

Meteoritics & Planetary Science 43, Nr 3, 451–460 (2008) Abstract available online at http://meteoritics.org

# Geochemistry and origin of metal, olivine clasts, and matrix in the Dong Ujimqin Qi mesosiderite

Ping KONG<sup>1, 2\*</sup>, Wen SU<sup>1</sup>, Xianhua LI<sup>1</sup>, Bernhard SPETTEL<sup>3</sup>, Herbert PALME<sup>4</sup>, Kejie TAO<sup>1</sup>

<sup>1</sup>State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, P.O. Box 9825, Beijing 100029, China

<sup>2</sup>Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100085, China

<sup>3</sup>Max-Planck-Institut für Chemie, P.O. Box 3060, D-55020 Mainz, Germany

<sup>4</sup>Institut für Geologie und Mineralogie, Univeristät zu Köln, 50674 Köln, Germany

\*Corresponding author. E-mail: pingkong@mail.igcas.ac.cn

(Received 25 February 2007; revision accepted 16 July 2007)

**Abstract**–The Dong Ujimqin Qi mesosiderite is the first recorded fall of a stony-iron meteorite in China. According to silicate textures and metal composition, this meteorite is classified as a member of subgroup IB. Instrumental neutron activation analyses (INAA) of metals show that the matrix metal has lower concentrations of Os, Ir, Re, and Pt, but higher concentrations of Ni and Au than the 7.5 cm metal nodule present in the meteorite. We attribute these compositional differences to fractional crystallization of molten metal. Studies of olivine clasts show that FeO contents are uniform in individual olivine crystals but are variable for different olivine clasts. Although concentrations of rare earth elements (REEs) change within olivine clasts, they all exhibit a vee-shaped pattern relative to CI chondrites. The relatively high concentrations of REEs in olivine and the shape of REE patterns require a liquid high in REEs and especially in light REEs. As such a liquid was absent from the region where basaltic and gabbroic clasts formed, mesosiderite olivine must have formed in a part of the differentiated asteroid that is different from the location where other mesosiderite silicate clasts formed.

#### INTRODUCTION

A meteorite shower fell on September 7, 1995, in the Arisilengtugacha area, 150 km to the southeast of the town of Dong Ujimqin Qi, Inner Mongolia, China. Three fragments were recovered, weighing 88.2 kg (no. 1), 38.0 kg (no. 2), and 2.6 kg (no. 3) (Tao et al. 1997). All three fragments are more or less covered by fusion crust. The meteorite was identified as a mesosiderite (Tao et al. 1997).

Mesosiderites are an unusual class of stony-iron meteorites containing broadly equal amounts of metal and silicates. The two phases are intimately mixed together. Two kinds of metal are present in mesosiderites: large metal nodules and fine-grained matrix metal. The metal nodules range in shape from subangular to well rounded (Hassanzadeh et al. 1990); the matrix metal is mostly in the form of millimeter or submillimeter grains, which are interstitial to silicates (Powell et al. 1971; Wasson et al. 1974). The silicate is characterized by diverse textures: large pyroxenitic, basaltic, gabbroic, and dunite clasts embedded in a fine-grained silicate matrix (Rubin and Jerde 1988;

Mittlefehldt 1990). Pigeonite-plagioclase gabbroic clasts show fractionation of rare earth elements (REEs) with extreme positive europium anomalies, larger than in any other known igneous rocks in the solar system (Mittlefehldt et al. 1992).

Mesosiderites have been subdivided according to silicate matrix textures (Floran 1978; Hewins 1984, 1988). The silicate matrix is metamorphosed to varying degrees: from slightly recrystallized (type 1) to total remelting (type 4, impact melts). According to modal proportions, mesosiderites are further divided into subgroups A and B, where A has more abundant plagioclase and B more abundant pyroxene.

Two main formation models exist for mesosiderites. The first class of models assume formation of mesosiderites by impact and mixing of a molten Fe-Ni core from a small differentiated body with the silicates of the basaltic surface of a larger one (Powell 1971; Floran 1978; Wasson and Rubin 1985; Rubin and Mittlefehldt 1993). In the second class of models, mesosiderites were formed by internal processes whereby basaltic crust of an asteroid is mixed with its own

Fig. 1. A cut surface of fragment no. 2 of the Dong Ujimqin Qi mesosiderite. The fragment measures about  $30 \times 30 \times 13$  cm<sup>3</sup> and weighs 38.0 kg. The metal nodule (lower right) has a clear boundary with the silicate matrix.

core (Hewins 1983; Haack et al. 1996; Scott et al. 2001). The rare occurrence of olivine clasts is a major concern of both models.

Olivine must be a major component of any differentiated body with an initially chondritic composition. However, unlike in pallasites, olivine is a minor component in mesosiderites: estimates are about 2 vol% of the silicates (Prinz et al. 1980; Ruzicka et al. 1994), and olivines in mesosiderites are compositionally quite variable (Powell 1971). Olivine usually occurs as large single crystals of up to several centimeters in mesosiderites (Mittlefehldt 1980). Mittlefehldt (1980) determined the composition of olivine clasts and Nehru and Zucker (1980) studied the textures and compositions of olivines and surrounding coronas. Ruzicka et al. (1994) proposed that olivine corona formation occurs largely after intensive millimeter-scale brecciation and after or during metal-silicate mixing. Nevertheless, there is still no clear picture of olivine formation.

In this paper, we report detailed studies of the compositions of matrix metal, metal nodules, olivine clasts, and matrix components in the Dong Ujimqin Qi mesosiderite. We hope that such detailed studies will ultimately allow the deciphering of the mechanism of mesosiderite formation.

## **EXPERIMENTAL METHODS**

## **Sample Description**

We studied fragment no. 2 (about  $30 \times 30 \times 13$  cm<sup>3</sup>) of the Dong Ujimqin Qi mesosiderite. At one corner there is a big metal nodule with a diameter of 7.5 cm (Fig. 1). The metal nodule has a clear boundary with matrix, which suggests that the nodule was solid or nearly solid during metal-silicate mixing. From Fig. 1, we can see small silicate inclusions exist inside the metal nodule. We have taken two pieces of the metal nodule and one piece of matrix metal for neutron activation analysis.

Many silicate clasts appear on the surface of the Dong Ujimqin Qi mesosiderite. Some are as big as 8 cm. Eight olivine clasts larger than 1 cm were separated from the mesosiderite by using an iron nail and a small hammer. In these clasts, olivine occurs as large crystals and is surrounded by pyroxene and finer plagioclase. The isolated clasts were crushed to 1 mm size and clean olivine grains were handpicked under a binocular microscope. A fraction of the olivine was used for the preparation of a polished section for electron microprobe analysis and the rest was prepared for inductively coupled plasma mass spectroscopy (ICP-MS) analysis of REEs and other trace elements.

## **Analytical Techniques**

Electron microprobe analyses (EMPA) of matrix minerals and olivine clasts were carried out at the Institute of Geology and Geophysics, Chinese Academy of Sciences in Beijing with a Cameca SX51. Some images were taken with a JEOL JXA-8100. Analyses were generally obtained at 15 keV accelerating voltage, 12 nA beam current, with 10 s counting time and ~5  $\mu$ m spot size. The microprobe analytical standards are provided by P&H Developments, from which albite is used as a standard for Na, periclase for Mg, corundum for Al, wollastonite for Si and Ca, orthoclase for K, rutile for Ti, rhodonite for Mn, phosphate for P, and specularite for Fe, NiO, and Cr<sub>2</sub>O<sub>3</sub> for Ni and Cr, respectively.

Neutron activation analyses of metals were performed in the Department of Cosmochemistry at the Max Planck Institute for Chemistry in Mainz, Germany. Samples were irradiated in the TRIGA reactor of the Institute of Nuclear Chemistry at the University of Mainz, Germany. The irradiation was conducted with a neutron flux of 4 ×  $10^{12}$  cm<sup>-2</sup>s<sup>-1</sup> for 6 hr. After irradiation, three runs of measurements were performed within 40 days. A detailed description of the instrumental neutron activation analyses (INAA) procedure can be found in Kong et al. (1996).

REEs and trace elements in olivine clasts were determined using a Perkin-Elmer Sciex ELAN 6000 ICP-MS at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. About 50 mg of sample powders were dissolved in high-pressure Teflon bombs using a HF-HNO<sub>3</sub> mixture for 48 hr at ~180 °C. An internal standard solution containing single element Rh was added (for monitoring drift in mass response during ICP-MS measurement), and the spiked sample solutions were diluted with 2% HNO<sub>3</sub> to a sample/solution weight ratio of 1/2000. A set of international standards including W-2, BHVO-1, SARM-4, and MRG-1 were used to calibrate element concentrations of measured samples.



Fig. 2. A representative view of the silicate matrix in the Dong Ujimqin Qi mesosiderite (backscattered electron image). Metal forms a net connecting silicate minerals. Matrix minerals include kamacite (Kam), sulfide (Sulf), spinel (Sp), pyroxene (Px), plagioclase (Plag) and silica (Si).

## RESULTS

Mesosiderites are classified into subgroups A and B based on the abundances of pyroxene in silicate matrices. Silicates in the matrix of the Dong Ujimqin Qi mesosiderite are mainly composed of pyroxene and plagioclase with minor olivine, spinel, silica, cordierite, merrillite, and stanfieldite (Figs. 2 and 3). Mapping of a small fraction of the silicate matrix in Dong Ujimqin Qi shows that pyroxene constitutes 70% of the silicates. From Fig. 3 we see pyroxene zoned in the matrix. EMPA analysis shows that the inner (darker) part of the pyroxene is Fe-poor, whereas the outer (lighter) layer is Fe-rich, which suggests crystallization from a melt. The sharp boundaries existing between silicate minerals in the matrix (Fig 3) indicate little metamorphic recrystallization of the matrix silicates. These features suggest that Dong Ujimqin Qi mesosiderite is a member of subgroup IB.

Compositions of common and minor minerals in the silicate matrix of Dong Ujimqin Qi mesosiderite, obtained via EMPA, are shown in Table 1. We have analyzed multiple spots for common minerals. The compositions of minerals are given as averages of multi-point analytical data.

INAA results for matrix metal and the big metal nodule are given in Table 2. In order to understand the characteristics of the metal, we have to know the purity of the samples we analyzed. From Table 1 we note high contents of Na in plagioclase and high contents of Mn and Cr in pyroxene and olivine. Thus, the low concentrations of these elements in the analyzed metals of Dong Ujimqin Qi mesosiderite indicate that the metals suffer little silicate contamination (<0.1% plagioclase, <0.6% olivine, and <0.3% pyroxene).



Fig. 3. Backscattered electron images of the silicate matrix in the Dong Ujimqin Qi mesosiderite. Silicates in the matrix of the Dong Ujimqin Qi mesosiderite are mainly composed of pyroxene and plagioclase with minor olivine, spinel, silica, cordierite, merrillite, and stanfieldite. Some pyroxene grains are zoned with Fe-poor cores and Fe-rich rims.

The compositions of the metal nodule and the matrix metal are to some extent similar, although there are some characteristic differences. For example, compared to the matrix metal, the concentrations of Os, Ir, Re, and Pt are high in the metal nodule, whereas the concentrations of Ni, Au, and W are low. Unlike in fractionated iron meteorites and in large metal nodules in chondrites (Hassanzadeh et al. 1990; Kong et al. 1998), refractory siderophile elements in mesosiderites are not strongly fractionated relative to solar abundances (Table 2; Hassanzadeh et al. 1990).

Major-, minor-, and trace-element concentrations for olivine clasts are given in Table 3. EMPA analysis shows that the content of FeO is uniform throughout an olivine clast, indicating that the olivine clasts are single crystals. Therefore, EMPA and ICP-MS results, obtained from two fractions of

	Olivine	Pyroxene	Plagioclase	Spinel	Cordierite	Merrillite	Stanfieldite
	(8 <sup>a</sup> )	(12)	(5)	(7)	(1)	(2)	(1)
SiO <sub>2</sub>	40.5	55.1	49.4	1.30	49.97	0.114	0.014
MgŌ	45.9	27.3	0.082	0.082	10.27	3.41	16.94
FeO	13.2	14.2	0.541	28.3	4.99	1.13	9.93
TiO <sub>2</sub>	0.034	0.146	0	0.304	0.002	0.012	0.027
$Al_2O_3$	0.012	1.39	31.3	23.5	33.91	0.02	0
CaO	0.022	1.49	16.4	0.329	0.084	47.19	23.94
$Cr_2O_3$	0.065	0.565	_b	37.6	0.178	0.018	0.054
MnO	0.302	0.597	0.047	0.508	0.228	0.292	1.35
Na <sub>2</sub> O	0.004	0.008	1.38	_	0.001	0.65	0.02
$K_2O$	0.007	0.001	0.050	_	0.003	0.033	0.002
NiO	0.047	0.031	_	0.205	0.011	0.008	0.045
$P_2O_5$	_	_	_	-	_	46.48	47.868
Total	100.1	100.8	99.4	97.7	99.6	99.36	100.19
	Fa 14	Fs 22	An 96				
	Fo 86	En 75	Ab 4				

Table 1. Compositions of matrix minerals in the Dong Ujimqin Qi mesosiderite (in wt%).

<sup>a</sup>Numbers of analyzed points.

<sup>b</sup>Not determined.

Table 2. INAA results for matrix metal and the big metal nodule in the Dong Ujimqin Qi mesosiderite (content in  $\mu g g^{-1}$ , otherwise as indicated).

	Metal nodule 1	Metal nodule 2	Matrix metal		
	20.54 mg	23.38 mg	33.31 mg	DM/CI <sup>a</sup>	
Fe (%)	89.61 (3 <sup>b</sup> )	91.23 (3)	89.4 (3)	4.7	
Na	7.6 (10)	0.8 (10)	10.3 (3)		
Cl	130 (10)		45 (20)		
K	6.4 (15)		<6.0		
Sc		< 0.15	<0.07		
Cr	21 (25)	<1.0	35 (10)		
Mn	6.6 (15)	6.8 (10)	15.0 (5)		
Со	4640 (3)	4922 (3)	4910 (3)	9.78	
Ni	70,300 (4)	75,500 (4)	84,900 (5)	7.72	
Cu	148 (4)	109 (5)	133 (5)	1.05	
Ga	8.00 (7)	7.36 (5)	7.66 (5)	0.766	
Ge	45 (2)	44 (15)	58 (20)	1.77	
As	11.5 (3)	12.1 (3)	12.5 (3)	6.72	
Sb	0.33 (15)	0.20 (25)	0.23 (15)	1.61	
Se	7.0 (25)	<7.0	<3.5		
Mo	6.50 (10)	6.1 (15)	5.6 (10)	6.03	
W	0.890 (7)	0.86 (10)	0.96 (5)	10.3	
Re	0.590 (4)	0.60 (10)	0.406 (5)	11.1	
Os	7.30 (10)	7.93 (5)	5.44 (5)	11.2	
Ir	6.06 (3)	6.23 (3)	4.36 (3)	9.06	
Pt	9.10(7)	9.03 (10)	8.20 (7)	8.28	
Au	1.087 (3)	1.09 (3)	1.16 (3)	8.28	
Ru	7.8 (20)	7.9 (25)	6.2 (10)	8.7	
Pd	3.89 (5)	4.1 (10)	4.00 (7)	7.14	
Ir/Ni	$8.62 \times 10^{-5}$	$8.25 \times 10^{-5}$	$5.14 \times 10^{-5}$		
Au/Ni	$1.55 \times 10^{-5}$	$1.44 \times 10^{-5}$	$1.37 \times 10^{-5}$		

<sup>a</sup>DM represents Dong Ujimqin Qi matrix metal; CI = composition of Cl chondrites from Wasson and Kallemeyn (1988).

<sup>b</sup>Numbers in brackets are analytical errors in percentage.

48.9
40.9 0.027
0.004
1.90 (4)
34.7 (5)
50.4 (9)
2240 (3) 1670 (3)
26.0 (4)
123 (5)
14.2 (4)
10.1 (5)
0.178 (
0.075 (
0.359 (
5.59 (1
0.091 (
0.521 (
0.049
8.44 (4)
164(3)
284 (1)
33.0 (8)
113 (6)
20(10)
0.0 (27) 16 (19)
2.3 (18)
15 (16)
3.5(10)
11 (12)
1.7 (19)
13 (13)
2.79 (6)
12 (13)
3 (38)
43



## Relative to CI - HM01 -HM02 0 HM03 HM04 $\nabla$ HM05 HM06 -1 HM07 HM08 ☆ 0.01 La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu

Fig. 4. REE concentrations in olivine clasts of the Dong Ujimqin Qi mesosiderite. Although the concentrations are variable in different olivine clasts, they all exhibit a vee-shaped pattern relative to the Cl composition.

the same clasts, should reflect identical compositional characteristics. From Table 3 we see olivine clasts are compositionally variable. Compared to matrix olivine, olivine generally more MgO-rich. clasts are Chromium concentrations in olivine obtained via EMPA are much lower than those determined by ICP-MS. The reason is that minute chromite inclusions are scattered throughout olivine grains. Those chromite inclusions can be easily avoided with EMPA, but were included in the olivine fractions analyzed by ICP-MS. As V and Ti are enriched in chromite, the V and Ti concentrations in olivine given in Table 3 may also suffer chromite contamination. Co and Ni concentrations are in the same range as obtained for other mesosiderites (Mittlefehldt 1980). We have analyzed Co in the matrix olivine using laser ablation ICP-MS (LA-ICP-MS), and found that the concentrations of Co are relatively constant in olivine crystals: 20-51 ppm (17 points with 16 points are in the range of 20-34 ppm). The concentrations of Co in olivine clasts determined by wet ICP-MS are in the range of 22-56 ppm (Table 3). The similar range of Co concentrations in olivine obtained by both LA-ICP-MS and ICP-MS suggest that the concentrations of Co and Ni in mesosiderite olivine obtained by the latter technique are not due to metal or iron oxide contamination.

The concentrations of Zr and Hf are highly variable in the olivine clasts, but the ratios of Zr/Hf are rather constant (Table 3), suggesting that Zr and Hf are in the same mineral phase. Concentrations of REEs are variable in the olivine clasts, showing a vee-shaped pattern (Fig. 4). There are extremely rare reports of REE concentrations for mesosiderite olivine in the literature. The existing sporadic data for mesosiderite olivine show a similar light and heavy REE-enriched pattern (Mittlefehldt 1980).

#### Petrography

Silicates in the matrix of the Dong Ujimqin Qi mesosiderite are mainly composed of pyroxene and plagioclase with minor olivine, spinel, silica, cordierite, merrillite, and stanfieldite (Figs. 2 and 3). Most olivine occurs as isolated grains in the matrix, but sometimes can be found embedded in pyroxene crystals. Silica normally appears inside plagioclase. Merrillite normally connects to pyroxene, and occasionally coexists with plagioclase and silica. Stanfieldite appears either beside or inside metal; silica sometimes occurs as inclusions inside standfieldite.

The occurrence of silica and olivine in the matrix suggests contrasting melt features: the formation of olivine indicates silica-undersaturated melt, whereas crystallization of silica requires silica-saturated melt. As FeO contents change from one olivine grain to another grain, and the most FeO-rich olivines are not in equilibrium with basaltic extracts (Stolper 1977), we believe that olivine grains in mesosiderite matrix did not crystallize together with other silicate minerals: pyroxene, plagioclase, and silica. Olivine may occur as xenoliths mixed with silica-rich melt; occasionally it may have served as the nucleus of crystallized pyroxenes.

## Subclassification of Dong Ujimqin Qi Mesosiderite

Mesosiderites are compositionally classified into two subgroups, A and B, on the basis of the modal abundances of orthopyroxene, plagioclase, and tridymite (Hewin 1984). Wasson and Rubin (1985) noted that the Ir/Ni ratios of the mesosiderite matrix metal could also resolve the two subgroups: Ir/Ni ratios are  $3.6 \times 10^{-5}$  and  $5.1 \times 10^{-5}$  for groups A and B, respectively. The Ir/Ni ratio for the matrix metal of Dong Ujimqin Qi mesosiderite is  $5.1 \times 10^{-5}$ , perfectly matching its IB classification based on silicate mineralogy. The large metal nodule has a higher Ir/Ni ratio of  $8.3 \times 10^{-5}$ .

The silicate matrix of mesosiderites has been affected by variable degrees of metamorphism, ranging from modest recrystallization to total remelting (Hewins 1983). Wasson et al. (1974) noticed that concentrations of Ga and Ge are lower in the metal of type I mesosiderites than in metal of other types. The Ga concentration in the Dong Ujimqin Qi matrix metal is 7.66 ppm, among the lowest found for mesosiderites. The metal composition further confirms the classification of the Dong Ujimqin Qi mesosiderite as subgroup IB.

## Formation of Metal in Mesosiderites

The metal nodule forms a clear boundary with silicate matrix (Fig. 1), which may indicate that the metal nodule was





Fig. 5. A backscattered electron image of metal grains in the Dong Ujimqin Qi mesosiderite. Taenite occurs irregularly within kamacite.

in a solid or nearly solid state during metal-silicate mixing. In contrast, metal in the matrix fills the cracks of silicate minerals (Fig. 2), suggesting that matrix metal was molten during metal-silicate mixing.

The composition of mesosiderite metal is intermediate between those of H and E chondrite metals (Kong and Ebihara 1997; Kong et al. 1997). However, compared to H and E chondrite metals, the metal in the Dong Ujimqin Qi mesosiderite has much lower Cr and Mn concentrations. We believe that the low Cr and Mn concentrations in the metal of Dong Ujimqin Qi mesosiderite are the result of exsolution during metamorphism. The opposite behavior is found for Ga, the concentrations of which increase from 7–9  $\mu$ g g<sup>-1</sup> in type I mesosiderite metals to as high as  $17 \,\mu g \, g^{-1}$  in metal of other mesosiderites (Hassanzadeh et al. 1990). We believe that Ga been reduced from silicates to metal during has metamorphism. Reduction of Ga from silicates to metal during metamorphism has also occurred in ordinary chondrites (Kong and Ebihara 1997).

As noted above there are some compositional differences between the metal nodule and the matrix metal in the Dong Ujimqin Qi mesosiderite. The concentrations of Re, Os, Ir, and Pt are higher, and those of Ni, Au, and W lower in the metal nodule than in matrix metal. In backscattered electron images, taenite occurs irregularly within kamacite in the matrix metal (Fig. 5). However, the compositional differences of the two kinds of metals are not caused by different proportions of kamacite and taenite. The study of Kong et al. (1995) demonstrates that except for Co, other siderophile elements are enriched in taenite compared to kamacite. The opposite trends of Ni, Au versus Re, Os, and Ir concentrations in the two kinds of metals argue against relating compositional differences of metals to variable proportions of kamacite and taenite.



Fig. 6. A plot of Ir/Ni versus Au/Ni for mesosiderite metal nodules. All data except Dong Ujimqin Qi are from Hassanzadeh et al. (1990). Unclassified mesosiderites are excluded from the plot.

Widom et al. (1986) and Kong et al. (1998) found that, relative to fine-grained metal, large metal nodules in H chondrites were depleted in refractory siderophile elements. Origins by impact-reduced distillation (Widom et al. 1986) and metamorphic diffusion (Kong et al. 1998) were proposed. However, the metal nodule in Dong Ujimqin Qi mesosiderite is rich in Re, Os, Ir, and Pt, in contrast to the feature in H chondrites. Thus, the proposed models for H chondrites are not applicable to the compositional differences of metals in mesosiderites.

Studies of iron meteorites show that during fractional crystallization of liquid metal, the refractory metals Re, Os, Ir, and Pt have a tendency to concentrate in solid metal, whereas Ni and Au prefer to remain in liquid metal (Wasson and Richardson 2000; Cook et al. 2004). The tendencies are generally consistent with experimental results (Chabot et al. 2003; Chabot and Jones 2003). We therefore suggest that the metal in Dong Ujimgin Qi has experienced a small degree of fractional crystallization. As Ir concentrations in mesosiderite metals change within 40% (Hassanzadeh et al. 1990), the fraction of crystallized metal should be <10%. The behaviors of W and Ga, however, are not compatible with the fractional crystallization model: concentrations of Ga should be positively correlated with that of Ni, whereas W should be negatively correlated with Ni. Mittlefehldt (1990) suggested that reduction of FeO out of the silicates occurred during or after the metal-silicate mixing process and applied this reaction to explain specific features of mesosiderite lithologies. As W and Ga are easily affected by reduction reactions, similar to Fe (Kong and Ebihara 1996), the concentrations of W and Ga may have been modified during the process of metal-silicate mixing and thus may not completely reflect the fractional crystallization experienced by the metal.

1000

100

10

0.1

0.01

Ce Pr

La

Nd

Sm

Relative to CI

Fig. 7. A plot of Ir versus Ni for mesosiderite metal nodules. All data except Dong Ujimqin Qi are from Hassanzadeh et al. (1990). The positive correlation of Ir and Ni concentrations for group A metals may reflect a redox state of metal-silicate equilibrium. The deviation of group B from group A may result from subtle crystallizing fractionation of metal that led to minor fractionation of Ir from Ni.

Wasson and Rubin (1985) and Hassanzadeh et al. (1990) noted that the Ir/Ni ratio is diagnostic for subgroup A or B. As demonstrated in Fig. 6, a plot of Ir/Ni versus Au/Ni can much better resolve the two groups than a simple Ni versus Ir plot (Fig. 7). It should be noted that the plots of Fig. 6 and Fig. 7 are for metal nodules in mesosiderites, and the Ir/Ni ratios for metal nodules are obviously different from those for matrix metals when comparing the two data sets of Wasson et al. (1973) and Hassanzadeh et al. (1990). To explain the compositional differences between group A and group B, Hassanzadeh et al. (1990) proposed a model where they assume that group A metal is more primitive and group B metal has experienced reduction during metal-silicate mixing. If this were true, we would expect the dilution of trace elements in metal to be more effective in matrix metal compared to metal nodules. Our results, however, show that the concentration of Ni is higher in the matrix metal than in the metal nodule, rather than lower as expected. Hassanzadeh et al. (1990) further proposed an alternative model where group B materials were made by the addition of core-mantleinterface materials to group A materials. The metal in the core-mantle-interface material should have high W and Ir but low Ni and Au, similar to the first 5% crystallized metal from a melt with an average mesosiderite metal composition. This model is compatible with our suggestion of subtle fractional crystallization of mesosiderite metal.

Figure 7 shows a complicated pattern of Ir versus Ni for mesosiderite metals. We suggest that the positive correlation of Ir and Ni concentrations for group A mesosiderites was established by the redox state of metal-silicate equilibrium, and the deviation of group B from group A results from subtle fractional crystallization of metal that led to minor

Fig. 8. Modeling of REE features of parent melts for HM01 and HM02 olivines in Dong Ujimqin Qi mesosiderite. Partition coefficients of REEs between olivine and melt are taken from the regression results of Béhard (2005). In calculation of partition coefficients of REEs, a MgO content of 23% is used. The parent melts required are high in REEs and especially high in light REEs.

Differentiation of mesosiderite olivine

Eu Gd Tb Dy Ho Er Tm

HM01

- HM02

HM01melt

- HM02melt

Yb Lu

fractionation of Ir from Ni. It appears that group B mesosiderites have sampled a larger fraction of solid metal than group A members, leading to higher concentrations of Ir and lower concentrations of Au and Ni than in type A mesosiderites.

#### **Formation of Olivine**

Prior (1918) suggested that mesosiderites formed via invasion of a pallasitic magma into a eucritic magma. Mittlefehldt (1980), on the other hand, argued that silicate clasts in mesosiderites came from the same parent body as the metal. Hassanzadeh et al. (1990) suggested that mesosiderites formed by accretion of a molten core accompanied by mantle materials, to a large degree consisting of olivine, onto the basaltic surface of a neighboring asteroid. Scott et al. (2001) proposed formation of mesosiderites by fragmentation and reaccretion of a large differentiated asteroid. Although olivine is a major concern in mesosiderite formation models, there is still no conclusive evidence regarding the origin of olivine in mesosiderites. Mittlefehldt (1980) listed some arguments for and against an internal origin of olivine.

We have argued, from Co centents, that Co and Ni in the olivine clasts of Dong Ujimqin Qi mesosiderite are not due to metal or iron oxide contamination. Analyses of olivine in pallasites give Ni concentrations between 20 and 40 ppm (Reed et al. 1979) versus the concentrations of 132–692 ppm observed in mesosiderite olivine, suggesting that olivines in these two major groups of stony-iron meteorites are very different. Recent precise determination of oxygen isotope compositions also shows that mesosiderites and pallasites are from different asteroidal sources (Greenwood et al. 2006).



We have shown that REEs exhibit a vee-shaped pattern in Dong Ujimqin Qi olivine (Fig. 4). The relatively high level of REEs and the shape of the normalized patterns are unusual, as REEs are incompatible in olivine, and as light REEs are more incompatible than heavy REEs (Béhard 2005). Thus we would expect light REEs to be more depleted than heavy REEs in olivine formed from a melt with a flat chondritic pattern. The observed pattern of REEs for mesosiderite olivine suggests formation of olivine either directly from melts enriched in light REEs or through matasomatism with REE-enriched melts. As some olivine clasts are as large as 10 cm and the composition of olivine is uniform throughout a clast, we believe that the olivine clasts in mesosiderites were formed by crystallization from REE-enriched melts. We have modeled the concentrations of REEs in parent melts for HM01 and HM02 olivine in Fig. 8. Partition coefficients of REEs between olivine and melt are taken from the regression results of Béhard (2005). A MgO content of 23% is used in the calculation of partition coefficients of REEs between olivine and melt. To achieve the compositions of parent melts for olivine clasts, we suggest that the melts formed by mixing a magma of olivine composition with different proportions of a late residual liquid that is light-REE-enriched. As olivine clasts analyzed in this study all have similar REE patterns, it appears that mixing of two magmas occurred on or near the crust of a differentiated asteroid. One possibility is that a shock event led the mixing process, the original olivine melted, mixed with a liquid that is highly enriched in REEs, and the olivine clasts in the mesosiderites crystallized from the mixed melt.

Studies of basaltic and gabbroic clasts in mesosiderites show that basaltic clasts have generally flat REE patterns with slightly depleted light REEs (Rubin and Jerde 1988; Mittlefehldt 1990), and gabbroic clasts have REE patterns more fractionated with enriched Eu but depleted light REEs (Rubin and Jerde 1988; Mittlefehldt et al. 1990). The REE patterns for basaltic and gabbroic clasts in mesosiderites indicate that the region where these clasts formed is cumulateenriched with an absence of late-stage liquid. As Eu is highly enriched in gabbroic clasts, the melt from where gabbroic clasts crystallized must be Eu-depleted. Such a liquid cannot be parental to mesosiderite olivine, as this would lead to a strong Eu depletion in olivine. Our results for the olivine clasts, however, show no consistent Eu anomaly. We believe, therefore, that basaltic and gabbroic clasts formed in a body different from that of olivine crystallization. Most probably olivine clasts accompanied with metal accreted onto a basaltic surface of a neighboring asteroid, as suggested by Hassanzadeh et al. (1990).

We have discussed above, based on mineral associations, that olivines in the matrix of mesosiderites are zenoliths and did not crystallize together with other silicate minerals. Did the matrix olivine come from the same differentiated body as the olivine clasts? As reduction has occurred during the metal-silicate mixing process (Mittlefehldt 1990), one would expect that matrix olivine should be more Mg-rich, as matrix olivine would be more easily reduced than larger olivine clasts. However, our results show the opposite: olivine clasts are more Mg-rich compared to matrix olivine. This may indicate that matrix olivine and olivine clasts came from different differentiated parent bodies.

## CONCLUSIONS

- 1. Both silicate textures and metal compositions suggest that the Dong Ujimqin Qi mesosiderite should be classified as subgroup IB.
- 2. There are some compositional discrepancies between the metal nodule and the matrix metal in Dong Ujimqin Qi mesosiderite. The compositional variations of metal appear to be a result of subtle fractional crystallization of the metal. We attribute the compositional differences between group A and group B metals to selective sampling during mesosiderite formation: group B mesosiderites have sampled more solid metal than group A members, thus having high concentrations of Ir but low concentrations of Au and Ni.
- 3. REEs show a vee-shaped pattern in Dong Ujimqin Qi olivine. The pattern requires addition of late-stage liquid in the region of olivine formation. As such a liquid is absent in the region where basaltic and gabbroic clasts formed, we believe that mesosiderite olivine may have formed in a body different from where the other silicate clasts formed.

*Acknowledgments*-This work is supported by the National Science Foundation of China (grant no. 40673054).

Editorial Handling-Dr. Christine Floss

#### REFERENCES

- Béhard J. H. 2005. Partitioning coefficients between olivine and silicate melts. *Lithos* 83:394–419.
- Chabot N. L. and Jones J. H. 2003. The parameterization of solid metal-liquid metal partitioning of siderophile elements. *Meteoritics & Planetary Science* 38:1425–1436.
- Chabot N. L., Campbell A. J., Jones J. H., Humayun M., and Agee C. B. 2003. An experimental test of Henry's Law in solid metalliquid metal systems with implications for iron meteorites. *Meteoritics & Planetary Science* 38:181–196.
- Cook D. L., Walker R. J., Horan M. F., Wasson J. T., and Morgan J. W. 2004. Pt-Re-Os systematics of group IIAB and IIIAB iron meteorites. *Geochimica et Cosmochimica Acta* 68:1413– 1431.
- Floran R. J. 1978. Silicate petrography, classification, and origin of the mesosiderites: Review and new observations. Proceedings, 9th Lunar and Planetary Science Conference. pp. 1053–1081.
- Greenwood R. C., Franchi I. A., Jambon A., Barrat J. A., and Burbine T. H. 2006. Oxygen isotope variation in stony-iron meteorites. *Science* 313:1763–1765.

- Haack H., Scott E. R. D., and Rasmussen K. L. 1996. Thermal and shock history of mesosiderites and their large parent asteroid. *Geochimica et Cosmochimica Acta* 60:2609–2619.
- Hassanzadeh J., Rubin A. E., and Wasson J. T. 1990. Compositions of large metal nodules in mesosiderites: Links to iron meteorite group IIIAB and the origin of mesosiderite subgroups. *Geochimica et Cosmochimica Acta* 54:3197–3208.
- Hewins R. H. 1983. Impact versus internal origins for mesosiderites. Journal of Geophysical Research 88:B257–266.
- Hewins R. H. 1984. The case for a melt matrix in plagioclase-POIK mesosiderites. Proceedings, 15th Lunar and Planetary Science Conference. pp. C289–297.
- Hewins R. H. 1988. Petrology and pairing of mesosiderites from Victoria Land, Antarctica. *Meteoritics* 23:123–129.
- Kong P. and Ebihara M. 1996. Metal phases of L chondrites: Their formation and evolution in the nebula and in the parent body. *Geochimica et Cosmochimica Acta* 61:2667–2680.
- Kong P. and Ebihara M. 1997. The origin and nebular history of the metal phase of ordinary chondrites. *Geochimica et Cosmochimica Acta* 61:2317–2329.
- Kong P., Ebihara M., Nakahara H., and Endo K. 1995. Chemical characteristics of metal phases of the Richardton H5 chondrite. *Earth and Planetary Science Letters* 136:407–419.
- Kong P., Ebihara M., and Nakahara H. 1996. Determination of eighteen siderophile element including all platinum group elements in chondritic metals and iron meteorites by instrumental neutron activation. *Analytical Chemistry* 68:4130–4134.
- Kong P., Tadashi M., and Ebihara M. 1997. Compositional continuity of enstatite chondrites and implications for heterogeneous accretion of the enstatite chondrite parent body. *Geochimica et Cosmochimica Acta* 61:4895–4914.
- Kong P., Ebihara M., and Xie X. 1998. Reevaluation of formation of metal nodules in ordinary chondrites. *Meteoritics & Planetary Science* 33:993–998.
- Mittlefehldt D. W. 1980. The composition of mesosiderite olivine clasts and implications for the origin of pallasites. *Earth and Planetary Science Letters* 51:29–40.
- Mittlefehldt D. W. 1990. Petrogenesis of mesosiderites: I. Origin of mafic lithologies and comparison with basaltic achondrites. *Geochimica et Cosmochimica Acta* 54:1165–1173.
- Mittlefehldt D. W., Rubin A. E., and Davis A. M. 1992. Mesosiderite clasts with the most extreme positive europium anomalies among solar system rocks. *Science* 257:1096–1099.
- Nehru C. E. and Zucker S. M. 1980. Olivines and olivine coronas in mesosiderites. *Geochimica et Cosmochimica Acta* 44:1103– 1118.
- Powell B. N. 1971. Petrology and chemistry of mesosiderites-II.

Silicate textures and compositions and metal-silicate relationship. *Geochimica et Cosmochimica Acta* 35:5–34.

- Prinz M., Nehru C. E., Delaney J. S., Harlow G. E., and Bedell R. L. 1980. Modal studies of mesosiderites and the related achondrites, including the new mesosiderite ALHA77219. Proceedings, 11th Lunar and Planetary Science Conference. pp. 1055–1071.
- Prior G. T. 1918. On the mesosiderite-grahamite group of meteorites: With analyses of Vaca Muerta, Hainholz, Simondium, and Powder Mill Creek. *Mineralogical Magazine* 18:151–172.
- Reed S. J. B., Scott E. R. D., and Long J. V. P. 1979. Ion microprobe analysis of olivine in pallasite meteorites for nickel. *Earth and Planetary Science Letters* 43:5–12.
- Rubin A. E. and Jerde E. A. 1988. Compositional differences between basaltic and gabbroic clasts in mesosiderites. *Earth and Planetary Science Letters* 87:485–490.
- Rubin A. E. and Mittlefehldt D. W. 1993. Evolutionary history of the mesosiderite asteroid: A chronologic and petrologic synthesis. *Icarus* 101:201–212.
- Ruzicka A., Boynton W. V., and Ganguly J. 1994. Olivine coronas, metamorphism, and the thermal history of the Morristown and Emery mesosiderites. *Geochimica et Cosmochimica Acta* 58: 2725–2741.
- Scott E. R. D., Haack H., and Love S. G. 2001. Formation of mesosiderites by fragmentation and reaccretion of a large differentiated asteroid. *Meteoritics & Planetary Science* 36:869– 881.
- Stolper E. 1977. Experimental petrology of eucritic meteorites. *Geochimica et Cosmochimica Acta* 41:587–611.
- Tao K., Yang Z., and Zhang P. 1997. A stony-iron meteorite fallen to Dong Ujimqin Qi, Inner Mongolia, China. Acta Petrologica Sinica 13:254–259.
- Wasson J. T. and Kallemeyn G. W. 1988. Compositions of chondrites. *Philosophical Transactions of the Royal Society of London A* 325:535–544.
- Wasson J. T. and Richardson J. W. 2000. Fractionation trends among IVA iron meteorites: Contrasts with IIIAB trends. *Geochimica et Cosmochimica Acta* 65:951–970.
- Wasson J. T. and Rubin A. E. 1985. Formation of mesosiderites by low-velocity impacts as a natural consequence of planet formation. *Nature* 318:168–170.
- Wasson J. T., Schaudy R., Bild R. W., and Chou C. L. 1974. Mesosiderites—I. Compositions of their metallic portions and possible relationship to other metal-rich meteorite groups. *Geochimica et Cosmochimica Acta* 38:135–149.
- Widom E., Rubin A. E., and Wasson J. T. 1986. Composition and formation of metal nodules and veins in ordinary chondrites. *Geochimica et Cosmochimica Acta* 50:1989–1995.