Refractory inclusions in the Adelaide carbonaceous chondrite.

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Refractory-element-enriched inclusions from carbonaceous chondrites are believed to be representative of the earliest material formed in the solar nebula [1] and have been the subject of numerous studies leading to profound changes in our perception of the physical and chemical state of the primitive solar nebula. Most of the inclusions have come from Allende (CV) [1] and Murchison (C2) [2,3,4], due mainly to the large amount of material available. We report the first detailed observations of refractory inclusions in the recently discovered carbonaceous chondrite, Adelaide, and show that Adelaide contains inclusions texturally and mineralogically similar to ones found in both Allende and Murchison as well as some previously unobserved types.

Adelaide was identified as a C2 chondrite with C3 affinities in Davy et al. [5] who characterized bulk properties and analyzed major phases. One Ca-Al-rich "chondrule" was recognized, but its mineralogy was not identified. The whole rock oxygen isotopic composition ($\delta^{17}O = -3.7\%$, $\delta^{18}O = -0.1\%$; R.N. Clayton, personal communication) suggests that Adelaide is a C3. We used cathodoluminescence and SEM back-scattered-electron imaging techniques to study a polished slab of Adelaide and observed that although the majority of chondrules, inclusions, and mineral fragments larger than ~50 $\mu$m are olivine-rich, several percent have refractory or Ca-Al-rich compositions. Plagioclase in Adelaide occurs in olivine chondrules and refractory inclusions and shows the same brilliant blue luminescence and intragrain variations in color found in Allende plagioclase [6]. Several Adelaide refractory inclusions were identified by a characteristic blue halo produced by the luminescence of their diopside rims. Mg-Al-spinel and Fe-poor olivine (Fa 0 to 5) exhibit the familiar red luminescence. One unusual feature identified by its distinctive yellow-green luminescence was Ca-Al-bearing glass adjacent to some refractory inclusions.

The types of inclusions observed in Adelaide are categorized and described below. The number of each type studied is given in parentheses.

- **Spinel-hibonite inclusion (1)** is a compact oval, $60 \times 40 \mu$m in cross-section, comprised of bladed $\approx 10 \mu$m hibonite crystals, blocky spinels, and equant perovskites up to $\approx 5 \mu$m in size enclosed by hibonite or spinel. Hibonite and spinel are intergrown and hibonite crystals project inward from the rim of the inclusion as also observed in Murchison [2,3]. Hibonite and spinel are enclosed by a layered rim consisting of an inner layer of $\mu$m-size, Fe-bearing spinels set in an alumino-silicate matrix and an outer 2-5 $\mu$m thick layer of diopside. This object is texturally and mineralogically very similar to spinel-hibonite inclusions observed in Murchison [2,3,4].

- **Spinel inclusions (2)** are elongated, $\approx 200 \times 400 \mu$m, with a primary mineral assemblage of $>90\%$ Mg-Al-spinel. Spinel is massive and encloses scattered 20 $\mu$m Ti-Al-pyroxenes. Melilite ($\text{Ak} 0$ to 5) is rare and occurs only as isolated grains between spinel and the rim. The rim is a generally featureless $\approx 10 \mu$m layer of diopside and fassaite, $\approx 2x$ thicker than rims on other Adelaide inclusions. Spinel inclusions are heavily altered and two unidentified Al-silicate secondary phases, one probably hydrated and the other Fe-rich (also possibly hydrated), comprise $>60\%$ of the interior, producing a cracked "mud-flat" texture.

- **Melilite inclusions (2)** occur in two varieties corresponding roughly to "fluffy" and "compact" Type A Allende inclusions [1]. The most abundant primary phase in both inclusions is melilite, $\text{Ak} 0$ to 5 in the fluffy inclusion, and $\text{Ak} 15$ to 30 in the compact inclusion. The fluffy inclusion has a very
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contorted appearance dominated by sinuous bands of diopside and melilite. Originally the fluffy inclusion was very porous; cavities are now filled with Al-silicate. Spinel is always mantled by melilite, creating a layered structure with the ~5 μm diopside rim bordering melilite which encompasses spinel.

The compact melilite inclusion is elongated, ~250 × 500 μm, but much less sinuous and consists of 1-5 μm euhedral spinels enclosed in coarse-grained, 20-40 μm melilites. Perovskite occurs as μm-size blebs. The compact inclusion is significantly less altered than the fluffy one, containing only scattered Al-silicates and few voids. The same contrast in degree of alteration exists between the two classes of Allende Type A inclusions [1]. In contrast to the fluffy inclusion the rim on the compact inclusion is comprised of an Fe-free spinel inner layer and a hedenbergite outer layer. The spinel layer is discontinuous and replaced by fassaite in some areas.

Anorthite inclusion (1) is a previously unobserved type consisting of coarse-grained, 20-40 μm anorthites, An 90 to 95, with ~1 to 3% FeO. Half of the inclusion is heavily altered and contains ~50% Fe-poor Al-silicate. No spinel, pyroxene, or refractory metals were observed. A ~5 μm layer of Al-poor, Ti-Fe-bearing diopside surrounds the inclusion.

Olivine-Pyroxene-Anorthite-Spinel inclusions (4), the most abundant of the refractory inclusions studied, are roughly equidimensional, 100 to 500 μm, and exhibit a variety of complex textural relationships among the 4 primary phases: olivine (usually Fo 90 to 100), pyroxene (diopside and/or fassaite), anorthite (An 90 to 100, + FeO), and Mg-Al-spinel. Spinel occurs only in the interior, enclosed within either anorthite or pyroxene. Filaments of pyroxene, 10-20 μm thick, often surround spinel-anorthite aggregates and always separate olivine from spinel. Olivine commonly forms an outer but discontinuous layer on OPAS's. In contrast to the other refractory inclusions, OPAS's have no rim and contain only scattered Al-silicate secondary phases.

Adelaide contains silica-poor hibonite-spinel inclusions found in Murchison, melilite-rich Type A inclusions common to Allende, plus new Ca-Al-rich inclusions (anorthite, OPAS). This potpourri suggests that Adelaide inclusions experienced a wider range of equilibration temperatures with the nebular gas or formed in a greater variety of environments than did inclusions in Murchison or Allende. Despite the variety of textural and mineralogical features, several patterns are consistent throughout all Adelaide inclusions. (A) The occurrence of olivine has several important consequences: olivine-bearing inclusions (a) have no rims, (b) contain Fe-Ni metal (others do not), and (c) are the least altered inclusions. These features suggest that interaction with the gas leading to rim formation and alteration ceased prior to olivine formation. (B) Diopside rims predominate, even on the fluffy melilite inclusion, similar to Murchison inclusions but unlike multilayered Allende rims. If rim formation occurred by reaction with nebular gas and breakdown of melilite [7], Adelaide fluffy (diopside rim) and compact (spinel-hedenbergite rim) melilite inclusions must have reacted with gases of different composition. (C) Excluding the compact melilite inclusion, spinel always occurs as an interior phase enclosed within melilite or anorthite. Adelaide spinel must have condensed prior to melilite, contrary to thermodynamic predictions [8], but in agreement with the absence of melilite from hibonite-spinel inclusions in Adelaide and Murchison [2,3,4].


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