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Time's Arrow in the Trees of Life and Minerals

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Abstract

Charles Darwin analogized the diversification of species to a Tree of Life. This metaphor aligns precisely with the taxonomic system that Linnaeus developed a century earlier to classify living species, because an underlying mechanism – natural selection – has driven the evolution of new organisms over vast timescales. On the other hand, the efforts of Linnaeus to extend his "universal" organizing system to minerals has been regarded as an epistemological misfire that was properly abandoned by the late nineteenth century.

The mineral taxonomies proposed in the wake of Linnaeus can be distinguished by their focus on external character (Werner), crystallography (Haüy), or chemistry (Berzelius). This article appraises the competition among these systems and posits that the chemistry-based Berzelian taxonomy, as embedded within the widely adopted system of James Dwight Dana, ultimately triumphed because it reflects Earth's episodic but persistent progression with respect to chemical differentiation. In this context, Hazen et al.'s (2008) pioneering work in mineral evolution reveals that even the temporal character of the phylogenetic Tree of Life is rooted within a Danan framework for ordering minerals.

INTRODUCTION

In an essay dedicated to the evolutionary biologist Ernst Mayr, Stephen Jay Gould (2000) expresses his indignation at the sheer luckiness of Carolus Linnaeus (1707-1778; Fig. 1). We recognize Linnaeus (1735) as the first to propose a classification system for living species that offers both philosophical coherence and observational harmony with the natural world. The irony of Linnaeus's triumph, Gould argues, is that the Swedish naturalist accepted the Old Testament as literal truth, and by modern standards, he would be deemed a strict Biblical Creationist. Linnaean taxonomy, on the other hand, succeeds only through the actuality of organic evolution operating over millions of years – a concept that Linnaeus would have considered heretical.

A Linnaean classification of species is structured upon a tree of logic, and serial divergence is its driving methodological tenet. At every juncture in the taxonomic tree, we ask a question, and the answer to that question sorts a species among two or more categories. Does the animal have a spinal cord (phylum *Chordata*) or not (phylum *Achordata*)? Does the mammal give birth to living young (subclass *Holotheria*), or does it lay eggs (subclass *Prototheria*, as represented by the platypus)? The lineage of modern humans follows a long series of such taxonomic forks. The trunk of the human tree is a domain that consists of the eukaryotes. Branching off of this trunk are four kingdoms – protists, fungi, plants, and animals. Humans follow the *Animalia* stem, which is further subdivided to encompass our phylum (*Chordata*), our class (*Mammalia*), our order (*Primata*), our family (*Hominidae*), our genus (*Homo*), and, finally, our species (*Homo sapiens*).

Linnaeus believed that he had cracked the Divine code, and in autobiographical musings, he proclaimed, "No one has been a greater Botanist or Zoologist…[No one] has more completely changed a whole science and initiated a new epoch (Blunt 2001)". In his zeal, he did not stop with living entities. Linnaeus applied his "universal" organizing system not only to the kingdoms of animals and plants but to stones as well -- his *Regnum Lapideum*. In doing so, Gould (2000) argues, Linnaeus "clearly over-reached," because "the logic that correctly followed the causes of order in the organic world… could not be extended to cover inorganic objects *not* built and interrelated by ties of genealogical continuity and evolutionary transformation."

Though brilliantly insightful in many respects, Gould's essay perpetuates two common misunderstandings of the mineral world, and it thereby wrongly diminishes the interconnected and dynamic character of our Earth's mineralogy. The first is a misconception that modern mineral classification eschews a Linnaean structure, when for a century and a half mineralogists actually have employed a Linnaean tree to organize the mineral kingdom. The second is the implication that a Tree of Minerals is atemporal – without an intrinsic chronology. Although the Trees of Life and of Minerals exhibit important distinctions, Hazen's pioneering insights on mineral evolution (Hazen et al. 2008, Hazen 2010) reveal some significant similarities. Namely, the taxonomic tree for minerals embodies time through the temporal intensification of chemical diversity.

The Tree of Life

In Hindu and Buddhist philosophies, the Tree of Life symbolizes many things – the bond between Earth (represented by the tree root) and Heaven (the tree's canopy); the immortality that arises from repetitive cycles of death (the loss of leaves) and rebirth (the emergence of buds); and the interconnectedness of all parts of our world system. The symbol appears especially prominently in Indian art and jewelry from the Mughal (or Mogul) period from AD 1526 to 1857, and it is still invested in Eastern tapestries today (James 1966; Alin 2013; Hann 2013).

In July 1837, ten months after he returned to England from his exploration of South America aboard the HMS *Beagle*, Charles Darwin added a new layer of meaning to the Buddhist symbol. As Darwin mulled over his nascent ideas of natural selection, he sketched a branching tree in a notebook to represent organic evolution. This Tree of Life was the only drawing to illustrate the first edition of his seminal work, *On the Origin of Species* (Fig. 2; 1859). In the sixth edition (1872, pp. 104) Darwin expressed the analogy in the following way:

> The affinities of all the beings of the same class have sometimes been represented by a great tree. I believe this simile largely speaks the truth. The green and budding twigs may represent existing species; and those produced during former years may represent the long succession of extinct species. At each period of growth all the growing twigs have tried to branch out on all sides, and to overtop and kill the surrounding twigs and branches, in the same manner as species and groups of species have at all times overmastered other species in the great battle for life.

In Darwin's hands, the Tree of Life serves as a metaphor for the proliferation of new and more complex life forms from a few ancient and simpler organisms.

As with Linnaean taxonomy, divergence is the expansive principle that underlies this concept: life forms diversify over time by splitting along multiple branches from a common forebear. Whether the identity of our progenitor is *Homo heidelbergensis, Homo erectus, Homo antecessor*, or another species (De Castro et al. 1997; Asfaw et al. 2002; Stringer 2012), the emergence of the intellectually more agile *Homo sapiens* forced our predecessors to extinction. Darwin realized that when a parent produces a new variant with which it cannot compete in the game of life, it is sowing the seeds for its own destruction, but it also is ensuring the proliferation of its line. Although the Tree of Life has suffered the loss of entire boughs during major extinctions, over time it has grown bushier as multiple new life forms have branched from parental stems.

In parallel with Darwin's phylogenetic Tree of Life, the branches of the Linnaean classification system for plants and animals increase in exponential profusion. Thus, unbeknownst to Linnaeus, what connects the trunk of his taxonomic tree to its outermost leaves is *time*. Because of the guiding principle of evolution, those organisms that congregated at the base of his system were simpler, and a traverse from the roots to the canopy of the Tree of Life is a journey forward in history and complexity.

EARLY EFFORTS AT MINERAL CLASSIFICATION

In the 1758 version of Linnaeus's *Systema*, which introduced the binomial nomenclature that labeled us as *Homo sapiens* and dogs as *Canis familiaris*, Linnaeus partitioned the class of Minerals into three orders: *Salia*, *Sulphura*, and *Mercuralia*. These terms may seem to translate into salts, sulfides, and mercury-containing compounds, but chemistry was not the over-arching organizing principle for Linnaeus. Most members of Mercuralia did not contain mercury, and many of today's well-known gems (Table 1) are grouped together in the same family of "colored, quartz-like soda minerals" (*Nitrum quartzosum coloratum*). Linnaeus did not know the chemical formulas for all of these minerals, and, as the reader may surmise, the Latin translations of Linnaeus's modifiers are colors: purple, red, blue, green, and yellow.

The emphasis on color was characteristic of the school of thought handed down to Linnaeus over many centuries (Laudan 1987). The Persian scholar Ibn Sīnā (Latinized to Avicenna, who lived circa AD 980-1037) proposed a mineral classification that distinguished minerals primarily on their external characteristics. Separating minerals on the basis of observable physical qualities such as color, shape, hardness, or density is the root of what came to be known as the *natural* classification system, and it prevailed through the next eight centuries (Eddy 2008). For example, Abraham Gottlob Werner (1749-1817), professor at the mining academy in Freiberg, proposed a widely used system that included seventy-seven varieties of color, with red alone apportioned into fifteen types: blood-red; flesh-red; scarlet-red; cherry-red; morning-red; and so forth. In his *Treatise on the*

External Characteristics of Fossils, Werner (1774) argued that "External Characters are thoroughly complete, certainly discriminative, most generally known, easily defined, and conveniently discovered, and hence principally and peculiarly related to oryctognosy (*ibid.* pp. 8)" – the last an archaic term that Werner coined for the science of mineral identification that is probably best left to history.

The weakness of external characteristics as a basis for mineral classification becomes evident when one considers the plight of natural historians far removed from the intellectual centers of the world. In the early 1800s, a naturalist in the United States charged with the arrangement of a mineral cabinet was forced to rely on gifts of specimens from foreign mineral collectors or on written mineral descriptions from European treatises (Greene and Burke 1978). The natural classification system of Werner challenged these early American scholars with imponderable questions: Is an unknown specimen straw-yellow or wine-yellow? Are the crystal shapes tubuliform or fistuliform? Is the external surface scaly or rough? A proper system for describing any kind of object relies on universal constants as the touchstones for classification.

Alternatives to the natural system: Chemistry and crystallography. The historiography of chemistry has been biased by a focus on the "gas revolutions" associated with Joseph Priestley and Antoine Lavoisier (Donovan 1996; Johnson 2008), but the importance of mineralogy in precipitating advances in chemistry has been clearly documented (Burke 1969; Laudan 1987; Anderson 2000; Eddy 2005, 2008). In the latter half of the eighteenth century, chemical mineralogy grew in importance due to the exploitation of minerals for economic and medicinal purposes, and the professionalization of the field can be traced to the emergence of mining schools, such as the Freiberg Mining Academy (established in Saxony in 1765), and to medical schools in which "chymie" required studies of local minerals, as at the University of Edinburgh.

Researchers in Sweden and in Scotland approached the problem of mineral classification from a distinctly different vantage than did Werner. Rather than describing the external attributes of a mineral with great exactitude, Johan Gottschalk Wallerius (1709-1785), Axel Fredrik Cronstedt (1722–1765), and John Walker (1731-1803) argued that the essence of a mineral is determined by deconstructing it into its most fundamental components (Eddy 2008). Admittedly, these investigators were hamstrung by a combination of challenges: their arsenal of chemical techniques for mineral decomposition was limited to heat and to dissolution in water, acids, and alkalis; and they worked within a metaphysical brew of Aristotelian and Paracelsian principles that classified all materials into such primary categories as Water, Earths, Salts, Inflammables, and Metals.

Although natural historians of the period tended to treat the natural and chemical approaches to mineral classification as immiscible philosophies, even the most ardent believers borrowed liberally from the other camp. Werner (1774, pp. 3), for example, acknowledged that "the composition is the most essential feature of minerals," and his focus on external features was grounded explicitly in pragmatism rather than principle. Likewise, John Walker, the Regius Professor of Natural History at the University of Edinburgh from 1779 to 1803, asserted that "the most useful System of Fossils [i.e., minerals], must therefore be a mixed method, founded on their Natural & Chemical Qualities combined," and Walker adopted the classes, orders, genera, and species of the Linnaean system in his chemistry-based classification framework (Eddy 2008, pp. 125-131).

In an effort to contravene this muddle, the French cleric René-Just Haüy (1743-1822) claimed to have discovered the key that would neatly unite both factions. Following his famous accident with a shattered calcite crystal, Haüy introduced geometry as a means of separating mineral species, and his ideas honored the spirit of both the natural and the artificial schools. In agreement with the latter, Haüy believed that interior elements defined a mineral species, but rather than deconstructing a mineral chemically, Haüy (1801) argued that the physical fracture of a mineral into its component parts – what he termed the *molécules intégrantes* – was the proper means of assaying the essential constituents of a mineral. At the same time, the precise measurement of edges and interfacial angles of cleavage fragments particularly satisfied those who were suspicious of chemically based forays into a mineral's interior. Unlike the murky world of chemistry, geometry was governed not by hypotheses but by laws that dated to Euclid.

In his proposed classification system, Haüy (1801, 1822) adopted chemistry as the criterion for the division of minerals into genera, orders, and classes along a Linnaean framework, but crystallography (as represented by the measured dimensions of cleavage fragments) served as the fundamental criterion that identified species (Burke 1968; André 2013). The British *Critical Review* lauded Haüy's accomplishment (Critical Review 1802, pp. 482,486):

> "It has been observed…that the two contending classes of mineralogists – those who depend chiefly on external characters as the means of distinguishing minerals, and those who think that the distinctions must be drawn from chemical analysis – should naturally yield to each other, and unite their powers… By founding crystallography on calculation, M. Haüy has created a science which no fashion can destroy: it rests on a foundation as certain as the Newtonian system of the world; and has contributed to fill many vacuities in the series [of minerals], which were apparently wanting in former systems. The reader will find that the author's theory is simple in its method, certain in its principles – resting on facts afforded by undoubted observation and unequivocal evidence.

This appraisal was re-asserted over a century later in the publication of eight hagiographic articles on Haüy in the third volume of *The American Mineralogist*. Whitlock (1918), for example, described Haüy "as one of the most profound analytical thinkers of two centuries," comparable to Newton, Lavoisier, and Linnaeus as fathering a science.

The enthusiasm of MSA's founders for the work of Haüy is a benign case of historical revisionism, undoubtedly tied to heady discoveries in the new field of X-ray diffraction (Wherry 1918). The realization that minerals consist of regularly ordered atoms led many diffractionists to equate Haüy's *molécules intégrantes* with the Braggs' conception of the unit cell, an error that is perpetuated in many mineralogy textbooks today. Although the kernel of Haüy's idea surely is echoed in the Braggs' model of crystallinity, Haüy's integrant molecules depart in many ways from a modern understanding of unit cells. For instance, Haüy identified the fundamental building blocks of crystals not only as parallelepipeds but also as octahedra, tetrahedra, hexagonal prisms, rhombic dodecahedra, and hexagonal bipyramids. More significantly, he conflated the primary "chemical molecule" of a mineral with its physical integrant molecule. Consequently, he insisted to his dying day (Haüy 1822) that the interfacial angles and the ratios of the edges of cleavage fragments uniquely identify a mineral species, even in light of discoveries by Eilhard Mitscherlich (1794–1863) that minerals with different compositions may exhibit the same primitive form (isomorphism) and that minerals with different forms may exhibit the same composition (polymorphism).

The profusion of different systems of mineral classification raised a profound question: Was any particular approach *correct* or *true*, as the Linnaean taxonomy of organisms seemed the one ineluctable system for the grouping of organic species? Edinburgh professor John Walker thought not, and he apparently was untroubled by the absence of a single solution. In a letter to a friend, Walker asserted, "I was taught from the Professor's Chair when I was fourteen, that there was an organisation in the fossil [i.e. mineral] kingdom; but I have long learned that there is not. It is now universally admitted, that there is no seminal principle in fossils…no organization, no species, but possible combinations, innumerable as the sands of the sea. (Eddy 2008, pp. 203)"

A surprising taxonomic insight: Elements are charged. In 1814, the Swedish chemist Jöns Jacob Berzelius (1779-1848) provided the crucial insight that ultimately would lead to a universal system for mineral taxonomy. Berzelius (Fig. 3) is a name that should resonate equally with Dana and Bragg among mineralogists, but to most of us he is as obscure as are the two minerals that memorialize him – berzelianite ($Cu_{2-x}Se$) and berzeliite ($NaCa_2(Mg,Mn)_2(AsO_4)_3$). It was Berzelius who invented the system by which elements are designated by symbols: H for hydrogen, Si for silicon, and Au for gold. He also took the next step and created the molecular formula: H_2O, SiO_2, and $CaCO_3$, for example, though he used superscripts (H^2O) rather than subscripts. While these contributions may appear merely as helpmates in note-keeping, they in fact signaled Berzelius's pioneering role in the development of the atomic theory, as promoted by the English chemist John Dalton (1766-1844) at the turn of the eighteenth century. Berzelius developed new analytical techniques in chemistry and measured the weights of thousands of compounds to support Dalton's ideas. In the process he discovered the elements silicon (Si), selenium (Se), thorium (Th), and cerium (Ce), and students in his laboratory added lithium (Li) and vanadium (V) to the list (Melhado 1981; Melhado and Frdngsmyr 2003).

Berzelius was interested in more than the ultimate constituents of matter. He wanted to understand what holds the atoms in matter together. To get at the answer to this conundrum, he exploited a precursor to the electric battery called a Voltaic pile, invented by the Italian physicist Alessandro Volta (1745-1827). The essence of the Voltaic pile, as with modern batteries, is the electric potential between the negative and positive electrodes.

Berzelius was fascinated by the tendency of many minerals to self-destruct when placed in the brine of a discharging Voltaic pile, a process we now know as electrolysis. Berzelius noticed that certain elements, particularly oxygen, migrated towards the electropositive terminal, whereas most metals migrated towards the negative electrode. Consequently, Berzelius inferred from the attraction of oxygen to the positive electrode that oxygen is negatively charged, and thus most metals are positively charged. He thereby developed a new terminology still in use today: oxygen is *electronegative* and metals are *electropositive*. Most substances, he inferred, consist of negatively charged entities and positive counterparts, and mineral compounds represent a bonding of these polar opposites. Berzelius thereby laid the foundations for electrochemical dualism, a cornerstone of modern chemical theory (Levere 2001).

Significantly, Berzelius recognized that the carriers of negative charge are not always single elements like oxygen, and he devised the term “radicals” (still in use, along with his coinages “catalysis” and “polymer”) to describe these charged groups. Thus he explained that chalcocyanite ($CuSO_4$) consists of the electropositive copper bonded to the electronegative sulfate radical (Berzelius 1814). He furthermore was the first to realize that silicon typically functions not as an electropositive metal but as a component in negatively charged oxide radicals; thereby he laid the basis for our understanding that silicate complexes, such as SiO_3^{2-}, SiO_4^{4-}, and $Si_2O_5^{2-}$, serve as the backbones of the silicate minerals that make up the Earth’s crust.

An avid mineral collector, Berzelius was eager to apply his theories towards a new approach to mineral classification. Never one to shy from confrontation, he criticized the traditional natural classification system for its lack of rigor: "A mineralogical arrangement founded on the external and easily perceived characters of fossils [i.e., minerals] is extremely convenient….But this arrangement is not a *scientific* system (Berzelius 1814 pp. 10, italics added)." In contrast, Berzelius believed that when a chemical approach is adopted and the natural system excluded, "order becomes at once visible in this apparent chaos, and mineralogy assumes the character of a science (*ibid.* pp. 14)." These words were aimed directly at the disciples of Werner, who had argued the opposite point in his *Treatise on the External Characters of Fossils* (1774) – namely, that internal characters (i.e., chemical compositions of minerals) "cannot be so accurately known and defined as [external characters] – a perfect knowledge of chemistry being requisite – a science which itself is not complete (*ibid.* pp. 5)."

THE TAXONOMIC CRISIS

The weaknesses of the Wernerian and Haüyan approaches were becoming evident even to some of their adherents. Werner (1774) classified gypsum and selenite as separate mineral species because they adopt different crystal shapes even though they possess the same chemical formula ($CaSO_4 \bullet 2H_2O$) and their other physical attributes are identical. Likewise, Werner placed sapphire (Al_2O_3) in the *siliceous* genus and opal ($SiO_2 \bullet nH_2O$) in the *aluminous* genus based on his perceptions of their external characters. Moreover, the emphasis that Haüy placed on crystallography was equally problematic, as it became clear that many minerals with cubic symmetry, for example, exhibit identically shaped integrant molecules but are compositionally distinct.

The moment was ripe for Berzelius to set the situation straight. But like an ill-fated boxer, Berzelius feinted left when he should have feinted right. The electrochemical dualism championed by Berzelius posed a quandary: Should the electropositive or the electronegative component serve as the primary dividing wall in his classification system? The biological analog for this first taxonomic cut might be the absence or presence of nuclei in an organism's cells – the factor that sieves the prokaryotes (e.g., bacteria) from the eukaryotes (e.g., plants and animals). When faced with the question of grouping minerals based on either their metallic or their electronegative constituents, Berzelius opted to go positive.

The outcry from the Wernerians was immediate and intense. Thomas Thomson (1773-1852), a Scottish chemist who founded the Wernerian Natural History Society of Edinburgh in 1808, fired off a critical review in 1815, the year after Berzelius's treatise appeared:

> "The object of Berzelius in the present little work is to show that all mineral species are really chemical compounds, composed of ingredients combined in definite proportions, and capable of being classified into orders, genera, and species, according to their composition, just as may be done with the salts. Though numerous analyses of minerals exist, yet it must be confessed that these definite proportions, this chemical composition according to the atomic theory, can be perceived only in a small number of individuals; while

the great body of the mineral kingdom seems to bid defiance to the application of the laws of chemistry (Thomson, 1815, pp 304)."

Thomson pointed out, with some justification, that impurities in natural minerals and the absence of standardized methods in chemical analyses yielded a high level of variation in the formulas derived for a given species. Thus, chemistry at the time was arguably less "scientific" than an acute visual characterization of the observable external parameters of a mineral specimen.

Even more problematically for Berzelius, it was patently evident to most chemists that minerals containing the same metal – iron, for example – could exhibit completely different physical properties and should not be classified within the same family. Pyrite (FeS_2) is reflective, brassy yellow in color, and commonly shaped as cubes, whereas hematite (Fe_2O_3) is dull gray to black with reddish overtones, and crystals tend to be shaped as hexagonal plates. Clearly, a logical mineral taxonomy would stipulate that pyrite is less closely related to hematite than to chalcopyrite ($CuFeS_2$), arsenopyrite (FeAsS), or even galena (PbS). At the other end of the spectrum, Wernerian and Haüyan mineralogists recognized that carbonate minerals with different metals – calcite ($CaCO_3$), magnesite ($MgCO_3$), and siderite ($FeCO_3$) – share many similarities with respect to their crystal shapes, their tendencies to fracture as rhombs, and their hardness. Berzelius's system illogically placed these apparently fraternal species in separate families. Lastly, many minerals contain a variety of metallic elements. What does one do with almandine garnet ($Fe_3Al_2Si_3O_{12}$)? Berzelius simply classified such minerals within multiple metal families, so that in his framework complex metallic oxides were not uniquely pigeonholed.

Berzelius soon acknowledged the error of his ways, and in the 1820s he proposed a solution: *Classify minerals not according to their metallic elements but according to their electronegative constituents* (Berzelius 1824; 1826). In this revised taxonomy, minerals were grouped primarily as oxides, sulfides, silicates, carbonates, and so forth (Fig. 4). Here was the beginning of the classification system that we use today, but, as happens in the modern political arena, Berzelius's detractors cited the ease with which he flip-flopped on the issue as a weakness of his entire approach. For the next twenty-five years, mineral classification persisted in its state of disorder, as dozens of schemes that attempted in various ways to combine chemistry, crystallography, and external characters were proposed (reviewed in Nicol 1849, pp. 99-107 and Dana 1854, pp. 5-8). Mitscherlich despaired in 1824 that "everyone … is developing a system of mineralogy of his own, according to his own method; I do not expect much good will result from this. (Burke 1968)"

Perhaps not surprisingly, in light of the nationalistic factors that played into this battle among German, Scottish, Swedish and French protagonists, the system that came to be most universally adopted arose not on the European stage but from the American hinterland.

DANA'S REVELATION

James Dwight Dana (1813-1895; Fig. 5) matriculated at Yale College in 1830 to study with Benjamin Silliman, the young country's best-known scientist. Silliman single-handedly established and edited *The American Journal of Science*, which for several decades was the only national science publication in the United States (Brown 1989). Silliman organized the Yale mineral collection along Wernerian lines, and Dana hewed closely to his mentor, marrying his daughter and succeeding him as the Silliman Professor of Natural History and Geology at Yale from 1850 to 1892 (Gilman 1899).

In 1837, at age 24 and while working as Silliman's laboratory assistant, Dana published the first edition of his *System of Mineralogy* (Dana 1837). This earliest version of what would become his magnum opus was widely praised in America and in Europe – but it did *not* revolutionize the science. Dana invoked physical characteristics of minerals – crystal shape, hardness, and the quality by which minerals break, called tenacity – as his organizing parameters. Moreover, in Linnaean fashion, he divided minerals into nested hierarchies: kingdoms, phyla, orders, on down to mineral species, to which he applied a Latinate binomial nomenclature.

By mid-century, however, analytical chemical techniques in the United States had matured to the point that the superiority of the Berzelian electrochemical framework became inescapable. Dana distanced himself from the Wernerian approach in his third edition of the *System* in 1850. By the fourth edition of 1854, the separation was complete. The pain of the divorce is apparent in his preface to the third edition (Dana 1850, pp. 5):

> To change is always seeming fickleness. But not to change with the advance of science is worse; it is persistence in error; and, therefore, notwithstanding the former adoption of what has been called the natural-history system, and the pledge to its support given by the author, in supplying it with a Latin nomenclature, the whole system – its classes, orders, genera, and Latin names – has been rejected… [T]here are errors in its very foundation which make it false to nature in its most essential points: and in view of the character of these errors, we are willing it should be considered a relic of the past.

In its place, Dana provided a taxonomy "in which the Berzelian method was coupled with crystallography, in a manner calculated to display the relations of species in composition as well as form." (Dana 1854 pp. 5).

Whereas John Walker in the 1790s considered multiple classification approaches as equally valid, Dana came to recognize a "correctness" in the compositionally based approach. Tellingly, in the transitional third edition, Dana (1850 pp. 5) treated the Berzelian system as a purely heuristic device, one that operated "simply as a convenient arrangement, and not an exhibition of the true affinities of species in the highest sense of the term (pp. 5)." But by the fourth edition of 1854, Dana had fully conceded. "The progress of Science has afforded the means of giving greater precision and simplicity to this arrangement, until now it seems entitled to become the authorized method of a System of Mineralogy.

Whether regarded from a physical or chemical point of view, the groupings appear in general to be a faithful exhibition of the true affinities of the species (pp. 5)".

Dana continued to update his *System of Mineralogy* through the sixth edition in 1892, and as Schuh (2007 pp. 201) observes, he followed "an essentially chemical system" from the 1850 edition onward (Fig. 6). In short time, Dana's treatise gained in comprehensiveness and stature, with the German mineralogists Karl Friedrich Naumann (1797-1873) and Paul Heinrich von Groth (1843-1927) adopting it in modified form. The Berzelian kernel has persisted to its most recent incarnation – the eighth edition published under the title *Dana's New Mineralogy* (Gaines et al. 1997).

Dana's legacy was and is widely acknowledged. The University of Munich awarded Dana an honorary doctorate in 1870, an impressive tribute from the nation at the forefront of chemistry in the latter half of the nineteenth century. Today, internationally curated mineral databases, such as MinDat.org and WebMineral.com, serve as searchable mineral encyclopedias for professional and amateur researchers, and they organize entries by Dana classification schemes (as well as a few rival but philosophically equivalent methods). Moreover, major mineral museums around the world organize their specimens by the Dana System. For example, the U.S. Museum of Natural History arranges its vast mineral research collection, with over 350,000 specimens, "according to Dana." Although subsequent mineralogists have proposed minor variations to the Dana System, most consider Dana the godfather of modern mineral classification.

A TREE OF MINERALS?

In his *Structure of Scientific Revolutions*, the philosopher of science Thomas Kuhn (1996) argues that the transition from one paradigm to another is marked by a "gestalt" switch, in which the acceptance of a new theoretical framework requires an utter rejection of the old, to the extent that even the language used to describe the old paradigm is incompatible with the new. Though little celebrated, the shift from a Linnaean to a Berzelian taxonomy has all the markings of a Kuhnian revolution, as it forced scientists to redefine the essence of a solid from its macroscopic exterior to an unseeable – and still at the time unknowable – internal character.

As evidenced by his decision to abjure a Latinate binomial nomenclature for minerals, Dana's efforts to shed all vestiges of a Linnaean epistemology created an impression that minerals are so different from life forms that Linnaean guidelines do not apply. Stephen Jay Gould (2000) voices exactly this misapprehension in his *Natural History* article. It should be evident from the preceding discussion, however, that a Linnaean logic *is* applied to minerals. The criteria for sifting one mineral from another, however, simply are not the physical characters that Linnaeus, Werner, Haüy, and their disciples selected.

As Berzelius realized, chemistry and not external appearance or symmetry constructs the sturdiest scaffold for mineral taxonomy. The electronegative components of minerals create a hierarchical tree of branching categories into which each mineral species can logically be located. This criterion turns out to be the fundamental key because the electronegative components are what matter most in determining the physical and chemical behavior of a mineral. Dana came to accept this relationship without understanding the basis for it. Thanks to the advent of X-ray crystallography, today we do. As with biological classification, a few mineral species do face some ambiguity in their placement – for example, do we rank tourmaline as a borate (since it has BO_3^{3-} radicals) or as a silicate (since it also has $Si_6O_{18}^{12-}$ radicals)? Notwithstanding these minor issues, the Dana system has served us well for 150 years.

A corollary is that mineralogists could, if we desired, employ a Latinate binomial nomenclature like that used for life: *Oxide hematitus* for hematite, perhaps, or *Pyroxene diopsidus* for diopside. Instead, we have chosen not to emulate our biological colleagues, and we tag each mineral with a single name -- by Dana's convention, ending in the suffix –*ite*. Negative reactions to recent efforts that complicate our simple monomial system – the induction of magnesiotaaffeite-2N'2S as an IMA-approved name comes to mind – seem to have strengthened the community's desire for simplicity.

Of course, the ~4800 minerals that currently are classified as separate species in a Danan system pale in comparison with the variability of the biological world, which may include ~8.7 million species of eukaryotes, of which 1.2 million have been identified thus far (Mora et al. 2011). The lack of mineral diversity becomes even more breathtaking in light of the broad agreement among paleontologists that living species represent only 1% of all of that have ever existed (Stearns and Stearns 2000). The Tree of Life is thus about 200,000 times bushier than is the Tree of Minerals. Moreover, the Tree of Minerals exhibits comparable levels of diversity among the major stems, whereas the distribution of species within the Tree of Life is notably uneven. For example, the order of beetles is easily the largest within the animal kingdom with nearly 400,000 species. In contrast, among crustal minerals, silicates (numbering 908 in the WebMineral database) only slightly edge out phosphates (829) with respect to diversity, with native elements (132) and organic minerals (45) bringing up the rear.

THE TEMPORAL CONNECTION

Since minerals *can* be classified by a Linnaean taxonomy, to what extent may we compare a Tree of Life to a Tree of Minerals? The differences between a Darwinian Tree and a mineral Tree are structurally important, but those disparities need not blind us to some profound likenesses. The key distinction between the two classification schemes is the role of causality, which is integral to biological evolution but less apparent in mineral development. Organic species that walk the Earth today owe their existence to a sequence of progenitors that are no longer extant. Humans would not be but for the emergence of a primate species about 50 million years ago within the class of mammals, and mammals would not exist without the emergence of an organism with a spinal cord in the kingdom of animals about 550 million years ago. As the Darwinian Tree of Life matures, seasonal blooming cycles displace earlier generations of leaves, and thus one can trace time's arrow through taxonomic branches and forks that embody multiple episodes of extinction and emergence.

The Tree of Minerals is not a deciduous tree, as is the Tree of Life; it is more akin to an evergreen, in that mineral extinction is not an integral part of the mechanism by which the tree branches multiply. Moreover, unlike living systems, minerals do not share a genetic code that is continually directing the development of new body parts and the repurposing of old ones in response to changing environments. The emergence of new mineral species thus would *not* seem contingent on the appearance of phylogenetically related predecessors.

But is that completely true? As is evident even within Dana's first mineral classification system, a quality of timeliness is intrinsic to mineral taxonomy based on Berzelian principles. As one traces Dana's mineral tree from the roots through to its outer branches (Fig. 7), shades of a temporal progression are apparent, as Hazen and his collaborators have outlined in their seminal papers on mineral evolution (Hazen et al. 2008, 2012; Hazen and Ferry, 2010; Grew and Hazen 2014). Hazen's thesis is that the creation of new environments during Earth's evolution has generated new geologic "ecosystems", and as a consequence, a mineralogical version of "the survival of the fittest" instigates the appearance of novel minerals in the aftermath of global changes. Thus, were one to map all of the known minerals within a Dana tree and then color the branches by the date of their first appearance on Earth, the picture would materialize less like the work of Jackson Pollock and more like that of Georges Seurat.

As Darwin (1845) intuited from the multiplicity of finches in the Galápagos Islands, increasing specificity in adaptation to a local environment amplifies diversity. Analogously, mineral evolution has been characterized by episodic increases in chemical singularities. Just as Linnaeus did not know why his system succeeded – his "luckiness" in Gould's (2000) view – Berzelius and Dana were unaware of the geological forces that have promoted increases in chemical specificity. They had little inkling of the iron catastrophe, plate tectonics or the other forces by which elements have been distilled through endless cycles of melting and recrystallization. Nor did they know that the emergence of photosynthetic cyanobacteria 3.5 Ga ago generated a global oxygenation of the atmosphere a billion years later that likely doubled the number of crustal minerals. The products of this last efflorescence are represented in the bushiest regions of the Dana tree by the some of the most baroque mineral hydrates and complex oxides, such as the hydrous phosphate hazenite [$KNaMg_2(PO_4)_2 \cdot 14H_2O$], whose relatives seem unlikely to have predated the origin of life (Fig. 7).

Gould (2000) closes his tribute to Ernst Mayr with a footnote to the important lesson that he learned from him – "that taxonomies are active theories about the causes of natural order, not … stamp albums for housing nature's obvious facts." That principle holds because even in the absence of a clear mechanism for order, a proper taxonomy is imbued with a discernible pattern that arises from an underlying dynamic process. The Linnaean system succeeded because it contains a genetic code. Without the Linnaean taxonomy to guide Darwin's conception of speciation, no theory of evolution by the mechanism of natural selection could have ensued.

Analogously, a Berzelian/Danan system of mineral classification set the stage for our present understanding of Earth's successive cycles of chemical segregation.

A chemically based taxonomy bested the competition because it embodies something true about developmental mechanisms in Earth's mineralogy. Unlike the Tree of Life, however, whose driving mechanism for divergence has remained the same since the Cambrian explosion, the Tree of Minerals is complicated by a progressive variation in the styles of chemical segregation responsible for mineral evolution. In this respect, time's arrow is more subtly enshrouded within the Tree of Minerals than of Life, but as our understanding of Earth's history deepens, the outlines of the arrow grow more apparent.

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Tables

Table 1. Selected Gem Minerals from the family *Nitrum quartzosum coloratum* (Linnaeus 1758)

Linnaean Name	Modern Gem Name	Formula
N.Q. purpureum	Amethyst	SiO_2
N.Q. rubrum	Ruby	Al_2O_3
N.Q. cæruleum	Sapphire	Al_2O_3
N.Q. viride	Emerald	$Be_3Al_2Si_6O_{18}$
N.Q. flavum	Topaz	$Al_2SiO_4(F,OH)_2$

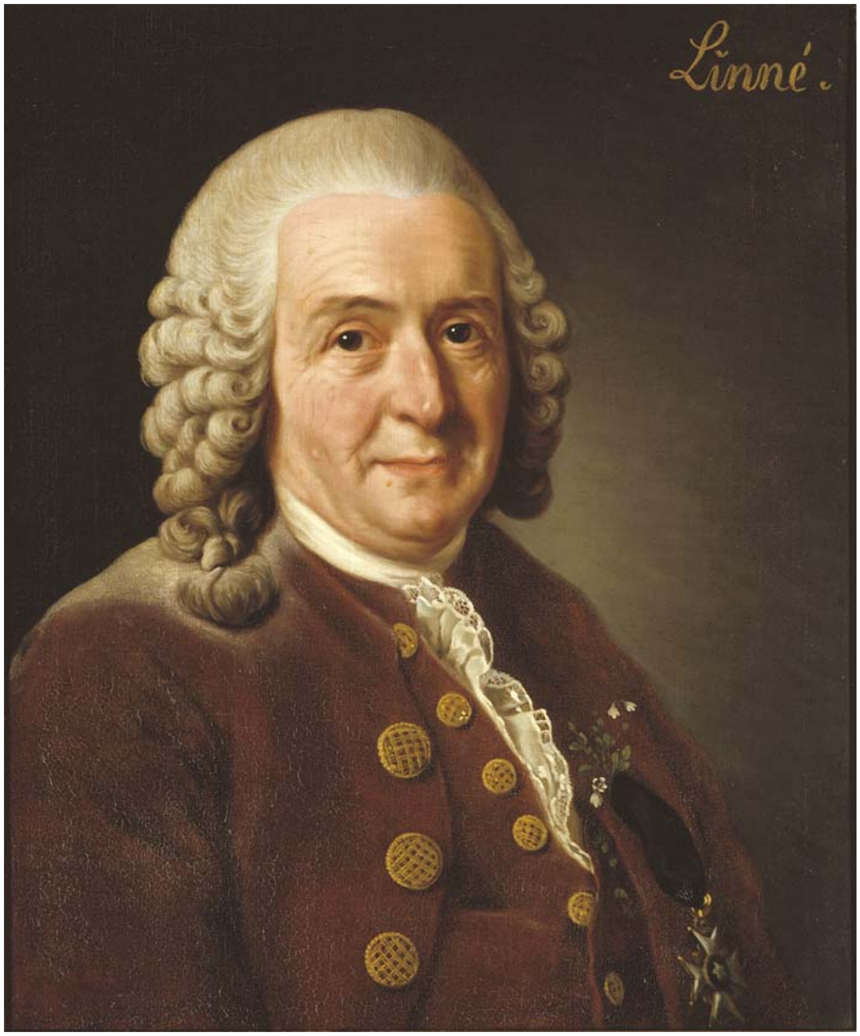

Figure 1 – Oil portrait of Carl von Linné by Alexander Roslin from the portrait collection at Gripsholm Castle, Mariefred, Södermanland, Sweden. (Public Domain)

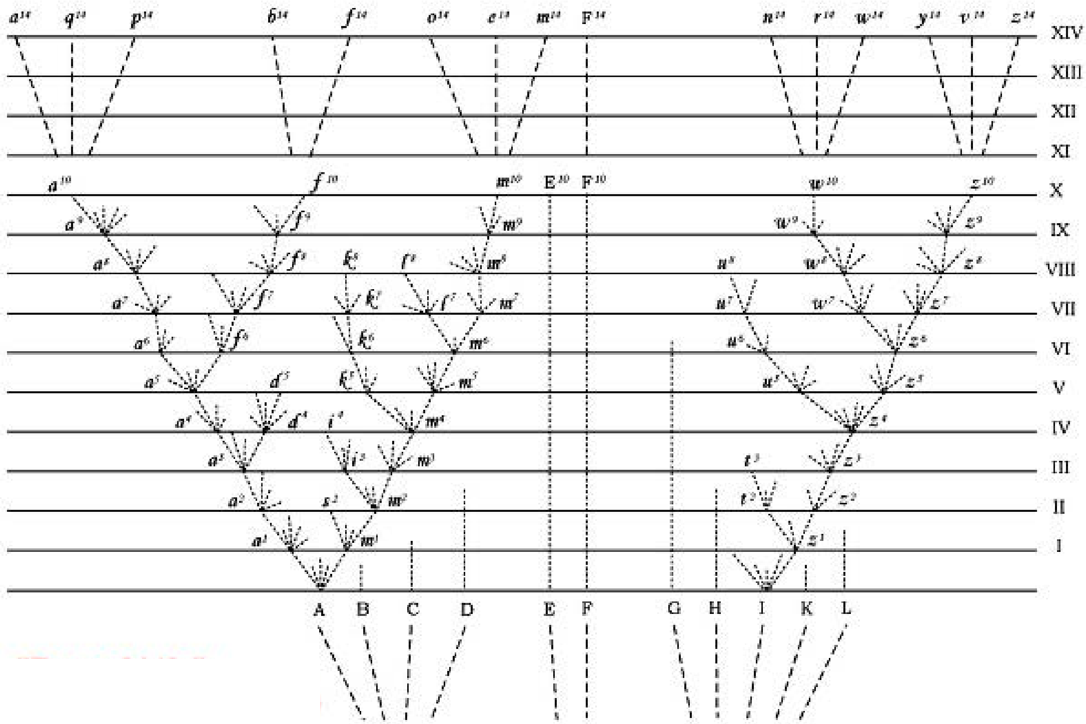

Figure 2 – The Tree of Life -- the only diagram in the 1859 edition of Darwin's *On the Origin of Species.* (Public Domain)

Figure 3 -- Daguerreotype of Jöns Jacob Berzelius by an unknown portraitist. (Public Domain)

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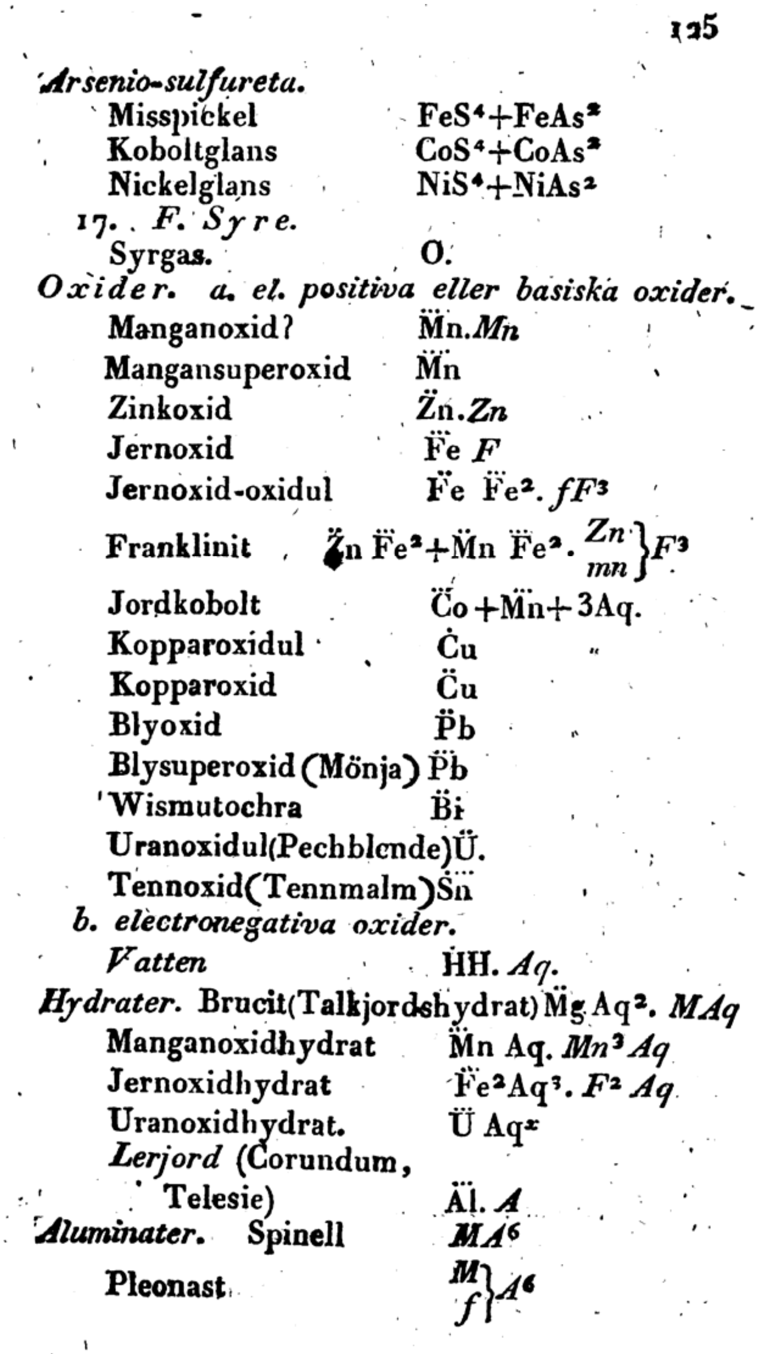

125

Arsenio-sulfureta.

Misspickel	FeS^4+FeAs^2
Koboltglans	CoS^4+CoAs^2
Nickelglans	NiS^4+NiAs^2

17. *F. Syre.*

Syrgas.	O.

Oxider. a. el. positiva eller basiska oxider.

Manganoxid?	$\ddot{Mn}.Mn$
Mangansuperoxid	$\dddot{Mn}$
Zinkoxid	$\ddot{Zn}.Zn$
Jernoxid	$\dddot{Fe}$ F
Jernoxid-oxidul	$\dddot{Fe}\ \ddot{Fe}^2.\ fF^3$
Franklinit	$\ddot{Zn}\ \dddot{Fe}^2+\ddot{Mn}\ \dddot{Fe}^2.\ \left.\begin{matrix}Zn\\mn\end{matrix}\right\}F^3$
Jordkobolt	$\dddot{Co}+\ddot{Mn}+3Aq.$
Kopparoxidul	$\dot{Cu}$
Kopparoxid	$\ddot{Cu}$
Blyoxid	$\ddot{Pb}$
Blysuperoxid (Mönja)	$\dddot{Pb}$
Wismutochra	$\dddot{Bi}$
Uranoxidul(Pechblende)	$\ddot{U}$.
Tennoxid(Tennmalm)	$\dddot{Sn}$

b. electronegativa oxider.

Vatten	$\dot{H}H.\ Aq.$

Hydrater. Brucit(Talkjordshydrat) $\ddot{Mg}\,Aq^2.\ MAq$

Manganoxidhydrat	$\ddot{Mn}\ Aq.\ Mn^3Aq$
Jernoxidhydrat	$\dddot{Fe}^2Aq^3.\ F^2\ Aq$
Uranoxidhydrat.	$\ddot{U}\ Aq^x$
Lerjord (Corundum, Telesie)	$\ddot{Al}.\ A$

Aluminater. Spinell MA^6

Pleonast	$\left.\begin{matrix}M\\f\end{matrix}\right\}A^6$

Figure 4 – The first classification of minerals based on the electronegative component from Berzelius (1824, p. 125). This excerpt includes sulfides, oxides, and hydrates.

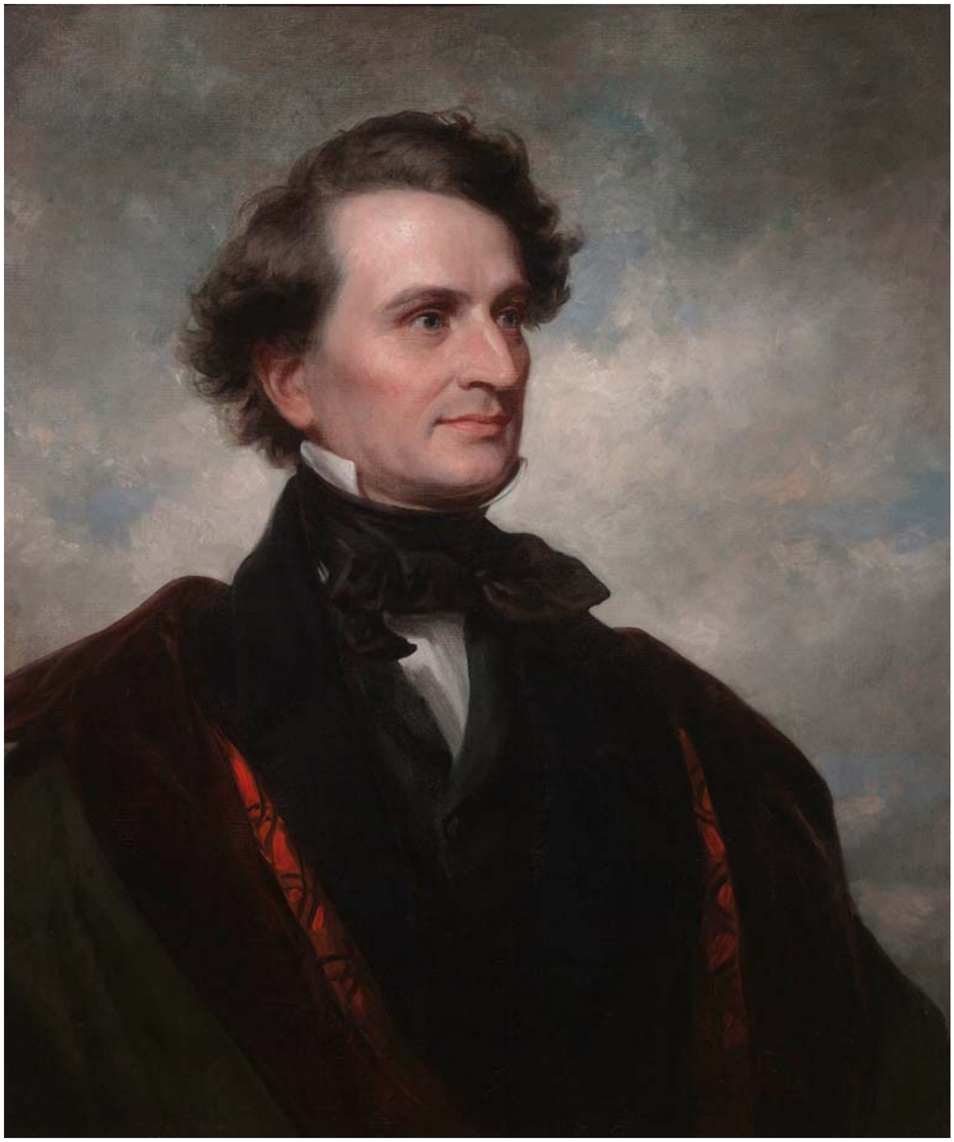

Figure 5 – Portrait of James Dwight Dana by the American artist Daniel Huntington. Courtesy of the Yale Art Gallery, Yale University, New Haven, Conn. (Public domain)

Dana's (1854) Classification of Minerals

I. Native elements

II. Sulfides, Arsenides, Antimonides, Selenides, and Tellurides

III. Chlorides, Bromides, and Iodides

IV. Fluorides

V. Oxides

  A. Simple Oxides

  B. Ternary Oxides

    i. Silicates

    ii. Tantalates and Columbates

    iii. Phosphates, Arsenates, Vanadates

    iv. Borates

    v. Tungstates, Molybdates, Chromates

    vi. Sulfates

    vii. Carbonates

VI. Hydrocarbons

Figure 6 – Modern representation of the taxonomic tree from Dana's fourth (1854) edition of his *System*.

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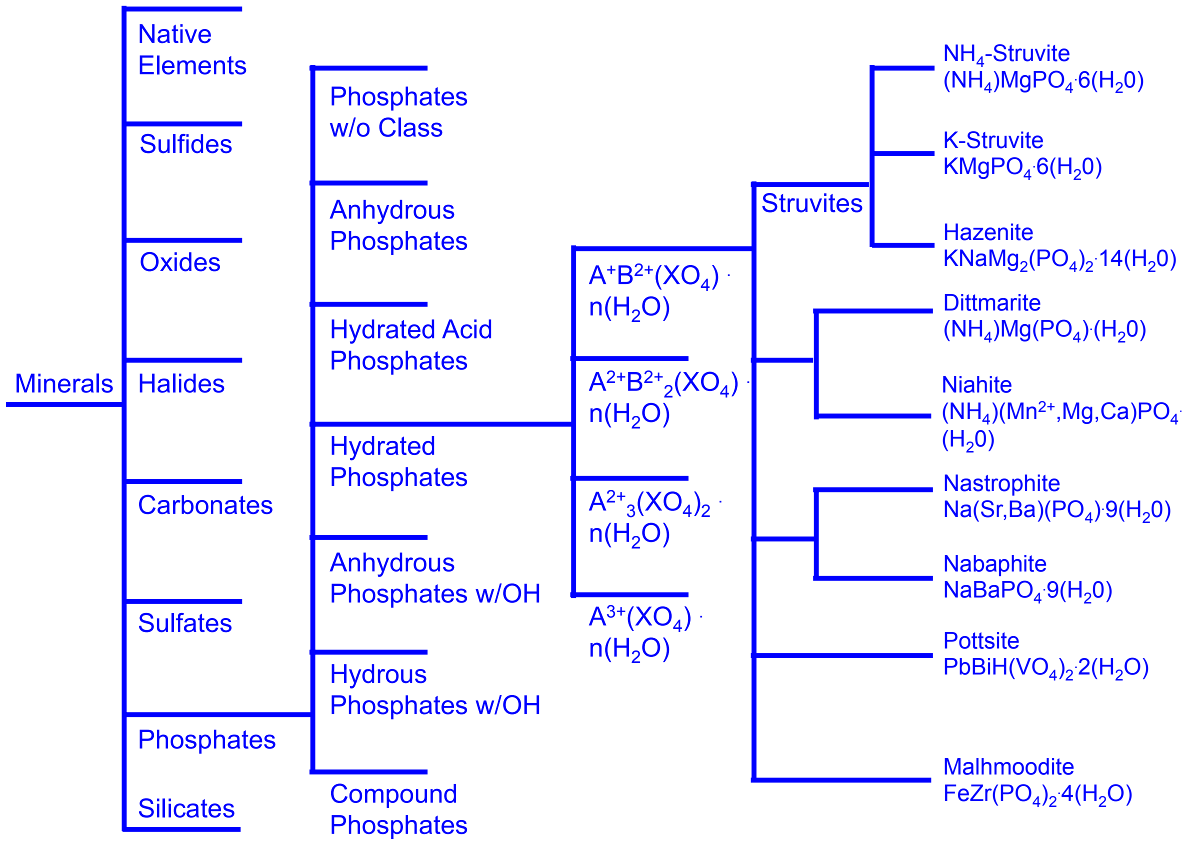

Figure 7 – A clade of hydrated phosphates from the Dana classification system from WebMineral.com.