CRYSTALLIZATION OF COMPACT TYPE A REFRACTORY INCLUSIONS: IMPLICATIONS FROM CRYSTAL ZONING AND TRACE ELEMENT DISTRIBUTION;

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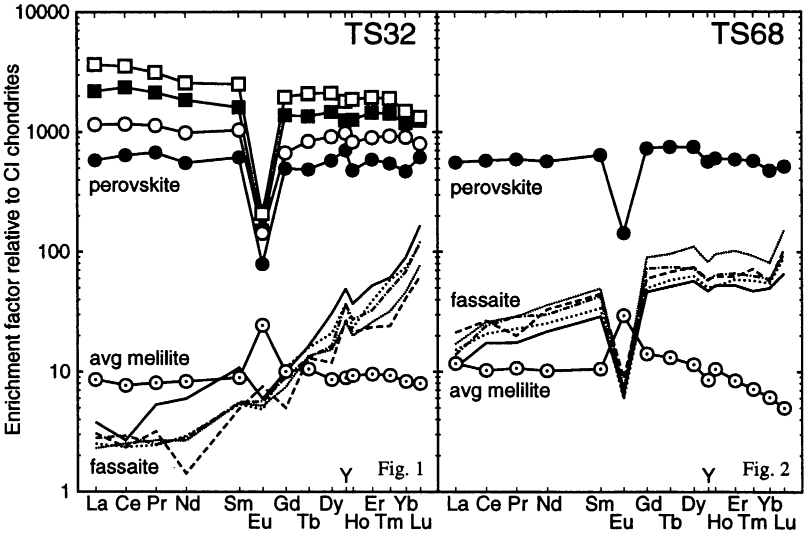
Abstract. Compact Type A inclusions (CTAs) are a major type of coarse-grained refractory inclusion found in CV3 chondrites, but they have not been thoroughly studied and their crystallization histories are not well understood. Our data show that in most CTAs both melilite and fassaite exhibit zoning trends and interelement correlations quite unlike those of their counterparts in Type B1 inclusions, suggesting that most CTAs did not form simply by crystallization of liquids. While some CTAs may have been molten, others show no evidence of such an origin.

Compact Type A inclusions are extremely melilite-rich (typically ~90 vol%) with minor spinel and perovskite. Many also contain fassaite, although Beckett's [1] melting experiments on a CTA composition did not yield fassaite. Some CTAs are dominated by polygonal melilite grains with 120° triple junctions. Others contain lath-shaped and blocky melilite crystals with straight or lobate edges, similar to the grains in the igneous mantles of Type B1 inclusions, and in some CTAs both textures can be found. These features combined with differences in melilite composition ranges from inclusion to inclusion led Teshima and Wasserburg [2] to conclude that CTAs were once completely molten droplets which experienced varying degrees of recrystallization and reequilibration without brecciation. Since that work, composition trends and crystal/liquid Ds have been determined for igneous melilite [3, 4, 5, 6], fassaite [7], and perovskite [8, 9] crystallized from Type B liquids, possibly allowing recognition of igneous trends in these phases in CTAs. We analyzed melilite in 6 CTAs from Allende and one from Efremovka, fassaite in five of these, and rhönite in one of these by electron probe. Three of the Allende inclusions were analyzed for trace elements by ion probe. Where possible, we emphasized determination of zoning trends in single crystals and comparison with previously observed trends in melilite and fassaite in Type B inclusions in order to determine whether the trends observed in CTAs could be produced by crystallization from a liquid, and to see whether the distribution of trace elements among the phases in CTAs is consistent with crystal/liquid or with crystal/crystal partitioning.

Zoning trends in melilite. Whether a melilite crystal grows from a liquid of Type A or Type B composition or condenses as a solid from the solar nebular gas, its magnesium content can be expected to increase with decreasing temperature. In most melilite grains in Type B1 inclusions Åk content varies regularly, gradually increasing with distance from the crystal core or, in the case of mantle grains, from the crystal rim nearest the inclusion margin. This is considered normal zoning. Many CTA melilite grains, however, are not systematically zoned but instead exhibit small-scale (~5 mole % Åk) oscillations from rim to rim. In a few cases oscillations are superimposed on a general trend of changing Åk, but in most cases the overall trend is flat. Some grains exhibit "sawtooth" patterns, with, for example, repeated sequences consisting of a gradual increase in Åk content up to a peak level, then a sharp decrease, then another gradual increase. In TS12, the rim of one such grain is adjacent to the edge of the inclusion. From that rim to the other, 450 μm away, Åk contents vary irregularly with distance between 12 and 18 mole % in the first 140 μm, increase from 12.5 to 19% over the next 200 μm (which include the center of the grain), decrease sharply to 13%, then steadily increase again to ~18% over the last 110 μm. In TS2, a grain that is over 2 mm long has variations that are more extreme and irregular than those just described, with "patches" of Åk$_{>50}$ in host melilite that is Åk$_{\sim 34}$. The patches are rounded to irregular in shape, ~20-200 μm across and 100-200 μm apart. In TS32, a blocky grain 750 μm across has a very unusual pattern in which the most Åk-rich melilite is found at its core. The composition of this grain varies from Åk$_{39}$ at the rim to Åk$_{24}$ 200 μm in, to Åk$_{50}$ at the core. In contrast, a blocky grain in TS19 is symmetrically zoned from Åk$_{18}$ at the core to Åk$_{34}$ 100 μm away (normal zoning); Åk contents remain roughly constant for the next ~100 μm, then drop sharply to Åk$_{\sim 22}$ at the rim (reverse zoning). Another blocky crystal in TS19 is zoned from Åk$_{1}$ at the crystal rim adjacent to the edge of the inclusion to Åk$_{24}$ 120 μm in; Åk contents decrease to 18 mole % over



the next 80 µm, increase to 29% over the next 200 µm with several small-scale oscillations, then decrease to 22% over the last 50 µm. This pattern, unlike others for CTA melilite, is qualitatively similar to some we have obtained for Type B1 mantle melilites [6]. Another difference between CTA melilite and that in Type B1 inclusions is that, except for several crystals in TS68, Na_2O contents are not correlated with Åk contents in CTAs. A positive correlation is expected for igneous melilite based on experiments [10] which show that crystal/liquid Ds for Na_2O are <1 for Åk <50 mole % and increase with Åk content.

Chondrite-normalized REE abundance patterns for CTA melilite (Figs. 1 and 2) are typically flat at 10×C1, with positive Eu anomalies (20×C1). With the exception of Ba, there is very little variation in trace element abundances within individual grains.

Zoning trends in fassaite. In the CTAs we analyzed, fassaite typically has 15-19 wt% Ti^{tot} (TiO_2 + Ti_2O_3) and Sc_2O_3 is 0.2-0.8 wt%, except in TS32, where fassaite has ~0.4-2 wt% Sc_2O_3. In contrast, most fassaite in Type B inclusions has ≤12 wt% Ti^{tot} and ≤0.25 wt% Sc_2O_3 (Fig. 3), and, in Type Bs, Sc_2O_3 and Ti^{tot} are positively correlated whereas in some CTAs they are (TS68, Ef3) and in others (TS32, A37) they are not. Another difference is that most fassaite in Type Bs is concentrically zoned with Ti-, Sc-rich cores and Mg-rich, Sc-poor rims [7] while most CTA fassaite crystals are asymmetrically zoned or are unzoned. One grain in TS68, however, has a homogeneous, Ti-rich interior and a rim that is relatively Ti-poor, like many B1 fassaites. In both CTA and Type B fassaite, MgO is strongly correlated with SiO_2 and anticorrelated with Ti^{tot}. TS32 fassaite has flat light REE (LREE) at 3×C1 (Fig. 1) and the heavy REE (HREE) increase steadily from Gd (8×) through Lu (~60-150×). TS68 fassaite is less strongly fractionated, with LREE at 20-30× and HREE at 40-100× (Fig. 2), similar to the patterns of B1 fassaite [7]. Incompatible trace element abundances are anticorrelated with Sc.

Perovskite. Except for deep negative Eu anomalies, chondrite-normalized REE patterns for perovskite are flat at 500-3500×C1 for TS32 and 500-600 for TS68. TS32 perovskite is slightly enriched in LREE relative to HREE.

Discussion. The complex zoning trends of most CTA melilite, with several changes in the direction of zoning within single crystals and the lack of Sc_2O_3-TiO_2 correlations in fassaite in some inclusions are not consistent with formation of these phases by fractional crystallization of liquids. Furthermore, in some CTAs, such as TS32, the distribution of REE among the constituent phases is also not consistent with crystal/liquid fractionation. We can estimate a bulk La content for TS32 of 18.5×C1 based on its mode [1] of ~1% perovskite at 1000×C1 and ~96% melilite+alteration products at ~ 9×C1. With a $D_{La}^{mel/L}$ (for $Åk_{21.6}$) of 0.34 [3], the melilite La content should be ~ 6×C1, which is close to the value observed. From a liquid of the bulk composition of TS32 [1], however, fassaite can crystallize only after ~ 80% fractionation of melilite, which is necessary to sufficiently enrich the residual liquid in Ti. This should also enrich the liquid in La to ~75×C1, which should yield fassaite whose La is ~22×C1, based on its D of 0.3 [7]. This is much higher than the observed La content, ~3×C1. In fact, the fassaite in TS32 has LREE contents much too low for it to have crystallized from the assumed bulk liquid after any degree of melilite crystallization. Taking into account the decrease in $D_{La}^{mel/L}$ with increasing Åk [3, 4] would make the discrepancy even greater. Perovskite is very late in the crystallization sequence [1] and some may be relict, so its effect on these calculations should be negligible. TS68, however, could have crystallized from a liquid. Crystallization of bulk TS68, with an assumed La content of 18.5×C1 and Tm at 21.6×C1 (unpub. data), to 80% mel would yield a residual liquid with La at ~70×C1 and Tm at ~95×C1. Fassaite crystallized from this liquid should have La at ~20×, as is observed, and Tm at ~41×C1, within a factor of 2 of the observed value (Fig. 2). Thus, there clearly are differences among CTAs; some may have been molten while others probably were not. These results also suggest that Ds derived for Type B liquids may be applicable to melts of Type A composition as well.

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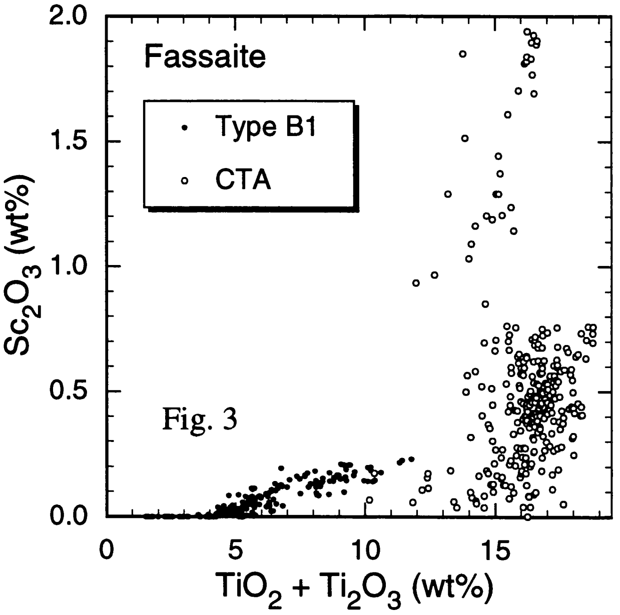

Fig. 3