WHERE ARE THE TROILITE-RICH IRON METEORITES FROM PLANETESIMAL CORES?

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Introduction: The dearth of sulfur-rich iron meteorites, especially in groups that fractionally crystallized, is a long-standing cosmochemical enigma [1-4]. Sulfur is abundant in chondrites, e.g., metallic Fe,Ni–FeS portions of H and L chondrites contain 8.5 and 15 wt.% S, respectively [5], but very few iron meteorites have >1 wt.% S [6]. Troilite is completely soluble in molten metal but almost insoluble in Fe,Ni (Fig. 1), so that metallic melts from H and L chondrites should contain 34 and 54 vol.% troilite, respectively. This is vastly more than is observed in nearly all iron meteorites. The lack of troilite in irons has been attributed to its mechanical weakness relative to metallic Fe,Ni, higher impact erosion, greater ablation during atmospheric entry, and speed of weathering on Earth [1]. However, this explanation is not entirely convincing, especially as many stony-irons, which formed from core molten metal, are rich in troilite. We review this problem in the light of recent discoveries of Antarctic and desert iron meteorites and theoretical studies of core crystallization.

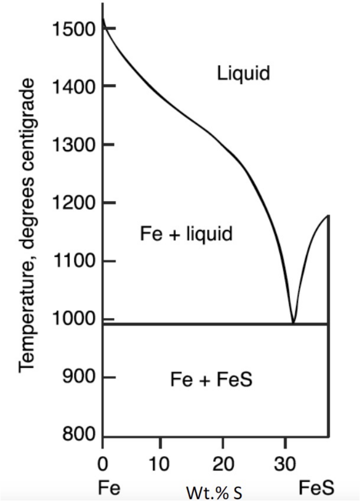

Fig. 1. Fe-FeS phase diagram [24].

Fractionally crystallized iron meteorites: The best evidence that chondritic levels of S were originally present in planetesimal cores comes from fractional crystallization modeling [3]. Simple models successfully match the distribution of Ni, Ga, Ge, Au, and Ir in three large groups of irons using experimentally determined solid-liquid distribution coefficients. Since these coefficients are very sensitive to the S concentration in the liquid, estimates of the initial S contents are well constrained (Table 1). Groups IIAB and IIIAB formed from cores that originally contained 17±1.5 and 12±1.5 wt. % S, respectively [3]. Group IIAB irons come from the first 38% of the crystallizing core; the core itself would have reached the Fe-FeS eutectic composition after 45% of the core had crystallized (Table 1; [3]).

Group IVB, which is remarkably depleted in Ga and Ge, has a very low estimated core S content and IVB irons are also S depleted (Table 1). This is likely due to volatile loss from molten metal dispersed during mantle removal [7, 8], or conceivably during partial melting [2]. Chemical trends in group IVA, which is also depleted in volatiles, cannot be modeled successfully: Ga-Au and Ge-Au trends require 9 wt.% S but Ir-Au requires 3 wt.% S [3]. However, metallic portions of the IVA Steinbach meteorite contain 4 wt.% S [9] suggesting that the original core S content was >2 wt.%. Thus, all large fractionally crystallized groups lack troilite-rich members. Only for group IVB can this be attributed to S loss prior to core crystallization.

Sulfur-rich iron meteorites: Four types of sulfur-rich iron meteorites have been discovered but none are from fractionally crystallized groups (**A-D**). Nearly all have dendritic or globular textures, chondrite-like Ir metal concentrations, cooled rapidly and very probably formed by impact melting of chondritic material [10-13]. **A)** *Group IAB complex irons* [15] including Mundrabilla (8 wt.% S [6]); Georgetown (iron), with similar S content (Fig. 2), San Cristobal and Waterville, both 3 wt.% S [6]. **B)** Cu-rich subgroup of *group IIE* irons [15] which includes Mount Howe 88403 (8 wt.% S [12]), Prospector Pool (~5 wt.% S [15]), and Meteorite Hills 00428 (3 wt.% S [12]). **C)** *S-rich ungrouped irons formed from chondritic impact melts*: Sahara 03505 (13 wt.% S [11]) and Lewis Cliff 86211 (15 wt.% S [13], Fig. 3). **D)** *Other ungrouped irons*: Soroti (12 wt.% S [6]). Soroti, San Cristobal, and Waterville lack dendrites: Soroti also has a low Ir content. Identifying S-rich irons that could be related to magmatic groups of irons is difficult as the compositional trajectory of fractionally crystallizing solids changes abruptly when the eutectic composition is reached [1, 25]. However, Cr and O isotopic compositions of ungrouped, S-rich, Ir-poor irons, e.g., Soroti and Santa Catherina [16, 25], could usefully be analyzed to test possible relationships.

Fate of S-rich residual molten metal in cores: The abundance of irons with S contents of 3-15 wt.%, which are clearly not from asteroidal cores, shows that S-rich irons can survive in space and on Earth. Another process is needed to explain the missing S-rich core samples. Refs. [17] and [18] speculate that S-rich melt was lost from the group IVA metallic core due to compaction. Two detailed studies of core solidification show how late-stage S-melts may have been ejected by ferrovolcanism. Less dense, S-rich molten metal may have erupted from impact-generated fractures in the shell of a partly solidified, IVA-like exposed core [19]. Excess pressure in sulfur-rich melt pockets between dendrites may also have caused dykes to propagate into the silicate mantle forming S-rich pallasites [20]. Since mantle and crustal meteorites have not been genetically linked to any magmatic group of irons (angrites are not related to IVB irons [21]), injecting late-stage S-rich melt through dikes into the mantle is a plausible way to dispose of the S-rich melt. Mantles and crusts of the parent bodies of magmatic irons were presumably fragmented and lost in early impacts [22].

Summary: Evidence that molten cores of planetesimals originally contained chondritic S abundances comes from fractional crystallization modeling, trapped melt in the Steinbach IVA iron, and abundant troilite in many mesosiderites [23]. Many S-rich iron meteorites have been identified but nearly all are chondritic impact melts and are not depleted in Ir and other incompatible elements. Residual S-rich, Ir-poor melt may have been ejected from crystallizing cores by ferrovolcanism through impact-fractured mantle [19, 20] and lost with the associated mantle and crustal material.

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Fig. 2. Slice of the IAB complex iron Georgetown showing troilite dendrites (brown) in metallic Fe,Ni (white). Photo courtesy of Anne Black, Impactika.

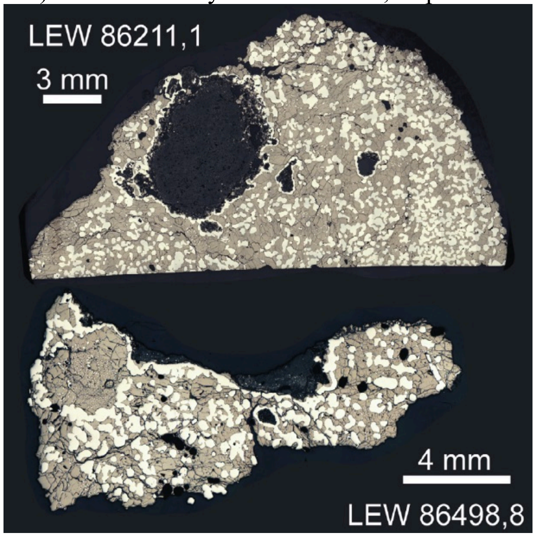

Fig. 3. Reflected light photomicrographs of the ungrouped irons LEW 86211 and 86498 from Lunning et al. [13].

Table 1. Table 1. Sulfur content of iron meteorites using planimetry [5] and core initial S and percent crystallization inferred from fractional crystallization models [3]. * Geometric mean.

Group	Sulfur content (wt.%)		Core initial	Percent crystallization*	
	Mean*	Range+	S (wt.%)	Group range	Eutectic
IIAB	0.15	0.1-0.3	17±1.5	38	45
IIIAB	0.54	0.1-2	`12±1.5	55	61
IVA	0.126	0.04-0.5	3-9		
IVB	0.031	0.02-0.05	1±1	72	97