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Reply to "A comment on 'An evolutionary system of mineralogy: Proposal for a classification of planetary materials based on natural kind clustering'"

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ABSTRACT

I welcome the "Comment" from Hatert et al. (2020) related to the proposal for an "Evolutionary system of mineralogy" (Hazen 2019) and thank them for their historically informed, conceptually nuanced, and consistently constructive contribution. They offer corrections related to two facets of my paper that seemed unfairly to criticize aspects of the International Mineralogical Association's Commission on New Minerals, Nomenclature and Classification (IMA-CNMNC) protocols for classifying minerals.

First, they note an unfortunate inferred ambivalence with respect to the relationship between the IMA system and the new evolutionary system. If I was once ambivalent, that view has changed. Having spent the past two years in an ongoing effort to develop this new historical approach, I am struck every day by the power of the IMA-CNMNC system of species classification and nomenclature, *which is fundamental and indispensable to the science of mineralogy*. As Hatert et al. suggest, any new approach to organizing natural solids, including one focused on planetary evolution, must rest on the foundation provided by the IMA-CNMNC and its many volunteers who selflessly bring order to the mineral kingdom. In the best scenario, the evolutionary system may one day emerge as one of several useful approaches that

complements and amplifies, but in no way replaces, this core IMA-CNMNC foundation, as clearly stated in the abstract of Hazen (2019).

Second, Hatert et al. (2020) offer corrections regarding the IMA-CNMNC approach to classification, in particular a mischaracterization of the formal process to incorporate amorphous phases, poorly crystalline materials, and loosely defined "mineraloids." I am grateful for the clarifications, as well as the implication that IMA protocols may facilitate the embrace of additional such phases in the future.

Finally, I welcome the chance to explore further the emerging concept of "natural kinds" as applied to the mineral kingdom. Here, our thoughts differ. I suggest that minerals, considered in their information-rich, idiosyncratic, paragenetic contexts (in contrast to IMA-CNMNC species), have the potential to represent quintessential examples of "natural kinds." Furthermore, when viewed in their evolutionary context, minerals offer an intriguing opportunity to expand the concept of "historical natural kinds" beyond its present limited and at times controversial use in biology, into the realm of the co-evolving geosphere and biosphere.

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INTRODUCTION

In mid-2018, I began to confront a knotty problem that had been with me for more than a decade: Is there a coherent, internally consistent way to place the qualitative narrative of "mineral evolution" (e.g., Zhabin 1979, 1981; Hazen et al. 2008) into a more quantitative and rigorous framework? Since the pioneering conceptual studies of the twentieth century (Bowen 1928; Gastil 1960; Laznicka 1973; Zhabin 1979, 1981; Meyer 1981), the idea of an evolving mineral realm has had intrinsic appeal. Geoscientists realize that minerals provide the most robust and information-rich testimony for billions of years of cosmic history. From the oldest presolar moissanite grains, now dated at a remarkable ~7 billion years (Heck et al. 2020), to the biominerals of our teeth and bones forming in real time, the mineral kingdom holds the key to unlocking secrets of planetary evolution through deep time.

For more than 60 years, from the time I would spend hours every month as a rapt middle-school student studying the fabled "Dana Collection" housed in row upon row of slant-topped glass displays at the American Museum of Natural History, I embraced the framework that would become the IMA classification system. I proudly displayed a growing collection on groaning bedroom shelves, with hand-written labels citing name, formula, crystal system, and locality. I learned early on that nothing in mineralogy is more fundamental than chemical composition and crystal structure; each species is defined by virtue of its unique combination of those two attributes.

But in 2018 I was faced with a dilemma. The emerging historical narrative of mineralogy, in which new kinds of minerals arise through an evolving combination of physical, chemical, and ultimately biological processes, did not always appear to fit comfortably into the system established by the IMA-CNMNC. At that time, I still could not decide whether I could build on the richness of the IMA-CNMNC foundation, or rather be forced to abandon at least some aspects of IMA nomenclature and start over, thus in a sense rejecting decades of deeply ingrained reverence for Dana and his elegant system.

Hazen (2019) presents the case for an evolutionary system of mineralogy, but it does so with an undertone of tension – a clear reflection of my struggles at the time. At each instance where my thoughts regarding "natural kinds" diverged from IMA-CNMNC approved "species," I felt the need to justify, to defend, even to criticize (gently, I hope) the IMA approach. If you read between the lines of Hazen (2019), I think you can sense that struggle, even as you see what I hoped to accomplish.

To the extent that I questioned, rather than built on, IMA-CNMNC's approach, I was wrong. After the first two years (of what may take a decade or more) of tackling the painstaking, rigorous, and all-consuming task of developing the evolutionary system, I have come to realize that the IMA-CNMNC system is utterly indispensable and foundational to our science in general, and to my project in particular. I am awed at the deep expertise and dogged hard work of the many volunteers who serve on IMA-CNMNC and associated committees (with special thanks to the four coauthors of this Comment). Simply put, it would be impossible to make any progress on a new, complementary system of mineralogy without the foundation of the IMA-CNMNC classification to build on.

Deviations from IMA-CNMNC protocols

Given the central and defining role of the IMA-CNMNC classification, any deviations from those conventions must be carefully justified. In the context of the evolutionary system of mineralogy, we have recognized three broad types of natural solids that we handle somewhat differently than rigorous IMA-CNMNC conventions allow.

As detailed in Hazen (2019) and subsequent contributions (Hazen and Morrison 2020, 2021; Morrison and Hazen 2020, 2021; Hazen et al. 2021), in some cases we split IMA species into two or more kinds, based on different paragenetic modes that result in distinct combinations of attributes. Thus, for example, we recognize several different natural kinds of diamond – stellar, impact, and mantle diamond, for example, each with quantitatively different combinations of trace element, isotopic, and morphological characteristics. In other instances, we lump two or more closely-related IMA species if they (1) form a continuous solid solution; (2) display an intermediate composition range, either in co-existing grains or within a zoned crystal; and (3) the grains formed by the same paragenetic process. Thirdly, we recognize as minerals some amorphous phases that have not yet gone through the rigorous IMA-CNMNC vetting process.

Thus far, in the first five published parts of the evolutionary system (Hazen and Morrison 2020, 2021; Morrison and Hazen 2020, 2021; Hazen et al. 2021), we recognize 445 different natural kinds stemming from 295 "root minerals" (260 of which are IMA approved species). We have found that in the great majority of cases, notably rare minerals with only one known mode of formation (Hazen and Ausubel 2016), our natural kinds map exactly onto IMA-CNMNC approved mineral species (which are not, themselves, natural kinds—see below).

Historical Natural Kinds

Hatert et al. (2020) raise concerns regarding the invocation of "natural kinds" when classifying minerals, citing Santana (2019) in opposition to the concept. In this instance, I strongly disagree and would welcome further dialog to explore this philosophical aspect of the classification of natural objects.

Characterizing a kind as "natural" amounts to conjecturing that it represents a genuine division in nature – a grouping that is, in an important sense, independent of human conventions, interests, and actions (e.g., Hawley and Bird 2011; Bird and Tobin 2015; Cleland et al. 2020). In that context, natural kind classification is essential to the articulation of successful theories (Quine 1969; Ellis 2001; Cleland 2019). It is true that a philosophical debate continues amongst those who argue for the existence of natural kinds as intrinsic types in the natural world, versus those who suggest that all categories are merely human constructs (Hacking 1999; Laporte 2004; Magnus 2012; Bird and Tobin 2015). I suggest that most mineralogists would side with the former "realist" camp; we would agree that quartz is a "real thing" that exists in the natural world – a "genuine division" independent of our solid-state models and systems of classification.

Nevertheless, Santana (2019) is correct in stating that mineral species *as defined by the IMA-CNMNC*, i.e., based on combinations of fictive end-member compositions and idealized structures that do not exist in nature, are not natural kinds. Rather they are exceptionally useful human idealizations of natural objects. On the other hand, defining mineral kinds through cluster analysis, thereby recognizing empirically defined idiosyncratic combinations of numerous measured attributes, holds the possibility of recognizing true "natural kinds" of minerals in the most rigorous sense (even though such analyses require large data resources that do not yet generally exist).

A frontier of philosophical discussions relates to the concept of adding a temporal dimension to natural kinds, i.e., "historical natural kinds," thus extending the idea to evolving systems (Griffiths 1999; Millikan 1999; Ereshefsky 2014; Godman 2019; Cleland et al. 2020). The application of this concept to biological species has proven controversial; some philosophers of science reject the viability of historical natural kinds because they represent contingent (i.e., non-lawlike) temporal patterns (Hacking 1991; Okasha 2002; Elder 2008; Ellis 2011). In particular, the transition from one historical biological parent species to daughter species tends to be gradual and fuzzy. Philosophers of biology have invoked "founder populations" (Ereshefsky 2014)–transitional individuals, not members of either parent or daughter species. In this context, a distinct species can only be recognized in retrospect, in the highly contingent context of subsequent evolution.

Here, intriguingly, minerals may provide a new and more convincing example of *historical* natural kinds to philosophers (Cleland et al. 2020). The formation of a stellar diamond *de novo* in the atmosphere of an aged star, or an olivine phenocryst from a cooling chondrule melt, points to specific, arguably deterministic historical origin events that result in diagnostic suites of physical and chemical properties. Because these processes are deterministic, similar stellar and nebular mineral-forming processes continue to occur throughout the universe. However, in the context of Earth and our solar system, such events were tightly constrained to a time more than 4.56 billion years ago (Hazen et al. 2021), and therefore may fulfill the rigorous criteria of historical natural kinds. In this respect, mineralogy may have much to offer in debates regarding historical natural kinds.

IMPLICATIONS

Time is a relentless variable. We experience our lives as a sequence of fleeting temporal slices. Now. …. and Now. ….. and Now.

When I was much younger, I thought of minerals as eternal, aesthetic objects – crystals with unchanging physical and chemical attributes that I could probe and quantify. That each specimen came from a different time and place – that each had a story to tell – was of little import.

With advancing age, and the dwindling days remaining to explore the miraculous world of minerals, time has become a more central, poignant parameter in my science. And here, minerals are key. They provide nature's most robust, most information-rich, most eloquent records of deep time. When you hold a mineral specimen in your hand, you are grasping history – a narrative that is waiting to be unlocked.

The emerging evolutionary system of mineralogy is a struggle to build a framework, albeit an imperfect and preliminary one, that will help us to tell the epic history of minerals on Earth and other worlds. And, as Hatert et al. (2020) have reminded us, at every step of the way that framework will be constructed on the solid foundation of the IMA-CNMNC system of classification.

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