Meteoritics & Planetary Science 40, Nr 9/10, 1377–1391 (2005)
Abstract available online at http://meteoritics.org

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

Anders MEIBOM[1†*], Kevin RIGHTER[2, 6], Nancy CHABOT[2††], Greg DEHN[3, 4], Angelo ANTIGNANO[4, 5], Timothy J. McCOY[4], Alexander N. KROT[1], Michael E. ZOLENSKY[6], Michael I. PETAEV[7], and Klaus KEIL[1]

[1]Hawai'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
[2]Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721, USA
[3]Department of Geology, Colorado College, Colorado Springs, Colorado 80903–3298, USA
[4]Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, D.C. 20560–0119, USA
[5]Department of Earth and Environmental Sciences, The George Washington University, Washington, D.C. 20052, USA
[6]NASA Johnson Space Center, Mail Code ST, Houston, Texas 77058, USA
[7]Harvard-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 Extraterrestré,` 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 (CB_a) and QUE 94411/HH 237 (CB_b) 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; Sugiura et al. 2000; Wasson and Kallemeyn 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 Kallemeyn 1990). For a detailed discussion of these issues, we refer to Campbell et al. (2001, 2002), Kallemeyn 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 CI (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 CI 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; Kallemeyn 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_2O_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 CI 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-

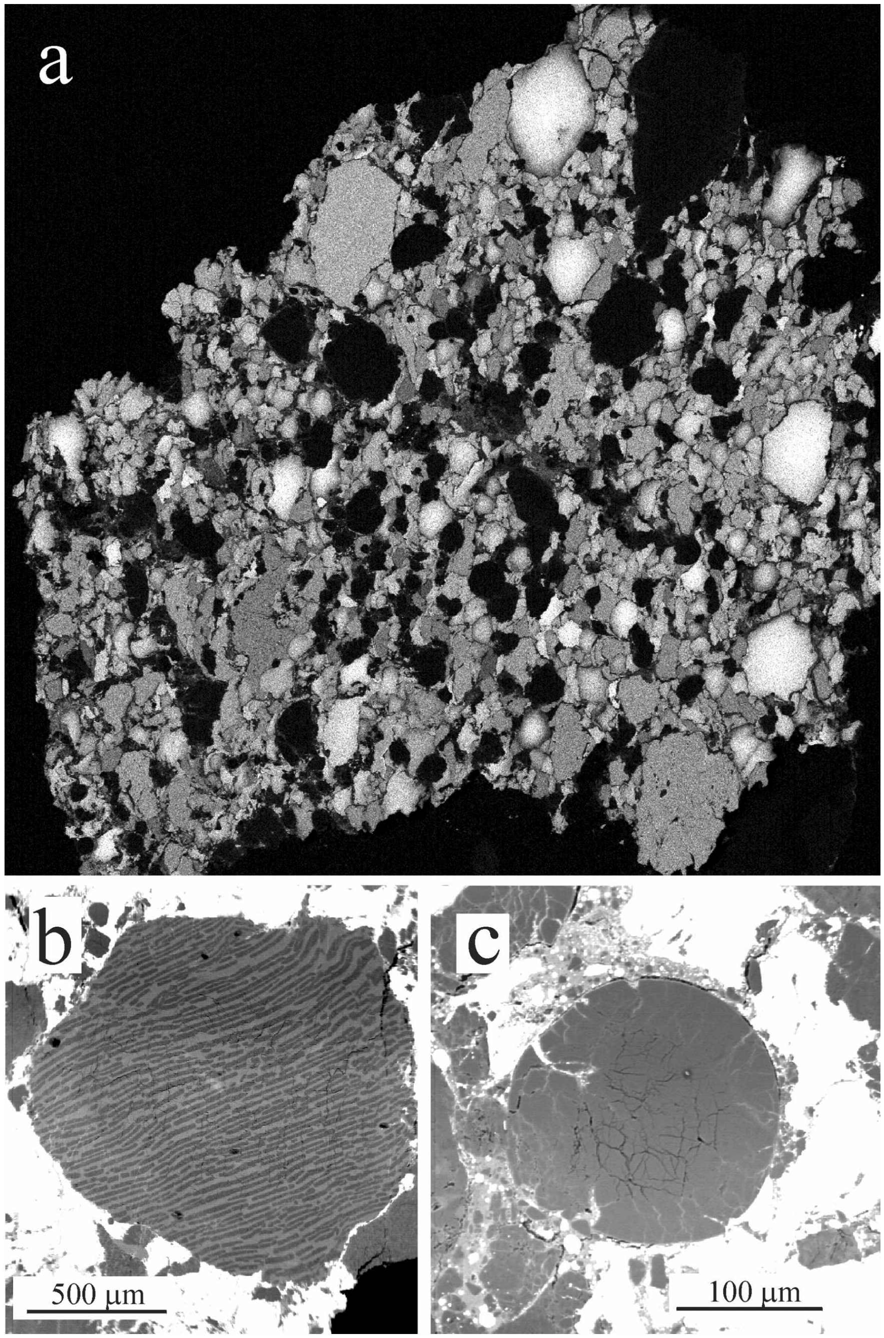

Fig. 1. a) Ni Kα X-ray map of Smithsonian Institution section QUE 94411-9. White and gray areas are Fe,Ni-metal grains. Black areas are silicates. Metal constitutes 75 vol% in this meteorite. About 15–20% of the metal grains are clearly zoned, with Ni concentrations decreasing from core (10–15 wt%) to 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.

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

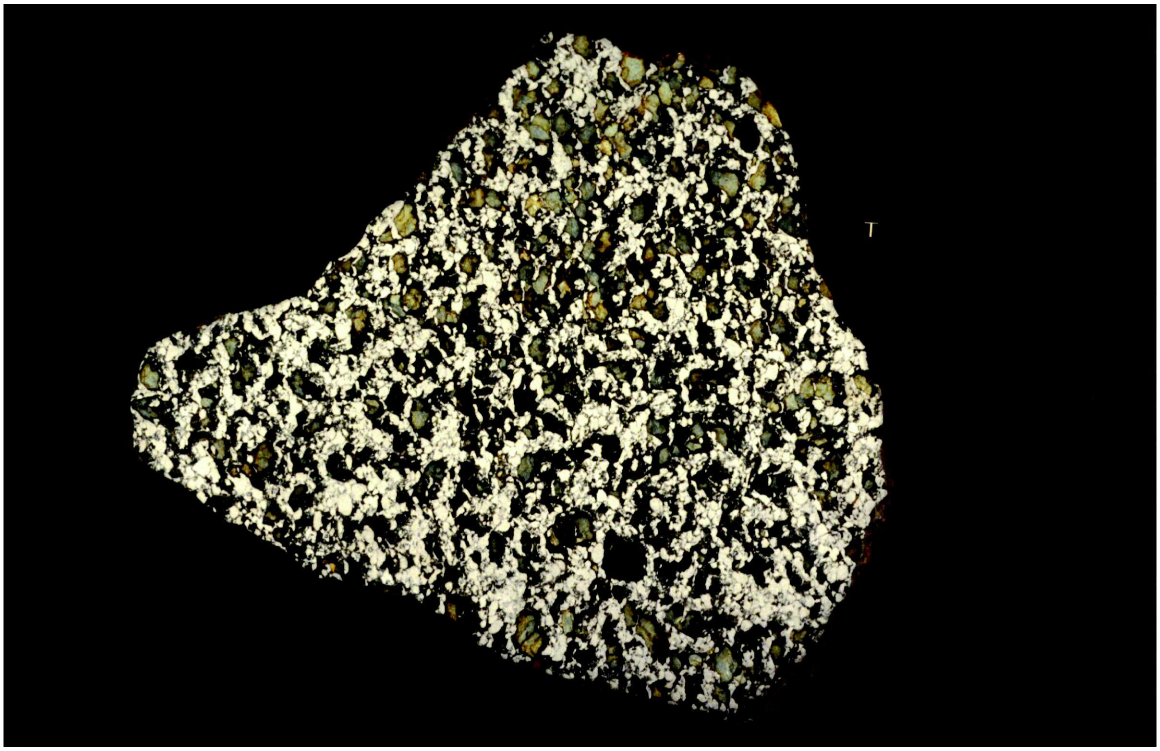

Fig. 2. Polished slab of Bencubbin (USNM 5625), with a surface area of ~550 cm^2. White is Fe,Ni metal; light gray and dark is silicate. Flattening of particles and preferred alignment in the vertical direction are apparent. The sample is roughly 25 cm across.

more FeO-rich (~22 wt%) than the chondrules (FeO <5 wt%) and enriched in moderately volatile lithophile elements (0.5–6 wt% Na_2O, 0.1–1 wt% K_2O, and 0.4–0.7 wt% MnO). Using the laser probe ^{40}Ar-^{39}Ar 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 ^{40}Ar and trapped ^{36}Ar, 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 cm^2) 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

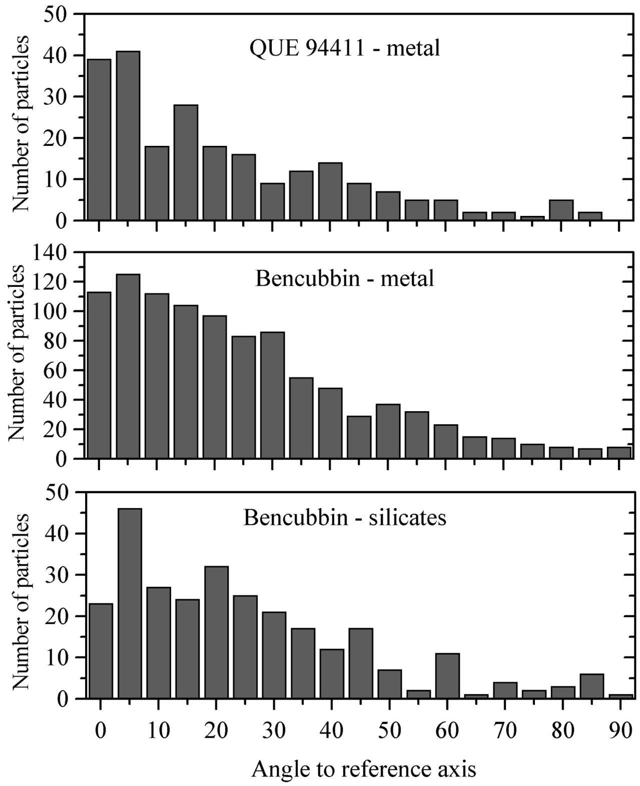

Fig. 3. The angle between the longest apparent axis of metal and silicate particles in QUE 94411 and Bencubbin and a reference axis. Top: 230 metal particles in QUE 94411-9 (Fig. 1a). Middle: 1007 metal particles in Bencubbin (USNM 5625; Fig. 2). Bottom: 273 silicate particles in Bencubbin (USNM 5625; Fig. 2).

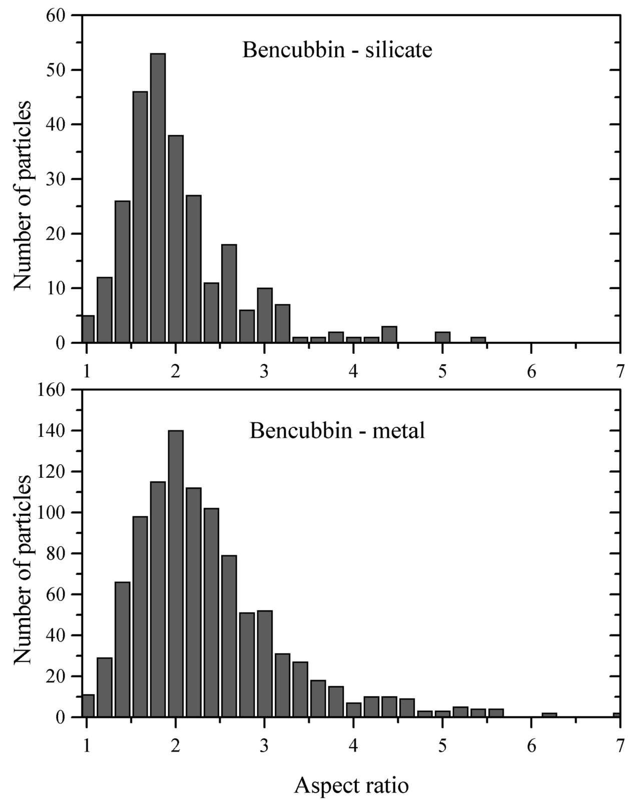

Fig. 4. Aspect ratios (major axis/minor axis) for 273 metal and 1007 silicate particles in Bencubbin (USNM 5625). Both types of particles exhibit a strong peak in their aspect ratios at around 1.8–2.0.

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

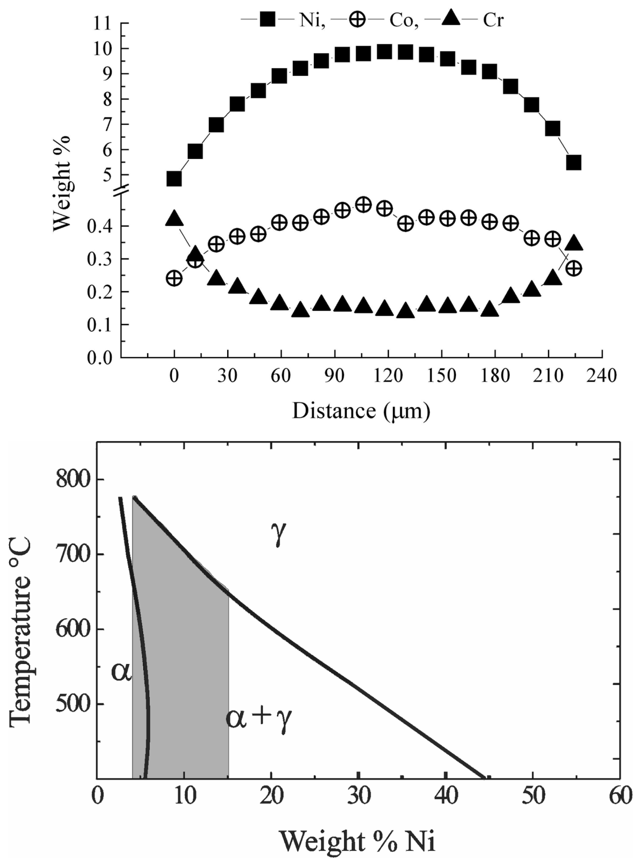

Fig. 5. Top: Electron microprobe analyses across a typical zoned Fe,Ni-metal grain in QUE 94411. Bottom: The Fe-rich corner of the binary Fe-Ni phase diagram. The Ni concentrations of single zoned metal grains in QUE 94411 and HH 237 typically range from 10–15 wt% in the center to ~3–6 wt% at the edge. This Ni range (shown in gray) falls well within the (α + γ) two-phase field.

around 90 μm. Metal particles range from 25–950 μm, also with a mode around 90 μm.

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_2O_3, 4 ± 2; Cr_2O_3, 1 ± 0.2; TiO_2, 0.12 ± 0.02; Na_2O, 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_2O_3, 1.5 ± 0.5; Cr_2O_3, 0.3 ± 0.1; TiO_2, <0.4 (detection limit); Na_2O, 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 CI 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 CI. The matrix lump

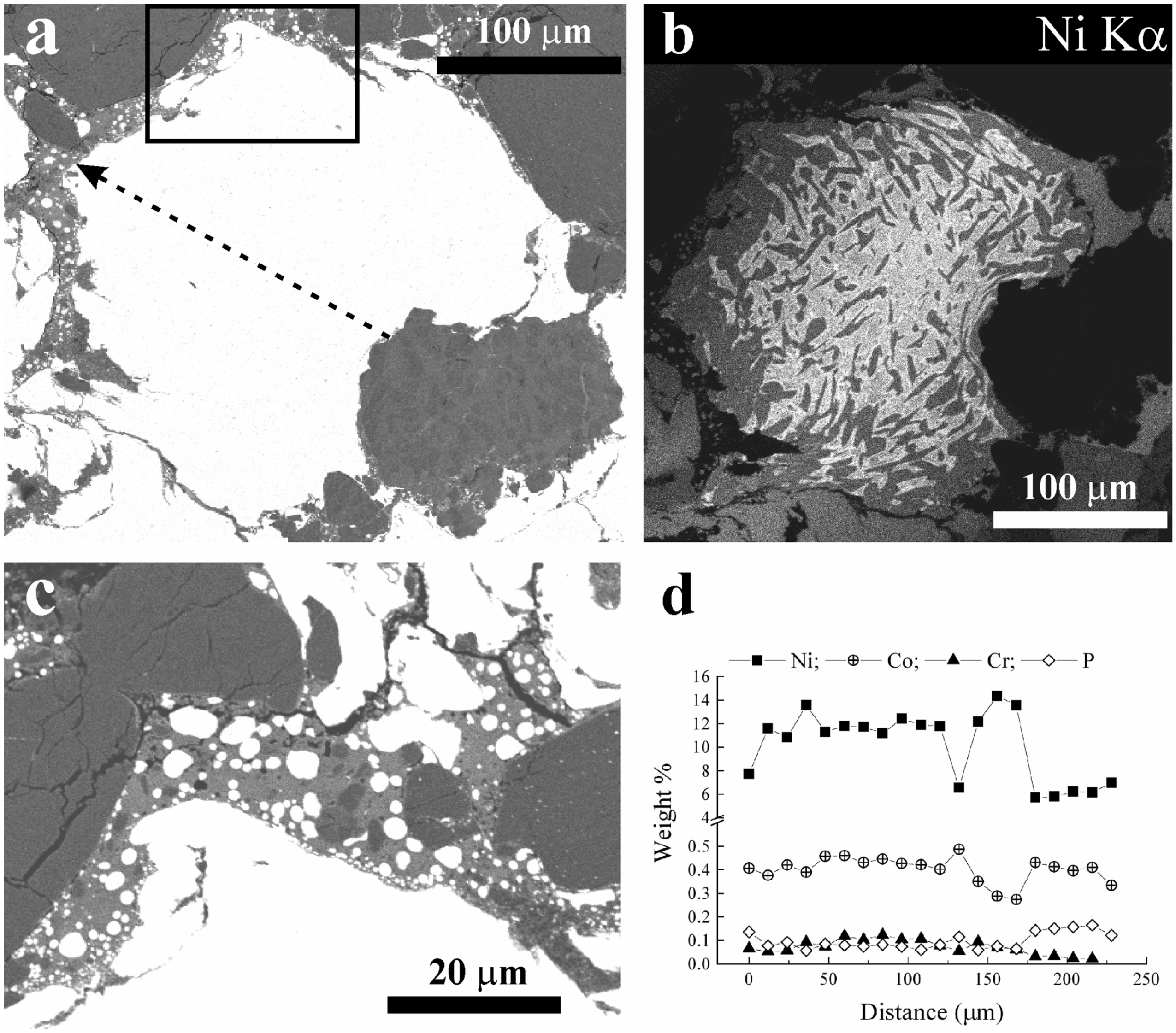

Fig. 6. a) A backscattered electron image of a decomposed metal grain in QUE 94411. b) An Ni Kα X-ray map of the same grain. Decomposition into kamacite and taenite has occurred, but the distribution of kamacite and taenite within the grain indicates that the grain was originally zoned with a Ni-rich core and decreasing Ni concentrations towards the edges. c) A magnified view of the rectangular area outline in (a). The decomposed grain is surrounded by shock melt. d) An electron microprobe traverse across the decomposed grain along the dashed line shown in (a).

in Fig. 10 is furthermore depleted in Ti by roughly a factor of >2 compared to CI.

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 Bencubbin 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).

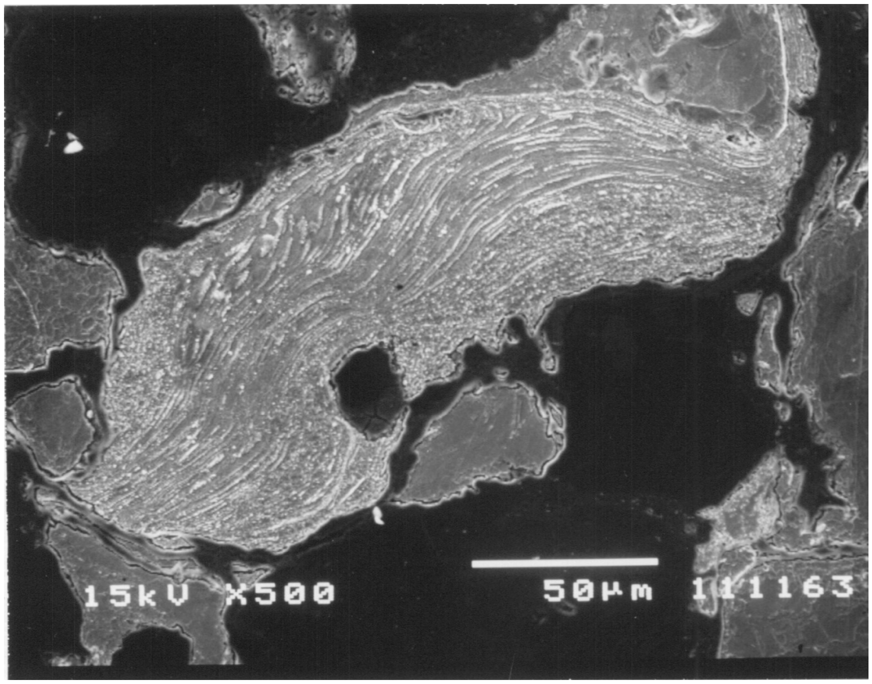

Fig. 7. A high-contrast SEM image of an etched Fe,Ni-metal grain in QUE 94411. The grain first decomposed into kamacite and taenite and was subsequently deformed, conceivably during the shock that produced the metal-silicate shock melt, supporting the conclusion that decomposition of the metastable zoned metal grains took place prior to the shock. Dark areas are silicates. Image courtesy of Rob Reisener.

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

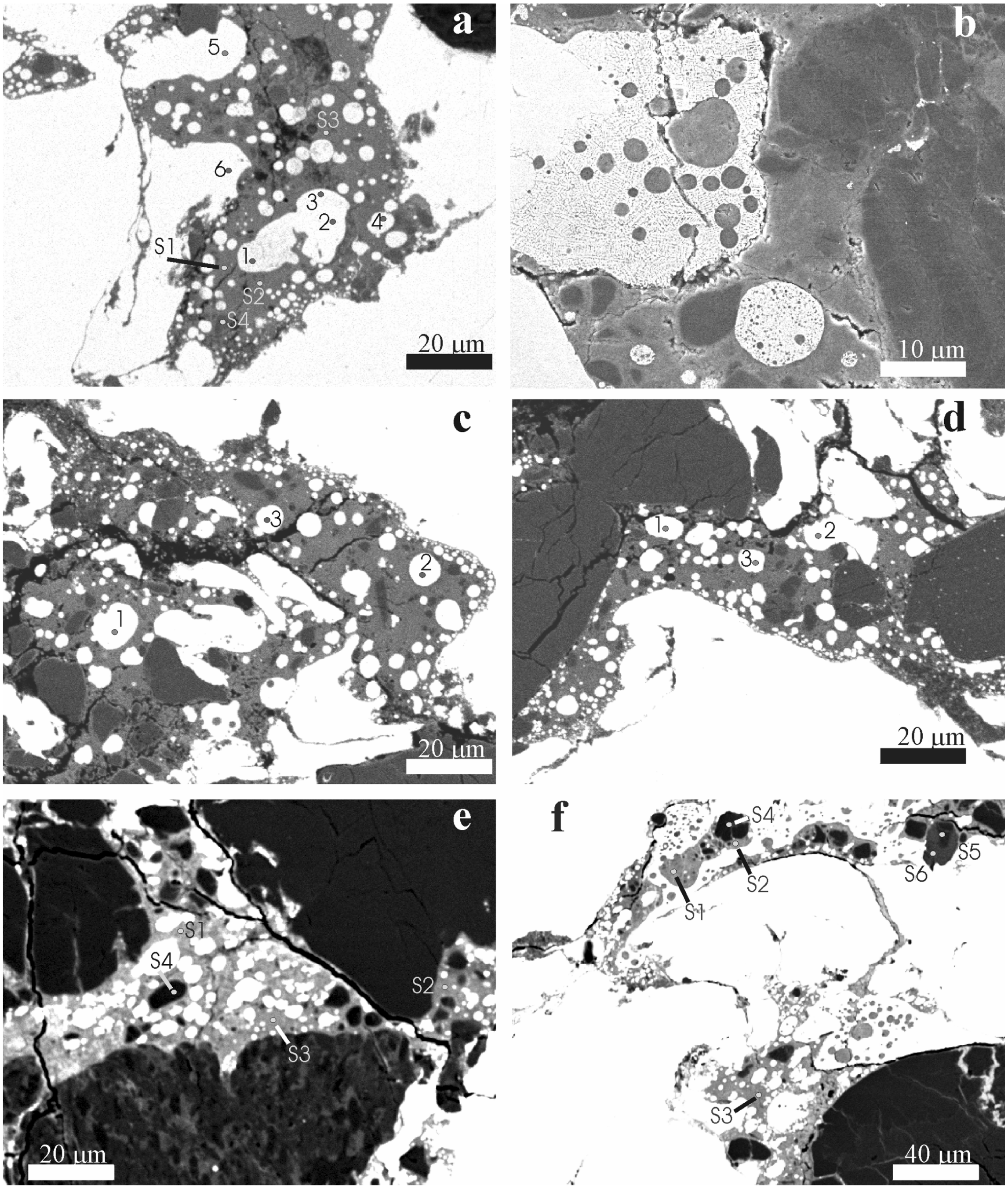

Fig. 8. Shock melt in QUE 94411 consisting of droplets of metal/sulfide embedded in silicate glass or vice versa. The texture indicates immiscibility of metal and silicate melt. This shock melt occurs throughout QUE 94411 interstitial to larger metal grains, chondrules, and fragments thereof and is welding the larger metal and silicate particles together. Numbers indicate analysis spots corresponding to the data in Table 1.

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 relict 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.

Metal melt							
Spot	Ni	Co	Cr	P	S	Fe	Total
a-1	5.4	0.3	0.1	0.1	3.3	81.6	90.8
a-2	5.5	0.3	0.2	0.3	0.0	94.4	100.8
a-3	6.6	0.3	0.1	0.1	3.7	87.0	97.8
a-4	6.1	0.3	0.2	0.2	4.0	85.2	95.9
a-5	7.6	0.4	0.2	0.1	0.0	91.8	100.3
a-6	5.5	0.3	0.2	0.3	0.0	93.7	100.0
c-1	4.6	0.2	0.2	0.2	0.0	95.2	100.4
c-2	5.0	0.3	0.1	0.2	3.3	88.7	97.6
c-3	5.8	0.3	0.1	0.1	3.4	88.5	98.3
d-1	6.6	0.4	0.1	0.1	3.1	83.0	93.3
d-2	5.3	0.3	0.4	0.1	0.0	93.7	99.8
d-3	6.7	0.3	0.1	0.1	4.7	85.5	97.4

Silicate melt									
Spot	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MgO	CaO	Na_2O	Total
a-s1	31.6	0.1	2.6	0.9	33.5	23.4	2.0	0.3	94.3
a-s2	34.3	0.1	2.8	0.9	30.6	25.4	2.0	0.3	96.4
a-s3	31.1	0.1	2.6	0.8	35.2	21.4	2.2	0.3	93.9
e-s1	21.9	b.d.	9.0	0.7	44.8	17.9	0.6	0.3	97.6
e-s2	34.9	0.1	3.0	0.8	28.4	26.2	1.9	0.4	96.7
e-s3	34.1	0.1	2.7	0.7	29.2	25.0	2.1	0.5	95.4
f-s1	32.3	0.1	3.4	1.3	35.0	22.1	2.1	0.4	98.0
f-s2	33.5	0.1	3.3	1.3	33.6	23.5	2.3	0.4	99.1
f-s3	29.8	0.1	3.2	1.1	36.6	20.6	2.1	0.4	95.4

Relict silicate grains in melt										
Spot	Min.	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MgO	CaO	Na_2O	Total
a-s4	Px	51.9	0.5	5.1	0.7	3.1	30.2	9.3	b.d.	100.8
e-s4	Px	53.6	b.d.	0.1	0.7	2.8	42.6	0.1	b.d.	100.0
f-s4	Ol	40.6	b.d.	0.1	0.5	5.1	53.8	0.3	b.d.	100.4
f-s5	Ol	41.4	b.d.	0.3	0.4	5.3	53.4	0.2	b.d.	101.1
f-s6	Px	51.2	0.8	20.0	0.4	2.4	10.5	15.8	0.3	100.9
n.s.	Px	49.6	b.d.	1.6	0.6	4.5	43.3	1.4	b.d.	101.0
n.s.	Px	54.8	b.d.	0.1	0.8	1.2	43.7	0.1	b.d.	100.7
n.s.	Px	51.1	0.2	10.9	0.6	3.4	33.0	2.4	b.d.	101.4

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

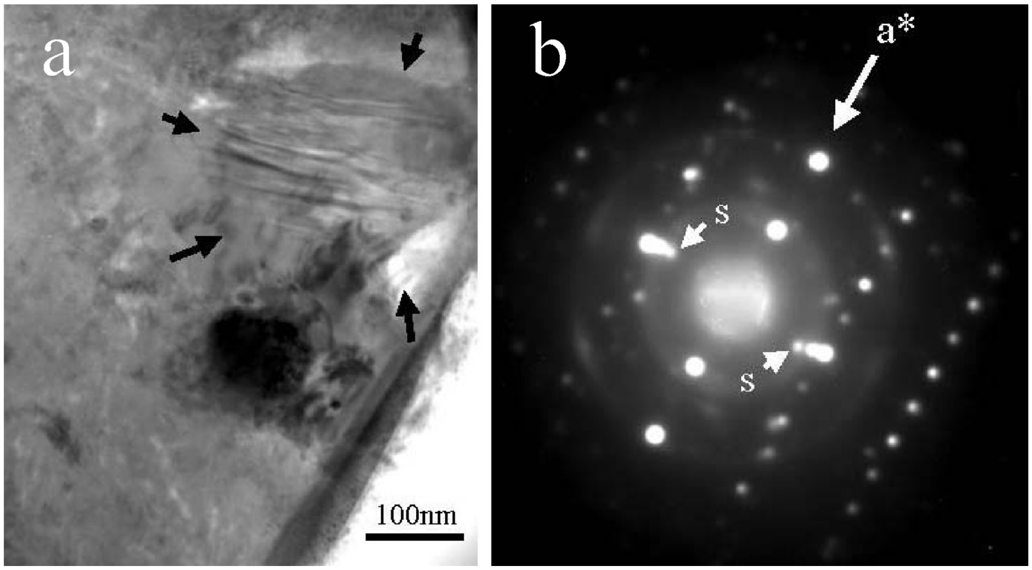

Fig. 9. a) A TEM bright field image of Fe,Ni-metal ferrite droplet (arrowed) set within shock melts. Twin planes are evident as twisted light and dark bars within the ferrite. b) Selected area electron diffraction pattern of twinned, bcc ferrite (martensite) from the metal grain shown in (a). "a*" indicates 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).

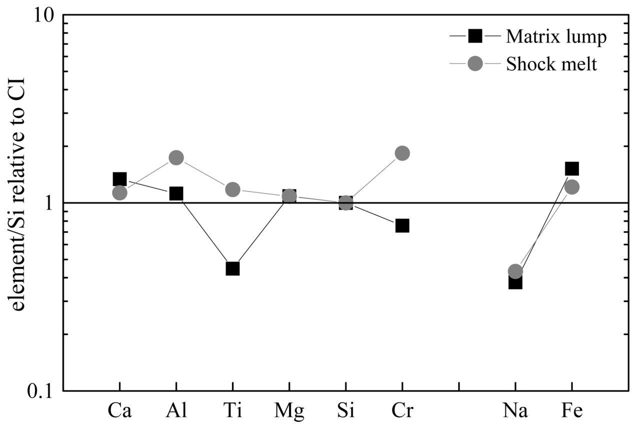

Fig. 11. The average compositions of the ferrous silicate component of the shock melt and the matrix lump (bulk) in QUE 94411, normalized to Si and CI.

shows an example of a metal grain that first decomposed and subsequently was mechanically deformed, presumably in the event that created the preferred orientation of the metal and silicate particles. The decomposed grain is surrounded by shock melt. Diffusion of heat from the shock-melted region does not appear, however, to have caused this initially metastable metal grain to decompose. In the immediate neighborhood of this grain are other smoothly zoned metal grains that did not decompose. Thus, the decomposition of the metal particle in Fig. 7 most likely occurred prior to the production of the shock melt, either in the nebula environment or in a different asteroidal setting. The same arguments can be applied to the decomposed grain in Fig. 6.

The presence of chemically zoned, metastable Fe,Ni-metal grains that would decompose into kamacite and taenite upon prolonged exposure to temperatures above ~300 °C (Zhang et al. 1993) in direct contact with the shock melt indicates rapid cooling, consistent with the TEM observations of martensitic textures in the metal droplets embedded in the shock melt (Fig. 9), and a limited increase in average temperature of the rock during the shock event. Most likely, the pre-shock temperature of these assemblages was quite low. This is also suggested by the sharp boundaries between the hydrous matrix lumps and the (anhydrous) silicates and metal in their immediate surroundings (Greshake et al. 2002). The almost total absence of aqueous alteration of the anhydrous host minerals indicates that the temperature of the bulk assemblage never was raised to the point where H_2O-rich fluids were released from the hydrous matrix material to cause alteration of the anhydrous silicates or corrosion of the metal.

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 ($\geq 10^{-6}$ 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 melts 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

Bhadeshia H. 2001. *Worked examples in the geometry of crystals*. London: Institute of Materials. 412 p.

Bischoff A. 1992. ALH 85085, Acfer 182, and Renazzo-type chondrites—Similarities and differences (abstract). *Meteoritics* 27:203–204.

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

Bischoff A., Palme H., Ash R. D., Clayton R. N., Schultz L., Herpers U., Stöffler D., Grady M. M., Pillinger C. T., Spettel B., Weber H., Grund T., Weber D., and Endress M. 1993a. Paired Renazzo-type (CR) carbonaceous chondrites from the Sahara. *Geochimica et Cosmochimica Acta* 57:1587–1603.

Bischoff A., Palme H., Schultz L., Weber D., and Spettel B. 1993b. Acfer 182 and paired samples, an iron-rich carbonaceous chondrite: Similarities with ALH 85085 and relationship to CR chondrites. *Geochimica et Cosmochimica Acta* 57:2631–2648.

Campbell A., Humayun M., and Weisberg M. K. 2002. Siderophile element constraints on the formation of metal in the metal-rich chondrites Bencubbin, Weatherford, and Gujba. *Geochimica et Cosmochimica Acta* 66:647–660.

Campbell A. J., Humayun M., Meibom A., and Krot A. N. 2001. Origin of zoned Fe,Ni metal grains in QUE 94411. *Geochimica et Cosmochimica Acta* 65:163–180.

Campbell A. J. and Humayun M. 2004. Formation of metal in the CH chondrites ALH 85085 and PCA 91467. *Geochimica et Cosmochimica Acta* 68:3409–3422.

Endress M., Keil K., Bischoff A., Spettel B., Clayton R. N., and Mayeda T. K. 1994. Origin of dark clasts in the Acfer 059/El Douf 001 CR2 chondrite. *Meteoritics* 29:29–40.

Gounelle M., Shu F. H., Shang H., Glassgold A. E., Rehm K. E., and Lee T. 2001. Extinct radioactivities and protosolar cosmic rays: Self-shielding and light elements. *The Astrophysical Journal* 548:1051–1070.

Grady M. M. and Pillinger C. T. 1990. ALH 85085: Nitrogen isotope analysis of a highly unusual primitive chondrite. *Earth and Planetary Science Letters* 97:29–40.

Greshake A., Krot A. N., Meibom A., Weisberg M. K., and Keil K. 2002. Heavily-hydrated lithic clasts in CH chondrites and the related, metal-rich chondrites Queen Alexandra Range 94411 and Hammadah al Hamra 237. *Meteoritics & Planetary Science* 37:281–293.

Grossman J. N., Rubin A. E., and MacPherson G. J. 1988. ALH 85085: A unique volatile-poor carbonaceous chondrite with possible implications for nebula fractionation processes. *Earth and Planetary Science Letters* 91:33–54.

Hezel D. C., Palme H., Brenker F. E., and Nasdala L. 2003. Evidence for fractional condensation and reprocessing at high temperatures in CH chondrites. *Meteoritics & Planetary Science* 38:1199–1215.

Kachaturyan A. G. 1983. *Theory of structural transformations in solids*. New York: Wiley. 534 p.

Kallemeyn G. W., Boynton W. V., Willis J., and Wasson J. T. 1978. Formation of the Bencubbin polymict meteorite breccia. *Geochimica et Cosmochimica Acta* 42:507–515.

Kelly S. and Turner G. 1987. Laser probe ^{40}Ar-^{39}Ar investigation of the polymict breccia Bencubbin (abstract). *Meteoritics* 22:427.

Krot A. N., Meibom A., Russell S., Young E., Alexander C. M., McKeegan K. D., Lofgren G., Cuzzi J. N., Zipfel J., and Keil K. 2000. Chondrules of the very first generation in Bencubbin/CH-like meteorites QUE 94411 and Hammadah al Hamra 237: Condensation origin at high ambient nebula temperatures (abstract #1499). 31st Lunar and Planetary Science Conference. CD-ROM.

Krot A. N., McKeegan K. D., Russell S. S., Meibom A., Weisberg M. K., Zipfel J., Krot T. V., Fagan T. J., and Keil K. 2001a. Refractory calcium-aluminium-rich inclusions and aluminium-diopside-rich chondrules in the metal-rich chondrites Hammadah al Hamra 237 and Queen Alexandra Range 94411. *Meteoritics & Planetary Science* 36:1189–1216.

Krot A. N., Meibom A., Russell S. S., Alexander C. M. O. D., Jeffries T. E., and Keil K. 2001b. A new astrophysical model for chondrule formation. *Science* 291:1776–1779.

Krot A. N., Meibom A., Weisberg M. K., and Keil K. 2002. The CR chondrite clan: Implications for early solar system processes. *Meteoritics & Planetary Science* 37:1451–1490.

Liffman K. and Brown M. J. I. 1996. The protostellar jet model of chondrule formation. In *Chondrules and the protoplanetary disk*, edited by Hewins R. E., Jones R. H., and Scott E. R. D. Cambridge: Cambridge University Press. pp. 285–302.

Mason B. 1996. *Antarctic Meteorite Newsletter* 19:17.

McCall G. J. H. 1968. The Bencubbin meteorite: Further details, including microscopic character of host material and two chondrite enclaves. *Mineralogical Magazine* 36:726–739.

McCall G. J. H. 1973. *Meteorites and their origins*. New York: Wiley. 352 p.

McKeegan K. D., Chaussidon M., and Robert F. 2000. Evidence for the in situ decay of ^{10}Be in an Allende CAI and implications for short-lived radioactivity in the early solar system (abstract #1999). 31st Lunar and Planetary Science Conference. CD-ROM.

Meibom A., Petaev M. I., Krot A. N., Wood J. A., and Keil K. 1999. Primitive FeNi metal grains in CH carbonaceous chondrites formed by condensation from a gas of solar composition. *Journal of Geophysical Research* 104:22,053–22,059.

Meibom A., Desch S. J., Krot A. N., Cuzzi J. N., Petaev M. I., Wilson L., and Keil K. 2000a. Large-scale thermal events in the solar nebula recorded in FeNi metal condensates in CH chondrites (abstract #1777). 31st Lunar and Planetary Science Conference. CD-ROM.

Meibom A., Desch S. J., Krot A. N., Cuzzi J. N., Petaev M. I., Wilson L., and Keil K. 2000b. Large-scale thermal events in the solar nebula: Evidence from Fe,Ni metal grains in primitive meteorites. *Science* 288:839–841.

Meibom A., Krot A. N., Keil K., Righter K., and Chabot N. 2000c. FeNi-metal/sulfide—Ferrous silicate shock melts in QUE 94411 and Hammadah al Hamra 237: Remains of the missing matrix (abstract #1420)? 31st Lunar and Planetary Science Conference. CD-ROM.

Meibom A., Petaev M. I., Krot A. N., Keil K., and Wood J. A. 2001. Growth mechanism and additional constraints on FeNi metal condensation in the solar nebula. *Journal of Geophysical Research* 106:32,797–32,801.

Melosh H. J. 1989. *Impact cratering*. Oxford: Oxford University Press. 245 p.

Mostefaoui S., Goresy A. E., Hoppe P., Gillet P., and Ott U. 2002. Mode of occurrence, textural settings and nitrogen isotopic compositions of in situ diamonds and other carbonate phases in the Bencubbin meteorite. *Earth and Planetary Science Letters* 204:89–100.

Newsom H. E. and Drake M. J. 1979. The origin of metal clasts in the Bencubbin meteoritic breccia. *Geochimica et Cosmochimica Acta* 43:689–707.

Perron C., Fieni C., and Guilhaumou N. 2001. Glassy material in Bencubbin: Clues to its thermal history (abstract). *Meteoritics & Planetary Science* 36:A160–A161.

Petaev M. I., Meibom A., Krot A. N., Wood J. A., and Keil K. 2000. The condensation origin of zoned metal grains in QUE 94411: Implications for the formation of Bencubbin/CH-like chondrites (abstract #1606). 31st Lunar and Planetary Science Conference. CD-ROM.

Petaev M. I., Meibom A., Krot A. N., Wood J. A., and Keil K. 2001. The condensation origin of zoned metal grains in QUE 94411: Implications for the formation of Bencubbin/CH-like chondrites. *Meteoritics & Planetary Science* 36:93–106.

Petaev M. I., Wood J. A., Meibom A., Krot A. N., and Keil K. 2003. The ZONMET thermodynamic and kinetic model of metal condensation. *Geochimica et Cosmochimica Acta* 67:1737–1751.

Ramdohr P. 1965. Uber 6 Mineralbestand van Pallasiten und Mesosideriten und einige genetische Uberlegungen. *Deutsche Akadamie der Wissenschafts*7:923–938.

Ramdohr P. 1973. The opaque minerals in stony meteorites. Amsterdam: Elsevier Publishing. 245 p.

Righter K. and Chabot N. L. 1998. Silicate and metal phases in the Queen Alexandra Range 94411 iron meteorite (abstract). *Meteoritics & Planetary Science* 33:A129.

Rubin A. E., Kallemeyn G. W., Wasson J. T., Clayton R. N., Mayeda T. K., Grady M., Verchovsky A. B., Eugster O., and Lorenzetti S. 2003. Formation of metal and silicate globules in Gujba: A new Bencubbin-like meteorite fall. *Geochimica et Cosmochimica Acta* 67:3283–3298.

Schoenbeck T. W. and Palme H. 2003. Silicon concentrations in metal grains of CB-, CH- and CR-chondrites—Implications for their formation (abstract #1605). 34th Lunar and Planetary Science Conference. CD-ROM.

Scott E. R. D. 1988. A new kind of primitive chondrite, Allan Hills 85085. *Earth and Planetary Science Letters* 91:1–18.

Scott E. R. D., Keil K. and Stöffler D. 1992. Shock metamorphism of carbonaceous chondrites. *Geochimica et Cosmochimica Acta* 56: 4281–4293.

Shang H., Lee T., and Glassgold A. E. 2000. Protostellar winds and chondritic meteorites. In *Protostars and planets IV*, edited by Mannings V., Boss A. P., and Russell S. S. Tucson, Arizona: The University of Arizona Press. 1422 p.

Shu F. H., Shang H. and Lee T. 1996. Toward an astrophysical theory of chondrites. *Science* 271:1545–1552.

Sneyd D. S., McSween H. Y., Sugiura N., Strangeway D. S., and Nord G. L. 1988. Origin of petrofabrics and magnetic anisotropy in ordinary chondrites. *Meteoritics* 23:139–149.

Stöffler D., Keil K., and Scott E. R. D. 1991. Shock metamorphism of ordinary chondrites. *Geochimica et Cosmochimica Acta* 55: 3845–3867.

Sugiura N., Zashu S., Weisberg M. K., and Prinz M. 2000. A nitrogen isotope study of bencubbinites. *Meteoritics & Planetary Science* 35:987–996.

Wasson J. T. and Kallemeyn G. W. 1990. Allan Hills 85085: A subchondritic meteorite of mixed nebular and regolithic heritage. *Earth and Planetary Science Letters* 101:148–161.

Weber D. and Bischoff A. 1994. The occurrence of grossite ($CaAl_4O_7$) in chondrites. *Geochimica et Cosmochimica Acta* 58: 3855–3877.

Weisberg M. K., Prinz M., and Nehru C. E. 1988. Petrology of ALH 85085: A chondrite with unique characteristics. *Earth and Planetary Science Letters* 91:19–32.

Weisberg M. K., Prinz M., Clayton R. N., Mayeda T. K., Grady M. M., and Pillinger C. T. 1995. The CR chondrite clan. *Proceedings of the NIPR Symposium on Antarctic Meteorites* 8: 11–32.

Weisberg M. K., Prinz M., Clayton R. N., Mayeda T. K., Sugiura N., and Zashu S. 1998. The Bencubbinite (B) group of the CR clan (abstract). *Meteoritics & Planetary Science* 33:A166.

Weisberg M. K. and Prinz M. 1999. Zoned metal in the CR clan chondrites (abstract). *Antarctic Meteorites* 24:187–189.

Weisberg M. K., Prinz M., Clayton R. N., Mayeda T. K., Sugiura N., Zashu S., and Ebihara M. 1999. QUE 94411 and the origin of Bencubbinites (abstract #1416). 30th Lunar and Planetary Science Conference. CD-ROM.

Weisberg M. K., Prinz M., Campbell A. J., and Humayun M. 2000. Origin of metal in the CB (Bencubbinite) chondrites (abstract #1466). 31st Lunar and Planetary Science Conference. CD-ROM.

Weisberg M. K., Prinz M., Clayton R. N., Mayeda T. K., Sugiura N., Zashu S., and Ebihara M. 2001. A new metal-rich chondrite group. *Meteoritics & Planetary Science* 36:401–418.

Weisberg M. K., Boesenberg J. S., and Ebel D. S. 2002. Gujba and origin of the Bencubbin-like (CB) chondrites (abstract #1551). 33rd Lunar and Planetary Science Conference. CD-ROM.

Zhang J., Williams D. B., and Goldstein J. I. 1993. The microstructure and formation of duplex and black plessite in iron meteorites. *Geochimica et Cosmochimica Acta* 57:3725–3735.

Zipfel J., Wlotzka F., and Spettel B. 1998. Bulk chemistry and mineralogy of a new "unique" metal-rich chondritic breccia, Hammadah al Hamra 237 (abstract #1417). 29th Lunar and Planetary Science Conference. CD-ROM.