

Sahara 03505 sulfide-rich iron meteorite: Evidence for efficient segregation of sulfide-rich metallic melt during high-degree impact melting of an ordinary chondrite

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Abstract—The Sahara 03505 meteorite is a 65 g sulfide-rich iron found in an undisclosed locality of the Sahara. It consists of roughly equal volumetric proportion of polycrystalline troilite (crystal size 1.5–7.5 mm) enclosing cellular/dendritic metallic Fe-Ni (width of the dendrite arms, ~100 µm). The mineral assemblage is completed by sparse skeletal crystals of chromite, abundant droplets, 5–100 µm in size, of anhydrous Fe-, Fe-Na-, and Fe-Mn-Mg-Ca-Na-K-phosphates, tiny crystals of schreibersite, and particles of metallic Cu.

The medium- to fine-grained quench texture, and cooling modeling suggest that Sahara 03505 formed through crystallization of a sulfur-rich metallic melt under rapid cooling conditions (1–4 °C s⁻¹). The low troilite/metallic Fe-Ni ratio (~0.6 by weight) shows that this liquid was generated at much higher temperatures (>1300 °C) with respect to the FeS-Fe,Ni cotectic liquids. Based on bulk chemistry and oxygen isotope composition of chromite, we propose that Sahara 03505 formed by extensive impact melting of an ordinary chondrite lithology, followed by the efficient segregation of the immiscible silicate and metallic liquids. The sulfur-rich metallic liquid rapidly cooled either by radiation into space as a small lump, or by conduction to a chondrite country rock as a vein intruded into the walls of an impact crater.

Sahara 03505 belongs to a small group of sulfide-rich iron meteorites which are characterized by medium- to fine-grained quench textures and by bulk chemistry that is different from the other iron meteorite groups. We propose here to use the descriptive term “sulfide-irons” for this meteorite group, by analogy with the stony-irons.

INTRODUCTION

Shock metamorphism of ordinary chondrites (OC) produces a wide spectrum of textural, mineralogical, and chemical effects that are mainly related to the energy of the impact and to the nature of the OC target material (e.g., Rubin 1985; Stöffler et al. 1988, 1991). Starting from shock stage S2, melting of OC material may occur, and at higher stages the proportion of melt may increase up to the eventual total melting of the target rock. At weak to moderate shock stages, melting is restricted mostly to metallic Fe-Ni and troilite, whereas at the highest shock levels melting involves also silicates. The segregation of metallic Fe-Ni plus troilite melts from silicates (molten or solid), and the eventual loss of sulfur by vaporization plays a prominent role in the near-surface chemical differentiation of OC parent bodies following

energetic impacts. Notwithstanding the high frequency of shocked OC showing evidence of melting and mobilization of metal + sulfide, and the occurrence of many impact-melt breccias, some of which represent highly or nearly completely melted OC (e.g., Takeda et al. 1984; Bogard et al. 1995; Mittlefehldt and Lindstrom 2001; Folco et al. 2004), discrete, centimeter-sized meteorites representing solidified metal-sulfide liquids generated by impact-melting are surprisingly very rare. Generally, the paucity of sulfide-rich iron meteorites, whichever their origin, is ascribed to their lower mechanical resistance, stronger ablation during atmospheric transit (Kracher and Wasson 1982), and faster weathering in the terrestrial environment. The study of this rare kind of extraterrestrial material is thus valuable for our understanding of the processes responsible for the chemical and mineralogical differentiation of asteroids.

Table 1. EPM analyses of metallic Fe-Ni, troilite and chromite in Sahara 03505.

n	Ni-poor metal 10	Ni-rich metal 8	Troilite 9	Chromite 5
Mg (wt%)	nd	nd	nd	<0.07
Al	nd	nd	nd	<0.04
Si	<0.02	<0.02	<0.02	<0.02
P	<0.04	<0.04	<0.04	nd
S	<0.05	<0.05	36.1–36.6	nd
Ti	nd	nd	nd	<0.03
V	nd	nd	nd	0.27–0.50
Cr	<0.03	<0.03	<0.03	44.5–45.1
Mn	<0.04	<0.04	<0.04	0.39–0.79
Fe	92.0–94.4	62.1–81.9	62.3–63.5	24.0–25.9
Co	0.61–0.70	0.25–0.51	<0.05	nd
Ni	4.9–7.4	17.3–40.4	<0.05–0.08	<0.05
Cu	<0.07	<0.07–0.09	<0.07–0.08	nd
Zn	<0.08	<0.08	<0.08	<0.08
Totals	99.5–100.8	98.1–102.9	99.1–99.9	98.2–100.1

n = number of analyses; nd = not determined.

Sahara 03505 is a small (65 g) sulfide-rich iron meteorite found as a single piece in an undisclosed locality of the Sahara. In our preliminary report (Connolly et al. 2007a), we described Sahara 03505 as a fine-grained intergrowth of dendritic metallic Fe-Ni and troilite and reported some bulk chemical data highlighting its similarities with the sulfide-rich Antarctic iron, Mount Howe 88403. Because of its quench texture similar to iron-sulfide blebs typically found in shocked chondrites (Scott 1982; Rubin 1985), we thought it was a good candidate for studying efficiently segregated metal + sulfide melts produced by impact melting. To verify this hypothesis, and thus contribute to the understanding of surface mineralogy and cosmochemical differentiation on asteroids, here we provide a discussion on the petrogenesis of Sahara 03505 based on a detailed characterization of its texture, mineralogy, bulk chemistry, and oxygen isotope composition.

SAMPLES AND ANALYTICAL METHODS

Before sampling, Sahara 03505 was a 65 g iron meteorite measuring about $6 \times 3 \times 1.5$ cm. Its external surface is covered with a thin (<0.1 mm), brown weathering crust of terrestrial limonitic products. No fusion crust is observed. A single triangular slice of ~80 mm² was cut from the 6.6 g end cut donated to the Museo Nazionale dell'Antartide. After subsampling for ICP-MS analysis (~350 mg), the slice was polished for metallographic, SEM-EDS, and EPMA studies.

Mineral compositions were determined with a CAMECA SX50 electron microprobe fitted with four wavelength dispersive spectrometers at the CNR Istituto di Geoscienze e Georisorse in Padua. Running conditions were 20 kV accelerating voltage, 20 nA beam current and 1 µm nominal beam spot. Counting times for the determined elements were 20 s and 10 s at peak and background, respectively. The manufacturer-supplied PAP procedure was

employed for raw data reduction. Pure elements and mineral standards were used for instrumental calibration. Average or selected mineral compositions of Sahara 03505 are reported in Tables 1 and 2.

The bulk chemical analysis of Sahara 03505 was performed at the Pisa University's Dipartimento di Scienze della Terra by conventional inductively coupled plasma-mass spectrometry (Thermo PQII Plus), following the procedure described in D'Orazio and Folco (2003). In order to get better accuracy, the sample solutions were measured using the standard additions method instead of an external calibration. At the concentration levels of Sahara 03505, the precision is better than 5% relative standard deviation (RSD) for Ni, Co, Cu, Ga, Mo, Ru, Rh, Pd, W, Ir, Pt, and between 5 and 10% RSD for Ge, As, Sn, Sb, Re, Au. Results are given in Table 3.

The oxygen isotope composition of chromite was measured with the CRPG-CNRS Cameca IMS 1270 ion microprobe in multicollection mode using three Faraday cups for ¹⁶O, ¹⁷O, and ¹⁸O, according to procedures previously described (Chaussidon et al. 2008). The size of the primary beam was approximately 25 µm in diameter. The oxygen isotope variations are reported in permil relative to the SMOW international standard using the classical delta notation [e.g., $\delta^{18}\text{O} = (^{18}\text{O}/^{16}\text{O}_{\text{sample}}/^{18}\text{O}/^{16}\text{O}_{\text{SMOW}} - 1) \times 1000$] and the deviations from the terrestrial mass fractionation line are noted $\Delta^{17}\text{O}$ and calculated according to $\Delta^{17}\text{O} = \delta^{17}\text{O} - 0.52 \times \delta^{18}\text{O}$. Results were corrected for instrumental mass fractionation by using a terrestrial magnetite standard: three replicate analyses of this standard yielded $\Delta^{17}\text{O}$ values reproducible within $\pm 0.26\text{‰}$ (1σ). No chromite standard being available, it was assumed that the instrumental mass fractionation was the same for magnetite and chromite.

Modal proportions of the mineral phases were estimated integrating point counting (2370 points counted on a 0.2 mm × 0.2 mm grid) and digital image analysis of the polished slice.

Table 2. Selected EPM analyses of anhydrous phosphates in Sahara 03505.

SiO ₂ (wt%)	0.46	0.50	0.07	<0.06	0.44	0.47
Cr ₂ O ₃	<0.10	0.14	<0.10	<0.10	<0.10	0.10
FeO	59.3	59.1	43.1	41.1	47.0	47.4
MnO	0.61	0.66	0.35	0.33	1.21	1.18
MgO	0.26	0.19	<0.08	<0.08	0.52	0.62
CaO	<0.06	<0.06	<0.06	<0.06	0.64	0.81
Na ₂ O	<0.19	0.26	7.1	17.6	7.53	6.61
K ₂ O	<0.05	<0.05	<0.05	<0.05	1.90	1.85
P ₂ O ₅	39.0	38.0	38.7	42.0	40.3	39.7
Total	99.7	98.9	99.3	101.2	99.7	98.8
Cation formula						
O	8	8	4	4	16	16
Si	0.03	0.03			0.05	0.06
Cr		0.01				0.01
Fe	2.96	2.99	1.07	0.98	4.61	4.69
Mn	0.03	0.03	0.01	0.01	0.12	0.12
Mg	0.02	0.02			0.09	0.11
Ca					0.08	0.10
Na		0.03	0.98	0.97	1.71	1.52
K					0.28	0.28
P	1.97	1.95	0.97	1.01	4.00	3.98

Table 3. Bulk chemistry of Sahara 03505 by ICP-MS.

Element	Conc.	Element	Conc.
Ni	90.2	Pd	4.4
Co	4.14	Sn	1.84
Cu	341	Sb	0.31
Ga	21.2	W	0.63
Ge	32.5	Re	0.38
As	11.2	Ir	3.55
Mo	6.6	Pt	7.8
Ru	5.6	Au	1.00
Rh	1.15		

Ni and Co are in mg g⁻¹, the remaining elements in µg g⁻¹.

RESULTS

Texture and Mineral Chemistry

The interior of Sahara 03505 consists of cellular/dendritic metallic Fe-Ni set in a matrix dominated by troilite (Fig. 1). Metallic Fe-Ni and troilite occur approximately in a 1:1 volumetric ratio (~49.6 vol% troilite, ~47.8 vol% metallic Fe-Ni). The metallic Fe-Ni dendrites are made up of primary trunks, up to 16 mm long and about 100 µm wide, and secondary branches, perpendicular to the primary trunks, with a spacing of about 100 µm (Fig. 1). The bulk density of the meteorite, determined by immersion in water, is 6.12 ± 0.02 g cm⁻³, concordant with its modal composition.

Troilite occurs as large (1.5–7.5 mm in length), poikilitic, anhedral crystals (Fig. 2a). It is very homogeneous in composition and contains only detectable trace amounts of Ni (up to 0.08 wt%) and Cu (up to 0.08 wt%), whereas Si, P, Cr, Mn, Co, and Zn were always found below the detection limit

of the used electron microprobe (Table 1). Some crystals located close to the external surface display multiple lenticular twinning with very thin (1–20 µm wide) twin lamellae (Fig. 2b).

Metallic Fe-Ni is made of a fine (1–5 µm) plessitic intergrowth of Ni-poor (down to 4.9 wt% Ni) and Ni-rich metal (up to 40.4 wt% Ni; Table 1) arranged into a “micro-Widmanstätten” pattern (Fig. 3a). Some inclusions of tiny schreibersite (1–5 µm) crystals are dispersed in the metallic Fe-Ni. The plessitic intergrowths appear homogeneously distributed, and the compositional zoning patterns observed in some metal dendrites of metal-troilite spherules occurring in shocked OC (e.g., Chen et al. 1995) were not observed.

Skeletal crystals of spinel with euhedral outline (~1.5 vol%), up to 2.5 mm in maximum length, are scattered throughout (Figs. 2c and 3b). They are characterized by a composition close to the chromite (FeCr₂O₄) end-member (Table 1).

Numerous spherical, or pear-shaped, droplets (grey to black in reflected light) of anhydrous Fe-, Fe-Na-, and Fe-Mn-Mg-Ca-Na-K-phosphates occur within the troilite often adhering to the edges of spinel crystals (Figs. 2d and 3c–e). They attain sizes variable between 5 and 100 µm in diameter and are present at a frequency of about 10–15 per mm². Analyses by EPMA (Table 2) indicate at least three different mineral species with the following cation formulas: (Fe,Mn)₃(PO₄)₂ (likely sarcopsite or graftonite), Na(Fe,Mn)(PO₄) (likely maricite), (Na,K)₂(Fe,Mn,Mg,Ca)₅(PO₄)₄ (unknown). The phosphate droplets are generally inhomogeneous (Figs. 3c and d), and three different phosphate phases may coexist in the same droplet along with some extremely small troilite particles (Fig. 3c); however, the droplets dominated either by (Fe,Mn)₃(PO₄)₂ or by Na(Fe,Mn)(PO₄) are prevailing.

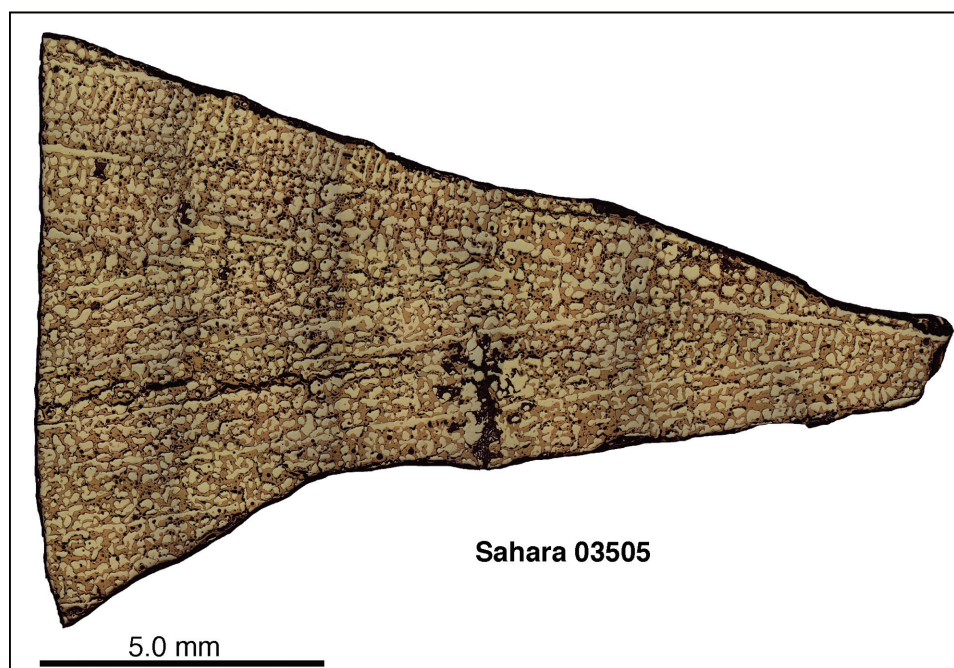


Fig. 1. The polished slice of Sahara 03505 studied in this work. The meteorite shows a dendritic/cellular texture made of dendrites of metallic Fe-Ni embedded in troilite. Note the large, dark, skeletal crystal of chromite in the lower central portion of the slice. Reflected polarized light.

Anhydrous Fe, Mn, Na, Ca, Mg, K, Cr phosphates are reported as small spherules (2–8 μm in diameter) within the metal-troilite inclusions of the severely shocked Yanzhuang (H6) chondrite (Chen and Xie 1996); in addition, these phases may occur in magmatic iron meteorites, particularly IIIAB irons, where they are often found in association with troilite and nearly stoichiometric FeCr_2O_4 spinel (Kracher et al. 1977; Olsen et al. 1999).

Very small (5–20 μm) particles of metallic Cu occur, with a frequency of ~ 0.1 per mm^2 , within troilite or at the metal-troilite interface (Fig. 3f).

Veinlets of terrestrial oxidation phases cross-cut the primary minerals and are more abundant toward the external surface.

Bulk Chemistry and Oxygen Isotope Composition

The FeS/metallic Fe-Ni weight ratio of Sahara 03505 is ~ 0.6 , about ten times lower than that (~ 5.7) of the near solidus melts formed at ~ 950 $^{\circ}\text{C}$ in the Ni-poor portion of the Fe-Ni-S ternary system (Hsieh et al. 1987). According to the Fe-Ni-S ternary system, the bulk composition of Sahara 03505 would be completely liquid at temperatures above 1300–1350 $^{\circ}\text{C}$ (Fig. 4), that is about 350–400 $^{\circ}\text{C}$ above the binary FeS-Fe eutectic. The relative proportion of troilite and metallic Fe-Ni in Sahara 03505 is intermediate between that of H and L ordinary chondrites (FeS/metallic Fe-Ni weight ratio = 0.31, 0.70 and 1.65 for average H-, L- and LL-chondrites falls, respectively; Jarosewich 1990).

Besides Ni and Co, we determined the bulk concentration

of an additional fifteen siderophile and chalcophile trace elements (Table 3). In Fig. 5, the bulk chemistry of Sahara 03505 is normalized to the average CI chondrite and Ni, and compared to the calculated bulk composition of the metal + sulfide contained in the average H, L and LL ordinary chondrites (Wasson and Kallemeyn 1988; Jarosewich 1990). The diagram of Fig. 5 plots the bulk compositions of the sulfide-rich irons, Mount Howe 88403 (Wasson et al. 1998), Sacramento Wash 005, and Meteorite Hills 00428 (Schrader et al. 2008), and a metal-sulfide nodule found in the Smyer H-chondrite impact melt breccia (Rubin 2002). The diagram shows that Sahara 03505 has a distribution of most elements comparable to these sulfide-rich materials and to the calculated compositions of the metal + sulfide portion of OC. Indeed, all these materials are characterized by concentrations of refractory and transitional elements close to chondritic values (except for the higher Re of Mount Howe 88403 and the higher Ir and Co of Meteorite Hills 00428), whereas they are progressively depleted in moderately volatile and volatile elements (Fig. 5).

The oxygen isotope composition of the chromite in Sahara 03505 was measured by ion microprobe (four spot analyses performed on two large skeletal crystals). The data show a few permil range (Table 4 and Fig. 6) with average values of $+2.2 \pm 0.3\text{‰}$ for $\delta^{17}\text{O}$, $+3.6 \pm 1.1\text{‰}$ for $\delta^{18}\text{O}$ and $+0.3 \pm 0.5\text{‰}$ for $\Delta^{17}\text{O}$ ($\pm 1\sigma$). Though the data show a scatter for $\delta^{18}\text{O}$ values (from +2.2 to +4.6‰) slightly higher than the two sigma external reproducibility ($\approx \pm 1\text{‰}$) defined from the analysis of the magnetite standard, the $\Delta^{17}\text{O}$ are the same for the four spots analyzed within our two sigma external

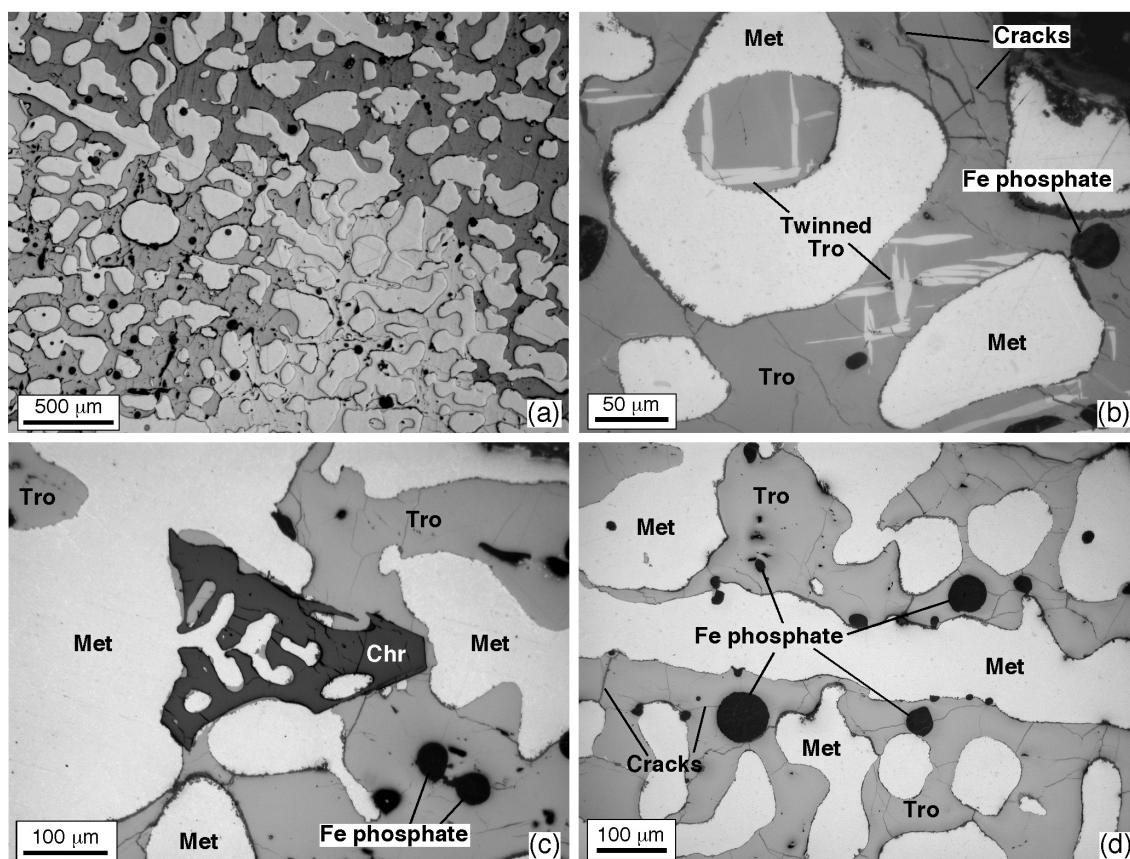


Fig. 2. Optical microscope views (reflected light) of Sahara 03505. a) Junction between three crystals of troilite characterized by different orientation and intensity of illumination (partially crossed polarized light). b) Detailed view of lamellar twinning of troilite (partially crossed polarized light). c) A skeletal crystal of chromite with euhedral outline (plane polarized light). d) Spherical droplets of anhydrous Fe-phosphate dispersed within troilite (plane polarized light). Abbreviations: Chr = chromite, Met = metallic Fe-Ni, Tro = troilite.

reproducibility ($\pm 0.52\%$). No obvious analytical reason, such as variation of instrumental mass fractionation, was found to explain the range of $\delta^{18}\text{O}$ (or $\delta^{17}\text{O}$) values.

DISCUSSION

Comparison with Similar Sulfide-Rich Iron Meteorites

Sahara 03505 has a textural and mineralogical affinity to the following sulfide-rich iron meteorites: Roberts Massif 04162 (52.3 g), Roberts Massif 04299 (55.2 g), Mount Howe 88403 (2470 g), Sacramento Wash 005 (52.3 g), Meteorite Hills 00428 (45.8 g). We could directly handle and examine just Mount Howe 88403, whereas for the description of the other meteorites we rely on the existing literature.

Roberts Massif 04162 and Roberts Massif 04299 (Connolly et al. 2007b) are two small paired Antarctic irons showing a texture very similar to Sahara 03505, but are characterized by lower FeS/metallic Fe-Ni ratios, and by closer spacing ($\sim 50\ \mu\text{m}$) of the secondary metal dendrite branches.

Mount Howe 88403 shows a coarser texture, and is characterized by troilite cells ($\sim 31\ \text{vol.}\%$) in a matrix of ataxitic metallic Fe-Ni. The troilite of Mount Howe 88403

shows more conspicuous lamellar twinning and is characterized by a discontinuous rim of schreibersite followed by a continuous thick rim of swathing kamacite (Clarke et al. 1990; Schrader et al. 2008). Similar to Sahara 03505, Mount Howe 88403 contains chromite and anhydrous Fe-Na phosphate.

Sacramento Wash 005 is made of metallic Fe-Ni, troilite ($\sim 26\ \text{vol.}\%$), metallic Cu, chromite, Ca-phosphate, iron oxide, and a Cu-Fe sulfide (Schrader et al. 2008). Interestingly, this meteorite contains a chondrule-bearing silicate inclusion interpreted as a fragment of an H4 ordinary chondrite.

Meteorite Hills 00428 (45.8 g) is made of metallic Fe-Ni, troilite ($\sim 12\ \text{vol.}\%$), metallic Cu, Ca-phosphate, and pyroxene (Russell et al. 2002; Schrader et al. 2008). The metallic Fe-Ni of this meteorite shows a weak Widmanstätten pattern with very thin ($100\text{--}200\ \mu\text{m}$) kamacite lamellae.

Ordinary Chondrite Parentage of Sahara 03505

In the previous paragraphs we emphasized that Sahara 03505 has a FeS/metallic Fe-Ni ratio much lower than that expected for minimum temperature melts in the Ni-poor portion of the Fe-Ni-S system. As H and L chondrites have

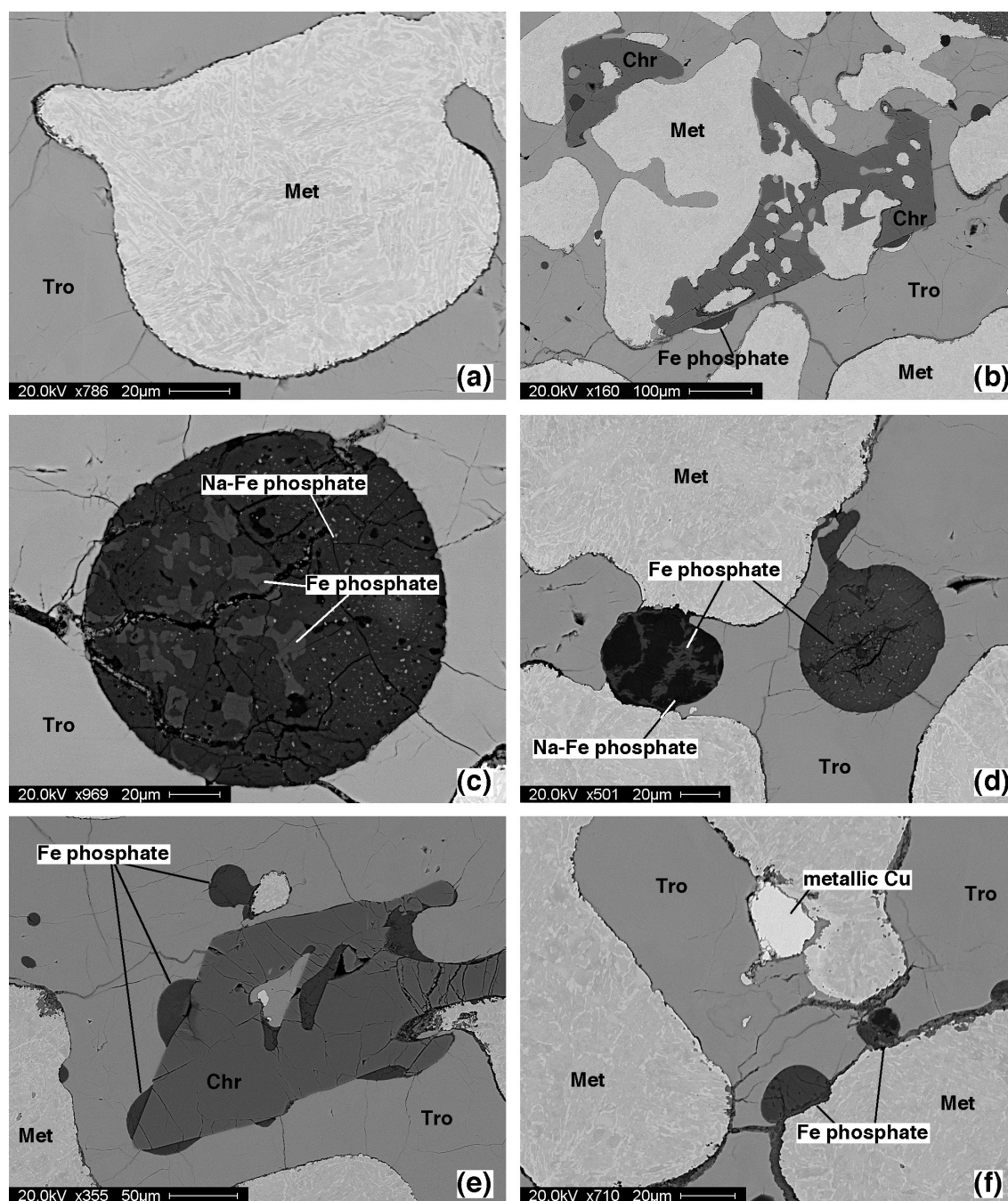


Fig. 3. Backscattered electron images of Sahara 03505. a) Plessitic texture of a metallic Fe-Ni cell. b) Intergrowth of a skeletal chromite and metallic Fe-Ni. c) Detailed view of a heterogeneous spherical drop of anhydrous phosphates. d) Two droplets of anhydrous phosphates: the darker one (left side) is mainly composed of NaFePO_4 ; the lighter one (right side) shows a peduncle and is mainly composed of $\text{Fe}_3(\text{PO}_4)_2$. e) Skeletal crystal of chromite showing some droplets of anhydrous phosphates adhering to its faces. f) Tiny particle of metallic copper at the interface between troilite and metallic Fe-Ni. Abbreviations: Chr = chromite, Met = metallic Fe-Ni, Tro = troilite.

troilite/metallic Fe-Ni ratios that encompass that of Sahara 03505, we propose that this latter may represent the liquid obtained through the total melting of the sulfide plus metal portion of an H- or L-chondrite at temperatures in excess of 1300 °C. During melting a significant proportion of O, Cr, and P (plus minor amounts of Na, Mn, and K), originally

hosted in the chromite plus phosphates of the OC, dissolved in the sulfur-rich metallic melt. At these high temperatures, a silicate melt should have coexisted with the metallic melt, therefore, the silicate melt could have supplied part of these lithophile elements to the metallic melt.

The siderophile and chalcophile trace-element

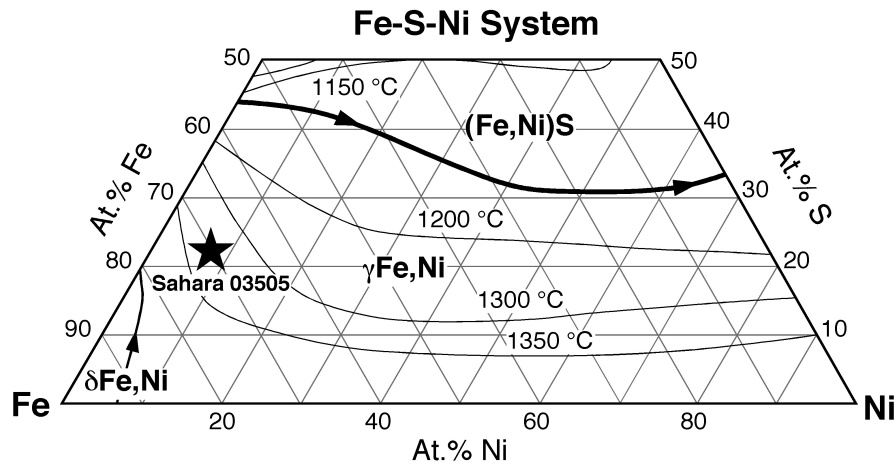


Fig. 4. Liquidus projection of the ternary system Fe-Ni-S (Hsieh et al. 1987) showing the bulk composition of Sahara 03505. The heavy line is the Fe,Ni monosulfide- γ Fe,Ni cotectic.

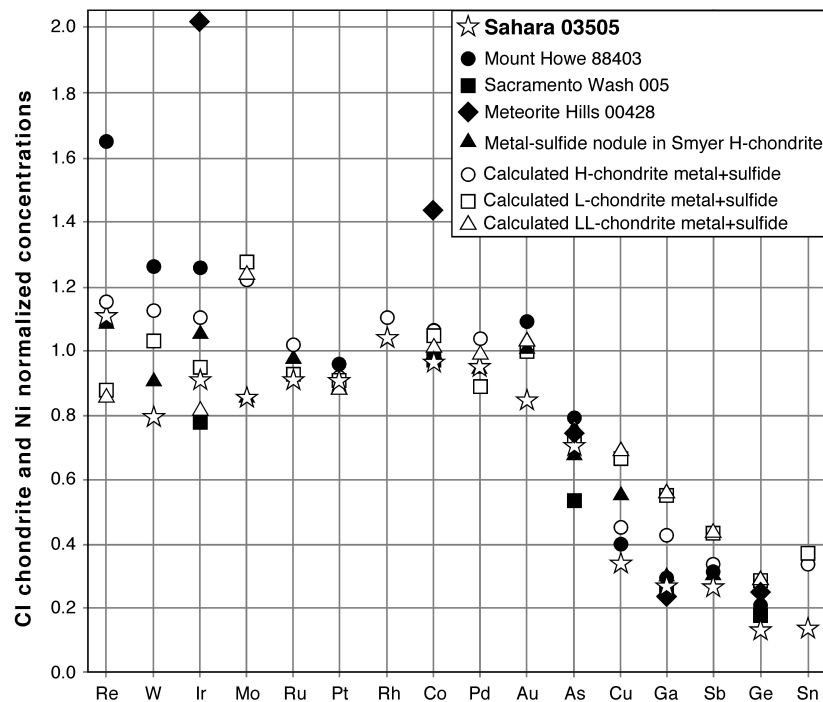


Fig. 5. Bulk concentration of siderophile and chalcophile elements of Sahara 03505 normalized to the CI chondrite and to Ni. In the diagram are also plotted the sulfide-rich iron meteorites Mount Howe 88403 (Wasson et al. 1998), Sacramento Wash 005, and Meteorite Hills 00428 (Schrader et al. 2008), the metal-sulfide nodule found in the Smyer H chondrite (Rubin 2002), and the calculated composition of the metal + sulfide portion of average H, L, and LL chondrite (Wasson and Kallemeyn 1988; Jarosewich 1990). Elements are ordered from left to right by decreasing 50% condensation temperature. CI composition from McDonough and Sun (1995).

Table 4. Microprobe oxygen isotope data (‰ relative to SMOW) for chromite of Sahara 03505.

Spot #	$\delta^{17}\text{O}$	$\pm 1\sigma$	$\delta^{18}\text{O}$	$\pm 1\sigma$	$\Delta^{17}\text{O}$	$\pm 1\sigma$
59-1	1.97	0.45	3.28	0.42	0.27	0.39
59-2	2.68	0.46	4.58	0.43	0.30	0.40
59-3	1.96	0.46	4.38	0.42	-0.32	0.39
59-4	2.06	0.45	2.21	0.42	0.91	0.39

concentrations of Sahara 03505 are those expected for a liquid obtained by total melting of the metal + sulfide portion of an OC (Fig. 5). The bulk chemistry of Sahara 03505 is similar to that of Sacramento Wash 005, for which the finding of an H4-chondrite inclusion sustains an origin related to impact melting on the H-chondrite parent body (Schrader et al. 2008).

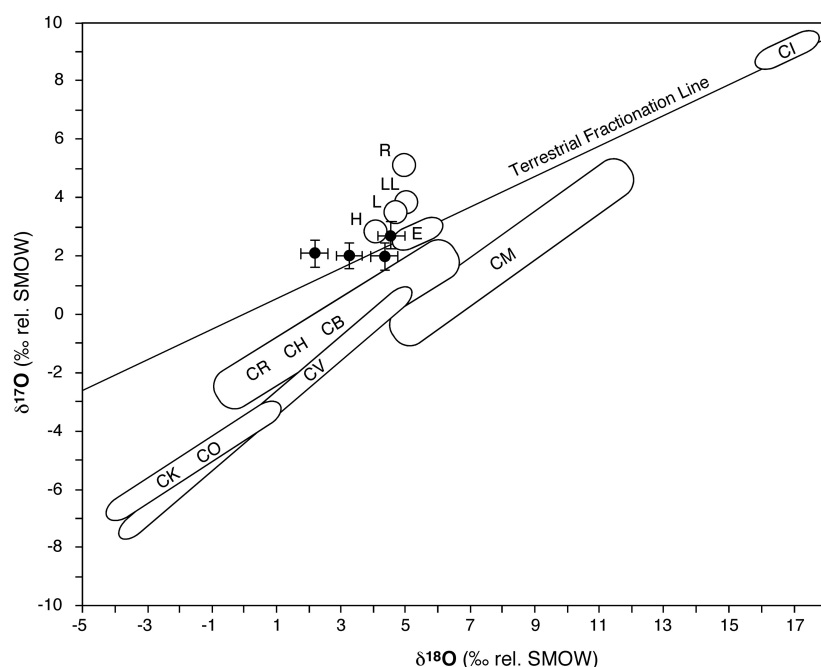


Fig. 6. Oxygen-isotope composition of chromites from Sahara 03505 (four spot analyses). For reference, the terrestrial fractionation line and the fields for the whole-rock major chondrite groups (from Clayton et al. [1991] and Clayton and Mayeda [1984, 1999]) are shown. Error bars are $\pm 1\sigma$.

The oxygen isotope data are also compatible with an OC parentage of Sahara 03505 and rule out any genetic association with both the rumurutite and carbonaceous chondrites (Fig. 6). The $\delta^{17}\text{O}$ range of chromite in Sahara 03505, from +1.96‰ to +2.68‰, is consistent with that found for bulk H-, L- and LL-chondrites (from $\sim +2.7$ to $\sim +3.7$ ‰, Clayton et al. 1991). The ~ 1 ‰ lower $\delta^{17}\text{O}$ values found could be understood in terms of equilibrium oxygen isotopic fractionation during parent body melting and crystallization of chromite since oxides such as magnetite are known to be the minerals formed with the lowest $\delta^{17}\text{O}$ (or $\delta^{18}\text{O}$) values during magmatic differentiation of silicate melts (e.g., Taylor and Sheppard 1986). The mean $\Delta^{17}\text{O}$ value found for the chromite ($+0.3 \pm 0.5$ ‰) is indistinguishable from that of bulk H chondrite falls ($+0.73 \pm 0.09$ ‰, Clayton et al. 1991) while it would be consistent within errors with that of L and LL chondrite falls ($+1.07 \pm 0.09$ ‰ and $+1.26 \pm 0.12$ ‰, respectively, Clayton et al. [1991]). The $\Delta^{17}\text{O}$ values of the chromites of Sahara 03505 are also indistinguishable from that of the enstatite chondrites ($+0.01 \pm 0.12$ ‰, Clayton and Mayeda [1984]). Bulk carbonaceous chondrites have negative $\Delta^{17}\text{O}$ values (from ~ -4.3 ‰ to ~ -1.4 ‰, Clayton and Mayeda 1999) clearly different from the present chromite. This is however not the case for CI chondrites which have a bulk $\Delta^{17}\text{O}$ value of $\sim +0.4$ ‰ (Clayton and Mayeda 1999), but their bulk $\delta^{17}\text{O}$ (or $\delta^{18}\text{O}$) values are high (e.g., $\delta^{17}\text{O} \approx +9$ ‰, Clayton and Mayeda 1999). This makes the formation of Sahara 03505 chromite, with $\delta^{17}\text{O} \approx +2$ ‰, from a CI precursor quite unlikely (considering only oxygen isotope

composition) unless strong oxygen isotopic fractionation are associated to this process.

Rapidly solidified metal-troilite mixtures occur as small (usually <1 cm) nodules in several shocked OC (Scott 1982), and have been interpreted as a product of impact melting on the OC parent bodies (Rubin 1985).

Finally, the occurrence of metallic Cu in Sahara 03505 (and in Sacramento Wash 005 and Meteorite Hills 00428; Schrader et al. 2008) recalls the ubiquitous finding of this phase in shocked OC (Rubin 1994).

Crystallization History

The microtexture of Sahara 03505, in particular the mutual geometrical relationships among the different phases, suggests the possible following solidification scenario: 1) nucleation and rapid growth of chromite skeletal crystals and dendritic metallic Fe-Ni; 2) unmixing of droplets of phosphate liquids from the residual iron sulfide liquid; 3) final crystallization of troilite from the residual iron sulfide liquid. The tiny crystals of metallic copper often nucleated onto the metallic Fe-Ni dendrites (Fig. 3f) and therefore should have formed after this phase. Copper has a preference to be partitioned into sulfur-rich liquid metal with respect to both solid iron monosulfide (Fleet et al. 1993) and solid metal (Chabot et al. 2003); thus, it is expected that metallic Cu would become supersaturated during a late stage of crystallization of Sahara 03505 melt (Rubin 1994).

Within the Fe-Ni-S system, a melt having the same Fe:

Ni:S proportions as Sahara 03505 would first crystallize γ Fe-Ni and then co-precipitate γ Fe,Ni and Fe monosulfide up to complete solidification (Fig. 4; Hsieh et al. 1987). This was not observed for Sahara 03505 which is made of metallic Fe-Ni dendrites in a matrix of polycrystalline troilite. We propose that this was due both to the occurrence of additional components (particularly oxygen, phosphorous and sodium) in the liquid system that caused the formation of immiscible Fe- and Fe-Na phosphate liquid droplets within the residual sulfide-rich liquid, and to the very fast crystallization, far from equilibrium conditions.

The history of Sahara 03505 is further complicated by the annealing which followed a moderate shock event. This event originated the lamellar twinning of troilite (Fig. 2b) and possibly rehomogenized the composition of the metallic Fe-Ni (Fig. 3a).

Cooling Rate

The rapid solidification of metallic melts almost invariably involves the formation of tree-like crystals (dendrites) characterized by primary (the “trunk”) and secondary (the “branches”) dendrite arms (Scott 1982). Experimental work on Fe-Ni alloys (Flemings et al. 1970) showed that the spacing between secondary dendrite arms (d) varies as a function of the inverse of the cooling rate (R). Scott (1982) proposed the following relation, with d in m and R in $K s^{-1}$:

$$R = 5.3 \times 10^5 d^{-2.9} \quad (1)$$

If the metallic melt solidified less rapidly, the secondary arms are substituted by more or less elongated cells. In this cases, Blau and Goldstein (1975) suggested that the width of adjacent elongated cells should be used in place of the spacing of secondary arms. Sahara 03505 shows well-developed primary arms but ill-defined secondary arms, forming a texture intermediate between dendritic and cellular. The width of the elongated cells varies between 60 and 95 μm , suggesting a cooling rate in the order of 1–4 $K s^{-1}$. These reasonably high cooling rates should be compared to theoretical cooling rates in limiting cases of heat transfer by radiation or by conduction through silicate materials.

The first case may apply to the ejection of a lump, or large drop, of sulfur-rich metallic liquid into space as expected for a large impact scenario. If the heat transfer is by radiation only, the cooling rate R ($K s^{-1}$) can be evaluated using the following equation for a crystallizing melt sphere (Tsuchiyama et al. 1980):

$$R = \frac{3\epsilon\sigma}{r\rho\left(C_p + \frac{\Delta H_c}{\Delta T_c}\right)}(T^4 - T_a^4) \quad (2)$$

where σ = Stefan-Boltzmann constant ($5.704 \times 10^{-12} J cm^{-2} s^{-1} K^{-1}$), ϵ = emissivity, C_p = specific heat ($J g^{-1} K^{-1}$), ΔH_c = enthalpy of crystallization ($J g^{-1}$), ΔT_c = temperature interval of crystallization (K), T_a = ambient temperature (K), r = radius (cm) and ρ = density ($g cm^{-3}$) of the molten sphere.

The cooling rate by radiation for molten spheres with composition as Sahara 03505 has been evaluated using the following parameters: $\epsilon = 0.28$ (emissivity of molten iron); $C_p = 0.66 J g^{-1} K^{-1}$ (weighted average of the C_p 's for FeS, Fe and Ni at 1400 K; Robie et al. 1978); $\Delta H_c = 298 J g^{-1}$ (weighted average of the ΔH_c 's for FeS, Fe and Ni; Robie et al. 1978); $\Delta T_c = 400 K$ (cooling from 1623 K to 1223 K); $T_a = 200 K$ (if the initial temperature of the sphere is $>3 T_a$, the contribution of the T_a term to R is $<1\%$); $T = 1623 K$; $\rho = 6.12 g cm^{-3}$. The calculations show that radiative cooling rates of 1–4 $K s^{-1}$ (i.e., 400 K in 400 or 100 seconds) may be obtained by spheres of about 4 and 1 cm of radius, respectively. Therefore, cooling by radiation of a small lump of sulfur-rich metallic melt is fully compatible with the quench structure observed for Sahara 03505.

As an alternative, Sahara 03505 could be representative of a metallic melt vein intruded into the wall of an impact crater and rapidly cooled by conduction to the relatively cool host rock. The thermal modeling of the solidification of a metallic liquid with the composition of Sahara 03505 is extremely complex as it will crystallize through a large interval of temperatures (about 400 K) and the thermal properties (diffusivity and conductivity) of its mineral components are poorly known. Nonetheless, we attempted to obtain a rough estimate of the time needed to solidify a dike with planar contacts intruded into an OC host rock at the temperature of 400 K. The calculations have been made much more simple assuming that the metallic liquid had the FeS-Fe eutectic composition (85 wt% FeS, 15 wt% Fe). Indeed, in this case the liquid crystallizes at a single definite temperature (1223 K), and Carslaw and Jaeger (1959) provided the solution of the problem. The calculations were simplified further using constant values of thermal diffusivity and thermal conductivity of $4.0 \times 10^{-6} m^2 s^{-1}$ and $15 W m^{-1} K^{-1}$, respectively, for the FeS-Fe solid eutectic, and $1.5 \times 10^{-6} m^2 s^{-1}$ and $4.1 W m^{-1} K^{-1}$, respectively, for the OC host rock. The results show that a dike of FeS-Fe eutectic liquid having a width of 3 or 6 cm, at the initial temperature of 1223 K, can solidify by conduction to a chondrite host rock, at the initial temperature of 400 K, in 100 or 400 seconds, respectively.

Summing up, notwithstanding the large uncertainties of these calculations, we can conclude that the quench texture of Sahara 03505 is compatible both with the radiative cooling of a small (~ 4 cm of radius) lump of sulfur-rich metallic melt ejected into space, and with the conductive cooling of a small (few centimeters wide) dike intruded into a relatively cold OC country rock. Both scenarios may be found during energetic impact events on OC parent asteroids.

Impact versus Internal Heating

The bulk chemistry of Sahara 03505, which suggests an origin by high-degree or total melting of an OC precursor, its quench texture, indicative of fast cooling, and the comparison with other sulfide-rich iron meteorites, suggest that the most likely process responsible for the genesis of Sahara 03505 is related to impact melting on a OC parent body. However we could not dismiss the possibility that the sulfide-rich metallic melt crystallized into Sahara 03505 was generated by asteroidal internal heating.

It is well known that the estimated initial sulfur content of magmas of magmatic iron meteorite groups (e.g., IIAB, IIIAB, IVA, IVB) is lower than that of the metallic Fe-Ni plus FeS portion of OC, taken as possible precursor materials of these magmas (e.g., Jones and Drake 1983). Keil and Wilson (1993) proposed that the sulfur depletion of metallic magmas resulted from removal from asteroids of sulfur-rich initial partial metallic melts by explosive pyroclastic volcanism. According to the model of Keil and Wilson (1993), the pyroclastic discharge of sulfur-rich metallic melts was driven by the occurrence of bubbles of sulfur gas trapped in the Fe,Ni-FeS cotectic melts, which gave a positive buoyancy to the bulk fluid. As we emphasized in the previous paragraphs, Sahara 03505 has a FeS/metallic Fe-Ni ratio much lower than that of cotectic melts; moreover it shows no bubbles at all. Given the whole size of the meteorite, the eventual gas bubbles should have been at least several cm in size. In conclusion we argue that our data do not sustain the hypothesis that the sulfur-rich metallic melt crystallized as Sahara 03505 formed by internal magmatism within an asteroid and erupted explosively at its surface.

CONCLUSIONS

1. The texture and mineral assemblage of Sahara 03505 indicate that it represents the product of rapid cooling and crystallization of a sulfur-rich metallic melt.
2. Modal proportions (low troilite/metallic Fe-Ni ratio) and bulk chemical composition show that this liquid is quite different from the FeS-Fe,Ni cotectic liquids.
3. Based on bulk chemistry and oxygen isotope data, we propose that Sahara 03505 formed by high-degree melting of an OC lithology (possibly H- or L-type), followed by an efficient segregation of the immiscible silicate and metallic liquids.
4. The processes responsible for the genesis of Sahara 03505 are fully compatible with an energetic impact scenario, with the sulfur-rich metallic melt rapidly cooled either by radiation into space as a small lump, or by conduction to a chondrite country rock as a vein intruded into the walls of an impact crater.
5. The paucity of metallic macro-meteorites similar to Sahara 03505 is imputable partly to the low resistance of

these materials during their extraterrestrial journey and their terrestrial atmospheric entry, and partly to the incomplete segregation of metallic melts from their hosts more commonly observed in shocked OC.

6. The finding of Sahara 03505 brings the number of sulfide-rich iron meteorites characterized by medium- to fine-grained quench textures to five. This poses a nomenclature issue, as the members of this little group of meteorites are compositionally (i.e., very rich in sulfur) and texturally (dendritic/cellular quench textures) quite different from the other iron meteorites. Accordingly, we propose here to use the descriptive term "sulfide-irons" for this meteorite group, by analogy with the stony-irons.

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