Was the ureilite parent body as large as Mars?

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Ureilites are a group of coarse-grained achondritic meteorites, distinct by their high carbon content. Carbonaceous materials appear as graphite and/or diamond between olivine and pyroxene grains in the matrix. The presence of diamonds is, often, attributed to the shock-induced transformation from graphite. However, a recent study [1] on Almahata Sitta MS-170, mainly based on the large size of diamonds and the sector zoning of nitrogen isotopes, suggests that they formed in the static high-pressure conditions of planetary interior.

We prepared thin sections by the focused ion beam (FIB) from the diamonds in Almahatta Sitta MS-170 and NWA10900 as well as from the graphite in NWA5884 for transmission electron microscopy (TEM) analysis. The abundance of dislocations, stacking faults and {111} twins in diamond samples indicate significant deformation. Moreover, large numbers of inclusions are found in diamonds. Electron energy-loss spectroscopy (EELS) showed that when a twinning is intersected with an inclusion in the diamond matrix, it transforms to graphite. This together with other morphological and crystallographical characteristics of the graphite and diamond phases points to the shock-induced transformation of diamond to graphite in Almahatta Sitta MS-170 and NWA10900.

Energy dispersive X-ray (EDX) spectroscopy and electron diffraction were used to chemically and structurally characterize the inclusions in diamond and graphite. Most of the inclusions in diamonds found in Almahatta Sitta MS-170 and NWA10900 are Fe-Ni-S-P type up to ~60 nm in diameter, each consisting of three phases: kamacite (Fe,Ni), troilite (FeS) and Schreibersite ($(Fe,Ni)_3P$). The inclusions always have euhedral shape indicating the existence of a parent phase that later broke down. Chemical analysis of complete inclusions (identified with electron tomography) agrees with the stoichiometric $(Fe_{0.93},Ni_{0.07})_3(S_{0.88},P_{0.12})$ phase that only forms above 20 GPa [2]. The ureilite parent body (UPB) needs to be at least about Mars-sized to generate such a pressure at its core-mantle boundary [3]. This is in the same size range estimated for the planetary embryos in the early Solar System.

Moreover, although the UPB did not go through an extensive magma ocean period, it was partially differentiated through segregation of Fe-S melt [4]. The existence of Mg-free chromite (Cr_2FeO_4) inclusions in diamond and the vein-like arrangement of Fe-S inclusions suggest that the diamonds are formed from the Fe-S-C melt at the pressures exceeding 20 GPa inside the UPB [3]. The inclusions in the graphitized regions of the Almahatta Sitta MS-170 and NWA10900 are also of Fe-S type, but, unlike the inclusions in the diamonds, they show arbitrary shapes and inhomogeneous distribution that relates to melting event. On the other hand, the graphite phase in the NWA5884 meteorite, which is a diamond-free ureilite, is dominated by silicate inclusions. The silicate inclusions form elongated veins inside the graphite pointing to their liquid state when trapped inside the graphite. This implies that the formation mechanism and environment of graphite in the NWA5884 meteorite is drastically different than the diamonds in the Almahatta Sitta MS-170 and NWA10900 meteorites.

References: [1] Miyahara M. et al. 2016 *Geochim. Cosmochim. Acta* 163: 14-26 [2] Gu T. et al. 2016 *Am. Mineral.* 101:205-210 [3] Nabiei F. et al. 2018 accepted in *Nat. Commun.* [4] Barrat J.A. et al. 2015 *Earth Planet. Sci. Lett.* 419: 93-100