Meteoritics & Planetary Science 41, Nr 6, 863–874 (2006)
Abstract available online at http://meteoritics.org

An anomalous eucrite, Dhofar 007, and a possible genetic relationship with mesosiderites

Akira YAMAGUCHI[1, 2*], Takehiko SETOYANAGI[3], and Mitsuru EBIHARA[1, 3]

[1]Antarctic Meteorite Research Center, National Institute of Polar Research, Tokyo 173-8515, Japan
[2]Department of Polar Science, School of Multidisciplinary Science, Graduate University for Advanced Studies, Tokyo 173-8515, Japan
[3]Department of Chemistry, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan
[*]Corresponding author. E-mail: yamaguch@nipr.ac.jp

(Received 09 March 2005; revision accepted 20 February 2006)

Abstract–We studied the texture, mineralogy, and bulk chemical composition of Dhofar 007, a basaltic achondrite. Dhofar 007 is a polymict breccia that is mostly composed of coarse-grained granular (CG) clasts with a minor amount of xenolithic components, such as a fragment of Mg-rich pyroxene. The coarse-grained, relict gabbroic texture, mineral chemistry, and bulk chemical data of the coarse-grained clast indicate that the CG clasts were originally a cumulate rock crystallized in a crust of the parent body. However, in contrast to monomict eucrites, the siderophile elements are highly enriched and could have been introduced by impact events. Dhofar 007 appears to have experienced a two-stage postcrystallization thermal history: rapid cooling at high temperatures and slow cooling at lower temperatures. The presence of pigeonite with closely spaced, fine augite lamellae suggests that this rock was cooled rapidly from higher temperatures (>0.5 °C/yr at ~1000 °C) than typical cumulate eucrites. However, the presence of the cloudy zone in taenite and the Ni profile across the kamacite-taenite boundaries indicates that the cooling rate was very slow at lower temperatures (~1–10 °C/Myr at <600–700 °C). The slow cooling rate is comparable to those in mesosiderites and pallasites. The two-stage thermal history and the relative abundance of siderophile elements similar to those for metallic portions in mesosiderites suggest that Dhofar 007 is a large inclusion of mesosiderite. However, we cannot rule out a possibility that Dhofar 007 is an anomalous eucrite.

INTRODUCTION

Eucrites are basalts or gabbros that probably made up the outer crust of the howardites, eucrites, and diogenites (HED) parent body, tentatively assigned to asteroid 4 Vesta (e.g., Binzel and Xu 1993). Mesosiderites are stony-iron meteorites composed of roughly equal parts of metal and silicates, the latter of which is broadly similar to HED meteorites. They may have been formed by impact-mixing of crustal and core materials of differentiated meteorite parent bodies. Chemical and O-isotopic compositional data suggest that the HED meteorites and silicate portions of mesosiderites originated on the same or closely related parent bodies. Eucrites and mesosiderites record the oldest igneous activity beginning with the early formation of parent bodies.

Basaltic eucrites formed originally from quickly cooled surface lava flows or shallow intrusions, and gabbroic eucrites crystallized in magma chambers in the crust. Basaltic and gabbroic clasts in mesosiderites may also have initially formed by similar igneous processes. However, there are systematic differences between these meteorites. Compared to eucrites, basaltic and gabbroic clasts in mesosiderites have greater modal abundances of silica minerals and Ca phosphates, and their pyroxenes tend to be more MgO-rich and have lower Fe/Mn ratios. Some of mesosiderite silicates have highly fractionated rare earth elements (REE) patterns (e.g., Rubin and Mittlefehldt 1992). These differences could be due to more complex igneous processes of mesosiderite silicates compared to those of eucrites, including remelting of early formed crust (e.g., Rubin and Mittlefehldt 1992). Alternatively, basaltic and gabbroic clasts in mesosiderites experienced complex thermal metamorphism causing partial melting and redistribution of trace elements at the time of metal-silicate mixing (Wadhwa et al. 2003). Some basaltic clasts in mesosiderites are almost indistinguishable from eucrites with respect to texture and bulk chemical compositions (e.g., Ikeda et al. 1990; Mittlefehldt et al. 1998). Apparently, these clasts must have escaped from mesosiderite metamorphism.

An achondrite, Dhofar 007 (~27 kg) was found in the Oman desert and was initially classified as a cumulate eucrite (Afanasiev et al. 2000). However, Yamaguchi et al. (2002a) showed that a coarse-grained clast (CG clast) in Dhofar 007 has a greater modal abundance of metallic phases and high bulk Ni and Co concentrations, and suggested a possible link with mesosiderites. We performed a petrologic and geochemical study to gain better understanding of the differentiation, shock, and thermal history of Dhofar 007. We compared Dhofar 007 to HED meteorites and mesosiderites to fill the gap in our knowledge of the geologic history of these meteorite groups. Preliminary results were presented by Yamaguchi et al. (2002a, 2003).

SAMPLES AND ANALYTICAL TECHNIQUES

We obtained several fragments of Dhofar 007. Most of them show an unbrecciated or deformed coarse-grained texture, but one of them contains a brecciated matrix. We made polished thin and thick sections (PTSs) of various portions in Dhofar 007 and examined these PTSs by optical and scanning electron microscopes (SEM) (JEOL JSM5900LV) equipped with energy dispersive spectrometer (EDS) (Oxford LINK ISIS) at the National Institute of Polar Research (NIPR). Compositional data for mineral phases were obtained with electron microprobe analyzers (EPMA) (JEOL JXA8800M and 8200) at NIPR. Operating currents of 12 nA and a focused beam were used for plagioclase, pyroxene, and other phases. Each element was counted for 30 s. For Mn in pyroxene, we used a focused beam with beam current of 30 nA for 60 s. We also examined compositions of pyroxene in the Moore County cumulate eucrite (USNM1664-1) for comparison. The modal abundances of various phases were determined by EPMA X-ray mapping.

A portion of the CG clast (0.882 g) was powdered for chemical analyses at the Tokyo Metropolitan University. We inspected PTSs of this portion to insure that it did not contain any material from the breccia matrix. A subsample of about 200 mg of the homogenized powder was used for prompt gamma-ray analysis (PGA) for determining major element composition. About 50 mg was used for instrumental neutron activation analysis (INAA). For determination of rare earth elements (REEs) and platinum group elements (PGEs), inductively coupled plasma mass spectrometry (ICP-MS) was applied. Approximately 10 mg of the powder was used for determining REEs, whereas about 200 mg sample was used for PGE in consideration of the heterogeneity of PGE. These analytical procedures were described in Latif et al. (1999), Shirai et al. (2003), Shinotuska and Ebihara (1997), and for PGA, INAA, ICP-MS of REE, and ICP-MS of PGE, respectively.

RESULTS

Texture

Dhofar 007 is a polymict breccia, mainly composed of coarse-grained granular clasts and a small portion of clastic matrix (Fig. 1). Most of the matrix materials are mineralogically similar to the CG clasts, but we found xenolithic components such as an impact-melt clast (1.9 × 2.0 mm), and a Mg-rich orthopyroxene fragment (1.5 × 2.5 mm). The boundaries between clast and brecciated portion are in many cases gradational. There are glassy impact-melt veins (10–30 µm thick) that transect the clasts and brecciated matrix (Fig. 1c).

The PTSs of the CG clast show a granular texture mainly composed of almost equal amounts of pyroxene (51 vol%) and plagioclase (47 vol%). The minor minerals include silica minerals (0.7 vol%), chromite (0.3 vol%), troilite (0.6 vol%), kamacite (0.02 vol%), taenite (0.04 vol%), Ca phosphate (0.06 vol%), and weathering products often associated with metallic phases. In most cases, the fine-grained equigranular portion is in contact with the coarse-grained granular portion with diffuse boundaries. Plagioclase grains are relatively finer-grained (~30–50 µm in size) in contrast to the pyroxenes (0.1–1 mm in size) and have granular to lath-like shapes (Fig. 2a). There are a few larger rectangular plagioclase grains (1.5 × 0.9 mm) with rounded pyroxene chadacrysts and dusty inclusions (FeS and P-rich phases) in the cores (Fig. 2b).

The impact-melt clast is composed of polymineralic clasts and mineral fragments (Fig. 1b). The texture of the pyroxene and plagioclase are similar to those in the CG clast. The grain boundaries of pyroxene and plagioclase are melted, forming thin glassy rims (~5–20 µm thick), and these minerals contain melt pockets. Pyroxene grain in the impact melt contains very thin augite lamellae (<1 µm) like those observed in the CG clast, and parts of which are vesiculated.

The Dhofar 007 breccia is slightly shocked. While the pyroxene and plagioclase in the CG clast show a weak mottled extinction, those in the clastic matrix are highly fractured and deformed, and some of them show strong mottled and patchy extinction due to heterogeneous shock effects. The impact-melt veins have sharp boundaries with the clasts and matrix, and consist of fine (<30 µm), subrounded and deformed fragments pyroxene, plagioclase, and opaque minerals in a glassy matrix (Fig. 1c).

Mineralogy

Pyroxenes in the CG clast and in most fragments in the clastic matrix are pigeonites that have closely spaced, very fine augite exsolution lamellae with an apparent thickness of <1 µm (Fig. 3). The distribution of augite lamellae is homogeneous and there is no remnant Ca zoning. Unlike

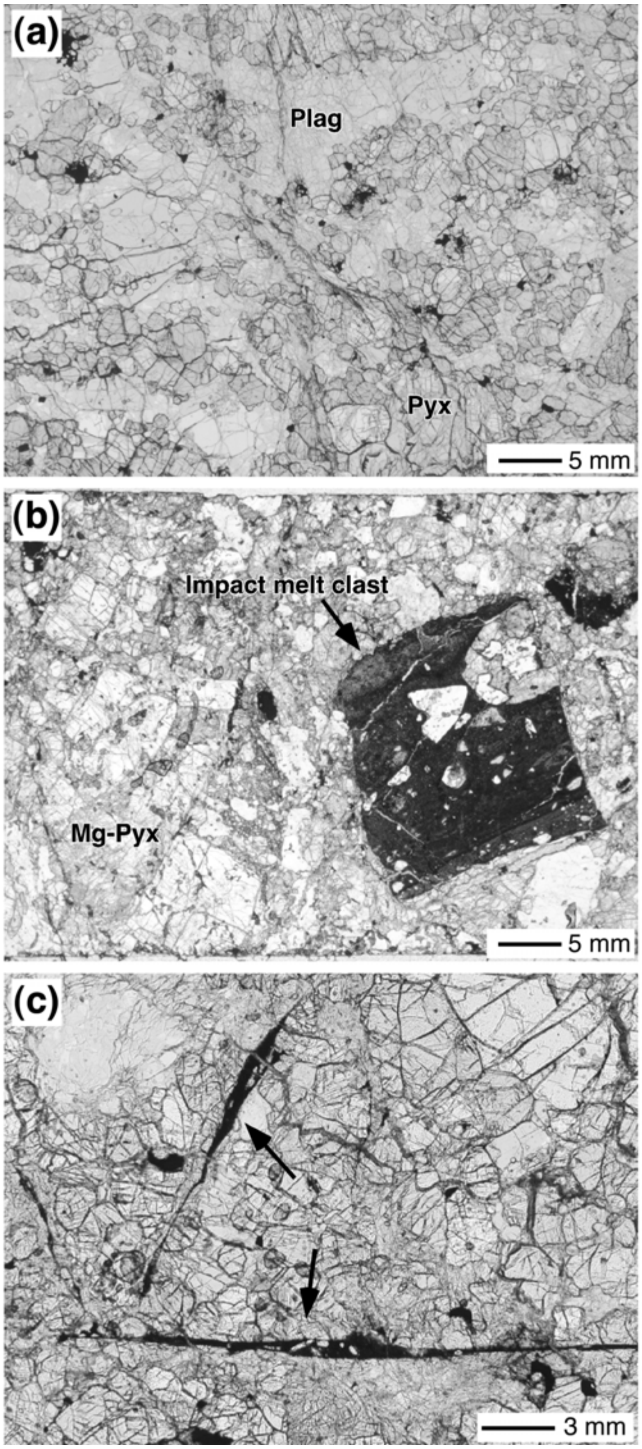

Fig. 1. Photomicrographs of Dhofar 007. a) A coarse-grained (CG) clast, b) brecciated matrix, and c) impact-melt veins. The CG clast (a) shows a granular texture, mainly composed of pyroxene and plagioclase. In (b), note the presence of a fragment of Mg-rich pyroxene (Mg-Pyx) and an impact-melt clast in the brecciated matrix (right) set in a brecciated matrix. In (c), black impact-melt veins (indicated by arrows) intersect a deformed, fine-grained portion. Plane light.

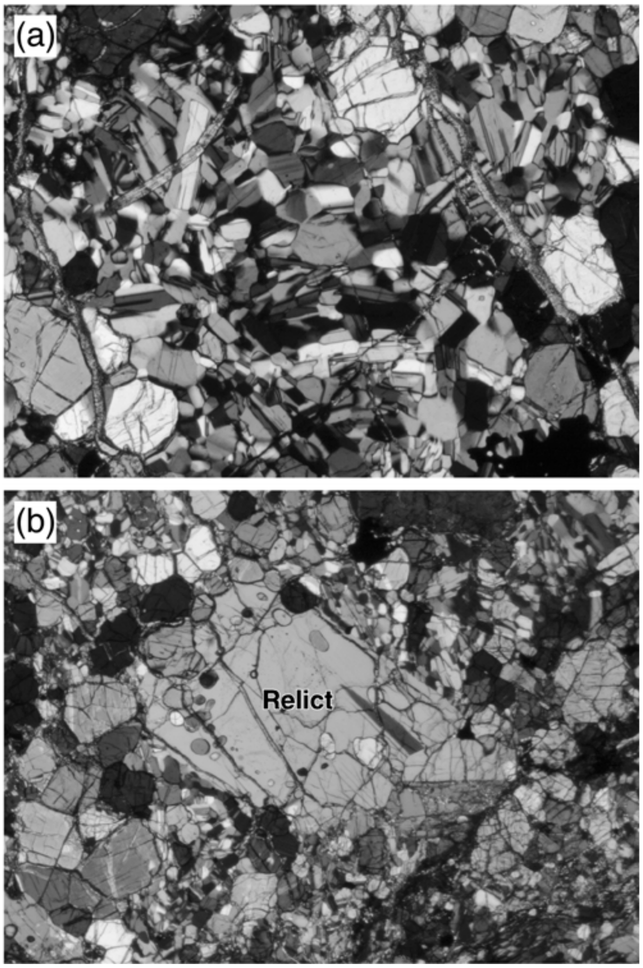

Fig. 2. a) Recrystallized plagioclase in CG clast, composed of fine-grained granular to lath-like plagioclase grains. b) Relatively large plagioclase lath, probably a relict igneous crystal (middle, "Relict") in granular portion in CG clast. Width is 1.29 mm for (a) and 2.6 mm for (b). Cross-polarized light.

many cumulate eucrites (Takeda 1997), well-developed inversion textures in pigeonites are lacking here. Chemical compositions of pyroxenes of the CG clast and most of the matrix fragments are scattered on a single tie line from $Wo_{2.9}En_{53}$–$Wo_{17}En_{48}$ because most thin augite lamellae are unresolvable by electron beam (Fig. 4; Table 1). The mg# (=Mg/(Mg + Fe) × 100) = 55.1 is within the range of cumulate eucrites (mg# = 45–67, Takeda 1997). The orthopyroxene fragment in the clastic matrix is chemically homogeneous ($Wo_{1.3}En_{83}$) (Fig. 4, Table 1). The ranges of molar Fe/Mn ratios of pyroxenes in the CG clast and brecciated matrix are 28.8–33.2 and 30.0–34.1, respectively, similar to those of Moore County pyroxenes (27.7–32.4) (Fig. 5). The ranges are also similar to those of other HED meteorites and are within the range of mesosiderite pyroxenes (16–35) (Mittlefehldt 1990). Plagioclase in Dhofar 007 displays a slight chemical variation ($An_{95}Or_{0.3}$ to $An_{91}Or_{0.3}$). We could not find

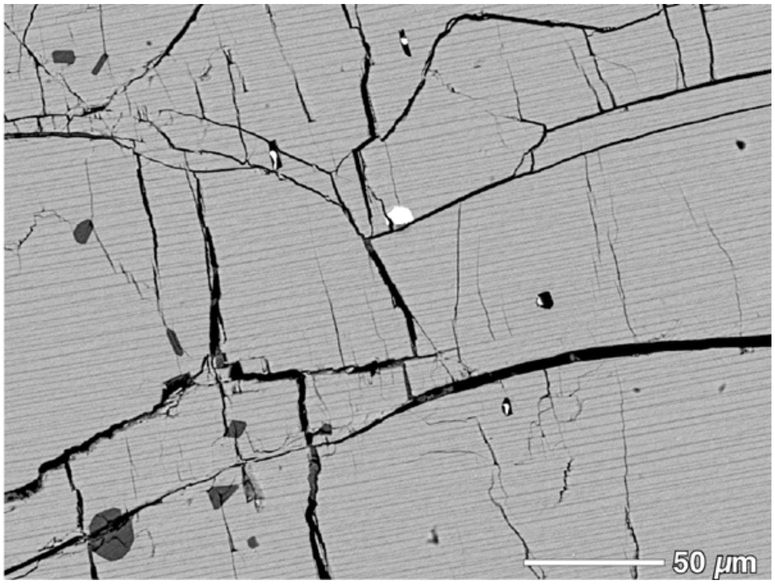

Fig. 3. Backscattered electron image (BEI) of pyroxene in the CG clast. Pigeonite (light gray) contains closely spaced, very fine augite lamellae (middle gray). White = opaque; dark gray = plagioclase.

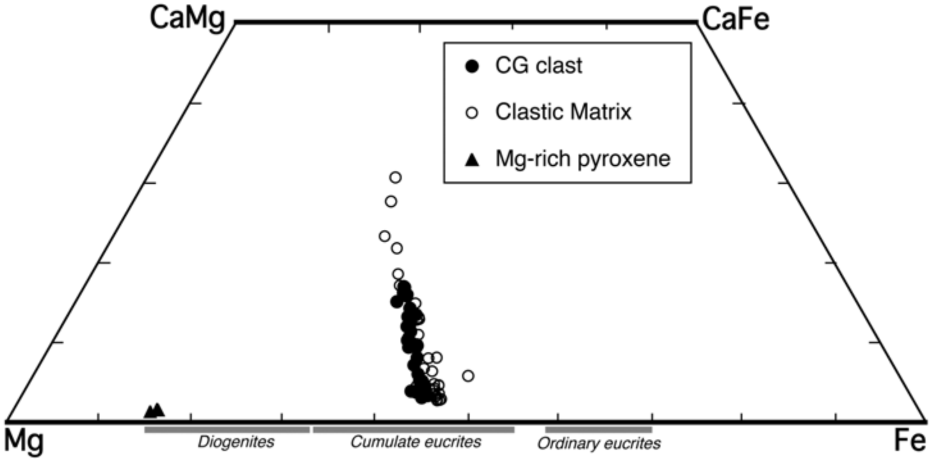

Fig. 4. Pyroxene compositions in Dhofar 007. The compositions are plotted along a single tie line due to incomplete spatial resolution of augite lamellae (Fig. 3) in the electron beam. Also, the ranges of low-Ca pyroxenes in ordinary eucrites, cumulate eucrites, and diogenites are shown (Takeda 1997).

significant differences in plagioclase compositions between coarse-grained and fine-grained regions or between relict plagioclases in CG clast and in clastic matrix. Chromite has homogeneous Al/Cr ratios, but has a slight chemical variation ($Ulv_{24.0}Chm_{61.1}$–$Ulv_{10.4}Chm_{70.9}$) and contains very fine needles (<1 × 20 μm) of Ti-rich phases, possibly ilmenite. The mineral chemistries except those of metallic phases (see below) are very similar to those of cumulate eucrites (e.g., Mittlefehldt et al. 1998).

We found taenite and kamacite closely associated with troilite (Figs. 6, 7). In most cases, these phases are rimmed by light gray weathering products. These metallic phases are not associated with impact-melt veins and brecciated matrix. In taenite in contact with kamacite, the Ni profile of the core (~10 μm) shows a flat pattern (39.6–40.6 wt%) with sharp zoning (up to 47.8 wt%) near (~4 μm thick) the boundary (Fig. 7). After etching by nital, we found several taenite grains which have the cloudy zone rimmed by clear taenite (Fig. 6a). The SEM observation shows that the cloudy zones are composed of bright island regions (~0.2 μm wide) and dark honeycomb regions (Fig. 6b). We could not find any systematic difference in the island width between the rims and cores of the cloudy zone.

Combined with the EPMA data and modal abundance of metallic phases, we estimate the bulk Ni concentration to be ~200–300 ppm, which is lower than the value (870 ppm) obtained by PGA (Table 2). Considering a sample amount (~200 mg) of well-homogenized powder, the PGA values

Table 1. Representative chemical compositions of minerals in Dhofar 007.

		Pyroxene CG clast			Mg-rich pyroxene		Chromite CG clast			Plagioclase CG clast		Silica minerals
		Low Ca	High Ca	Bulk			Low Ti	High Ti		Core	Rim	CG clast
SiO_2		52.4	52.1	51.8	56.1					45.5	46.3	98.5
Al_2O_3		1.01	1.25	0.78	0.81		8.93	7.41		34.2	33.7	0.52
TiO_2		0.30	0.32	0.35	0.03		3.91	9.36				0.14
FeO		26.3	20.9	24.7	10.3		34.9	35.1				0.03
MnO		0.94	0.61	0.78	0.32		0.55	0.76				
MgO		18.0	16.1	17.7	30.5		1.70	1.40		0.07	0.11	
CaO		1.35	7.76	4.20	0.80					19.2	18.6	0.16
Cr_2O_3		0.51	0.71	0.54	0.72		50.6	45.3				
Na_2O										0.59	0.97	0.03
K_2O										0.15	0.07	0.15
Total		100.8	99.8	100.9	99.6		100.7	99.3		99.7	99.8	99.4
	Wo	2.9	16.7	8.7		Usp	10.4	24.0	Or	0.3	0.4	
	En	53.3	48.2	51.2		Chm	70.9	61.1	An	94.5	91.0	

should be representative for the CG clast of Dhofar 007. The differences could be due to the lower resolution of X-ray mapping for the small phases and partial replacement of FeNi metals to weathering products. Thus, the metallic phases are major carrier phases of Ni and other siderophile elements.

Bulk Composition of CG Clast

The bulk composition of the CG clast is consistent with HED meteorites (Table 2). The MgO concentration (9.45 wt%) is higher than those of noncumulate eucrites (6–8 wt%) and cumulate eucrites (~9 wt%) (e.g., Barrat et al. 2003). However, the Cr_2O_3 (0.45 wt%) is intermediate between those of cumulate eucrites and noncumulate eucrites. Features such as Fe/Mn (=30.5), Al_2O_3/Na_2O (=36.4), and Al_2O_3/CaO (=1.15) ratios confirm that the CG clast belongs to HED meteorites or igneous clasts from mesosiderites (e.g., Barrat et al. 2003), which is consistent with their mineral chemistries. The Al_2O_3 and CaO abundances of Dhofar 007 are greater than those in basaltic eucrites, consistent with its greater modal abundance of plagioclase. The chondrite-normalized REE data show a slight enrichment of all REE (1.3–2.0 × chondrites) with a positive Eu anomaly (normalized Eu/Eu* ratio = 3.14) and a moderate increase from light to heavy REE (chondrite-normalized La/Lu = 0.66), similar to a cumulate eucrite, Binda (Barrat et al. 2000) (Fig. 8).

In spite of the mineralogical evidence for the hot-desert weathering such as oxidation of FeNi metals, the bulk composition shows little evidence of weathering. The Ba concentration (13.9 ppm), which is one of the most sensitive indicators for hot desert weathering, is lower than the values for eucrites recovered from Sahara (30–125 ppm) (Barrat et al. 2003). There is a marginal depletion of Ce due to weathering (Fig. 8). Although not common, the Ce anomaly is observed in meteorites from hot desert (Crozaz et al. 2003).

Compared to monomict eucrites, siderophile elements in the CG clast are highly enriched, for example, Ni at 265× the bulk of Moore County (MC) (Morgan et al. 1978), Pd at 93× MC, Os at 10× MC, and Au at 40× MC. Similar sizes of the powdered sample were used for both PGA and ICP-MS so that the analytical values could be representative. The CI-normalized ratios of Ir/Ni ($(Ir/Ni)_{CI}$ (=1.21), $(Au/Ni)_{CI}$ (=0.78), $(Os/Ni)_{CI}$ (=0.73), and $(Ni/Co)_{CI}$ (=0.71)) are similar to those of the averaged compositions for metallic portions of mesosiderites ($(Ir/Ni)_{CI}$ = 1.05–1.72, $(Au/Ni)_{CI}$ = 0.88–1.14, $(Os/Ni)_{CI}$ = 0.65–1.02, and $(Ni/Co)_{CI}$ = 0.74–1.02) (Fig. 9) (Hassanzadeh et al. 1990; Shen et al. 1998). The $(Au/Ni)_{CI}$ and $(Ni/Co)_{CI}$ ratios for the CG clast are within the range of basaltic/gabbroic clasts in mesosiderites (0.34–36.3 for $(Au/Ni)_{CI}$, 0.51–7.17 for $(Ni/Co)_{CI}$) except for the $(Ir/Ni)_{CI}$ ratio (=1.21), which is significantly higher than values for mesosiderite basalts/gabbros ($(Ir/Ni)_{CI}$ = 0.02–0.51) (Rubin and Jerde 1987; Mittlefehldt 1979, 1990; Ikeda et al. 1990; Kimura et al. 1991).

DISCUSSION

Petrogenesis

Except for some features such as high abundances of siderophile elements and the presence of Ni-rich phases (kamacite and taenite), the petrology and bulk chemical composition of the CG clast in Dhofar 007 are broadly similar to those of cumulate eucrites. The oxygen isotopic composition (Miura et al. 2004) and Fe/Mn ratios in pyroxenes (Fig. 5) of Dhofar 007 imply a genetic relationship with HED meteorites and/or mesosiderite silicate clasts. We do not observe significant enrichment of the silica minerals and Ca phosphates that are commonly observed in silicate clasts in mesosiderites. The REE data of the CG clast are within the range of cumulate eucrites and do not show extreme LREE depletions or pronounced positive Eu/Sm ratios similar to those observed in mesosiderite gabbroic

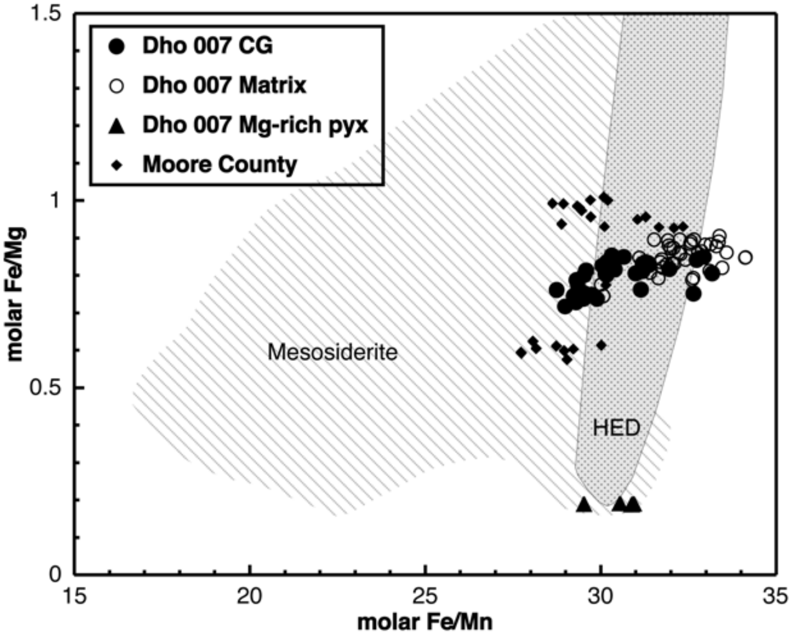

Fig. 5. Molar Fe/Mg versus Fe/Mn for pyroxenes in Dhofar 007 and in the Moore County cumulate eucrite. The fields for mesosiderites and HED meteorites are also shown (Mittlefehldt et al. 1998). Note that the compositions of Dhofar 007 are plotted near the field for HED meteorites.

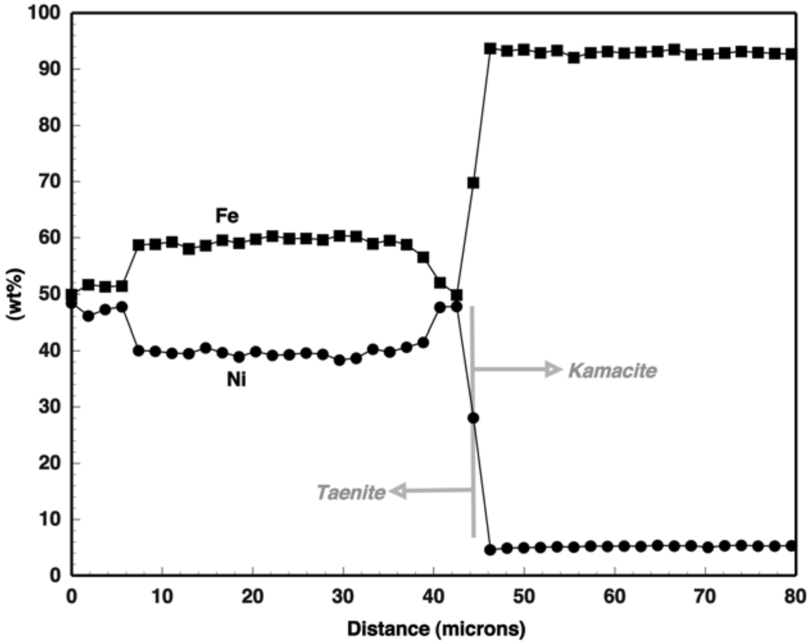

Fig. 6. An Fe and Ni profile across the kamacite-taenite boundary. The analyzed positions are indicated in a line across the taenite and kamacite boundary in Fig. 7a. The Ni profile of the core shows a flat pattern with a sharp zoning near the boundary with kamacite.

clasts (Barrat et al. 2000; Mittlefehldt 1990; Rubin and Mittlefehldt 1992). The bulk REE data and relatively magnesian nature of the CG clast is consistent with its cumulate origin, in agreement with the coarse-grained gabbroic texture. The positive Eu anomaly in cumulate eucrites can be explained by plagioclase accumulation, which is consistent with a greater modal abundance of plagioclase (47 vol%) than those of eucrites (39.4–44.6 vol%) (Delaney et al. 1984). The relict coarse-grained granular texture and the compositions of pyroxene and plagioclase of the CG clast are consistent with cumulate origin.

The CG clast is enriched in siderophile elements compared to other monomict eucrites. Igneous processes cannot account for the high abundance of siderophile elements in the CG clast. The formation of cumulate rocks requires a large scale melting and slow cooling in magma chambers that causes crystal accumulation. Such melting and slow cooling would cause segregation of metallic phases (depletion of PGEs) from the silicate magma because of the density differences between silicates and metallic phases. In monomict and unbrecciated eucrites, the abundance of siderophile elements is extremely low (Morgan et al. 1978; Warren and Jerde 1987). Therefore, we suggest that the siderophile elements (and metallic phases) were introduced by the contamination from projectile materials having high abundances of PGE during impact events. It is unlikely that siderophile elements were incorporated by the later impact events that produced impact-melt veins and (unrecrystallized) breccia texture because kamacite and taenite, carrier phases of siderophile elements, are not associated with these shock textures. The contamination of siderophile elements could have taken place before recrystallization of the CG clast.

Relative abundances of siderophile elements in the CG clast of Dhofar 007 CG can be sensitive tracers for identifying projectile materials. The slightly high Co/Ni ratio of the CG clast (Fig. 9) indicates that the contaminants could be iron meteorites rather than chondritic materials. If Dhofar 007 is a silicate inclusion of a mesosiderite, or if the contaminants (or impactors) were iron meteorites similar in composition to mesosiderite metal, the amount of metal incorporated to the CG clast can be estimated based on the average abundance of siderophile elements in metals of mesosiderites (Hassanzadeh et al. 1990). Assuming that the precursor of the CG clast did not contain siderophile elements, the contribution from mesosiderite metals would be 0.5–1 wt% based on the concentrations of Os, Ir, Pt, and Au (Table 2). This metal concentration is consistent with estimated amounts of kamacite, taenite, and troilite (0.1, 0.04, and 0.9 wt%, respectively) in the CG clast calculated from the modal abundances.

As discussed above, it is unlikely that PGEs were introduced during igneous processes. We suggest that Fe-FeS liquids were mixed with silicate portions during impact melting or mobilized into microcracks and fractures in the silicate portions formed by impact. This process commonly occurs in shocked ordinary chondrites, causing "shock darkening" (Rubin 1992). The evidence of shock in the silicates could have been subsequently erased by recrystallization.

Postcrystallization Shock and Thermal History

The bulk chemical composition and remnant coarse-grained gabbroic texture of the CG clast indicate that most parts of Dhofar 007 were cumulates crystallized in deep interior of the crust (see above). However, compared to typical cumulate eucrites (e.g., Moore County, Serra de Mage) (Takeda 1997), we found a significant difference in the thermal history. Pyroxenes in ordinary cumulate eucrites have no chemical zoning, and are generally orthopyroxenes partly or totally inverted from pigeonite and have thick augite lamellae and/or blebs because of very slow cooling rate under plutonic conditions (Takeda 1997). The absence of Ca zoning in pyroxenes in Dhofar 007 is consistent with slow cooling at high temperatures (>1000 °C) (Yamaguchi et al. 1996). However, in contrast to pyroxenes in ordinary cumulate eucrites (e.g., Moore County, Serra de Mage), pyroxenes of Dhofar 007 are not inverted to orthopyroxene, and instead they have very fine augite exsolution lamellae, similar to those in basaltic eucrites (Fig. 3). The presence of the fine lamellae indicates that the CG clast was cooled very rapidly from high temperatures (>1000 °C). The rapid cooling prevented the formation of exsolution and decomposition textures in pyroxenes. The estimated cooling rate of the CG

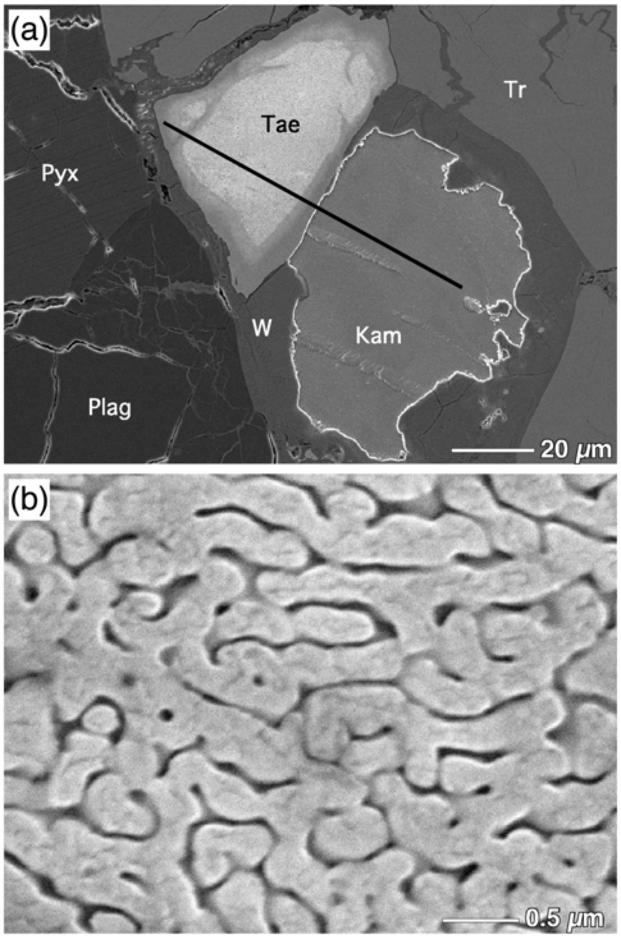

Fig. 7. a) An SEM image of taenite and kamacite. The sample was etched with ~2% nital. Taenite has a cloudy light gray core surrounded by a middle gray rim. Tae = taenite; Kam = kamacite; Tr = troilite; Pyx = pyroxene; Plag = plagioclase; W = weathering products. b) An enlarged image of the cloudy zone. It is composed of bright island regions (~0.2 μm wide) and dark honeycomb regions.

Table 2. Bulk chemical compositions of coarse-grained clast in Dhofar 007[a].

NAA/PGA		
SiO_2	(%)	46.2 ± 1.2
TiO_2	(%)	0.205 ± 0.009
Al_2O_3	(%)	12.6 ± 0.3
Cr_2O_3	(%)	0.446 ± 0.009
FeO	(%)	15.7 ± 0.6
MnO	(%)	0.52 ± 0.04
MgO	(%)	9.4 ± 0.6
CaO	(%)	11.0 ± 0.8
Na_2O	(%)	0.347 ± 0.002
K_2O	(%)	0.029 ± 0.003
S	(ppm)	4650 ± 320
Sc	(ppm)	21.61 ± 0.01
V	(ppm)	81.6 ± 6.0
Co	(ppm)	59.8 ± 0.7
Ni	(ppm)	929 ± 32
As	(ppm)	0.50 ± 0.06
ICP-MS		
Y	(ppm)	3.17 ± 0.08
Ru	(ppb)	52 ± 1
Rh	(ppb)	7.9 ± 0.2
Pd	(ppb)	37 ± 4
Ba	(ppm)	13.9 ± 0.3
La	(ppm)	0.386 ± 0.003
Ce	(ppm)	0.908 ± 0.005
Pr	(ppm)	0.152 ± 0.003
Nd	(ppm)	0.705 ± 0.004
Sm	(ppm)	0.261 ± 0.005
Eu	(ppm)	0.330 ± 0.003
Gd	(ppm)	0.393 ± 0.009
Tb	(ppm)	0.077 ± 0.008
Dy	(ppm)	0.58 ± 0.01
Ho	(ppm)	0.132 ± 0.002
Er	(ppm)	0.406 ± 0.005
Tm	(ppm)	0.0611 ± 0.0007
Yb	(ppm)	0.427 ± 0.003
Lu	(ppm)	0.067 ± 0.001
Os	(ppb)	30 ± 1
Ir	(ppb)	49 ± 2
Pt	(ppb)	49 ± 1
Au	(ppb)	9.2 ± 1.0

[a] Uncertainties for NAA/PGA are due to counting statistics and those for ICP-MS are standard deviation of replicated measurements.

clast based on the thickness of augite lamellae (<1 μm thick) is >0.52 °C/yr at 850–1200 °C, which is four orders of magnitude greater that those of cumulate eucrites (e.g., 0.95–0.96 °C/10^4 yr for Moama) (Miyamoto and Takeda 1977). This cooling rate suggests that the CG clast was excavated from hot interior by impact event(s).

The presence of the fine-grained granular portion and finely recrystallized plagioclase indicates that the CG clast experienced brecciation (and/or melting) and recrystallization by impact at high temperatures. Ostertag and Stöffler (1982) performed annealing experiments of shocked plagioclases. They showed that recrystallization of diaplectic glass takes place in 50 h at 900 °C that at 1000 °C recrystallization occurs instantaneously. The overall optical orientation of newly formed crystals from diaplectic glass is still maintained constant (Ostertag and Stöffler 1982). However, the orientation of recrystallized plagioclase in Dhofar 007 is almost random, indicating that the plagioclase was once melted by shock. We suggest that the recrystallization took place for a short time at high temperature at ~1000 °C after the precursor rock was shock-melted at >40–50 GPa. Thus, the CG clast is likely to be an impact-melt rock. It is possible that the recrystallization of plagioclases were related to impact events and occurred during the rapid cooling at high temperatures, which produced the thin augite lamellae in pyroxenes.

In contrast, the compositions and textures of metallic phases suggest that the CG clast cooled very slowly at lower temperatures. The Ni profile (especially flat Ni profile in the core) of the taenite grain (Fig. 6) indicates a very slow cooling rate (<1–10 °C/Ma) from ~700 °C to 400 °C (Saikumar and Goldstein 1988). Such a cooling rate is almost comparable to those of mesosiderites (Scott et al. 2001). The presence of the cloudy zone in taenite also implies slow cooling below 300 °C. Yang et al. (1997) suggested that the island width in the cloudy zone in taenite is related to the cooling rate. The island width in the cloudy zone in taenite in the CG clast is about 200 nm (Fig. 7b), which can be produced by the cooling rate of 1–10 °C /Myr. This cooling rate is similar to those of pallasites, and one order of magnitude greater than those of mesosiderite (0.1–1 °C /Myr) (Yang et al. 1997).

After the recrystallization, Dhofar 007 experienced two shock metamorphic events at low temperatures. One formed the brecciated matrix and the next event formed shock melt veins that penetrate the brecciated matrix. The shock pressures can be estimated from plagioclase textures. The absence of isotropic plagioclase suggests that shock pressure from the last impact event (i.e., after recrystallization of the CG clast) was less than 20–30 GPa, and the shock residual temperature was 200–250 °C (Bischoff and Stöffler 1992) assuming a typical surface temperature of asteroids (Miyamoto and Takeda 1977). This temperature may be high enough to affect the texture of the cloudy zone in taenite. Thus, it is also possible that the cloudy zone in taenite was formed by shock heating and slow cooling in thick regolith. Alternatively, the formation of the cloudy zone in taenite is more simply explained by the slow monotonous cooling from high temperatures (~700 °C).

Origin of Dhofar 007 and Comparison with Silicate Clasts in Mesosiderites

On the basis of data, the Dhofar 007 meteorite appears to have experienced the following stages (Table 3): 1) primary crystallization under plutonic conditions, 2) impact event that produced impact melt or fragmental breccia, 3) thermal event

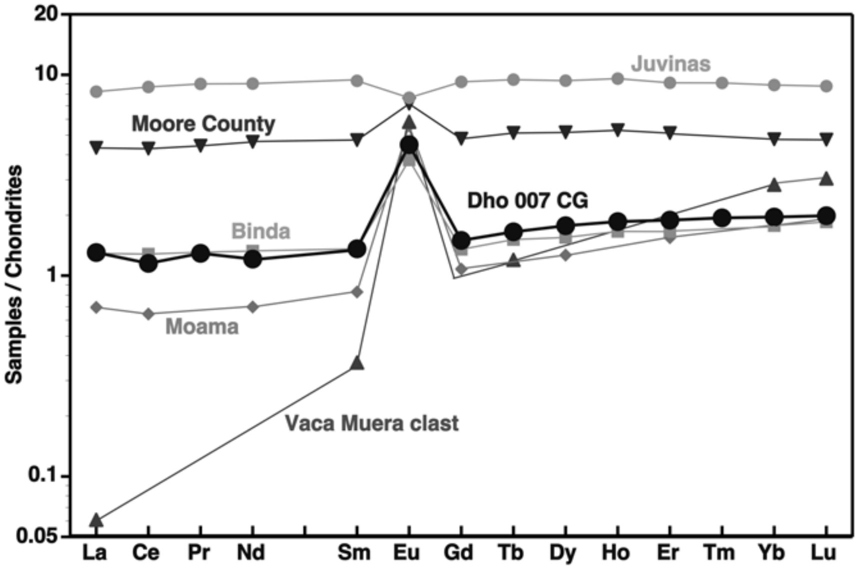

Fig. 8. Chondrite-normalized REE patterns of CG clast in Dhofar 007, Juvinas (noncumulate eucrite), Moore County, Binda, and Moama (cumulate eucrites), and a gabbroic clast from a mesosiderite, Vaca Muerta (Hamet et al. 1978; Mittlefehldt 1990; Barrat et al. 2000; Yamaguchi et al. 2002b).

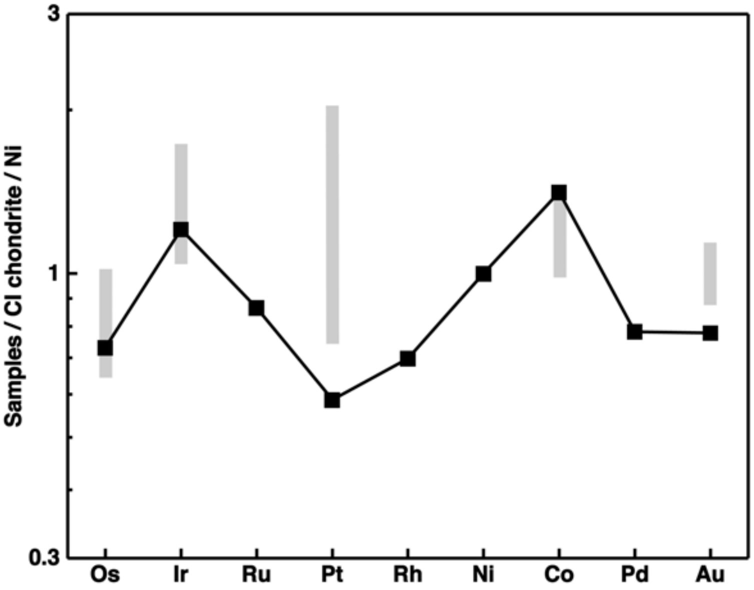

Fig. 9. Siderophile element concentrations of the Dhofar 007 CG normalized to CI chondrite values and Ni. The gray bars are the range for mesosiderite metals (Os, Ir, Pt, Co, and Au) (Hassanzadeh et al. 1990; Shen et al. 1998).

that recrystallized the CG clast, 4) rapid cooling from high temperature (~1000 °C) producing a very fine exsolution (001) lamellae of augite, 5) very slow cooling at low temperatures (<700 °C) that produced the metal textures, and 6) impact event(s) that produced shock melt veins and breccia texture.

The thermal history from stages 1 to 5 is similar to that of mesosiderites (e.g., Scott et al. 2001). Mesosiderites cooled through 1150 to 850 °C at ~0.1 °C/yr, and in the temperature range 400–250 °C, they cooled exceptionally slowly at <0.5 °C/Myr (Scott et al. 2001). Recently, Korochantseva et al. (2005) determined the ^{39}Ar–^{40}Ar age of Dhofar 007 to be between 3.4–4.5 Ga, with the last total reset age at 3.9 ± 0.2 Ga. They suggested that the slowly rising apparent ages within the age spectrum of the whole rock sample are due to either slow cooling or reheating at 3.4 Ga. This age may correspond to the events 5 and/or 6.

The thermal history and the high abundance of the siderophile elements suggest that Dhofar 007 is related to a silicate clast in mesosiderite or perhaps, a metal-poor

Table 3. Petrogenetic history of Dhofar 007.

Stage	Event	Shock and thermal history	Petrology and geochemistry
1	Primary crystallization	Cooled very slowly	Bulk chemical composition similar to those of cumulate eucrites Relict gabbroic texture
2	Impact event	Shock-melted at >40–50 GPa Brecciated	Recrystallized texture
3	Thermal event	Cooled slowly (>1000–1100 °C)	Absence of Ca zoning
4	Thermal event	Cooled rapidly (~1–100 °C/yr at 800–1000 °C)	Fine (001) augite lamellae
5	Thermal event	Cooled slowly (~1–10 °C/yr at <700 °C)	Texture of metallic phases
6	Impact events	Shocked at <20–30 GPa Brecciated	Breccia texture, shock melt veins

mesosiderite. Dhofar 007 was recovered as 37 pieces weighing a total of 21,270 g (Afanasiev et al. 2000). The amount of the total weight is comparable to a sphere ~26 cm in diameter, assuming that the density of silicate is 3 g/cm^3. In contrast, the silicate clasts in mesosiderites are typically less than ~10 cm in length (e.g., McCall 1966; Rubin and Jerde 1987). There are two other types of metal-poor mesosiderites. Elephant Moraine (EET) 92023 is a small, gabbroic meteorite (21.78 g) which contains a significant amount of FeNi metal (0.5%) (Kaneda and Warren 1998). This meteorite has REE abundances similar to those of Moore County and highly enriched siderophile abundances, and thus this meteorite possibly has a genetic relationship with mesosiderite (Kaneda and Warren 1998; Okamoto et al. 2004). The Eltanin mesosiderite was found as submillimeter- to centimeter-sized fragments recovered in the sediment core of the ocean floor and the original size before impact was estimated to ~1–4 km in size (Gersonde et al. 1997). Analyses of fragments of the Eltanin mesosiderite suggest that the precursor asteroid contains 4 ± 1 wt% of metal (Kyte 2002). The modal abundance of metal (~0.5–1 wt%) of Dhofar 007 is smaller than those of EET 92023 and Elatanin.

The Dhofar 007 CG clast contains a significant amount of siderophile elements introduced from metal, but we could not find any characteristic mineralogical features observed in mesosiderite silicates such as the presence of silica minerals and Ca-phosphates formed by redox reactions formed by metal-silicate mixing. In mesosiderite clasts, the degree of redox reaction varies; some basaltic clasts in mesosiderites may be mineralogically indistinguishable from HED meteorites (e.g., Ikeda et al. 1990). Thermal histories of individual mesosiderites may also have varied, considering the diversity in sizes and temperatures of the components in metal-rich and metal-poor regions after metal-silicate mixing. Because of this same reason, the degree of siderophile contamination and redox reactions could have varied considerably. A question remains how we can distinguish eucrites from some unaltered silicate clasts from mesosiderites. There is another question whether mesosiderites are formed by the mixing of iron meteorite with HED meteorites, and if not, whether the available evidence is consistent with the mesosiderites and HED meteorites having originated in different geological provinces of the same parent body. In other words, several large cratering events may have produced a variety of breccias, including HED breccias and mesosiderites. Several eucrites have petrologic evidence of large cratering events. A cumulate eucrite, Moore County, and several basaltic eucrites (e.g., Ibitira and EET 90020) show of evidence of rapid cooling from high temperature, implying a large-scale impact event during thermal metamorphism (Miyamoto and Takeda 1994; Miyamoto et al. 2001; Yamaguchi et al. 2001). This petrologic evidence is consistent with the recent discovery of craters up to ~450 km in diameter on asteroid 4 Vesta (Thomas et al. 1997). Also, the large impact events on Vesta that could have caused metal-silicate mixing are followed by slow cooling into deep burial as suggested by Wasson and Rubin (1985). In this case, the mesosiderites were buried deeply while HED meteorites were located near the surface of the parent body.

CONCLUSIONS

Dhofar 007 is a polymict breccia that is mostly composed of coarse-grained granular (CG) clasts with minor amount of xenolithic components such as a fragment of Mg-rich pyroxene. The coarse-grained relict gabbroic texture and bulk chemical data of the CG clast indicate that Dhofar 007 was originally a cumulate rock crystallized deep in a crust of the parent body. The presence of pigeonite with closely spaced, fine augite lamellae indicates that this rock cooled more rapidly from high temperatures (~1000 °C) than common cumulate eucrites, such as Moore County and Serra de Mage. The siderophile elements are highly enriched compared to those in monomict eucrites and could have been introduced by impact events. The recrystallized texture, cooling history, and the enrichment of siderophile element all suggest that the gabbroic clast experienced shock melting before its incorporation to the breccia. The texture and compositions of metallic phases indicate that the cooling rate was very slow at about <1–10 °C/Myr below 600–700 °C, similar to those in mesosiderites and pallasites. The slow cooling rates indicates that this rock was buried deep in the thick regolith on the parent body. The similarity of cooling history and the relative abundance of siderophile elements to those for metallic portions in mesosiderites suggests that Dhofar 007 is likely a large inclusion of mesosiderites. However, we cannot rule out a possibility that Dhofar 007 is an anomalous eucrite.

Acknowledgments–We thank H. Takeda and K. Misawa for discussion, T. Fagan for discussion and improving the English, the Smithsonian Institution for loaning a PTS of Moore County, J.-A. Barrat, G. Benedix, and R. Korotev for constructive reviews. This work is supported by Grants-in-Aid for Scientific Research from the Ministry of Education, Science, and Technology, Japan, no. 12740300 (A. Y.) and 15340193 (M. E.).

Editorial Handling—Dr. Randy Korotev

REFERENCE

Afanasiev S. V., Ivanova M. A., Korochantsev N. N., and Nazarov M. A. 2000. Dhofar 007 and Northwest Africa 011: Two new eucrites of different types (abstract). *Meteoritics & Planetary Science* 35:A19.

Barrat J. A., Blichert-Toft J., Gillet P., and Keller F. 2000. The differentiation of eucrites: The role of in situ crystallization. *Meteoritics & Planetary Science* 35:1087–1100.

Barrat J. A., Jambon A., Bohn M., Blichert-Toft J., Sautter V., Göpel C., Gillet P., Boudouma O., and Keller F. 2003. Petrology and geochemistry of the unbrecciated achondrite Northwest Africa 1240 (NWA 1240): An HED parent body impact melt. *Geochimica et Cosmochimica Acta* 67:3959–3970.

Binzel R. P. and Xu S. 1993. Chips off of asteroid 4 Vesta: Evidence for the parent body of basaltic achondrite meteorites. *Science* 260:186–191.

Bischoff A. and Stöffler D. 1992. Shock metamorphism as a fundamental process in the evolution of planetary bodies: Information from meteorites. *European Journal of Mineralogy* 4: 707–755.

Crozaz G., Floss C., and Wadhwa M. 2003. Chemical alteration and REE mobilization in meteorites from hot and cold deserts. *Geochimica et Cosmochimica Acta* 67:4727–4741.

Delaney J. S., Prinz M., and Takeda H. 1984. The polymict eucrites. Proceedings, 15th Lunar and Planetary Science Conference. pp. C251–C288.

Hamet J., Nakamura N., Unruh D. M., and Tatsumoto M. 1978. Origin and history of the adcumulate eucrite, Moama as inferred from REE abundances, Sm-Nd, and U-Pd systematics. Proceedings, 9th Lunar Science Conference. pp. 1115–1136.

Hassanzadeh J., Rubin A. E., and Wasson J. T. 1990. Compositions of large metal nodules in mesosiderites: Links to iron meteorite groups IIIAB and the origin of mesosiderite subgroup. *Geochimica et Cosmochimica Acta* 54:3197–3208.

Gersonde R., Kyte F. T., Bleil U., Diekmann B., Flores J. A., Gohl K., Grahl G., Hagen R., Kuhn G., Sierro F. J.,Völker D., Abelmann A., and Bostwick J. A. 1997. Geological record and reconstruction of the late Pliocene impact of the Eltanin asteroid in the Southern Ocean. *Nature* 390:357–363.

Ikeda Y., Ebihara M., and Prinz M. 1990. Enclaves in the Mt. Padbury and Vaca Muerta mesosiderite: Magmatic and residue rock types from different cumulate sources. *Proceedings of the NIPR Symposium on Antarctic Meteorites* 3:99–131.

Korochantseva E.V., Trieloff M., Buikin A. I., Hopp J., and Meyer H.-P. 2005. ^{40}Ar/^{39}Ar dating and cosmic-ray exposure time of desert meteorites: Dhofar 300 and Dhofar 007 eucrites and anomalous achondrite NWA 011. *Meteoritics & Planetary Science* 40:1433–1454.

Kaneda K. and Warren P. H. 1998. Fe-Ni metal bearing unique eucrite EET 92023: Its petrography, siderophile concentration, and petrogenesis (abstract). *Meteoritics & Planetary Science* 33:A81.

Kimura M., Ikeda Y., Ebihara M., and Prinz M. 1991. New enclaves in the Vaca Muerta mesosiderite: Petrogenesis and comparison with HED meteorites. *Proceedings of the NIPR Symposium on Antarctic Meteorites* 4:263–306.

Kyte F. T. 2002. Composition of impact melt debris from the Eltanin impact strewn field, Bellingshausen Sea. *Deep-Sea Research II* 49:1029–1047.

Latif S. A., Oura Y., Ebihara M., Kallemeyn G. W., Nakahara H., Yonezawa C., Matsue T., and Sawahata H. 1999. Prompt gamma-ray analysis (PGA) of meteorite samples, with emphasis on the determination of Si. *Journal of Radioanalytical and Nuclear Chemistry* 239:577–580.

McCall G. J. H. 1966. The petrology of the Mount Padbury mesosiderite and its achondrite enclaves. *Mineralogical Magazine* 35:1029–1060.

Mittlefehldt D. W. 1979. Petrographic and chemical characteristics of igneous lithic clasts from mesosiderites and howardites and comparison with eucrites and diogenites. *Geochimica et Cosmochimica Acta* 43:1917–1935.

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., McCoy T. J., Goodrich C. A., and Kracher A. 1998. Non-chondritic meteorites from asteroidal bodies. In *Planetary materials*, edited by Papike J. J. Washington, D.C.: Mineralogical Society of America. pp. 1–195.

Miura Y. N., Sugiura N., Kusakabe M., and Nagao K. 2004. Noble gases in Northwest Africa 1670, a new angrite, and oxygen isotopes of this angrite and some achondrites (abstract). *Antarctic Meteorites* 28:50–51.

Miyamoto M. and Takeda H. 1977. Evaluation of a crust model of eucrites from the width of exsolution lamellae. *Geochemical Journal* 11:161–169.

Miyamoto M. and Takeda H. 1994. Evidence for excavation of deep crustal material of a Vesta-like body from Ca compositional gradients in pyroxene. *Earth and Planetary Science Letters* 122: 343–349.

Miyamoto M., Mikouchi T., and Kaneda K. 2001. Thermal history of the Ibitira noncumulate eucrite as inferred from pyroxene exsolution lamella: Evidence for reheating and rapid cooling. *Meteoritics & Planetary Science* 36:231–237.

Morgan J. W., Higuchi H., Takahashi H., and Hertogen J. 1978. A "chondritic" eucrite parent body: Inference from trace elements. *Geochimica et Cosmochimica Acta* 42:27–38.

Okamoto C., Ebihara M., and Yamaguchi A. 2004. Geochemical study of metal-rich eucrites from Antarctica (abstract). *Antarctic Meteorites* 28:68–69.

Ostertage R. and Stöffler D. 1982. Thermal annealing of experimentally shocked feldspar crystals. Proceedings, 13th Lunar and Planetary Science Conference. pp. A457–A463.

Rubin A. E. 1992. A shock dark-metamorphic model for silicate darkening and compositionally variable plagioclase in CK and ordinary chondrites. *Geochimica et Cosmochimica Acta* 56: 1705–1714.

Rubin A. E. and Jerde E. A. 1987. Diverse eucritic pebbles in the Vaca Muerta mesosiderite. *Earth and Planetary Science Letters* 84:1–14.

Rubin A. E. and Mittlefehldt D. W. 1992. Classification of mafic clasts from mesosiderites: Implication for endogenous igneous processes. *Geochimica et Cosmochimica Acta* 56:827–840.

Saikumar V. and Goldstein J. I. 1988. An evaluation of the methods to determine the cooling rates of iron meteorites. *Geochimica et Cosmochimica Acta* 52:715–726.

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.

Shen J. J., Papanastassiou D. A., and Wasserburg G. J. 1998. Re-Os systematics in pallasite and mesosiderite metal. *Geochimica et Cosmochimica Acta* 15:2715–2723.

Shinotsuka K. and Ebihara M. 1997. Precise determination of rare earth elements, thorium, and uranium in chondritic meteorites by inductively coupled plasma mass spectrometry: A comparative study with radiochemical neutron activation analysis. *Analytica Chimica Acta* 338:237–246.

Shirai N, Nishino T., Li X., Amakawa H. and Ebihara M. 2003. Precise determination of PGE in a GSJ reference sample JP-1 by ID-ICPMS after nickel sulfide fire assay preconcentration. *Geochemical Journal* 37:531–536.

Takeda H. 1997. Mineralogical records of early planetary processes on the howardite, eucrite, diogenite parent body with reference to Vesta. *Meteoritics & Planetary Science* 32:841–853.

Thomas P. C., Binzel R. P., Gaffey M. J., Storrs A. D., Wells E. N., and Zellner B. H. 1997. Impact excavation on asteroid 4 Vesta: Hubble space telescope results. *Science* 277:1492–1495.

Wadhwa M., Shukokyukov A., Davis A. M., Lugmair G. W., and Mittlefehldt D. W. 2003. Differentiation history of the mesosiderite parent body: Constraints from trace elements and manganese-chromium isotope systematics in Vaca Muerta silicate clasts. *Geochimica et Cosmochimica Acta* 67:5047–5069.

Warren P. H. and Jerde E. A. 1987. Composition and origin of Nuevo Laredo trend eucrite. *Geochimica et Cosmochimica Acta* 51: 713–725.

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.

Yamaguchi A., Taylor G. J., and Keil K. 1996. Global crustal metamorphism of the eucrite parent body. *Icarus* 124:97–112.

Yamaguchi A., Taylor G. J., Keil K., Floss C., Crozaz G., Nyquist L. E., Bogard D. D., Garrison D., Reese Y., Wiesmann H., and Shih C.-Y. 2001. Postcrystallization reheating and partial melting of eucrite EET 90020 by impact into the hot crust of asteroid 4 Vesta ~4.50 Ga ago. *Geochimica et Cosmochimica Acta* 65:3577–3599.

Yamaguchi A., Setoyanagi T., and Ebihara M. 2002a. Origin of a recrystallized magnesian eucrite, Dhofar 007 (abstract). *Antarctic Meteorites* 27:177–179.

Yamaguchi A., Clayton R. N., Mayeda T. K, Ebihara M., Oura Y., Miura Y. N., Haramura H., Misawa K., Kojima H., and Nagao K. 2002b. *Science* 296:334–336.

Yamaguchi A., Ebihara M., and Setoyanagi T. 2003. An anomalous eucrite, Dhofar 007, and a possible genetic relationship with mesosiderites (abstract #1377). 34th Lunar and Planetary Science Conference. CD-ROM.

Yang C.-W., Williams D. B., and Goldstein J. I. 1997. A new empirical cooling rate indicator for meteorites based on the size of the cloudy zone of the metallic phases. *Meteoritics & Planetary Science* 32:423–429.