mirror features related to the topology of groups of nodes. Similarly, edges in interactive network visualizations are commonly referred to as "springs" or "rubber bands,

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while their interconnections include pathways," "bridges," and "holes." Given this richness of topological attributes, it is not surprising that networks embed arrows, cycles, and trees.

Network representations of mineral systems inherently cluster minerals with similar pressure-temperature-composition (*P-T-X*) formation environments in proximity, while suites of minerals with dissimilar *P-T-X* origins typically lie far apart. Consequently, mineral networks embed *P-T-X* gradients that are essentially arrows of changing formation conditions (e.g., Figure 5). For example, a network of primary igneous minerals inevitably embeds Bowen's reaction series (Morrison et al. 2017; their Figure 2B; Hazen et al. 2023b).

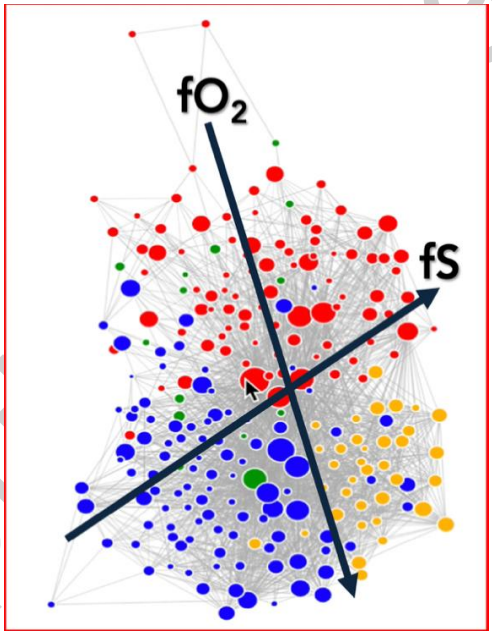


Figure 5. Mineral networks, by virtue of their structural relationships among coexisting minerals, embed arrows of temperature, pressure, and composition. This unipartite network displays 243 coexisting copper-bearing minerals. Node sizes indicate relative abundances, while node colors reveal compositional information: red = sulfur but no oxygen; blue = oxygen but no sulfur; orange = oxygen and sulfur; green = no oxygen or sulfur. The strong separation of copper minerals into different compositional groups suggests orthogonal arrows of increasing oxygen and sulfur fugacities (after Morrison et al. 2017).

Mineral systems can also be represented by bipartite networks, which employ two different kinds of nodes. For example, the evolutionary system of mineralogy employs networks in which

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nodes representing each mineral species are linked by edges to nodes representing different formation processes or environments (Figure 6; see also Hazen and Morrison 2020; Morrison et al. 2023a). In a such a bipartite network each mineral node is connected to one or more formation nodes, while each formation node is connected to one or more mineral nodes. The topology of these networks typically features peripheral fans of minerals that are only connected to one formation node, as well as dense interior arrangements of mineral nodes that are linked to multiple formation nodes (Hazen et al. 2023b; Morrison et al. 2024).

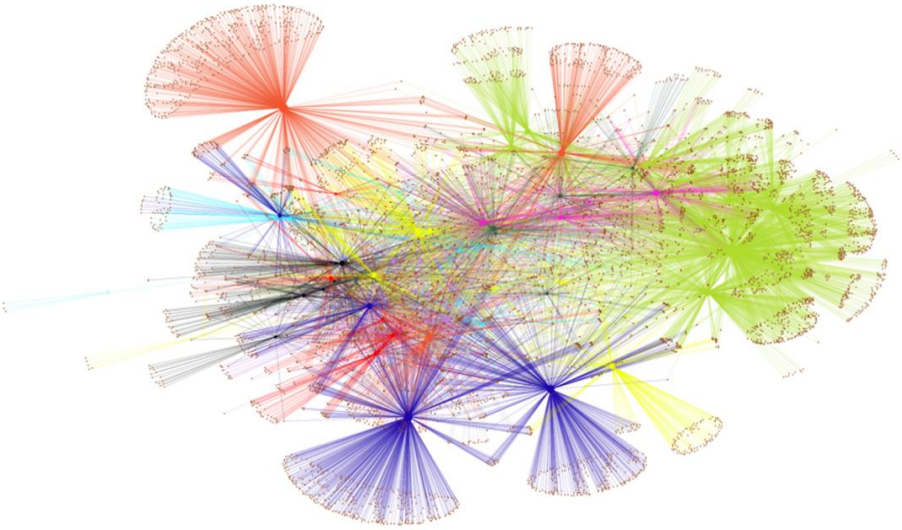


Figure 6. This bipartite network displays ~5,700 mineral nodes (small brown circles) connected to 57 different nodes representing modes of mineral formation. Edges are colored according to those formation modes (e.g., green = biologically mediated minerals; red = igneous minerals). Courtesy of Anirudh Prabhu.

Because bipartite mineral networks simultaneously display all observed combinations of minerals species and their formation processes, they inevitably embed cycles of mineral formation. For example, a cycle of mineral-forming processes related to subduction includes the seafloor crystallization of primary igneous minerals; hydrothermal alteration, including serpentinization; high-temperature alteration during

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subduction; and partial melting, magma formation, and volcanism, leading to new primary igneous minerals (Figure 7).

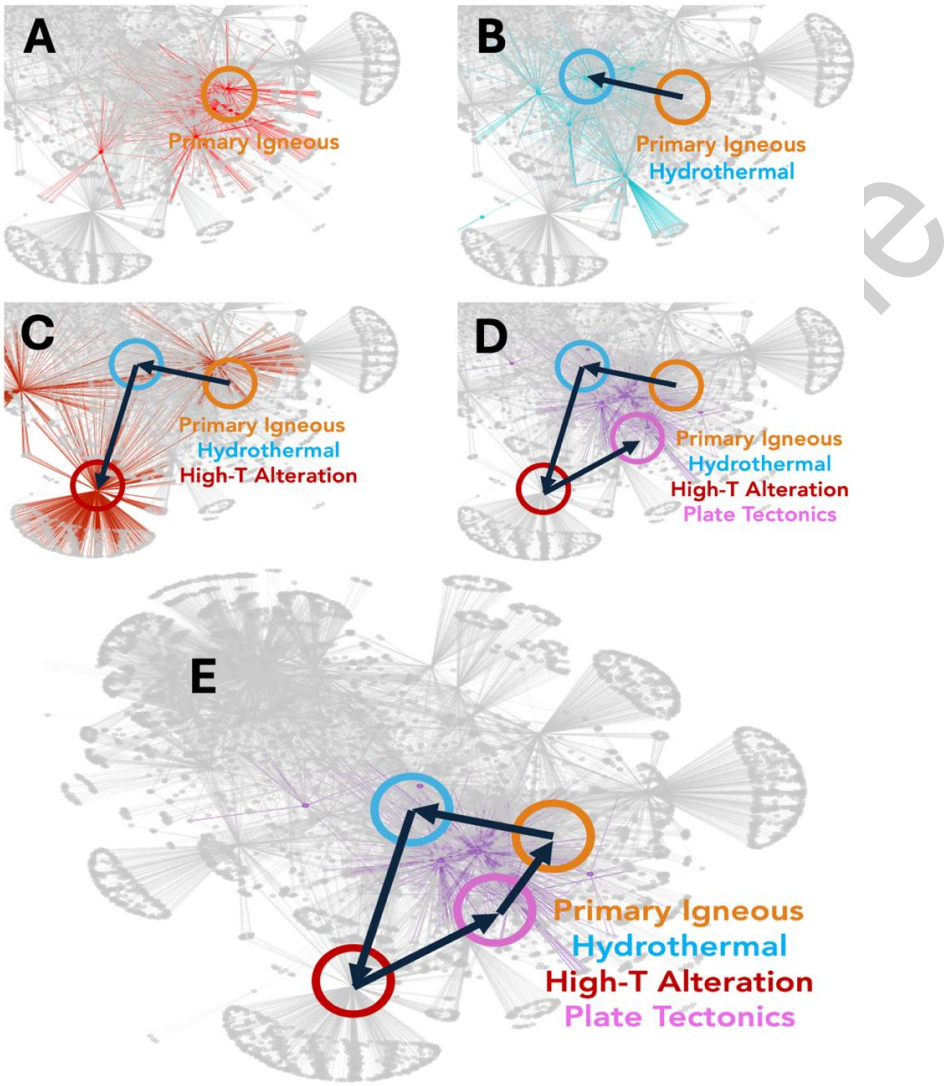


Figure 7A-E. This bipartite network of ~5700 mineral species linked to 57 different modes of formation embeds mineral cycles associated with subduction-driven plate tectonics. A sequence of four mineral-forming processes (highlighted by circles) links minerals that (**A**) initially form by seafloor crystallization of primary igneous minerals (orange circle); (**B**) then experience hydrothermal alteration, including serpentinization (blue circle); (**C**) followed by high-temperature alteration during subduction (red circle); and (**D**) then undergo partial melting, magma formation, and volcanism (purple circle), leading to new primary igneous minerals (**E**), which thus complete the cycle.

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Layered onto the embedded arrows and cycles of mineral networks are myriad tree-like arrangements of mineral associations. Each mineral node has one or more nearest neighbors, with additional nodes separated by one or more intermediate minerals. Such branching network topologies are revealing of high-dimensional relationships among nodes and can be quantified by metrics such as degree centrality, betweenness centrality, shortest path, and modularity (Barrat et al. 2004; Newman 2010). Indeed, a mineral network that assigns links based on structural and chemical similarities will inevitably embed the entire hierarchical tree of the Dana classification system.

Implications

As mineralogists and petrologists, choosing the metaphors we use to frame our field matters. Well-chosen metaphors not only illuminate science for new audiences, both students and the general public, but they also have the potential to guide the thoughts of seasoned practitioners. In the case of mineral evolution, network analysis is especially powerful in informing current thinking and guiding future research. The inherent multi-dimensionality of mineral networks enables visualization of complex chemical, structural, environmental, and other associations—aspects of the mineral kingdom not readily apparent from large, tabulated data resources.

Consider three examples of research in progress. First, a mineral association network based on carefully observed equilibrium mineral assemblages (e.g., Hazen et al. 2023b; their Figure 1) must embed every possible phase diagram for those phases, including phase diagrams with numerous compositional dimensions. Experimental determination of phase equilibria in a mineral system of 10 or more chemical components is intractable. However, a well-crafted unipartite network based on natural equilibrium mineral associations has the potential to reveal

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such high-dimensional phase equilibria, while holding the possibility of extracting thermochemical parameters of yet unmeasured minerals.

A second opportunity lies in association analysis, which facilitates the prediction of new mineral localities based on known association rules (Morrison et al. 2023b). Like individuals in any human community, each mineral species has its frequent associations, as well as antipathies. Large tabulations of known mineral occurrences at hundreds of thousands of mineral localities (*e.g.*, https://mindat.org, accessed 10 May 2026) is now leading to a deeper understanding of how the distributions of previously identified species can point to as yet undiscovered phases, including those of economic interest. Mineral networks provide the most complete and visually revealing representation of these mineral associations and antipathies—data that are helping to transform historical mineralogy into a predictive science.

Finally, important information about planetary-scale processes may lie in the network topologies of all-mineral networks. Application of network analysis to the web of molecular reactions in planetary atmospheres point to unique topological features of Earth as a living planet, thus suggesting that atmospheric networks may be valuable in the search for biosignatures on other planets and moons (Wong et al. 2023b). Ongoing work is now exploring the possibility that mineral network topologies may have distinctive feature that also reveal signs of a living planet. With the prospect of imaging aspects of the surface mineralogy of exoplanets by current and future space telescopes (Zieba et al. 2023; Hammond et al. 2025), the findings of mineral network science may play a central role in the search for life on worlds beyond our solar system.

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We conclude that mineral networks, which embed arrows, cycles, and trees in their multi-dimensional graphs, offer a uniquely relevant visual and computational metaphor for evolving mineral systems.

Acknowledgments

This contribution is dedicated to Peter J. Heaney on the occasion of his retirement from the faculty of the Pennsylvania State University. His long career and many contributions to the science and philosophy of mineralogy have engaged and informed countless scholars, and they provided the inspiration for this effort.

I thank Margaret Hazen, Peter Heaney, Yanzhang Li, Sarah Rugheimer, and Michael Wong for helpful discussions and constructive reviews of an earlier version of the manuscript. I am grateful to Associate Editor Sergey Krivovichev, Principal Editor Stuart Mills, and Managing Editor Helen Kerbey for their rapid and thoughtful handling of this contribution.

Funding

This work was supported by the Deep-time Digital Earth program, the John Templeton Foundation, a private foundation, and the Carnegie Institution for Science.

Competing interests: The author declares none.

Prepublication

https://doi.org/10.1180/mgm.2026.10245 Published online by Cambridge University Press

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