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XENOLITHS IN THE CM2 CARBONACEOUS CHONDRITE LON 94101: IMPLICATIONS FOR COMPLEX MIXING ON THE ASTEROIDAL PARENT BODY.

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Introduction: Xenoliths are foreign clasts that occur in various classes of meteorites, e.g. [1,2,3]. A recent study reveals the presence of several distinct classes of xenoliths in regolith-bearing meteorites, including in over 20 different carbonaceous chondrites [4]. The most common types of xenoliths are fine-grained hydrous clasts, often referred to as C1 or CI clasts in the literature, although their mineralogy is actually more similar to hydrous micrometeorites [5,6]. Xenoliths in meteorites present an opportunity to study material not yet classified or available as separate meteorites, and can provide additional information on processes in the dynamic early history of the Solar System.

Here we have performed chemical and mineralogical analyses of xenoliths in the CM2 carbonaceous chondrite LON 94101, using scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

Methods: Three polished thin sections of LON 94101 were coated with 10 nm of carbon, prior to backscatter electron (BSE) imaging and qualitative energy dispersive (ED) X-ray analyses in a field emission Zeiss Sigma SEM operated at 20 kV. TEM analyses were performed on three focused ion beam (FIB) liftouts of matrix in three types of xenoliths in one of the thin sections. The foils were cut using a FEI Nova 200 Dualbeam FIB instrument, and welded on to a Cu support. Diffraction contrast images and diffraction patterns were acquired using a FEI T20 TEM operated at 20 kV.

Results: A total of sixteen xenoliths were discovered in the three thin sections; twelve fine-grained hydrous clasts ("CI-like clasts"), and four additional different xenoliths. The fine-grained hydrous clasts are irregular to rounded and vary in size from ~40-400 µm, but most are ~200 µm in diameter (Fig. 1a). They consist of clusters of iron oxide framboids, iron-nickel sulfides and Fe-Mg carbonates set in a fine-grained phyllosilicate matrix. ED X-ray analyses show that the matrices of these xenoliths have lower iron concentrations compared to the matrix of the host CM2. TEM diffraction contrast images reveal that the matrix is composed of a mixture of two types of fine-grained phyllosilicates, one is slightly coarser than the other. Embedded in the matrix of the cut FIB foil is also a ~4 µm large grain, giving a diffraction pattern consistant with breunnerite. The coarser variety of the two phyllosilicates occurs as a rim around the breunnerite grain (Fig. 1b).

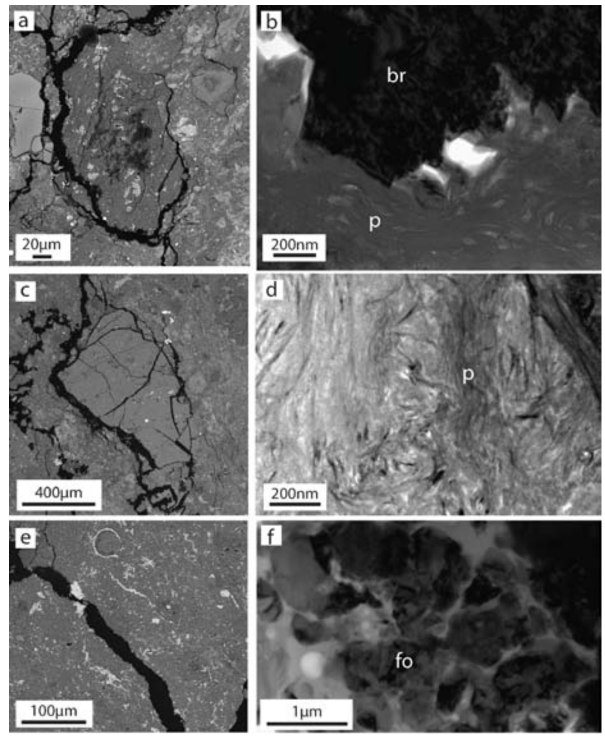

Fig. 1a) A BSE image of a fine-grained hydrous clast ("CI-like clast") with clusters of iron oxide framboids. **b)** A TEM diffraction contrast image of the matrix of a), showing phyllosilicates (p) wrapping around a breunnerite grain (br). **c)** A BSE image of a fine-grained hydrous clast lacking iron oxide framboids. **d)** A TEM diffraction contrast image of the matrix of c), showing fine-grained phyllosilicates (p). **e)** A BSE image of an anhydrous clast with elongated wavy iron-nickel sulphides (bright features). **f)** A TEM diffraction contrast image of the matrix of e), showing grains of forsterite (fo, dark-grey) in an ultrafine matrix (light-grey). All are from LON 94101.

The four additional different xenoliths are: 1) An irregular ~0.8 mm diameter hydrous clast with Ca-carbonates, iron-nickel sulphides, iron oxides (but no clusters of framboids) and a rare olivine in a fine-grained phyllosilicate matrix (Fig. 1c;d). 2) An irregular ~1.2 mm diameter unhydrous clast with elongated wavy iron-nickel sulphides, olivine and Ca-pyroxene in a matrix composed of ~1 µm diameter grains of olivine (forsterite) set in an ultrafine material (Fig. 1e;f). 3) An irregular ~2 mm diameter hydrous "carbonate clast" composed of ~50 area% carbonates (as determined by point-counting), set in a fine-grained phyllosilicate matrix (Fig. 2a). The carbonates occur as abundant ~10-20 µm diameter grains of Fe-Mg carbonate (~4 mole% $CaCO_3$, ~42 mole% $MgCO_3$ and ~54 mole% $FeCO_3$) and a few slightly larger ~50 µm diameter grains of Ca-Mg carbonate (~50 mole% $CaCO_3$, ~44 mole% $MgCO_3$ and ~6 mole% $FeCO_3$). This xenolith also contains clusters of iron oxide framboids and one grain of olivine. 4) A large hydrous ~4 mm diameter xenolith with up to ~1 mm long crystals of iron-sulphides set in a fine-grained phyllosilicate matrix (Fig. 2b). This xenolith also contains grains of Ca-carbonates, iron-nickel sulphides and a chondrule composed of olivine that has been partially replaced by Ca-carbonate.

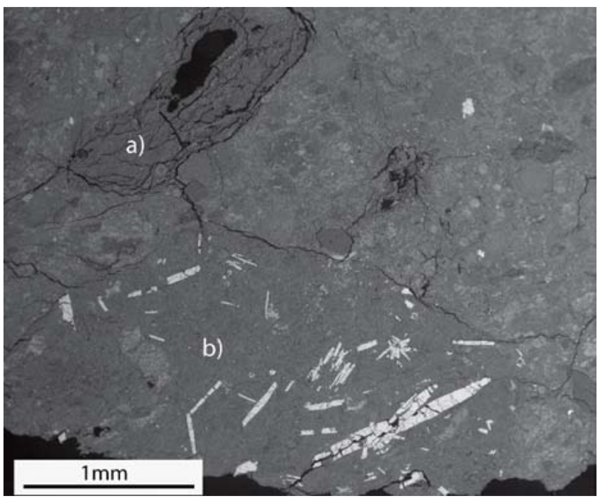

Fig. 2. A BSE image of LON 94101 showing **a)** an irregular "carbonate clast" and **b)** a hydrous fine-grained clast with large crystals of iron-sulphide (bright elongated crystals).

Discussion: The presence of several distinct types of xenoliths in LON 94101, and in other carbonaceous chondrites, indicate a complex mixing involving material from various sources in a dynamic environment on the asteroidal parent bodies. This mixing probably took place in shallow crustal levels during impacts of foreign bodies.

The definite origins of the xenoliths are unknown, but they may be derived from parent bodies not yet available as individual meteorites. They could also be derived from the same asteroid as their host, but from various locations that have witnessed different alteration histories. The most common xenoliths are the fine-grained hydrous clasts. They are to some extent similar to CIs in that they contain clusters of iron oxide framboids and FeMg-carbonates (breunnerite) in a fine-grained phyllosilicate matrix. Also, ED X-ray analyses of their matrices show lower iron concentrations compared to the host CM2 matrix, consistent with differences in iron concentrations between CIs and CM2s [7], but since CMs display a petrologic range from type 1 to 2 [8], they could also be CM1s. However, more detailed previous studies suggest that their mineralogy is most similar to hydrous micrometeorites [5,6].

Xenoliths can provide information on the relative timing of aqueous alteration and accretion/mixing by impacts. All of the xenoliths in LON 94101, except one, are hydrous. The presence of the anhydrous xenolith implies that its accretion must have occurred after the most severe period of aqueous alteration on the LON 94101 parent body. The matrix of the anhydrous xenolith is unaffected by secondary processes. However, a certain degree of aqueous alteration has probably affected this xenolith since it contains elongated wavy iron-nickel sulphides. Similar textures have been reported surrounding anhydrous silicate grains in other CMs, and are interpreted as late-stage aqueous reactions [9].

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