Introduction: Primitive xenolithic CI-like carbonaceous (C) clasts are sometimes hosted within meteorites of a different origin (ordinary chondrite, ureilite, howardite, and eucrite) [1, 2]. These xenoliths contain aggregates of macromolecular carbon (MMC), which are often present as discrete grains and exhibit a wide range of structural order and chemical compositions [1]. The Carancas meteorite is a H4-5 that impacted south of Lake Titicaca, Peru in 2007. While the meteorite exhibits extensive recrystallization of the matrix indicating metamorphism [3], it contains dark, CI-like clasts that show no evidence of heating. Similar to other xenolithic clasts, the examined C clast of Carancas contains MMC, which however exists in the form of a vein-like structure dissimilar to the typical occurrence of MMC in meteorites. We investigated the organic and isotopic compositions of the organic-rich vein with C,N,O-X-ray absorption near-edge structure (XANES), Raman spectroscopy, and NanoSIMS, in order to constrain its possible origin.

Samples and Analytical Techniques: Two ~100 nm-thick focused ion beam (FIB) sections (Carancas 1 with the C-rich vein, and Carancas 2) were subsampled from a selected Carancas C clast using a Quanta 3d field-emission gun FIB instrument at NASA JSC. The FIB sections were analysed with C,N,O-XANES microscopy using the scanning transmission X-ray microscopes (STXM) at BL4U of UVSOR, Institute for Molecular Science. The sections were then studied with a Jobin-Yvon Horiba LabRAM HR (800 mm) Raman microscope at The Open University (OU) using a 514.53-nm (green) laser for which the power was maintained at ~60 μW. The Raman C parameters (param.) – the peak position (ω) and full width half-maximum (Γ) of each Raman band – were determined by simultaneous peak fitting to the two-peak Lorentzian and Breit–Wigner–Fano model [4] and linear baseline correction. The H,C,N,O isotopic compositions of the ~150 nm Au-coated FIB sections were analysed by isotopic imaging with a NanoSIMS 50L ion microprobe at OU with a primary Cs+ beam of 1.5–3.5 pA.

Results and Discussion:

C,N,O-XANES. The STXM elemental map outlines the ~10 μm C-rich vein (red area) in the Carancas 1 section (Figure 1A). The C-XANES spectrum of the C-rich vein (Figure 2) shows two major absorption features: (1) 285.0 eV: alkynyl and aromatic (C=C) carbon, and (2) 286.5 eV: ketone (C=O), nitrile (C≡N), and/or pyrrole and imidazole [5]. A weak 288.7 eV peak was observed which corresponds to carboxyl carbon (O=C=O). The notable feature at 286.5 eV is also consistent with the strong C=O feature (~531.0 eV) in the O-XANES spectrum. The presence of ketones suggests the onset of aqueous alteration on the parent body [6]. The N-XANES spectrum shows adsorption features around 398.6 and 399.7 eV (amide, pyrrole [C=N], nitrite [C≡N], pyridine) and 401.1 eV (amide, pyrrole [C=NHx]) [5], which are consistent with the 286.5 peak identified in the C-XANES spectrum as potentially nitrile and pyrrole in addition to ketone.

Figure 1. (A) STXM elemental map of Carancas 1. (B) NanoSIMS 12C elemental map, and isotopic images of (C) δD and (D) δ13C.

The C-rich vein is unique in its organic chemistry. It is atypical of primitive chondritic insoluble organic matter (IOM) (e.g. Murchison), as the 286.5 eV feature is less prominent and the 288.7 eV feature is more pronounced in the latter (Figure 2). Thus, the C-rich vein has a higher ketone but lower carboxyl content, which indicates that aqueous alteration occurred on the parent body but the process was not severe, as carboxylic acid would have been formed via further oxidation of ketone. The C=O feature of the vein in the O-XANES spectrum is prominent and comparable to the OM in interplanetary dust particles (IDPs), but the carboxyl content is significantly lower in the vein.
Raman spectroscopy. The most typical Raman peaks of carbonaceous materials are the first-order defect (D) band at ~1360 cm⁻¹ and the graphite (G) band at ~1580 cm⁻¹ [7]. Changes in the param. of the OM in C chondrites correspond to the nature of the organic precursors and the structural order of the aromatic units [e.g., 8]. We compared the param. of the organics hosted within the C-rich vein and the matrix of the Carancas meteorite to the IOM of chondritic meteorites. Carancas OM shows an affinity to the primitive (unheated) CM chondrites (Figure 3). The OM in the C-rich vein is more primitive than its matrix and its param. are comparable to IDPs. We have also studied a raw grain, IOM and a FIB section prepared from Murchison matrix, and found that the param. are not influenced by the sample form, thus allowing direct comparison between the FIB section of the Carancas meteorite to the meteoritic IOM.

![Figure 2. C-XANES spectra of the C-rich vein (organic) and the matrix (inorganic) of the Carancas 1 FIB section.](image)

![Figure 3. The Γ₀ and Γ₀ of the Carancas sample compared to that of the IOM of meteorite IOM [10].](image)

NanoSIMS analysis. We used the isotopic compositions of the Carancas sample to interpret the origin of its OM. NanoSIMS isotopic images are shown in Figure 1 (C,D), and the C vs. H isotopic compositions are plotted in Figure 4. In general, the C, H isotopic compositions of the Carancas C clast sample are different from that of ordinary chondrites (which typically have higher δD values, >2000‰) but show an affinity to CMs/CIs. The C-rich vein is depleted in ¹³C (δ¹³C=-19 ± 1‰) and D (δD=+316 ± 73‰) compared to the C clast matrix (δ¹³C=-6 ± 1‰; δD=+754 ± 52‰) (Figure 4). Carancas 2 does not contain a similar C-rich vein and probably better represents the meteorite bulk. The C,H isotopic values of Carancas 2 (δ¹³C=-15 ± 1‰; δD=+911 ± 41‰) are comparable to that of CIs. The lower δD enrichments in C1s compared to the CR2s (δD=-3000‰) indicates the exchange of D-poor water during aqueous alteration [10, 11]. The δ¹⁵N value of the C-rich vein (~31 ± 16‰) is slightly higher than that of the matrix (~100 ± 4‰).

![Figure 4. The C vs. H isotopic composition of the Carancas samples compared to meteorite IOM [10].](image)

Conclusion: The studied Carancas meteorite C clast is an heated primitive CI material that was incorporated into the D-type parent body subsequent to the latter’s thermal event. The varied isotopic compositions of the C-rich vein and the C clast bulk suggest that they were processed under different aqueous conditions but the water is D-poor in both events, or the C-rich vein was produced in a later, shorter aqueous event that sequestered organics from the surroundings and resulted in further isotopic fractionation. The association of the C-rich vein with parent body aqueous alteration likely accounts for its vein-like structure. The XANES features of the C-rich vein in Carancas suggest that it originates from a parent body that is enriched in O- and N-bearing compounds.