

HIGH-TEMPERATURE HYDROTHERMAL ALTERATION RECORDED IN A DARK INCLUSION IN THE NWA 2900 CK CARBONACEOUS CHONDRITE

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Introduction: Dark inclusions are rock fragments with low visible reflectance and have mineralogical and petrological features different from the host meteorites. They show a variety of mineralogy and petrology: some contain chondrules [e. g., 1-3], while the others have no chondrules [e. g., 4, 5]. The former shows mineralogy similar to hydrous carbonaceous chondrites such as the CM type. The latter consists entirely of fine-grained materials with/without chondrules that are complete replacement by phyllosilicates. In this study, we performed a mineralogical study of a dark inclusion in the NWA 2900 CK3.5-3.7 carbonaceous chondrite and found many large diopside veins in the inclusion. Such large veins have not been previously reported from any carbonaceous chondrite. We constrained the formation temperature of the dark inclusion thermodynamically, based on the mineralogy and the bulk chemical composition of the inclusion.

Results: The dark inclusion is 1.0×2.5 cm in size and consists mainly of dark and fine-grained material (typically $<20\mu\text{m}$ but occasionally $100\mu\text{m}$ in grain size). It does not contain chondrules, but contains many bright veins. The fine-grained material consists mainly of olivine ($\text{Fa}_{34.8 \pm 0.52}$), magnetite, plagioclase ($\text{Ab}_{63.6 \pm 7.1}$, $\text{An}_{35.8 \pm 7.3}$), Cr spinel crystals, and a small amount of tiny pentlandite. On the other hand, the bright veins ($\sim 1\text{cm}$ long and $\sim 100\mu\text{m}$ width) cross-cut an entire region of the dark inclusion, connecting with other veins, forming a network structure. Besides the long veins, many small veinlets ($\sim 100\mu\text{m}$ long) also occur. The veins and veinlets consist mainly of crystalline diopside with high Wo contents ($\text{Wo} > 40$), some variations of $\text{Mg}/(\text{Mg} + \text{Fe} + \text{Ca})$ ratio ($51.9 > \text{En} > 31.1$), and low concentrations of minor elements such as Al, Na, Mn, Cr, and Ti. The relative abundance of the major five minerals, normalized to 100wt%, in the dark inclusion, is estimated to be olivine 61.8wt%, diopside 16.8wt% magnetite 14.8wt%, plagioclase 4.0wt%, and spinel 2.6wt%.

Discussion: The diopside compositional features, such as high Wo and En contents, and low minor-element concentrations and the absence of phyllosilicate in the inclusion are consistent with a high-temperature hydrothermal origin of the dark inclusion and the diopside veins [e. g., 6-10]. Within the veins, thin and long drain-like structures of Fe-bearing diopside are present within Mg-rich diopside, suggesting step-by-step formation of the veins during cooling of the high temperature fluids. The dark inclusion is embedded in an unbrecciated host CK chondrite, which suggests that the inclusion accreted in the early solar nebula together with chondrules and CAIs to form the CK chondrite parent asteroid. Since the diopside veins occur only in the dark inclusion and terminate at its edge, it is probable that the dark inclusion was formed by high-temperature aqueous alteration in a different (previous) asteroid, excavated by a subsequent impact, and later arrived to the accreting, host CK parent asteroid.

Thermodynamic calculations were performed with conditions that a rock with the bulk chemical composition of the dark inclusion equilibrated with water at various temperatures up to 900°C and water/rock ratios of 0.25, 1, 2.6, and 4 (oxygen mol). The equilibrated mineral combination and the relative mineral abundance were obtained and then compared with those of the dark inclusion. The results indicate that the dark inclusion formed at a temperature higher than 800°C . No carbonaceous chondrites are known to have experienced aqueous alteration at such a high temperature. Assuming that the heat source was ^{26}Al , the dark-inclusion is likely to have formed before chondrule formation. The timing of formation depends on the water/rock ratio (water-rich asteroids are difficult to heat and thus are required to form earlier). Because water-free asteroids need have formed at 2.2 Myr after CAIs to reach the peak temperature of 800°C [11], the dark inclusion must have formed before this time. This early formation date is consistent with the observation that chondrules are absent in the dark inclusion and that the host CK chondrite is an accretionary breccia.

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