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Foreign Meteoritic Material of Howardites and Polymict Eucrites

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Abstract—Howardites and polymict eucrites are fragments of regolith breccias ejected from the surface of a differentiated (eucritic) parent body, perhaps, of the asteroid Vesta. The first data are presented demonstrating that howardites contain, along with foreign fragments of carbonaceous chondrites, also fragments of ordinary chondrites, enstatite meteorites, ureilites, and mesosiderites. The proportions of these types of foreign meteoritic fragments in howardites and polymict eucrites are the same as in the population of cosmic dust particles obtained from Antarctic and Greenland ice. The concentrations of siderophile elements in howardites and polymict eucrites are not correlated with the contents of foreign meteoritic particles. It is reasonable to believe that cosmogenic siderophile elements are concentrated in howardites and polymict eucrites mostly in submicrometer-sized particles that cannot be examined mineralogically. The analysis of the crater population of the asteroid Vesta indicates that the flux of chondritic material to the surface of this asteroid should have been three orders of magnitude higher than the modern meteoritic flux and have been comparable with the flux to the moon's surface during its intense meteoritic bombardment. This provides support for the earlier idea about a higher meteoritic activity in the solar system as a whole at approximately 4 Ga. The lithification of the regolith (into regolith breccia) of the asteroid Vesta occurred then under the effect of thermal metamorphism in the blanket of crater ejecta. Thus, meteorite fragments included in howardites provide record of the qualitative composition of the ancient meteorite flux, which was analogous to that of the modern flux at the Earth surface.

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INTRODUCTION

Howardites and polymict eucrites belong to the achondritic meteorites of group HED (howardite–eucrite–diogenite) and are polymictic breccias. Their mineralogic and isotopic composition, traces of impact metamorphism, and the occurrence of microcraters, tracks, and noble gases of the solar type suggest that these rocks are regolith breccias, i.e., the lithification products of the loose surface material (regolith) of the parent bodies of meteorites of this type (Bunch, 1975). Howardites consist of fragments of eucrites (gabbro and basalts), diogenites (pyroxenites), and monomineralic fragments of these rocks submerged in fine-grained clastic matrix. Polymict eucrites differ from howardites in having low contents of diogenite fragments (≤10 vol %; Fukuoka et al., 1977).

An foreign meteoritic component was first discovered in howardites when their noble gases and trace elements were examined (Mazor and Anders, 1967; Müller and Zähringer, 1966). The very first data on the concentrations of siderophile elements in howardites, eucrites, and diogenites testified that howardite breccias contain 2–3% chondritic component, which was the closest to CM chondrites (Chou et al., 1976). Only some howardites show a distribution of trace elements suggesting the presence of meteoritic material different from that of carbonaceous chondrites (Chou et al., 1976).

Mineralogically, chondritic clasts of the CM or CV3 types were first identified in the Kapoeta howardite (Wilkening, 1973). Innumerous fragments of CM carbonaceous chondrites and rare clasts of CR chondrites were later documented in the Jodzie (Bunch et al., 1979), Kapoeta (Smith, 1982), Bholghati (Laul ad Gosselin, 1990; Wang et al., 1990), and Erevan (Nazarov et al., 1994, 1995) howardites and in the LEW 85300 polymict eucrite (Zolensky et al., 1996). It was then demonstrated that HED breccias contain more foreign fragments whose mineralogical composition and texture correspond to those of CM chondrites. Mineralogic evidence of the presence of material other than that of carbonaceous chondrites remains disputable. They include a few documented fragments with textures resembling chondrules (Mason, 1983; Olsen et al., 1990) and particles of nickel-iron that could be fragments of chondritic and iron impactors (Klein and Hewins, 1979; Hewins, 1979; Pun et al., 1998). Our research was centered on studying foreign meteoritic fragments in howardites and polymict eucrites in order to assay the qualitative and quantitative characteristics of the meteorite flux in the vicinity of the HED parent body, which was located within the asteroid belt, and to compare the flues of meteoritic particles on the orbits of this body and the Earth. Some preliminary results of this study were presented in (Lorenz et al., 2001, 2002).

MATERIALS AND METHODS

This study was conducted on polished and transparent polished sections of the Erevan, Yurtuk, Dhofar 018, and Dhofar 1302 howardites and the Dhofar 055, Dhofar 275, Dhofar 930, Dhofar 1286, NWA 1813, and Smara polymict eucrites from the meteorite collection of the Russian Academy of Sciences and the NWA 776 and NWA 1664 howardites from the collection of the Vienna Museum of Natural History in Austria (NHMW). The meteorites of the Dhofar and NWA series were found in the deserts of Oman and Northwest Africa, respectively. The thin sections were examined under an optical microscope at the Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, and the Vienna Museum of Natural History; on a Jeol ASEM 4600 scanning electron microscope at the Vienna Museum of Natural History; and were analyzed by Camebax Microbeam (at the Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences), ARL-SEMQ (at the Vienna Museum of Natural History), and Cameca SX 100 (Institute of Geosciences at the Vienna University). The Ni and Co concentrations were determined by INAA at the Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences. Radiochemical neutron activation analysis (RNAA) was conducted at the same institute to determine Ir concentrations by the method (Parry et al., 1988; Kolesov and Sapozhnikov, 1995).

PETROGRAPHY AND MINERALOGY OF METEORITIC FRAGMENTS

The Dhofar 018 howardite was determined to contain particles that were identified as fragments of ordinary chondrites, carbonaceous chondrites, enstatite meteorites, ureilites, and mesosiderites. The Erevan howardite contains one mesosiderite-like fragment. In a thin section of the Dhofar 930 polymict eucrite, we found 30 fragments of carbonaceous chondrites and one fragment of supposedly enstatite meteorite. The NWA 776 howardite is noted for anomalously high content of carbonaceous chondrite fragments (~120 particles/cm^2) of variable texture. The Yurtuk, NWA 1664, and Dhofar 1302 howardites and the Dhofar 055, Dhofar 275, Dhofar 1286, and Smara polymict eucrites contain no inclusions of meteoritic material other than rare iron-nickel particles.

Ordinary Chondrites

The material of ordinary chondrites is contained in howardites in the form of aggregates of silicates and Fe–Ni metal, metal–troilite inclusions, and chondrule-like objects.

Metal–silicate aggregates. The Dhofar 018 howardite (examined area 5.9 cm^2) was the first in which an inclusion was found whose mineralogy and composition of phases correspond to ordinary chondrites. A fragment of irregular shape approximately, 400 μm across is a metal–silicate aggregate of olivine ($Fo_{73–74}$, Fe/Mn = 55), orthopyroxene ($En_{76–77}Wo_2$, Fe/Mn = 31), albitic plagioclase ($An_{77.8}Ab_{15.6}$), kamacite (6 wt % Ni), and troilite (Fig. 1a). The olivine contains inclusions of taenite (22 wt % Ni) and pentlandite. The albite composes poikilitic inclusions in olivine and small round inclusions in the metal. Silicate grains have even round boundaries with metal and are chemically unzoned. The albite-rich plagioclase has never before been described in HED meteorites. At the same time, the mineral association described above is typical of ordinary chondrites. The X_{Mg} of the pyroxene and olivine are identical with those of these minerals in LL chondrites (Fig. 2a). The absence of compositional variations of the silicates led us to class this fragment with the sixth petrological type. The metal content in the aggregate is much higher than in LL chondrites, perhaps, because of the unrepresentativeness of such a small fragment. It is also possible that this metal–silicate aggregate is a fragment of primitive achondrite (acapulcoite or lodranite), which are spread not as widely as ordinary chondrites.

Chondrule-like objects. Chondrule-like objects were found in Dhofar 018 in the form of fragments 200–800 μm across (Fig. 1b) with parallel linearly elongated skeletal olivine crystals (Fo_{79}, Fe/Mn = 92) and interstitial glass (Fig. 1c, Table 1). The glass contains trails of troilite inclusions and rare chromite inclusions. The texture of this object is atypical of hypocrystalline rocks, including those of ultrabasic composition, in HED meteorites and corresponds to so-called barred chondrules, which are widespread in ordinary chondrites. The olivine composition lies within the range established for LL chondrites (Fig. 2a). The mesostasis of this object is enriched in CaO and Al_2O_3 and is poor in Na_2O compared to the mesostasis of the chondrules in ordinary chondrites, a fact that led us to class this object with Ca–Al chondrules.

Metal–troilite objects. Two unique metal–troilite inclusions were found in Dhofar 018 (Lorenz et al., 2001). The inclusions (150 μm) consist of numerous camacite grains in troilite (Fig. 1d). The texture of these inclusions is very similar to that of eutectic metal and troilite melts, but the modal troilite concentrations is 24 wt %, i.e., lower than in the FeS–Fe eutectic (~30 wt % FeS) but is close to the troilite concentration in the metal-troilite constituent of H chondrites (Wilkening, 1978).

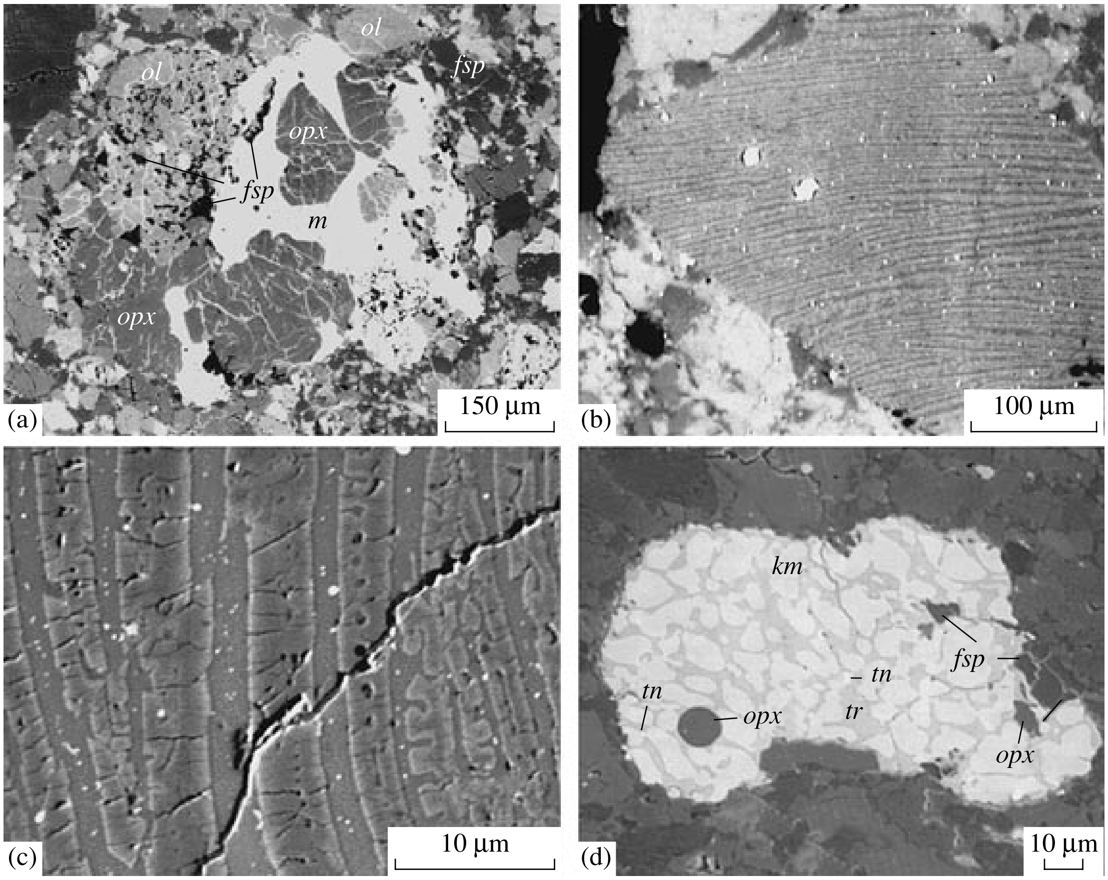

Fig. 1. Ordinary chondrite fragments in HED breccias.

(a) Metal–silicate aggregate, ordinary chondrite fragment in the Dhofar 018 howardite; (b) chondrule-like fragment in the Dhofar 018 howardite, reflected-light optic micrograph: pale gray skeleton olivine crystals, the interstitial space in between is filled with glass (dark gray) with inclusions of Fe–Ni metal (white); (c) inner structure of a chondrule-like object; (d) metal–troilite aggregate in the Dhofar 018 howardite. Phases: *ol*—olivine, *opx*—orthopyroxene, *fsp*—feldspar, *m*—metal, *km*—kamacite, *tn*—taenite, *tr*—troilite. Figs. 1a and 1c are BSE images, Fig. 1d is SE image.

One of the fragments contains small (~5 μm) tetrataenite inclusions (54.7 wt % Ni) at the boundary between kamacite and troilite and rare rounded or angular inclusions of orthopyroxene and plagioclase, which are spatially restricted to the boundaries of the fragment. The high Ni concentration in the metal and the very low (as compared to HED meteorites) troilite/metal ratio suggest that such objects are xenoliths. Their texture and composition correspond to those of aggregates described in ordinary chondrites (Wilkening, 1978) and experimentally shock-metamorphosed samples of chondritic material (Schmitt, 2000). These objects were most probably produced by the impact melting of a chondrite or primitive achondrite impactor during its collision with the parent body of the howardite.

Carbonaceous Chondrites

A thin section 500 mm^2 of the Dhofar 018 howardite was determined to contain four clasts of carbonaceous chondrites 500, 200, 150, and 50 μm in size (Lorenz et al., 2001). These clasts have irregular shapes and are cut by numerous fractures. They consist of a heterogeneous phyllosilicates matrix with grains of olivine ($Fo_{46–98}$) and orthopyroxene ($En_{64–94}Wo_{1–5}$) and aggregates of troilite, pyrrhotite, and magnetite grains (2–10 μm). The accessory phases are schreibersite, chromite, Mg–Al spinel, sulfides enriched in P and Cr (Nazarov et al., 1998), Fe–Cr–Ni–Mn sulfide, and an unidentified FeO–MnO–SiO_2 phase. Carbonaceous chondrite clasts in Dhofar 018 are very small, vary in texture, and can be fragments of more than one impactor.

The concentration of carbonaceous chondrite clasts in the NWA 776 carbonaceous chondrite is unusually high compared to those in all other known howardites (Lorenz et al., 2002; Zolensky et al., 1996). We found 105 clasts in this howardite, with their sizes broadly varying from 5 to 1500 μm, over an area of 85 mm^2. The average size of carbonaceous clasts in NWA 776 is 100 μm, and their modal content is 1.02 vol %. Many fragments are round and have sharp boundaries with the surrounding material, a feature that could be caused by the abrasion of their less resistant material when the

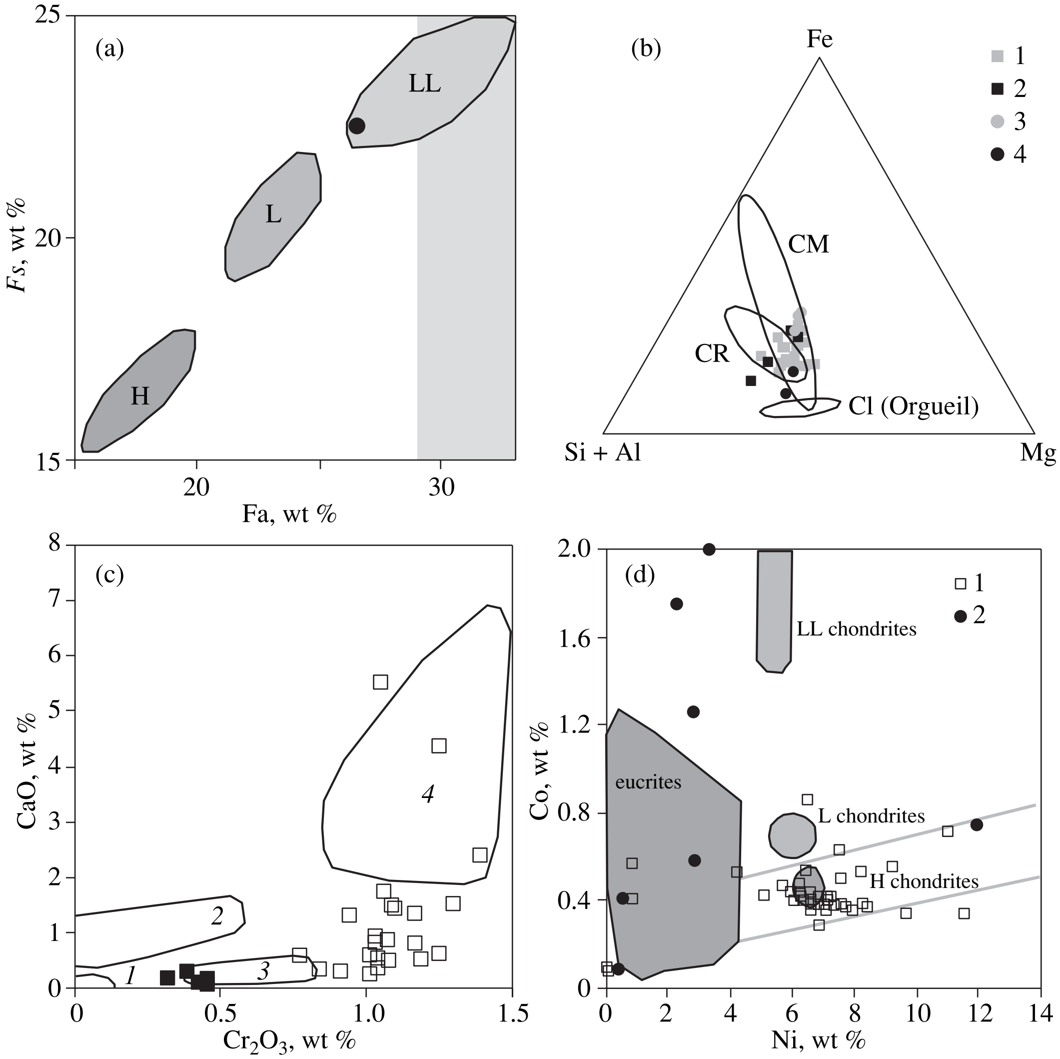

Fig. 2. Chemical composition of minerals in meteoritic fragments in HED breccias.

(a) Olivine and pyroxene compositions in a metal–silicate aggregate (solid circle) in a chondrule-like object from the Dhofar 018 howardite (shaded fields); data on equilibrium ordinary chondrites are from (Dodd, 1981). (b) Component (at %) of phyllosilicates in the matrix of carbonaceous clasts in (1) the NWA 776 and (2) Dhofar 018 howardites and the composition of phyllosilicates in (3) CM clasts and (4) CR clasts from howardites (Zolensky et al., 1996). Fields: CM, CR, and CI chondrites (Weisberg et al., 1993). (c) CaO and Cr_2O_3 concentrations in (*1*) olivine and (*2*) pyroxene from primitive achondrites and in (*3*) olivine and (*4*) pyroxene from ureilites. Solid and open squares—olivine and pyroxene, respectively from the Dhofar 018 howardite. (d) Composition of metal particles: (1) impact melts; (2) pyroxenites. The diagram also shows the composition of metal in equilibrium L, LL, and H chondrites (Afiattalab and Wasson, 1980). Polygonal fields correspond to the composition of iron meteorites.

breccia was formed. Fragments smaller than 5 µm were crushed between particles of the matrix breccia and occur as flake-shaped or stringy particles of phyllosilicates and separate magnetite crystals. Some aggregates of anorthite ($An_{91.7}Ab_{7.7}$) and magnesian olivine ($Fo_{98.6}$), as well as individual olivine grains ($Fo_{98.5}$), which seem to originate from carbonaceous chondrite, were also found in the matrix of this breccia. Carbonaceous chondrite fragments contained in NWA 776 can be classified into three groups according to their texture and the composition of silicate grains in the matrix.

The fragments of type I (Fig. 3a) contain 50 vol % of the matrix with included grains (20–50 µm) of forsterite, enstatite, Ca carbonate, troilite, kamacite (5 wt % Ni), schreibersite (25–44 wt % Ni), spinel (9.38 wt % Cr_2O_3), and rare P–Cr–Fe–Ni sulfides, along with flakes or granular aggregates of phyllosilicates. Some olivine grains contain inclusions of metallic iron and spinel. The heterogeneous matrix in places abounds in magnetite dust or troilite. The phyllosilicates aggregates are intersected by thin veinlets filled with iron hydroxides. One of the clasts contains a silicate phase between phyllosilicates. The composition of this phase is close to amesite $Mg_2Al(SiAl)O_5(OH)_4$. The fragments of type II (Fig. 3b) contain approximately 80 vol % of the homogeneous matrix with included grains and fragments of olivine ($Fo_{97.4–99.6}$), orthopyroxene ($En_{97}Wo_{0.5}$), Fe and Fe–Ni sulfides, and magnetite framboids and their aggregates. Group III includes fragments with a very fine-grained mixture of the matrix material and angular fragments of forsterite grains and troilite inclusions (Fig. 3c). Some of these clasts have a porous matrix.

The textures and mineral assemblages of the fragments can occur in carbonaceous chondrites of several types, and hence, no unambiguous classification of carbonaceous fragments in howardites is possible. The carbonaceous fragments of group I, which are aggregates of olivine, pyroxene, sulfides, and phyllosilicates with rare spinel in a phyllosilicates matrix can generally be classed with the group of CM chondrites. The fragments of group II, which are noted for a dense fine-grained matrix, the absence of large phyllosilicates aggregates, and the abundance of euhedral magnetite crystals, correspond to CR chondrites (Zolensky et al., 1996). The relatively small sizes of many carbonaceous chondrite fragments make them not representative enough. For example, most of the examined fragments contained no chondrules. The composition of the phyllosilicates matrix of carbonaceous chondrites varies depending on their type (Weisberg et al., 1993; Zolensky et al., 1996). The Mg–Fe–(Si + Al) diagram in Fig. 2b shows the compositional fields of phyllosilicates contained in carbonaceous chondrites of various groups, according to (Weisberg et al., 1993), and the compositions of phyllosilicates contained in carbonaceous clasts from some howardites, according to (Zolensky et al., 1996). Phyllosilicates in the examined clasts group mostly within the field of CM chondrites, but some points plot outside this field and near the field of CR chondrites. The obtained CR/CM proportion of the clasts is equal to 0.2, which is consistent with the data in (Zolensky et al., 1996) for other howardites and coincides with the analogous ratio for the modern falls of carbonaceous chondrites at the Earth. The texture of clasts of group III is not typical of any known types of carbonaceous chondrites. These clasts could be the material of carbonaceous chondrites that was affected by intense thermal or shock metamorphism and suffered the partial transformation of phyllosilicates into olivine under the effect of high-temperature annealing. Practically all of the fragments differ in size, texture, and composition and, hence, some of them could be individual particles but not fragments of one or more large impactors.

The Dhofar 930 polymict eucrite was determined to include 30 fragments of carbonaceous chondrites from 100 to 1500 μm in size, which were found in a thin section 3 cm^2 in area. The compositions and textures of these fragments are very similar. They are contained in breccia within a small area and seem to be parts of a single impactor. Three fragments are noted for a dark fine-grained matrix and aggregates of round magnetite grains. No fragments of carbonaceous meteorites were found in the Yurtuk, NWA 1664, and Dhofar 1302 howardites and the Smara, NWA 1813, Dhofar 275, and Dhofar 1286 polymict eucrites.

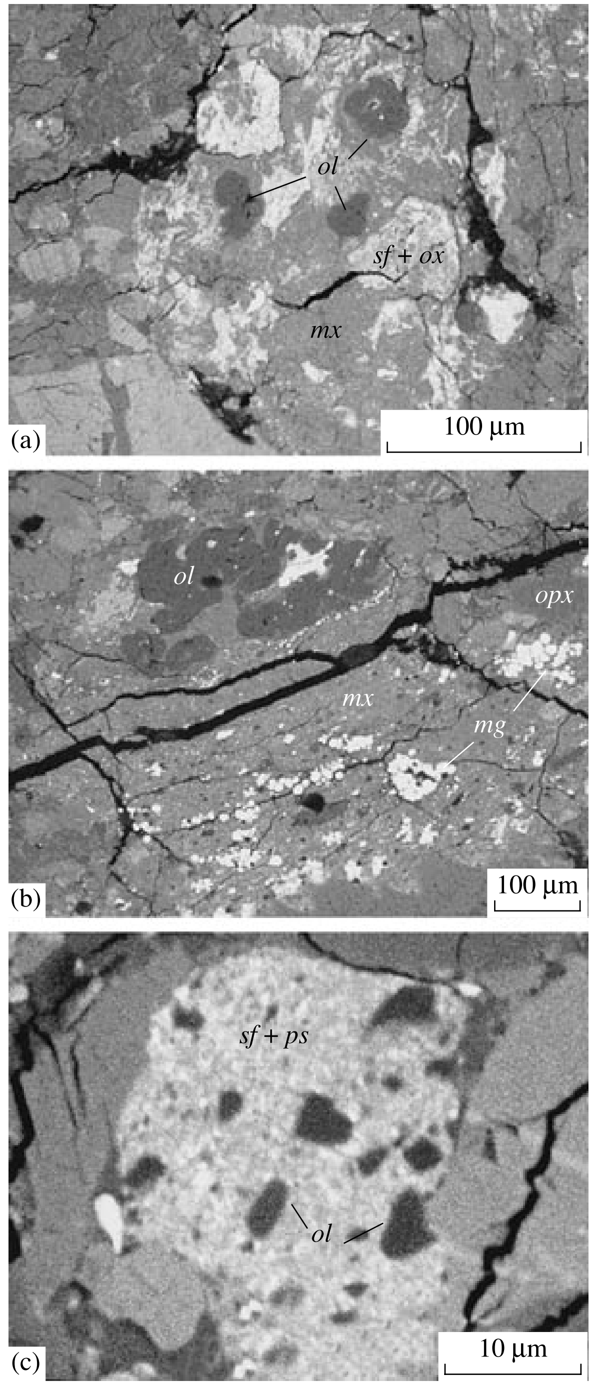

Fig. 3. Carbonaceous chondrite fragments in the NWA 776 howardite.

(a) Fragment of the CM type: *mx*—phyllosilicate matrix, *sf* + *ox*—iron sulfides and oxides, other symbols as in Fig. 1; (b) fragment of the CR type: *mg*—magnetite, other symbols as in Fig. 1; (c) fragment of an unidentified type: *sf* + *ps*—sulfides and phyllosilicates, other symbols as in Fig. 1. This figure and Figs. 4, 5 are BSE images.

Table 1. Chemical composition (wt %) of silicates in meteoritic fragments

Meteorite	Silicates	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total	Fe/Mn, at %	End members
		Ordinary chondrite fragments												
Dhofar 018, fragment of ordinary chondrite	Olivine	37.7	0.02	n.d.	0.03	24.7	0.45	36.0	0.03	n.d.	n.d.	98.93	55	$Fo_{72.8}$
	Orthopyroxene	55.6	0.15	0.14	0.13	14.7	0.47	28.5	0.87	n.d.	n.d.	100.6	31	$En_{76.4}Wo_{1.67}$
	Plagioclase	67.9	0.03	22.6	0.02	1.28	n.d.	0.50	1.87	5.15	0.66	100.01		$Ab_{77.8}An_{15.6}$
Dhofar 018, chondrule-like object	Olivine	38.8	n.d.	0.04	0.41	20.2	0.22	41.7	0.12	n.d.	n.d.	101.5	92	$Fo_{78.68}$
	Mesostasis	50.4	1.24	13.2	0.24	17.2	0.20	2.13	14.0	1.33	0.02	99.96	86	
		Enstatite meteorite fragments												
Dhofar 018, fragment of enstatite meteorite	Pyroxene	60.2	n.d.	0.15	0.03	0.98	n.d.	39.4	0.45	n.d.	n.d.	101.2		$En_{97.8}Wo_{0.8}$
	Plagioclase	68.6	n.d.	20.9	0.03	0.43	n.d.	1.11	2.1	3.36	0.89	97.4		$Ab_{65.8}An_{22.8}$
Dhofar 930, metal–olivine aggregate	Olivine	41.2	0.24	0.41	0.11	1.00	0.06	55.2	0.51	n.d.	n.d.	98.7	17	$Fo_{98.9}$
		Ureilite fragment												
Dhofar 018	Pyroxene, core	56.7	0.06	0.77	1.03	10.0	0.39	31.1	0.55	n.d.	n.d.	101.6	26	$En_{82.6}Wo_{1.05}$
	Pyroxene, outer zone	54.9	0.14	1.64	1.19	14.6	0.54	26.7	1.67	n.d.	n.d.	101.38	27	$En_{73.9}Wo_{3.3}$
	Mesostasis	50.8	0.82	19.7	n.d.	13.7	0.37	1.97	12.1	0.68	0.06	100.2		$Ab_{9.1}An_{90.3}$
	Olivine in mesostasis	38.8	n.d.	0.03	0.45	21.7	0.49	39.0	0.11	n.d.	n.d.	100.6	44	$Fo_{76.2}$
	Ca-pyroxene in mesostasis	51.9	0.24	2.89	1.05	17.2	0.67	19.6	5.52	n.d.	n.d.	99.1	26	$En_{59.1}Wo_{12.0}$
		Association of HED silicates and meteoritic metal												
Dhofar 275	Pyroxene	50.4	0.33	1.16	0.62	27.5	0.87	14.3	3.96	n.d.	n.d.	99.1	31	$En_{43.9}Wo_{8.8}$
	Plagioclase	45.7	0.28	33.1	0.35	0.82	0.23	0.19	17.6	0.78	0.42	99.5		$Ab_{7.3}An_{90.2}$
Dhofar 018	Pyroxene	47.4	0.30	0.36	0.33	34.0	1.05	12.9	2.00	0.89	n.d.	99.2	32	$En_{38.7}Wo_{4.3}$
	Plagioclase	42.4	n.d.	33.5	n.d.	n.d.	0.5	0.20	23.1	0.30	n.d.	100		$Ab_2An_{97.8}$
	Olivine	31.2	0.20	0.07	0.09	53.6	1.13	12.9	0.03	0.16	0.03	99.4	47	$Fo_{30.1}$
Erevan	Pyroxene	52.7	0.21	0.83	0.22	22.6	0.71	21.1	2.29	0.03	n.d.	100.7	32	$En_{59.5}Wo_{4.7}$
	Plagioclase	45.9	n.d.	34.4	n.d.	1.69	0.03	0.10	17.6	1.35	0.09	101.2		$Ab_{12.1}An_{87.4}$

Note: here and in Tables 2–4, n.d. means not detected (concentrations below the detection limit).

Enstatite Meteorites

A fragment of enstatite meteorite found in the Dhofar 018 howardite (Lorenz et al., 2001) is 800 µm across (Fig. 4a) and contains euhedral crystals of practically pure enstatite ($En_{97–98}Wo_{1–2}$), with the interstitial space in between filled with plagioclase ($Ab_{65.8}An_{22.8}$), diopside, and troilite. The troilite typically has high and variable concentrations (wt %) of Cr (2.57–3.74), Ti (0.25–2.2), and Mn (0.12–1.81) (Table 2). The pyroxene contains small inclusions of Si-bearing metallic Fe (0.3 wt % Ni, 2.7–3.5 wt % Si), a Fe–Cr–Si metallic phase (72.7 wt % Fe, 22.7 wt % Cr, 1.9 wt % Si; Table 2), and troilite. One of the inclusions contains sulfide of composition close to Cr-rich violarite $FeNi_2S_4$. The troilite contains inclusions of iron hydroxide rich in K_2O and Cr_2O_3. The composition of the phases is typical of enstatite meteorites and testifies to strongly reduced conditions under which they were formed. The absence of a chondritic texture and low modal metal content suggest that this fragment is enstatite achondrite (aubrite), although mineral grains in aubrites are much larger. At the same time, this enstatite fragment could be enstatite chondrite that underwent shock melting, as was proposed for the ungrouped Yamato 8404, 8414, and 86004 (Lin and Kimura, 1998) and NWA 1253 (Lorenz et al., 2002) enstatite achondrites.

A metal–silicate aggregate 150 µm in size found in the Dhofar 930 polymict eucrite consists of a rounded kamacite inclusion (5.69 wt % Ni, 1.02 wt % Si) in association with olivine (Fo_{99}) fragments. This olivine is more magnesian than this mineral in HED meteorites and H chondrites, is enriched in CaO (0.51 wt %) relative to olivine in EH chondrites (0.14–0.21 wt %) but has the same Cr_2O_3 content (0.11 wt %) as olivine from EH chondrites (0.05–0.66 wt %). The metal of this fragment is enriched in Si, as is typical of enstatite meteorites. The silicate/metal ratio is in this fragment higher than one and is close to the analogous values of enstatite chondrites rather than aubrites (which are poor in this metal).

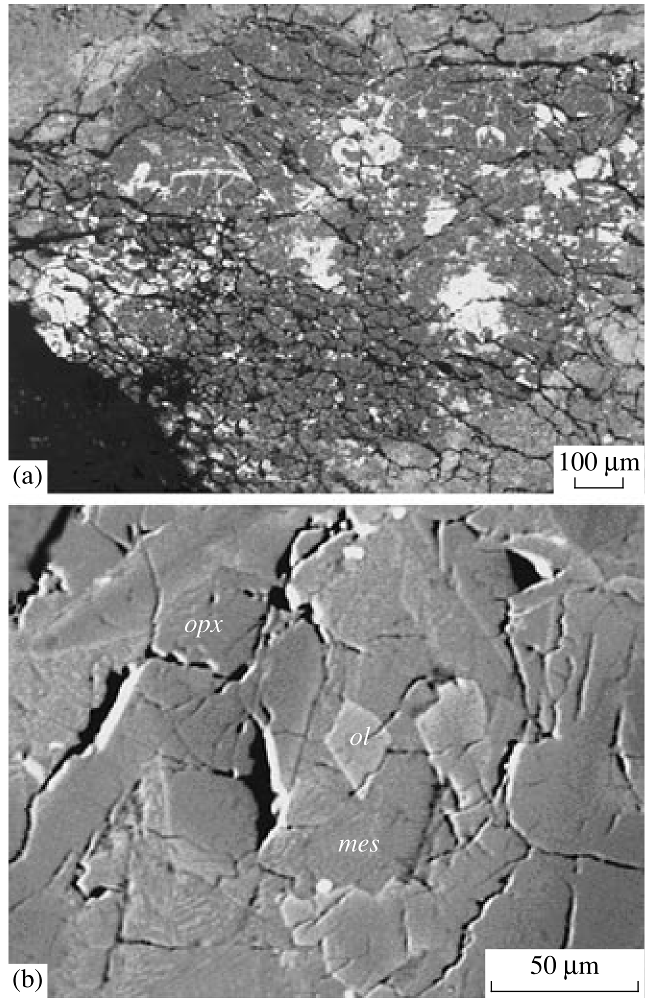

Fig. 4. Fragments of enstatite and ureilite meteorites in the Dhofar 018 howardite.

(a) Fragment of an enstatite meteorite, the interstitial space between enstatite crystal (dark gray) is filled with Fe–Mn–Cr sulfides and Fe hydroxides replacing them (pale gray and white, respectively); (b) fragment of an ureilite-like rock: *opx*—orthopyroxene, *mes*—mesostasis, *ol*—olivine.

Ureilites

The achondrite fragment 7 × 5 mm found in the Dhofar 0.18 howardite (Fig. 4b) has a hypocrystalline texture and consist of equant or elongated grains of orthopyroxene (50–200 µm) and interstitial cryptocrystalline aggregates (~10 vol %), which is locally seen to consist of fine-grained graphical intergrowths of 2- to 5-µm crystals of clinopyroxene and plagioclase ($An_{90.5}Ab_{8.9}$) (Table 1). The orthopyroxene grains have normal zoning with $En_{82.6}Wo_{1.1}$ (Fe/Mn = 26) in the cores and $En_{74.0}Wo_{3.3}$ (Fe/Mn = 27) in the margins. The orthopyroxene contains rare inclusions of chromite and ilmenite. The mesostasis includes elongated and equant euhedral crystals of olivine ($Fo_{76.2}$, Fe/Mn = 44), pyroxene ($En_{59.1}Wo_{12.0}$, Fe/Mn = 25), and rare grains of troilite and silica. The hypocrystalline texture of this rock and the zoning of its pyroxene grains testify that the rock cooled relatively rapidly and was not affected by strong thermal metamorphism. A distinctive feature of this rock is the richness of its silicates in Cr_2O_3, as is typical of ureilites (Fig. 2c) and generally atypical of meteorites of all other types. However, ureilites are dominated by olivine but not pyroxene. It is possible that the fragment was produced by the impact melting of an ureilite-like impactor or some of its low-melting constituent.

Association of HED Silicates and Metal

Some howardites in polymict eucrites contain aggregates of silicates of the same composition as in the host breccia and metallic iron. These metal–silicate aggregates have variable modal composition and the

Table 2. Chemical composition (wt %) of metal and sulfides in meteoritic fragments

Meteorite	Mineral	Fe	Ni	Co	S	P	Si	Cr	Mn	Ti	Mg	Total
		Ordinary chondrite fragments										
Dhofar 018, fragment of ordinary chondrite	Kamacite	92.0	5.73	n.d.	n.d.	0.02	0.31	n.d.	n.d.	n.d.	n.d.	98.1
	Taenite	76.1	22.3	n.d.	0.16	0.08	0.28	n.d.	n.d.	n.d.	n.d.	98.9
	Troilite	59.7	0.24	n.d.	38.0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	97.9
	Pentlandite	36.8	29.9	n.d.	32.1	n.d.	0.31	n.d.	n.d.	0.25	0.22	99.6
		Enstatite meteorite fragments										
Dhofar 018, fragment of enstatite meteorite	Kamacite	94.0	0.29	n.d.	n.d.	0.04	3.20	0.33	n.d.	n.d.	n.d.	97.9
	Fe–Cr metal	72.7	0.82	n.d.	0.35	0.09	1.91	22.7	0.63	n.d.	n.d.	99.2
	Troilite	54.7	0.61	n.d.	38.9	n.d.	n.d.	3.10	1.04	1.00	n.d.	99.4
	Violarite	15.3	35.6	n.d.	39.9	n.d.	n.d.	3.21	n.d.	0.61	n.d.	94.5
Dhofar 930, metal–olivine fragment	Kamacite	92.7	5.69	n.d.	n.d.	0.58	1.01	n.d.	n.d.	n.d.	n.d.	99.9
		Association of HED silicates and meteoritic metal										
Dhofar 275, metal–silicate fragment	Kamacite	91.7	4.13	2.48	n.d.	0.11	0.40	n.d.	n.d.	n.d.	n.d.	98.8
	Taenite	56.9	39.4	1.67	n.d.	n.d.	0.33	n.d.	n.d.	n.d.	n.d.	98.3
Dhofar 018, metal–silicate fragment	Kamacite	94.3	4.16	n.d.	n.d.	n.d.	0.29	n.d.	n.d.	n.d.	n.d.	98.8
	Taenite	46.5	52.1	n.d.	n.d.	n.d.	0.39	n.d.	n.d.	n.d.	n.d.	99.0
Erevan, metal–silicate fragment	Kamacite	92.4	5.78	0.42	n.d.	n.d.	0.17	n.d.	n.d.	n.d.	n.d.	98.8
	Tetrataenite	45.4	51.0	0.14	0.11	n.d.	0.73	n.d.	n.d.	n.d.	n.d.	97.4
	Troilite	62.6	0.19	0.08	35.8	n.d.	0.33	n.d.	n.d.	n.d.	n.d.	99.0

grades of their thermal metamorphism. Some of these objects contain metal of kamacite and taenite composition, which makes them different from the silicate aggregates in HED meteorites.

The Dhofar 275 polymict eucrite contains a coarse-grained aggregate of anhedral pyroxene grains ($En_{43.9}Wo_{8.8}$, Fe/Mn = 31) with very thin augite lamellae, plagioclase ($An_{90.2}Ab_{7.3}$), and two inclusions of metallic iron (Fig. 5a). The metal inclusions have very complicated morphologies of their boundaries with the host silicates and locally compose veinlet networks. The metal is enriched in Co and consists of kamacite (4.13 wt % Ni, 2.48 wt % Co) and taenite (39.5 wt % Ni, 1.67 wt % Co). The metal veinlets could be generated during the shock-induced mixing of the silicate material of the regolith and the molten metal of the iron or chondrite impactor. The high Co concentration suggests that this metal was related to LL chondrites.

The metal–silicate fragment found in the Dhofar 018 howardite (Fig. 5b) is 90 × 30 μm and consists of grains of kamacite (15–30 μm, 4.18 wt % Ni) and less ubiquitous tetrataenite (52.2 wt % Ni) with inclusions of pyroxene with low Ca concentrations ($En_{38.7}Wo_{4.3}$, Fe/Mn = 32), plagioclase ($An_{98.0}Ab_{2.0}$), minor olivine (Fo_{30}, Fe/Mn = 47), and occasional silica. Subhedral olivine and pyroxene grains of olivine and orthopyroxene have a homogeneous composition, and silica grains have smooth rounded outlines in contact with kamacite. The modal composition of the fragment is as follows (vol %): pyroxene = 15, plagioclase = 6, olivine = 2, kamacite = 72, and taenite = 10.

The metal–silicate aggregate in the Erevan howardite consists of a elliptical fragment approximately 800 μm long, which has sharp contacts with the surrounding breccia (Fig. 5c) and a granoblastic texture. The rock consists of (vol %) 44.6 orthopyroxene ($En_{59.5}Wo_{4.7}$, Fe/Mn = 32), 28.4 plagioclase ($An_{87.4}Ab_{12.1}$), 27.0 kamacite (5.78 wt % Ni, 0.42 wt % Co), and accessory clinopyroxene ($En_{17.5}Wo_{28.8}$), chromite, troilite, and tetrataenite (50.9 wt % Ni). The kamacite contains irregularly shaped and rounded inclusions of orthopyroxene and plagioclase. The texture of the rock suggests that it was affected by intense thermal metamorphism. Inasmuch as the fragment has sharp boundaries with the surrounding breccia, and its pyroxene/plagioclase ratio in the silicate fraction is higher than in the surrounding breccia and eucrites, it is reasonable to believe that the fragment was not produced in situ but is a fragment of a mesosiderite impactor or a rock from another part of the parent body.

The fragments described above are noted for high modal metal contents, and their textures suggest the mixing of molten metal and silicates and a high grade of thermal metamorphism. The mineral assemblages of these fragments, their relative sizes, and the textural relations between their phases are typical of mesosiderites. However, available data are insufficient to determine whether these objects are fragments of mesosiderite impactors or were formed by the mixing of HED silicates and chondritic metal or the metal of iron meteorites.

Meteoritic Metal

The polymict breccias contain meteoritic metal as small (<20 μm) particles in the matrix and inclusions in impact melts. The meteorites discussed here have metal modal concentration of approximately 0.001 vol %. The metal is contained in them in the form of kamacite or, more rarely, taenite and sometimes occurs in association with troilite. The endogenic metal of the eucrite parent body occurs as inclusions in eucrite and diogenite fragments. In a Ni–Co plot (Fig. 2d), the compositions of the meteoritic particles group within a relatively compact field, whereas the compositions of the endogenic metal of eucrites broadly vary. Metallic meteoritic particles differ from metal in diogenites and eucrites by Ni and Co concentrations. The Ni contents in the meteoritic metal vary within the range of 5–15 wt % at a Ni/Co ratio of 15–25. Single taenite grains contain 40–50 wt % Ni. The Ni/Co ratio of the endogenic metal of eucrites and diogenites is 1.6–3.3. The meteoritic metal particles in impact melts have Ni and Co concentrations close to those in the metal of H chondrites and iron meteorites. The metal of the metal–troilite melts produced during the destruction of chondritic impactors is also compositionally close to the metal of H and L chondrites. The matrices of all of the examined meteorites contain metal particles of both meteoritic and endogenic genesis.

Single particles with high Co concentrations were found in the Dhofar 275 polymict eucrite (3.6–3.9 wt % Ni, 1.4–2.5 wt % Co). Metal of this composition is contained in the Kapoeta (Pun et al., 1998) and Yamato-7308 (Ikeda and Takeda, 1984) howardites. These particles can be fragments of LL chondritic impactors, although analogous Co concentrations are typical of metal inclusions in diogenite clasts and some fragments of cumulate eucrites (Hewins, 1979; Ikeda and Takeda, 1984).

The metallic particles of HED breccia should also contain fragments of iron impactors, which can be identified by the typical distribution of siderophile elements. It is now hard to determine the proportions of metallic particles from chondrites and iron meteorites in howardites and polymict eucrites. With regard for the wider spread of troilite than metal, the frequent simultaneous occurrence of these phases typical of ordinary chondrites, and the statistics of terrestrial falls, it may be concluded that metal of chondritic origin should be spread more widely.

A metallic particle of unusual composition was found in the Yurtuk howardite. The ~5-μm fragment contains (wt %) 76.3 Cu, 17.9 Ni, and 3.27 Fe. The composition of this particle is atypical of terrestrial minerals and artificial alloys used in the preparation of

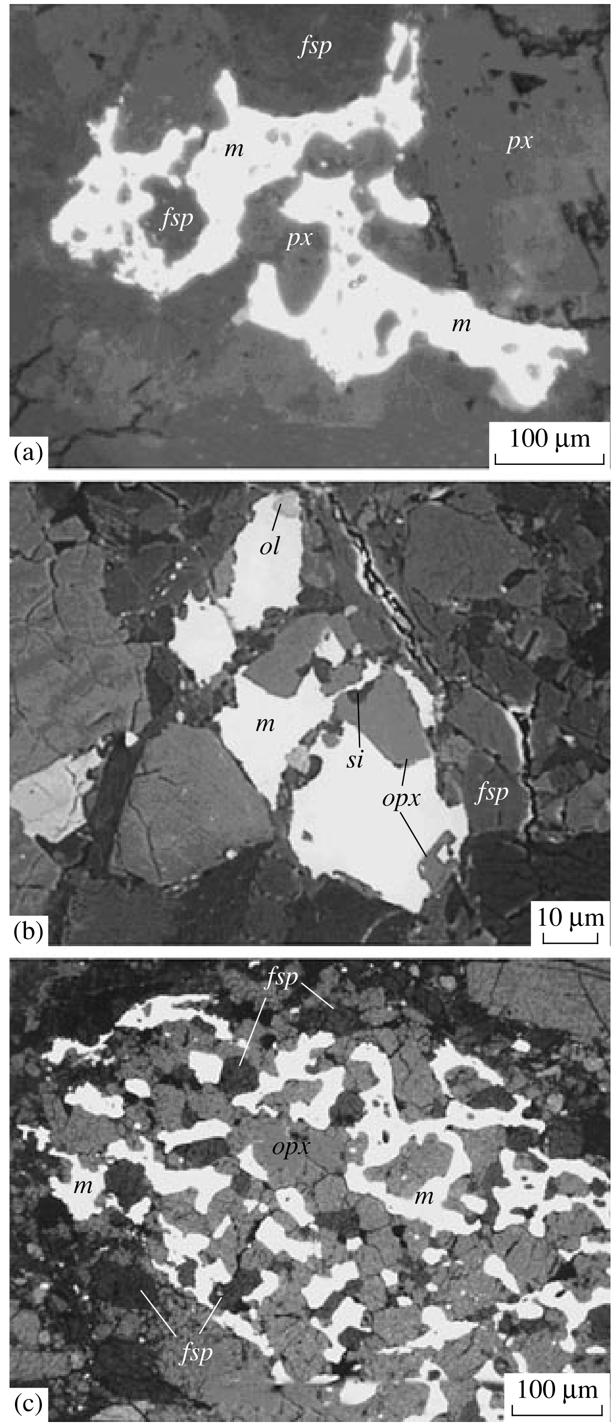

Fig. 5. Metal–silicate aggregates in howardite.
(a) Aggregate of metal and silicates in the Dhofar 275 polymict eucrite, reflected-light optical micrograph; (b) aggregate of metal and silicates in the Dhofar 018 howardite; (c) aggregate of metal and silicates in the Erevan howardite. Phases: *m*—metal, *si*—silica, other symbols as in Fig. 1.

petrographic thin sections and for electron microscopic studies and seems not to result from laboratory contamination. Native copper, which was found as small inclusions in ordinary chondrites (Rubin, 1997) sometimes

Table 3. Concentrations of siderophile elements in the material of CM chondrites in polymict breccias

Meteorite, fragment	Co, ppm	Ni, ppm	Ir, ppb	Ni/Co	Ni/Ir, $\times10^{-3}$	Di	CM Ni	CM Ir	CM Co
Polymict eucrites									
Dhofar 055									
Polymict eucrite fragment	11.5	36.8	n.d.	3.2	–	10	0.2	–	0.7
Breccia fragment with a high glass content	6.85	110	n.d.	16.0	–	10	2.0	–	1.0
Dhofar 275									
Polymict eucrite fragment	13.1	15.1	n.d.	1.2	–	10	0	–	1.0
Howardite breccia fragment	10.6	140	14.0	13.2	10.0	15	1.7	2.3	0.4
Fragment of impact breccia with glass	13.1	665	9.76	51	68.1	10	5.4	1.6	1.0
Dhofar 300	7.2	140	23.7	19	6	10	1.0	3.9	0.0
Dhofar 1301	12.2	310	13.2	25	23	10	2.4	2.2	0.5
NWA 1813	5.4	105	n.d.	20	–	10	0.7	–	–
Smara	6.8	180	9.10	26	20	10	1.4	1.5	0.0
Howardites									
Dhofar 018	19.0	240	8.70	13	28	22	1.8	1.7	1.4
Dhofar 1302	10.2	290	13.9	28	21	20	2.3	2.3	0.5
Yurtuk	17.3	250	n.d.	14.5	–	45	1.8	–	0.7
NWA 1664									
Polymict eucrite inclusion	14.5	50	n.d.	3	–	10	0.3	–	1.2
Bulk composition	14.3	120	n.d.	8.39	–	30	0.8	–	0.6

Note: Di is the concentration of the diogenite component, vol %; CM Ni, CM Ir, and CM Co are the calculated concentrations (wt %) of the CM chondritic component in polymict breccias.

contains Ni and Fe admixtures (Kleinschrot and Okrusch, 1999). Diogenites also contain inclusions of Cu–Ni sulfides and native Cu (Sideras et al., 2004). The high Ni concentration and the absence of S suggest that this particle may be of chondritic origin.

Concentrations of Siderophile Elements

The results of INAA and RNAA analyses of whole-rock samples and clasts of polymict breccias (Table 3) demonstrate that some of them contain more Ni, Ir, and Co than unbrecciated eucrites. The ratios of siderophile elements in the breccias are close to the chondritic values, a fact highlighting the presence of a foreign meteoritic component. The Ni and Co concentrations in the Dhofar 055 polymict eucrite and in an inclusion of impact melt fall within the ranges established for polymict eucrites (Table 4), but the impact melt inclusion is enriched in Ni (110 ppm) compared to the groundmass of the meteorite (36.8 ppm) and has a Ni/Co ratio (equal to 16) close to the chondritic one (20). The Dhofar 275 polymict eucrite contains the following types of material distinguished according to concentrations of siderophile elements: (1) fragments of polymict eucrites with Ni and Co concentrations of 15.1 and 13.1 ppm, respectively; (2) fragments of howardite breccias enriched in siderophile elements and having Ni/Co and Ni/Ir ratios close to those in chondrites; and (3) fragments of breccias with high glass contents and also enriched in Ni and Ir relative to polymict eucrites (Table 3).

The Dhofar 300 polymict eucrite has an elevated Ni concentration (140 ppm) compared to that of monomict eucrites and a Ni/Co ratio (19) close to the chondrite value. In terms of Ni and Co concentrations, the Dhofar 1301 polymict eucrite approaches howardites and shows chondrite Ni/Ir and Ni/Co ratios (Tables 3, 4). The Dhofar 1813 and Smara meteorites are characterized by concentrations of siderophile elements analogous to those in polymict eucrites (Tables 3, 4). The Dhofar 018, Dhofar 1302, and Yurtuk howardites have concentrations of siderophile elements corresponding to those determined for howardites (Table 4) and Ni/Co and Ni/Ir ratios close to those in chondrites. The Ni and Co concentrations in the NWA 1664 howardite correspond to the minimum concentrations of these elements in meteorites of this type, but an inclusion in the NWA 1664 polymict eucrite is even more strongly depleted in siderophile elements.

Table 4. Average concentrations of siderophile elements in howardites, eucrites, diogenites, and CM chondrites

Meteorite type	Reference	Ni, ppm	Co, ppm	Ir, ppb	Ni/Co	Ni/Ir, $\times10^{-3}$
Cumulate eucrites	1, 2, 8, 9	10.4	6.94	n.d.	1.5	3455.6
Non-cumulate monomict eucrites	1, 2, 3, 7, 10, 11, 12, 13	10.5 (2.1–33.0)	5.99 (2.1–10.0)	0.12 (0.004–0.36)	1.8	87.8
Polymict eucrites	1, 2, 3, 4, 7	53.8 (12–150)	7.64 (4.81–12.0)	0.42 (0.03–0.65)	7.0	126.9
Howardites	3, 4, 12, 13	381 (97–584)	25.8 (20.5–29.0)	16.7 (3.1–21.0)	14.75	22.78
Diogenites	3, 4, 6, 9, 14	57.1 (2.1–172)	22.8 (16.2–38.1)	1.5 (0.0004–6.8)	2.5	38.9
CM chondrites	15	12000	575	595	20.9	20.2

Note: Numerals in parentheses show the ranges of element concentrations. References: (1) Kitts and Lodders, 1998; (2) Paul and Lipschuts, 1990; (3) Chou et al., 1976; (4) Waenke et al., 1977; (5) Mittlefehldt, 1994; (6) Mittlefehldt, 2000; (7) Palme et al., 1983; (8) Mittlefehldt, 1979; (9) Mittlefehldt and Lindsrom, 1993; (10) Palme et al., 1988; (11) Palme et al., 1978; (12) Waenke et al., 1972; (13) Laul and Gosselin, 1990; (14) Wolf et al., 1983; (15) Wasson and Kallemeyn, 1988.

The concentrations of siderophile elements can be used to quantitatively evaluate the content of the foreign meteoritic component in the meteorites discussed in this paper. The background Ni, Co, and Ir concentrations were taken equal to their concentrations in monomictic noncumulate eucrites and diogenites (Table 3), which are endogenic magmatic rocks from the HED parent body. The proportions of these elements in howardites were assayed from the concentrations of fragments of iron-rich (eucrite) (*En* < 65) and magnesian (diogenite) (*En* > 65) pyroxenes (Table 3), because the composition of pyroxenes in eucrites and diogenites normally do not overlap. For the Yurtuk howardite, we used the concentrations of the diogenite component (Labotka and Papike, 1980; Lindstrom and Mittelfehldt, 1992). We did not determine the contents of the diogenite component in polymict eucrites but instead assumed it to be equal to 10 vol %. This is the maximum value for these rocks, and it allowed us to obtain the minimum content of the foreign meteoritic component. The latter was assumed in accordance with the chemistry of CM chondrites, which are predominant in HED breccias.

The concentrations of foreign meteoritic component, which were calculated from the Ni, Co, and Ir concentrations, usually vary but are mutually correlated. The Ni concentrations yield the highest calculated contents of meteoritic material. These differences can be related to certain compositional features of the original rocks and meteoritic material.

The calculations indicate (Table 3) that the concentration of the meteoritic component is at a minimum in the Dhofar 055 polymict eucrite and in eucrite fragments and eucrite breccia of the Dhofar 275. The NWA 1813, Smara, and Dhofar 300 polymict eucrites contain 0.3, 1.0, and 1.5 wt % of the CM material, respectively (Table 3) (here and below we discuss the values calculated based on the Ni concentrations). The meteoritic component also enriches (1.7 wt %) inclusions in howardite breccias in the Dhofar 275 meteorite. The Yurtuk and Dhofar 018 contain 1.8 wt % chondritic material. Rock fragments from the Dhofar 055 and Dhofar 275 polymict eucrites are enriched in impact melt and contain 2.0 and 5.4 wt % of the CM component, respectively.

DISCUSSION

Mineralogical Diversity of Meteoritic Material in HED Breccias

The results of our studies were the first to demonstrate that the foreign meteoritic component of polymict eucrites and howardites consists not only of carbonaceous chondrites, as was thought previously, but also of ordinary chondrites, mesosiderites, enstatite meteorites, and ureilites. The meteoritic fragments are quantitatively dominated by carbonaceous chondrites, and fragments of ordinary chondrites and differentiated meteorites (iron, mesosiderites, and achondrites) account for no more than 1% of the overall amount of all meteoritic xenoliths contained in HED breccias. An analogous proportion was determined for the population of particles of cosmic dust found in Antarctic and Greenland ice (Walter et al., 1995). Thus, the flux of interplanetary particles near the orbit of the HED parent body (or bodies) qualitatively corresponded to the modern micrometeorite flux to the Earth. It should be mentioned that the statistics of meteorite falls at the Earth is largely controlled by the so-called atmospheric filter effect: the destruction of bodies mechanically less resistant in the Earth's atmosphere (Kurat et al., 1994). Because of this, meteorite falls are dominated by ordinary chondrites (82%), which are followed by achondrites and iron meteorites (14%), whereas carbonaceous chondrites account for as little as 2.5% (Kurat et al., 1994).

However, the qualitative composition of the cosmic material flux is not the only factor controlling the proportions of meteoritic fragments in HED breccias. As was demonstrated above, carbonaceous chondrite particles in howardites and polymict eucrites usually display no traces of intense thermal alterations, while meteorite inclusions of other types were affected by thermal metamorphism and underwent complete or partial destruction. Furthermore, there are differences between the sizes of carbonaceous chondrite particles (up to 1.5–2 mm) and fragments of other types (100 μm and less). Particles of carbonaceous chondrites are less resistant mechanically, and hence, their preservation in the form of relatively large fragments implies their very slow accretion on the surface of the HED parent body. The fluxes of iron meteorites and ordinary chondrites were likely dominated by high-velocity particles that were then practically completely destroyed by collisions.

The differences between the velocities of impactors of various composition could be partly related to some features of the destruction of bodies in the asteroid belt. It is reasonable to hypothesize that iron and chondritic impactors could acquire high velocities during the catastrophic high-velocity breakup of their parent bodies, and carbonaceous impactors received their velocities mostly during the low-velocity impact abrasion of the surfaces of carbonaceous asteroids. Moreover, the sources of low-velocity particles could be comets that travel along orbits intersecting the asteroid belt. Their ejected particles may have low velocities relative to those of asteroids. For example, the collisions of cometary nuclei with asteroids could result in the capture of asteroid material, which was then released when the nuclei later approached the Sun (Solc et al., 1994). These ideas are consistent with the IRAS results obtained on the solar dust nebula. The analysis of the IR reflection spectra of the interplanetary dust obtained by the IRAS satellite demonstrates that the solar dust nebula contains from two to five populations of particles produced by the dust belts of asteroids and periodical comets (Divine, 1992; Renard et al., 1995). In the ecliptic plane, interplanetary dust is formed mostly during the destruction of asteroids of the main belt, and the sizes of the particles do not exceed thereby 50 μm (Zook and McKay, 1986). The dust traces of comets contain particles 1–1000 μm in size, which were ejected from the parental nuclei with velocities of a few meters per second (Sykes, 1988). Hence, the hypothesis of the cometary origin of the carbonaceous chondrite particles contained in howardites seems to be plausible. Meteoritic particles of other types are most likely of asteroid origin.

However, the fact of the even partial preservation of meteoritic fragments compositionally different from carbonaceous chondrites in the breccias requires an explanation, because, at velocities of the order of 5 km/s, which are usual for the asteroid belt, a direct collision results in the complete melting of the impactor (Melosh, 1989). At the same time, a collision with a target in the tail of an impactor results in the ejection of small fragments (because of certain features of shock wave propagation) that are not affected by shock compression (Melosh, 1989). These fragments have high velocities relative to the impactor but can be preserved owing to stopping-down in the loose layers of the target or its surface topographic features. It is also possible that a certain role can be played by collisions at low angles. The numerical simulations of this process (Pierazzo and Melosh, 2000) demonstrates that the fraction of the solid impactor material increases at collision angles smaller than 60° and reaches ~15% of the impactor mass at an angle of 30°. If the collision angle is lower than 15°, all material of the impactor remains solid. However, this model also predicts that fragments produced by collisions at very low angles can acquire significant velocities, which are higher than the escape velocity from the asteroid surface. Nevertheless, the effect of acute collision can be partly achieved if the size of the impactor is much smaller than the topographic roughness of the target surface. In this situation and at favorable angles of the target surface, fragments of the impactor can be slowed down in the loose regolith of the asteroid.

Correlation between the Concentrations of Meteoritic Fragments and Siderophile Elements in HED Breccias

As follows from literature data (Table 3), the concentrations of Ni, Co, and Ir systematically increase from monomict to polymict eucrites and howardites. The reason for this is an increase in the contents of the meteoritic and, to an insignificant extent, diogenite components. Our data show that the examined HED breccias may contain up to 1.8 wt % chondritic material, which is consistent with the results of earlier studies, according to which most howardites bear 1–3% meteoritic component (Mazor and Anders, 1967; Laul et al., 1972; Chou et al., 1976). However, innumerous fragments of carbonaceous chondrites were described only in a few of them (Wilkening, 1973; Bunch et al., 1979; Zolensky, 1996).

No chondritic particles were found in the Dhofar 275 polymict eucrite. Fragments of the polymict eucrite breccias contain no disseminated chondritic material. High concentrations of CM components were found in howardite fragments and breccias with a glass cement in this meteorite.

The modal concentration of carbonaceous chondrite fragments in the Dhofar 018 howardite (0.001 wt %) is three orders of magnitude lower than the content of disseminated chondritic material estimated by the concentrations of siderophile elements (1.8 wt %). The enrichment of the Dhofar 018 howardite in siderophile elements could be related to the presence of numerous fragments of hypocrystalline rocks and glass of presumably impact genesis, which can be significantly enriched in the impactor material. The high content of these fragments possibly reflects the long-lasting regolith history of the source material of this breccia. The occurrence of ordinary chondrite and enstatite meteorite fragments (whose percentage in the flux is low) in the Dhofar 018 howardite provides further support for this conclusion. This does not, however, rule out that all the ordinary chondrite fragments found in Dhofar 018 belong to a single impactor.

HED breccias show no correlation between the modal contents of foreign meteorite inclusions and the concentrations of the meteoritic component, which is estimated from the concentrations of siderophile elements. This means that much of the chondritic material is contained in these rocks in a disseminated form. Impact melts contain 1–3 wt % of the CM chondrite material (Mittlefehldt and Lindstrom, 1993; our data). The average concentrations of impact melt in howardites is 2.7% (Fuhrman and Papike, 1982; Pun et al., 1998). This implies that mass of chondrite material in impact melts is equal to approximately 0.05% of the breccia mass. This means that impact melts contain as little as 2.5% of the overall CM chondrite material contained in the breccias, and siderophile elements should be concentrated mostly in submicrometer-sized meteorite particles inaccessible for microscopic examination.

Comparison of the Parameters of the Meteorite Flux at the Moon and the Parent Body of HED Meteorites

The Moon is now the only planetary body that was studied and could be an analogue of the parent body of HED meteorites. However, the geneses of regolith on the surface of the Moon and the parent body of HED meteorites were likely different because of their different gravity, which controlled the velocities of impactors and the scatter and deposition of the ejecta. Lunar soil samples were determined to contain only single fragments of L chondrites (Semenova et al., 1990), enstatite meteorites (Haggerty, 1972), and carbonaceous CM chondrite (Zolensky et al., 1996).

Extensive dates on lunar rocks, howardites, and eucrites (Bogard, 1995) demonstrate that the evolutionary histories of the Moon and HED parent body involved the reset of the ^{39}Ar-^{40}Ar geochronometer corresponding to the episode of active meteorite bombardment at 3.7–4.1 Ga for the Moon and 3.4–4.1 Ga for the HED asteroid. The simultaneousness of the meteoritic bombardment of the Moon and HED asteroid could be caused by the high intensity of the meteorite flux throughout the solar system at that time (Wasson et al., 1975; Bogard, 1995). It is thus reasonable to suggest that the meteorite flux at the HED asteroid did not then differ from the meteorite flux at the Moon's surface. The flux of cosmic material at the HED asteroid's surface (perhaps, asteroid Vesta) (McCord et al., 1970; Larson and Fink, 1975) can be evaluated from the extent of cratering of its surface. The analysis of Vesta's spectral images (Thomas et al., 1997; Gaffey, 1997) shows that the surface of this asteroid includes equant structures composed of heterogeneous material, with elevation magnitudes of up to 20 km, which can be interpreted as impact craters. In particular, a huge impact crater 420 km in diameter was identified near the south pole of Vesta. The central peak of this crater and its ejecta consist of diogenite material with an olivine admixture (Gaffey, 1997). Judging from the albedo characteristics, the ring peak of the crater and the rest of Vesta's surface are made up of eucrites and howardites. Thus, the excavation depths of smaller craters did not exceed the thickness of the asteroid's crust, and their ejecta are of eucrite composition.

Table 5 reports the masses of impactors for ten reliably identified craters. These masses were calculated according to the dependence between the radius of an impactor and the diameter of its crater, collision velocity, and gravity (Housen et al., 1983) for a collision velocity of 5 km/s and a density of the impactor equal to 2.6 g/cm^3, i.e., as that of carbonaceous chondrites (Wasson, 1974). Models proposed for the formation of craters (Bazilevskii et al., 1983; Melosh, 1989) also make it possible to quantify the content of the impactor material in the crater ejecta (Table 5). The calculations were conducted for an asteroid 526 km in diameter and target rocks with a density of 3.2 g/cm^3, which corresponds to the average density of eucrites and howardites (Wasson, 1974). It as also assumed that the diameter of the bowl of the crater is equal to 60% of the ring peak diameter, and its depth is equal to 1/10 of its diameter (Melosh, 1989), and about 15 vol % of the impactor material acquires a velocity higher than the escape velocity for Vesta and leaves the asteroid (Melosh, 1989).

The calculated content of the impactor material (corresponding to carbonaceous chondrite in composition) in the ejecta of Vesta's craters ranges from 0.2 to 0.5 wt %, reaching a maximum of 1.2 wt % for the crater 420 km in diameter. The average Ni concentration in the ejecta of this crater is 120 ppm, and that of Ir is 7 ppb (Table 5). The average Ni concentration in the ejecta of smaller craters was estimated at 33 ppm and Ir at 2 ppb. In terms of the concentration of the meteoritic component, the model ejecta of the largest crater correspond to howardites and lunar regolith (Wasson et al., 1975), whereas the ejecta of smaller craters are comparable in this parameter with polymict eucrites. Inasmuch as the continuous cover of ejecta spreads for a distance roughly equal to the doubled diameter of the crater (Melosh, 1989), the ejecta of the largest crater should cover the entire surface of Vesta. It is quite possible that the ejected deposits of this crater 420 km in diameter suffered thermal metamorphism that resulted in the reset of the Ar chronometer at ~4 Ga. Since only this crater had an excavation depth greater than the thickness of the eucritic crust, this crater could be the only source of the diogenite material contained in howardites. The flux of meteoritic material at the surface of an asteroid can be represented in the form of the mass of impactors falling per surface unit per time unit. The total mass of the impactor material supplied to the surface of Vesta during the formation of the craters over

Table 5. Contents of carbonaceous chondrite material, Ni, and Ir in crater ejecta at Vesta's surface

Visible diameter of the crater, km	Impactor mass, kg	Ejecta mass, kg	Content of impactor material in ejecta, wt %	Content of Ni in ejecta, mg/g	Content of Ir in ejecta, ppb
147	2.2E+15	2.2E+17	0.5	45.4	2.7
105	6.1E+14	8.1E+16	0.3	33.7	2
63	8.6E+13	1.8E+16	0.2	21.6	1.3
168	3.7E+15	3.2E+17	0.5	51.2	3.1
84	2.6E+14	4.2E+16	0.3	27.8	1.7
84	2.6E+14	4.2E+16	0.3	27.8	1.7
63	8.6E+13	1.8E+16	0.2	21.6	1.3
42	1.8E+13	5.3E+15	0.2	15.2	0.9
168	3.7E+15	3.2E+17	0.5	51.2	3.1
420	1.3E+17	4.7E+18	1.2	118.9	7.1

4 Ga is 1.3×10^4 g/cm^2, which corresponds to an annual flux of 3.4×10^{-6} g/cm^2. This flux is three orders of magnitude higher than the flux at the Moon's surface (2.9×10^{-9} g/cm^2 per year) after the cessation of meteoritic activity (past 3.7 Ga) (Wasson et al., 1975). It is thus reasonable to suggest that all of the craters discussed here, including the crater 420 km in diameter, whose ejecta contain the bulk of the material of the impactors, were formed during the ancient meteorite bombardment, when the flux of large impactors was more intense than the later flux. The flux at Vesta's surface at 3.4–4.1 Ga should be equal to 3.4×10^{-5} g/cm^2 per year, and the meteoritic material should be disseminated in the layer of crater ejecta 2 km thick. This estimate is of the same order as the estimated ancient flux at the Moon's surface (1×10^{-4} g/cm^2 per year), which was based on the Ir concentration in the layer of highland impactites 25 km thick. Thus, the ancient meteorite flux at Vesta was equal to the flux at the Moon or was slightly lower.

Because the lithification of the regolith took place mostly during active meteorite bombardment via thermal metamorphism, meteorite particles contained in howardites provide information on the ancient flux of meteoritic material. If so, then the qualitative composition of the ancient flux at Vesta's surface did not differ from the modern meteoritic flux at the Earth, which is at variance with the concept that the ancient meteoritic bombardment was of different geochemical composition (for example, Morgan et al., 1977).

CONCLUSIONS

Foreign meteoritic material contained in howardites and polymict eucrites consists not only of carbonaceous chondrite fragments, which are predominant, but also fragments of ordinary chondrites and differentiated meteorites of various types. The flux of cosmic material at the surface of the HED parent body did not qualitatively differ from the modern flux at the Earth.

Mineralogical observations indicate that foreign meteoritic particles compose two populations characterized by different accretion rates at the surface of the HED asteroid.

The predominance of carbonaceous chondrite fragments in HED breccias was likely predetermined by the composition of the meteoritic material on the orbit of the HED parent body (supposedly, the asteroid Vesta) and the low relative velocities of the carbonaceous chondrite particles with respect to this body.

The preservation of meteorites of other types could be controlled by certain features of the destruction of high-velocity impactors during their collision with the surface of the HED asteroid at low angles to its surface topographic features.

The concentration of the meteoritic component in HED breccias estimated from the concentrations of siderophile elements is higher than the modal concentration of meteoritic particles and impact melt. The bulk of siderophile elements seems to be contained in HED breccias in very small particles that cannot be identified under a microscope.

The flux of cosmic material at Vesta's surface during its active bombardment could be as high as 3.4×10^{-5} g/cm^2 per year, which only insignificantly differs from the ancient meteoritic flux at the Moon's surface. Meteoritic particles contained in howardites seem to be the material of the ancient flux.

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