A Mars-sized planet inferred from characterization of inclusions in extraterrestrial diamonds

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Ureilites are a group of coarse-grained meteorites originating from the mantle of their parent body. These rocks are distinguished by their high carbon content. Carbonaceous materials usually in the form of graphite and diamond can be found between the silicate grains. Despite many investigations, the origin of diamond in ureilites remains controversial. A recent study (*1*) noted the large size of diamonds and the sector zoning of nitrogen isotopes in the diamond grains in a ureilite meteorite, and thus concluded that the diamonds are formed at static high-pressure condition inside the ureilite parent body (UPB) in contrast to the shock-induced formation of diamonds from graphite or direct CVD growth from the nebula.

In this study, thin sections made from the ureilite diamonds and graphite by focused ion beam (FIB) instrument are investigated with transmission electron microscopy (TEM) techniques. Diamond-graphite phase relationship is studied with electron diffraction and electron energy loss spectroscopy (EELS) of carbon K-edge in magic angle condition. The results reveal a highly deformed diamond matrix as evidenced by a large number of crystalline faults, particularly {111} mechanical twinnings. When these twinning are intersected with inclusions in the diamond matrix, they have transformed to graphite. As evidenced by morphological features, graphitization causes the large diamond grains (up to 100 μm) to break down into fragments with similar crystallographic orientations that are separated with graphite bands. Such large diamond crystallites can only be formed in the static high-pressure conditions of the planetary interior.

Moreover, here we report the first discovery of inclusions in ureilite diamonds. These inclusions are structurally and chemically characterized by nano-beam electron diffraction and energy dispersive X-ray spectroscopy (EDX). Three different types of inclusions are found, all of which have well-defined euhedral shapes. The majority of inclusions are the Fe-S type with the sizes of up to ~60 nm, each consisting of two main phases: kamacite (Fe, Ni) and troilite (FeS) and one minor phase: schreibersite ($(Fe, Ni)_3P$). Interestingly, none of these minerals are found as a stand-alone inclusion and they are always together contained in a euhedral shape. This suggests that the inclusions were formed as a single high-pressure mineral and later decomposed to the three observed phases. In order to measure the total composition of inclusions, we used electron tomography technique through acquiring HAADF tilt series from the diamond matrix with inclusion. This allowed us to reconstruct the volume of inclusions and to identify the intact inclusions in the thin section. Quantification results from EDX on intact inclusions indicates that they have the stoichiometric composition of $(Fe_{0.93}, Ni_{0.07})_3(S_{0.88}, P_{0.12})$. This phase can only form above ~20 GPa (*2*). Therefore, UPB should have been at least about a Mars-sized planetary body to exert required pressure for the formation of diamonds and inclusions at its core-mantle boundary (3).

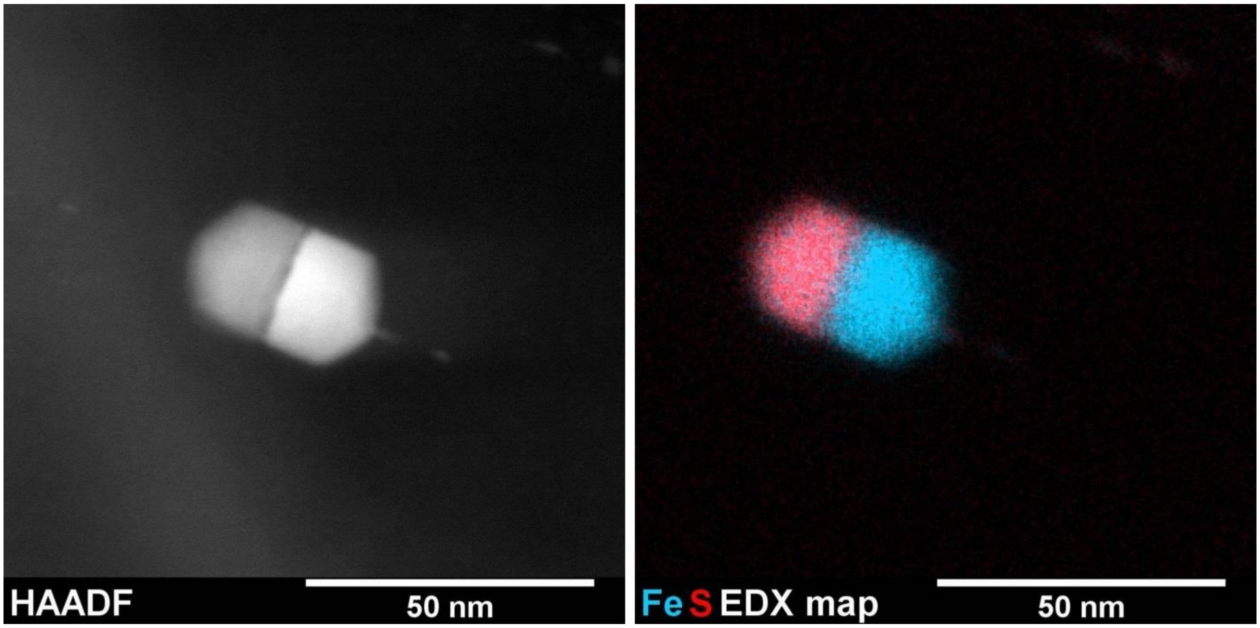

Figure 1- HAADF image and EDX map of an Fe-S type inclusion in diamond matrix.

References:

1. M. Miyahara *et al.*, *Geochim. Cosmochim. Acta*. **163**, 14 - 26 (2015).

2. T. Gu, Y. Fei, X. Wu, S. Qin, *Am. Mineral.* **101**, 205 - 210 (2016).

3. F. Nabiei *et al.*, Accepted in *Nat. Commun.* (2018).