A NANOSCALE ANALYTICAL STEM STUDY OF THE PARIS METEORITE

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Introduction: Paris is considered to be the least altered CM chondrite [1]. It is a breccia with evidence of heterogeneous aqueous alteration, containing both metal-rich lithologies with abundant amorphous silicates as well as metal-poor lithologies with abundant phyllosilicates. In the least altered lithologies, Paris has been found to preserve material closely resembling GEMS (glass with embedded metal and sulfides) from interplanetary dust particles (IDPs) [2]. If the GEMS-like material in Paris can be confirmed to be related to IDP GEMS, it may uniquely demonstrate the progression of silicates from the interstellar medium and/or early solar nebula to incorporation into a growing planetesimal and subsequent alteration. If the GEMS-like material in Paris is unrelated to IDP GEMS, it may represent a significant yet altogether unexplored class of objects in primitive meteorites.

GEMS grains have yet to be unambiguously identified in meteorites. While the GEMS-like material in Paris has textural similarities to IDP GEMS as well as comparable average chemical compositions as measured by energy-dispersive X-ray spectroscopy (EDS), the ubiquity of nanophase components throughout the GEMS-like material makes comparisons difficult and necessitates more detailed scrutiny before definitive identifications can be asserted. The same is true for GEMS-like material that has recently been observed in the CR chondrite LaPaz Icefield 02342 [3] and whose nanophase components also await definitive mineral identification. Inclusions in GEMS and GEMS-like objects are ~1–30 nm in size, smaller than the thinnest TEM sections. Nanodiffraction [4] is able to obtain diffraction patterns from regions <1 nm. Unlike with EDS, it is more easily discerned when multiple phases are contributing to an electron diffraction pattern, and it is possible to remove the contribution from unwanted phases. Nanodiffraction can therefore provide essential mineralogical information on the often-neglected smallest class of objects in meteorites.

Samples and Methods: Section 2010-1 of the Paris meteorite was provided by the Muséum National d'Histoire Naturelle. Nine electron-transparent lamellae were lifted out with a TESCAN LYRA3 FIB-SEM at the University of Chicago and thinned and polished with an FEI Helios NanoLab 660 Dual Beam FIB at the Hawai‘i Institute of Geophysics & Planetology (HIGP). Areas of interest were chosen from a range of petrologic settings with possibly different formation histories and varying degrees of aqueous alteration. The final size of each lamella was <100 nm × ~15 μm × 7–8 μm with a ~5 μm protective strap. The sections were examined using a FEI Titan3 G2 scanning transmission electron microscope (STEM) equipped with a Genesis 4000 Si(Li) solid-state X-ray energy-dispersive spectrometer (EDAX Inc.) at HIGP. The sections were imaged using both conventional bright-field and high-angle annular dark-field (HAADF) modes. Elemental compositions were measured by EDS, while crystallographic information was acquired by electron diffraction—either nanodiffraction for nanoscale phases or SAED (selected area electron diffraction) for larger phases. In some cases, high-magnification lattice-fringe images were also taken.

Results: Preliminary EDS and diffraction analyses indicate compositional and mineralogical differences between the nanophase inclusions in IDP GEMS and Paris GEMS-like material. Notably, nanophase FeNi metal grains have yet to be identified in Paris. Grains with EDS spectra suggestive of FeNi metal have diffraction patterns inconsistent with metal and, instead, are identified as carbides or oxides, demonstrating the problem with relying on EDS spectra alone in identifying nanoscale phases. The nano-inclusions are predominantly pyrrhotite and pentlandite. Nanophase pentlandite appears to be more prevalent in more highly altered matrix material but is also found in the least altered matrix material of Paris. Pentlandite is not found as inclusions within IDP GEMS and is usually considered to be evidence of hydration when present in IDPs [5]. Other mineral phases identified in our Paris sections include low-iron, Mn-enriched (LIME, Mn/FeO ≥1) silicates, an enstatite platelet, and two forsterite whiskers.

Discussion and Conclusions: While the matrices of Paris and other primitive chondrites contain material with textural and elemental similarities to GEMS from cometary IDPs, nanodiffraction reveals mineralogical differences between the respective nano-inclusion populations. At this time, it is unclear if the differences between IDP GEMS and the GEMS-like material of Paris require an independent origin, or if the differences are solely the result of alteration. The presence of LIME silicates, enstatite platelets, and forsterite whiskers confirms the incorporation of vapor phase condensates into the CM parent body and may suggest a relationship between the Paris matrix and cometary material, but more studies are needed to verify such a relationship.

References: [1] Hewins R. H. et al. (2014) *Geochimica et Cosmochimica Acta* 124:190–222. [2] Leroux H. et al. (2015) *Geochimica et Cosmochimica Acta* 170:247–265. [3] Nittler L. R. et al. (2019) *Nature Astronomy*, https://doi.org/10.1038/s41550-019-0737-8. [4] Cowley J. M. (1999) *Microscopy Research & Technique* 46:75–97. [5] Zolensky M. E and Thomas K. L. (1995) *Geochimica et Cosmochimica Acta* 59:1407–1412.