An evolutionary system of mineralogy. Part II: Interstellar and solar nebula primary condensation mineralogy (>4.565 Ga)

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ABSTRACT

The evolutionary system of mineralogy relies on varied physical and chemical attributes, including trace elements, isotopes, solid and fluid inclusions, and other information-rich characteristics, to understand processes of mineral formation and to place natural condensed phases in the deep-time context of planetary evolution. Part I of this system reviewed the earliest refractory phases that condense at \( T > 1000 \) K within the turbulent expanding and cooling atmospheres of highly evolved stars. Part II considers the subsequent formation of primary crystalline and amorphous phases by condensation in three distinct mineral-forming environments, each of which increased mineralogical diversity and distribution prior to the accretion of planetesimals >4.5 billion years ago.

(1) Interstellar molecular solids: Varied crystalline and amorphous molecular solids containing primarily H, C, O, and N are observed to condense in cold, dense molecular clouds in the interstellar medium (10 < \( T < 20 \) K; \( P < 10^{-13} \) atm). With the possible exception of some nanoscale organic condensates preserved in carbonaceous meteorites, the existence of these phases is documented primarily by telescopic observations of absorption and emission spectra of interstellar molecules in radio, microwave, or infrared wavelengths.

(2) Nebular and circumstellar ice: Evidence from infrared observations and laboratory experiments suggest that cubic \( \text{H}_2\text{O} \) (“cubic ice”) condenses as thin crystalline mantles on oxide and silicate dust grains in cool, distant nebular and circumstellar regions where \( T \sim 100 \) K.

(3) Primary condensed phases of the inner solar nebula: The earliest phase of nebular mineralogy saw the formation of primary refractory minerals that solidified through high-temperature condensation (1100 < \( T < 1800 \) K; \( 10^{-6} < P < 10^{-2} \) atm) in the solar nebula more than 4.565 billion years ago. These earliest mineral phases originating in our solar system formed prior to the accretion of planetesimals and are preserved in calcium-aluminum-rich inclusions, ultra-refractory inclusions, and amoeboid olivine aggregates.

Keywords: Classification, mineral evolution, natural kinds, vapor deposition, condensation, nebular mineralogy, interstellar mineralogy, chondrite meteorites

INTRODUCTION

The incremental, episodic emergence of mineral diversity and distribution through more than 13 billion years of cosmic evolution provides the basis for an “evolutionary system” of mineral classification—one that emphasizes the formation of solid phases by a progression of physical, chemical, and ultimately biological processes (Hazen et al. 2008; Hazen and Ferry 2010; Hazen 2019; Hazen and Morrison 2020). This system amplifies the official classification protocols of the International Mineralogical Association’s Commission on New Minerals, Nomenclature and Classification (IMA, CNMNC; e.g., Burke 2006; Mills et al. 2009; Schertl et al. 2018), which defines each mineral “species” on the basis of its unique combination of end-member composition and idealized crystal structure. More than 5500 approved mineral species are now recognized by the IMA system (https://rruff.info/ima; accessed 27 March 2020).

By design, the IMA classification system is predicated on identifying the minimum amount of information (as measured in bits; e.g., Krivovichev 2012, 2013) required to distinguish one species from another. Consequently, IMA procedures cannot capture the information-rich complexity of natural mineral specimens—their trace and minor elements, fractionated isotopes, structural defects, varied magnetic and electrical properties, external morphologies, solid and fluid inclusions, spectral features, petrologic environments, ages of both formation and subsequent diagenetic episodes, and myriad other attributes that have the potential to tell the story of each individual sample’s origin and alteration via interactions with a succession of environments through deep time. We conclude that IMA protocols are insufficient to classify minerals in their evolutionary contexts.

Accordingly, we propose an “evolutionary system of mineralogy” that amplifies and modifies the IMA scheme in three ways, each of which is informed by those information-rich aspects of natural mineral specimens—attributes that are the essence of historical science discovery in the “messy, uncontrollable world of nature” (Cleland 2013; see also Cleland 2011). We split some IMA species into two or more “natural kinds”—subdivisions that recognize fundamentally different idiosyncratic combinations of attributes that arise from distinct paragenetic modes. Thus, for example, we view isotopically anomalous nanoscale diamond con-