COMPLEX ZONING IN FASSAITE: A RECORDER OF GROWTH AND RESORPTION IN TYPE B1 CAIS.

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Introduction: Type B1 CAIs are a major type of refractory inclusion in CV3 carbonaceous chondrites. An intriguing feature of fassaite in many Type B1 inclusions is complex zoning within single crystals. Seen in backscattered electron images (BEIs), the zoning reflects irregular, sometimes patchy, distributions of TiO_2 and correlated and anticorrelated oxides; this zoning is not synonymous with sector zoning. Several interpretations of complex zoning have been proposed. Paque [1] suggested that the patchy core of a grain she studied was relict and that the texture resulted from metamorphic recrystallization or metasomatism. Kennedy et al. [2], however, found no isotopic or trace element contrasts between the core and the normally zoned rim of the grain and concluded that the patchy core was not relict. These authors later suggested [3] that the patches represent trapped melt pockets related to the incorporation of spinel by pyroxene, but patchy zoning can be found in spinel-free fassaite. In his study of Allende Type B1 CAI 5241, Meeker [4] suggested that patchy fassaite formed from assemblages of small crystals + melt that cooled quickly. Another unsupported explanation, also presented in [4], is that patchy fassaite represents annealed cracks through which fluid could have flowed. Another possibility is partial melting of inclusions, leading to leaking of melt into relict fassaite grains. We have undertaken a study *via* SEM, EMP and IMP of patchy fassaite in several Allende Type B1 CAIs because a better understanding of this feature could yield important insights into the crystallization histories of Type B CAIs.

Observations: Normally-zoned fassaite has Ti, V, and Sc contents that decrease and Mg contents that increase smoothly with distance from core to rim [5]. For this study we have focussed on complexly zoned fassaite grains in TS23, TS34, and 5241 that have relatively low-Ti cores enclosed in optically continuous fassaite of higher Ti content. The contacts between low- and high-Ti material, seen in BEIs, are sharp whether they are straight or irregular. **TS23 PF1** is an anhedral grain 1.1 mm long and up to 1.0 mm wide. It encloses many euhedral, 10-50 µm spinel grains and is dominated by an inner zone with 5.7 wt % TiO_2^{tot} (all Ti as TiO_2) enclosed in a normally-zoned, ~50-100 µm-wide outer zone whose TiO_2^{tot} contents decrease from ~6-7 wt % at the contact with the inner zone to 3-4 wt % at the edge of the grain. Both zones also enclose several angular, ~50 µm, Ti-rich (6.1-7.1 wt %) patches. Results show that the relatively Ti-rich patches in this grain neither have the same composition nor plot along the same Mg-Ti trend as either the relatively Ti-poor host or the Ti-rich fassaite near the outside of the grain. Ion probe analysis of an interior Ti-rich patch shows that it is slightly richer in refractory elements than the host fassaite, whether they are compatible (Sc, Zr) or incompatible (REE) in fassaite. The Ti-rich patches near the outside of the grain appear to be related to the outer, Ti-rich layer, but Ti-rich patches in the interior of the grain are not, and must be from a different generation of melt.

TS23 PF3 (Fig. 1) is 1 x 0.4 mm and has a two-zone core: one light (in electron albedo), with low TiO_2^{tot} contents; and one dark, with lower TiO_2^{tot} contents. The core and several nearby, irregularly-shaped islands, also with light and dark zones, are enclosed in relatively Ti-rich (~7 wt % TiO_2^{tot}) fassaite that is normally zoned, with Ti contents decreasing from the contact with the core to the edge of the crystal. Grains PF6 and PF9 in TS34 also have isolated Ti-poor regions enclosed in Ti-rich ones.

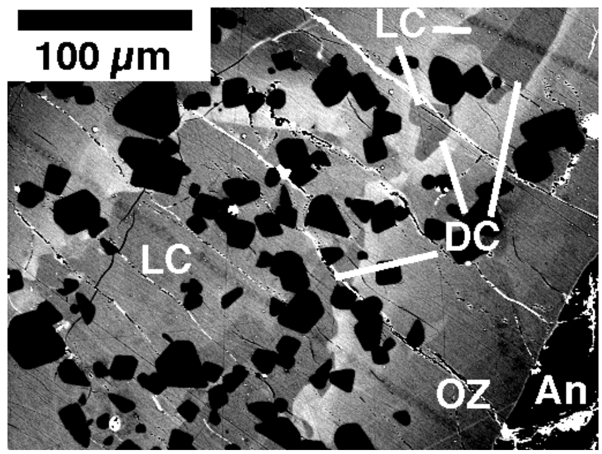

Fig. 1. BEI of PF3 from TS23. OZ: Outer Zone; DC: Dark Core; LC: Light Core; An: Anorthite. Albedo correlates dirctly with TiO_2 content.

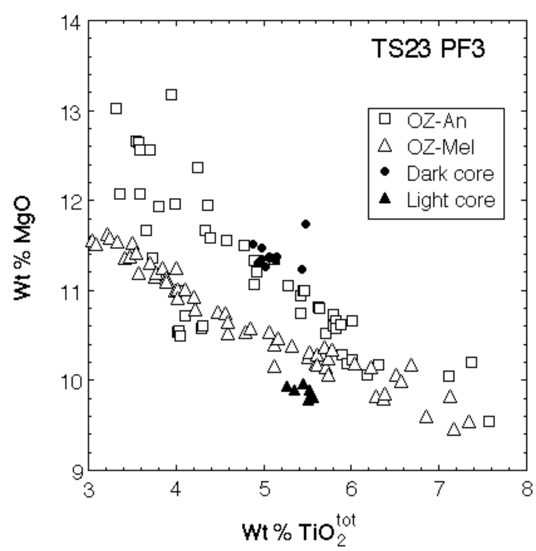

Fig. 2. Mg-Ti trends in TS23 PF3. OZ-An, OZ-Mel: Traverses in outer zone toward An and Mel, respectively.

Analysis of TS23 PF3 shows that, on a plot of MgO *vs.* TiO_2^{tot} (Fig. 2), the light and dark cores have compositions quite distinct from each other and from the outer zone (OZ). Another unusual feature of this crystal is that the OZ exhibits two fractionation trends. The trend from the dark core to the grain boundary adjacent to anorthite has a higher MgO/TiO_2^{tot} ratio than does the trend from the light core to the edge that is adjacent to melilite and alteration products. Dark core analyses plot on the high-Mg fractionation trend of the OZ, but the light core does not plot on either trend. Another core-OZ difference is that V contents in the core have a narrow range, between ~450-700 ppm, and do not vary as a function of Sc content, whereas in the OZ, the range is 200-1900 ppm and abundances are strongly correlated with Sc. The textural relationships suggest that the core is relict and had partially dissolved, forming the islands, before the OZ crystallized. The chemical contrasts between the core and OZ are consistent with these inferences. The light core, based on its higher Ti and lower Mg contents, probably formed first, followed by the dark core. They were partially melted, then enclosed in the OZ. The core zones are fairly uniform in composition and probably grew much more slowly than the strongly zoned OZ did. The two trends in the OZ may reflect local effects of cocrystallization with anorthite *vs.* cocrystallization with melilite.

In **5241 ZF1**, the low-Ti (~7 %) core (inner zone) is adjacent to two, weakly-zoned, intermediate bands of higher (~9-10 %) TiO_2^{tot} contents, and all are enclosed in a strongly normally-zoned outer band. Grain ZF4 is similarly zoned except that it has only one intermediate zone [6]. In addition, both ZF1 and ZF4 in 5241 have interior regions at the contacts between the inner and intermediate zones with highly irregular, chaotic zoning. In ZF1, TiO_2^{tot} contents in the patches range from ~3.5-11.4 wt %. Wollastonite and anorthite are also present.

The compositions of this patchy fassaite define, with some scatter, normal fractionation trends, and their Mg-Ti trend overlaps that of the outer zone of the crystal (Fig. 3). The inner and intermediate zones, however, define a trend in which MgO contents decrease more sharply with increasing Ti content. Unless the crystal grew from the outside in prior to adding the outer zone, the inner zone of ZF1 formed first, followed by the intermediate zones. These zones have trace element trends offset from one another as in ZF4 [6] and probably reflect crystallization from different generations of melt. Based on petrography and the contrast in trends (Fig. 3), these zones probably are relict with respect to the last heating event, which generated the melt from which the outer zone crystallized. This melt intruded into cavities in ZF1, forming the patchy regions. The trapped liquid continued to fractionate until solidus or near-solidus temperatures were reached, leading to the observed wide range of TiO_2 contents and the presence of anorthite among the patches. Heterogeneities among isolated pockets could account for the scatter in the trends compared to that of the outer zone.

Discussion: We can address some of the previous suggestions for the origin of patchy fassaite. There is no spinel within ~100 µm of the patchy regions in 5241 ZF1, so they do not appear to be related to spinel incorporation [3]. The patchy fassaite in ZF1 has wide composition ranges, inconsistent with metamorphic recrystallization [1] or with annealing [4]. It likely formed from an intrusion of melt at the time the outer zone was crystallizing.

If these inclusions had experienced uniform cooling from temperatures near the liquidus until the solidus was reached, it is highly unlikely that the complex zoning patterns described here would have formed. The inclusions considered here experienced one or more heating episodes in which fassaite melted incompletely, causing corroded outlines of some zones. Assuming a closed system, one way to account for the increases in Ti, Sc and V that gave rise to the various zones is if high enough temperatures were reached that some anorthite melted in addition to fassaite; then, upon cooling, there probably would have been more anorthite nuclei present than there were during primary crystallization, causing more anorthite to crystallize than had melted, leading to higher Ti, Sc and V contents in later melts and fassaite. Melilite in 5241 [4] and TS23 is not continuously zoned but instead shows discontinuities which may be responses to the same thermal events that affected the fassaite. In contrast, we note that in at least two B1s from Axtell, fassaite does not exhibit patchy zoning, and the melilite is also uniformly zoned. This is to be expected if melilite and fassaite cocrystallized, recording the same thermal events (or lack thereof). We agree with the suggestion [6] that 5241, and other CAIs [1] experienced multiple partial melting-crystallization episodes.

References: [1] Paque J. (1990) *LPS XXI,* 932. [2] Kennedy A. et al. (1990) *LPS XXI,* 621. [3] Kennedy A. et al. (1997) *GCA 61,* 1541. [4] Meeker G. (1995) *Meteoritics 30,* 71. [5] Simon S. et al. (1991) *GCA 55,* 2635. [6] Davis A. et al. (1998) *LPS XXIX,* abst. #1948.

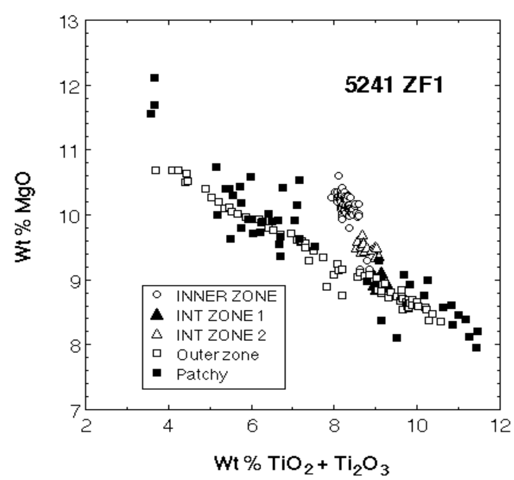

Fig. 3. Plot of MgO vs. TiO_2 + Ti_2O_3 in 5241 ZF1. Note overlap of patchy and outer zone compositions, and the different trend defined by the inner and intermediate zones.