PETROLOGY AND CHEMISTRY OF THE MILES IIE IRON. II: CHEMICAL CHARACTERISTICS OF THE MILES SILICATE INCLUSIONS

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Abstract: A total of nine silicate inclusions (6 gabbroic, 3 cryptocrystalline) were isolated from slab samples of the Miles IIE iron meteorite. They were studied petrologically and then analyzed by instrumental neutron activation analysis, along with the host metal. Based on the siderophile element abundances in the host metal phase, Miles can be classified as a IIE iron but in some aspects it does not match the siderophile abundances of either IIE or anomalous IIE (IIE-An) irons. It may be a member of a third group of IIE irons, tentatively named fractionated IIE. Compared with the average H chondrite, the highly siderophile elements (Re, Os, Ir) are relatively more depleted than the less refractory siderophiles, except for Cu which is as depleted as the highly siderophile elements. This suggests that the metal phase of Miles was not simply produced by a vaporization/fractional condensation process. Rather, it was produced by the melting of H chondritic materials, followed by melt-solid segregation. At least a part of the immiscible sulfide in which Cu was distributed to a considerable degree, was removed from the metal melt. Silicate inclusions have variable amounts of siderophile elements, but their relative abundances are similar to those of the metal phase. This suggests that the siderophile elements in the silicate inclusions have the same genesis as those in the host metal. Plagiophile elements (Al, Na and K) are all enriched in the silicate inclusions, especially in the cryptocrystalline inclusions, with K being the most abundant, successively followed by Na and Al. This fractionation of the plagiophile elements must have occurred during the fractional crystallization process, when the silicate inclusions formed. Rare earth elements (REE) are fairly enriched in the silicate inclusions (especially in the gabbroic inclusions) but their concentrations are slightly lower than that expected from the degree of partial melting of H chondritic materials. A mechanical loss of Ca-phosphate in sampling is suggested for the inconsistency in the REE abundances. Based on the REE abundance variations in the silicate inclusions of several IIE irons, including Miles, we infer that the degree of differentiation of the parental liquids from which silicate inclusions formed was highly variable; it increased from Watson to Weekeroo Station, with Miles being intermediate.

1. Introduction

Iron meteorites are genetically classified into two groups; magmatic and non-magmatic. Group IIE irons, together with IAB and IIICD irons, are considered to be non-

magmatic in origin (Scott and Wasson, 1976), possibly formed from impact-pro-
duced melts (Wasson et al., 1980; Wasson and Wang, 1986), and generally charac-
terized by the presence of silicates inclusions. Wasson and Wang (1986) classified
the IIE meteorites into two subgroups, normal IIE and anomalous IIE (hereafter IIE-
An), based on the degree of correlation between several pairs of elements in the metal
phases. Based on the textures and mineral compositions of the silicate inclusions,
McCoy (1995) separated IIE irons into the primitive and differentiated subgroups. In
this classification, Netschaëvo and Techado belong to the primitive IIE subgroup.

Since IIE irons have silicate inclusions, the O-isotope compositions and radio-
metric ages of these inclusions can be measured. The similarity in O-isotope compo-
sition between IIE silicates and H chondrites suggests a genetic relationship (Clayton
et al., 1983; Rubin et al., 1986). Radiometric ages of the IIE silicates are spread in
a wide range, from 4.5 Ga for Colomera (Rb-Sr age; Sanz et al., 1970), Weekeroo
Station (Ar-Ar age; Niemeyer, 1980) and Techado (Ar-Ar age; Garrison and Bogard,
1995) to 3.5 Ga for Kodaikanal (K-Ar age; Bogard et al., 1969) and Watson (K-Ar
age; Olsen et al., 1994), with other IIE irons falling within this range. One hypoth-
esis for the formation of IIE irons suggests that they were produced as impact melts
near the surface of a parent body (ies) having an H chondritic composition (Wasson
and Wang, 1986). This model was supported by other researchers (Olsen et al., 1994;
Casanova et al., 1995; Ikeda and Prinz, 1996). McCoy (1995) proposed an alterna-
tive model that IIE irons were produced in the core-mantle region of a parent body
and were heated by impacts at a later stage.

Miles is the latest recognized IIE iron (Wlotzka, 1994), and was found in
Queensland, Australia in 1992, with a total mass of 265 kg. Based on the chemical
composition of the metal phase (data by Wasson in Wlotzka, 1994), Miles was rec-
ognized as a IIE iron. McCoy (1995) further grouped it as a differentiated IIE iron.
Ikeda and Prinz (1996) examined silicate inclusions of the Miles meteorite in detail
and found that there are two types, having gabbroic and cryptocrystalline textures.
These textures suggest that the silicates were melted and not primitive.

Chemical compositions of the silicate inclusions in a limited number of the IIE
iron meteorites have been determined. This is especially true for the trace element
compositions of the silicate inclusions in the differentiated IIEs. Evensen et al. (1979)
determined rare earth element (REE) abundances in several silicate inclusions isolat-
ed from Weekeroo Station and found non-chondritic abundances. Olsen et al. (1994)
systematically analyzed a single, large silicate inclusion (~100 g) in Watson, not only
for REE but also for other trace elements and found unfractionated, almost
chondritic REE abundances.

In order to increase our understanding of the chemical characteristics of the sil-
icate inclusions in the IIE irons, instrumental neutron activation analysis (INAA) was
employed for analyzing separated silicate inclusions from the Miles IIE iron for the
determination of major, minor and trace elements. These silicates were examined petro-
logically prior to INAA and these results are reported in a companion paper (Ikeda
et al., 1997a). In addition to the silicate inclusions, the host metal was also analyzed
by INAA. Based on these data, our aim in this study is to (i) characterize the chem-
ical composition of the Miles silicate inclusions, (ii) find relationships between the

chemical compositions and the petrological data, and (iii) elucidate the origin of Miles and the other IIE irons with silicates.

2.   Experimental Methods

2.1. Samples

Miles consists of an Fe-Ni metal host and many silicate inclusions. IKEDA and PRINZ (1996) petrologically examined 29 silicate inclusions in an earlier study, and an additional 20 inclusions were petrologically examined by IKEDA et al. (1997a) for this study. Of those, nine inclusions weighing 6.1 mg to 35.8 mg were analyzed by INAA. The textures and mineral assemblages of the silicate inclusions analyzed are summarized in Table 1. The inclusions have been grouped into two types, gabbroic and cryptocrystalline, based on their textures; the gabbroic ones are predominant (IKEDA and PRINZ, 1996). Of the nine inclusions analyzed, six are gabbroic and three are cryptocrystalline in texture.

2.2. Neutron activation analysis

The silicate inclusions were separated from slab samples by using an instrument similar to a dental pick. Initially, each inclusion was mechanically purified by removing adhering metal using a scraper, and each was then rinsed in acetone with ultrasonication. After weighing, the inclusions were heat-sealed doubly in clean plastic bags. In addition to the silicate inclusions, the host metal was simultaneously analyzed. A piece (11.2 mg) from the metal portion was prepared in the same way as for the silicate inclusions. The samples were irradiated in a TRIGA II reactor of the Institute for Atomic Energy, St Paul's (Rikkyo) University, along with chemical standards and the Allende reference standard (split 11, position 11) prepared by the Smithsonian Institution, and a basaltic standard rock sample, JB-1 of the Geological

Table 1.   Mineral assemblages of the Miles inclusions analyzed by INAA.

Inclusion	Cpx	IPig	Opx	Pl	Ant-P	Kf	Tridy	Cry-Ab	Chm	Rut	Aml	Ilm	Wht	Apt	Ol
Gabbroic															
1B	**		**	*		*	*		*	*			*		
1C	**		**	**		*			*	*	*	*		*	*
1D	*		*	**	*	*									
1F	**	*	**	*	*	*	*		*			*			
1I	**		**	*		*	*		**	*	*	*		*	*
1J	*		*	**	*	*	*		*					*	
Cryptocrystalline															
1E			*	*				**	*	*			*		
1G	*		**	*				**	*					*	*
1H	*		*					**	*					*	*

**: major, *: minor.

Abbreviation: Cpx (high Ca pyroxene), IPig (inverted pigionite), Opx (orthopyroxene), Pl (Plagioclase), Ant-P (antiperthite, or anorthoclase), Kf (K-feldspar), Tridy (tridymite), Cry-Ab (Cryptocrystalline albite), Chm (chromite), Rut (rutile), Aml (armalcolite), Im (ilmenite), Wht (whitlockite), Apt (Cl-apatite), Ol (olivine).

Survey of Japan. Irradiations were successively done two times, with different irradiation times (100 s and 6 h). After the first irradiation, the metal samples were measured immediately, while the silicate samples were measured after cooling for a few minutes. The INAA method used in this work is essentially the same as that described in KONG et al. (1996).

3. Results and Discussion

3.1. Host metal

The elemental composition of the host metal is shown in Table 2, which also includes the analytical data of Wasson (in WLOTZKA, 1994) for comparison. Our data are mainly consistent with those of Wasson, except for Ir, and especially Pt. Our Ir

Table 2. Chemical compositions (in ppm, or otherwise indicated) of the metal of Miles and other IIE iron groups.

	Fe(%)	Co	Ni(%)	W	Mo	Re	Os	Ir	Ru
Miles									
This study[a]	91.2(1)	4580(1)	7.55(1)	0.818(2)	5.95(1)	0.102(4)	1.24(13)	0.894(1)	4.25(13)
Literature[b]		4430	7.96	0.86		0.100		1.12	
IIE irons[c]									
Normal IIE		4500	8.49	1.20		0.569		5.8	
		150	*0.56*	*0.12*		*0.141*		*1.4*	
Anomalous IIE		4350	8.15	1.14		0.515		4.5	
		180	*0.42*	*0.15*		*0.215*		*1.7*	
Ungrouped		5370	9.38	0.44		0.096		0.70	
		5350, 5380	*9.25, 9.50*	*0.37, 0.50*		*0.091, 0.100*		*0.69, 0.71*	
H chondrites									
Bulk[d]	27.5	810	1.60	0.16	1.7	0.070	0.82	0.76	1.11
Metal[e]	87.1	4400	9.8	0.61	3.8	0.361	3.16	3.40	5.4

	Pt	Rh	Pd	Au	Cu	As	Sb	Ga	Ge
Miles									
This work	7.06(4)	1.47(7)	2.99(6)	0.976(1)	172(5)	10.4(1)	0.384(5)	29.8(1)	70.8(17)
Literature	4.6			1.13	182	9.52		26.6	
IIE irons									
Normal IIE				1.29	220	11.7		24.6	70.6
				0.32	*56*	*3.5*		*2.8*	*3.4*
Anomalous IIE				1.19	279	10.6		24.6	65.5
				0.25	*58*	*3.7*		*2.5*	*1.3*
Ungrouped				2.13	150	20.6		25.4	66.2
				2.06, 2.20	*142, 158*	*18.7, 22.4*		*25.0, 25.7*	*62.1, 70.2*
H chondrites									
Bulk	1.40	0.22	0.87	0.215	82	2.05	0.070	6.0	13
Metal	8.6	1.1	5.0	1.34	520	12.6	0.55	9.7	63

[a]Values in parentheses are errors due to counting statistics (in %; 1σ). [b]Data by WASSON (WLOTZKA, 1994). [c]Mean values and standard deviations (in italics; 1σ) for normal IIEs (n=8) and anomalous IIEs (n=4). For ungrouped irons, mean values and individual data (in italics) are shown. Data from WASSON and WANG (1986). [d]WASSON and KALLEMYN (1988). [e]KONG and EBIHARA (1997).

value is ~20% lower than the Wasson value. A similar variation of Ir contents was observed by WASSON and WANG (1986) in their duplicate analyses of the Netschaëvo IIE iron, suggesting that Ir is heterogeneously distributed in the metal portion of IIE irons. Our Pt value is about 50% higher than that of the WASSON value and since no systematic determination of Pt has been carried out for IIE irons we cannot evaluate the discrepancy. Based on the siderophile abundances in their metal analyses, WASSON and WANG (1986) classified the potential IIE irons into three groups, normal IIE, IIE-anomalous (IIE-An) and ungrouped iron. In Table 2, mean values and standard deviations (1σ) of the individual data are cited from WASSON and WANG (1986) for these three groups.

It can be noted in Table 2 that the Re and Ir contents in Miles are extremely low compared with those in both normal IIE and IIE-An irons. They are rather close to, or nearly equal to, the values for the Seymchan and Lonaconing meteorites, which were considered to be ungrouped irons, rather than IIE-An, by WASSON and WANG (1986). These two meteorites are characterized by low abundances of not only Re and Ir, but also W, compared with other IIE irons (normal IIE and IIE-An) (WASSON and WANG, 1986). Miles shows a depletion of W compared to other IIE irons (Table 2). Thus, the Re, Ir and W contents in Miles metal are lower than the IIE average, and close to the average values for the Seymchan and Lonaconing irons.

Figure 1 shows element-Ni diagrams for eight elements in Miles (this study) and those in other group IIE irons (WASSON and WANG, 1986). The Miles data of WASSON also are shown in this figure for comparison. The composition of the Miles iron is generally close to that of the normal IIE irons except for Ir and W. The Ir and W values in Miles differ from the trend defined by the normal IIE irons, being depleted in those elements. The two ungrouped irons also have lower Ir and W contents, but their compositions are far from that of Miles. It may be worth pointing out that Weekeroo Station, an anomalous IIE, is between the normal IIE band and Miles on the Ir-Ni and W-Ni plots. Our Ga and As values of Miles are also slightly off the IIE band, being located above the IIE band, although their absolute contents are within the ranges for IIE irons. One may suspect that our data are biased at least for these two elements. Considering that the same analytical procedure yielded very consistent data of Ga and As for reference materials (KONG et al., 1996), chemical heterogeneity rather than interlaboratory bias can explain such an inconsistency for Ga and As data. The Miles iron may be grouped with the IIE irons but cannot be designated either normal IIE or IIE-An. The Low abundances of Re and Ir (and possibly Os) in Miles are close to those of the ungrouped irons (Table 2), but these meteorites are not located at identical positions on Fig. 1. Based on these considerations, Miles may be part of a third group of IIE irons, which is tentatively named fractionated IIE.

The elemental abundances in the Miles host metal are shown in Fig. 2, where their abundances are normalized to the H chondrite average (WASSON and KALLEMEYN, 1988) and bulk H chondrite metal (KONG and EBIHARA, 1997) (Table 2). Both abundance patterns are roughly parallel to one another. The data appear to be divided into two groups of elements; a Re-Os-Ir-Cu group, and the others. Elements in each group have similar H chondrite-normalized abundances. Interestingly, the highly refractory siderophile elements (Re, Os, Ir) are depleted compared with the less refractory
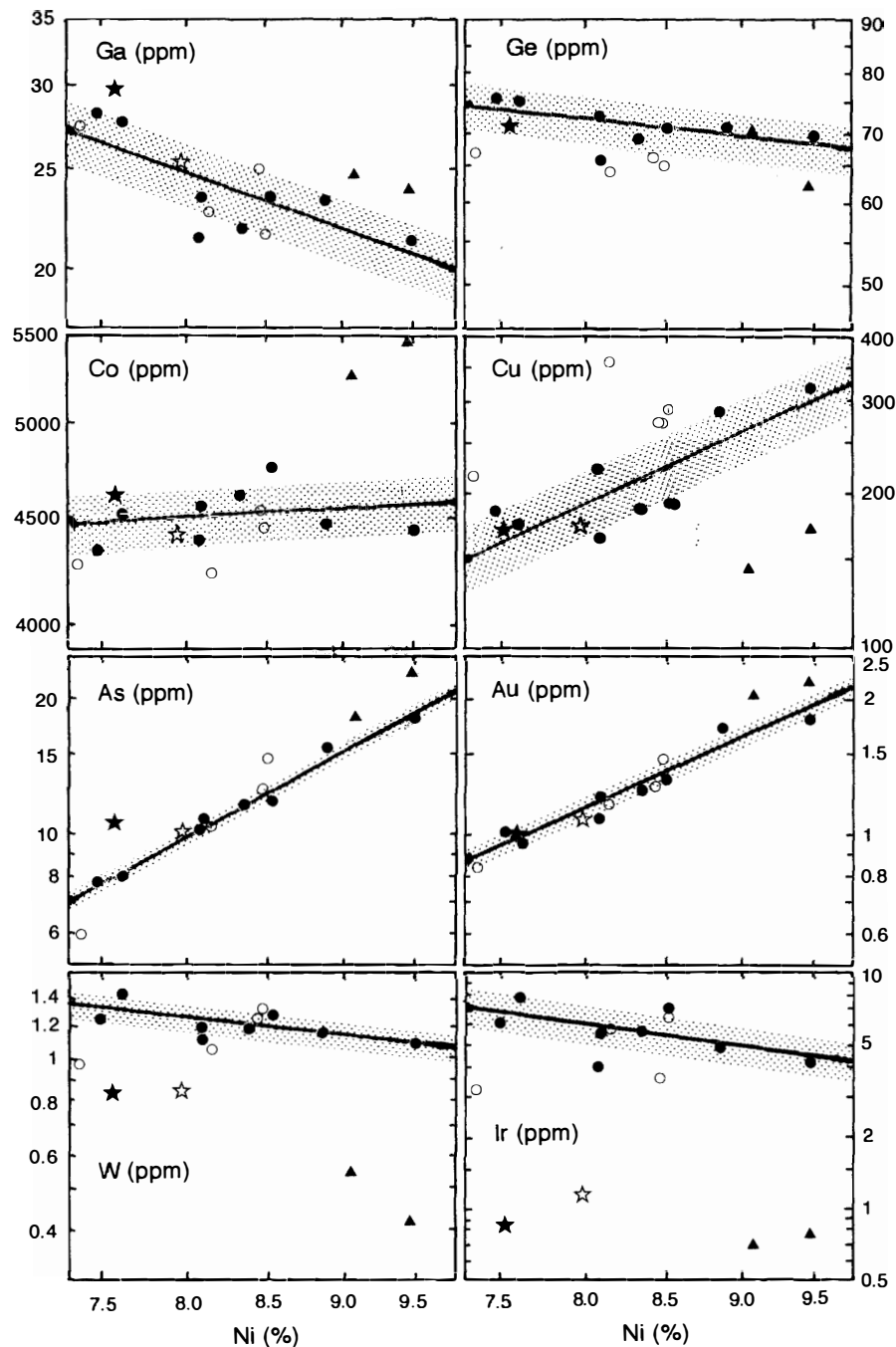
Fig. 1. Element-Ni diagrams for eight elements in Miles and those in other group IIE irons
(WASSON and WANG, 1986). The data of Miles from this study and WASSON are indi-
cated by solid and open stars, respectively. For comparison, normal IIE (solid cir-
cles), IIE-An (open circles) and the ungrouped irons Seymchan and Lonaconing (solid
triangles) are shown separately as well as shaded bands corresponding to one stan-
dard deviation of the normal IIE data (all these data from WASSON and WANG, 1986).
The composition of the Miles iron is generally close to that of the normal IIE irons
except for Ir and W, which are depleted in Miles. The Miles iron may be grouped
with the IIE irons but cannot be designated either normal IIE or anomalous IIE. Miles
may be tentatively grouped with the fractionated IIE irons, which is a third group of
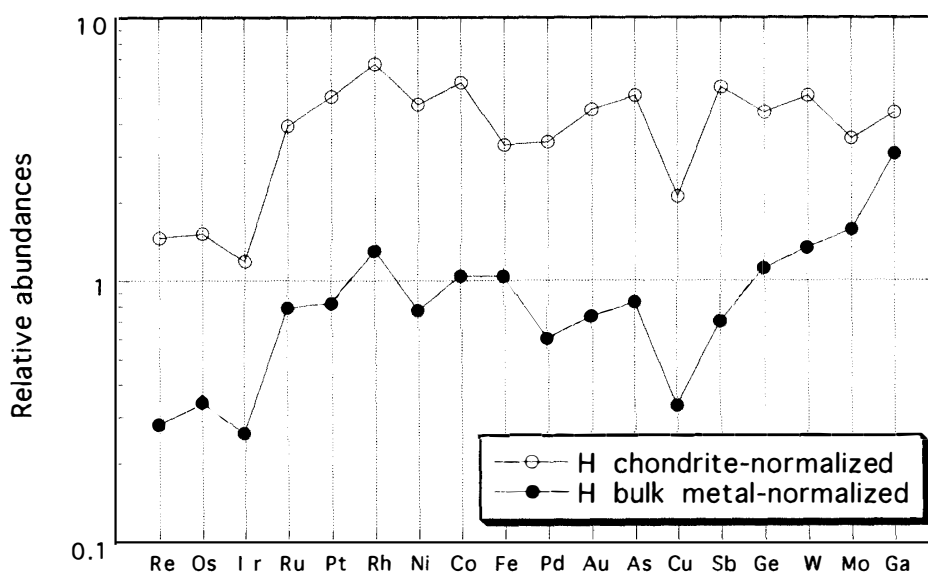IIE irons.

Fig. 2.   Elemental abundances in the Miles metal normalized to the H chondrite average (WASSON and
         KALLEMEYN, 1988) and bulk H chondrite metal (KONG and EBIHARA, 1997). The highly refracto-
         ry siderophile elements (Re, Os, Ir) and Cu are relatively depleted in the Miles host metal com-
         pared with those in the H chondrite metals. It is inferred that the Miles host metal is residual
         metal after segregation of solid metal. Probably, Cu was preferentially taken into sulfide under
         reducing conditions, which is suggested by the considerably higher abundance of Ga in the Miles
         metal than that in the H chondrite metal.

siderophiles. As the partition coefficients of these elements, between metal and sili-
cates, are very high or at least higher than those for the less refractory elements (PEACH
and MATHEZ, 1993; O'NEILL et al., 1995), the Miles host metal cannot be the prod-
uct of the metal/silicate partitioning of H-chondritic materials.

   RUBIN (1995) determined the refractory siderophile element abundances in metal
separates from the Rose City meteorite, which is an H chondritic impact breccia, and
discussed the fractionation of these elements during fractional crystallization. Although
only nine elements were determined for the metal separates from Rose City, compar-
ing with 17 elements for the Miles metal, the siderophile abundance patterns (nor-
malized to the mean bulk composition of H chondrite metal) are surprisingly similar
for the "refractory-poor" metal separates of Rose City and Miles. RUBIN (1995) esti-
mated the distribution coefficients between solid and liquid metal for the H
chondritic material; 4.7 for Ir and Os, 1.5 for W, 1.2 for Co, 1 for Ni and Fe, 0.90
for As, 0.5 for Au and 0.27 for Ga. If these values and the H bulk metal-normalized
abundance patterns of the Miles host metal (Fig. 2) are considered, Miles is residual
metal after an equilibrium (or quasi-equilibrium) distribution. RUBIN (1995) interpret-
ed the abundance patterns of the siderophile elements, similar to that in Miles host
metal, in the context that they were established by vaporization followed by fraction-
al condensation. If this hypothesis can be applied to the Miles host metal, the low
abundance of Cu, which is less refractory than the siderophile elements, can be
explained by invoking another process which must have occurred prior to the frac-
tional condensation. It may be worth pointing out that a depletion of Cu was also

observed in the metal nodules and veins in heavily shocked ordinary chondrites (Widom et al., 1986). In those metal samples, Ir and Re were also found to be severely depleted, as in the case for the Rose City metal. No data for Cu were presented for the metal from Rose City in Rubin (1995).

Presumably, the Miles host metal was produced by melting of H-chondritic material. The siderophile elements are quantitatively enriched in the metal-sulfide melt, without significant fractionation. With cooling, solid metal is segregated from the residual metal melt. Assuming that the solid and melt metal formed equally, the (relative) elemental abundances in this melt can be calculated to be Ir/Ni/Ga=0.35/1.0/1.6 by using distribution coefficients estimated by Rubin (1995). This is roughly consistent with the H-normalized abundances of these three elements in the Miles host metal, suggesting that the Miles host metal was the residual melt fraction after partial segregation of solid metal from the metal-sulfide liquid, which was probably produced by shock heating. Copper is a siderophile element in ordinary chondrites but becomes partly chalcophile in enstatite chondrites (Allan and Mason, 1973), suggesting that Cu behaves as a chalcophile element when the redox state becomes reductive. Probably, Cu was preferentially taken into sulfide in Miles, resulting in the depletion of Cu in the metal phases. Such a preferential uptake of Cu from metal into sulfide must also have occurred in the heavily shocked meteorites. At least, a part of the immiscible sulfide melt, in which Cu was distributed to a considerable degree, was separated and removed from the metal melt.

It should also be noted that the relative abundance of Ga is higher than the expected value on the H metal-normalized pattern (Fig. 2). Such a high abundance cannot be the result of a vaporization/fractional condensation model. Gallium contents in metal are relatively low compared with those of the other siderophile elements such as As and Sb, which have similar volatilities to Ga in ordinary chondrites (Kong and Ebihara, 1997). Thus, a considerable amount of Ga is present in non-metallic, possibly silicate phases. The partition coefficient of Ga between metal and silicate varies, depending upon the oxygen fugacity (Schmitt et al., 1989), from 10 for $f_{o_2} = 10^{-12}$ atm to 1.8 for 10^{-11} atm at 1300°C. The metal/silicate partition coefficient of Ga in the least metamorphosed ordinary chondrites is 0.5 or less (Kong and Ebihara, 1996, 1997), suggesting that the distribution of Ga occurred under highly oxidizing conditions. If melting occurred under more reducing conditions, the Ga distributed in the non-metal phases would be moved into metal phases. This can be an explanation for the higher than expected abundance of Ga in the Miles host metal. An unfractionated value of Ga which falls on the H chondrite-normalized abundance pattern suggests that Ga quantitatively resides in the metal phase.

3.2. Silicate inclusions

The chemical compositions of nine silicate inclusions in the Miles meteorite are shown in Table 3. The data are separated into gabbroic inclusions and cryptocrystalline inclusions, and the mean values are also given.

3.2.1. Siderophile elements

The siderophile elements are generally depleted in the silicate inclusions compared with those in H chondrites (Fig. 3). There seems to be no apparent difference

Table 3.   Chemical compositions (in ppm, or otherwise indicated) of silicate inclusions in the Miles IIE iron.

	weight(mg)	Na,%	Mg,%	Al,%	K,%	Ca,%	Sc	Ti	V	Cr	Mn	Fe,%	Co	Ni,%
Gabbroic														
IB	26.2	2.07	5.08	1.68	0.31	3.39	19.5	2020	70	4140	2350	11.4	378	0.80
IC	60.4	3.90	4.20	5.55	–[a]	4.47	24.1	–	108	4070	1310	7.4	302	0.64
ID	10.0	5.37	0.97	7.90	3.30	2.50	10.0	3230	52	2060	620	3.0	104	0.149
IF	5.6	0.529	11.3	0.91	0.24	1.67	23.3	2120	131	5320	3830	14.7	427	1.15
II	19.5	0.923	10.0	1.57	–	2.45	14.3	4320	410	5410	4030	13.9	343	0.70
IJ	13.9	4.77	1.59	6.67	–	2.69	8.47	–	51	1660	505	5.0	220	0.46
mean[b]		*2.9*	*5.5*	*4.1*	*1.28*	*2.9*	*16.6*	*2900*	*137*	*3800*	*2110*	*9.2*	*300*	*0.65*
Cryptocrystalline														
IE	10.3	6.34	0.84	8.45	0.68	0.43	4.43	2350	–	427	378	3.3	141	0.81
IG	30.2	3.23	6.51	4.37	0.56	3.05	25.0	2730	113	5550	2070	9.0	263	0.90
IH	8.8	5.10	0.45	6.02	1.26	–	6.13	3360	15	1770	283	25.9	1310	2.50
mean		*4.9*	*2.6*	*6.3*	*0.84*	*1.7*	*11.9*	*2800*	*64*	*2600*	*910*	*12.7*	*570*	*1.4*
Error[c]		1	3-9	2	2-14	4-22	1	5-10	3-13	1	2-4	1-9	1	1-2

	Zn	As	Se	La	Ce	Sm	Eu	Yb	Lu,ppb	Hf	Ir,ppb	Au,ppb
Gabbroic												
IB	37.3	0.55	1.46	0.76	4.0	1.04	0.21	1.18	181	0.45	63	49
IC	14	–	–	0.59	2.4	0.73	0.37	0.73	138	–	36	25
ID	16.6	–	2.67	–	2.5	0.75	0.23	0.66	96	0.33	–	10.0
IF	69.3	0.55	3.88	1.06	3.8	1.07	–	1.61	220	1.13	–	30
II	1240	1.56	–	1.39	–	0.50	0.15	0.42	–	–	89	70
IJ	–	–	1.35	–	–	0.33	0.36	0.31	36	0.26	27	17.9
mean	*275*	*0.89*	*2.34*	*0.95*	*3.2*	*0.74*	*0.27*	*0.82*	*142*	*0.54*	*54*	*34*
Cryptocrystalline												
IE	30.3	–	2.69	–	–	0.084	0.42	–	58	0.98	–	8.4
IG	139	–	–	–	–	0.20	0.10	0.29	64	0.66	30	22
IH	–	2.34	3.00	3.08	6.9	0.68	–	0.48	71	0.63	298	250
mean	*85*	*2.34*	*2.85*	*3.1*	*6.9*	*0.32*	*0.26*	*0.38*	*64*	*0.76*	*164*	*94*
Error	1-19	10-25	3-17	4-10	5-10	1-8	2-24	3-16	3-18	3-20	2-7	1-14

[a]Below detection limit. [b]Means of quantitative values. [c]Errors due to counting statistics (in %;1σ).

in the siderophile element contents between the gabbroic and cryptocrystalline inclusions. Both types of inclusions contain tiny metal grains (both taenite and kamacite in the gabbroic inclusions, and kamacite in the cryptocrystalline inclusions) (IKEDA and PRINZ, 1996). Cryptocrystalline inclusion IH consists of kamacite, orthopyroxene (opx), whitlockite, small chromite grains and cryptocrystalline albite groundmass (IKEDA et al., 1997a) and has the highest abundances of siderophile elements of the inclusions studied. The siderophile abundances in the host metal are compared with those in the silicate inclusions in Fig. 3, and it can be seen that the siderophile abundance patterns for inclusion IH and the host metal are very similar.

Except for IH, the other two cryptocrystalline inclusions have relatively lower contents of siderophiles than those in the gabbroic inclusions. This is consistent with the petrologic observation that the gabbroic inclusions generally have higher contents of metal. In spite of the difference in absolute content, the abundance patterns of the siderophile elements, including that for the host metal, are similar to one another, as
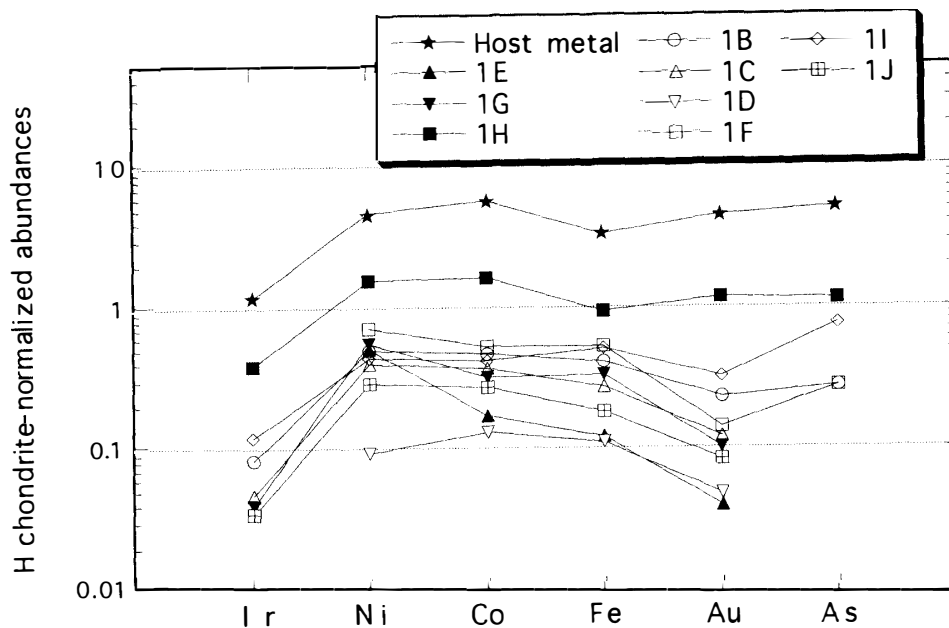
Fig. 3. Siderophile element abundances in the silicate inclusions normalized to the H chondrite average. There is no apparent difference in siderophile abundances between gabbroic inclusions (open symbols) and cryptocrystalline inclusions (closed symbols). They are generally similar to that for the host metal (star). It is suggested that the siderophile elements in the silicate inclusions have interacted with the host metal and the two appear to be genetically related.

shown in Fig. 3. This suggests that the siderophile elements in the silicate inclusions have interacted with the host metal and the two appear to be genetically related. A part of the Fe is contributed by mineral phases which do not contain siderophiles, such as silicates (olivine and/or orthopyroxene) and oxides (chromite and/or ilmenite). This may explain the relatively high abundance of Fe in the (normal) silicate inclusions (except for 1H), when compared with that in the host metal and inclusion 1H.

3.2.2. Non-siderophiles

The H chondrite-normalized abundances of the non-siderophile elements, excluding the REE, in the silicate inclusions are shown in Fig. 4. Only Mg shows a depletion in all of the inclusions, when compared with the bulk H content. Magnesium is generally more depleted in the cryptocrystalline inclusions than in the gabbroic inclusions. The Mg depletion is consistent with the low abundance of olivine (and opx) in the Miles silicate inclusions; olivine was mostly held in the silicate residue in impact melting (Ikeda et al., 1997a). The inclusions which have a relatively high content of Mg (1F, 1I, 1G, 1B and 1C) all have a high occurrence of opx (Table 1). This grouping of inclusions can also be found for Mn, Cr, and V, suggesting that these elements are largely hosted in the opx. An exceptionally high content of V and Zn (Table 2) in 1I may be due to chromite, which was observed to occur most abundantly in the inclusion (Table 1), and has a high ZnO content ranging from 1.4 to 2.0 wt% (Ikeda et al., 1997a). Chromium contents are also contributed by chromite, but the degree of its contribution must be lower for Cr than for Zn and V because Cr is also contained in other phases such as clinopyroxene (cpx) and armalcolite (Ikeda and Prinz, 1996).
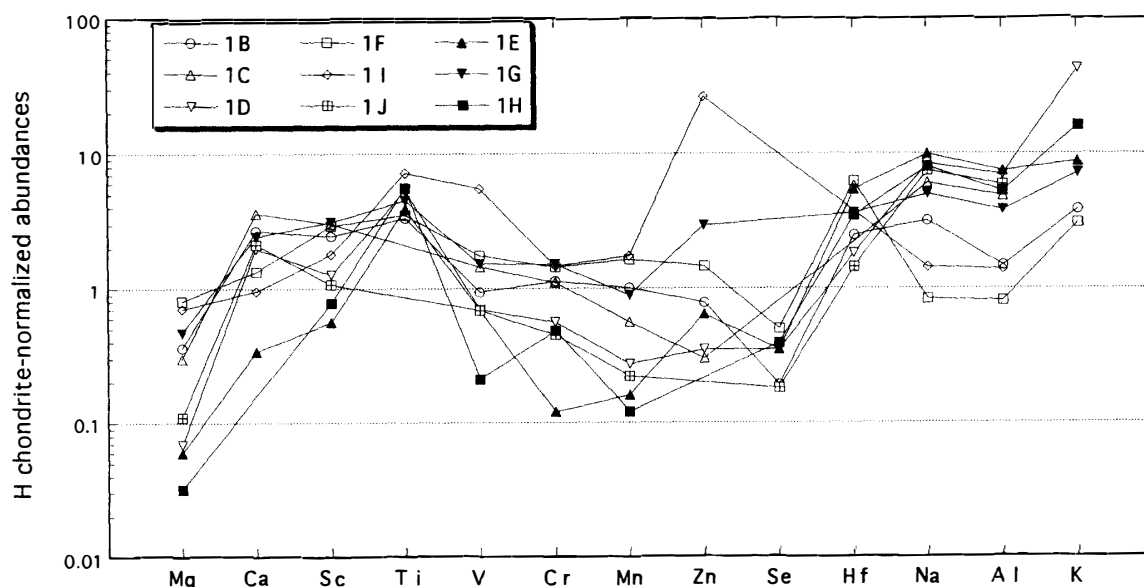
Fig. 4. H chondrite-normalized abundances of non-REE lithophile and chalcophile elements (left) and
plagiophile elements (right) in the silicate inclusions of Miles. Only Mg shows a depletion in all
of the inclusions, when compared with the bulk H content. The Mg depletion is consistent with
the low abundance of olivine in the Miles silicate inclusions; olivine was mostly left in the sili-
cate residue after impact melting. Plagiophile elements are generally enriched in the Miles sil-
icate inclusions, but are fractionated among them. Such fractionation must have occurred dur-
ing the fractional crystallization process, when silicate inclusions formed.

Scandium shows a fairly small variation among the elements plotted in Fig. 4. Note
that some values are missing for Ti and Se. The grouping of inclusions that is observed
for Mg, V, Cr and Mn can be also found for Sc, but the order of the contents among
the groups differs. Scandium is probably mainly present in cpx rather than opx. This
is consistent with the distribution of these elements in equilibrated ordinary chondrites
(MASON and GRAHAM, 1970; ALLEN and MASON, 1973).

As observed in silicate inclusions in Weekeroo Station and Kodaikanal (BUNCH
and OLSEN, 1968), Na, K and Al are also enriched in the Miles silicate inclusions. As
expected, these plagiophile elements are generally more abundant in the cryptocrys-
talline inclusions than in the gabbroic inclusions (Fig. 4). Inclusions 1F, 1I and 1B
contain plagioclase only as a minor constituent mineral (Table 1), and the plagiophile
elements are accordingly relatively depleted. Nevertheless, their H-normalized abun-
dance is about unity or more than that, showing no absolute depletion. Potassium is
the most abundant of the three plagiophile elements concerned and is successively fol-
lowed by Na and Al. This order is consistent with the order of crystallization sequence
postulated for the Miles gabbroic inclusions (IKEDA and PRINZ, 1996). Fractionation
among these plagiophile elements must have occurred during the fractional crystal-
lization process, when the silicate inclusions formed.

3.2.3. Rare earth elements

Rare earth elements are generally enriched in the Miles silicate inclusions com-
pared with chondritic abundances (Fig. 5). The REE in the gabbroic inclusions are lit-
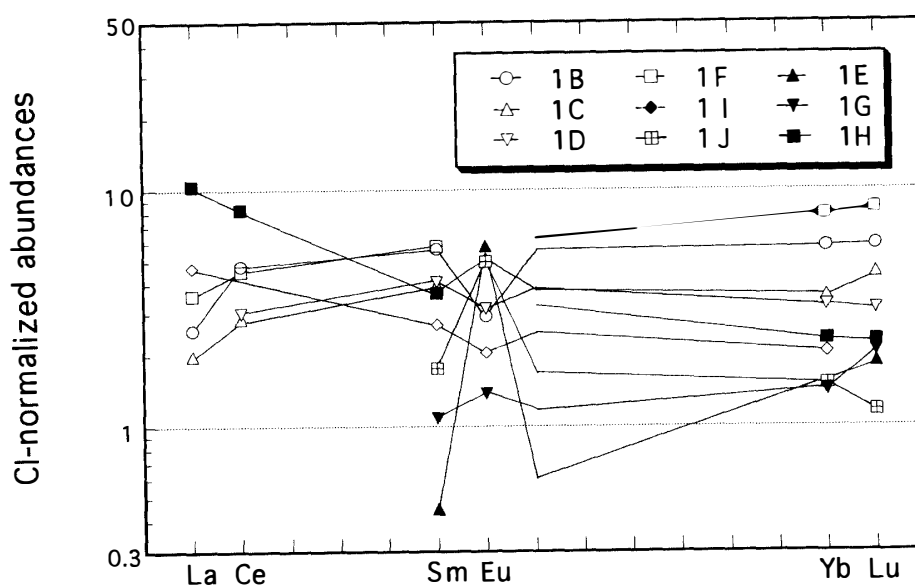tle fractionated and are concentrated by a factor of 3.2 to 4.6. IKEDA and PRINZ (1996)

Fig. 5. CI-normalized REE abundance patterns for gabbroic inclusions (open symbols) and cryptocrystalline inclusions (closed symbols). REE are generally enriched in the Miles silicate inclusions compared with chondritic abundances. The REE in the gabbroic inclusions are little fractionated whereas those in the cryptocrystalline inclusions are highly fractionated and variable. Based on the REE abundance variations in the silicate inclusions, it is inferred that the degree of differentiation of the parental H chondritic material to form silicate inclusions is variable in the IIE irons; it increases from Watson to Weekeroo Station, with Miles being intermediate.

calculated the degree of partial melting to be ~25%. If we assume that the initial material was H chondritic, and that the REE were quantitatively taken into the melt in partial melting, from which silicate inclusions formed, the H chondrite-normalized REE abundances should be at least ~5× chondritic average or higher. This is slightly higher than the observed values for the gabbroic inclusions. Compared with the REE abundances in the gabbroic inclusions, those in the cryptocrystalline inclusions in Miles are highly fractionated and variable. The Sm in the gabbroic inclusions varies by a factor of 3.3, whereas it is 8.1 in the cryptocrystalline.

The REE are highly enriched in Ca-phosphate in the ordinary chondrites (Curtis and Schmitt, 1979; Ebihara and Honda, 1983). When the H chondritic parent body was heated, metal and sulfide were first to melt. With further heating, Ca phosphates were melted. Under the reducing conditions when melting occurred, as suggested by the redistribution of Ga, the P was reduced and incorporated into the metal-sulfide melt whereas the REE enriched in the Ca-phosphate were taken into the silicate melt. Later, the P in the metal melt reacted with the silicate melt (having CaO) to form Ca-phosphate. This process is discussed in the companion paper in detail (Ikeda et al., 1997a). With the formation of Ca-phosphates, the REE partitioned in the silicate melt were redistributed into the Ca-phosphates.

It is highly probable that the gabbroic inclusions were derived from such a single parental silicate melt, where the REE abundances were unfractionated and con-

centrated by a factor of 5 to 6. With the crystallization of phosphate, the Ca-phosphate must accommodate the REE in the individual inclusions, but its content is not necessarily correlated with the REE abundances. If the cryptocrystalline inclusions are assumed to have resulted from a higher abundance of residual melt and a smaller amount of phenocrysts than those for the gabbroic inclusions (IKEDA et al., 1997a), a slightly higher abundance of REE can be expected for the cryptocrystalline inclusions.

The cryptocrystalline inclusions studied were all found to contain whitlockite as seen by microscopic observation of the polished sections, but the INAA data for REE in the isolated inclusions are not so high, especially for inclusions 1E and 1G (Fig. 5). It is therefore highly possible that Ca-phosphate was partly lost in sampling, considering that phosphates tend to be located at the margins of the inclusions rather than inside them (IKEDA et al., 1997a). A slightly lower abundance of the REE in the gabbroic inclusions than that expected from the degree of partial melting could also be explained by a mechanical loss of phosphates from the silicate inclusions when they were isolated from the slab samples. As the cryptocrystalline inclusions are rounded-shaped whereas the gabbroic inclusions have irregular outlines, the phosphate in the cryptocrystalline inclusions was more easily lost than that in the gabbroic inclusions.

The phosphates in ordinary chondrites are likely to quantitatively accommodate the light and middle REE, but are less accommodating to the heavy REE (EBIHARA and HONDA, 1984). Thus, if some phosphates were lost in sampling, the REE pattern would be characterized by a lower abundance of REE, especially of the light REE, and an increasing inclination. Inclusions 1B and 1F show a slightly increasing inclination with increasing atomic number, but show still higher REE abundances. This suggests that the degree of mechanical loss may, in fact, have been small, if any, especially for the gabbroic inclusions.

Phosphate was found to be relatively enriched in the silicate inclusions of the Watson IIE iron, with nearly chondritic REE abundances (OLSEN et al., 1994). In contrast, highly fractionated REE patterns were observed in the silicate inclusions separated from Weekeroo Station (EVENSEN et al., 1979). Based on the REE abundance variations in the silicate inclusions, it is inferred that the degree of differentiation of the parental H chondritic material to form silicate inclusions is variable in the IIE irons. It increases from Watson to Weekeroo Station, with Miles being in between.

3.3. Formation of Miles and other IIE irons

It has been proposed that the IIE irons were produced by impact in the near-surface region of a chondritic parent body (e.g., WASSON and WANG, 1986). McCoy (1995) presented an alternative hypothesis for the formation of IIE irons that the metal-silicate mixing occurred in a core-mantle environment. As previously discussed, elemental abundances in the Miles silicate inclusions are considerably fractionated, placing this meteorite in the differentiated IIE group (McCoY, 1995). A similar variation was found by petrologic observation (IKEDA and PRINZ, 1996; IKEDA et al., 1997a). In contrast, some IIE irons preserve chondritic characteristics in their silicate inclusions. The silicate portion of Netschaëvo has chondritic elemental abundances, contains some chondrules, and contains uniformly distributed metal whose composition is similar to that of the surrounding metal matrix (BILD and WASSON, 1977). Yamato-791093 also

has a silicate portion which has unfractionated, chondritic elemental abundances (IKEDA *et al.*, 1997b). Watson is less primitive, compared with these two meteorites, having lost metal/sulfide phases after nearly total melting, but it still preserves chondritic characteristics (*e.g.*, unfractionated REE) in the silicate inclusions, showing no differentiation (OLSEN *et al.*, 1994). Thus, there are large variations in the degree of differentiation in the silicate portions of IIE irons. If IIE irons were formed at the core-mantle boundary, the parent body must have been large enough for its center to be entirely melted, possibly larger than the ordinary chondrite parent bodies if they formed at nearly the same time. With such a large parent body, it would appear to be impossible to keep undifferentiated silicate material at the core-mantle boundary. Rather, a surface or near-surface origin for the IIE irons and their silicates seems to be more plausible. Considering the similarity in the chemistry and mineralogy between the silicate inclusions of the IIE irons and the H chondrites, the parent body of the IIE irons must have been H chondritic. Since the silicates in Miles was melted, the surface material must have been heated. The heat source is tentatively ascribed to impact. In this case, individual IIE irons could be derived from separate cratering events (RUBIN *et al.*, 1986).

IIE irons have a large variation of radiometric ages, from 3.5 Ga for Kodaikanal to 4.5 Ga for Colomera. Both of these IIE meteorites are classified as highly differentiated. The most primitive IIE iron recovered so far, Netschaëvo, has a young age of 3.74 Ga (NIEMEYER, 1980). These facts indicate no correlation between the degree of differentiation and the age of the silicate portions. Apparently, the degree of differentiation is dependent on the scale of the impact. In the case of Miles, impact was moderately severe and a melt sheet was formed at the base of the impact site. The metal/sulfide phases were totally melted, whereas the silicates were partly melted (about 25% according to IKEDA and PRINZ, 1996) and the residual silicate was removed from the melt. When the metal melt was partly solidified, solid-melt separation occurred in the metal phase. At least, a part of the immiscible sulfide was separated and removed from the metal melt. After the segregation of solid metal, the partly recrystallized silicates were mixed with the metal melt. At this stage, equilibration was established between the silicate portion and the metal matrix. Finally, the P in the metal melt was exsolved and reacted with CaO in the silicate melt to form Ca-phosphates, which tend to be located in the outer parts of the silicate inclusions.

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