An evolutionary system of mineralogy, Part V: Aqueous and thermal alteration of planetesimals (~4565 to 4550 Ma)

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ABSTRACT

Part V of the evolutionary system of mineralogy explores phases produced by aqueous alteration, metasomatism, and/or thermal metamorphism—relicts of ancient processes that affected virtually all asteroids and that are preserved in the secondary mineralogy of meteorites. We catalog 166 historical natural kinds of minerals that formed by alteration in the parent bodies of chondritic and non-chondritic meteorites within the first 20 Ma of the solar system. Secondary processes saw a dramatic increase in the chemical and structural diversity of minerals. These phases incorporate 41 different mineral-forming elements, including the earliest known appearances of species with essential Co, Ge, As, Nb, Ag, Sn, Te, Au, Hg, Pb, and Bi. Among the varied secondary meteorite minerals are the earliest known examples of halides, arsenides, tellurides, sulfates, carbonates, hydroxides, and a wide range of phyllosilicates.

Keywords: Philosophy of mineralogy, classification, mineral evolution, natural kinds, meteorite mineralogy, thermal metamorphism, aqueous alteration, metasomatism

INTRODUCTION—HISTORICAL NATURAL KINDS

The evolutionary system of mineralogy characterizes “historical natural kinds” (Boyd 1991, 1999; Hawley and Bird 2011; Magnus 2012; Khalidi 2013; Ereshefsky 2014; Godman 2018; Cleland et al. 2020) based on paragenetic modes of minerals, as manifest in their distinctive combinations of attributes. In accord with Godman’s (2018) concept of “historical essences,” our approach to mineral classification relies on a closely linked pairing of “individuation” and “causal explanation.” In other words, mineral classification in a historical context must be based equally on diagnostic suites of mineral properties and the inferred processes by which those distinctive properties arose.

We contend that the information-rich natures of different mineral kinds, including their trace and minor elements, isotopic ratios, structural defects, solid and fluid inclusions, morphologies, zoning, twinning, and myriad other physical and chemical characteristics, are direct consequences of their physical, chemical, and/or biological modes of origin and, in many cases, subsequent alteration (Hazen 2019). The evolutionary system thus embraces the intrinsic data-rich characters and varied historical contexts of minerals while building on standard protocols of the Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association (IMA), which discriminate among mineral “species” based exclusively on idealized major element chemical composition and atomic structure (e.g., Burke 2006; Mills et al. 2009; Schertl et al. 2018; Hatert et al. 2021; Hazen 2021).

The first five parts of the evolutionary system collectively encompass the variety of condensed phases formed in presolar environments and during the first 15 to 20 Ma of the solar system, most of which are accumulated and preserved in meteorites. Part I (Hazen and Morrison 2020) cataloged stellar minerals that predate our solar nebula, i.e., prior to 4.567 Ga. Subsequently, in Part II, we explored primary interstellar and nebular condensates commencing ~4.567 Ga (Morrison and Hazen 2020), while the primary mineralogy of chondrules from ~4.566 to 4.561 Ga was the focus of Part III (Hazen et al. 2021). Part IV summarized the primary asteroidal mineralogy of non-chondritic meteorites from ~4.566 to 4.560 Ga, as well as high-pressure impact mineralogy preserved in meteorites (Morrison and Hazen 2021). Note that primary and secondary minerals in IDPs (e.g., Rietmeijer 1999; Brownlee 2016) and comets (e.g., Brownlee 2014) will be summarized in a later part of this series.

These first four parts of the evolutionary system of mineralogy were relatively straightforward in their blending of diagnostic attributes with causal explanation, as required for a valid enumeration of historical kinds (Godman 2018). For example, stellar minerals possess characteristic isotopic anomalies that derive directly from nucleosynthetic processes in evolving stars—attributes that set them apart from all other mineral occurrences. Likewise, the primary condensates of calcium-aluminum-rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs), the primary igneous phases of chondrules, and the primary minerals of differentiated asteroids display ranges of physical and chemical characteristics that reveal direct links between their presumed modes of origin and their diagnostic mineral attributes. Similarly, in the case of impact minerals, the appearance of micrometer-scale, dense high-pressure phases in the context of lower-pressure assemblages provides a clear connection between mineral properties and the rapid and violent shock events that formed them. However, in Part V we encounter a more nuanced and potentially problematic situation.

Part V continues our systematic exploration of pre-terrestrial mineralogy with an examination of “secondary” asteroidal