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Formation of metal and silicate globules in Gujba: A new Bencubbin-like meteorite fall

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Abstract—Gujba is a coarse-grained meteorite fall composed of 41 vol% large kamacite globules, 20 vol% large light-colored silicate globules with cryptocrystalline, barred pyroxene and barred olivine textures, 39 vol% dark-colored, silicate-rich matrix, and rare refractory inclusions. Gujba resembles Bencubbin and Weatherford in texture, oxygen-isotopic composition and in having high bulk δ^{15}N values (~+685‰). The ^{3}He cosmic-ray exposure age of Gujba (26 ± 7 Ma) is essentially identical to that of Bencubbin, suggesting that they were both reduced to meter-size fragments in the same parent-body collision. The Gujba metal globules exhibit metal-troilite quench textures and vary in their abundances of troilite and volatile siderophile elements. We suggest that the metal globules formed as liquid droplets either via condensation in an impact-generated vapor plume or by evaporation of preexisting metal particles in a plume. The lower the abundance of volatile elements in the metal globules, the higher the globule quench temperature. We infer that the large silicate globules also formed from completely molten droplets; their low volatile-element abundances indicate that they also formed at high temperatures, probably by processes analogous to those that formed the metal globules. The coarse-grained Bencubbin-Weatherford-Gujba meteorites may represent a depositional component from the vapor cloud enriched in coarse and dense particles. A second class of Bencubbin-like meteorites (represented by Hammadah al Hamra 237 and QUE 94411) may be a finer fraction derived from the same vapor cloud. *Copyright © 2003 Elsevier Ltd*

1. INTRODUCTION

The Bencubbin-like meteorites constitute a set of five metal-rich, quasi-chondritic rocks divided into two textural classes on the basis of grain size and inclusion type. Hammadah al Hamra 237 (HH237) and Queen Alexandra Range 94411 (QUE 94411) (here collectively called HQ) are fine-grained rocks that contain light-colored silicate globules, spinel-, melilite- and hibonite-rich refractory inclusions, some compositionally zoned metallic Fe-Ni grains, a few large metal globules, and rare small hydrated lithic clasts (e.g., Zipfel et al., 1998; Campbell et al., 2001; Petaev et al., 2001; Weisberg et al., 2001; Greshake et al., 2002; Krot et al., 2002). Bencubbin, Weatherford and Gujba (here collectively called BWG) are coarse-grained rocks that contain large light-colored silicate globules, large metal globules, rare refractory inclusions, and unzoned metallic Fe-Ni grains (e.g., Weisberg et al., 2001, 2002). Both classes are characterized by high bulk metal/silicate weight ratios (1.7–3), high δ^{15}N values (~400–1000‰) and O-isotopic compositions similar to, but somewhat below, those of CR carbonaceous chondrites and CH meteorites on the standard three-isotope diagram. The entire set of Bencubbin-like meteorites was dubbed "CB chondrites" by Weisberg et al. (2001), but because these rocks differ significantly in texture and bulk chemistry from normal chondrites and may have formed by non-nebular processes, we find this designation potentially misleading and do not use it.

Bencubbin is a polymict breccia containing silicate globules, carbonaceous and ordinary chondritic clasts (Lovering, 1962; McCall, 1968; Kallemeyn et al., 1978, 2001; Weisberg et al., 1990), metal globules (Newsom and Drake, 1979; Campbell and Humayun, 2000; Campbell et al., 2002) and a ^{15}N-rich composition (Prombo and Clayton, 1985; Franchi et al., 1986; Sugiura et al., 2000). Weatherford is a polymict breccia that includes metal globules, silicate globules, a carbonaceous chondrite clast and a ^{15}N-rich composition (Mason and Nelen, 1968; Prombo and Clayton, 1985; Weisberg et al., 1995, 2001).

Gujba is the first observed fall of the Bencubbin-like meteorites (Fig. 1). It fell on 3 April 1984 as a >100-kg mass in a cornfield near the village of Bogga Dingare in northeastern Nigeria (Islam and Ostaficzuk, 1988). Much of the meteorite was hammered into pieces by local people and most of the mass is now missing. Like Bencubbin (Simpson and Murray, 1932) and Weatherford (Beck and LaPaz, 1949), Gujba was originally misclassified as a mesosiderite. Unofficial synonyms of Gujba include Gidan Wire and Godogodo.

2. ANALYTICAL PROCEDURES

A 65-g slab of Gujba, removed from a 282-g specimen obtained by meteorite collector Eric Twelker, was examined visually and with a binocular microscope (Fig. 1). The Gujba

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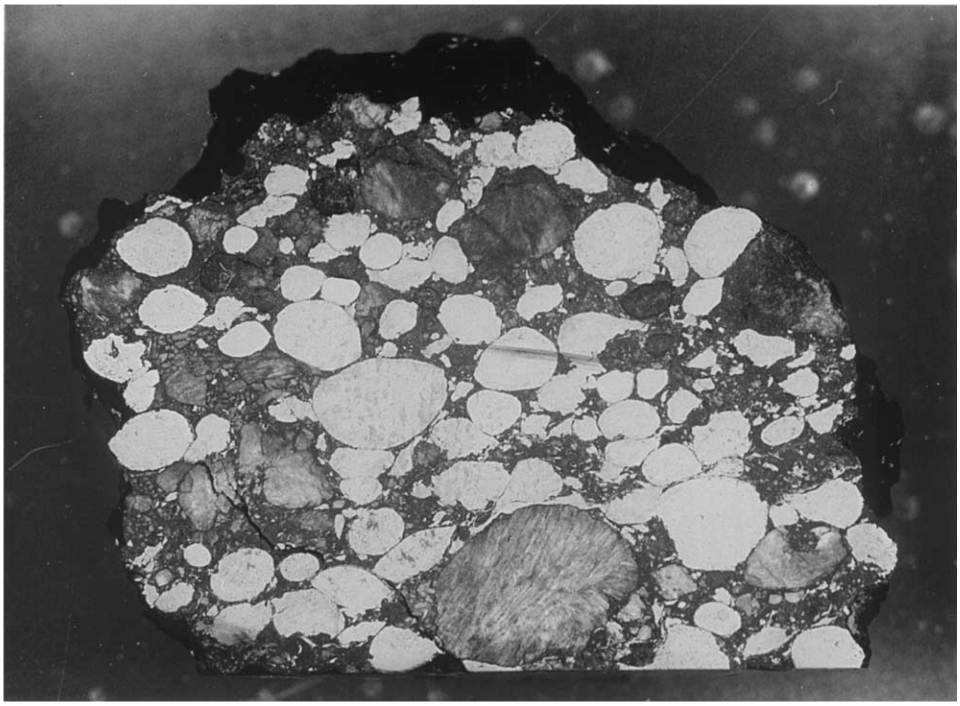

Fig. 1. A 65-g slab of Gujba composed of 41 vol% large metal globules (white), 20 vol% large silicate globules (light gray to dark gray) and 39 vol% fine-grained dark silicate-rich matrix (very dark gray). Reflected light. The slab is 4 cm across.

slab was cast into epoxy, polished and examined petrographically. Modal abundances were calculated from a digital image of the slab using Adobe Photoshop software. Grain sizes were determined visually with a ruler and microscopically using a calibrated reticle. Minerals were analyzed with the UCLA Cameca "Camebax-microbeam" electron microprobe using a focused beam, a sample current of ~12 nA at 15 kV, 20-s counting times, and natural and synthetic standards. Pouchou and Pichoir corrections (the Cameca version of ZAF corrections) were applied.

Several metal globules and silicate globules were removed from the Gujba slab with stainless-steel dental tools, cast in epoxy, polished and examined with a petrographic microscope. Modal abundances of troilite and metal were obtained with an automatic point counter.

Metal and silicate globules and dark, silicate-rich matrix material from Gujba were analyzed by INAA. Bencubbin dark matrix (~640 mg) was also analyzed. Samples were irradiated for 3 h in the nuclear reactor at the University of California, Irvine, with a nominal neutron flux of 1.5×10^{12} neutrons cm^{-2} s^{-1}. Samples and several standards were counted on high-resolution Ge detectors four times during the next four weeks. Silicate samples were reirradiated and counted immediately to determine Mg, Al and V. The detailed silicate procedure is described in Kallemeyn et al. (1989); the iron meteorite procedure is described in Wasson and Kallemeyn (2002). Data were reduced using the SPECTRA program of Grossman and Baedecker (1986).

The oxygen-isotopic composition of a silicate globule was determined using BrF_5 extraction (Clayton and Mayeda, 1963) and mass-spectrometric analysis of the evolved O_2 (Clayton et al., 1976).

Nitrogen and carbon extraction was attained by high-resolution stepped-combustion–mass spectrometry using Open University's *Finesse* static vacuum system (Verchovsky et al., 1997). Small chips of material were wrapped in degassed high-purity platinum foil and heated in incremental steps from room temperature to 1400°C. Each heating step lasted for the same fixed time and took place in the presence of excess oxygen gas. The C abundance was measured using a capacitance manometer within a known volume. Nitrogen abundances were determined from the ion beam current.

Noble gases were analyzed in two samples from a silicate globule. Samples were heated in vacuum at 90°C for several days to remove adsorbed terrestrial atmospheric gases. Then He, Ne and Ar were extracted in a single step by radio-frequency heating at 1700°C and measured in the Bern system-B mass spectrometer (Eugster and Michel, 1995). Details of the blank and background corrections as well as analytical procedures are in Eugster and Michel (1995).

The trapped Ne isotopic composition and the shielding indicator $(^{22}Ne/^{21}Ne)_c$ were obtained from a three-isotope plot (cf. Eugster and Michel, 1995); $(^{20}Ne/^{22}Ne)_{tr} = 11.1$ and $(^{22}Ne/^{21}Ne)_c = 1.054$. The following assumptions were made for the partitioning of the noble gas components: $^3He_{tr} = 0$, $(^{36}Ar/^{38}Ar)_c = 0.65$ and $(^{36}Ar/^{38}Ar)_{tr} = 5.32$. The bulk chemical composition of the silicate globule was used to calculate the ^3He, ^{21}Ne and ^{38}Ar production rates following the procedures of Eugster and Michel (1995). For the shielding correction of the ^{21}Ne production rate, we adopted the formula given by Lorenzetti et al. (2003) that was derived for aubrites, whose Mg, Al and Si concentrations are very similar to those of Gujba.

3. RESULTS

3.1. Petrography and Mineralogy

Gujba (Fig. 1) is an unweathered fall (weathering stage W0; Wlotzka, 1993). It contains remarkably ellipsoidal metal and silicate globules (as well as irregular globule fragments), roughly oriented in a WSW-ENE direction in Figure 1. We measured the orientations of 84 globules in the slab and found that 83% of them are oriented within 30° of the mean azimuth. Bencubbin components also exhibit a preferred orientation (McCall, 1968). Gujba texturally resembles Bencubbin (fig. 1 of Newsom and Drake, 1979) and Weatherford (fig. 1 of Mason and Nelen, 1968) except that Gujba is unbrecciated and most of its coarse metal and silicate globules are unfragmented. Our slab of Gujba (~10.4 cm^2) consists of three major components: (1) 41 vol% kamacite globules, (2) 20 vol% large light-colored silicate globules, and (3) 39 vol% dark-colored, fine-grained silicate-rich matrix. Also present are small, rare refractory inclusions (Weisberg et al., 2002). It is possible that the proportions of the major components vary from specimen to specimen.

The ellipsoidal and spheroidal kamacite globules range from 0.4 to 7 mm in maximum dimension. The vast majority of smaller metal grains tend to be irregular in shape. The kamacite globules have highly variable amounts (0.005–5.0 vol%) of Cr-bearing troilite and distinct textures (described below).

There are four basic globule textures (Fig. 2) that correlate with mean troilite modal abundance: (a) predominantly troilite-free, quasi-equant kamacite enclaves separated by lenses of arcuate troilite (e.g., globule 6 which contains 29 mg/g FeS); (b) troilite-free kamacite enclaves and troilite-bearing kamacite enclaves separated by minor arcuate troilite (e.g., globules 2, 4, 5, having a mean FeS content of 23 ± 7 mg/g); (c) troilite-free and troilite-bearing kamacite enclaves with no arcuate troilite separating them (e.g., globule 1; 16 mg/g FeS); and (d) globules that are nearly troilite free (e.g., globule 3; 0.14 mg/g FeS). Petrographic details follow.

Globule 6 (Fig. 2a) consists of 200–600-μm-wide quasi-equant kamacite enclaves separated, and, in some cases, partially surrounded by arcuate lenses of troilite. Many of the arcuate troilite lenses are three-lobed with the angles between adjacent lobes ranging from ~100° to ~160° and averaging ~120°. Although the vast majority of kamacite enclaves contain little (<0.5 vol%) or no troilite, a few contain up to 2 vol% troilite occurring in the form of 20–30-μm-wide spherules. The troilite spherules themselves contain ~1–3 vol% metal blebs that are 1–2 μm in diameter.

Globules 2, 4 and 5 (Fig. 2b) have fewer arcuate lenses of troilite than globule 6. Approximately 50% of the 150–1800-μm-wide kamacite enclaves are troilite-free; the remaining 50% contain 10–20 vol% 5–10-μm-size troilite spherules typically separated by 5 to 20 μm. Most of the troilite in these globules occurs in these small spherules. Some adjacent troilite-bearing and troilite-free kamacite enclaves are not separated by arcuate troilite.

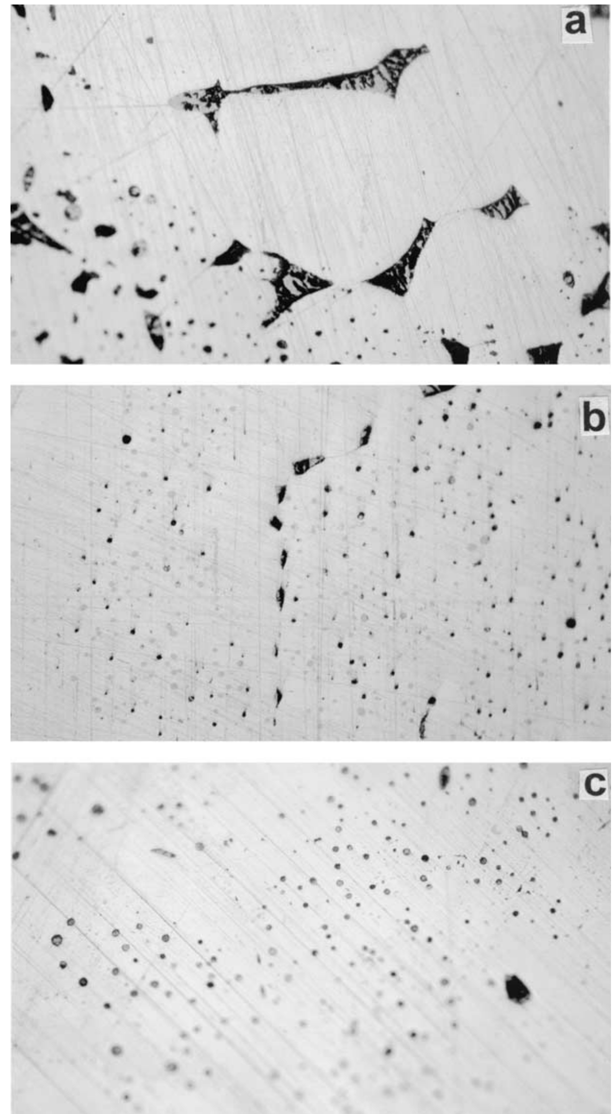

Fig. 2. Textures of separated metal globules. Thin lines are scratches due to sawing. (a) Globule 6 is dominated by quasi-equant kamacite enclaves separated by lenses of arcuate troilite. Most kamacite enclaves (e.g., center) lack internal troilite blebs, although a few enclaves (e.g., bottom) contain numerous troilite blebs. (b) Globule 5 has fewer (and smaller) arcuate lenses of troilite. The globule consists primarily of troilite-free and troilite-bearing kamacite enclaves. Most troilite occurs as 20–30-μm-wide spherules. Globules 2 and 4 have similar textures. (c) Globule 1 contains no arcuate troilite; it consists of adjacent troilite-free and troilite-bearing kamacite enclaves. Reflected light. All images are to the same scale, 800 μm across.

Globule 1 (Fig. 2c) contains no arcuate troilite but consists of troilite-free, 300–1000-μm-wide kamacite enclaves adjacent to similarly sized enclaves containing 5–10 vol% 5–10-μm-size troilite spherules spaced 20–50 μm apart. Also present in the troilite-bearing enclaves are a few 15 × 50-μm-size troilite ellipsoids.

Troilite is very rare in globule 3. The largest troilite grain is 15 × 50 μm in size; this grain contains ~1 vol% metal blebs that are 0.5–1 μm in diameter. Troilite in globule 3 contains much more Cr (7.8 wt%) than troilite in the other globules in

Table 1. Compositions of metal and sulfide (wt%) in metal globules determined by electron microprobe analysis.[a]

	Globule 1		Globule 2		Globule 3		Globule 4		Globule 5		Globule 6	
	Metal	Sulfide	Metal	Sulfide	Metal	Sulfide	Metal	Sulfide	Metal	Sulfide	Metal	Sulfide
No. grains	5	5	7	4	5	2	4	4	4	4	7	5
Fe	92.3 ± 0.8	60.1 ± 0.4	93.0 ± 0.9	62.4 ± 1.6	92.5 ± 0.8	54.3 ± 0.3	93.1 ± 0.9	60.7 ± 1.2	92.7 ± 0.9	61.1 ± 1.1	92.4 ± 1.2	59.2 ± 2.2
Ni	6.8 ± 0.7	0.20 ± 0.12	6.3 ± 0.2	0.36 ± 0.26	6.9 ± 0.3	0.13 ± 0.04	6.9 ± 0.7	0.17 ± 0.15	6.6 ± 0.3	0.09 ± 0.05	6.8 ± 0.5	0.15 ± 0.07
Co	0.28 ± 0.04	<0.04	0.29 ± 0.04	<0.04	0.28 ± 0.04	<0.04	0.31 ± 0.05	<0.04	0.30 ± 0.03	<0.04	0.29 ± 0.04	<0.04
S	<0.04	35.9 ± 0.8	<0.04	34.6 ± 2.0	<0.04	38.3 ± 0.2	<0.04	36.6 ± 0.8	<0.04	36.7 ± 0.1	<0.04	37.2 ± 0.6
Cr	0.12 ± 0.03	3.1 ± 0.3	0.10 ± 0.03	1.8 ± 0.9	0.28 ± 0.02	7.8 ± 0.4	0.14 ± 0.05	3.0 ± 1.2	0.10 ± 0.02	2.2 ± 0.7	0.24 ± 0.04	3.2 ± 1.4
Total	99.5	99.3	99.7	99.2	100.0	100.5	100.4	100.5	99.7	100.1	99.7	99.8

[a] Errors are 1 standard deviation.

Gujba (1.8–3.2 wt%; Table 1). The high Cr content suggests the possibility that tiny inclusions of a Cr-rich sulfide (e.g., daubréelite, $FeCr_2S_4$) are present in the troilite grains (although we did not observe such inclusions microscopically).

The coarse light-colored silicate globules are ellipsoidal to spheroidal and range from 0.8 to 10 mm in maximum dimension. The textures of most of the large silicate globules are cryptocrystalline with 50–400-μm-size, randomly oriented extinction domains. Each individual domain consists of bundles or narrow fan-like arrays of elongated magnesian low-Ca pyroxene crystals (Fs1.1-4.8 Wo0.7-5.9; mean: Fs2.0 Wo1.0; Table 2) with interstitial feldspathic glass. Smaller silicate globule fragments (50–600 μm) exhibit either cryptocrystalline (C) or barred pyroxene (BP) textures. Barred pyroxene textures are a variety of radial pyroxene (RP) texture in which the pyroxene bars are subparallel and do not radiate from a single point on the globule surface. In the BP objects, the individual pyroxene bars average ~6 μm in width; in the small C-textured objects, the individual bars average 2 to 4 μm in width. Weisberg et al. (2002) also reported small silicate globules with barred olivine (BO) textures. Many of the BO objects have intercalated olivine and low-Ca pyroxene bars; a few BO objects contain olivine bars separated by feldspathic glass (M. K. Weisberg, personal communication). Rare silicate globules contain magnesian olivine (Fa1.5; Table 2) or calcic pyroxene (Fs1.6Wo32.9; Table 2). None of the silicate globules contains metallic Fe-Ni or troilite.

The dark-colored, fine-grained silicate matrix is relatively rich in carbon (~0.5 wt%). The matrix contains small silicate globule fragments, small irregular metal globules (~100 μm) and smaller (2–50 μm size) irregular metal grains, blebs and veins. In some cases, the small metal particles surround silicate globules; in other cases, metal veins are connected to large metal globules. We show below that the bulk composition of the dark matrix is very similar to that of the light-colored silicate globules, indicating that the matrix is composed mainly of fragmented silicate globules.

Bencubbin dark matrix, also analyzed by INAA, is similar to the Gujba dark matrix in being composed mainly of fragmented silicate globules and metallic Fe-Ni. Small amounts of troilite are also present (e.g., McCall, 1968).

3.2. Shock Features

Low-Ca pyroxene and olivine grains exhibit undulose extinction, and olivine grains lack planar fractures, suggesting that the Gujba whole rock is shock stage S2. However, some features (detailed below) in Gujba are consistent with a higher shock-stage classification.

The inside edges of some kamacite globules contain long (up to 2 mm) stringers of fine-grained silicate mixed with troilite. Some of the arcuate troilite lenses in the kamacite globules (see below) appear to have been remelted; they consist of pure troilite cores flanked by light-colored troilite-metal mixtures containing ~60 vol% irregular to elongated, vermicular metal grains separated by 1–2-μm-thick troilite regions. Some of the metal grains within the arcuate troilite lenses are martensitic in composition, ranging from 9.0 to 15.5 wt% Ni.

Present in the matrix are fine-grained assemblages of metal and silicate that resemble the texture of shock veins in ordinary

Table 2. Mean compositions of mafic silicates (wt %) in light-colored clasts.

	Olivine[a]	Low-Ca pyx	Calcic pyx
No. grains	2	20	2
SiO_2	42.3 ± 0.8	57.9 ± 0.8	53.7 ± 0.7
TiO_2	0.05 ± 0.01	0.17 ± 0.04	0.54 ± 0.02
Al_2O_3	0.17 ± 0.06	0.83 ± 0.25	3.3 ± 0.3
Cr_2O_3	0.26 ± 0.03	0.54 ± 0.06	0.96 ± 0.45
FeO	1.5 ± 0.2	1.4 ± 0.5	1.0 ± 0.3
MnO	0.04 ± 0.03	0.09 ± 0.05	0.22 ± 0.30
MgO	54.8 ± 0.8	37.3 ± 0.4	23.3 ± 0.1
CaO	0.22 ± 0.03	0.54 ± 0.01	16.2 ± 1.5
Na_2O	<0.04	<0.04	0.06 ± 0.05
total	99.3	98.8	99.3
mol% Fa	1.5 ± 0.2		
mol% Fs		2.0 ± 0.8	1.6 ± 0.5
mol% Wo		1.0 ± 0.0	32.9 ± 2.4

[a] The appreciable amount of Al_2O_3 may be due to overlap of the electron beam on adjacent feldspathic material during microprobe analysis.

chondrites, except that the metal-silicate assemblages in Gujba lack troilite. Ramdohr (1973) dubbed this a "spontaneous fusion" texture. In some cases, metal globules adjacent to these assemblages include patches of cellular troilite indicative of shock-heating and quenching. Also present in the matrix are 40–100-μm-thick metal veins, some of which contain 10–30-μm-size silicate fragments surrounded by 5–12-μm-thick rinds (which themselves consist of fine-grained silicate intimately mixed with metal). The occurrence of shock-produced diamonds in Bencubbin (Mostefaoui et al., 2002) suggests the possibility that such phases are also present in Gujba.

3.3. Composition of Major Components of Gujba

3.3.1. Silicate Globule

The bulk composition of a silicate globule from Gujba (Table 3), determined by neutron-activation analysis, shows a relatively flat pattern of refractory lithophile abundances at 1.2–1.4 × CI, lower abundances of non-volatile V, Mg and Cr, significant depletions in moderately volatile Mn (0.55 × CI) and very low abundances of the more volatile lithophile elements Na and K (0.08 × CI and 0.07 × CI, respectively) (Fig. 3a). These data are consistent with the broad-beam electron microprobe analyses of Weisberg et al. (2001) that show <0.1 wt% Na_2O and K_2O in the silicate globules in Bencubbin and Weatherford.

Figure 3b plots the siderophile- and chalcophile-element abundances. This diagram shows a very low abundance of the refractory siderophile Ir (0.025 × CI), a similarly low abundance of the common siderophile Ni (0.024 × CI), and moderately higher abundances of the other common siderophiles (Co: 0.055 × CI; Fe: 0.064 × CI). The abundances of the volatile siderophiles Au and Sb are appreciably higher (0.58 × CI and 0.48 × CI, respectively), but those of chalcophile Se and Zn are much lower (0.022 × CI and 0.009 × CI, respectively).

3.3.2. Dark Matrix

Gujba dark matrix has a very similar lithophile abundance pattern to the silicate globule (Fig. 3a). Relative to the silicate globule, the dark matrix is slightly enriched in V and Cr, slightly depleted in Mn, and slightly enriched in Na and K. Bencubbin dark matrix has a similar lithophile element composition although it has somewhat lower refractory lithophile abundances.

Siderophile element abundances are very different between the Gujba dark matrix and silicate globule (Fig. 3b). Whereas the silicate globule has low abundances of Ir and common siderophiles, the dark matrix is enriched in these elements: refractory siderophile abundances (Os, Ir, Ru) are at 3.4–3.6 × CI, and Ni, Co and Fe are at 2.6–3.0 × CI. The CI-normalized Co/Ni and Fe/Ni abundance ratios also differ between the silicate globule (2.3 and 2.6) and the dark matrix (0.98 and 0.87).

Bencubbin dark matrix has siderophile and chalcophile abundance patterns similar to those of the Gujba dark matrix (Fig. 3b).

3.3.3. Kamacite Globules

Six 42–390-mg kamacite globules were separated from Gujba, examined petrographically and analyzed by INAA. Bulk compositions of the individual globules are listed in Table 4; siderophile-element abundances are plotted in Figure 4. There are correlations among the globules between troilite texture and mean troilite abundance. Both properties reflect the mean S concentration. There is a weaker trend between the troilite texture and the concentrations of volatile siderophile elements.

The bulk compositions of the kamacite globules overlap the compositional range of Gujba metal globules in table 2 of Campbell et al. (2002). In the present study, refractory siderophiles (Ir, Re, Pt) span the range from 0.8–0.9 × CI in globule 3 to ~2 × CI in globule 1. However, W is quite variable, ranging from 0.6 × CI in globule 5 to 2.4 × CI in globule 4.

Common siderophiles in all the globules are essentially unfractionated from CI: e.g., the Co/Ni concentration ratios in the globules (4.6×10^{-2} to 4.8×10^{-2}; Table 4) are within 3% of the CI value (4.7×10^{-2}; Wasson and Kallemeyn, 1988). (For plotting purposes, the CI Re value is assumed here to be 45 ng/g rather than 37 ng/g [Wasson and Kallemeyn, 1988] to reduce the otherwise implausibly large fractionation of Re from Ir. We suspect calibration errors in past analyses of Re.)

Volatile siderophiles in the globules show increasing depletions relative to CI with increasing volatility (Fig. 4). Nevertheless, there are significant differences among the globules in volatile siderophile abundances. (For purposes of discussion, we consider Cu and Ga to be volatile siderophiles even though they are partly chalcophile under reducing conditions.)

Globule 6 (which has more arcuate troilite than the other globules) contains relatively high CI-normalized volatile-siderophile/Ni abundance ratios: Au: 0.56; As: 0.41; Cu: 0.15; and Ga: 0.04.

Globule 4 has the highest concentrations of volatile siderophiles, but the average of the CI-normalized volatile-siderophile/Ni abundance ratios of globules 2, 4 and 5 (considered

Table 3. Composition of Gujba components and Bencubbin dark matrix determined by INAA.[a]

	Na (mg/g)	Mg (mg/g)	Al (mg/g)	Si (mg/g)	S (mg/g)	K (μg/g)	Ca (mg/g)	Sc (μg/g)	V (μg/g)	Cr (mg/g)	Mn (mg/g)	Fe (mg/g)	Co (mg/g)	Ni (mg/g)	Cu (μg/g)	Zn (μg/g)
dk mx 1	0.57	105	11.4			67	12.8	8.15	71.5	3.24	0.795	455	1.35	29.6		9
dk mx 2	0.55	93	10.4			46	11.2	6.61	70.7	3.17	0.745	494	1.64	34.8		7
dk mx av	0.56	99	10.9	(126)		56	12.0	7.38	71.1	3.20	0.770	474	1.50	32.2		8
Ben dk mx	0.71	98	9.7			57	10.2	6.63	68.4	3.32	1.04	483	1.46	31.4		6
sil globule	0.88	209	23.7	(244)		88	27.4	16.0	116	4.62	2.26	25.0	0.060	0.56		6
av met glob					6.9					2.46		924	3.10	66.2	92	
bulk Gujba	0.29	56	6.3	(70)	5.0	29	7.1	4.26	36.8	2.95	0.51	673	2.22	47.5	51	3

[a] Dk mx = dark matrix; sil = silicate; met = metal; glob = globule; av = average; Ben = Bencubbin. Bulk composition of Gujba estimated from modal proportions and estimated densities: 41 vol % metal globules (7.8 g cm^{-3}), 20 vol % silicate globules (3.2 g cm^{-3}), 39 vol % matrix (5 g cm^{-3}). Values in parentheses are estimates: Se in the metal globules estimated from the S concentration assuming the cosmic S/Se ratio of 3010; S in the matrix estimated from Se using the cosmic S/Se ratio; Os and Ru estimated from the Ir concentration assuming cosmic Os/Ir and Ru/lr ratios of 1.06 and 1.54, respectively. In the matrix and silicate globules, Si determined from estimated SiO_2; SiO_2 was derived by difference after assuming that Na, Mg, Al, K, Ca, Cr and Mn occur as Na_2O, Al_2O_3, K_2O, CaO, Cr_2O_3 and MnO and that 25 mg/g Fe occur as FeO.

together because of their similar textures) are similar to those of globule 6.

Globule 1 (which lacks arcuate troilite) contains lower CI-normalized volatile-siderophile/Ni abundance ratios than globules 2, 4, 5 or 6: Au: 0.38; As: 0.30; Cu: 0.04; and Ga: 0.02.

Globule 3 (which has very little troilite) contains the lowest CI-normalized volatile-siderophile/Ni abundance ratios: Au: 0.13; As: 0.11; Cu: 0.01; and Ga: 0.01.

3.4. Bulk Chemical Composition

An estimate of Gujba's bulk composition (Table 3) was made by combining in modal proportions the mean compositions of metal globules (Table 4), silicate globules (Table 3) and dark matrix (Table 3) and assuming the following densities for each component: 7.8, 3.2 and 5.0 g cm^{-3}, respectively.

It is widely accepted that Bencubbin silicates are basically chondritic in bulk composition. Because chondrite groups can be distinguished by their differences in bulk composition, it is germane to plot Bencubbin-like meteorites with those of established chondrite groups on ratio diagrams in which the numerator elements have different volatilities. Figure 5a shows Sb (a volatile siderophile) plotted against Ir (a refractory siderophile); both elements are normalized to Ni (a common siderophile). In this diagram, Gujba dark matrix plots relatively near (but outside) the H-chondrite cluster; its Sb/Ni ratio is lower than those of all H chondrites and its Ir/Ni ratio is higher than the vast majority of H chondrites. Gujba dark matrix has approximately the same Ir/Ni ratio as Bencubbin dark matrix, but has a much higher Sb/Ni value. The CH meteorite ALH 85085 contains appreciably higher Sb/Ni and lower Ir/Ni ratios than dark matrix in either Gujba or Bencubbin.

Figure 5b shows Zn (a volatile chalcophile/lithophile) plotted against Al (a refractory lithophile); both elements are normalized to Mn (a chalcophile/lithophile). The dark matrix in Gujba and Bencubbin plots in a broad region in the lower right of the diagram (i.e., the high-Al/Mn, low-Zn/Mn corner) along with a Gujba silicate globule. The CH meteorites (represented by ALH 85085) have similar Al/Mn contents but much higher Zn/Mn values. Well-established carbonaceous chondrite groups have even higher Zn/Mn ratios and various Al/Mn ratios.

These diagrams are consistent with the view that Gujba is more-or-less chondritic in bulk composition, but they also indicate that Gujba is not closely related to any of the principal chondrite groups. Gujba is moderately similar in bulk composition to Bencubbin but appears to have higher contents of volatiles.

3.5. Oxygen Isotopic Composition

The oxygen-isotopic compositions of Gujba silicates are very similar to those of Bencubbin, Weatherford and QUE 94411 (Fig. 6). The respective $\delta^{18}O$, $\delta^{17}O$ and $\Delta^{17}O$ values (in‰ relative to SMOW) are: Gujba light-colored silicate globules (+0.53, −2.19, −2.47); Gujba dark-colored silicate matrix (+0.98, −1.78, −2.29); Bencubbin (+0.90, −1.80, −2.27) (Weisberg et al., 1995); Weatherford (+1.69, −1.65, −2.53) (Weisberg et al., 1995); and QUE 94411 (+1.50, −1.47, −2.25) (Weisberg et al., 2001). Lying somewhat higher in $\delta^{18}O$ along a mass-fractionation line through the Gujba-Bencubbin-Weatherford-QUE 94411 data points is HH237 (+2.70, −0.77, −2.17) (Weisberg et al., 2001). All of these meteorites appear to be related; they lie above the CV-CK-CO chondrite field and below (although rather close to) the CH-CR field on the standard three-isotope diagram (Fig. 6). The oxygen-isotopic compositions of the Bencubbin-like meteorites show clearly that they are related to carbonaceous chondrites.

3.6. Nitrogen and Rare Gases

Bencubbin-like meteorites are characterized by a significant enrichment in ^{15}N relative to other chondrite groups (Prombo and Clayton, 1985; Franchi et al., 1986; Sugiura et al., 2000). Gujba dark matrix has a total N content of 144 μg/g and a $\delta^{15}N$ value of ~+685‰. The heaviest N was released at temperatures characteristic of carbide or metal decomposition, with $\delta^{15}N$ reaching +790‰. The Gujba $\delta^{15}N$ value is intermediate between those of Weatherford and Bencubbin (Fig. 7). The CH meteorite ALH85085 has a similar $\delta^{15}N$ content (Grady and Pillinger, 1990). Nitrogen in the other Bencubbin-like meteorites occurs in metal grains containing Cr-rich troilite, within a C-rich phase enclosed in metal, in shock-melted regions of the

Ga (μg/g)	As (μg/g)	Se (μg/g)	Ru (ng/g)	Sb (ng/g)	La (ng/g)	Sm (ng/g)	Eu (ng/g)	Yb (ng/g)	Lu (ng/g)	W (μg/g)	Re (ng/g)	Os (ng/g)	Ir (ng/g)	Pt (μg/g)	Au (ng/g)
1.1	1.78	1.40	2540	92	329	207	90	220	39			1600	1440		131
0.59	1.69	0.95	2400	62	277	171	81	215	29			1980	1790		136
0.84	1.74	1.18	2470	75	303	189	86	218	34			1790	1615		134
1.1	2.36	1.20	2280	34	252	158	59	174	26		179	1640	1560		270
		0.95	300	159	687	419	174	422	68				25		180
1.91	3.66	(2.3)	(5900)	<150						0.81	387	(4070)	3840	8.2	385
1.3	2.61	(1.8)	(4120)	<150	178	110	48	120	19	0.45	214	(2850)	2670	4.5	278

matrix, and in SiC and Al_2O_3 grains (Sugiura et al., 2000; Mostefaoui et al., 2001).

The cosmic-ray produced noble gases and calculated cosmic-ray exposure (CRE) ages (T_e) are given in Table 5. Although there is a large uncertainty, the CRE age of Gujba (26 ± 7 Ma) is similar to the ^{3}He CRE age of Bencubbin (27 Ma) as calculated from the data of Begemann et al. (1976) and of L. Schultz (unpublished data, 1970; given in Schultz and Franke, 2000). Because the chemical composition of the samples analyzed by these authors is not known, we used the same production rates for Gujba and Bencubbin. The similarity of the two CRE ages is consistent with the possibility that these meteorites were ejected by the same collisional event from a common parent body. (Although L chondrites have a broad T_e peak centered at ~28 Ma [fig. 1 of Marti and Graf, 1992], bulk and phase compositional data show that L chondrites are not closely related to the Bencubbin-like meteorites.)

The high metal content of Gujba could have caused significant matrix effects thereby raising the ^{21}Ne and ^{38}Ar production rates. On the other hand, the ^{3}He production rate is lower in metal-rich material than in metal-poor silicates. Our preferredCRE age of 26 ± 7 Ma (Table 5) is an average value of the ages obtained based on the three nuclides. We conclude that these effects will partly cancel each other out and are accounted for by the relatively large error limits.

4. DISCUSSION

4.1. Origin of Metal Globules

4.1.1. Textural Evidence for Quenching

Metal globule 6 consists mainly of troilite-free kamacite enclaves separated by arcuate lenses of troilite (Fig. 2a). The texture is similar to that of metal veins in the Rose City H chondrite (fig. 9 of Rubin et al., 2001) except that many of the Rose City veins have embedded patches of silicate. Another difference is the composition of the metal: kamacite (68 mg/g Ni) in globule 6, martensite with a mean value of 98 mg/g Ni in Rose City (Rubin, 1990).

Rose City is an impact-melt breccia (e.g., Mason and Wiik, 1966; Rubin, 1995) and its metal veins formed by impact melting and vaporization followed by fractional condensation. The intergrown metal-sulfide texture in Rose City formed after quenching from high temperatures. The martensitic composition of the metal indicates that the rock experienced little annealing; it did not cool slowly enough to unmix kamacite and taenite.

The similarities in texture of globule 6 to that of Rose City suggest that globule 6 experienced a similar thermal history. It probably quenched from high temperatures, but because of the low bulk Ni content of the metal, coarse kamacite-taenite intergrowths did not form within globule 6. The occurrence of minor amounts of martensitic metal within some arcuate troilite lenses inside some metal globules indicates that the Gujba whole rock was not appreciably annealed.

The textures of globules 2, 4 and 5 (Fig. 2b) differ from that of globule 6 mainly in having kamacite enclaves that contain abundant troilite spherules. A somewhat similar texture occurs in Bitburg, an iron meteorite that was smelted and quenched (fig. 352 of Buchwald, 1975). One significant difference between Bitburg and Gujba metal globules 2, 4 and 5 is the occurrence of kamacite in Gujba and abundant martensite in Bitburg. The overall similarity in texture, however, implies that the metal globules in Gujba were quenched.

Globule 1 (Fig. 2c) resembles globules 2, 4 and 5 in possessing some kamacite-rich enclaves with numerous troilite blebs, but differs from them in containing no arcuate troilite. Although globule 1 has a nearly identical troilite abundance to globule 2, it is appreciably lower than that of globules 4, 5 and 6 (Table 4). Globule 1 also probably formed by quenching, but its S content was too low (and/or its cooling rate too rapid) to allow formation of arcuate troilite.

Although troilite is very rare in globule 3, it seems reasonable to conclude that globule 3 formed in a manner analogous to that of the other globules, i.e., by quenching of a *S*-poor melt.

Weisberg et al. (2001) referred to the metal globules in Bencubbin as "aggregates" with interstitial troilite outlining the metal grains that constitute the aggregate. This label presupposes a model wherein quasi-equant metal grains became

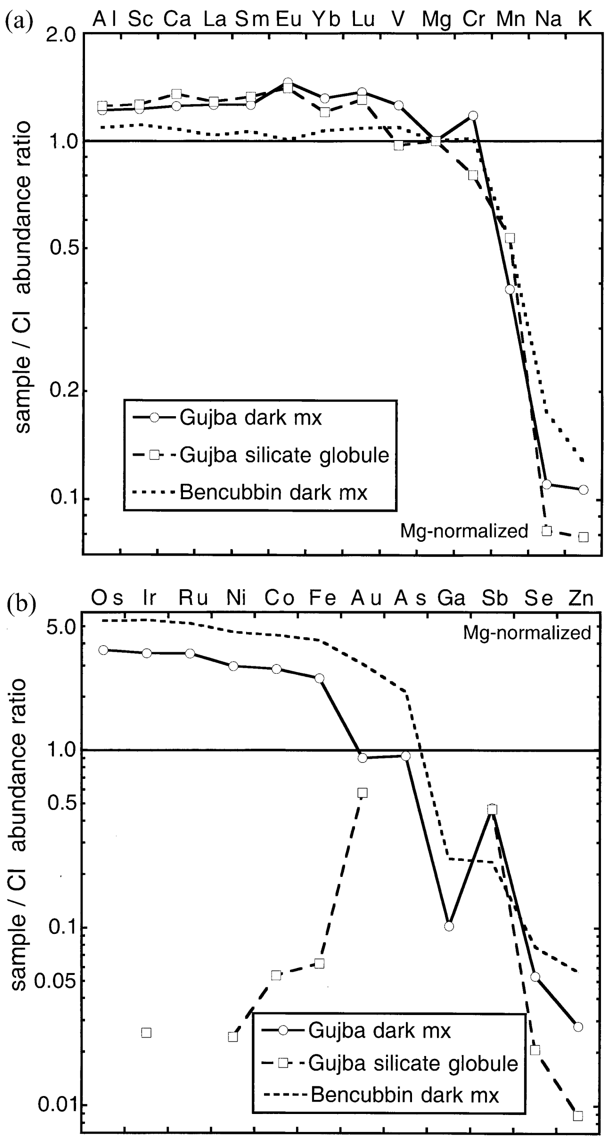

Fig. 3. Element abundance ratios of a silicate globule and a sample of dark matrix from Gujba. Also plotted is a sample of Bencubbin dark matrix. Data are normalized to Mg and to CI chondrites. Elements are plotted from left to right in order of decreasing volatility. (a) Lithophile elements. The refractory lithophiles in both components exhibit relatively flat patterns at ~1.2–1.3 × CI. Vanadium, Mg and Cr are depleted in the silicate globule; the matrix is depleted in Mg, slightly depleted in Cr, but not depleted in V. Both components have very low Mn (0.4–0.5 × CI) and even lower Na and K (~0.08–0.11 × CI) abundances. Bencubbin dark matrix has a pattern similar to that of Gujba dark matrix. (b) Siderophile and chalcophile elements. In the dark matrix sample, there is a progressive decrease in siderophile elemental abundances with increasing volatility: refractory siderophiles (Os, Ir, Ru) are high (~3.5 × CI), common siderophiles (Ni, Co, Fe) are slightly lower (2.5–3.0 × CI), and volatile siderophiles (Au, As, Sb) are much lower (0.45–0.90 × CI); Ga is particularly depleted (0.1 × CI). The chalcophiles (Se, Zn) have even lower abundances (0.028–0.055 × CI). Although very poor in siderophiles, the silicate globule has a siderophile elemental abundance pattern somewhat complementary to that of the dark matrix. Osmium is low (~0.025 × CI); Ni, Co and Fe show progressive increases (0.025, 0.055 and 0.06 × CI, respectively). Gold (0.6 × CI) and Sb (0.45 × CI) have much higher abundances; Se (~0.02 × CI) and Zn (0.009 × CI) are very low. The Bencubbin dark matrix sample has a similar siderophile/chalcophile pattern to that of Gujba dark matrix.

coated with troilite and then coalesced into larger objects (aggregates) while moving in space or through an impact cloud. As shown here, however, the texture of individual BWG metal globules is not aggregational. The globules formed from quenched liquid droplets; their quench textures resemble those of rapidly cooled metal-sulfide assemblages in Rose City and Bitburg.

4.1.2. Volatility Effects

The compositions of the metal globules seem to have been determined by volatility effects. Groups of elements of similar volatility tend to be in approximately solar proportions. For example, the refractory siderophiles Ir, Re and Pt have fairly flat CI- and Ni-normalized abundance ratios (Fig. 4). The mean Pt/Ir ratio of the globules (2.1) is within 5% of the CI value.

The same effects are observed with the common siderophile elements Co and Ni, whose 50%-condensation temperatures at 10 Pa (10^{-4} atm) are nearly identical to each other (1351 and 1354 K, respectively; Wasson, 1985). The Co/Ni ratios in the globules are within 3% of the CI value (4.7×10^{-2}).

A similar trend occurs for the volatile siderophile elements. The difference between the 50%-condensation temperatures of Au (1225 K) and As (1157 K) at 10 Pa is only 68 K. If volatility controlled the concentrations of elements in the globules we would expect their As/Au ratios to be roughly similar to the chondritic ratio of 12.8. This is the case: the As/Au ratios of the globules range from 8.4 to 10.6 (i.e., from 34 to 17% below the CI ratio). The mean Au/Ni (5.95×10^{-6}) and As/Ni (5.65×10^{-5}) ratios of the globules are 44 and 33%, respectively, of the CI ratios (1.35×10^{-5} and 1.72×10^{-4}, respectively; Wasson and Kallemeyn, 1988).

Because Ga and Au differ significantly in their 50%-condensation temperatures at 10 Pa (918 and 1225 K, respectively), it is not surprising that the Ga/Au ratios of the globules (3.1–7.4) are much lower than the CI ratio (68). This is also reflected in the low mean Ga/Ni ratio of the globules (2.95×10^{-5}), a value that is only 3.2% of the CI ratio (9.16×10^{-4}); the mean Au/Ni ratio of the globules is much greater, i.e., 44% of the CI ratio.

4.1.3. Condensation and Impact Melting

Impact-generated vapor clouds have been inferred to have produced diverse materials on different parent objects. For example, Lowe et al. (1989) suggested that the 3.4-Ga-old beds of millimeter-size spherules in marine sediments were produced by giant impacts on Earth. We suggest that these spherules formed mainly in the vapor cloud. Some magnetic spheroids recovered from the 65-Ma-old Cretaceous–Tertiary (KT) Boundary layer are Ir-rich (Smit and Kyte, 1984), suggesting that these spheroids originated in the vapor cloud associated with the KT impact event.

Volatile-rich, alumina-poor glass spherules from a mature lunar highland soil were modeled by Keller and McKay (1992) as having formed by the condensation of impact-produced vapors.

Large metal nodules in ordinary chondrites were inferred to have formed by impact-vaporization and subsequent fractional condensation of siderophile-element-rich vapors (Widom et al.,

Table 4. Compositions of separated metal globules determined by INAA.[a]

	Mass (mg)	FeS (mg/g)	S (mg/g)	Cr (mg/g)	Fe (mg/g)	Co (mg/g)	Ni (mg/g)	Cu (μg/g)	Ga (μg/g)	As (μg/g)	W (μg/g)	Re (ng/g)	Ir (μg/g)	Pt (μg/g)	Au (μg/g)
1	110.5	16.0	5.8	2.18	923	3.05	66.8	32	1.55	3.40	0.80	623	5.34	13.8	0.342
2	41.5	15.9	5.8	1.52	926	3.07	63.8	56	1.10	3.00	0.77	403	4.02	9.3	0.356
3	119.8	0.14	0.05	3.12	914	3.46	75.5	10	0.61	1.43	0.73	303	3.13	5.9	0.135
4	62.8	21.5	7.8	3.04	927	3.01	63.2	207	3.74	5.18	1.44	381	3.89	8.2	0.505
5	389.7	30.2	11.0	2.08	928	2.97	62.2	132	2.17	4.36	0.35	327	3.25	5.4	0.470
6	237.1	29.4	10.7	2.85	924	3.04	66.0	115	2.27	4.62	0.75	287	3.38	6.7	0.504

[a] The FeS volumetric abundance was determined by point counting; the FeS mass abundance was determined assuming densities of 4.67 and 7.85 g cm^{-3} for troilite and metallic Fe-Ni, respectively. The S content was calculated from the modal FeS mass abundance. The Fe content represents total Fe.

1986; Rubin, 1995, 1999). However, most ordinary-chondrite metal nodules probably formed within cracks and voids in the host rock rather than through the agency of an impact plume.

It seems plausible that the metal globules in Gujba, Bencubbin and Weatherford formed by condensation in an impact-generated vapor plume (Kallemeyn et al., 2001). A similar conclusion was reached by Campbell et al. (2002) who analyzed some metal globules from these meteorites by laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) and used thermodynamic modeling to demonstrate that the compositions of metal globules in the Bencubbin-like meteorites deviate from those expected from condensation in the solar nebula.

The spheroidal to ellipsoidal shapes of the Gujba metal globules indicate that they were shaped by surface tension and thus formed as liquid droplets. Liquid condensation requires the gas pressure to have been high enough for the condensation temperature to have been above the liquidus. At lower pressures, only gas-solid condensation could have occurred.

Condensation of liquid metal droplets could conceivably have occurred either in the solar nebula (Newsom and Drake, 1979) or from an impact plume generated during an energetic collision on an asteroid (e.g., Wasson and Kallemeyn, 1990; Kallemeyn et al., 2001).

We suggest that it is unlikely that the metal globules formed in the solar nebula. The pressures of Fe, Ni, S, etc. required to condense liquid droplets at canonical dust-to-gas ratios are far too high. In fact, equilibrium calculations for a vaporization event by Ebel and Grossman (2000) require an unrealistically high pH_2 of 100 Pa (10^{-3} atm) and a 500 × enrichment in dust to allow condensation of iron-sulfide liquids. In addition, the refractory-siderophile-element/Ni ratios in most of the globules exceed CI values by significant amounts; e.g., the Ir/Ni, Pt/Ni, Re/Ni and W/Ni ratios in globule 1 exceed CI values by factors of 1.9, 2.3, 2.7 and 1.3, respectively.

High gas pressures and high nonvolatile/volatile ratios could occur during an energetic collision at the surface of an asteroid. Melt may have been produced both by shock compression ($P \cdot \Delta V$ effects) and by condensation from a vapor plume.

If we assume that the metal globules formed by condensation within an impact-induced vapor plume, we must conclude from the occurrence of metal and silicate globules in Gujba, Bencubbin and Weatherford that both silicates and metallic Fe-Ni were present at the asteroid surface. This is consistent with the hypothesis that the target asteroid was an undifferentiated chondritic parent body. The similarities of the Bencubbin-like meteorites in oxygen-isotopic composition to carbonaceous chondrites indicate that the target asteroid was a carbonaceous chondrite. However, we cannot rule out an alternative suggestion by Campbell et al. (2002) that the Bencubbin-like meteorites formed by the collision of a metal-rich body and a reduced silicate body.

We model globule 3, which contains the lowest concentrations of volatile siderophile elements and S, as having quenched at the highest temperatures. Rare sulfide blebs crystallized from the melt. Chromium is elevated both in the metal and the sulfide (Tables 1 and 4).

Globules 1 and 2 quenched at lower temperatures than globule 3. They acquired somewhat higher concentrations of volatile siderophile elements and appreciably more S. We suggest that, after supercooling of the liquid, kamacite crystallized from the melt. In globule 2, some kamacite grains grew slowly and excluded S, which thereby became enriched in the residual melt. Other kamacite grains grew rapidly (possibly because they nucleated on tiny refractory metal nuggets) and incorporated more S; these formed kamacite enclaves containing small troilite blebs. The *S*-rich residual melt crystallized into arcuate troilite lenses separating the kamacite enclaves. Globule 1 formed in a similar manner except that there was little S-rich residual melt.

Globules 4 and 5 quenched at still-lower temperatures. They have higher abundances of volatile siderophile elements and S than globules 1, 2 and 3. They formed analogously but with appreciably higher abundances of S-rich residual melt.

The precursor droplet of globule 6 quenched at about the same temperature as that of globule 5, but almost all of the crystallizing kamacite excluded S. The S-rich residual melt crystallized into abundant arcuate lenses of troilite.

Among the metallic clasts in Bencubbin are rare ones that contain up to 2.3 wt% Si (Newsom and Drake, 1979; Weisberg et al., 1990). It seems possible that these metal particles formed in high-temperature regions of the vapor plume. As shown by Rambaldi et al. (1980), solid metal that condenses at higher temperatures (in a region having higher pressure) will have a higher equilibrium content of Si than metal formed at equilibrium at lower temperatures.

An alternative model is to consider the metal globules evaporative residues. If this model is correct, then metal droplets must have melted, coalesced to form globule-sized objects, and boiled. Globules 4, 5 and 6 would have been removed from the heat first, thereby retaining higher concentrations of S and volatile siderophiles than the other globules. Globule 3 would

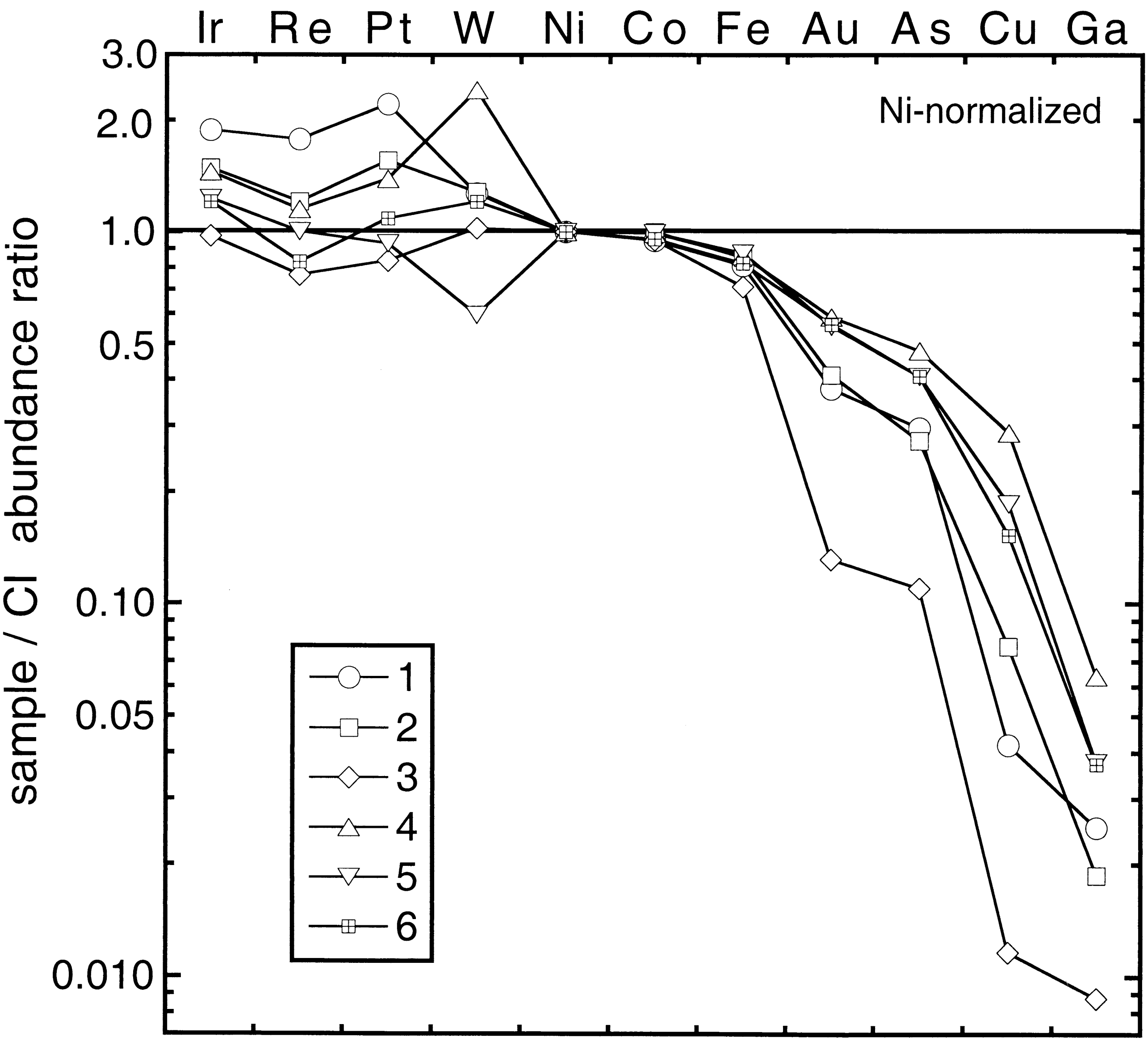

Fig. 4. Element abundance ratios of six kamacite globules from Gujba. Data are normalized to Ni and to CI chondrites. Elements are plotted from left to right in order of decreasing volatility. The globules vary the most in their abundances of volatile siderophiles. These abundances also correlate with globule texture. Globules 2, 4, 5 and 6 have the highest volatile siderophile abundances and contain arcuate troilite; globule 1 lacks arcuate troilite and has lower abundances; and globule 3, which has the lowest volatile siderophile abundances, is extremely depleted in troilite. CI-chondrite values used for normalization are from Wasson and Kallemeyn (1988) except for Re, which was assumed to be 45 ng/g to reduce the fractionation from the Ir abundance.

have experienced the greatest degree of evaporation, thereby losing the highest amounts of volatile siderophiles and S. Both condensation and evaporation models can account for the origin of the metal globules in Gujba and the other Bencubbin-like meteorites.

In either case, it is possible that S isotopic fractionation occurred during condensation/evaporation. If so, the sulfide-bearing metal particles that condensed at the highest temperatures (e.g., globules 1 and 2) may have heavier S isotopes than particles that formed at lower temperatures (e.g., globules 5 and 6).

4.2. Origin of Silicate Globules

All of the textural types of silicate globules (C, BP, BO) consist of elongated pyroxene or olivine crystals with interstitial CaO-rich feldspathic glass. Small grains of diopside occur adjacent to the bars in many of these objects. Chondrules with such textures formed via rapid crystal growth within quickly cooled (and somewhat undercooled), completely molten, silicate-rich droplets (Hewins, 1997). The precursor droplets of these chondrules were superheated long enough to have melted all preexisting crystalline material (Lofgren and Russell, 1986;

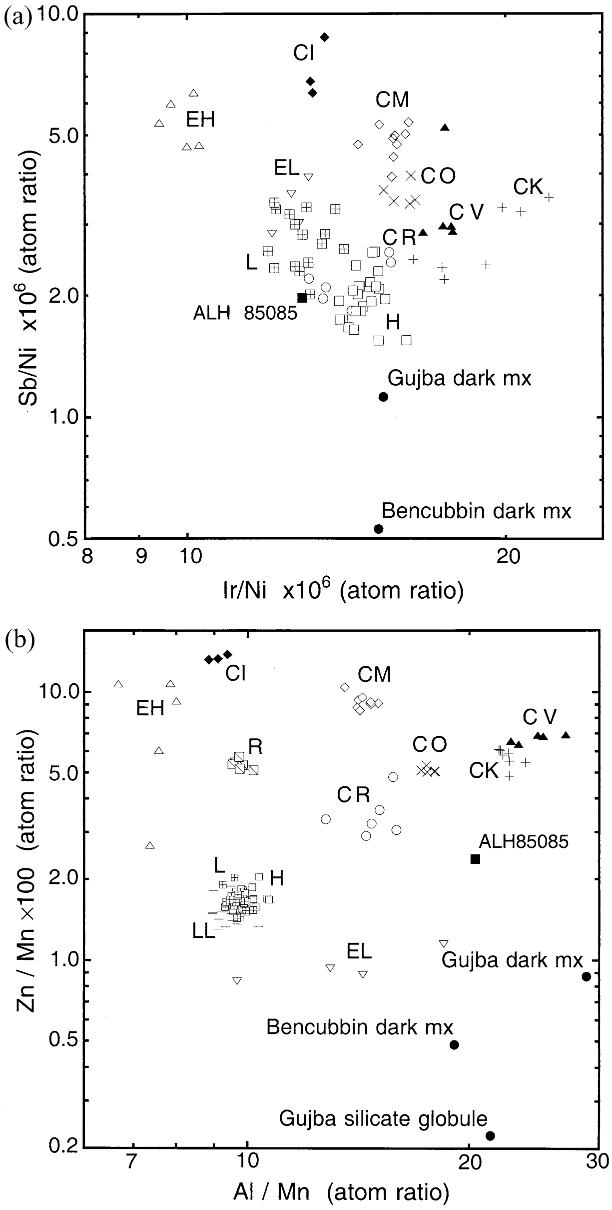

Fig. 5. Compositional diagrams comparing dark matrix material in Gujba and other Bencubbin-like meteorites to major chondrite groups. (a) The Sb/Ni vs. Ir/Ni diagram shows that Gujba and Bencubbin dark matrix lie outside the range of H and L ordinary chondrites, CR carbonaceous chondrites and CH meteorites (CH is represented by ALH 85085), and EH and EL enstatite chondrites. Gujba has nearly the same Ir/Ni ratio as Bencubbin but has much higher Sb/Ni. (The Sb/Ni ratio of the silicate globule is off-scale at ~137; the absence of metal in the globule and the high Sb value indicate that Sb is largely oxidized.) (b) In the Zn/Mn vs. Al/Mn diagram, Gujba and Bencubbin dark matrix plot in the low-Zn/Mn-high-Al/Mn corner, away from the ordinary, carbonaceous and enstatite chondrite groups. The Gujba silicate globule has a similar composition.

Hewins, 1989). Thus, the textural evidence indicates that the silicate globules in Gujba, Bencubbin and Weatherford formed by quenching of totally molten silicate droplets. Because Fe-O bonds break at high temperatures (>1200 K or so, depending on the oxygen fugacity), the target rocks may have been more ferroan than the resulting silicate globules.

Although troilite and metallic Fe-Ni occur as primary phases in most chondrules in primitive ordinary chondrites, a minor fraction of droplet (C, BP, RP, BO) chondrules are free of opaque minerals (Rubin et al., 1999). Because these chondrules formed from completely molten precursor droplets, a metal-troilite melt may have been lost by centrifugal action (Grossman and Wasson, 1985). The absence of troilite in the silicate globules in Gujba, Bencubbin and Weatherford therefore cannot be used as a constraint on the initial abundance of S in these objects. Similarly, the loss of a metal-troilite melt could account for the low (sub-CI-level) abundances of siderophile elements in the silicate globules (Fig. 3b).

The analyzed silicate globule has fractionated abundances of common siderophile elements; its CI-normalized Co/Ni and Fe/Ni abundance ratios are high, 2.3 and 2.6, respectively. The refractory siderophile, Ir, has a low abundance ratio, comparable to that of Ni (Fig. 3b). Because the silicate globules are free of metallic Fe-Ni and troilite, they probably lost their metallic Ir, Ni, Co and Fe. Because Ir and Ni are less oxidizable (i.e., more noble) than Fe and Co, the relatively high Co/Ni and Fe/Ni abundance ratios suggest that Co and Fe were retained partly as oxides during the event that resulted in metal loss.

The silicate globule has very low concentrations of the moderately volatile lithophile elements Na and K (Fig. 3a). Volatile siderophiles (Au, Sb; 0.45–0.60 × CI) and chalcophiles (Se, Zn; 0.009–0.02 × CI) are also low (Fig. 3b). The low volatile-element concentrations in the silicate globule indicate that the globule probably formed at high temperature.

Low volatile-element concentrations can be achieved by one of two end-member processes, i.e., by condensation at high temperatures and quenching before appreciable condensation of volatiles, or by devolatilization of objects that initially contained substantial volatile-element concentrations. It seems most plausible that the silicate globules formed by the same general process as the metal globules in the same meteorites: i.e., either by condensation or evaporation in a vapor plume.

Ebel and Grossman (2000) found that silicate liquids are stable condensates at 100 Pa (10^{-3} atm) at dust (nonvolatile) enrichments of ~12.5 relative to canonical nebular values. Silicate liquids and iron-sulfide liquids can coexist at 100 Pa at dust enrichments of ~1000. Although Ebel and Grossman (2000) modeled CI-like composition dust in the solar nebula, condensation in vapor plumes generated by impacts on the parent body of the Bencubbin-like meteorites would have occurred under conditions of far more extreme dust enrichments; thus, their calculations offer only qualitative constraints on the processes under consideration. For example, in the solar nebula, the H_2O/H_2 ratio buffers the oxygen fugacity (fo_2), but in an impact plume, the mix of vaporized oxides control fo_2.

4.3. Relationship of BWG to HQ

There are two competing models for the formation of the Bencubbin-like meteorites. Model 1 interprets the fine-grained HQ rocks as very-high-temperature nebular products formed in an oxidizing environment, probably relatively near the Sun (e.g., Krot et al., 2001a) and the coarse-grained BWG rocks as

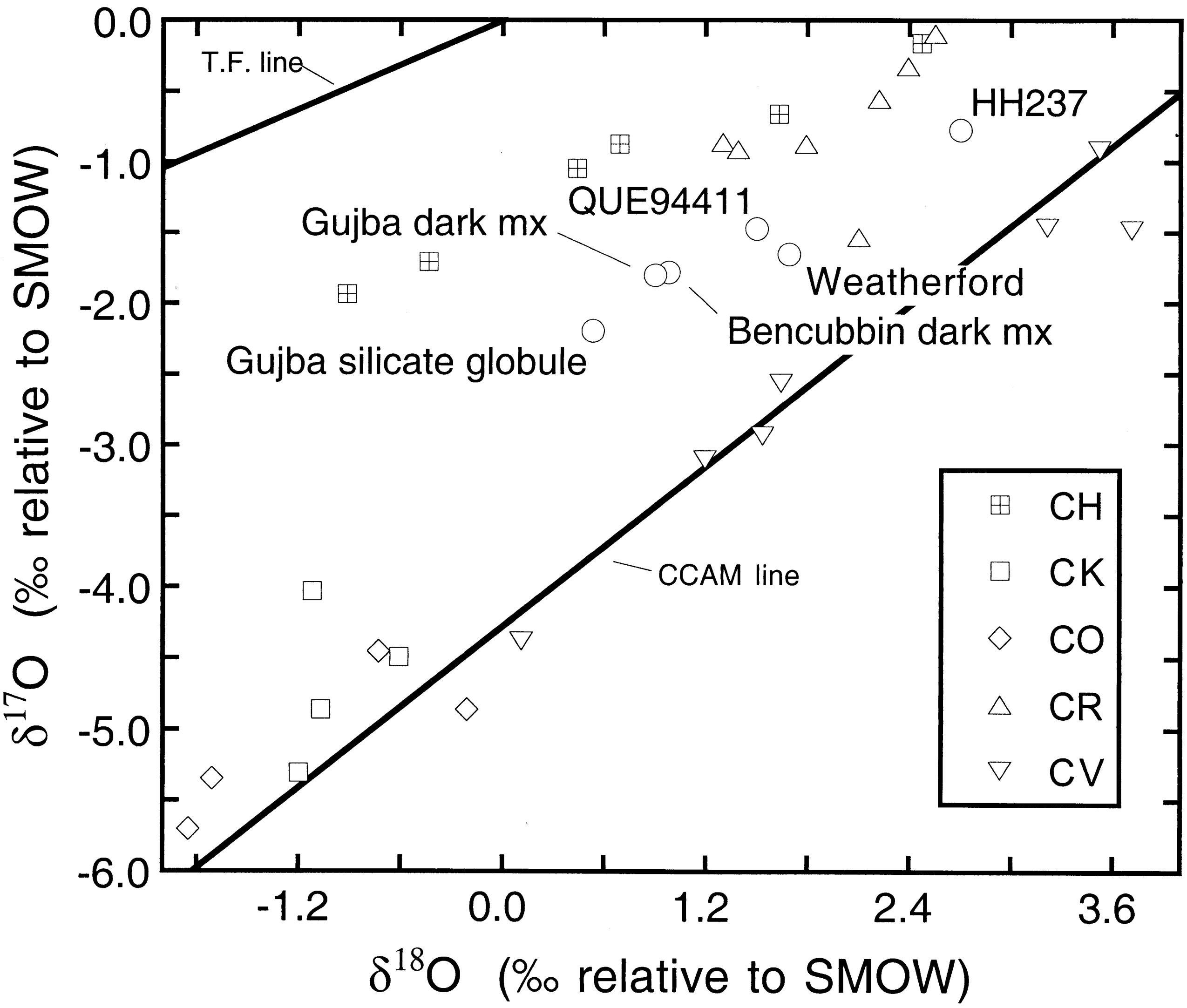

Fig. 6. O-isotopic compositions of Gujba and other Bencubbin-like meteorites compared to major chondrite groups. A light-colored silicate globule and a sample of dark matrix from Gujba plot on a line of slope ~0.5–0.6 along with Bencubbin dark matrix, QUE 94411 and HH237. This line lies below the CH-CR line and above the CCAM line (represented here by CO, CK and CV points).

impact products derived from fine-grained HQ precursors on an HQ-rich asteroid. Model 2 postulates that all five Bencubbin-like meteorites (and perhaps the related CH meteorites as well) formed within impact plumes on chondritic asteroids (Wasson and Kallemeyn, 1990; Kallemeyn et al., 2001).

The small symmetrically zoned metal grains in the HQ meteorites have higher concentrations of common siderophiles (Ni, Co) and refractory siderophiles (Ru, Rh, Os, Ir, Pt) in their cores than in their rims (Campbell et al., 2001). In contrast, Cr and P are slightly enriched in the rims relative to the cores (Campbell et al., 2001; Weisberg et al., 2001). The zoned metal grains were modeled by Campbell et al. (2001) as having formed in the solar nebula, either by a non-equilibrium fractional condensation process or by deposition of refractory-siderophile-poor coatings on refractory-siderophile-rich cores followed by diffusion. Meibom et al. (2001) suggested that the larger zoned metal grains formed over longer temperature intervals and grew at a constant rate.

It seems plausible that the nebular model for forming HQ is incorrect and that the zoned metal grains in HQ were also produced in an impact plume (a possibility also discussed by Campbell et al., 2002), perhaps in a portion of the vapor cloud of relatively low density. The refractory siderophiles may have formed in the vapor cloud as incompletely volatilized residues, followed by the condensation of Fe, Ni, Co, Cr and P.

The absence of zoned metal grains in the coarse-grained BWG rocks suggests that the HQ and BWG materials condensed at different times and at different regions within the vapor plume. The presence of a few coarse metal globules in QUE 94411 (fig. 1 of Weisberg et al., 2001) as well as in the BWG rocks also suggests that the nebular model is incorrect or oversimplified. The fine-grained HQ rocks are unlikely to have

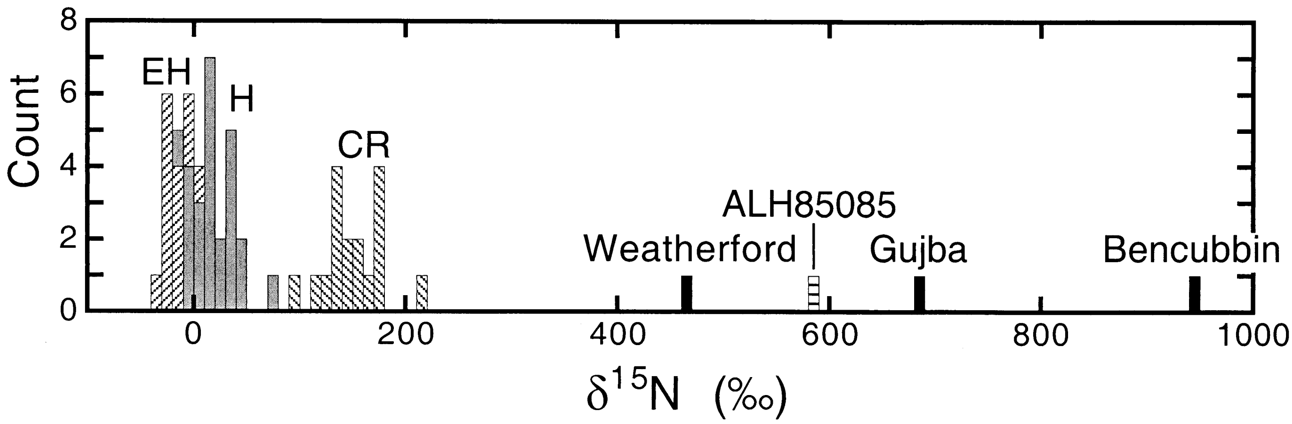

Fig. 7. N-isotopic compositions of Gujba and other Bencubbin-like meteorites compared to those of carbonaceous chondrite groups. The $\delta^{15}N$ value of Gujba ($\sim$+685‰) lies in between the data for Weatherford and Bencubbin and far above that of typical H, EH or CR chondrites. ALH 85085 (CH) lies within the same $\delta^{15}N$ range as the Bencubbin-like meteorites.

been the target materials from which the BWG rocks were derived by impact processes if both types of rocks contain some of the same impact-plume-derived components.

If the HQ zoned metal grains formed by condensation in an impact plume, the silicate-rich objects likely formed in the same manner. The BO, BP and C-textured chondrule-like silicate globules may have condensed at relatively high temperatures, thus accounting for their low abundances of moderately volatile elements (e.g., Na, K, S).

The high $\delta^{15}N$ values of the Bencubbin-like meteorites were probably derived from the target rocks. This is similar to the suggestion of Sugiura (1999) that the high $\delta^{15}N$ in these meteorites was derived from CH meteorite targets by shock heating. The principal N carriers were degassed; the liberated N was acquired by the metal at elevated temperatures (Sugiura, 1999).

4.4. Refractory Inclusions

Refractory inclusions occur in Gujba (Weisberg et al., 2002) and in HQ (Zipfel et al., 1998; Weisberg et al., 2001). Under the assumption that the Bencubbin-like meteorites formed in an impact plume, there are two possible modes of origin for the refractory inclusions: they are either relict nebular products introduced into the meteorites by regolith gardening processes or they are high-temperature condensates (or evaporative residues) from the vapor cloud. Krot et al. (2001a,b) pointed out that if the HQ refractory inclusions were nebular materials acquired from a regolith, then porphyritic chondrules (which are the most abundant chondrule textural type in most chondrite groups) would also have been incorporated. Their absence from HQ mitigates against the regolith model. The regolith model could be tested by searching for diaplectic glass or minerals with planar deformation features in the refractory inclusions; these should be present if the inclusions were derived from shocked target rocks.

4.5. Enrichment in Metallic Fe-Ni

The bulk metal/silicate weight ratios of the Bencubbin-like meteorites (e.g., 1.7 in Gujba, $\sim$3 in Bencubbin) are much

Table 5. Rare gas measurements of Gujba silicate globule.[a]

	Mass (mg)	^{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
Gujba-1	23.85	942 ± 30	28.0 ± 0.8	362 ± 12	18.2 ± 0.3	1.86 ± 0.03	1.167 ± 0.015	5.17 ± 0.05	1.425 ± 0.030
Gujba-2	19.51	735 ± 25	42.4 ± 1.3	334 ± 12	17.5 ± 0.2	3.33 ± 0.04	1.377 ± 0.025	5.17 ± 0.06	1.103 ± 0.030

	csmg ^{3}He	csmg ^{21}Ne	csmg ^{38}Ar	csmg ^{22}Ne/^{21}Ne	trapped ^{36}Ar	trapped ^{20}Ne/^{36}Ar
Gujba-1	51.8 ± 1.7	12.8 ± 0.4	1.59 ± 0.70	1.053 ± 0.050	253 ± 10	0.070 ± 0.004
Gujba-2	42.0 ± 1.3	9.1 ± 0.3	1.88 ± 0.90	1.055 ± 0.050	301 ± 10	0.115 ± 0.006
Gujba mean	46.9 ± 5.0	11.0 ± 2.0	1.74 ± 0.15	1.054 ± 0.050	277 ± 24	0.092 ± 0.023

	Production rates—P (10^{-8} cm^3 STP/g)			Cosmic-ray exposure ages—T (Ma)			
	P_3	P_{21}	P_{38}	T_3	T_{21}	T_{38}	$T_{preferred}$
Gujba	1.755	0.58	0.056	26.7 ± 4.0	19.0 ± 3.0	31.2 ± 5.0	26 ± 7

[a] csmg = cosmogenic. Uncertainties are 2σ errors.

higher than in any chondrite group (e.g., 0.24 in H, 0.41 in EH chondrites; modified from Jarosewich, 1990). The O-isotopic compositions of the Bencubbin-like meteorites indicate that they were derived from carbonaceous chondrites. However, the metal/silicate ratios greatly exceed those of the most metal-rich carbonaceous chondrites: CR, 0.20 (in Y793495; Weisberg et al., 1993); CO, 0.18 (in Kainsaz; Rubin et al., 1985); CV, 0.12 (in Efremovka; McSween, 1977). Even the metal-rich CH meteorite ALH 85085 (which Wasson and Kallemeyn, 1990, modeled as a non-chondrite that formed in an impact plume) has a metal/silicate weight ratio (0.78; Grossman et al., 1988) much lower than that of the Bencubbin-like meteorites. We therefore suggest that the high metal/silicate ratios of the Bencubbin-like meteorites are products of an impact process. The surviving target materials expected among the products of an impact event may include the ordinary and carbonaceous chondrite clasts in Bencubbin and Weatherford.

Particles suspended in a vapor plume can be sorted during deposition. As the energy in the cloud diminishes, the first particles to settle are those with the highest settling velocities. These will include the coarse and dense grains. Perhaps the coarse-grained BWG meteorites represent an early depositional component enriched in coarse and dense particles. It seems possible that the small particles and dense particles that constitute the HQ meteorites were formed in a different, less turbulent part of the cloud (perhaps settling to a distal region of the deposit). The finest grains and uncondensed gas from the plume seem not to be represented in our meteorite collections; they may have escaped into space. The elevated metal/silicate ratios in the Bencubbin-like and CH meteorites relative to those of the established carbonaceous-chondrite groups indicate that density settling from the vapor plume was significant.

5. CONCLUSIONS

The Bencubbin-like meteorites comprise two related classes of rocks, both of which appear to have formed from metal and silicate droplets either by condensation or evaporation in an impact-generated vapor plume. The wide range in volatile contents in the metal globules is attributed to quenching over a range of temperatures. The target may have been a metal-rich carbonaceous-chondrite parent body (perhaps resembling CR chondrites). It seems possible that the refractory inclusions in these meteorites formed by condensation at high temperatures from the vapor cloud after nucleating on relict refractory material suspended in the plume. We suggest that the coarse metal globules in Bencubbin, Weatherford and Gujba formed at moderately high gas pressures in one part of the cloud; the small symmetrically zoned metal grains in HH237 and QUE 94411 formed under similar conditions in a different portion of the vapor plume. The silicate globules in all of the Bencubbin-like meteorites formed as liquid droplets at high temperatures and gas pressures and acquired minor-to-negligible abundances of volatile elements. Metal and silicates may have been separated by centrifugal effects.

The dark-colored fine-grained silicate matrix in Gujba is composed mainly of crushed silicate globules and probably formed by parent-body impact-gardening processes. The similar ^{3}He cosmic-ray exposure ages of Gujba and Bencubbin (26 ± 7 and 27 Ma, respectively) are consistent with simultaneous ejection from one parent body by an energetic collision.

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