Shock melts in QUE 94411, Hammadah al Hamra 237, and Bencubbin: Remains of the missing matrix?

Anders MEIBOM1†*, Kevin RIGHTER2, 6, Nancy CHABOT2††, Greg DEHN3, 4, Angelo ANTIGNANO4, 5, Timothy J. MCCOY4, Alexander N. KROT1, Michael E. ZOLENSKY6, Michael I. PETAEV7, and Klaus KEIL1

1Hawai‘i Institute of Geophysics and Planetology, School of Ocean and Earth Science and Technology, University of Hawai‘i at Manoa, Honolulu, Hawai‘i 96822, USA
2Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721, USA
3Department of Geology, Colorado College, Colorado Springs, Colorado 80903–3298, USA
4Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, D.C. 20560–0119, USA
5Department of Earth and Environmental Sciences, The George Washington University, Washington, D.C. 20052, USA
6NASA Johnson Space Center, Mail Code ST, Houston, Texas 77058, USA
7Harvard-Smithsonian Center for Astrophysics and Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts 02138, USA
†Present address: Muséum National d’Histoire Naturelle, Laboratoire d’Etude de la Matière Extraterrestre, USM 0205 (LEME), Case Postale 5257 rue Cuvier, 75005 Paris
††Present address: Department of Geological Sciences, 112 A.W. Smith Building, Case Western Reserve University, Cleveland, Ohio 44106, USA
*Corresponding author. E-mail: meibom@mnhn.fr

(Received 27 January 2004; revision accepted 30 October 2004)

Abstract—We have studied the CB carbonaceous chondrites Queen Alexandra Range (QUE) 94411, Hammadah al Hamra (HH) 237, and Bencubbin with an emphasis on the petrographical and mineralogical effects of the shock processing that these meteorite assemblages have undergone. Iron-nickel metal and chondrule silicates are the main components in these meteorites. These high-temperature components are held together by shock melts consisting of droplets of dendritically intergrown Fe,Ni-metal/sulfide embedded in silicate glass, which is substantially more FeO-rich (30–40 wt%) than the chondrule silicates (FeO <5 wt%). Fine-grained matrix material, which is a major component in most other chondrite classes, is extremely scarce in QUE 94411 and HH 237, and has not been observed in Bencubbin. This material occurs as rare, hydrated matrix lumps with major and minor element abundances roughly similar to the ferrous silicate shock melts (and CI). We infer that hydrated, fine-grained material, compositionally similar to these matrix lumps, was originally present between the Fe,Ni-metal grains and chondrules, but was preferentially shock melted. Other shock-related features in QUE 94411, HH 237, and Bencubbin include an alignment and occasionally strong plastic deformation of metal and chondrule fragments.

The existence of chemically zoned and metastable Fe,Ni-metal condensates in direct contact with shock melts indicates that the shock did not substantially increase the average temperature of the rock. Because porphyritic olivine-pyroxene chondrules are absent in QUE 94411, HH 237, and Bencubbin, it is difficult to determine the precise shock stage of these meteorites, but the shock was probably relatively light (S2–S3), consistent with a bulk temperature increase of the assemblages of less than ~300 °C. The apparently similar shock processing of Bencubbin, Weatherford, Gujba (CBa) and QUE 94411/HH 237 (CBb) supports the idea of a common asteroidal parent body for these meteorites.

INTRODUCTION

The two recently recovered, essentially identical meteorites Queen Alexandra Range (QUE) 94411 (paired with QUE 94627) (Righter and Chabot 1998; Weisberg et al. 1999) and Hammadah al Hamra 237 (HH 237) (Zipfel et al. 1998) are cognate with other metal-rich chondrites including Bencubbin, Weatherford, and Gujba, and it has been suggested that they belong to the same group called the carbonaceous and Bencubbin (CB) meteorites (Campbell
et al. 2002; Rubin et al. 2003; Weisberg et al. 2001, 2002). These metal-rich meteorites are also related to the CH chondrites (Bischoff 1992; Bischoff et al. 1993b; Campbell and Humayun 2004; Grady and Pillinger 1990; Grossman et al. 1988; Scott 1988; Sugiuara et al. 2000; Wasson and Kalleneym 1990; Weisberg et al. 1988) and the CR chondrites (e.g., Bischoff et al. 1993a) and all belong to the CR clan (Krot et al. 2002; Weisberg et al. 1995, 1998, 2001). Note that the recent classification of QUE 94411, HH 237, Bencubbin, Weatherford, and Gujba into a single CB group (Weisberg et al. 2001) is not accepted by all researchers, for example, Bischoff (personal communication 2004). The CH chondrites, QUE 94411 and HH 237 have recently attracted much attention because they greatly extend the range of metal-silicate and volatile element fractionations in chondritic materials and because they contain both metallic and silicate components that are believed to preserve a record of very energetic and dynamic high-temperature processes in the earliest phases of the solar nebula (e.g., Campbell et al. 2001; Campbell and Humayun 2004; Hezel et al. 2003; Krot et al. 2001b, 2002; Meibom et al. 1999, 2000b; Petaev et al. 2001, 2003; Weber and Bischoff 1994; Weisberg et al. 2001). Other workers have argued that the various components of these metal-rich meteorites are formed in an impact-induced vapor plume (e.g., Rubin et al. 2003; Wasson and Kalleneym 1990). For a detailed discussion of these issues, we refer to Campbell et al. (2001, 2002), Kalleneym et al. (1978), Krot et al. (2001b, 2002), Petaev et al. (2001), and Rubin et al. (2003).

The focus of the work presented here is on shock features, but we approach this investigation with the view that the studied meteorites contain some components that formed directly in the solar nebula.

QUE 94411 and HH 237 are agglomerates of irregularly outlined Fe,Ni-metal grains and chondrules (Fig. 1a). Both meteorites are extremely enriched in Fe,Ni-metal (65–80 vol%), which is reflected in their bulk siderophile element abundances: siderophile elements more refractory than Pd are enriched by a factor of ~14 relative to Mg and Cl (Righter and Chabot 1998; Weisberg et al. 1999, 2001; Zipfel et al. 1998). More volatile siderophile elements (e.g., As, Ga, and S) are strongly depleted relative to Mg and Cl and these depletions correlate positively with increasing volatility, suggesting that high temperature fractionation controlled the observed element abundances (Krot et al. 2001b, 2002; Weisberg et al. 2001; Zipfel et al. 1998). Iron-nickel metal in QUE 94411 and HH 237 is characterized by a roughly solar Co/Ni ratio and variations in Ni concentration from ~3 wt% to ~15 wt% (Weisberg and Prinz 1999). A large fraction (~20%) of Fe,Ni-metal grains in QUE 94411 and HH 237 is chemically zoned with Ni and Co decreasing from core to edge and Cr increasing from core to edge (Weisberg and Prinz 1999; Weisberg et al. 1999). Similar chemical zoning patterns were observed in a few Fe,Ni-metal grains in CH chondrites, and it was suggested that this type of Fe,Ni-metal grain formed by gas-solid condensation from the nebular gas, in thermal events characterized by a range in pressure and temperature conditions and dust-gas ratios (Campbell et al. 2001; Campbell and Humayun 2004; Meibom et al. 1999, 2001; Petaev et al. 2001, 2003; Schoenbeck and Palme 2003; Weisberg et al. 2000, 2001). A few, anomalously large (mm-size) “metallic chondrules” (or fragments thereof) in QUE 94411 and HH 237, consisting of blocks of kamacite metal with abundant Cr-bearing troilite inclusions at their interfaces, are similar to the Fe,Ni-metal particles in Bencubbin, Weatherford, and Gujba (Campbell et al. 2002; Rubin et al. 2003; Weisberg et al. 2001, 2002). All other Fe,Ni-metal grains in QUE 94411 and HH 237 are S-free, consistent with a high-temperature origin by gas-solid condensation. The origin of the “metal chondrules” is still under debate. Some workers have argued for an impact origin of both the metal chondrules and the large silicate objects in Bencubbin (e.g., Campbell et al. 2002; Kalleneym et al. 1978; Rubin et al. 2003). Throughout this text, we will refer to the large silicate objects in Bencubbin simply as “chondrules.”

Silicates in QUE 94411 and HH 237 are present as chondrules or chondrule fragments with cryptocrystalline and microporphyritic textures; the latter type is also commonly referred to as “barred olivine” chondrules (Weisberg et al. 2001). These chondrules are all relatively poor in FeO (<5 wt%) and highly depleted in Mn, K, Na, and S (Krot et al. 2001b, 2002; Weisberg et al. 1999, 2001; Zipfel et al. 1998). Chromium concentrations are relatively high (0.4–0.8 wt% Cr$_2$O$_3$) and the chondrules contain extremely little or no Fe,Ni-metal. The microporphyritic chondrules are enriched in Ca, Al, and Ti over Si-normalized Cl levels by a factor of 2–4 (Krot et al. 2001b). Cryptocrystalline chondrules have highly variable abundances of these elements, ranging from essentially CI level to <0.1× CI. Krot et al. (2001b) suggested that chondrules in QUE 94411 and HH 237 formed either by fractional gas-liquid condensation of silicates in a dust-free environment or by prolonged heating of gas-solid precursor dust above liquidus temperatures to the point where all relict grains, which could have acted as nucleation sites during subsequent solidification, had disappeared. Hence, the majority of Fe,Ni-metal and silicates in QUE 94411 and HH 237 appear to have formed at high temperatures in the nebula and must have been isolated/removed from the cooling gas before more volatile components condensed out (Krot et al. 2000; Meibom et al. 2000b; Petaev et al. 2001). Fine-grained matrix material surrounds coarse-grained chondritic components (chondrules, CAIs, and Fe,Ni-metal nodules) in most chondrite classes. However, in QUE 94411 and HH 237, such fine-grained matrix material is sparsely distributed as heavily-hydrated lumps (Greshake et al. 2002; Meibom et al. 2000c). In Bencubbin and Weatherford, similar fine-grained material has not been observed. Coarse-grained components in all CB chondrites are held together by Fe,Ni-
Shock melts in QUE 94411, Hammadah al Hamra 237, and Bencubbin

metal/sulfide ferrous silicate shock melts (Campbell et al. 2002; Meibom et al. 2000c; Newsom and Drake 1979; Ramdohr 1973; Rubin et al. 2003; Weisberg et al. 2001). Here we report mineralogical, petrographical, and TEM observations of the shock melts and matrix lumps in QUE 94411 and HH 237 and of the petrographic properties of Bencubbin. Preliminary results of this study were presented by Meibom et al. (2000c).

PREVIOUS WORK ON SHOCK FEATURES

Ramdohr (1965, 1973) and McCall (1973) described shock melts in Bencubbin as melt droplets of Fe,Ni-metal and troilite embedded in silicate glass, a texture Ramdohr (1965, 1973) referred to as “spontaneous fusion.” Newsom and Drake (1979) and Perron et al. (2001) analyzed the silicate glass and chondrules in Bencubbin and found the glass to be

Fig. 1. a) Ni Kα X-ray map of Smithsonian Institution section QUE 94411-9. White and gray areas are Fe,Ni-metal grains. Black areas are silicates. Metal constitutes 75 vol% in this meteorite. About 15–20% of the metal grains are clearly zoned, with Ni concentrations decreasing from core (10–15 wt%) to edge (3–6 wt%) (Fig. 5). The image is about 1 cm across. b) Microporphyritic or “barred olivine” chondrule consisting of low- and high-Ca pyroxenes and olivine. c) Cryptocrystalline pyroxene-rich chondrule.
more FeO-rich (~22 wt%) than the chondrules (FeO < 5 wt%) and enriched in moderately volatile lithophile elements (0.5–6 wt% Na₂O, 0.1–1 wt% K₂O, and 0.4–0.7 wt% MnO). Using the laser probe ⁴⁰Ar–³⁹Ar technique and based on “a range of assumptions,” Kelly and Turner (1987) determined an age for the silicate glass portion of the shock melt in Bencubbin of 3.7–4.0 Ga, which is consistent with an impact origin. These authors noted that the age determination was complicated by the presence of a high concentration of excess ⁴⁰Ar and trapped ³⁶Ar, the presence of a nearby aubrite-like clast, and partial loss of argon during the shock event that produced the shock melt.

QUE 94411 was first described by Mason (1996), who tentatively classified it as a silicate-rich iron meteorite. Righter and Chabot (1998) reported metal and silicate analyses in QUE 94411 and realized that this meteorite was in fact a metal-rich chondrite, very similar to HH 237, which was first described by Zipfel et al. (1998). Metal grains and silicates in QUE 94411 and HH 237 are held together by shock melts of composition and texture similar to that in Bencubbin (Newsom and Drake 1979; Weisberg et al. 1999; Zipfel et al. 1998).

**ANALYTICAL TECHNIQUES**

We studied sections QUE 94411-6,-7,-9 and the paired meteorite QUE 94627-4, several HH 237 sections, and Bencubbin (USNM 5625; ~550 cm²) by optical microscopy. We also studied the QUE 94411 and HH 237 sections with a DSM 962 scanning electron microscope, and Cameca electron microprobes at the University of Hawai’i and the University of Arizona. Electron microprobe analyses (EMPA) were obtained using 15 kV accelerating voltage, 10–30 nA currents, a focused (~1 μm in diameter) beam, and well-characterized metal, silicate, oxide, and sulfide standards. The interference of the Fe Kβ-line on the Co Kα-line was corrected for in metal analyses. Matrix corrections were applied using a PAP software routine for both microprobes. Regions with shock melts in QUE 94411 were selected for more detailed characterization by TEM using a JEOL 2000FX (200kV) STEM. Selected Fe,Ni-metal droplets were ion milled to make them electron-transparent. Energy dispersive spectroscopy (EDS) analyses were obtained with a LINK EXL detector. Short exposures and low beam currents were used during imaging in order to minimize electron beam damage. Laboratory-derived k factors were used to reduce the STEM EDS data, which are considered to be accurate only to within about 8% relative. We performed EDS analyses on the STEM following high-resolution imaging, which permitted collection of both structural and compositional information on the metal grains.

Measurements of average diameter, orientation and aspect ratio of metal and silicate particles were performed by digitizing four points on the outline of metal and silicate particles in QUE 94411 (using Fig. 1a) and Bencubbin (using a mylar sheet with particles from USNM 5625 outlined); the

Fig. 2. Polished slab of Bencubbin (USNM 5625), with a surface area of ~550 cm². White is Fe,Ni metal; light gray and dark is silicate. Flattening of particles and preferred alignment in the vertical direction are apparent. The sample is roughly 25 cm across.
first two points defining the major axis, and the second two defining the minor axis. Orientations were determined by measuring with the digitizer the angle of the major axis of each particle to an axis of reference that, for practical reasons, was chosen to be roughly parallel to the apparent lineation of the particles. In addition, for Bencubbin, the extent of particle flattening was determined by calculating the aspect ratio (major axis/minor axis).

HH 237 is significantly more weathered than QUE 94411, so we therefore focused our studies on QUE 94411 in the Discussion section below. However, in general, HH 237 has the same properties as QUE 94411 and our discussions below are equally valid for HH 237.

RESULTS

There is strong evidence for mechanical deformation, i.e., flattening and particle alignment in both QUE 94411 (Fig. 1a) and HH 237 as well as in Bencubbin, Weatherford, and Gujba (Rubin et al. 2003). Flattening was evaluated by the distribution of measured angle between the longest apparent axis of metal or chondrules and a reference axis. If the orientation of the metal particles was random, these distributions would be essentially flat; i.e., all orientations would be equally probable. However, the distributions are peaked at low angles (about 5 degrees) and more than 85% of the particles have the longest axis oriented with an angle less than 45 degrees from the reference axis (Fig. 3). This demonstrates that the metal and chondrules in QUE 94411 and Bencubbin are preferentially oriented in one direction. Similar observations were made on Gujba (Rubin et al. 2003). Furthermore, in Bencubbin, both metal particles and chondrules exhibit a strong mode in their aspect ratio around 1.8–2 (Fig. 4), indicating a common deformational event for both types of particles. We note that not all sections of QUE 94411 or Bencubbin show preferred orientation and elongation of the metal and chondrules. This is because some sections are cut parallel to the plane of deformation of the particles. In those sections, all particles look essentially spherical and no preferred orientation can be determined.

In this study we find that the size of Bencubbin chondrules falls in the range of 0.2–1.4 cm, with a mode between 0.65 and 0.70 cm. Bencubbin metal particles are somewhat smaller, from 0.15–1.0 cm, with a mode between 0.25 and 0.30 cm. In contrast, metal and silicate particles in QUE 94411 and HH 237 are about an order of magnitude smaller. Chondrules range from 30–920 µm with a mode...
Metastable Metal Grains

Chemically zoned Fe,Ni-metal grains with decreasing concentrations of Ni and Co and increasing concentrations of Cr from core to edge (Fig. 5) make up roughly 15–25% of the metal in QUE 94411 and HH 237, depending on the thin section at hand (Fig. 1a). Most of the zoned Fe,Ni-metal grains have Ni concentrations in the core exceeding 10 wt% (up to ~15 wt%), and fall in the two-phase (α + γ)-field of the FeNi binary phase diagram (Fig. 5), rendering these particles metastable and susceptible to a Widmanstätten-like exsolution of kamacite upon prolonged heating at temperatures above ~300 °C (Zhang et al. 1993). A few metastable metal grains have decomposed (Fig. 6), and there are rare examples of decomposed grains that have subsequently suffered mechanical deformation (Fig. 7). However, in general, the metastable metal grains did not suffer extensive decomposition.

Melts

The melts consist of immiscible droplets of dendritically intergrown Fe,Ni-metal/sulfide surrounded by ferrous silicate glass, with abundant magnesian silicate fragments embedded (Fig. 8). Table 1 gives electron microprobe data for the Fe,Ni-metal/sulfide component, the silicate glass, and relict silicate fragments embedded therein. The Fe,Ni-metal/sulfide droplets are compositionally variable: (in wt%) Fe, 91 ± 5; Ni, 6 ± 1; Co, 0.3 ± 0.05; Cr, 0.2 ± 0.1; P, 0.16 ± 0.08; S, 2.2 ± 2. The Co/Ni ratio in metal-sulfide droplets is close to solar, similar to most Fe,Ni-metal in CR clan meteorites (Weisberg et al. 1995). Glassy ferrous silicate material displays some compositional variation: (in wt%) SiO$_2$, 32 ± 4; MgO, 24 ± 3; FeO, 35 ± 5; CaO, 2 ± 0.5; Al$_2$O$_3$, 4 ± 2; Cr$_2$O$_3$, 1 ± 0.2; TiO$_2$, 0.12 ± 0.02; Na$_2$O, 0.4 ± 0.05. Relict magnesian (FeO <5 wt%) silicate fragments embedded in the ferrous silicate glass are compositionally similar to the prevalent chondrule silicates (Table 1, Fig. 8) (Krot et al. 2001b; Meibom et al. 2000c) and generally preserve their angular appearance (e.g., Figs. 8e and 8f).

TEM observations of Fe,Ni-metal droplets embedded in the melts (Fig. 8) show that these metal particles in part consist of twisted, polysynthetically-twinned plates, separated by planar dislocations (Fig. 9). Metal with this particular texture is martensitic. Martensite generally denotes any diffusionless, structural transformation resulting in a persistent metastable phase with a high degree of short range order (Bhadeshia 2001; Kachaturyan 1983). When iron is rapidly cooled below a critical transition temperature (Tc ~910 °C for fcc austinite) it undergoes a first-order structural transformation to the bcc form ferrite. Rapid cooling thus results in ferrite consisting of polysynthetically-twinned plates, which is referred to as martensite (Kachaturyan 1983).

Matrix Lumps

Rare, fine-grained hydrated matrix lumps are present both in QUE 94411 and HH 237 (Greshake et al. 2002; Meibom et al. 2000c) and are quite similar to those described for CR and CH chondrites (Bischoff et al. 1993b; Endress et al. 1994). These matrix lumps consist of phyllosilicates, prismatic sulfides, framboidal magnetite, and Ca carbonates (Fig. 10). Broad-beam analyses (beam diameter ~15 µm) of 120 spots yield an average bulk composition of this clast of: (in wt%) SiO$_2$, 20 ± 5; MgO, 15 ± 4; FeO, 28 ± 10; CaO, 1.5 ± 2; Al$_2$O$_3$, 1.5 ± 0.5; Cr$_2$O$_3$, 0.3 ± 0.1; TiO$_2$, <0.4 (detection limit); Na$_2$O, 0.2 ± 0.1. The variations reported here and above represent the variations from spot to spot as a result of sample heterogeneity and are much larger than the analytical uncertainties associated with each measurement. The bulk composition of the matrix lump and the ferrous silicate component of the melts normalized to Si and Cl are shown in Fig. 11. Both the matrix lump and the ferrous silicate melt are depleted in Na by a factor of 3 relative to Cl. The matrix lump...
Shock melts in QUE 94411, Hammahal Hamra 237, and Ben cubbin

DISCUSSION

Based on the textural observations and observed similarities in bulk compositions of the matrix lumps and ferrous silicate portions of the melt (Fig. 11), it is inferred that fine-grained, porous material, compositionally similar to the matrix lumps, was originally present between the Fe,Ni-metal grains and chondrules in QUE 94411 and HH 237, but was preferentially melted by a shock event. A genetic relationship between the melt and the matrix lumps is indicated by similarities in major element (Si, Mg, Fe, Ca, and Al) abundances at roughly CI level and high concentrations of FeO (~30–40 wt%), which is about one order of magnitude higher than the FeO concentrations in chondrule silicates (<5 wt%). The ferrous silicate portion of the shock melt is also enriched in Cr. This Cr is most likely derived from the Cr-rich outer parts of the zoned Fe,Ni-metal condensates (Fig. 5), chipped off and oxidized during shock melting. Although fine-grained hydrated matrix material similar to that in QUE 94411 (Fig. 10) has not been observed in Ben cubbin and Weatherford, we suggest that such hydrated and porous matrix material was also present between the silicate and metal particles and became the source of the FeO-rich shock melt that now holds these meteorites together (McCall 1968; Newsom and Drake 1979; Ramdohr 1965, 1973).
Shock Stage and Metal Grains

We infer that the alignment (essentially a flattening) of the metal grains and the strong deformation of a few individual grains is due to a shock event that also welded silicates and Fe,Ni-metal grains together by producing an Fe,Ni-metal/sulfide–ferrous silicate shock melt (Fig. 8).

The extent of damage caused by a shock wave propagating into solid material depends on a number of parameters including shock pressure, as well as material parameters such as mineralogy, polycrystallinity, density discontinuities, and porosity. At moderate shock pressure, variations in material strength and phase transitions will modify the shock front as it passes through the material and cause the resulting damage of the target to be heterogeneously distributed (Bischoff and Stöffler 1992; Melosh 1989; Stöffler et al. 1991). In a chondritic assemblage, differences in shock impedance (defined as the product of shock wave velocity and mineral density) between different minerals in a rock will lead to large local differences in shock pressure and particle velocity, which in turn leads to strong shear movements amongst particles/domains of different properties (Bischoff and Stöffler 1992). Despite such complications, for ordinary and carbonaceous chondritic assemblages the equilibrium peak pressure, which characterizes the final state before decompression, can be estimated fairly precisely from the main mineral constituents, i.e., olivine and pyroxene, following the shock stage classification of Stöffler et al. (1991). However, this shock classification scheme is not directly applicable to QUE 94411, HH 237, and Bencubbin because of the absence of large, well-defined olivine and pyroxene crystals. At the same time, these meteorite assemblages offer perhaps the most extreme example of ubiquitous shock impedance variation, between the dominant Fe,Ni-metal phase (the densest phase) and the porous matrix component (Greshake et al. 2002; Meibom et al. 2000c), which is inferred to have been distributed between the metal and silicate particles prior to the shock event. This ubiquitous shock impedance variation makes these meteorites more likely to be dominated by “disequilibrium” shock effects (e.g., localized melting) (Stöffler et al. 1991) and makes estimates of the equilibrium peak pressure more ambiguous.

Metal and porous matrix material respond differently to the passing of a shock wave. Because of their high density, and corresponding high shock impedance, metal particles will experience relatively high shock pressures, which can lead to deformation, and moderate particle velocities, which cause flow of the particles. In contrast, the low density (low shock impedance) and low strength of the porous matrix material makes it prone to “absorb” the shock compression by simply collapsing. In doing so, porous material experiences a strong increase in particle velocity and therefore receives more heat. Physically, porous matrix material receives more PdV (P = pressure; V = volume) work during shock compression (Bischoff and Stöffler 1992; Melosh 1989) and will therefore experience locally higher post shock temperatures. Furthermore, the CB chondritic matrix material is characterized by a hydrous mineralogy.
with corresponding low melting point. The heavily hydrated matrix lumps observed in QUE 94411 and HH 237 are dominated by the phyllosilicates serpentine and saponite, contain no anhydrous silicates, and are broadly similar to type 1 and type 2 chondrite matrix material; in particular CI matrix (Greshake et al. 2002). In this situation, even mild (S2-S3; Stöffler et al. 1991) shock, which would leave olivine crystals only slightly damaged, might cause melting in the porous domains of the chondritic assemblage (Bischoff and Stöffler 1992). This effect is seen in both ordinary and carbonaceous chondrites where opaque melt veins and melt pockets, with textures similar to those observed here, are present at relatively low shock levels (S2–S3) that caused only minor damage to the olivine crystals (i.e., undulatory
Table 1. Electron microprobe analyses of droplet-shaped metal/sulfide particles, silicate glass, and relic silicate grains in shock-melted regions of QUE 94411. Individual analysis spots are marked in Figs. 8a–f. Low totals in some metal particles are due to the presence of small Si-rich inclusions in the droplet-shaped, fine-grained metal-sulfide intergrowths (Fig. 8b). Low totals in the silicate melts might be due to hydrated phases or the presence of small sulfides.

<table>
<thead>
<tr>
<th>Spot</th>
<th>Min.</th>
<th>SiO$_2$</th>
<th>TiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>Cr$_2$O$_3$</th>
<th>FeO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na$_2$O</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>a-s4</td>
<td>Px</td>
<td>51.9</td>
<td>0.5</td>
<td>5.1</td>
<td>0.7</td>
<td>3.1</td>
<td>30.2</td>
<td>9.3</td>
<td>b.d.</td>
<td>100.8</td>
</tr>
<tr>
<td>e-s4</td>
<td>Px</td>
<td>53.6</td>
<td>b.d.</td>
<td>0.1</td>
<td>0.7</td>
<td>2.8</td>
<td>42.6</td>
<td>0.1</td>
<td>b.d.</td>
<td>100.0</td>
</tr>
<tr>
<td>f-s4</td>
<td>Ol</td>
<td>40.6</td>
<td>b.d.</td>
<td>0.1</td>
<td>0.5</td>
<td>5.1</td>
<td>53.8</td>
<td>0.3</td>
<td>b.d.</td>
<td>100.4</td>
</tr>
<tr>
<td>f-s5</td>
<td>Ol</td>
<td>41.4</td>
<td>b.d.</td>
<td>0.3</td>
<td>0.4</td>
<td>5.3</td>
<td>53.4</td>
<td>0.2</td>
<td>b.d.</td>
<td>101.1</td>
</tr>
<tr>
<td>f-s6</td>
<td>Px</td>
<td>51.2</td>
<td>0.8</td>
<td>20.0</td>
<td>0.4</td>
<td>2.4</td>
<td>10.5</td>
<td>15.8</td>
<td>0.3</td>
<td>100.9</td>
</tr>
<tr>
<td>n.s.</td>
<td>Px</td>
<td>49.6</td>
<td>b.d.</td>
<td>1.6</td>
<td>0.6</td>
<td>4.5</td>
<td>43.3</td>
<td>1.4</td>
<td>b.d.</td>
<td>101.0</td>
</tr>
<tr>
<td>n.s.</td>
<td>Px</td>
<td>54.8</td>
<td>b.d.</td>
<td>0.1</td>
<td>0.8</td>
<td>1.2</td>
<td>43.7</td>
<td>0.1</td>
<td>b.d.</td>
<td>100.7</td>
</tr>
<tr>
<td>n.s.</td>
<td>Px</td>
<td>51.1</td>
<td>0.2</td>
<td>10.9</td>
<td>0.6</td>
<td>3.4</td>
<td>33.0</td>
<td>3.4</td>
<td>2.4</td>
<td>101.4</td>
</tr>
</tbody>
</table>

n.s. = not shown in Fig. 7; b.d. = below detection limit; px = pyroxene; ol = olivine.

extinction and planar fractures (Scott et al. 1992; Stöffler et al. 1991). Thus, light shock (S2–S3; 5–20 GPa) was most probably responsible for the shock features observed in QUE 94411, HH 237, and Bencubbin. The preferred orientation of chondrules and metal particles (Fig. 3) and their elongated shapes (Fig. 4) would, by comparison to ordinary and carbonaceous chondrites, indicate shock stage S3 (Scott et al. 1992; Sneyd et al. 1988). The higher pressures within this range (i.e., 15–20 GPa) are consistent with the findings of shock-produced diamonds in Bencubbin (Mostefaoui et al. 2002). Gujba generally appears to be less shocked (i.e., S2), although Rubin et al. (2003) report evidence for locally higher shock pressures.

### Localized Heating

The high-Ni (>8 wt% Ni) Fe,Ni-metal grains are metastable at temperatures below about 700–650 °C and would decompose into kamacite (α) and taenite (γ) upon prolonged thermal metamorphism at temperatures above ~300 °C (Zhang et al. 1993). However, only a few of the metastable zoned Fe,Ni-grains in QUE 94411 have decomposed into a plessitic intergrowth of kamacite and taenite, indicating that the temperature of the rock never was raised significantly over ~300 °C (Zhang et al. 1993). Figure 6 shows a rare example of a metal grain in QUE 94411 that did decompose into a kamacite-taenite intergrowth. Figure 7
Shock melts in QUE 94411, Hammadah al Hamra 237, and Bencubbin

Fig. 9. a) A TEM bright field image of Fe,Ni-metal ferrite droplet (arrowed) set within shock melts. Twin planes are evident as twisted light and dark bars within the ferrite. b) Selected area electron diffraction pattern of twinned, bcc ferrite (martensite) from the metal grain shown in (a). “a*” indicates the direction of the a-dimension for the metal phases. Diffraction spots labeled “s” are interpreted to be from remnant austenite within the ferrite.

Fig. 10. A BSE image of a hydrated matrix lump in QUE 94411. It consists of fine-grained silicates and phyllosilicates with larger, prismatic grains of sulfide, clusters of framboidal magnetite, and Ca carbonates (Greshake et al. 2002).
The limited degree of melting of chondrules, the dendritic textures of the shock melts, and the martensitic textures in shock melt metal droplets are all consistent with low pre-shock temperatures, localized heating, and rapid cooling of shock melted/heated material. Relict magnesian chondrule fragments embedded in ferrous silicate glass generally preserve their angular appearance (Figs. 8e and 8f) and do not appear to have contributed significantly to the composition of the ferrous silicate portions of the shock melt, also consistent with rapid quenching of the shock melt.

**Implications for the Accretion History of QUE 94411 and HH 237**

It has been suggested that chondrules and Fe,Ni-metal grains in QUE 94411 and HH 237 formed by condensation following large-scale thermal events that resulted in the complete vaporization of a region(s) of the solar nebula with enhanced dust/gas ratios (Campbell et al. 2001; Krot et al. 2000; Meibom et al. 2000c; Petaev et al. 2000). As a possible astrophysical setting for this event, it was proposed that early in the evolution of the nebula, when mass accretion rates through the disk onto the sun were very high (>10⁻⁶ solar masses year⁻¹) and temperatures near the mid-plane of the disk inside of a few AU high enough to vaporize precursor dust, gas convectively moved from the midplane to cooler regions above it, and the metal grains and chondrules condensed in these parcels of rising gas (Krot et al. 2000; Meibom et al. 2000c). Fine-grained matrix material was absent in this region during formation of Fe,Ni-metal and chondrules. The presence of matrix lumps and ferrous silicate shock melts in QUE 94411 and HH 237 (Fig. 10) with CI-like bulk compositions that are not complementary to chondrules (e.g., not highly enriched in volatile elements) is consistent with this model. This hydrated matrix material must have formed in a much colder region of the nebula; its presence in QUE 94411 and HH 237 could be explained either as a) a late addition to the QUE 94411/HH 237 parent body during regolith gardening, or b) as material that accreted together with Fe,Ni-metal and chondrules into the original parent asteroid.

If QUE 94411 and HH 237 are regolith breccias (scenario a) it would imply that metal and chondrules accreted into relatively large objects in the absence of matrix at high temperatures prior to condensation of more volatile elements. However, the slow cooling rates expected from accretion into planetesimals at high temperature seem inconsistent with the survival of the chemically zoned, metastable FeNi-metal grains in these meteorites (Meibom et al. 1999). On the other hand, if QUE 94411 and HH 237 are accretion breccias (scenario b), it would imply that metal grains and chondrules, which formed at high ambient temperatures (T ≥ 1200 K) (Campbell et al. 2001; Krot et al. 2001b; Meibom et al. 2000a; Petaev et al. 2000), were rapidly transported from hot to colder nebula regions, where hydrated matrix material could exist, prior to condensation of volatile elements. A strong stellar wind emanating from the early sun might provide a mechanism for transporting the zoned metal particles and chondrules outward to nebula regions, where
significantly lower temperatures prevail (Liffman and Brown 1996; Shang et al. 2000; Shu et al. 1996). As a potential test for the stellar wind transport mechanism, we suggest a search for radiation damage in Fe,Ni-metal grains and isotope anomalies in light elements (e.g., Li, Be, B) in chondrules, which might have been produced by spallation during radiation by energetic particles, such as those in solar flares (Gounelle et al. 2001; McKeegan et al. 2000).

**Implications for Classification of CB Chondrites**

Weisberg et al. (2001, 2002) noted the many mineralogical, petrological, and isotopic similarities between Bencubbin (also Weatherford and Gujba), QUE 94411, and HH 237. These similarities include a high metal abundance, metal with nearly solar Co/Ni ratios, Cr-rich troilite inclusions in large metal “chondrules,” similar volatile element depletion patterns, reduced silicate mineralogy, similar O-isotope compositions, and heavy N-isotopic compositions. On this basis, Weisberg et al. (2001, 2002) proposed to classify these five meteorites together as a group called CB (for carbonaceous and Bencubbin), implying a common asteroidal parent body, and placed the CB group within the CR-clan. However, it was also noted that important differences exist between QUE 94411/HH 237 and Bencubbin, Weatherford, and Gujba that complicate this classification. For example, refractory lithophile elements in these meteorites are above CI levels, but display great variability, from 1.1–1.5× CI, which is greater than within any other established chondrite group, and particle size varies significantly (see above). Weisberg et al. (2001) suggested dividing the CB group into CB\(_a\) (Bencubbin/Weatherford) and CB\(_b\) (QUE 94411/HH 237). This subdivision was also spurred by the lack of Ca-Al-rich inclusions in Bencubbin and Weatherford. However, a refractory inclusion has been identified in Gujba (Weisberg et al. 2002) with a mineralogy very similar to that of refractory inclusions in QUE 94411 and HH 237 (Krot et al. 2001a, 2002). This observation, combined with the findings of this study, which indicate similar shock processing of QUE 94411/HH 237 and Bencubbin, Weatherford, and Gujba (Rubin et al. 2003), lend support to the idea of a common asteroidal parent body for these meteorites. If this model is correct, a similar age for the shock melt in Bencubbin and in QUE 94411 would be expected. The tentative age determination of the shock melt in Bencubbin (3.7 ± 4.0 Ga) (Kelly and Turner 1987) is obviously relevant. Precise age determinations of the shock melts in both Bencubbin and QUE 94411 would form powerful constraints on any model for the origin of these meteorites.

**Acknowledgments—**Samples for this study were kindly made available by the Smithsonian Institution and J. Zipfel. This work was supported in part by NASA grant NAGW5-10610 and NAG5-13131 (A. N. Krot, P. I.), NAG 5-4212 (K. Keil, P. I.), NAG5 9435 (M. Drake, P. I.) and a cosmochemistry grant to M. Zolensky. Constructive reviews by Addi Bischoff and Paul Buchanan are greatly appreciated.

**Editorial Handling—**Dr. Wolf Uwe Reimold

**REFERENCES**


