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Invited Review

Silicate-bearing iron meteorites and their implications for the evolution of asteroidal parent bodies

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ABSTRACT

Silicate-bearing iron meteorites differ from other iron meteorites in containing variable amounts of silicates, ranging from minor to stony-iron proportions (~50%). These irons provide important constraints on the evolution of planetesimals and asteroids, especially with regard to the nature of metal–silicate separation and mixing. I present a review and synthesis of available data, including a compilation and interpretation of host metal trace-element compositions, oxygen-isotope compositions, textures, mineralogy, phase chemistries, and bulk compositions of silicate portions, ages of silicate and metal portions, and thermal histories. Case studies for the petrogeneses of igneous silicate lithologies from different groups are provided. Silicate-bearing irons were formed on multiple parent bodies under different conditions. The IAB/IIICD irons have silicates that are mainly chondritic in composition, but include some igneous lithologies, and were derived from a volatile-rich asteroid that underwent small amounts of silicate partial melting but larger amounts of metallic melting. A large proportion of IIE irons contain fractionated alkali-silica-rich inclusions formed as partial melts of chondrite, although other IIE irons have silicates of chondritic composition. The IIEs were derived from an H-chondrite-like asteroid that experienced more significant melting than the IAB asteroid. The two stony-iron IVAs were derived from an extensively melted and apparently chemically processed L or LL-like asteroid that also produced a metallic core. Ungrouped silicate-bearing irons were derived from seven additional asteroids. Hf–W age data imply that metal–silicate separation occurred within 0–10 Ma of CAI formation for these irons, suggesting internal heating by ^{26}Al. Chronometers were partly re-set at later times, mainly earlier for the IABs and later for the IIEs, including one late (3.60 ± 0.15 Ga) strong impact that affected the “young silicate” IIEs Watson (unfractionated silicate, and probable impact melt), Netschaëvo (unfractionated, and metamorphosed), and Kodaikanal (fractionated). Kodaikanal probably did not undergo differentiation in this late impact, but the similar ages of the “young silicate” IIEs imply that relatively undifferentiated and differentiated materials co-existed on the same asteroid. The thermal histories and petrogeneses of fractionated IIE irons and IVA stony irons are best accommodated by a model of disruption and reassembly of partly molten asteroids.

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1. Introduction

Silicate-bearing irons contain more or less silicates, often in the form of inclusions. Their existence is a bit of a conundrum, because most irons are widely accepted to have formed by the crystallization of metallic melt during differentiation in asteroidal parent bodies, a process that would be expected to separate buoyant silicate from dense metal. Iron meteorites come in two varieties, those that show good chemical evidence for fractional crystallization of metal from a large molten reservoir, and those that do not. Both can contain silicates (Table 1), although silicates are more prevalent in the non-fractional variety. The fractional irons are thought to have formed as cores in at least eleven different asteroid parent bodies (e.g., Scott and Wasson, 1975; Wasson, 1985; Haack and McCoy, 2005; Chabot and Haack, 2006; Goldstein et al., 2009). In contrast, the origin of the non-fractional irons is far less certain. Do they represent partial or incomplete differentiation? Did they form by impact processes, which possibly mixed core with mantle or crustal materials? Did they form by localized impact melting in an asteroidal megaregolith? Was a combination of these (or other) processes involved?

The IAB/IIICD and IIE groups are the main silicate-bearing iron meteorite groups. They show relatively little evidence for fractional crystallization of metal, and contain from a couple to tens of percent of silicates, mainly as millimeter to centimeter-sized inclusions (e.g., Scott and Wasson, 1975; Wasson and Wang, 1986; Choi et al., 1995; Wasson and Kallemeyn, 2002; Mittlefehldt et al., 1998; Benedix et al., 2000). Although they have been called "non-magmatic irons" (Wasson, 1985; Wasson and Wang, 1986), this is misleading as the metallic host was at least partly molten (Haack and McCoy, 2005; Chabot and Haack, 2006; Goldstein et al., 2009). In many IABs and some IIEs, silicates have "ultrametamorphosed chondrite" to "igneous" (or achondrite) assemblages. In some IAB, IIE, and ungrouped irons, the silicates are felsic, and apparently differentiated to basaltic or more evolved andesitic to rhyolitic igneous rocks (Prinz et al., 1983b; Armstrong et al., 1990; Ruzicka et al., 1999, 2006; Takeda et al., 2000, 2003a; Ruzicka and Hutson, 2010). It is not clear how such extensive silicate differentiation could have occurred in asteroidal bodies, especially in those that did not also experience extensive metal differentiation.

The IVA group is in some ways even more puzzling. Although IVA meteorites are mostly devoid of silicate and are generally agreed to have formed by fractional crystallization in a core setting (e.g., Ulff-Møller et al., 1995; Scott et al., 1996; Wasson and Richardson, 2001; Wasson et al., 2006), two members – Steinbach and São João Nepomeceno – paradoxically contain so much silicate (roughly 50%) that they are properly termed stony iron meteorites (e.g., Scott et al., 1996; Haack et al., 1996; Ruzicka and Hutson, 2006). They contain a silicate assemblage unlike those in other irons.

Silicate-bearing irons are important because they challenge our understanding of the early evolutionary processes that affected planetesimals and asteroids, and because they may offer unique insights about relationships between different meteorite groups. They may have something to tell us about the nature of core formation processes in asteroids, the processes involved in melting chondritic planetesimals to make metal-dominated or silicate-dominated asteroidal igneous rocks, and the origin of stony iron meteorites. More specifically, there are several important questions that potentially can be answered from the study of silicate-bearing irons. (1) Did they form in a fundamentally different way than other irons, i.e., in some way other than core formation? (2) To what extent and under what conditions were these meteorites heated, and how did silicates and metal avoid separation during melting? (3) What was the nature of the process by which silicate became enclosed in a metal-rich matrix? (4) What petrogenesis was involved in creating evolved (non-chondritic) silicate mineralogies and rock types in some irons? (5) How does one interpret radiometric ages, including young or discrepant ages, and can one devise an evolutionary framework for irons? (6) What implications do they have for the origin and evolution of asteroidal parent bodies