MACRO- AND MICROSTRUCTURES IN ORDINARY CHONDRITES: IMPLICATIONS FOR IMPACT DEFORMATION AND ANNEALING PROCESSES.

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Introduction: Impact deformation is known from experiments and observations of chondrites to result in metal grain foliation and a decrease in porosity [1-5]. Here we re-examine evidence for these processes in light of additional data for ordinary chondrites, including measurements of 3D metal fabrics by micro-CT (µCT), and olivine microstructures by transmission electron microscopy (TEM) and optical microscopy (OM) [6-10]. Microstructures imply that some chondrites experienced significant post-shock annealing [6,9,10], deformation while hot [7-11], or both [10], consistent with other evidence for high-temperature deformation [5,12,13] and post-shock annealing [e.g., 14,15]. We suggest that macro- and microstructures can be used to identify chondrites that formed directly below impact craters on already warm parent bodies.

Samples and Methods: Ordinary chondrites of various groups (H, L, LL) and mainly equilibrated types were studied. Samples include (1) "reference" L6 of different shock stages [16] (Park, GRO 85209, Holbrook, Leedey, Bruderheim, Morrow County, Alfianello, Tenham), (2) H and LL chondrites identified as either post-shock-annealed or hot-deformed including Portales Valley (H6/7) [9,13,15], Kernouvé (H6) [5,9,10,12,13,15], MIL 99301 (LL6) [7,9,10,15], Spade (H6) [14,15], Saint-Séverin (LL6) [11,17] and Butsura (H6) [13]; and (3) two other H6 chondrites, Estacado and Queen's Mercy. Samples were analyzed by µCT for metal grain fabric (preferred shape orientation) and OM for shock stage (olivine deformation), and some samples were analyzed for porosity via µCT, He pycnometry and bead methods, and for olivine microstructures by TEM.

Results: Relationships between shock stage, preferred orientation of metal grains, and porosity in ordinary chondrites are shown in Fig. 1 and 2. Samples in our study are shown by closed symbols, and published data by crosses. Multiple values are shown for some meteorites in which different samples were measured. Conventional shock stage is determined by the highest shock stage shown by at least 25% of olivine grains measured [16]; some meteorites show evidence for being breccias composed of a wide mix of individual grain shock stages (Holbrook, S1- thru S4-dominant; Saint-Séverin S2- thru S4-dominant; Spade S1- and S4-dominant; and Butsura and MIL 99301, S1-dominant but containing admixtures of more highly shocked material). Saint-Séverin also displays a breccia (clastic) texture.

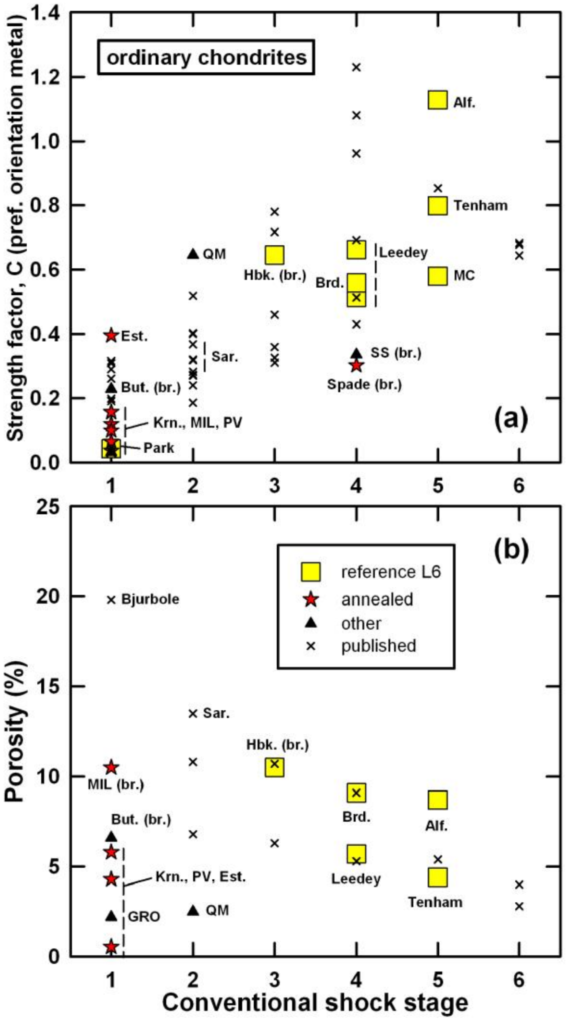

Fig.1. Relationship between conventional shock stage and (a) strength factor C (related to degree of metal grain preferred orientation) and (b) porosity. Abbreviations: br. = breccia; MIL = MIL 99301; PV = Portales Valley; Krn. = Kernouvé; Est. = Estacado; But. = Butsura; GRO = GRO 85209; QM = Queen's Mercy; Sar. = Saratov; Hbk. = Holbrook; Brd. = Bruderheim; SS = Saint-Séverin; Alf. = Alfianello; MC = Morrow County.

Preferred orientation of metal is quantified by a metric (strength factor C) that is related to the alignment of asymmetric metal grains, with higher C-values corresponding to more preferred orientation and greater foliation [e.g., 5]. For porosity, best values are assumed. Finally, meteorites showing TEM or OM evidence for significant post-shock annealing effects are identified in Fig. 1 and 2 by star symbols. Evidence for significant post-shock annealing is best established by TEM for Portlales Valley, Kernouvé, and MIL 99301 in the form of numerous subgrain boundaries in olivine, which is evidence for microstructural recovery occurring at a temperature sufficiently high to cause significant diffusion in olivine [6,9,10]. Good examples of apparent subgrain boundaries are also observed by OM for these meteorites as well as for Spade and Estacado. OM data suggest the possible presence of subgrain boundaries in Saint-Séverin and Park, although subgrain boundaries are not characteristic for Park in areas examined by TEM [10]. No observations for potential subgrain boundaries are available for GRO 85209 or Queen's Mercy; but for other samples we studied, subgrain boundaries are uncommon.

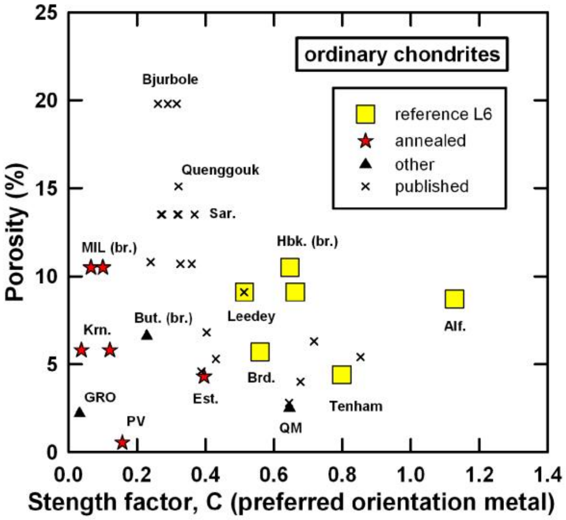

Fig.2. Relationship between strength factor C and porosity. Abbreviations as in Fig.1.

Discussion: Our data strengthen the conclusion that metal grains in ordinary chondrites were deformed and oriented by shock deformation [e.g., 4,5], as evidenced by a rough correlation between between shock stage and strength factor C (Fig. 1a). Given that metal grains become foliated [4,5], preferred orientation must occur by compaction of metal grains that behave in a ductile fashion during shock deformation. This implies that porosity should reduce as compaction increases. Indeed, measurements for reference L chondrites and for published meteorites do show a crude inverse correlation between shock stage and porosity (Fig. 1b), and a crude inverse correlation between strength factor C and porosity (Fig. 2). Thus, there is evidence that shock deformation of ordinary chondrites caused both a flattening of metal grains as well as a collapse of pores, in agreement with experimental results [1-3] and previous work [4-5].

However, there is evidence that shock compaction processes in ordinary chondrites were influenced by additional factors. Evidence is the presence of low porosities for some chondrites with low-moderate shock stages (Fig. 1b) and a low degree of metal preferred orientation (Fig. 2). If shock results in compaction, low-shock meteorites should be the most porous, but this is not always the case. Most meteorites that have lower porosities than expected based on their shock stages and metal fabrics are of the "annealed" variety (Fig. 1b, 2), and at least Kernouvé and MIL 99301 in this group show evidence for deformation occurring while the parent body was warm [9,10].

There are two possible explanations for the low-porosity, apparently weakly-shocked chondrites: (1) post-shock annealing helped obliterate olivine strain and/or porosity in these meteorites, and (2) shock occurred under conditions different from other chondrites, which allowed more reduction of porosity. Both explanations may be correct. Annealing and recovery could have obliterated strain and caused a reduction in shock stage [10,15], and elevated temperatures would have permitted additional compaction during deformation [2]. These features can be explained by the formation of annealed chondrites at depth directly below an impact crater on an already warm parent body.

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