An evolutionary system of mineralogy, Part IV: Planetesimal differentiation and impact mineralization (4566 to 4560 Ma)

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ABSTRACT

The fourth installment of the evolutionary system of mineralogy considers two stages of planetesimal mineralogy that occurred early in the history of the solar nebula, commencing by 4.566 Ga and lasting for at least 5 million years: (1) primary igneous minerals derived from planetesimal melting and differentiation into core, mantle, and basaltic components and (2) impact mineralization resulting in shock-induced deformation, brecciation, melting, and high-pressure phase transformations. We tabulate 90 igneous differentiated asteroidal minerals, including the earliest known occurrences of minerals with Ba, Cl, Cu, F, and V as essential elements, as well as the first appearances of numerous phosphates, quartz, zircon, and amphibole group minerals. We also record 40 minerals formed through high-pressure impact alteration, commencing with the period of asteroid accretion and differentiation. These stages of mineral evolution thus mark the first time that high pressures, both static and dynamic, played a significant role in mineral paragenesis.

Keywords: Classification, mineral evolution, planetesimals, non-chondrite meteorites, iron meteorites, stony-iron meteorites, achondrites, differentiation, shock minerals

INTRODUCTION

The evolutionary system of mineralogy amplifies the well-established International Mineralogical Association (IMA) classification system, which is based on mineral species that display unique combinations of idealized chemical composition and crystal structure (e.g., Burke 2006; Mills et al. 2009; Schertl et al. 2018). We expand on IMA protocols by incorporating time and parageneses as central aspects of mineral classification. The emphasis is thus on the historical sequence of physical, chemical, and ultimately biological processes that led to the observed diversity and distribution of minerals on Earth, as well as on other planets and moons (Hazan et al. 2008; Haazen 2019). Previous contributions in this series considered stellar minerals that predate our solar nebula, prior to 4.567 Ga (Part I; Haazen and Morrison 2020); primary interstellar and nebular condensates commencing ~4.567 Ga (Part II; Morrison and Haazen 2020); and the primary mineralogy of chondrules from ~4.567 to ~4.563 Ga (Part III; Haazen et al. 2021).

In this contribution, we consider the primary mineralogy of planetesimals and their shattered asteroidal remnants, as preserved in diverse suites of non-chondritic meteorites (Mittlefehldt et al. 1998; Krot et al. 2014; Mittlefehldt 2014). All of these meteorites reflect large-scale igneous processing within more than 100 presumed parental asteroidal objects (Keil et al. 1994; Grady and Wright 2006), which ranged from tens to hundreds of kilometers in diameter, coupled in many cases with evidence for transformative impact events. Each non-chondritic meteorite thus tells a story of the time when gravity and high pressures first began to play central roles in mineral evolution.

Asteroids are thought to have formed within the first few million years of the solar nebula and thus experienced thermal processing, and in larger bodies melting and differentiation, associated with heating by short-lived radionuclides, as well as melting and other forms of alteration by high-energy impact processes. Accordingly, this contribution features minerals formed in two broad paragenetic categories. First, in Part IVA, we examine the primary igneous mineralogy of differentiated asteroids, encompassing a diversity of iron, stony-iron, and achondrite meteorites. In Part IVB, we consider meteoritic shock minerals that formed through various impact processes at a range of scales and intensities.

PART IVA: PRIMARY MINERALOGY OF NON-CHONDRITE METEORITES

The first rocks of the solar system were components of chondrite meteorites, whose minerals formed at high temperatures (>600 °C) and low pressures (<10^2 atm) prior to 4.56 Ga. Chondrites are sedimentary accumulations of four principal components (Kerridge and Matthews 1988; Hewins et al. 1996; Brearley and Jones 1998; Scott and Krot 2014; Rubin and Ma 2017, 2021; Russell et al. 2018; Morrison and Haazen 2020; Haazen et al. 2021): (1) inclusions, including refractory calcium-aluminum inclusions and amoeboid olivine aggregates, that formed primarily through condensation from an incandescent vapor phase near the protosun; (2) chondrules, which are igneous droplets ranging from tens of micrometers to several centimeters in diameter that formed in rapid heating and cooling environments; (3) assemblages of Fe-Ni metal alloys and other opaque phases; and (4) a fine-grained matrix (to be considered in Part V of this series). In addition, chondrite meteorites often incorporate a small fraction of presolar Stardust grains with a suite of refractory minerals that formed in the expanding, cooling atmospheres of earlier generations of stars (Clayton and Nittler 2004; Lodders and Amari 2005; Lugaro 2005; Davis 2011, 2014; Zinner 2014; Nittler and Ciesla 2016; Haazen and Morrison 2020).

The earliest stages of clumping in the solar nebula have been