Itqiy: A metal-rich enstatite meteorite with achondritic texture

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Abstract–Itqiy is a unique coarse-grained, metal-rich enstatite meteorite that was found in the Western Sahara and consists of two rocks together weighing 4.72 kg, which are both completely coated with fusion crust. We report results from our electron microprobe and instrumental neutron activation analysis techniques.

Itqiy consists of subhedral, equigranular, millimeter-sized enstatite, ~25 vol% of millimeter-sized kamacite and a few tiny intergrowths of sulfides and kamacite. Relic chondrules are absent. Pyroxene ($Fs_{0.2}$) is chemically similar to enstatite in EL chondrites, but the metal is closer in composition to that in EH chondrites. Sulfides resemble those in E chondrites but their compositions are distinct from those in both EL and EH chondrites. Itqiy clearly formed under very reducing conditions, but it does not appear to have formed from EH or EL chondrites.

Two thermal events can be distinguished. Silicate compositions including rare earth element abundances indicate loss of partial melt and slow cooling. Heterogeneous sulfides indicate a subsequent reheating and quenching event, which may have been due to shock as many enstatite grains show shock stage S3 features.

INTRODUCTION

Enstatite meteorites represent the most reduced naturally-occurring material of our solar system (Keil, 1968). They comprise two main groups, chondrites and achondrites (aubrites), as well as several ungrouped samples that exhibit anomalous characteristics. The enstatite chondrites (E chondrites) are subdivided into EL chondrites with relatively low metal abundances and EH chondrites with comparatively high metal contents (*e.g.*, Sears *et al.*, 1982; Kallemeyn and Wasson, 1986; Keil, 1989; Zhang *et al.*, 1995; Kong *et al.*, 1997). Both subgroups essentially consist of nearly FeO-free enstatite as a major component and lesser amounts of Si-bearing kamacite and troilite (Table 1).

Some E chondritic samples show intermediate chemical features between the EH and EL subgroups and might represent a new grouplet (*e.g.*, Lin and Kimura, 1998; Kimura and Lin, 1999). Others were melted once and therefore only ambiguously match the characteristics of either EH or EL chondrites (Lin and Kimura, 1998). In addition, several melt breccias are known among E chondrites (*e.g.*, McCoy *et al.*, 1995; Rubin *et al.*, 1997; Weisberg *et al.*, 1997).

One of the ungrouped, anomalous enstatite meteorites is Zaklodzie, which was found in Poland recently (Stepniewski *et al.*, 2000). Similar to Itqiy, it has been classified as an ungrouped enstatite-rich meteorite (Grossman, 2000; Grossman

and Zipfel, 2001) and is composed mainly of euhedral and subhedral enstatite. Unlike Itqiy though, interstices are filled with plagioclase acting as a groundmass. Additional accessory phases are kamacite and troilite. Schreibersite was also identified. Overall, the chemical composition and mineralogy of Zaklodzie reveals parallels to EL chondrites whereas its texture can be described as either highly metamorphosed or achondritic. We will shortly discuss mineralogical-chemical similarities between Itqiy and Zaklodzie. A supplementary comparison of the noble gas records will be published in a second paper.

Aubrites are pyroxenites consisting of primarily FeO-free enstatite that underwent igneous processing and brecciation. Modally, they are related to E chondrites and might have formed from an E chondritic precursor (*e.g.*, Watters and Prinz, 1979; Okada *et al.*, 1988; Keil, 1989; Casanova *et al.*, 1993a,b; McCoy *et al.*, 1997). A variety of lithic clasts found in aubrites reveal igneous textures and testify to the igneous parentage as well as complex fractionation and crystallization history of these meteorites. The dominance of enstatite and depletion or absence of feldspar (relative to chondrites) are characteristic for both aubrites and Itqiy.

SAMPLES AND ANALYTICAL METHODS

Itqiy consists of two separate pieces of 410 and 4310 g, respectively. A nomad of Western Sahara recovered the 410 g

TABLE 1. Selected minerals of enstatite meteorites.

Mineral	Composition	Type 6	Aubrites	Itqiy
Enstatite	$MgSiO_3$	o	c/o	c
Diopside	$CaMgSi_2O_6$	–	+	–
Olivine	Mg_2SiO_4	–	–	–
Plagioclase	$NaAlSi_3O_8$–$CaAl_2Si_2O_8$	+	+	–
Metal	Fe,Ni	+	+	+
Troilite	FeS	+	+	m
Oldhamite	CaS	+	+	+
Alabandite (ELs)	(Mn,Fe,Mg)S	+	v	m
Niningerite (EHs)	(Mg,Fe,Mn)S	–	–	m
Daubreelite	$FeCr_2S_4$	+	v	m
Graphite	C	+	+	–
Schreibersite	$(Fe,Ni,Co)_3P$	+	v	?
Perryite	$(Ni,Fe)_5(Si,P)_2$	+	v	?

Abbreviations: o = orthorhombic, c = monoclinic, + = present, – = absent, v = variable, m = present as a mix-phase, ? = may be present; modified from Dodd (1986).

piece ~10 years ago after he had (supposedly) witnessed its fall. Last year, the main mass was found by a French meteorite dealer who then forwarded parts of it to the University of Arizona for classification. Both parts of Itqiy were completely covered with fusion crust and macroscopically exhibit a fresh appearance.

For our investigation, three slabs (UA1886, UA1887, UA1888), two thin sections (from UA1886), and four bulk specimens (179.6 and 132.2 mg taken from UA1887, 119.6 and 97.7 mg taken from UA1888) were available. Two of the slabs (UA1886, UA1887) were cut with water. The electron microprobe analyses of one of the slabs (UA1887) and one thin section were performed with a Cameca SX-50 electron microprobe using the procedures of Kring *et al.* (1996). The same thin section was also studied with a petrographic microscope in order to investigate weathering grade and shock stage as well as to differentiate between opaque minerals and to determine the relative abundances of opaque and non-opaque phases. The four whole-rock specimens representing two weathered (UA1887) and two unaltered specimens (UA1888) were studied *via* instrumental neutron activation analysis (INAA) using the procedure described by Hill *et al.* (1991).

PETROLOGY AND CLASSIFICATION

In hand specimen, Itqiy exhibits a coarse-grained achondritic or highly recrystallized texture. About three-quarters of the sample comprise a silicate phase while the rest is made of metal. The distribution of silicate and metal generally appears homogeneously. The silicates form subhedral, equigranular crystals with a grain size of ~0.5 to 4 mm in diameter (on average 1 mm across). The metal is also present as grains ranging in size from 0.2 to 2 mm. Additionally, it

passes through the rock as a network of veins. No other minerals could be macroscopically observed.

A modal analysis of slab UA1887 (cut with water) distinguished three main phases and quantified them as 77.6% silicate, 14.3% metal, and 8.4% "rust" (*i.e.*, about one-third of the metal phase has been converted into "limonitic" mineral assemblages). A later investigation of UA1888 (cut without water), however, revealed a significantly smaller amount of weathering. Also, the concentrations of siderophile elements as determined by INAA turned out to be consequently lower in UA1887. Finally, the macroscopic view of UA1887 does not display brownish staining typical for ordinary chondrite finds and our experience as to oxidation of metal within thin sections of recent falls gives us reason to believe that Itqiy might indeed be a fall as witnessed by a nomad ~10 years ago. The determination of its ^{14}C age, which will be subject of a second paper, could add valuable information to this question.

Under the microscope, the silicate phase displays second order interference colors inherent to clinopyroxene. In most cases, it is penetrated by a network of tiny metal veins and globules. Numerous triple junctions between individual grains are indicative of extensive recrystallization (Fig. 1). Many crystals exhibit undulose extinction and irregular fractures, some even show mosaicism. The former features point to shock stages 2–3, according to Rubin *et al.* (1997). The mosaicism is indicative of shock stage 4. However, no twinning (neither shock-induced nor polysynthetic) was observed. Instead, a lamellae-texture with kinking could be identified in some pyroxene crystals. Those fine bands did not reveal exsolution or twinning attributes but hint at a deformation process. We therefore lean towards classifying Itqiy as shock stage S3.

Aside from silicate and metal, a few intergrowths of sulfides and metal were detected (Fig. 2). They appear as intergranular
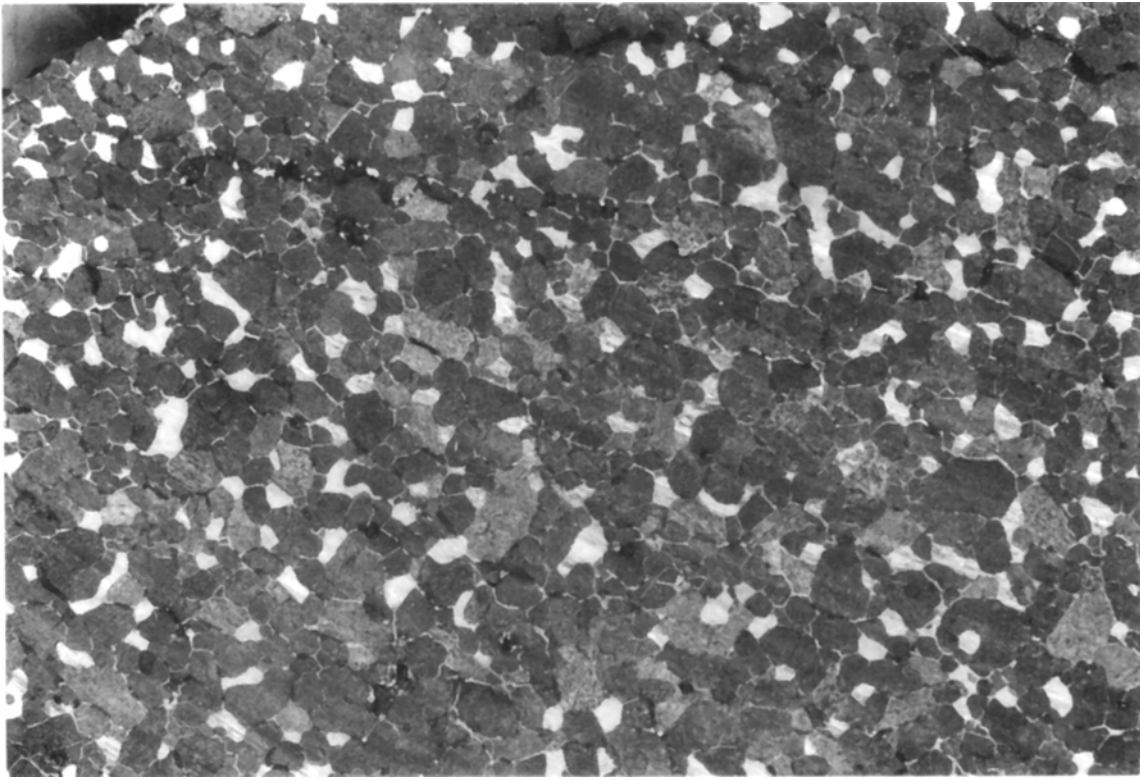
FIG. 1. Two coarse-grained minerals are distinguishable in Itqiy (micrograph in reflected light; field of view is 3 cm across): a silicate and a metal phase. The overall distribution of both components is relatively homogeneous.
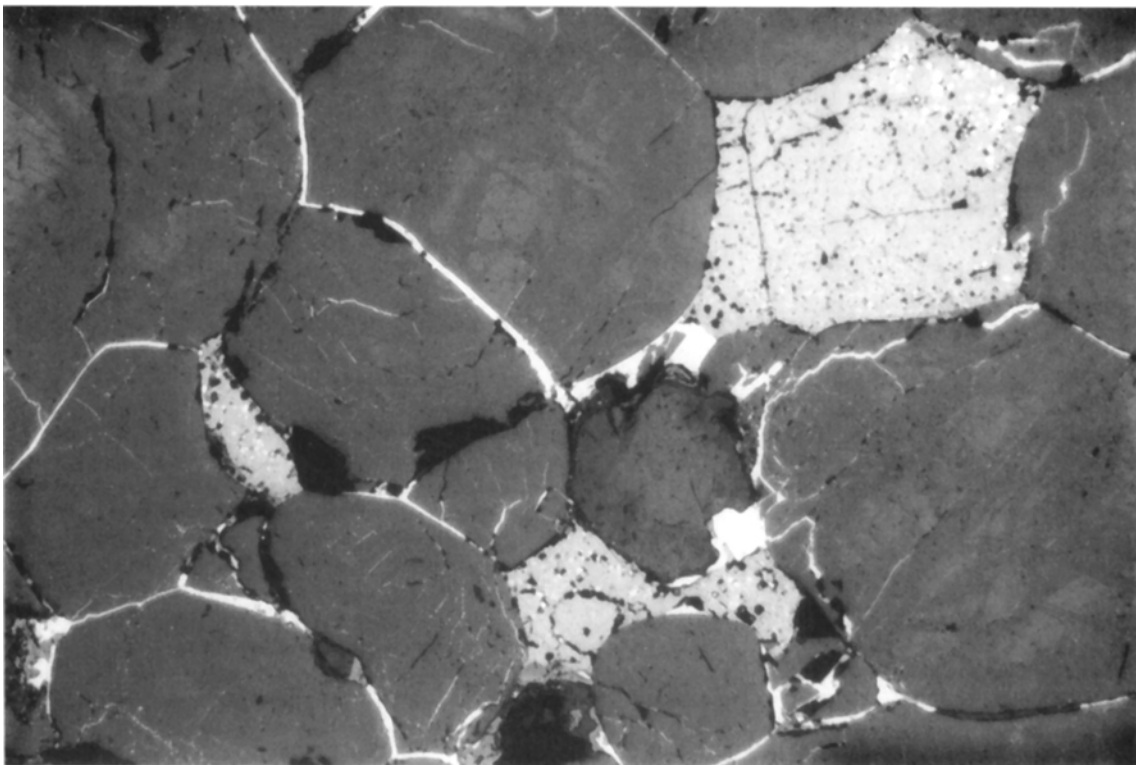

FIG. 2. At higher magnification (reflected light; field of view is 2 mm across), a few millimeter-sized, intergranular sulfide assemblages become apparent.

assemblages of about 0.2 to 1 mm in diameter. At high magnification, three different sulfide phases and metal globules could be identified within these regions (Fig. 3). No relic chondrules are present.

According to our microprobe data (Table 2), the pyroxene is almost pure enstatite and shows a very homogeneous composition ($En_{96.8}Fs_{0.2}Wo_{3.0}$). No zoning was observed. In terms of abundances of Na_2O, FeO, and MnO, it resembles the pyroxene found in EL chondrites, but the CaO content is considerably higher (Fig. 4). Itqiy's wollastonite content is not higher than that typically found in type 4–6 ordinary chondrites though ($Wo_{0.5-4.5}$ for type 4–6 ordinary chondrites: Brearley and Jones, 1998) and the bulk Ca concentration of Itqiy equals those of E chondrites as well as CI carbonaceous chondrites (Fig. 5).

The metal fraction of Itqiy essentially consists of kamacite that reveals compositional similarities to EH chondrites. In fact, it exactly plots in the range of EH chondrites when
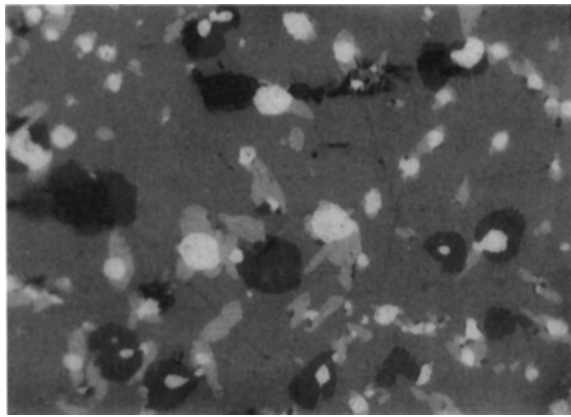

FIG. 3. In reflected light, the sulfide regions reveal three different sulfide minerals, which are associated with metal globules (field of view is 1 mm across). The dark grey host phase is a Mg-Mn-Fe sulfide of variable composition. The two other sulfides represent oldhamite (CaS, black) partly surrounding the metal drops and a light grey troilite-daubreelite mix-crystal (~43 wt% Fe, ~39 wt% S, ~11 wt% Cr).
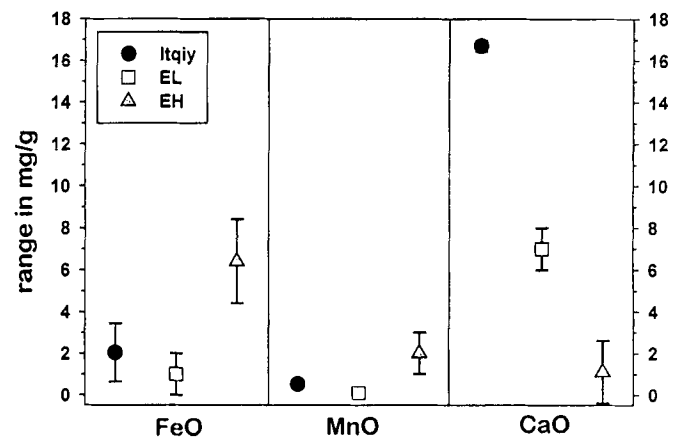

FIG. 4. Plot visualizing the amounts of selected oxides in enstatite of Itqiy as well as EH and EL chondrites (E chondritic data taken from Sears *et al.*, 1982). The bars represent the concentration ranges observed in Itqiy and E chondrites, respectively. In general, Itqiy's silicate phase compositionally rather resembles EL chondritic enstatite. Only the CaO content is considerably higher.

TABLE 2. Average electron microprobe analyses of mineral phases in Itqiy.

	Main meteorite					Sulfide region				
	Enstatite		Metal	Sulfides in metal		Metal	Host phase I	Host phase II	Fe-Cr sulfide	Oldhamite
Na_2O	0.03	Mg	0.03	24.1	Mg	0.01	6.85	9.45	0.33	0.88
SiO_2	59.1	Si	3.14	0.03	Si	1.13	0.04	0.04	0.05	0.04
P_2O_5	b.d.	Mn	0.02	3.42	Mn	0.46	25.2	22.9	1.65	3.06
MgO	38.8	Fe	90.1	11.9	Fe	92.4	18.7	16.4	42.9	1.23
Al_2O_3	0.64	Cu	0.03	0.09	Cu	0.04	0.03	0.04	0.05	0.03
K_2O	b.d.	Zn	0.05	0.04	Zn	0.01	0.03	0.04	0.03	0.02
CaO	1.66	S	0.03	49.1	S	0.07	40.8	42.2	38.6	42.9
MnO	0.05	P	0.16	b.d.	P	0.24	0.01	0.01	b.d.	0.01
TiO_2	0.03	Ca	0.01	4.46	Ca	0.05	2.61	2.82	1.41	49.2
FeO	0.30	Ti	b.d.	0.03	Ti	0.01	0.23	0.10	2.95	0.03
Cr_2O_3	0.02	V	0.01	0.15	V	0.02	0.06	0.12	0.17	0.01
NiO	0.02	Cr	0.19	5.95	Cr	0.43	3.84	4.61	10.7	0.29
Total	100.71	Co	0.33	0.02	Co	0.23	0.01	0.01	b.d.	0.01
	$N = 142$	Ni	5.76	0.07	Ni	4.40	0.01	0.05	0.06	0.01
		Total	99.85	99.45	Total	99.46	98.41	98.82	98.86	97.67
			$N = 19$	$N = 4$		$N = 10$	$N = 25$	$N = 18$	$N = 20$	$N = 23$

Concentrations are in wt%. Abbreviations: N = number of analysis points, b.d. = below detection limits.
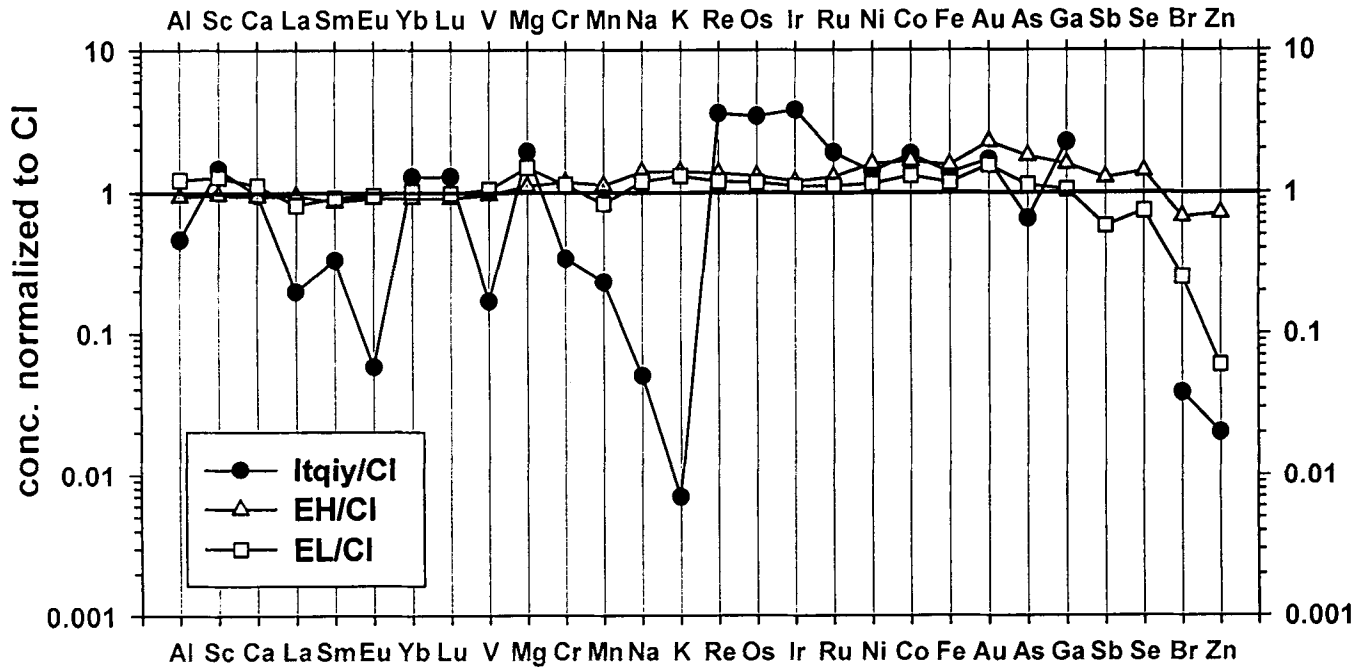
FIG. 5. Normalized concentrations of several major and minor elements in Itqiy obtained by INAA. The data averaged from four specimens show some discrepancies from the elemental patterns of EH and EL chondrites, namely depletion of Na, K, V, and Eu as well as an enrichment of the siderophile elements Re, Os, and Ir.

comparing the concentrations of Si and Ni (Fig. 6). We measured an average concentration of 5.8 wt% Ni and 3.1 wt% Si (from 120 data points).

Within the thin section UA1887 we located a few intergranular sulfide regions of 0.2 to 1 mm in diameter that represent assemblages of three different sulfide minerals and kamacite. In two occurrences, the same type of associated sulfides and kamacite has been observed as small spherules (~0.1 mm in diameter) within enstatite grains. The host mineral is a Mg-Mn-Fe sulfide of variable composition (Table 2). This type of sulfide has occasionally also been detected as tiny inclusions within the metal grains or veins. In E chondrites, Mg-Mn-Fe sulfides are present as either niningerite or alabandite, depending on the subgroup (Table 1). Niningerite is diagnostic of EH chondrites, whereas alabandite represents a typical sulfide of only EL chondrites. In Itqiy, the Mg-Mn-Fe sulfides reveal highly variable elemental abundances and plot neither in the niningerite nor the alabandite compositional range (Fig. 7). Two of the three areas we have analyzed show intermediate contents of MgS, MnS, and FeS. These areas represent the host phase of the sulfide assemblages. Another tiny area exhibits a composition close to that of niningerite but yields even higher amounts of MgS and less MnS. This sulfide was detected in the form of an inclusion within the main kamacite phase.

The three different phases embedded in the Mg-Mn-Fe host sulfide are Fe-Cr sulfide, oldhamite and metal droplets (Fig. 3).
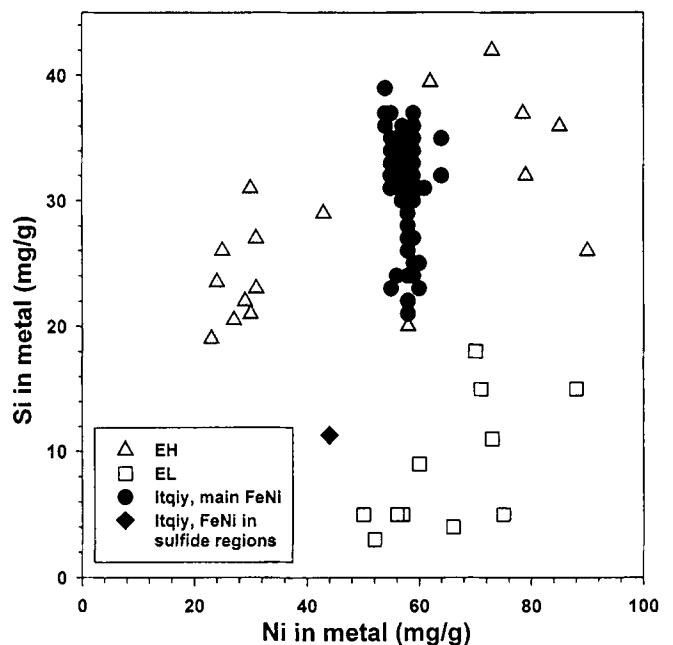

FIG. 6. Diagram comparing the concentrations of Si and Ni in kamacite of EH, EL chondrites, and Itqiy (E chondritic data taken from Zhang et al., 1995). Itqiy's main metal fraction (120 data points) lies well in the range of EH chondritic abundances. The composition of the metal globules within the sulfide assemblages differs from this trend, however, and instead rather matches EL chondritic values.
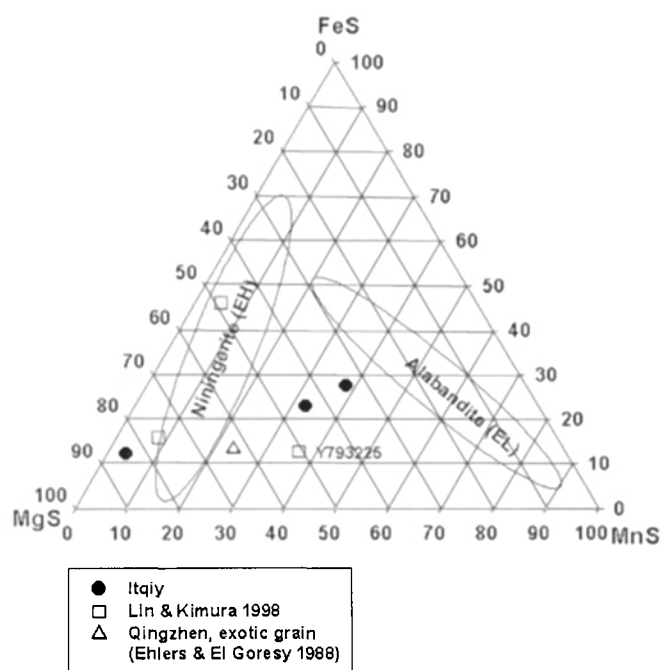
FIG. 7. Determination of the elemental abundances in Itqiy's Mg-Mn-Fe sulfides reveals variable concentrations. Neither pure niningerite nor alabandite but only mix-phases can be identified. Shown are also three unusual E chondrites investigated by Lin and Kimura (1998) as well as the composition of an exotic grain found and described by Ehlers and El Goresy (1988) (diagram modified after Brearley and Jones, 1998).
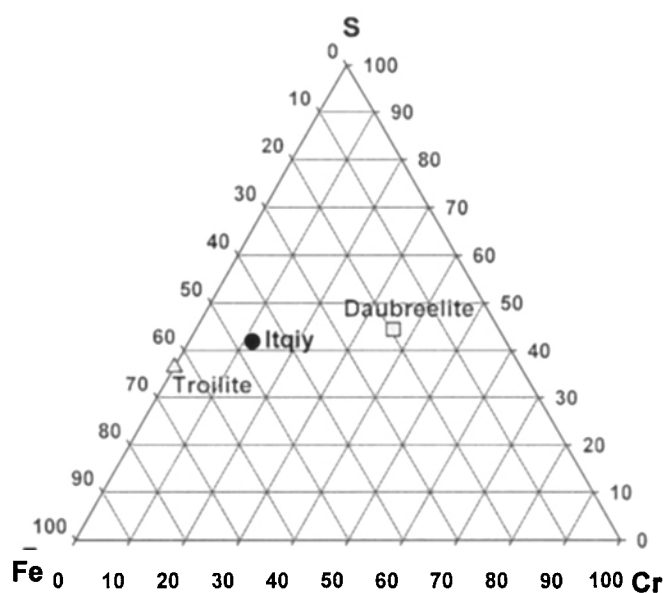
FIG. 8. The chemical composition of the Fe-Cr sulfide we located in Itqiy represents a mix-crystal between troilite and daubreelite, which are typical sulfides of E chondrites. The observed concentrations of Fe and Cr point at the occurrence of a thermal event with temperatures increasing above 650 °C and subsequent quenching.

A typical Fe-Cr sulfide in E chondrites is daubreelite (Table 1). In Itqiy, however, we find a mix-phase of daubreelite and troilite (Fig. 8, Table 2). It contains ~43 wt% Fe, 39 wt% S, and 11 wt% Cr and often forms exsolution lamellae (Fig. 9). In E chondrites, troilite has been observed to show similar features (Ramdohr, 1973). The relatively high Mn content (1.65 wt%) and negligible concentration of Zn (0.03 wt%) observed in Itqiy's Fe-Cr sulfide are consistent with EL chondritic data (Lin and El Goresy, 2001, unpubl. data). Oldhamite either appears as distinct droplets or spherically surrounds the metal drops. The kamacite spherules associated with the sulfides are especially abundant in the vicinity of adjacent metal grains or veins. Interestingly, the chemical composition of these tiny metal globules differs from that of the main kamacite fraction. It consistently shows EL chondritic Si and Ni abundances (10 different data points, Fig. 6, Table 2).

In brief, the main mineralogical phases of Itqiy, enstatite and kamacite, partly show affinity to EL and partly to EH chondrites. At the same time, we observe chemical parameters in the silicate as well as the bulk sample (see below) that do not match those of E chondrites at all. A similar conclusion can be drawn as to the complex Mg-Mn-Fe and Fe-Cr sulfide phases we identified in Itqiy. In general, these sulfides are characteristic for E chondrites. Their chemical compositions in Itqiy though are unusual (*i.e.*, the elemental abundances in
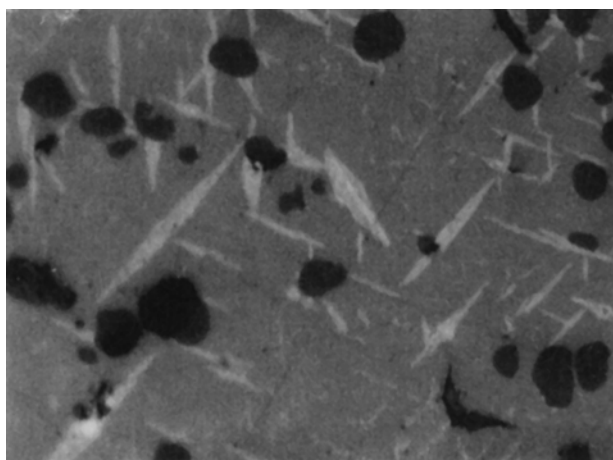

FIG. 9. Troilite-daubreelite mix-crystals forming exsolution lamellae as observed within the sulfide assemblages (in reflected light).

the Mg-Mn-Fe sulfide vary considerably showing neither exactly EH nor EL chondritic concentrations whereas the chemical composition of the Fe-Cr sulfide represents a mix-phase that is partly consistent with an EL chondritic chemistry).

INSTRUMENTAL NEUTRON ACTIVATION ANALYSIS RESULTS

With INAA, we determined the concentrations of 28 major and minor elements including six rare earth elements (REE) (Table 3). Figure 5 shows this range of elements normalized

TABLE 3. Elemental concentrations determined by INAA.

	Itqiy UA1886 cut/water		Itqiy UA1888 cut w/o water			
	179.6 mg	132.2 mg	119.6 mg	97.72 mg	Mean EH	Mean EL
Na	237.8	*251.4*	237.3	235.4	6720	5740
Mg	18.2	18	18.3	18.7	10.6	14.2
Al	0.409	0.407	0.39	0.386	0.8	10.5
K	4.6	–	–	3.6	799	740
Ca	0.83	0.87	0.85	0.91	0.85	1.01
Sc	8.62	8.81	8.45	8.39	5.55	7.36
V	*11.2*	*11*	9.7	9.4	54.5	59.3
Cr	830	*1008*	886	853	3130	2990
Mn	426	*1320*	560	426	2190	1630
Fe	*22.35*	*21.48*	25.48	25.08	28.7	21.6
Co	*824*	*781*	955	925	833	665
Ni	*13890*	*13060*	15610	15150	17400	12600
Zn	–	–	8.2	5.9	220	18
Ga	*19.6*	*18*	22.5	22.6	15.9	10.6
As	*1.397*	*1.364*	1.279	1.211	3.42	2.15
Br	0.119	0.22	–	–	2.4	0.9
Sr	–	–	46	–	–	–
Ru	–	–	2.3	1.6	0.912	0.791
Ba	*46*	*36*	66	64	–	–
La	–	0.03	–	–	0.232	0.197
Sm	0.052	*0.087*	0.049	0.051	0.133	0.141
Eu	<0.003	0.002	0.003	0.004	0.053	0.055
Ho	*0.044*	*0.081*	0.061	0.056	–	–
Yb	0.190	0.226	0.212	0.200	0.15	0.169
Lu	0.029	0.037	0.037	0.028	0.023	0.025
Hf	0.28	0.30	–	–	–	–
Ta	–	0.2	–	–	–	–
W	0.11	0.139	0.116	0.123	–	–
Re	*0.09*	–	–	0.114	0.05	0.044
Os	*1.39*	*1.19*	1.76	1.67	0.654	0.589
Ir	*1.438*	*1.324*	1.789	1.761	0.563	0.519
Au	*0.228*	*0.22*	0.245	0.243	0.325	0.224
U	0.11	–	–	–	–	–

Concentrations are in ppm except for Mg, Al, Fe, Ca (%). Uncertainties are 1–5% for Na, Mg, Al, Sc, Cr, Mn, Fe, Co, Ni, Ga, As, Sm, Os, Ir, Au; 5–10% for Ca, V, Yb; 10–20% for Zn, Br, Ho, Lu, Re; 20–30% for K, Sr, Ru, Ba, Hf, Ta, W, U; 30% for La. Concentrations in italic letters were not considered for the average values because of probable alteration. Mean EH and EL data are from Kallemeyn and Wasson (1986).

to CI abundances and compared with the same concentrations in EH and EL chondrites. While the E chondrites generally yield abundances close to those of CI chondrites, Itqiy's pattern reflects a number of significant and unusual deviations. The most striking discrepancy is obvious for K and Na.

Focusing on the REE, we find a distribution pattern that is depleted in light (L)REE (0.2 × CI for La) and slightly enhanced in heavy (H)REE (Fig. 10). Also, the determined pattern shows a characteristic negative Eu anomaly. By inference, Itqiy's REE signature matches the typical partitioning behavior of clinopyroxene, which usually excludes the LREE and Eu more efficiently than the HREE (Colson et al., 1988; Schwandt and McKay, 1998; see also Pun and Papike, 1995). This pattern is consistent with the loss of a partial melt. Aside from LREE, Itqiy also reveals considerable depletion of K and Na (Fig. 5). The partition coefficients of K and Na for clinopyroxene are rather low, and both elements tend to concentrate in plagioclase (e.g., McKay and Weill, 1976; Jones and Layne, 1997).

Another element that is significantly depleted in Itqiy is V. It appears likely that its relatively low abundance is also due
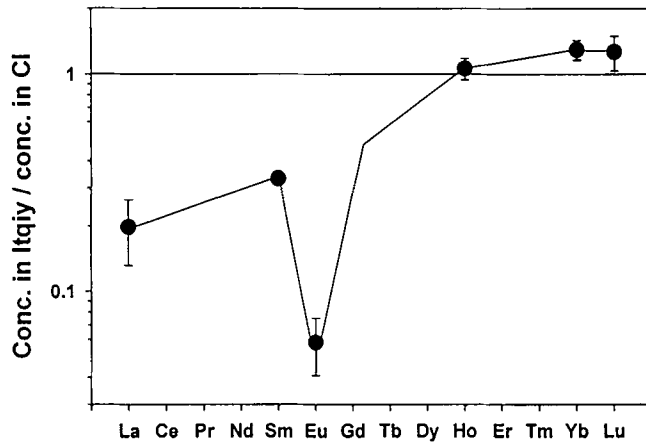
FIG. 10. The REE partitioning in Itqiy is characterized by a pyroxene pattern. The concentrations are relatively low. This particular distribution signature reflects the trend usually observed in clinopyroxene.
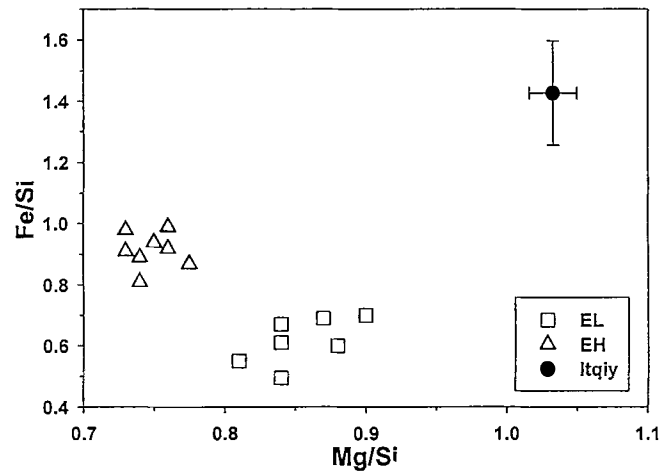

FIG. 11. Bulk ratios of Fe/Si and Mg/Si in E chondrites and Itqiy (E chondritic data taken from Zhang *et al.*, 1995). Itqiy's Fe/Si and Mg/Si ratios plot considerably off the EL and EH chondritic ranges. Mg and Fe amounts of Itqiy were directly determined *via* INAA. The Si concentration was estimated from electron microprobe data.

to the loss of a partial melt. The partition coefficient of V between sulfide and oxide phases shows a strong dependence on the fO_2/fS_2 and is attributable to a change of valence state from 4+ to 3+, with decreasing O_2 fugacity. In a reducing environment, V would concentrate in a sulfide melt (Gaetani and Grove, 1997). Applying these interrelations to Itqiy, low O_2 fugacities are required to have been present not only at the formation time of Itqiy's source rock but also at the time of the first major thermal event in order to establish the observed V depletion.

Aside from the apparent loss of V, Fig. 5 displays a significant enrichment of Re, Os, and Ir with factors of 2.4, 2.8, and 3.3, respectively. These siderophile elements usually concentrate in the solid metal phase during igneous fractionation (Rambaldi and Cendales, 1980). Thus, the enrichment of Re, Os, and Ir in Itqiy is at least qualitatively in accord with the idea of partial melting and subsequent loss of the liquid.

DISCUSSION

Itqiy exhibits several mineralogical and chemical similarities to E chondrites, yet it cannot be unambiguously assigned to either EH or EL chondrites. A number of incompatibilities with an E chondritic classification also exists in general. In the following we want to shed some light on the unusual aspects of Itqiy's composition and explore possible explanations in order to reconstruct part of the meteorite's evolutionary path.

The rather high amount of metallic Si, the presence of metal inclusions within the enstatite grains, the occurrence of CaS, and the practical absence of FeO in pyroxene suggest, as for E chondrites (*e.g.*, Kallemeyn and Wasson, 1986), highly reducing conditions during the formation of the meteorite's parent body. The coarse grain size, homogeneous composition of the silicate phase, and abundant triple junctions between enstatite grains yield constraints on the thermal history of Itqiy.

They are compatible with either a long-term metamorphic process or an igneous event that involved slow cooling and hence allowed extensive recrystallization and equilibration. Since plagioclase is completely absent from the investigated rock and the abundance of sulfides is comparatively low, however, we suggest that the latter scenario (*i.e.*, partial melting) took place and removed plagioclase and sulfide components along with the LREE, K and Na.

On a bulk compositional basis, E chondrites can usually be distinguished and classified as EL or EH chondrites in terms of their Mg/Si and Fe/Si ratios. The concentrations of Fe and Mg were well quantified by INAA (Table 3). Si, on the other hand, is undeterminable with this technique. Hence, we estimated its bulk abundance from the microprobe data. According to the modal analysis, Itqiy contains 77.6 vol% enstatite with an average of 27.7 wt% Si and 22.6 vol% kamacite with an average of 3.13 wt% Si. Taking into account the different densities of enstatite and kamacite, these numbers sum up to 17.7 wt% Si in the bulk sample.

With 17.7 wt% Si, 18.3 wt% Mg, and 25.3 wt% Fe, the Mg/Si and Fe/Si ratios in Itqiy turned out to be considerably higher than those of both EH and EL chondrites (Fig. 11). It would appear that it is difficult to make Itqiy using either class of E chondrites as a starting material. Loss of plagioclase by partial melting, as suggested above, would remove some Si, but not nearly enough to move the bulk composition so far away from the enstatite chondrites. In addition, some Fe would have to be lost with the sulfide-rich melt, so the Fe/Si ratio in the residue would not change much for modest degrees of partial melting. The high metal content in Itqiy is difficult to reconcile with partial melting, as some metal should be lost with the initial metal-sulfide eutectic melt. If indeed Itqiy formed as a residue from partial melting, the starting composition would have to be more metal rich than any of the known enstatite chondrites.

So far we have only considered small degrees of partial melting, but if we consider large degrees of partial melting, this process could, in principle, enrich the metal content if it melts at a higher temperature than the enstatite. The enrichment of the refractory platinum metals noted earlier, would also argue for a large degree of partial melting, as an enrichment of a factor of 3 requires that a minimum of two-thirds of the original material be lost. Such high degrees of partial melting, however, would produce a much greater depletion of LREE and alkali elements than observed, so our favored hypothesis is that Itqiy formed from a body initially enriched in metal and refractory platinum elements.

Even though the coarse grain sizes and lack of mineral zoning imply equilibrium conditions, the compositions of the Mg-Mn-Fe and Fe-Cr sulfides argue against an equilibrated process. Most likely, two heating events appear to have taken place in Itqiy's history. We assume that first a high-temperature process established the extensive recrystallization and equilibration of enstatite. This event produced a sulfide- and plagioclase-rich magma, most of which was subsequently lost from the system and led to depletion of sulfide phases and feldspar. The presence of oldhamite coincides with this interpretation. According to a melting experiment with the EH4 chondrite Indarch, oldhamite in aubrites has formed from a sulfide-rich magma (McCoy et al., 1999; see also Dickinson et al., 1991; Dickinson and McCoy, 1997; Hsu, 1998; McCoy, 1998). Hence, oldhamite in Itqiy may also well have an igneous origin. In addition, the low Zn content of Itqiy's Fe-Cr sulfide can be explained in a similar way as low Zn amounts in daubreelite of EL chondrites and may result from depletion due to high (metamorphic or igneous) temperatures (Lin and El Goresy, 2001, unpubl. data). Regarding the chemical composition of the Fe-Cr sulfide as well as the variable elemental abundances in the Mg-Mn-Fe sulfide, however, a later, second heating event followed by abrupt cooling is likely to have happened. As described in El Goresy et al. (1988), there exists an invariant reaction of troilite to daubreelite in EH3 chondrites (see also El Goresy and Kullerud, 1969). Possibly, the Fe-Cr sulfide in Itqiy represents an incomplete stage of this reaction and was most probably produced by quenching of a sulfide-rich melt. Rapid cooling may also be responsible for the heterogeneous concentrations of Mg, Mn and Fe in the host sulfide of the sulfide assemblages. The cause for this second heating event may have been an impact event since many enstatite crystals show S3 shock features.

An impact scenario would also be compatible with rapid cooling and producing the observed Fe-Cr and probably Mg-Mn-Fe sulfide mix-phases (A. El Goresy, pers. comm., 2001). Alternatively, one could explain the texture, petrology and chemical composition of Itqiy by a single igneous event that started out as a slow process with gradually decreasing temperatures until about 800 to 750 °C. Around that point, cooling must have speeded up considerably, possibly caused by the liberation of the Itqiy meteoroid via impact.

In the literature, a couple of other E chondrites with unusual compositions of their Mg-Mn-Fe sulfides have been reported (Fig. 7). For instance, the EH melt rock Yamato (Y)-793225 shows intermediate Mg-Mn-Fe abundances similar to those found in Itqiy's host sulfide. Based on this observation, Lin and Kimura (1998) suggest this meteorite to represent a new grouplet of E chondrites. However, based on their investigation, Y-793225 experienced slow cooling.

Recently, another unusual enstatite meteorite, Zaklodzie, has been recovered. In accordance with Itqiy, the chemical composition of minerals in Zaklodzie is rather typical for enstatite chondrites and it also seems to be either a highly metamorphosed or a melted (achondritic) meteoritic sample (Stepniewski et al., 2000). However, it contains a considerable amount of plagioclase, a different set of sulfides (~6.5 wt% troilite) and significantly less metal. Also, the CaO content of enstatite is lower than in Itqiy ($En_{97.7-99.1}Fs_{0.1-1.6}Wo_{0.7-0.9}$ $vs.$ $En_{96.8}Fs_{0.2}Wo_{3.0}$). Thus, despite some general similarities, we believe neither that both meteorites represent the same material nor that Itqiy was directly derived from Zaklodzie-like material. In fact, a recent study of Zaklodzie classifies this meteorite as an impact melt (Burbine et al., 2000).

CONCLUSIONS

Itqiy exhibits an overall homogeneous, coarse-grained texture. The dominating phase is a low Ca pyroxene that partly resembles EL chondritic enstatite. The other main constituent of this meteorite is kamacite, which rather shows EH chondritic compositional characteristics.

As accessory phases, three different sulfides have been identified. They occur in distinct millimeter-sized regions and are associated with kamacite globules. The host phase of these sulfide assemblages is a Mg-Mn-Fe sulfide that reveals variable elemental abundances. The other sulfide minerals are oldhamite and a Fe-Cr sulfide. All sulfides are typical for E chondrites. The Mg-Mn-Fe-S and Fe-Cr-S phases of Itqiy, however, exhibit unusual compositions. Interestingly, the metal globules within the sulfide regions exhibit EL chondritic Si and Ni abundances in contrast to EH chondritic concentrations in the main kamacite fraction.

Itqiy's REE pattern reveals a significant depletion of LREE (0.2 × CI for La). This suggests the removal of a LREE-rich partial melt and reflects partitioning of REE into clinopyroxene. In addition, K, Na and V are depleted in Itqiy. They were probably fractionated into plagioclase and sulfide components, and subsequently removed from the parent rock. Thus, a partial melting process can account for the absence of plagioclase, the low abundance of sulfides, the REE pattern and the depletion of K, Na, and V found in Itqiy. It most likely also established the extensive recrystallization and equilibration of enstatite as well as the relative overabundance of Re, Os, and Ir.

Later in Itqiy's history, an impact event might have occurred causing various shock features like undulose extinction,

irregular fractions, and mosaicism in many enstatite grains. An impact scenario is also consistent with the existence of a troilite-daubreelite mix-phase as well as the variable chemical composition of the Mg-Mn-Fe sulfide.

The reduced nature of Itqiy reflected by its mineral composition suggests a relationship to enstatite chondrites, but bulk abundances of Mg, Fe, and Si in Itqiy reveal considerably higher Mg/Si and Fe/Si ratios than those found in EL or EH chondrites. In addition, several elemental concentrations as well as the amount of kamacite within the sample differ significantly from E chondritic values. The discrepancies cannot be explained by low degrees of partial melting from an enstatite chondritic source material.

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