A UNIQUE GRAPHITE AND AMPHIBOLE-BEARING CLAST IN QUE 99177: AN EXTENSIVELY METAMORPHOSED XENOLITH IN A PRISTINE CR3 CHONDRITE. N. M. Abreu and A. J. Brearley, Department of Earth and Planetary Sciences, MSC03-2040, University of New Mexico, Albuquerque, NM87131-1000, USA (abreu@unm.edu, brearley@unm.edu).

Introduction: CR chondrites are primitive carbonaceous chondrites, recording variable degrees of aqueous alteration and negligible thermal metamorphism [1-2]. QUE 99177 is one of the most primitive CR chondrites described to date, containing glassy chondrule mesostasis and interchondrule matrix dominated by amorphous silicates and nanosulfides that attest to a complete lack of thermal metamorphism [3]. QUE 99177 contains a unique clast that shows signs of high-temperature processing. We have studied the petrography and mineral chemistry of this clast using SEM and EMPA.

Results: The clast in QUE 99177 is an irregularly-shaped object approximately 1 mm^2 in area. The corners of the clast are rounded (**Fig. 1**). The clast is juxtaposed against typical fine-grained matrix along much of its periphery, but on one side is directly in contact with a chondrule. The boundary between the clast and the host matrix is very distinct.

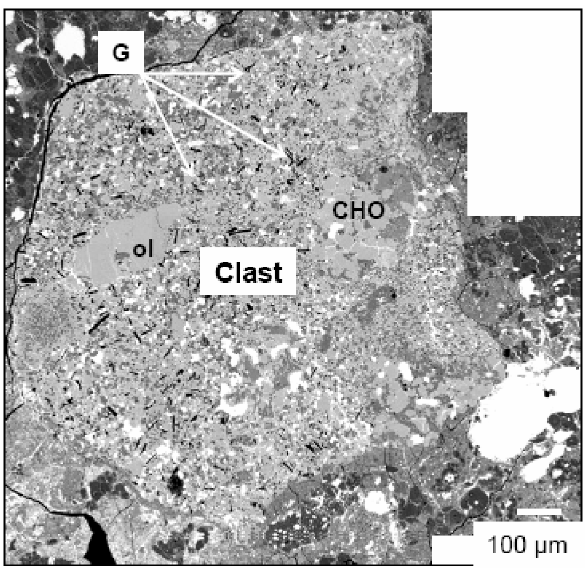

Fig. 1: BSE image of the graphite (G) and amphibole-bearing clast in QUE 99177.

The QUE 99177 clast consists a coarse-grained matrix (~47.6 vol%) in which are embedded a few larger objects (~44.6 vol%) that are either large, isolated silicate grains or recrystallized chondrule relics (**Fig. 2**). Matrix contains olivine pyroxene, amphiboles, Fe-sulfides, and graphite. Approximately 15.4 vol% of the clast consists of anhedral to sub-rounded, coarse-grained (up to ~100µm), FeO-rich (Fa_{36-41}) matrix olivine. Finer-grained (<50µm) amphiboles and pyroxene are randomly mixed with olivine and represent ~19.3 vol% of the volume of the clast. Amphiboles are indistinguishable from pyroxenes in all BSE images and were identified through EMPA point analysis. They are aluminous (average Al_2O_3= 11.7 wt%), Ca- and Na-rich (average CaO= 7.7 wt% and Na_2O= 4.25 wt%), and contain variable amounts of Fe (FeO=8.6-28.3 wt%). Amphibole totals range from 97-99.6 oxide wt%, suggesting OH, Cl, or F may be present. These compositions are most consistent with SiO_2-rich and TiO_2-poor kaersutite. Matrix contains abundant (~6.6 vol%), relatively large (up to ~ 80 µm) sulfides. Most sulfides consist of pyrrhotite with variable amounts of Fe and compositionally variable pentlandite. Dispersed throughout the matrix, abundant graphite laths (~6.4 vol% of the clast) ranging from >5-70µm were observed. Assuming the density of this clast falls within the chondritic meteorite density range, graphite content of the clast is 4-6.7 wt%. However, graphite content is an upper-end estimate, as small voids throughout the clasts that may have been counted as graphite.

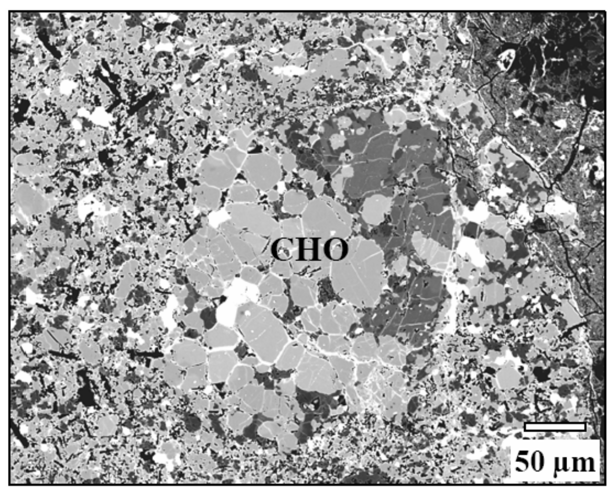

Fig. 2: BSE image of recrystallized matrix and chondrules from a graphite and amphibole-rich clast next to host matrix in QUE 99177.

Four chondrule relics and a large olivine crystal that appear to be a chondrule fragment have been identified (e.g. **Fig. 2**). One region that contains large olivine phenocrysts and a jagged outline was also observed. It is not clear if this area formed by heating of a chondrule or by heating and compaction of matrix.

These chondrules are composed of olivine, pyroxene, anhedral amphiboles, and sulfides. Chondrule olivines have similar composition to those in the matrix ($Fa_{36.5-40.5}$) and represent ~26.6 vol% of the clast. As in the matrix, amphiboles are anhedral to rounded and show a similar range of compositions, albeit more variability in Ca contents. Amphiboles contain variable amounts of Ca, Al, Fe and Mg within the same chondrule. Ca-rich amphiboles are close to kaersutite composition and Ca-poor amphiboles are more similar to magnesiokatophorite. Chondrule sulfides (Ni-bearing pyrrhotite) are nearly as abundant as in the matrix (~ 5 vol%), and are found only in the interiors of porphyritic chondrules.

Discussion: These observations show that the amphiboles and graphite-bearing clast differs from the QUE 99177 host in a number of important respects including: (1) extensively recrystallized chondrules, (2) Fe-rich compared to the surrounding matrix, (3) abundant, large, highly-equilibrated silicate crystals, (4) absence of metal, (5) presence of amphiboles and (6) presence of abundant, large graphite laths.

Clearly, the mineralogy of this clast is highly unusual. The occurrence of graphite and amphiboles in the same object set this clast apart from any known chondrite or chondritic clast. Although graphite has been previously reported in texturally similar graphite-rich clasts in LL3 chondrite Krymka [4,5], this is the first documented occurrence of this material in a carbonaceous chondrite. To our knowledge, the only other reported occurrence of amphiboles in a chondritic meteorite is from the R6 chondrite LAP 04840 [6]. LAP 04840 contains, aluminous, possibly hydrous amphiboles, along with olivine, opx, plag, Cr-magnetite, and sulfides [6]. Unlike amphiboles in the QUE 99177 clast, many olivines in LAP 04840 are euhedral. Furthermore, LAP 04840 shows signs of oxidation such as the presence of magnetite, this is not the case for the clast in QUE 99177, where graphite is observed instead.

Provenance and Classification: While it is clear that this clast formed from a chondritic precursor, this precursor should also meet the following criteria: (1) matrix/chondrule ratio~1; (2) high FeO content, (3) very high C-content; (4) high sulfide abundance. The clast's large matrix-to-chondrule ratio rules out an ordinary or enstatite chondrite precursor. C-contents in this clast are above those in all meteorite groups, with the exception of some CI chondrites [7] and unique CC Tagish Lake [8]. Unlike the QUE 99177 clast, chondrules are absent in CI chondrites and Tagish Lake is thoroughly hydrated and oxidized. Thus, if the QUE 99177 clast originated from Tagish Lake-like material, it would have to have lost O and H_2O, while retaining nearly all its C. Metal is conspicuously absent from this clast, but sulfides are abundant in the relict chondrules and matrix. Combined, sulfides constitute ~ 11.6 vol% of the clast. One possibility is that metal in the clast has undergone sulfidization. If all these sulfides formed by this mechanism, the clast's precursor must have been very metal rich. CR clan chondrites contain large amounts of metal [7], consistent with the proportion of opaques observed in the QUE 99177 clast and similar matrix/chondrule ratios. However, complete sulfidization of the metal in the precursor material would be necessary. Furthermore, CR clan C-contents are far too low [7] compared to those observed in the QUE 99177 clast. A CC origin cannot be ruled out, yet the available evidence suggests that the potential precursor has not been sampled by our collections. Finally, the QUE 99177 may have originated from an extraordinarily C-rich R-chondrite precursor.

Textural characteristics of chondrules, level of olivine and pyroxene recrystallization and equilibration are most consistent with petrologic type 5. Metamorphism could have happened in its final location in the QUE 99177 parent body or in a different location in the QUE 99177 or other parent body, prior to final lithification. The clear boundary between the clast and host indicates that the QUE 99177 clast was emplaced after processing, probably during asteroidal regolith gardening. C-content in chondrites decreases as petrologic type increases, this is likely to result from labile C escaping from highly porous parent bodies as metamorphic temperatures increased. In order to preserve the high C-content observed in the QUE 99177 clast, metamorphism must have occurred in far from the asteroidal surface, where carbonaceous materials could not easily escape.

References: [1] Weisberg et al. (1993) *GCA, 57, 1567-1586*. [2] Kallemeyn et al. (1994) *GCA, 58, 2873-2888* [3] Abreu N. M. and Brearley A. J. (2006) *LPS XXXVII*, Abstract # 2395. [4] Semenenko et al. (2004) *GCA, 68, 455-475.* [5] Semenenko et al. (2005) *GCA, 69, 2165-2182.* [6] McCanta et al. (2006) *MAPS, 41*, 5376. [7] Brearley A. J. & Jones R. (1998). In *Planetary Materials* p. 3-1 - 3-398. [8] Grady et al. (2002) *MAPS, 37, 713-735*.

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