FeNi-Metal/Sulfide – Ferrous Silicate Shock Melts in QUE94411 and Hammadah al Hamra 237: Remains of the Missing Matrix ?

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Introduction. QUE94411 (QUE) and Hammadah al Hamra 237 (HH237) are affiliated with Bencubbin-like, CH, and CR chondrites (the CR clan) [1-3]. They are extremely rich in FeNi metal (~ 70 vol%) and depleted in moderately volatile elements (Mn, Na, K, S) [4]. About 20% of the FeNi metal grains in QUE and HH237 are chemically zoned in Fe, Ni, Co, Cr and platinum-group elements indicating an origin by gas-solid condensation [4-10]. Silicates are mainly present as FeO-poor (<4 wt%) cryptocrystalline chondrules or, less abundant, so-called "barred olivine" chondrules [3, 11] and probably formed at high ambient temperatures prior to FeNi metal condensation [11]. Matrix-like material has not previously been observed in QUE and HH237. Here we describe the mineralogy of metal/sulfide–ferrous silicate shock melt that occurs between chondrules and metal grains in QUE and HH237. We suggest that this shock melt is the remains of the missing matrix component and are related to rare, hydrated matrix lumps found in QUE and HH237.

Results. Petrographic observations indicate that regions between chondrules and metal grains in QUE and HH237 are filled by FeNi-metal/sulfide–silicate shock melt (Fig. 1) [3, 12]. The shock melt consists of immiscible droplets of dendritically intergrown FeNi-metal and sulfide (most likely FeS) surrounded by silicate melt, or vice versa. We used a Cameca SX50 electron microprobe and appropriate mineral standards to obtain quantitative analyses of the shock melt components. The FeNi-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 FeNi metal in CR clan meteorites. The silicate portion of the shock melt consists of angular-to-rounded magnesian chondrule fragments embedded in glassy ferrous silicate material; the latter shows some compositional variations: (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. Figure 2 shows a region of a (~3 mm^2) fine-grained, hydrated matrix lump in QUE. The matrix lump consists of phyllosilicates, prismatic sulfides, framboidal magnetite, and Ca-carbonates. Broad-beam analyses (∅=15 μm) of 120 spots yield an average bulk composition of the clast (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. Bulk compositions of the matrix lump and ferrous silicate component of the shock melt (normalized to Si) are very similar and roughly CI for the major elements (Si, Mg, Fe, Ca, and Al) indicating a genetic relationship; they are slightly depleted in Na by a factor of 3 relative to CI; the matrix lump is depleted in Ti by a factor of >2, the silicate portion of the shock melt is enriched in Cr, which was perhaps derived from the Cr-rich outer parts of the zoned FeNi metal condensates by oxidation during the shock melting (Fig. 3).

Discussion. Based on the observed similarity in bulk composition of the matrix lump and ferrous silicate portions of shock melt, we infer that fine-grained, porous material, compositionally similar to the matrix lump, was present between the FeNi-metal grains and chondrules in QUE and HH237, but was preferentially heated by the shock wave and melted [13]. The presence of chemically zoned, metastable FeNi-metal grains, which would decompose into kamacite and taenite upon prolonged exposure to temperatures above ~300°C, in direct contact with the shock melt indicates rapid cooling and limited increase in average temperature of the rock during the shock event. This is also consistent with the limited degree of melting of chondrules and the dendritic textures in FeNi metal-sulfide droplets. Relict magnesian chondrule fragments (FeO <4 wt%) embedded in ferrous silicate glass generally preserve their angular appearance and did not contribute significantly to the ferrous (~35 wt% FeO) silicate portions of the shock melt. Because porphyritic olivine-pyroxene chondrules are absent in QUE and HH237 [11], the shock stage of these meteorites is difficult to determine.

Implications for the accretionary history of the QUE and HH237 parent body. We have suggested that chondrules and FeNi metal grains in QUE and HH237 formed by condensation following a large scale thermal event that resulted in complete vaporization of a solar nebula region with enhanced dust/gas ratio [8-11]. According to this model, fine-grained matrix material was absent in this region during chondrule formation. The CI-like bulk compositions of the matrix lump and ferrous silicate shock melts in QUE and HH237, which are not complementary to chondrules, are consistent with this model. The presence of hydrated matrix material in QUE could be explained either ***A)*** as a late addition to the QUE/HH237 parent body during regolith gardening or ***B)*** as material that accreted together with FeNi metal and chondrules into the original parent asteroid. A search for implanted solar wind gasses and Ar-Ar dating of the shock-event(s) experienced by QUE and HH237 should help to distinguish between the two scenarios. If QUE and HH237 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 volatile elements. However, this seems inconsistent with the survival of chemically zoned, metastable FeNi-metal grains in these meteorites [7]. If QUE and HH237 are accretionary breccias (scenario ***B)***, it would imply that metal grains and chondrules were rapidly transported from hot to colder

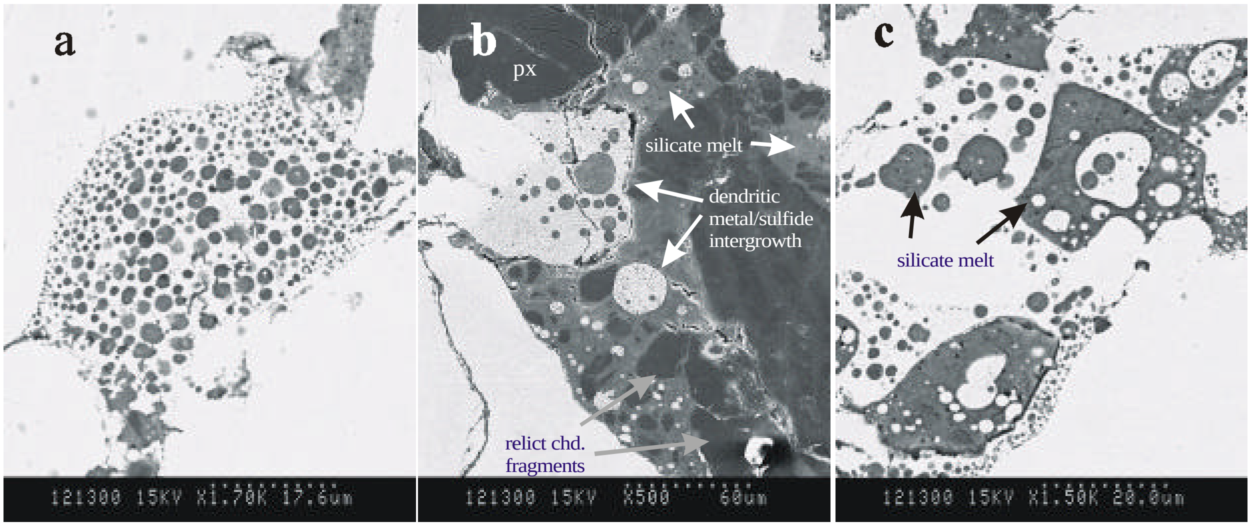

Figure 1 a-c). BSE images of shock-melted material in QUE94411. This immiscible metal/sulfide-silicate melt, omni-present in QUE and HH 237, occurs interstitially between metal and silicate "glueing" the rock together. FeNi metal and sulfide form dendritic intergrowths due to rapid cooling. The silicate melt is significantly more oxidized (FeO 35±5 wt%) than chondrule silicates (FeO <4 wt%) [10]. Chondrule-derived fragments with angular edges are ubiquitous in the silicate glass; they seem not to have been molten.

nebula regions (where hydrated matrix material could exist) prior to condensation of volatile elements, e.g. by the *X*-wind [14, 15]. Important constraints, which any succesful transport mechanism must meet, are the extreme metal/silicate ratios in QUE and HH237 and the apparent lack of size-sorting between metal particles and chondrules [11].

QUE and HH237 (like other CR clan meteorites) are characterized by heavy N (high $^{15}N/^{14}N$ ratios: $\delta^{15}N$ = 150–200 ‰), which appears to be associated with the shock melts [16]. We suggest that the CI-like matrix material described above contains the carrier phase of the anomalous N. This would also apply to CH chondrites, which contain abundant CI-like matrix lumps [17].

Figure 2. BSE image of the hydrated matrix lump in QUE. It consists of finegrained silicate and phyllosilicates with larger grains of sulfide, cluster of framboidal magnetite, and carbonates.

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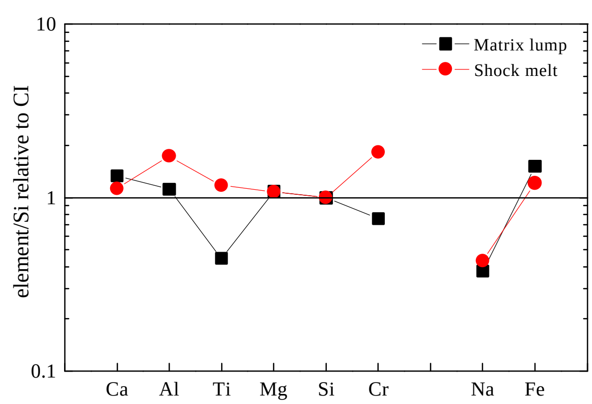

Figure 3. Average compositions of ferrous silicate component of the shock melt and the matrix lump (bulk) in QUE normalized to Si and CI.