THREE DIMENSIONAL PETROGRAPHY OF KERNOUVÉ: A STORY OF VEIN FORMATION, COMPACTION, AND METAMORPHISM. J. M. Friedrich[1,2], A. Ruzicka[3], D. S. Ebel[2], J. Thostenson[4], R. A. Rudolph[4*], M. L. Rivers[5], R. J. Macke[6], and D. T. Britt[6], [1]Department of Chemistry, Fordham University, Bronx, NY 10458, [2]Department of Earth and Planetary Sciences, American Museum of Natural History, New York, NY 10024 (email: friedrich@fordham.edu), [3]Cascadia Meteorite Laboratory, Department of Geology, Portland State University, 1721 SW Broadway, Portland, OR, 97207, [4]Microscopy and Imaging Facility, American Museum of Natural History, New York, NY 10024, [5]Consortium for Advanced Radiation Sources, University of Chicago, Argonne, IL 60439, [6] Department of Physics, University of Central Florida, Orlando, FL 32816. [*]Current Address: GE Inspection Technologies, 50 Industrial Park Road, Lewistown, PA 17044.

Introduction: Metallic veins in ordinary chondrites, like those found in Kernouvé (H5, S1), have been attributed to impact or shock processes on the parent body [1-8]. However, Kernouvé is widely known to exhibit few traditional signs of shock loading [5,9-11] and has a very old ^{39}Ar-^{40}Ar age (4.46 Ga) [1], making the significance of vein formation in Kernouvé unclear. One possibility is early vein formation followed by partial obliteration due to thermal metamorphism [2, 6]. We examine this scenario here.

Samples and Methods: We examined two samples of the Kernouvé chondrite with x-ray microtomography (μCT): USNM 359 (0.7 g) and AMNH 470 (4.7 g). The former was imaged at the GSECARS 13-BM beamline located at the Advanced Photon Source of the Argonne National Laboratory and the latter was imaged with the GE phoenix v|tome|x s μCT system at the American Museum of Natural History. μCT resolutions were 11.9 and 11.2 μm/voxel respectively. To extract visualization and quantitative compaction data from our data, we used techniques described previously [12-16]. We determined the porosity of two specimens (#499 and #1379) from the Vatican collection (29.7 and 18.0 g) with ideal gas (He) pycnometry. We also used traditional petrographic methods to infer the shock stage of Kernouvé.

Results: Our petrographic observations verify the S1 classification of Kernouvé [9]. Each sample contained a large (up to cm-sized) metallic vein (Figure 1) like those observed by others [2,4,6,7], but which we imaged in 3D. Besides veins, μCT data also indicate that Kernouvé has considerable interior porosity (Figure 1).

Kernouvé porosity. Mean porosity by ideal gas pycnometry was 6.8%. μCT-visible porosity at the resolutions described above was 4.4 ± 1.3%. Our results are consistent with previous determinations of Kernouvé porosity [17]. The slightly lower value of porosity derived from μCT compared to that from pycnometry is also consistent with previous studies that used both techniques [13-15], and can be explained by the presence of voids smaller than the imaging resolution. More importantly, the presence of interior porosity in Kernouvé indicates that the meteorite was incompletely compacted.

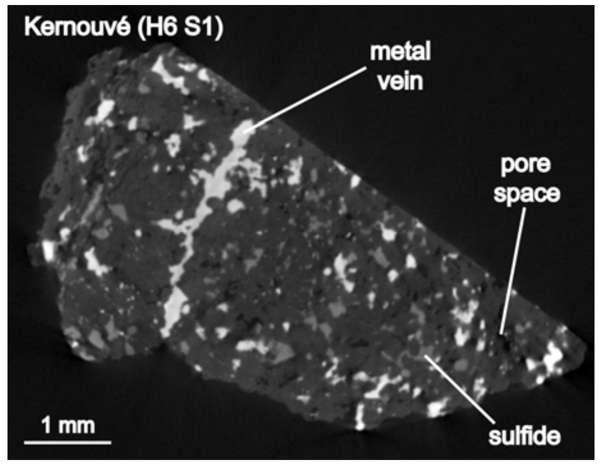

Figure 1. A μCT slice of the AMNH 470 Kernouvé (H6, S1) chondrite sample. A metallic vein and intragraunlar porosity can readily be imaged with resolutions of ~11 μm/voxel.

Degree of compaction. We used techniques described in [12] to quantitatively evaluate the degree of compaction experienced by Kernouvé and an additional 16 ordinary chondrites of varying chemical classes and petrographic types. Results are shown in Figure 2. Here we use the ratios of ellipsoid tensors, summed over all metal grains, as an indicator for overall preferred orientation (as indicated by the strength factor). Our expanded database increases the number of S1 shock stage samples and includes chemical classes other than L chondrites, which made up our original dataset [12]. Our results show that Kernouvé does not possess significant preferred orientation of metal grains, consistent with other low shock stage meteorites (Figure 2). These data suggest that the meteorite was not significantly compacted by a late shock event.

Vein visualization and 3D shape. The 3D structure of metal veins in one of our Kernouvé samples is shown in Figure 3. The vein in this sample is discontinuous with the two pieces appearing to be offset. The other sample also contains a vein of similar proportions and structure, but is continuous. Each vein has an overall prolate to triaxial (or scalene) structure and a striking complexity of shape.

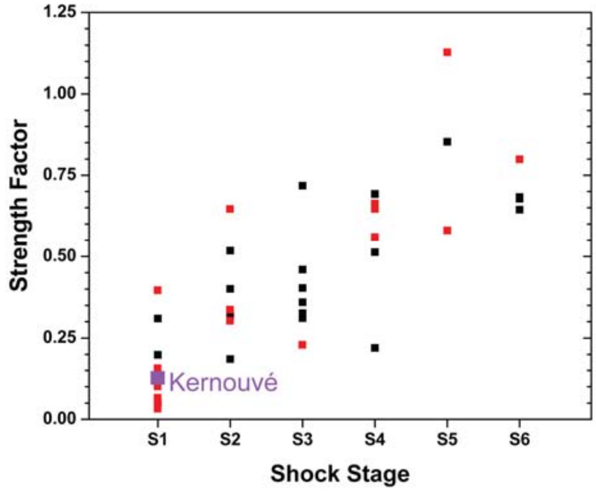

Figure 2. Degree of compaction, as given by the strength factor determined by collective orientation of metal grains in chondritic samples [12], versus shock stage. Kernouvé is not only mildly shocked, but also poorly compacted. Data in black [12] incorporated only L chondrites; new data (red symbols and Kernouvé) incorporating H and LL chondrites, demonstrate that the scheme holds for chondrites other than L.

Discussion and Conclusions: The metal vein in Kernouvé can be explained as a pre-metamorphic shock-induced structure, given the evidence for current weak compaction and low shock stage. However, it is not clear how one explains high porosity and low shock stage if the meteorite experienced early shock sufficiently strong to mobilize metal into a vein-like structure. Some combination of unusual conditions during shock (e.g. high temperatures) or mobility of metal during metamorphism may be needed.

One possible mechanism occurring early on the H chondrite parent body follows: blocks of slightly indurated but porous material were disturbed by an impact which caused a physical concentration of metallic phases akin to slickensides. Shearing of these materials caused the warm, ductile metal grains to be concentrated on rock surfaces. This process would have imparted the rocks with indicators cited by [4,5] as shock induced. This event happened early in the history of the chondrite otherwise shearing forces would have imparted a preferred orientation upon the metal grains. Subsequent annealing due to radiogenic heating erased any preferential orientation and further coalesced the vein metal. The final compaction of the material occurred yielding the porosity seen in the samples today. The material escaped other major shock episodes.

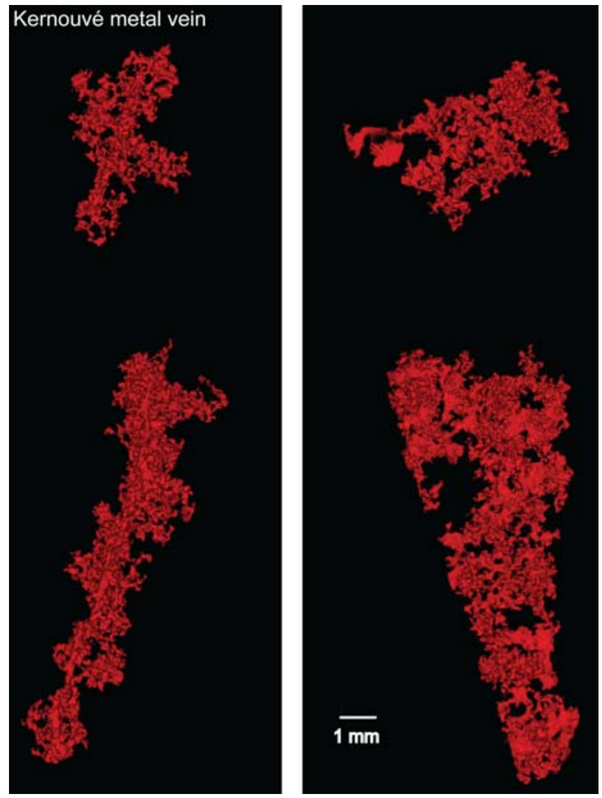

Figure 3. 3D visualization of two discontinuous metal veins in Kernouvé (AMNH 470). Views are rotated 90° on a vertical rotation axis; an "edge-on" view is shown at left and a "face on" view at right. The complexity of shape and degree of interconnectivity indicates a pre-metamorphic origin for the metallic vein structures.

References: [1] Turner G. et al. (1978) *Proc. Lunar Plan. Sci. Conf., 9,* 989-1025. [2] Hutson M. (1989) *LPS XX,* 436-437. [3] Rubin A. E. (1992) *Geochim. Cosmochim Acta, 56,* 1705-1714. [4] Rubin A. E. (2003) *Geochim. Cosmochim Acta, 67,* 2695-2709. [5] Rubin A. E. (2004) *Geochim. Cosmochim Acta, 68,* 673-689. [6] Hutchison R. (2001) *Phil. Trans. R. Soc. Lond. A, 359*, 2077-2093. [7] Michel-Lévy M. C. (1981) *Earth Plan. Sci. Lett., 54,* 67-80. [8] Leroux H. et al. (1996) *Meteorit. Planet. Sci., 31,* 767-776. [9] Stöffler D. et al. (1991) *Geochim. Cosmochim Acta, 55*, 3845-3867. [10] Schmitt R. T. (2000) *Meteorit. Planet. Sci., 35,* 545-560. [11] Reisener R. J. and Goldstein J. I. (2003) *Meteorit. Planet. Sci., 38,* 1679-1696. [12] Friedrich et al. (2008) *Earth Planet. Sci. Lett. 275*, 172-180. [13] Friedrich J. M. et al. (2008) *Planet. Space Sci., 56,* 895-900. [14] Sasso M. R. et al. *Meteoritics & Planet. Sci., 44,* 1743-1753. [15] Friedrich J. M. and Rivers M. L. *GCA* (in press). [16] Ketcham R. A. (2005) *Geosphere, 1,* 32-41. [17] Michel-Lévy M. C. (1978) *Meteoritics*, 13, 305-309.