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Noble gases and mineralogy of meteorites from China and the Grove Mountains, Antarctica: A 0.05 Ma cosmic ray exposure age of GRV 98004

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Abstract–We determined the mineralogical and chemical characteristics and the He, Ne, and Ar isotopic abundances of 2 meteorites that fell in China and of 2 meteorites that were recovered by the 15th Chinese Antarctic Research Expedition. Guangmingshan (H5), Zhuanghe (H5), and Grove Mountain (GRV) 98002 (L5) yield cosmic ray exposure (CRE) ages of 68.7 ± 10.0 Ma, 3.8 ± 0.6 Ma, and 17.0 ± 2.5 Ma, respectively. These ages are within the range typically observed for the respective meteorite types. GRV 98004 (H5) had an extremely short parent body-Earth transfer time of 0.052 ± 0.008 Ma. Its petrography and mineral chemistry are indistinguishable from other typical H5 chondrites. Only 3 other meteorites exist with similarly low CRE ages: Farmington (L5), Galim (LL6), and ALH 82100 (CM2). We show that several asteroids in Earth-crossing orbits, or in the main asteroid belt with orbits close to an ejection resonance, are spectrally matching candidates and may represent immediate precursor bodies of meteorites with CRE ages ≤0.1 Ma.

INTRODUCTION

In the framework of a collaboration with Chinese researchers on the characterization of newly recovered meteorites, we obtained 4 chondrites to study their noble gas inventory. Within 20 yr, 2 H5 chondrites fell near the city of Zhuanghe, Liaoning province in China. The first one was named Zhuanghe (Grady 2000). It was a 2.90 kg stone that fell on August 18, 1976 into muddy soil in the village of Shishan. The second one was named Guangmingshan (Grossman 2000) and was a 2.91 kg stone that fell on December 30, 1996 into frozen ground in the village of Guangmingshan. We obtained samples of these meteorites to characterize the mineralogy, chemical composition, and noble gases. Preliminary mineralogical studies were published by Lin et al. (2000). In this work, we also report on our investigations of 2 chondrites collected by the 15th Chinese Antarctic Research Expedition. Grove Mountain (GRV) 98002 (L5) and GRV 98004 (H5) were found in 1999 on blue ice near the Grove Mountains in East Antarctica (Grossmann 2000).

The objective of this work is the determination of the mineralogical and chemical characteristics and of the noble gas inventory of the 4 meteorites. Furthermore, we will determine the cosmic ray exposure (CRE) ages, the gas retention ages from U, Th-He, and ^{40}K-^{40}Ar decay, and the trapped noble gas concentrations.

EXPERIMENTAL PROCEDURE

Mineralogy and Chemistry

Polished thin sections (PTS) for petrographic study were prepared from 4 chips about 1 mm thick. After observation under the optical microscope, the PTS were analyzed using a JEOL 733 electron probe microanalyzer (EPMA) at Ibaraki University, Japan. The analyzing conditions were 15 keV of accelerating voltage and 20 nA of beam current (with the exception of 10 nA for plagioclase). The X-ray overlapping of K_α lines by K_α lines of the successive elements (e.g., Co by Fe, Mn by Cr) was deconvolved. The analyses of silicates were corrected according to Bence and Albee (1968) and those of metals by the conventional ZAF program (where [Z] is the atomic number, [A] is the adsorption of X-rays in the specimen, and [F] is the fluorescence caused by other X-rays generated in the specimen). Modal compositions of these meteorites were calculated from mapping data of EPMA (Lin and Kimura 1998), which cover each entire section.

Noble Gases

The meteorite samples were crushed in a stainless steel mortar to a grain size of <750 μm and gases were extracted by radio-frequency heating in a single step at 1700°C. Completeness of the gas release was checked by adding a final extraction step at 1740°C. The mass spectrometric analyses and background corrections were performed according to the description of Eugster et al. (1993) using our system B. The following blanks were subtracted (units of 10^{-8} cm^3 STP): ^3He – <0.00004, ^4He – 0.02, ^{20}Ne – 0.0008, ^{40}Ar – 0.4.

PETROGRAPHY AND MINERAL CHEMISTRY

Petrography

The GRV 98002, GRV 98004, Guangmingshan, and Zhuanghe meteorites have been significantly metamorphosed. The matrix of these meteorites is well-recrystallized and becomes transparent under the optical microscope. Outlines of chondrules are somewhat blurred but are still readily recognized. No glass exists in the chondrules. Instead, plagioclase occurs interstitially by olivine and pyroxene. Most metallic Fe-Ni and troilite are coarse-grained. These petrographic characteristics are typical for type 5 ordinary chondrites.

Among the 4 chondrites, GRV 98002 is the most heavily metamorphosed, followed by Zhuanghe, Guangmingshan, and GRV 98004 in order of lower modification. In GRV 98002, only a few chondrules remained. They are large (mostly 0.5–1.0 mm in diameter) and show porphyritic textures. In contrast, GRV 98004 contains abundant chondrules with readily delineated boundaries. The chondrules in GRV 98004 are smaller, most with diameters of 200–600 μm and only a few of up to 1.0 mm. Common textures of the chondrules are barred, radial, porphyritic, and granular. The size of the plagioclase increases from <10 μm in GRV 98004 to 10–20 μm in Guangmingshan, 10–30 μm in Zhuanghe, and 20–60 μm in GRV 98002. The degree of recrystallization of the matrix increases in the same order.

Table 1 gives the modal compositions of the 4 chondrites. Compared to the other 3 meteorites, GRV 98002 contains more olivine and plagioclase and less low-Ca pyroxene and kamacite (except for GRV 98004). The abundance ratio of taenite/kamacite is much higher than that in Guangmingshan and Zhuanghe (Table 1). The modal composition of GRV 98002 is typical of L-group chondrites. Except for the low abundance of kamacite in GRV 98004, GRV 98004, Guangmingshan, and Zhuanghe have nearly identical abundance proportions among major phases, and they are typical of H-group chondrites. The low abundance of kamacite in GRV 98004 is due to terrestrial weathering, indicated by the presence of a large amount of weathered products (probably limonite) along boundaries of opaque minerals. Assuming all weathered products (14.0 wt%; Table 1) are limonite and were produced from kamacite, an original abundance of 11.5 wt% of kamacite is estimated, which is close to the range of H-group but is distinctly higher than L-group chondrites.

As depicted above, GRV 98004 is heavily weathered. The volume ratio of weathered products to a sum of opaque mineral plus the weathered products is 77%, suggestive of a weathering grade of W3 according to the scheme of Wlotzka (1993). GRV 98002 is weakly weathered with minor weathered products surrounding a few grains of metallic Fe-Ni and troilite. The degree of weathering is referred to as W1. Both Guangmingshan and Zhuanghe are fall meteorites preserved in a fresh state.

GRV 98002 and Zhuanghe show several thin shock veins across the sections. They are readily recognized under transmitted light, with the appearance of dark veins. The veins consist mainly of troilite, metallic Fe-Ni, and small fragments of silicates, with little melt. In addition, silicates in both meteorites are commonly fractured. Undulose extinction of silicates is more common in Zhuanghe than in GRV 98002. Shock degrees of both chondrites are referred to as S2 based on the scale proposed by Stöffler et al. (1991). In Guangmingshan, fracturing and undulose extinction of silicates is common, while in GRV 98004, most silicates show sharp extinction, fracturing being less common. The degree of

Table 1. Modal compositions of the investigated meteorites, normalized to 100 wt%.

	GRV 98002 (L5)	GRV 98004 (H5)	Zhuanghe (H5)	Guangmingshan (H5)
Olivine	42.3	37.1	35.9	36.8
Low-Ca pyroxene	26.3	33.3	32.5	30.7
Ca-pyroxene	5.1	2.6	3.7	3.5
Plagioclase	8.4	5.5	5.9	4.8
Taenite	4.2	1.9	1.4	1.3
Kamacite	2.7	2.6	15.2	18.4
Troilite	9.7	2.7	4.4	3.7
Phophate	0.3	0.3	0.3	0.4
Chromite	0.0	0.0	0.7	0.4
Weathered products[a]	1.0	14.0	0.0	0.0

[a]Assuming all limonite.

shock metamorphism of GRV 98004 and Guangmingshan is referred to as S1.

Mineral Chemistry

The compositions of major silicates are rather homogeneous in all 4 chondrites, and their averages are listed in Table 2. Obviously, the compositions of silicates are consistent with the above classification of these chondrites based on petrography. Olivine ($Fa_{24.3–26.4}$), low-Ca pyroxene ($Fs_{20.6–22.2}Wo_{1.2–3.5}$), and high-Ca pyroxene ($En_{46.3–46.9}Fs_{8.1–8.6}Wo_{44.6–45.4}$) in GRV 98002 contain higher FeO, within the range of L-group chondrites. The other 3 chondrites have very similar compositions of silicates (Table 2), and they are typical of H-group chondrites. Olivine in the 4 meteorites does not contain detectible CaO. The percent of the mean standard deviation (PMD) of the Fa content of olivine is low for GRV 98002 (1.5%), and it increases in the following order: Guangmingshan (2.3%) <GRV 98004 (2.6%) <Zhuanghe (3.1%). The PMD of the Fs content of low-Ca pyroxene increases in the same order: GRV 98002 (2.2%) <Guangmingshan (2.6%) <GRV 98004 (3.8) <Zhuanghe (4.0%). The homogeneous compositions of silicates confirm that they are type 5 ordinary chondrites. Furthermore, the increasing sequence of PMD values are consistent with the degree of thermal metamorphism of these chondrites, referred by petrography as described above, with the exception of Zhuanghe. However, the compositional variation of the silicates in Zhuanghe is probably due to shock metamorphism since it shows more intense shock effects than the others. Compositions of high- and low-Ca pyroxenes, which are in contact with each other, were also analyzed to determine the equilibrium temperatures of these meteorites in their parent bodies using a 2 pyroxene thermometer (Lindsley and Andersen 1983). The results are given in Table 3 and are consistent with type 5 ordinary chondrites (Dodd 1981).

Compositions of kamacite and taenite are plotted in Fig. 1; their average data are summarized in Table 4. Kamacite in GRV 98002 contains significantly higher Co in comparison to the other 3 meteorites. The Co content of kamacite in GRV 98002 is in the range of the L-group chondrites, while the others are within the H-group range (Rubin 1990). The Co content of taenite exhibits a similar trend and is higher in GRV 98002 (Fig. 1b). Furthermore, taenite in GRV 98002 shows a wide range of composition; it displays a negative correlation between Ni and Co. The heterogeneity is related to zoning of taenite in contact with kamacite, which occurs as a step-like profile (Fig. 2a). The zoning of taenite in GRV 98002 probably suggests the presence of metastable phases of metallic Fe-Ni formed during slow cooling below 400°C, based on the phase diagram (Yang et al. 1997). Taenite grains in both

Table 2. Average compositions of olivine, pyroxene, and plagioclase (in wt%).[a]

	Olivine				Low-Ca pyroxene				Ca-pyroxene				Plagioclase			
	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d
	(45)	(70)	(89)	(38)	(35)	(52)	(30)	(28)	(6)	(8)	(11)	(2)	(39)	(12)	(27)	(21)
SiO_2	38.3	39.6	39.5	39.2	55.5	56.7	56.8	56.3	53.4	54.4	54.6	53.8	66.4	65.9	66.3	65.5
TiO_2	b.d.	b.d.	b.d.	b.d.	0.13	0.12	0.15	0.15	0.40	0.49	0.43	0.47	b.d.	b.d.	b.d.	0.03
Al_2O_3	b.d.	b.d.	b.d.	b.d.	0.15	0.17	0.17	0.17	0.51	0.78	0.64	0.54	21.1	21.1	21.3	21.0
Cr_2O_3	b.d.	b.d.	b.d.	b.d.	0.06	0.06	0.04	0.05	0.83	0.82	0.69	0.83	b.d.	b.d.	b.d.	b.d.
FeO	23.0	17.6	18.1	18.2	13.9	11.0	11.4	11.4	5.13	3.45	3.41	4.04	0.23	0.29	0.37	0.29
MnO	0.38	0.37	0.37	0.37	0.42	0.43	0.43	0.45	0.16	0.10	0.14	b.d.	b.d.	b.d.	b.d.	b.d.
MgO	37.7	42.2	41.9	41.8	27.9	30.3	30.2	30.0	16.1	16.5	16.4	16.6	b.d.	0.13	0.02	0.02
CaO	b.d.	b.d.	b.d.	b.d.	0.97	0.64	0.61	0.61	21.6	22.4	22.5	22.3	2.19	2.53	2.57	2.45
Na_2O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.65	0.59	0.56	0.55	9.98	9.95	9.81	9.53
K_2O	b.d.	b.d.	0.01	0.01	b.d.	b.d.	0.01	0.01	b.d.	b.d.	0.02	0.02	0.99	0.85	0.73	0.99
Fa/Fs/Or	25.5	19.0	19.5	19.7	21.4	16.8	17.3	17.3	8.3	5.6	5.5	6.5	5.5	4	–	–
Wo/An	–	–	–	–	1.9	1.2	1.2	1.2	45.0	46.7	46.9	46.0	10.2	11.7	12.1	11.7

[a]a = GRV 98002; b = GRV 98004; c = Guangmingshan; d = Zhuanghe. The numbers in parentheses are the number of analysis points. Fa = Fayalite content of olivine (mol%); Fs = ferrosilite content of pyroxene (mol%); Wo = wollastonite content of pyroxene (mol%); An and Or = anorthite and orthoclase contents of plagioclase (mol%); b.d. = below detection limits. These are: 0.03 wt% for TiO_2 and Cr_2O_3; 0.02 wt% for Al_2O_3, MgO, CaO, and Na_2O; 0.06 wt% for MnO; and 0.01 wt% for K_2O.

Table 3. Compositions of high- and low-Ca pyroxene couples and related equilibrium temperatures.

Meteorite	Ca pyroxene	Low-Ca pyroxene	Temperature(°C)[a]
GRV 98002	$En_{46.5}Fs_{8.2}Wo_{44.3}$	$En_{76.9}Fs_{21.3}Wo_{1.9}$	~800
GRV 98004	$En_{47.9}Fs_{5.7}Wo_{46.4}$	$En_{82.4}Fs_{16.0}Wo_{1.3}$	~700
Guangmingshan	$En_{47.9}Fs_{5.1}Wo_{47.0}$	$En_{81.6}Fs_{17.3}Wo_{1.1}$	~700
Zhuanghe	$En_{47.5}Fs_{6.5}Wo_{46.0}$	$En_{81.7}Fs_{17.2}Wo_{1.1}$	~700

[a]According to Lindsley and Andersen (1983).

Table 4. Average compositions of kamacite and taenite (in wt%).[a]

	Kamacite				Taenite			
	a (29)	b (36)	c (27)	d (56)	a (57)	b (17)	c (30)	d (23)
Co	0.83	0.49	0.49	0.50	0.46	0.14	0.12	0.09
Fe	93.4	93.3	92.4	93.3	74.7	57.4	63.1	55.6
Ni	4.90	6.29	6.39	5.65	23.7	41.8	35.6	43.2

[a]a = GRV 98002; b = GRV 98004; c = Guangmingshan; d = Zhuanghe. The numbers in parentheses are the number of analysis points.

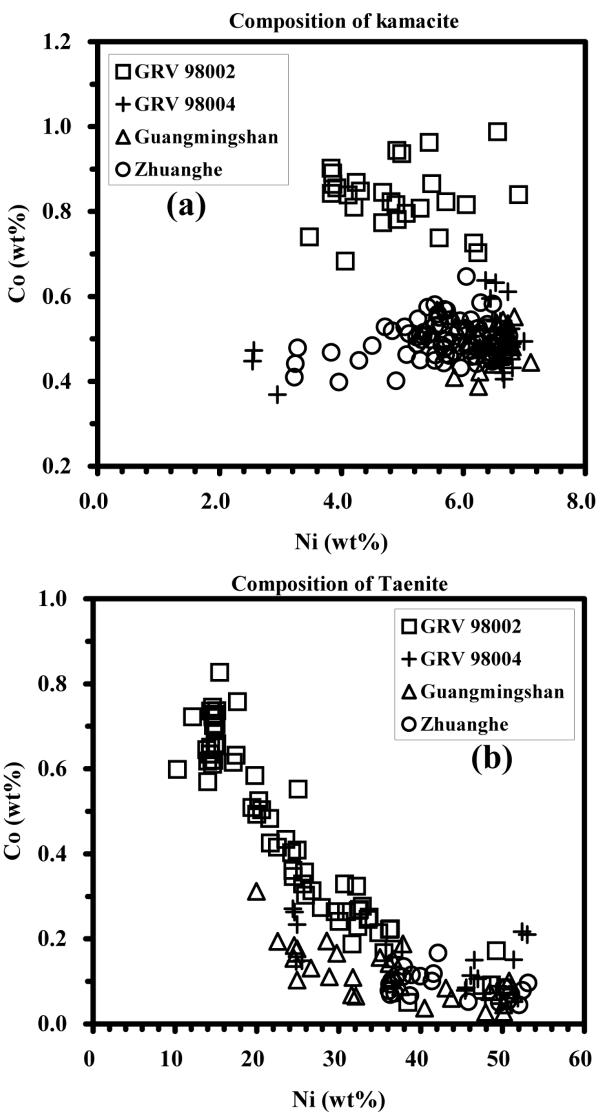

Fig. 1. Ni-Co plots of kamacite (a) and taenite (b). Kamacite and taenite in GRV 98002 (L5) contain higher Co than kamacite and taenite in the other 3 H5 chondrites. Taenite in GRV 98002 shows a wide range of Co and is negatively correlated with Ni. Three analyses of kamacite in GRV 98004 yield the lowest Ni contents.

Guangmingshan and Zhuanghe commonly show typical "M" type zonings (Figs. 2c and 2d). In contrast, the grains in contact with kamacite in GRV 98004 have a high and relatively constant Ni content, while the coexisting kamacite has much lower Ni content (Fig. 2b) than other separate kamacite grains (Fig. 1a). The very low Ni content of kamacite and the high and constant Ni content of the coexisting taenite suggest an equilibrium at very low temperature, according to the metallic Fe-Ni phase diagram (Yang et al. 1997). Possibly, GRV 98004 experienced a very slow cooling at low temperatures in its asteroidal body.

NOBLE GAS COMPONENTS

The noble gas results are given in Table 5. The errors correspond to a 95% confidence level. The isotopic abundances were partitioned into cosmic ray produced (cosmogenic; c), trapped (tr), and radiogenic (r) components (Table 6). We made the following assumptions: for GRV 98002, GRV 98004, and Zhuanghe, we assumed $^{3}He_{tr}$ and $^{4}He_{tr}$ = 0. For Guangmingshan, we observed a ratio of $(^{20}Ne/^{36}Ar)_{tr}$ >1, indicating the presence of solar Ne and, consequently, of solar He. After subtracting cosmogenic ^{20}Ne (see below), we obtain ~1.7×10^{-8} cm^3 STP/g $^{20}Ne_{tr}$ (Table 6). We assume $^{20}Ne_{tr}$ to originate from solar particle irradiation. To calculate $^{4}He_{tr}$, we adopt the following ratio: $(^{4}He/^{20}Ne)_{tr} = 390 \pm 200$, as calculated from the Fayetteville data of Wieler et al. (1989). The upper and lower limits allow for the solar wind value and for other gas rich meteorites, respectively. Furthermore, from the Fayetteville data, we calculated a ratio of $(^{4}He/^{3}He)_{tr}$ = 3300, which is in good agreement with the ratio of 3200 obtained by Eugster et al. (1993) for the Ngawi chondrite. Thus, Guangmingshan yields 660×10^{-8} cm^3 STP/g $^{4}He_{tr}$ and 0.2×10^{-8} cm^3 STP/g $^{3}He_{tr}$. For calculating $^{4}He_{c}$, we adopt a ratio of $(^{4}He/^{3}He)_{c} = 6.1 \pm 0.3$ (Alexeev 1998), which agrees with a value of 6.2 ± 0.2 (Welten et al. 2003). The assumptions of $(^{4}He/^{20}Ne)_{tr}$ and $(^{4}He/^{3}He)_{c}$ are not critical for the calculation of $^{3}He_{c}$ (Table 6) but are for the calculation of $^{4}He_{r}$. With the above assumptions, we find $480 \pm 360 \times 10^{-8}$ cm^3 STP/g $^{4}He_{r}$.

All other assumptions for the partitioning of Ne and Ar are those given by Eugster et al. (1993). The concentrations of trapped ^{36}Ar are well within the range of 1–3 × 10^{-8} cm^3 STP/g for the type 5 chondrites given by Marti (1967). This component of trapped noble gases dominates the noble gas inventory of primitive meteorites. It is called "planetary" or trapped gas of type Q (cf., Ott 2002). Table 6 gives the results for the cosmogenic, trapped, and radiogenic components.

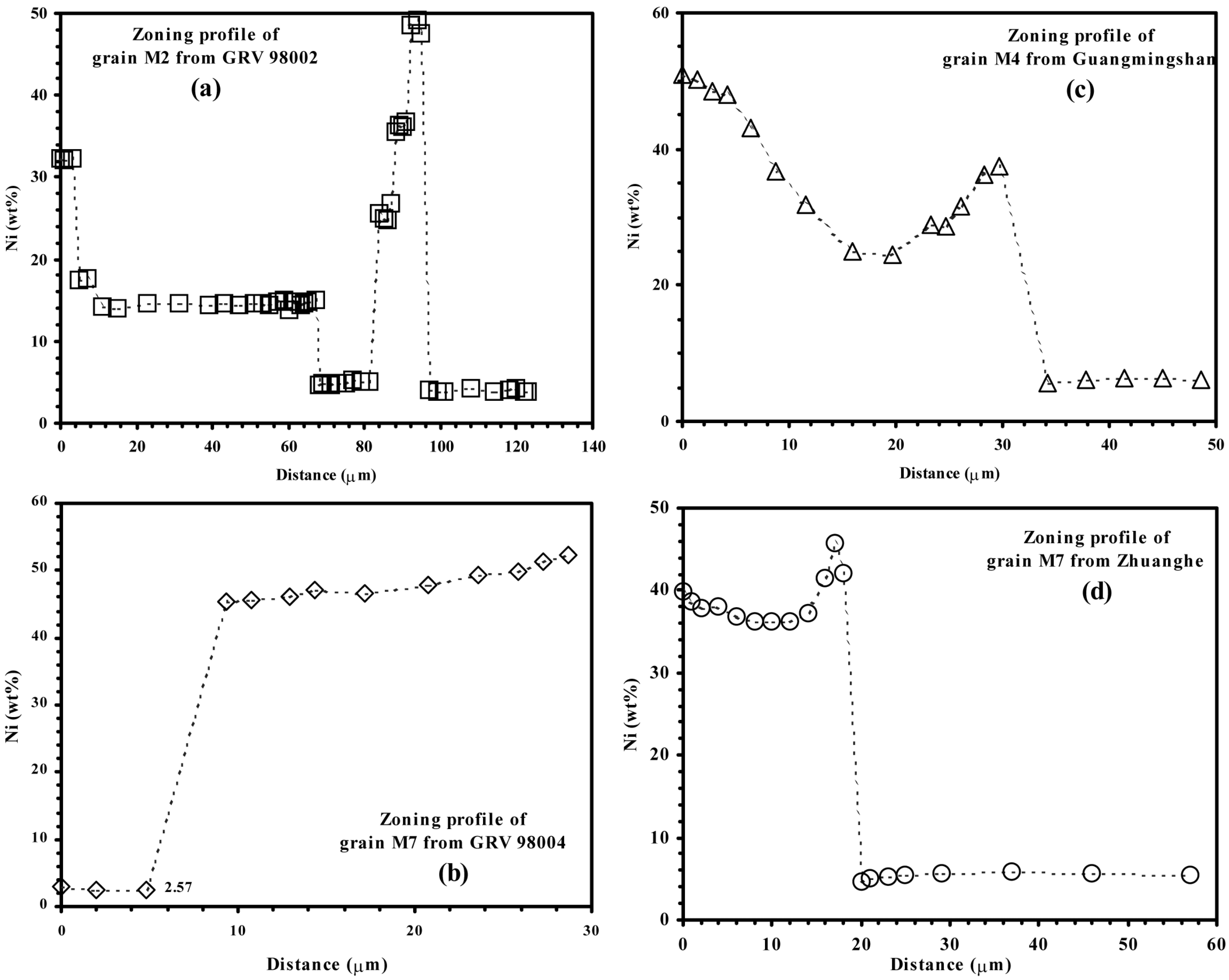

Fig. 2. Zoning profiles of metallic Fe-Ni in GRV 98002 (a), GRV 98004 (b), Guangmingshan (c), and Zhuanghe (d). The composition of the taenite grain of GRV 98002 is polycrystalline. In contrast, the taenite grain of GRV 98004 yields a high and nearly constant Ni content, while the coexisting kamacite is very low in Ni.

CRE AGES AND THERMAL HISTORY

CRE Ages

The cosmic ray exposure (CRE) age is defined as the length of time a small meteoroid (meter-sized or less) was exposed to cosmic rays while orbiting in space. This time is measured from the amounts of certain isotopes produced by cosmic ray particles. In this work, CRE ages were calculated using production rates that were derived according to the method proposed by Eugster (1988). In this method, the cosmogenic ratio $^{22}Ne/^{21}Ne$ is used for the shielding correction of the production rates. For GRV 98004, this ratio could not be determined because of extremely low abundances of cosmogenic Ne. For GRV 98002 and Zhuanghe, the measured $(^{22}Ne/^{21}Ne)_c$ ratio is <1.07. In such cases, this ratio is an unreliable shielding indicator, as demonstrated by Welten et al. (2003). Thus, we adopted an average shielding for H chondrites corresponding to a ratio of $(^{22}Ne/^{21}Ne)_c = 1.11$. The production rates for ^3He, ^{21}Ne, and ^{38}Ar and resulting CRE ages are given in Table 7.

The CRE ages calculated from the 3 nuclides generally agree within about ±20%, although the T_{21} ages are, on average, about 20% higher than the T_3 and T_{38} ages. However, we don't find an obvious reason for this discrepancy. The preferred CRE ages (T_{pref}) are the average values for the 3 individual ages, except for GRV 98004, where T_{38} is of low quality (experimental error of ^{38}Ar >50%). In the section "Petrography," we stated that GRV 98004 is heavily weathered. Could weathering be the cause for its extremely low CRE age? In an interdisciplinary study of weathering effects in ordinary chondrites from the Algerian Sahara, Stelzner et al. (1999) measured the noble gases in 6 meteorites with weathering grades W1–W5. These authors concluded

Table 5. Results of He, Ne, and Ar measurements.

Meteorite	^{4}He	^{20}Ne	^{40}Ar	$^{4}He/^{3}He$	$^{20}Ne/^{22}Ne$	$^{22}Ne/^{21}Ne$	$^{36}Ar/^{38}Ar$	$^{40}Ar/^{36}Ar$
	10^{-8} cm^3 STP/g							
GRV 98002 (L5)	670 ± 20	8.42 ± 0.30	6970 ± 200	26.1 ± 0.3	0.883 ± 0.010	1.047 ± 0.010	2.42 ± 0.03	2336 ± 70
GRV 98004 (H5)	1390 ± 50	0.40 ± 0.04	6170 ± 200	17715 ± 700	6.44 ± 0.90	3.31 ± 0.40	4.90 ± 0.20	5723 ± 200
Guangmingshan (H5)	1770 ± 50	21.3 ± 0.6	5150 ± 160	17.12 ± 0.17	0.863 ± 0.009	1.131 ± 0.012	0.928 ± 0.011	1652 ± 40
Zhuanghe (H5)	374 ± 10	1.79 ± 0.05	4600 ± 150	75.9 ± 1.0	0.913 ± 0.030	1.016 ± 0.030	3.64 ± 0.10	2258 ± 100

Table 6. Cosmogenic, trapped, and radiogenic noble gases. Concentrations in 10^{-8} cm^3 STP/g.

	Cosmogenic				Trapped		Radiogenic	
Meteorite	^{3}He	^{21}Ne	^{38}Ar	$^{22}Ne/^{21}Ne$	^{20}Ne	^{36}Ar	^{4}He	^{40}Ar
GRV 98002 (L5)	25.7 ± 1.0	9.11 ± 0.40	0.765 ± 0.030	1.040 ± 0.010	0.87 ± 0.40	2.48 ± 0.20	536 ± 20	6970 ± 200
GRV 98004 (H5)	0.078 ± 0.005	0.0172 ± 0.0035	0.0198 ± 0.0100	n.d.[a]	0.38 ± 0.04	1.07 ± 0.06	1390 ± 50	6170 ± 200
Guangmingshan (H5)	103.2 ± 3.0	21.8 ± 0.9	3.16 ± 0.15	1.125 ± 0.012	1.7 ± 0.6	1.07 ± 0.05	480 ± 360	5150 ± 200
Zhuanghe (H5)	4.93 ± 0.20	1.93 ± 0.10	0.202 ± 0.020	1.01 ± 0.05	0.24 ± 0.10	1.91 ± 0.10	348 ± 10	4600 ± 150

[a]n.d. = not determined.

Table 7. Production rates[a], CRE ages, and gas retention ages.

	Production rates (10^{-8} cm^3 STP/g per Ma)			CRE ages (Ma)				Gas retention ages (Ga)	
Meteorite	P_3	P_{21}	P_{38}	T_3	T_{21}	T_{38}	T_{pref}	T_4	T_{40}
GRV 98002 (L5)	1.61	0.455	0.0504	15.7	20.0	15.2	17.0 ± 2.5	1.6 ± 0.1	4.63 ± 0.16
GRV 98004 (H5)	1.58	0.309	0.0499	0.049	0.056	(0.40)[b]	0.052 ± 0.008	3.6 ± 0.8	4.53 ± 0.15
Guangmingshan (H5)	1.57	0.290	0.0487	65.9	75.2	64.9	68.7 ± 10.0	1.6 ± 1.0	4.23 ± 0.15
Zhuanghe (H5)	1.61	0.423	0.0545	3.06	4.56	3.71	3.8 ± 0.6	1.1 ± 0.1	4.05 ± 0.15

[a]Calculated according to Eugster (1988).
[b]Experimental error >50%.

that the cosmogenic ^{3}He, ^{21}Ne, and ^{38}Ar concentrations, as well as the cosmogenic $^{22}Ne/^{21}Ne$ ratio, measured at different locations within the meteorites, were uniform within the given error limits. Thus, the calculated cosmic ray exposure ages and gas retention ages are not affected by the terrestrial weathering processes.

The results obtained for the CRE and gas retention ages of GRV 98004 (Table 7) lead us to the same conclusion: helium, typically being more affected by weathering process than the heavier noble gases, yields, within experimental errors, the same CRE and gas retention ages, respectively, as those based on neon and argon.

GRV 98002, Guangmingshan, and Zhuanghe show CRE ages in the range (Fig. 3) typically observed for the L and H chondrites, respectively (cf., Marti and Graf 1992). However, GRV 98004 is exceptional: its CRE age is 0.052 ± 0.008 Ma. A similarly low CRE age is rarely observed. Patzer et al. (1999) discussed the exposure history of chondrites with low CRE ages. In the following, we review the cases where CRE ages <0.1 Ma were reported. Several authors analyzed the Farmington L5 chondrite and found extremely low abundances of cosmogenic gases. Patzer et al. (1999) and Patzer and Schultz (2001) determined the CRE ages of 2 individual stone fragments of the Galim chondrite fall. One fragment is of type LL6 and another one of type EH3. Rubin (1997) suggested that both types belong to the same fall and that the Galim meteoroid represents an LL chondritic polymict breccia with EH chondritic clasts. The noble gas data of Patzer et al. (1999) confirmed this interpretation. Another very low CRE age is that of the CM2 chondrite ALH 82100. Nishiizumi et al. (1993) obtained an age of 0.04 Ma from radionuclides.

In Table 8, we list the concentrations of $^{3}He_c$, $^{21}Ne_c$, $^{4}He_r$, and $^{40}Ar_r$ for the meteorites with short CRE ages. The results obtained by 4 different research groups for the Farmington meteorite agree quite well. Table 9 gives the CRE ages for Farmington L5, Galim LL6, and Galim EH3. The difference between the CRE ages of the LL6 and EH3 fragments of Galim can be explained by pre-irradiation of the EH clasts before they became part of the LL parent body regolith (Patzer et al. 1999). Considering the T_{21} age for Galim to be more reliable than the T_3 age (possible ^{3}He loss due to heating processes, see below), we now have 4 chondrites of 4 different types with extremely low CRE ages: Farmington L5 (0.032 Ma), Galim LL6 (0.033 Ma), GRV 98004 H5 (0.052 Ma) and, from radionuclide activities, ALH 82100 CM2 (0.04 Ma).

Thermal History

Is it possible that these low CRE ages are the result of noble gas loss in space due to solar heating? This could have happened for meteorites that had orbits with small perihelion distances or that experienced a catastrophic event during their exposure in space resulting in gas loss. CRE ages that were calculated from radionuclides are insensitive to thermal events that affect noble gases. Thus, the 0.04 Ma age of ALH 82100 should be reliable. For Farmington, we also have ^{26}Al data. Anders (1962) obtained, by γ-γ coincidence spectrometry, an activity of 3.6 ± 2.5 dpm/kg (as compared to

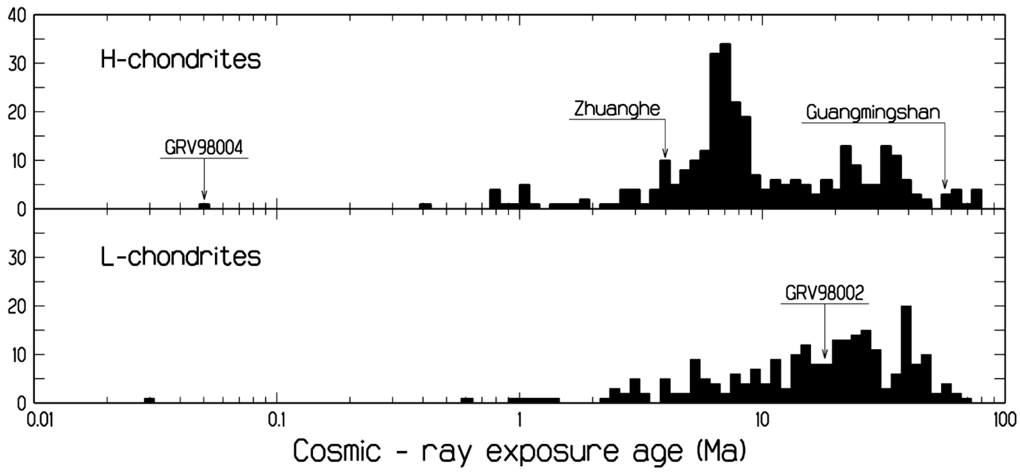

Fig. 3. CRE age histograms of H and L chondrites. The data are from Marti and Graf (1992) and updates. The chondrites dated in this work are indicated.

Table 8. Cosmogenic and radiogenic noble gases, analyzed by other authors, of meteorites with CRE ages <0.1 Ma. Concentrations in 10^{-8} cm^3 STP/g.[a]

Meteorite	Cosmogenic component ^3He	Cosmogenic component ^{21}Ne	Radiogenic component ^4He	Radiogenic component ^{40}Ar	Ref.
Farmington (L5)	0.06	–	185	285	1
	–	–	120	370	2
	0.06	–	105	380	2
	0.046	0.0093	118	581	3
	0.036	0.008	67	283	4
	0.060	0.012	120	545	4
Average	0.052	0.0098	119	403	–
Galim (LL6)	0.036	0.011	926	6141	4
	0.038	0.011	1850	5814	4
Average	0.037	0.011	1388	5978	–
Galim (EH3)	0.066	0.020	910	7120	4
	0.064	0.018	880	6295	4
	0.062	0.018	886	6713	5
Average	0.064	0.0187	892	6709	–

[a]Where necessary, a correction of a few percent for trapped Ne was applied by us. Typical experimental errors are ~10%. Authors: 1 = Zähringer (1966); 2 = Heymann (1967); 3 = Wieler, personal communication (2002); data from Wieler, personal communication (1996) in Schultz and Franke (2002) are not correct; 4 = Patzer et al. (1999); 5 = Patzer and Schultz (2001).

an equilibrium activity for L5 chondrites of 64 dpm/kg), and calculated a CRE age of <0.2 Ma. De Felice et al. (1963) measured an even lower activity for ^{26}Al of 0.8 dpm/kg, corresponding to a CRE age of 0.013 Ma. Using accelerator mass spectrometry, Nishiizumi (personal communication) analyzed ^{10}Be and ^{36}Cl and obtained an age of 0.034 ± 0.002 Ma. Another valuable tool for discussing the thermal history of meteorites is the T_3/T_{21} versus T_4/T_{40} diagram, where T_4 and T_{40} are the U, Th-^4He, and the ^{40}K-^{40}Ar gas retention ages, respectively (Fig. 4). The data points that lie within the broken lines have T_3 and T_{21} CRE ages that agree within experimental errors of 20%. This is the case for Farmington, Guangmingshan, and GRV 98004. These meteorites did not experience a heating event after the parent body break up. Such an event would have resulted in a severe decrease of the $^3He/^{21}Ne$ ratio, unless this event occurred early in the CRE history. All meteorites displayed in Fig. 3 yield a ratio T_4/T_{40} <1, indicating loss of radiogenic ^4He on the parent body before the onset of the CRE. Galim and Zhuanghe show a loss of cosmogenic ^3He and of radiogenic ^4He. We conclude that these 2 meteorites must have experienced a thermal event after having been expelled from their parent asteroid. Their ^3He CRE ages are certainly too low. Did the same event also affect the ^{21}Ne CRE age? For Zhuanghe, we realize that the ^{21}Ne CRE age is not lower than the ^{38}Ar age, indicating no ^{21}Ne loss (Table 7). For Galim (Table 9), no ^{38}Ar age was determined. However, the following general considerations argue for the reliability of the ^{21}Ne age of Galim: for many chondrites that show ^3He loss, the ^{21}Ne age is in agreement with the ^{81}Kr-Kr age. The

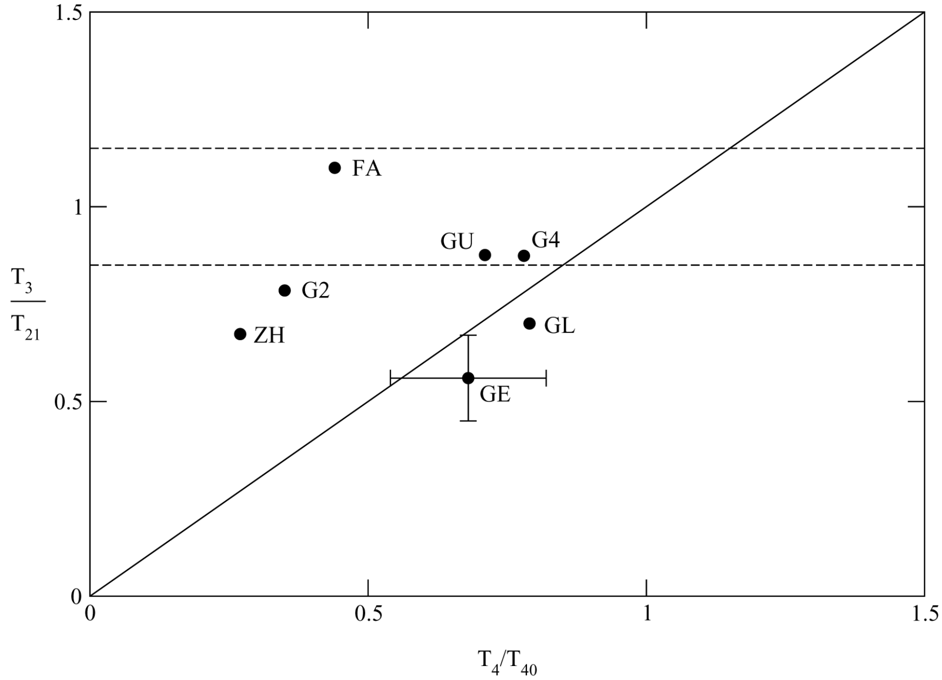

Fig. 4. Ratio of CRE ages (T_3/T_{21}) versus ratio of gas retention ages (T_4/T_{40}) for chondrites. The typical experimental errors of ~20% are shown. The data points falling on the solid line represent meteorites that lost the same proportion of cosmogenic ^{3}He and radiogenic ^{4}He. This indicates a heating event late in the meteorite's cosmic ray exposure history as a consequence of solar heating. Meteorites with T_4/T_{40} <0.8 and lying between the broken lines lost radiogenic ^{4}He before they were exposed to cosmic rays, that is, at or before break-off from their parent body.

Table 9. CRE ages from ^{3}He (T_3), ^{21}Ne (T_{21}), radionuclides (T_{rad}), and preferred CRE age (T_{pref}) and gas retention ages of meteorites with CRE ages <0.1 Ma. Ages in 10^6 years.[a]

	CRE age				Gas retention age		
Meteorite	T_3	T_{21}	T_{rad}	T_{pref}	T_4	T_{40}	Ref.
GRV 98004 (H5)	0.049	0.056	–	0.052 ± 0.008	3600	4530	1
Farmington (L5)	0.033	0.030	0.034	0.032 ± 0.003	420	950	2, 3
Galim LL6 fraction	0.023	0.033	–	0.033 ± 0.007	3500	4450	2
Galim EH3 fraction	0.041	0.073	–	0.073 ± 0.015	3060	4480	2
ALH 82100 (CM2)	–	–	0.04	0.04	–	–	4

[a]The production rates for ^{3}He and ^{21}Ne according to Eugster (1988) for the respective types of meteorite and average shielding were adopted. For calculation of T_4 and T_{40}, the average chemical composition of the respective type of meteorite from Wasson and Kallemeyn (1988) was adopted. Typical experimental errors are ~15%. 1 = this study; 2 = from data in Table 8; 3 = Nishiizumi, personal communication (2003); 4 = Nishiizumi et al. (1993).

latter dating method is insensitive to gas loss (see references below). Good examples of chondrites with ^{3}He loss are Laochenzhen (T_{21} = 36.2 Ma and T_{81} = 36.7 Ma; Eugster et al. 1993), Lunan (26.6 Ma and 26.8 Ma; Eugster et al. 1987), and Guangrao (18.5 Ma and 15.1 Ma; Eugster et al. 1987). Thus, we conclude that the ^{21}Ne CRE age of Galim is most probably valid.

POSSIBLE PARENT BODIES FOR METEORITES WITH EXTREMELY SHORT CRE AGES

Table 9 gives all meteorites for which a CRE age of <0.1 Ma has been measured. They have no obvious common link and they represent 4 different chondrite types. What were their immediate precursor bodies? Farmington and Galim are falls but, as shown below, only the orbit for Farmington was determined. Arnold (1965) mentioned the importance of knowing the orbital parameters for Farmington being a meteorite with an extremely short CRE age. In a remarkable study of hundreds of newspaper reports on eyewitness observations of the fall event, Levin et al. (1976) succeeded in showing that Farmington had an orbit similar to the Earth orbit-crossing Apollo objects. In fact, all meteorites for which the orbital elements were determined come from the orbit of the Apollo objects: Pribram H5, Lost City H5, Innesfree L5, Neuschwanstein EL6 (all photographic network observations), Peekskill H6, Moravka H5–6 (videotape recording), Tagish Lake C2 (satellite observation), and Dhajala H 3.8 (eyewitness reports). The fact that these meteorites had an Earth-crossing orbit does not mean they must have been broken off an Apollo object. Morbidelli and Gladman (1998) concluded that most meteorites are fragments of main belt asteroids that have orbits between that of Mars and Jupiter. They acquired most of their CRE as <3 m objects in the belt before they were emplaced in a resonance and were ejected into an Earth-crossing orbit. This explains that most meteorites have CRE ages of >1 Ma.

The following 2 scenarios result in a short CRE for meteoroids: a) the parent body of a meteoroid is a main belt asteroid with an orbit close to the 3:1 Kirkwood gap or the ν_6 secular resonance (cf., Wetherill 1985; Wisdom 1985; Binzel 1989; Gaffey et al. 1993; Farinella et al. 1998). This meteoroid was rapidly ejected from the main asteroid belt into an Earth-crossing orbit. Gladman et al. (1997) calculated that objects from the 5:2 resonance have a median time to Earth-crossing of only 0.2 Ma; b) on the other hand, the immediate precursor body of a meteorite with short CRE age might be an Earth-crossing Apollo or an Earth-approaching Amor object as first suggested by Heymann and Anders (1967), Wetherill (1974 and 1976), and Levin et al. (1976). In fact, Morbidelli and Gladman (1998) have shown that a fraction of meteorites may come directly from Earth-crossing objects but that this fraction is less than a few percent. This is not in conflict with the present situation, having a small number of meteorites with very short CRE ages: only ~10 out of >1000 ordinary chondrites have CRE ages <1 Ma (Marti and Graf 1992; Eugster 2003).

Are there possible source bodies for ordinary and carbonaceous chondrites among the Apollo objects? Until about a decade ago, for the most common meteorites (the ordinary chondrites) to reach the earth's surface, the spectral analogues were rare among the asteroids that had been spectrally surveyed. However, during recent years, the progress in the field of spectroscopy was enormous: CCD detectors are now able to obtain visible and near-infrared reflectance spectra of objects as small as a few tens of meters (cf., Binzel et al. 2001a; Burbine et al. 2003). Furthermore, processes exist in the space environment that can transform spectra of ordinary chondrite-like material into those of S-type asteroids (cf., Britt et al. 1992; Chapman 1996; Binzel et al. 1996). Binzel et al. (2001a) found that S(IV)-type asteroids have a red-sloped spectrum with strong 1 and 2 μm adsorption bands and that this red slope is the primary spectral difference between this asteroid type and ordinary chondritic meteorites. Pieters et al. (2000) have shown that the spectral difference between chondrites and S-type asteroids is a natural consequence of space weathering on semi-transparent minerals (along with reduced albedo and band strength). These authors found that the presence of nanophase reduced iron (npFe) on the surface of regolith grains accounts for a change in optical properties of a planetary surface that is exposed to the space environment. Ordinary chondrite parent bodies, thus, are perfectly compatible with the mineralogy of many S-type asteroids.

Numerous spectral matches to ordinary chondrites have now been found in the near-Earth asteroid population of the Q-type and S(IV)-type objects. Q-type objects, as defined by Gaffey et al. (1993), consist mainly of olivine, pyroxene, and metal. The S(IV)-type asteroids are a subtype of the S-asteroids and are composed of olivine, orthopyroxene, and Fe/Ni metal in highly variable abundance. As first proposed by Levin et al. (1976), 1862 Apollo (Q-type) may be a possible source body of the Farmington chondrite. The Q-type asteroids were later identified as a spectroscopic match with the ordinary chondrites (cf., McFadden et al. 1985; Bell et al. 1989). 1862 Apollo is not the only Q-type near-Earth object. Other possible Earth-crossing source bodies for the ordinary chondrites with extremely low CRE age are: 1980 WF and 1981 QA (type Q; Tholen 1989), 1998 ST49, 1999 CF9, 2000 AC6, 9969 Braille (type Q; Binzel et al. 2001b), the Q-like asteroids 1991 WA, 1993 UB, 1995 WL8, 1995 YA3, 2102, and 5660 (Binzel et al. 1996), 433 Eros (type S; Trombka et al. 2000; Veverka et al. 2000), 1605 Toro (type S; Tholen 1989), 10302 1989 ML (shock-darkened chondrite-like; Binzel et al. 2001a), and 2002 NY 40 (Rivkin et al. 2003).

Possible source bodies for the CM chondrites are the C- and G-type asteroids because they have low albedos and relatively featureless spectra (Burbine 1998). 13 Egeria and 19 Fortuna (both G-type) are likely candidates for ALH 82100 (CRE age 0.04 Ma), as these main belt asteroids are located near the 3:1 resonance. Among the Apollo objects, the candidates are 1998 FG3 and 1998 UT18 (Binzel et al. 2001b).

CONCLUSIONS

The CRE ages of GRV 98002 (L5), Guangmingshan (H5), and Zhuanghe (H5) are 17.0 ± 2.5 Ma, 68.7 ± 10.0 Ma, and 3.8 ± 0.6 Ma, respectively. These ages are in the range of the CRE ages typical for the ordinary chondrites. GRV 98004 is exceptional: its CRE age is 0.052 ± 0.008 Ma. Among the >1600 meteorites for which a CRE age was determined, only 4 have an age ≤0.1 Ma: Farmington (L5, 0.032 Ma) Galim (LL6, 0.033 Ma), GRV 98004 (H5, 0.052 Ma), and ALH 82100 (CM2, 0.04 Ma). These low ages are not caused by noble gas diffusion loss after parent body break-up, as they are concordant with the CRE ages from radionuclides (Farmington and ALH 82100) or the ^{21}Ne CRE ages can be shown to be reliable (Galim and GRV 98004). Either these meteorites were broken off an asteroid in the main belt and were rapidly ejected through a resonance such as the 3:1 Kirkwood gap, the 5:2 resonance, or the ν_6 secular resonance or their immediate precursor body was an Earth-crossing Apollo object. Possible parent bodies of the ordinary chondrites are the Q-type and S(IV)-type asteroids and for the CM chondrites, possible parent bodies are those of C-type and G-type. Numerous spectral matches with ordinary chondrites and CM chondrites, respectively, have been identified in the near-Earth asteroid population and among the main belt asteroids with orbits close to the ejection resonances.

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