EVIDENCE FOR IMPACT SHOCK MELTING IN CM AND CI CHONDRITE REGOLITH SAMPLES.

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Introduction: C class asteroids frequently exhibit reflectance spectra consistent with thermally metamorphosed carbonaceous chondrites [1], or a mixture of phyllosilicate-rich material along with regions where they are absent [2]. One particularly important example appears to be near-Earth asteroid 1999 JU3, the target of the Hayabusa II sample return mission [1], although not all spectra indicate this [3]. In fact most spectra of 1999 JU3 are featureless, suggesting a heterogeneous regolith. Here we explore an alternative cause of dehydration of regolith of C class asteroids – impact shock melting. Impact shock melting has been proposed to explain some mineralogical characteristics of CB chondrites [4], but has not been considered a major process for hydrous carbonaceous chondrites. What evidence is there for significant shock melting in the very abundant CMs, or less abundant but still important CI chondrites?

Possible Agglutinates: We located in the Orgueil CI chondrite an apparent agglutinate grain containing melted matrix grading into merely desiccated phyllosilicates (Figure 1). The melt partially devitrified into normally-zoned olivine crystals (Figure 1c) which sit in mesostasis glass. It is interesting that these glasses have partially devitrified to olivine, in contrast to the situation for lunar agglutinates (Lindsay Keller, personal communication, 2014). This could be due to a higher olivine normative composition, and the difficulty of quenching a liquid with an almost pure olivine composition (Gary Lofgren personal communication, 1999). We have found similar objects in CM2 chondrites, and they are potentially widespread.

Shock Melt Vein Material: We have previously reported on shock melted C2 chondrite materials in the Kaidun meteorite breccia lithologies (mainly C and E chondrites), some of which have experienced post-shock aqueous alteration which severely masks the evidence for shock [5,6]. Two examples are shown in Figure 2, both from Kaidun. In these melt vein samples zoned acicular olivine and plagioclase (potassium-rich anorthoclase) crystals have nucleated into pyroxene-composition mesostasis. In one example in Figures 2a and b (from a CM1 lithology in Kaidun) the entire assemblage has been altered to phyllosilicates, which preserve most aspects of the compositions and even the zoning. These veins are apparently identical to shock melt veins in shergottites and at least one terrestrial impact crater - Meteor Crater [7].

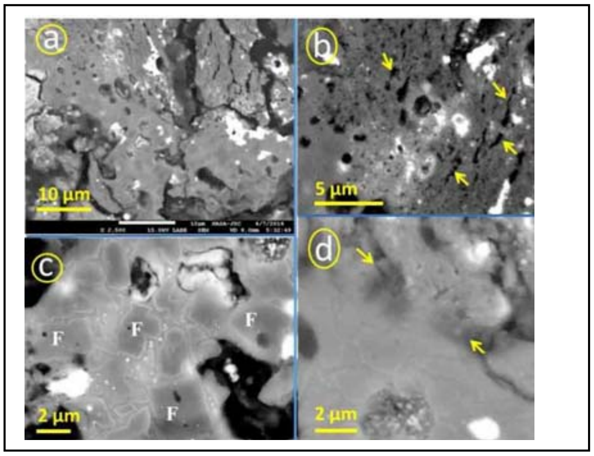

Figure 1. BSE images of a probable agglutinate in Orgueil. (a) Image of the entire agglutinate grain. (b) Close-up of partially dehydrated (heated) matrix at the edge of the agglutinate. Arrows indicate dehydration cracks in the matrix phyllosilicates. (c) Close-up of the center of the agglutinate grain, where complete melting has occurred, and cooling has produced normally-zoned olivine crystals (forsterite cores – F) in mesostasis glass. (d) Close-up of the gradation between melted and unmelted material at the agglutinate edge.

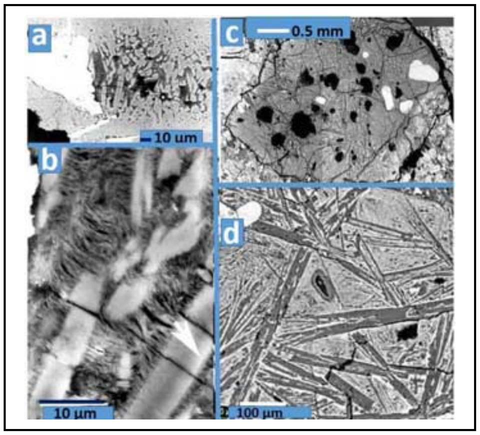

Figure 2. BSE images of shock melt vein materials in Kaidun. (a) & (b) From the CM1 lithology, serpentine faithfully pseudomorphs a vein originally consisting of zoned, acicular olivine crystals nucleating into pyroxene composition mesostasis. (c) & (d) A fragment of a vein, still fresh, consisting of acicular plagioclase ($An_{22}Ab_{76}Or_2$) nucleating into augite mesostasis (mainly $Fs_{22}Wo_{36}$). After [5].

Glassy Beads: In every carbonaceous chondrite (even CI chondrites) we encounter 10-100µm-sized beads of glass or phyllosilicates which could arguably be microchondrules (whatever the origin of those may be?), but when obviously vesicular are more likely a product of impact. Two typical examples are shown in Figure 3, one (from Orgueil) which is still non-crystalline, and the other (from the Nogoya CM2 chondrite) which we suggest has been altered from glass to serpentine. Again, unless the original glassy state has been preserved, which for such small objects must be a rare occurrence, it is perhaps impossible to ascribe these particular objects to impacts. Fortunately a few survivors are present.

Melted Sulfides: In some meteorites masses of melted sulfides record a flash heating event. Figure 4 illustrates one of many troilite masses in the Jbilet Winselwan CM2 chondrite which have obviously been melted, and had matrix silicate grains injected inward. For the sulfur to have not completely evaporated requires rather rapid cooling. This particular example in from an especially highly shocked portion of this meteorite, although the entire meteorite exhibits evidence of a heating event [8,9]. In addition to the melted sulfides this meteorite also contains partially equilibrated olivine aggregates and chondrules, matrix phyllosilicates transformed into olivine (verified by synchrotron XRD at SPring-8), and areas of finely comminuted, size-sorted olivine grains. A study of shock-melted sulfides in an LL6 chondrite indicated that they produced reflectance spectra that differed significantly from samples with unmelted sulfides [10].

Implications: It is often thought that hydrous asteroids would generally disrupt, and not experience or preserve significant evidence of impact melting. However, we find that even the water-rich CI and CM chondrites contain evidence of impact shock. To see this one must look carefully at the regolith breccias, and see past the post-shock aqueous alteration which has generally obscured mineral textures. We suggest that these materials will be present in significant quantity on the surfaces of C-class asteroids, where they can be explored by spacecraft such as Hayabusa II and O-Rex.

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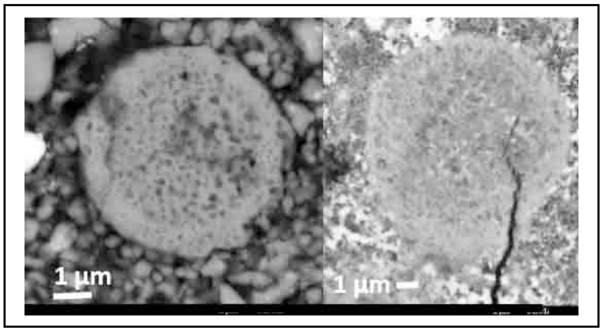

Figure 3. Beads. (left) Vesicular glassy bead from Orgueil. (right) Serpentine bead in Nogoya. Note the mottling, resembling the vesicular glassy Orgueil bead.

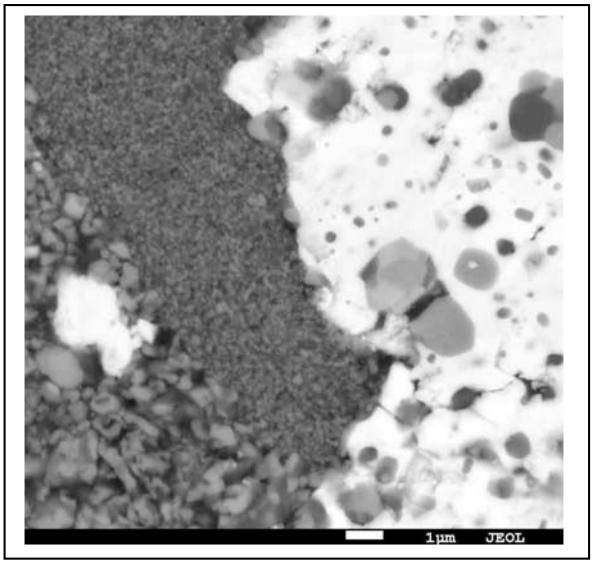

Figure 4: BSE image of melted troilite (white – on the right) in the Jbilet Winselwan CM chondrite. Embedded matrix silicates (grey) in the troilite include olivine and low-Ca pyroxene. Note the unexplained area of well-sorted olivine grains in the center of the image, adjacent to the troilite.