REFRACTORY INCLUSIONS IN THE UNIQUE CARBONACEOUS CHONDRITE ACFER 094

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ABSTRACT

Acfer 094 is an unshocked, nearly unaltered carbonaceous chondrite with an unusual suite of refractory inclusions. The refractory inclusions in a newly prepared thin section and a small aliquot of disaggregated material were studied to compare the population with previous work and to report new or unusual inclusion types. A total of 289 Ca-, Al-rich inclusions in the thin section and 67 among the disaggregated material, having a total of 33 different mineral assemblages, were found. Inclusions are largely unaltered and typically ≤200 µm across. The most common are gehlenitic melilite+spinel±perovskite, spinel+perovskite, and spinel with a thin, silicate rim, typically melilite±diopside. Such rims and (thicker) mantles are very common among Acfer 094 inclusions, and they exhibit a variety of zoning patterns with respect to åkermanite and FeO contents. In the thin section about 13% of the inclusions contain hibonite and ~5% are grossite-bearing; in the disaggregated material, the percentages are 14 and 9, respectively, comparable to previous work. Among the unusual inclusions are a fine-grained, porous, Ti-rich hibonite+spinel+perovskite+melilite inclusion with a compact, coarse, Ti-poor hibonite+spinel+melilite clast; two inclusions in which hibonite has reacted with grossite; two inclusions with an FeO-rich spinel or spinel-like alteration product; and a small object consisting of fassaite enclosing euhedral spinel, the first fragment of a Type B inclusion reported from Acfer 094. Inclusions similar to those found in CM or CV chondrites are rare; Acfer 094 contains a distinctive population of inclusions. The population, dominated by small, melilite-bearing inclusions, is most similar that of CO chondrites. A distinguishing feature is that in Acfer 094, almost every phase in almost every inclusion contains 0.5 – 1.5 wt% FeO. It did not simply diffuse in from the matrix, implying exposure to non-solar, relatively oxidizing nebular conditions.
INTRODUCTION

Acfer 094 is a unique Type 3 carbonaceous chondrite. It was first described as having trace element characteristics of CM chondrites and mineralogical features of CO chondrites (Bischoff et al. 1991), and it has defied classification ever since. As pointed out by Newton et al. (1995), its O-isotopic composition is not consistent with membership in either of those groups, and its C and N isotopic compositions do not match any group. Its matrix is an unequilibrated assemblage consisting of nodules of amorphous silicates enclosing crystalline silicates and sulfides (Greshake 1997; Keller et al. 2009). Studies show that the amorphous silicates have excess oxygen, consistent with hydration, but little phyllosilicate formation occurred (Greshake 1997; Keller et al. 2009). This shows that hydration was limited, and the presence of amorphous silicates indicates that Acfer 094 experienced minimal alteration on the parent body. Presolar silicates are easily destroyed by aqueous alteration and are more abundant in Acfer 094 than in almost all other meteorites (Vollmer et al. 2009), further indicating a highly pristine nature. It is also essentially unshocked (Newton et al. 1995), and clastic material is very rare in the matrix (Greshake 1997; Bland et al. 2007). Much work has been done on Acfer 094 because it is a unique, pristine carbonaceous chondrite.

Work that has been done on the refractory inclusion population shows that it also is not readily classified in comparison to those of known groups, contributing to the uniqueness of Acfer 094. Weber (1995) showed that the refractory inclusions are largely unaltered and are most similar to Ca-, Al-rich inclusions (CAIs) from CO and CR chondrites. Krot et al. (2004) studied three thin sections of Acfer 094 and concluded that, while the CAIs in it are most similar to those from CO chondrites, they are a mineralogically distinct population. Chondrites can be heterogeneous, as most of them, including Acfer 094, are breccias. The CAI population in this unique meteorite should be characterized as thoroughly as possible to search for heretofore undiscovered CAI types, and to learn as much as possible from them. Therefore, when the U. S. National Museum of Natural History acquired a previously unstudied sample of Acfer 094, a polished thin section was requested in order to: document the refractory inclusion population in it; compare the population with previous descriptions of Acfer 094 CAIs; and to report any new or unusual inclusions. Objects from a small aliquot (<~0.1 g) of Acfer 094 that had previously been disaggregated at Washington University in a search for presolar grains, were also hand-picked, mounted and polished. Preliminary results of this study were given by Simon and Grossman (2009).

ANALYTICAL METHODS

The ~50 mm² thin section (USNM 7233-1) was searched for refractory inclusions by simultaneously collecting backscattered electron images and Al Kα X-ray maps at 15 kV with a JEOL JSM-5800 LV scanning electron microscope (SEM) equipped with an Oxford/Link ISIS-300 energy-dispersive X-ray analysis system (EDS). Phases in Al-rich objects found this way were identified by EDS. Hand-picked particles were mounted in epoxy, polished, carbon-coated, and examined with the SEM. Quantitative wavelength-dispersive analyses were collected with a fully automated Cameca SX-50 electron microprobe operated at 15 kV. Data were reduced using the modified ZAF correction procedure PAP (Pouchou and Pichoir 1984).
RESULTS

CAI population in thin section

A total of 289 Al-rich objects and 22 amoeboid olivine aggregates (AOAs) were found in the thin section. Most of the Al-rich objects are partially to completely enclosed in one or more rim layers of melilite, aluminous diopside, anorthite, or forsterite. Some have mantles of melilite with rims of Al-diopside. An enclosing layer of melilite is termed a “mantle” if it is relatively thick compared to the diameter of the inclusion and if melilite is also present in the interior of the inclusion; a “rim” is defined herein as a thin, outer layer of a phase not present in the interior. Refractory inclusions in Acfer 094 are mostly fragments and are typically smaller and finer-grained than those found in CV3 chondrites. Even including the rims and mantles they are typically <200 µm across. Many inclusions have melilite as either a major interior phase, mantle or rim. The melilite is largely unaltered. Approximately 13% of the inclusions found contain hibonite and 5% contain grossite. In comparison, ~10% of the inclusions found by Krot et al. (2004) are hibonite-bearing and ~10% are grossite-bearing.

The CAIs in the present section have 27 different mineral assemblages (not including rim phases). The 15 most abundant ones (four or more occurrences), accounting for over 94% of the inclusions, are listed in Table 1 and the remainder are given in Table 2. Representative examples of some of the common inclusion types are shown in Fig. 1. For the purposes of classification, pyroxene is identified as either Ti-rich (Tpyx), with >3 wt% Ti as TiO$_2$ (TiO$_2^{tot}$), or Ti-poor (diopside, or “Diop”). The most common inclusions consist of gehlenitic melilite either enclosing fine spinel-perovskite, poikilitically (Fig. 1a) or as a mantle in nodular inclusions (Fig. 1b). The next most abundant are spinel-perovskite inclusions (Fig. 1c). In these, anhedral perovskite grains are enclosed in spinel and this assemblage is typically enclosed in a silicate rim, usually melilite-diopside. Spinel grains with silicate rims are the third most abundant type of Al-rich object, followed by fine intergrowths of anhedral anorthite and pyroxene (Fig. 1d) and spinel-pyroxene inclusions (Fig. 1e). The one shown in Fig. 1e is a fragment of a larger, probably convoluted inclusion reminiscent of the “OC” inclusion type first recognized among Murchison inclusions (MacPherson et al. 1983).

CAIs in the disaggregated material

A total of 67 CAIs and six AOAs were found in the (>1 µm) disaggregated material. Most occur within incompletely disaggregated meteorite fragments and were found by Al-mapping. The proportion of Sp+Mel±Pv inclusions (19.4%) is about the same as that in thin section (22.5%); Sp+Pv inclusions (10.4%) are less abundant and An+Pvyx inclusions (20.9%) are more abundant than in thin section (Table 1). Four inclusions, all hibonite-bearing, have mineral assemblages that were not found in the thin section. They are hibonite+grossite+spinel (two samples), corundum+hibonite+grossite+spinel and hibonite+kushiroite (CaTs-rich pyroxene; Kimura et al. 2009). The latter is likely a fragment of a hibonite-aluminous pyroxene spherule like those previously seen in Acfer 094 (Krot et al. 2004) and other carbonaceous chondrites (Simon et al. 1998).

Hibonite- and grossite-bearing inclusions
Most commonly, hibonite occurs as laths enclosed in spinel and perovskite, with the assemblage enclosed in melilite. Unlike those in CM chondrites, hibonite-spinel inclusions in Acfer 094 commonly have melilite rims (e.g., Fig. 2a). On the other hand, like their counterparts in CMs (e.g., MacPherson et al. 1983), many Acfer hibonite-bearing inclusions have cavities. Hibonite also occurs as a cluster of laths with interstitial perovskite (Fig. 2b) and in grossite-bearing inclusions (see below). Occurrences in thin section include a relatively coarse, platy hibonite crystal with inclusions of perovskite and Zr-, Y oxide (Fig. 2c) and a small (25 µm) inclusion fragment consisting of hibonite and corundum.

A typical grossite-bearing inclusion is shown in Fig. 3a. It has a core of massive, anhedral grossite enclosing fine perovskite grains, and a melilite rim. The grossite is partially separated from the melilite by a discontinuous layer of spinel. Grossite and hibonite occur together in inclusions that display a wide range of textures. In some cases the two phases are not in contact with each other, typically because hibonite and grossite are enclosed in, and therefore separated by, spinel. They occur in different parts of a relatively large, porous inclusion, 59-1 (Fig. 3b), which consists of anhedral grains of grossite, hibonite and spinel, all with melilite rims. The inclusion has anorthite and diopside rim layers along one edge. In inclusion L5-1 (Fig. 3c), anhedral grossite occurs in interstices between hibonite laths. Some of the hibonite has reacted, presumably with nebular gas, to form spinel. In contrast, in two, more compact hibonite-grossite-spinel-perovskite-melilite inclusions, 59-2 (Fig. 3d, e) and 59-6 (Fig. 3f, g), the contacts between hibonite and spinel are straight and smooth whereas those between hibonite and grossite are irregular. Inclusion 59-2 is a rounded object with anhedral spinel and perovskite enclosed in melilite, with hibonite, minor grossite and cavities concentrated toward one end. Inclusion 59-6 is also rounded, with a core of perovskite, grossite, hibonite and melilite enclosed in spinel, all enclosed in a mantle of melilite+perovskite. In both of these inclusions contacts between spinel and melilite are rounded and embayed (Fig. 3e, 3g). Another interesting inclusion is L5-2 (Fig. 3h). It is very small, just ~20 x 10 µm. The interior of the inclusion consists mainly of grossite and perovskite, with a few ~µm-sized grains of very Al-rich phases, probably corundum and hibonite. The grossite-rich area is enclosed in a chain of subhedral spinel grains having unusual compositions (see below). The outer edges of the spinel grains are smoothly aligned with each other, unlike the inward-facing crystal faces, which jut into the adjacent grossite. Outside of the spinel is a thin layer of anorthite and thicker layer of aluminous diopside.

Other Notable Inclusions

Compound Inclusion

One inclusion fragment, 59-3 (Fig. 4), has a fairly complex texture. It has a relatively coarse-grained, compact clast in a finer-grained, porous host (Fig. 4a, b). The clast consists of hibonite and spinel in a melilite mantle. The host consists of anhedral to subhedral hibonite, perovskite and spinel. The contact between the clast and host is curved on a large scale (Fig. 4a) and jagged on a fine scale (Fig. 4b). Within ~50 µm of the clast, the host is quite spinel-rich, unlike the other side of the inclusion, which is hibonite-rich. Portions of both regions are shown in Fig. 4c, with the spinel-rich region to the left and the hibonite-rich region to the right. In both regions many grains have thin rinds of melilite. The inclusion also has a sequence of rim layers, from innermost to outermost, of melilite, anorthite and diopside along two of its edges.
**Perovskite-rich inclusion**

One inclusion, 27-3 (Fig. 5), consists of a typical mineral assemblage of hibonite, spinel and perovskite with a melilite rim. Unlike most other Acfer 094 inclusions, in which perovskite occurs as tiny blebs, the perovskite in this inclusion is relatively coarse, dominantly occurring as grains up to ~20 µm across, in addition to tiny blebs, with interstitial hibonite. Spinel occurs interstitially and partially encloses some perovskite grains. Perovskite composes 44 vol % of the inclusion. Krot et al. (2004) also reported a very perovskite-rich inclusion from Acfer 094.

**Type B Inclusion Fragment**

One small (30 x 30 µm), unrimmed fragment, shown in Fig. 6, is best described as a fragment of a Type B inclusion, the first one reported from Acfer 094. It consists of euhedral spinel partially enclosed in Ti-bearing pyroxene. Unlike this inclusion, most inclusions in Acfer 094 have rims, Ti-poor pyroxene (if any) and finer-grained, anhedral spinel.

**Rim layers on inclusions**

Approximately half of the inclusions have a partial to complete rim layer, mantle or sequence of layers. Of these, ~60% have rims consisting of only aluminous diopside, ~30% have only melilite, and ~10% have both. Those with both commonly have relatively thick melilite and thin Al-diopside rims, and some inclusions have sequences of layers, typically melilite, anorthite and diopside. Where both melilite and diopside rims are present, the latter is the outermost layer. The melilite layers in both rims and mantles occur as continuous bands, with no indications of grain boundaries visible either in the SEM or optically. Although melilite may have originally been present in the Wark-Lovering rim sequences (Wark and Lovering 1977; Wark and Boynton 2001) that occur on coarse-grained refractory inclusions, the rims on Acfer inclusions clearly differ from Wark-Lovering rims, which always contain a spinel-rich layer. The Acfer pyroxene rims are similar to those on some inclusions in CM chondrites (e.g., Simon et al. 2006), but are more compact than the Al-diopside rims of the “OC” inclusion type described by MacPherson et al. (1983). Unaltered melilite rims are also found on inclusions in CH chondrites (Kimura et al. 1993; Weber and Bischoff 1994).

**Mineral Chemistry**

Melilite occurs in many of the inclusions, as either a major constituent, mantle or rim. A comparison of the åkermanite contents of melilite in mantles and rims with that in spinel-melilite-perovskite inclusions is shown in Fig. 7. The melilite in mantles and rims, with average compositions of Åk_{9.1} and Åk_{8.8}, respectively, and an overall range of Åk_{9-23} (Fig. 7a), tends to be more gehlenitic than that in the melilite-rich inclusions, which has a wider range and an average composition of Åk_{14} (Fig. 7b). To see if the mantles or rims are zoned, a total of 15 fine-scale (1 µm point spacing) electron probe traverses were conducted across mantles on four inclusions and across rims on five inclusions. The traverses average 6.4 µm in length. There is no strongly dominant zoning trend. Among the ten mantle traverses, åkermanite contents increase toward the edge of the inclusion in two of the cases, decrease then increase in three cases, increase then decrease in one sample, and the remainder have two or more reversals. In the two of the five rim
traverses, åkermanite contents increase toward the edge of the inclusion; in two others they decrease then increase; and in the other one they decrease, increase then decrease. Even traverses taken on opposite sides of a nodule can be different from each other.

All melilite is enriched in FeO relative to that in CAIs in other meteorites. As shown in Fig. 8a, melilite in rims and mantles contains at least 0.5 wt% FeO and most of the analyses are between 0.5 and 1.2 wt%. Most of the melilite in the interiors of melilite-rich inclusions (Fig. 8b) also has significant FeO contents although some are as low as ~0.1 wt%. In the interior melilite, there is a slight decrease in the minimum FeO content observed as a function of åkermanite content, whereas in the mantle melilite, the minimum FeO content does not vary with åkermanite content. The lack of correlation between FeO and åkermanite contents in melilite rims and mantles on Acfer inclusions contrasts with mantle melilite of Allende Type B1 inclusions (Fig. 8c), in which åkermanite-poor melilite, which occurs at the outermost edges of the inclusions, is the most FeO-rich. In the Acfer 094 rims and mantles there is no consistent relationship between FeO content and distance from the contact with the matrix. In the 15 traverses mentioned above, one rim is unzoned with respect to FeO and the others exhibit four different trends: six have FeO increasing then decreasing toward the outer edge of the inclusion; four have FeO decreasing then increasing; three have increasing FeO; and one has decreasing FeO contents. Note the order of magnitude difference in FeO contents between Acfer 094 and Allende.

Hibonite in Acfer 094 also has elevated FeO contents relative to most other occurrences, and a range of TiO₂ contents from 1 to 7 wt%. Representative electron probe analyses are given in Table 3 and data are plotted in Fig. 9. Mg commonly enters hibonite along with Ti⁴⁺ or Si⁴⁺ in a coupled substitution for two Al³⁺ cations. Thus, Mg contents are typically strongly correlated with Ti + Si cation abundances, as is seen in Fig. 9a. It is generally assumed that any Fe found in hibonite has replaced Mg, and plots of Mg + Fe vs. Ti + Si cations in hibonite typically yield better 1:1 correlations than plots of Mg vs. Ti, supporting this assumption. That is not the case here, however, as the Mg + Fe cation totals tend to plot well above the 1:1 line when plotted against Ti + Si (Fig. 9b). Figures 9c and 9d show why. If Fe were substituting for Mg, a negative correlation between those cation abundances would be expected, and this is not observed (Fig. 9c). Most of the hibonite analyzed has between 0.05 and 0.10 cations of Fe per 19 oxygen anions (~0.4 – 1.1 wt% FeO) regardless of its Mg content. Exceptions are ACM4, with very low, Murchison-like Fe contents, and L5-1, with very high contents, even for Acfer 094, of 1.1 - 2.6 wt% FeO. The Mg contents of the unusual hibonite of L5-1 do not correlate with its Ti + Si contents (Fig. 9a); its Fe contents correlate instead (Fig. 9d) and are anticorrelated with Al. Thus, Fe, rather than Mg, substituted with Ti for Al during formation of the hibonite in L5-1. For the remaining samples, the Fe contents are likely secondary, as calculation of correlation coefficients does not indicate any significant covariation between FeO and the other oxides analyzed, at least partially because most samples have nearly uniform FeO contents, with ranges within samples typically ≤ 0.2 wt%. In addition, Fe can enter four different crystallographic sites in hibonite (Burns and Burns 1984), and it is possible that secondary Fe, instead of doing so systematically as in L5-1, enters various sites in a somewhat opportunistic, haphazard way, replacing different cations and resulting in an absence of strong correlations.

Spinel is MgAl₂O₄ with 0.1 – 0.9 wt % V₃O₅, 0.05 – 1.8 wt % TiO₂, 0 – 0.35 wt % Cr₂O₃, and, like melilite and hibonite, ~0.5 – 1.2 wt% FeO. These oxide contents are illustrated in Fig. 10. Also plotted are compositions of spinel from analogous inclusions in Murchison. In spinel from spinel+mellilite+perovskite inclusions there is little overlap between Acfer 094 and Murchison (Figs. 10a, b). In these inclusions, the Acfer spinel has lower TiO₂ and higher FeO
contents than that from Murchison. Compositions of spinel from hibonite-bearing inclusions overlap on a plot of $V_2O_3$ vs. $TiO_2$ (Fig. 10c) but not on a plot of $Cr_2O_3$ vs. $FeO$ (Fig. 10d), because of the higher $FeO$ contents of the Acfer spinels. In some inclusions, contents of $Cr_2O_3$ and $FeO$ are anticorrelated, and in others there is no correlation.

Both L5-1 and L5-2 contain an unusual phase, occurring as discrete grains that look like spinel, that is either highly altered spinel, a secondary phase that is the product of a reaction between spinel and grossite, or a fine intergrowth of the two, as its compositions and stoichiometry can be approximated by a combination of these phases. Representative analyses are given in Table 4 and data are plotted in Fig. 11. Contents of $FeO$ are positively correlated with $MgO$ with a linear slope (Fig. 11a), indicating uniform $Mg/(Mg + Fe)$ ratios (also see Table 4). Abundances of $Cr_2O_3$ (Fig. 11b) and $MnO$ (Fig. 11c) are directly correlated with $MgO + FeO$, but $TiO_2$ contents (Fig. 11c) are not. $CaO$ is negatively correlated with $MgO + FeO$ (Fig. 11d), and contents of $CaO$ extrapolate to ~18 wt% at 0% $MgO + FeO$ for both samples, not far below the value for pure grossite, 21.6 wt%. The number of total cations varies with $Ca$ and $(Mg + Fe)$ cation amounts, suggestive of a mixture of phases with different cation/oxygen ratios. The cation totals extrapolate to ~2.97 per four oxygen anions, consistent with spinel, for a $Ca$-free composition (Fig. 11e). For a $(Mg + Fe)$-free composition, they extrapolate to 2.815 cations per four oxygen anions (Fig. 11f), or 4.93 per seven oxygens, approaching the value of 5 characteristic of pure $CaAl_2O_4$.

Most of the pyroxene in Acfer inclusions is aluminous diopside, with a wide range of $Al_2O_3$ (0.5-21.4 wt%) and $Ti$ contents, occurring in rims on inclusions. Some rims are zoned with $Ti$ and $Al$ contents decreasing from the interiors toward the edges. Like Murchison (Simon et al. 2006), pyroxene in the interiors of Acfer inclusions tends to be $Ti$- and $Al$-rich compared to that in rims. An extreme example is Acfer 094 inclusion 19-3 (Fig. 1e), which has $Ti$-, $Al$-rich pyroxene in the interior and a rim of nearly $Ti$-free aluminous diopside. Compositions of pyroxene from this sample are plotted in Fig. 12. The $Ti$-rich pyroxene has average $TiO_2^{tot}$ and $Ti^{3+}/(Ti^{3+} + Ti^{4+})$ contents of 7.8 wt% and 0.33, respectively.

In contrast, the Type B-like fragment 23-3 (Fig. 6) contains fassaite with a composition like that found in Allende Type B inclusions. The average of six very similar analyses of fassaite in 23-3 is: $MgO$, 9.6 wt %; $Al_2O_3$, 18.1; $SiO_2$, 39.8; $CaO$, 24.9; $Sc_2O_3$, below detection; $Ti$ as $TiO_2$, 6.4; $V_2O_3$, 0.14; $Cr_2O_3$, 0.10; and $FeO$, 1.2. This gives a $Ti^{3+}/(Ti^{3+} + Ti^{4+})$ ratio of 0.53, corresponding to 3.0 wt % $Ti_2O_3$ and 3.0 wt % $TiO_2$. Except for its $FeO$ content, this composition plots on trends defined by Allende fassaite compositions on oxide-oxide plots (e.g., Simon et al. 1991; Simon and Grossman 2006).

The other phases found, grossite, perovskite and anorthite, all have near-end-member compositions except for $FeO$ contents of ~0.5 – 2 wt%. The corundum that was found is too fine-grained for electron probe analysis.

**DISCUSSION**

**Comparisons with CAIs in other types of carbonaceous chondrites**

While the differences between the CAI populations in Acfer 094 and those in the CH, CB and CR chondrites pointed out by Krot et al. (2004) are also found in the present work, some of their other contrasts with CAIs in other chondrite types no longer hold true due to findings in the present study. Unlike previous studies, we found a spinel-hibonite spherule (Fig. 2a) and a
relatively coarse, platy hibonite crystal (Fig. 2c), both of which are similar to refractory materials found in CM2 chondrites (e.g. MacPherson et al. 1983; Ireland 1988). Spinel-fassaite inclusion 23-3 (Fig. 6) must be considered a likely fragment of a Type B inclusion, the first reported from Acfer 094. We note that, as in the CH chondrites, grossite-bearing inclusions are not as rare as in most chondrites, and inclusions commonly have melilite rims. Despite these findings, we agree with Krot et al. (2004) that, of the known chondrite types, the CAI population of Acfer 094 is most similar, but not identical, to that of the CO chondrites. The most common type of inclusion in Acfer 094, small, relatively fine-grained, melilite-dominated inclusions (e.g., Fig. 1a), is also quite common in the CAI populations of CO and CR chondrites (Weber and Bischoff 1997; Russell et al. 1998). In CRs, however, spinel-pyroxene aggregates are more abundant and hibonite- and grossite-bearing inclusions are more rare than in Acfer 094 (Weber and Bischoff 1997; Aléon et al. 2002).

Although several of the inclusions from CO chondrites shown in Russell et al. (1998) resemble inclusions in Acfer 094 (melilite enclosing fine spinel; hibonite + spinel enclosed in melilite; hibonite-pyroxene spherules), the populations are not identical, as pointed out by Krot et al. (2004). Small inclusions consisting of spinel+melilite±perovskite are found in Acfer 094 and in CM2 chondrites but the populations are not the same. The inclusions in Acfer 094 are melilite-dominated fragments, while most of those in CM2s are spinel-dominated spherules (Simon et al. 2006), and the two suites have different spinel compositions (Fig. 10). The Acfer inclusions exhibit a unique combination of sizes, textures, mineral assemblages, and mineral compositions. Two additional features that help distinguish the Acfer 094 CAI population from those of other chondrites are the melilite rims on many inclusions and the relatively high FeO contents of most of the phases in most of the inclusions. Most CAIs in CO chondrites have rims consisting of diopside and Fe-rich spinel (Russell et al. 1998) rather than melilite. Russell et al. (1998) showed that the FeO contents of melilite and spinel increase with increasing petrologic grade. Inclusions in CO3.0 chondrites, such as ALH77307 and Colony, have low FeO contents. Unlike inclusions in CO3 chondrites of comparable petrologic grade, those in Acfer 094 have high FeO contents.

**Pristinity of the Acfer 094 matrix: Implications for Refractory Inclusion Histories**

**FeO contents of primary phases in refractory inclusions**

The matrix of Acfer 094 mainly consists of ~40 vol% amorphous silicate, ~ 30% submicron grains of forsterite (Fa0.1), ~20% submicron enstatite (Fs0.3), and ~10% other material, with <1% phyllosilicate (Greshake 1997). The nearly FeO-free mineral grains are enclosed in the FeO-rich (25-30 wt%) amorphous material (Greshake 1997; Keller et al. 2009). Amorphous silicate is highly reactive and easily converted to other phases. In Acfer 094 it has excess oxygen, consistent with hydration, which could have caused oxidation of Fe metal, giving the amorphous silicate its observed high FeO contents (Keller et al. 2009). The extent of hydration was very limited, however, either because of low fluid abundances, low temperatures, or both, as the submicron olivine and pyroxene grains enclosed in it did not gain significant amounts of FeO. Transmission electron microscopy shows that the sparse phyllosilicates that can be found in the matrix have lattice fringes only nanometers in length, an observation that is also consistent with limited, incipient hydration (Greshake, 1997). It is highly unlikely that CAIs gained significant amounts of FeO from the amorphous silicate in the matrix when submicron olivine and pyroxene...
grains enclosed in it did not. If the matrix did not undergo alteration on the parent body, then the chondrules and inclusions in Acfer 094 did not either. Thus it is highly likely that not only are the FeO contents of CAIs pre-accretionary features, but so too are the cavities that are found in many of the CAIs. This implies that cavities found in refractory spherules in CM chondrites (MacPherson et al. 1983; Simon et al. 2006) may be primary as well.

Another constraint on the uptake of FeO by phases in Acfer 094 CAIs is that it was not accompanied by smaller $^{16}$O enrichments, as is commonly observed, for example, in FeO-rich relative to FeO-poor olivine (Leshin et al. 1997; Jones et al. 2000). The CAIs in Acfer 094 are as $^{16}$O-rich as CAIs in other chondrites, with $\delta^{17}$O = -40 to -50‰ (Fagan et al. 2003), and they do not have the same oxygen isotopic composition as the matrix. The $\delta^{17}$O values of most matrix grains are between -20 and +10‰ (Yurimoto et al. 2008).

While it can be concluded that the FeO contents of Acfer 094 CAIs are pre-accretionary, to account for them by equilibrium processes in the solar nebula requires special conditions, such as condensation from, or alteration of the precursor assemblages in, a system that was highly enriched in $^{16}$O-rich dust relative to gas or water relative to hydrogen compared to a system of solar composition (e.g. Fedkin et al. 2008). Dust enrichment would elevate the oxygen fugacity of the system and inhibit Fe evaporation from inclusions that were molten. In addition, low total pressures, $\sim 10^{-6}$ atm, would be required to retain a gas-solid condensation sequence that includes the observed refractory phases. At higher pressures, $\sim 10^{-3}$ atm, and chondritic dust enrichments of 100× or more, liquid condenses and neither the Ca-aluminates nor melilite are predicted to form (Ebel and Grossman 2000).

**Melilite rims and mantles**

Many inclusions in Acfer 094 and CH chondrites (Kimura et al. 1993; Weber and Bischoff 1994) are enclosed in a layer of melilite rather than a sequence of multiple layers of different phases. Most melilite rims are petrographically similar to each other, typically between 5 and 15 µm thick and gehlenitic, with <15 mol% Åk (Fig. 7a). There is no dominant zoning trend and no strong correlation of trends with the mineral assemblage of the host inclusions, though it does appear that, in the rims on spinel-perovskite inclusions, åkermanite contents tend to decrease and then increase with distance from the spinel/melilite contacts at their inner edges. This is the most common zoning pattern found in this study. In addition, several inclusions have melilite rims in which åkermanite contents increase toward the outside of the inclusion, which is normal zoning assuming growth in that direction, making it unlikely that such rims are solidified melts that crystallized inward. The simplest explanation is that many of the CAIs in Acfer 094 likely encountered a region of the nebula where melilite was condensing.

Interpretation of FeO contents in the rims is also not straightforward. They do not vary systematically either with distance from the edges of inclusions nor with åkermanite contents. They do not simply reflect inward diffusion of FeO from the matrix, and therefore may be primary features, reflecting a variety of thermal histories. If FeO did enter the inclusions by diffusion from the outside inward, it must have been redistributed in heating events prior to accretion.

**Formation of grossite-bearing inclusions**
Grossite-bearing inclusions are relatively rare in most carbonaceous chondrites, and the occurrences reported here can improve our understanding of their formation. Grossman et al. (1988) and Kimura et al. (1993) favored an igneous origin for grossite-bearing inclusions they studied, whereas Krot et al. (2004) favored a condensation origin for most of the grossite-bearing inclusions they found in their study of Acfer 094. Weber and Bischoff (1994) provided strong evidence for both condensate and igneous grossite-bearing inclusions. Samples in the present suite also provide evidence that grossite can be found in once-molten inclusions and that it also occurs in inclusions that likely were never molten. Let us consider here whether the data and observations for inclusions 59-2, 59-6, 59-1, L5-1 and L5-2 are more consistent with an igneous or gas-to-solid condensation origin, or perhaps a combination of these processes.

The first two, 59-2 (Fig. 3d, e) and 59-6 (Fig. 3f, g), are both compact, rounded inclusions. Both have spinel-hibonite-grossite-perovskite assemblages enclosed in gehlenitic melilite. The spinel is rounded and embayed where in contact with melilite but spinel-hibonite contacts are straight. This texture is reminiscent of the hibonite-bearing Type A inclusions found in Allende by Simon et al. (2001), which contain spinel-hibonite rafts enclosed in melilite, also with straight hibonite-spinel contacts and rounded melilite-spinel contacts. Those authors presented strong evidence that the oxide assemblages are relict and were unstable when enclosed in silicate melts. That possibility must be considered for 59-2 and 59-6 as well. A way to evaluate an igneous vs. a condensate origin is to compare the observed phase assemblage and inferred crystallization sequence with those predicted by fractional crystallization and equilibrium condensation models.

The bulk compositions of 59-2 and 59-6, calculated from average phase compositions and their weight proportions, are given in Table 5. They are similar to each other, and for both compositions the liquidus phase is spinel, followed by melilite, grossite and hibonite (Beckett and Stolper 1994). In both inclusions, however, hibonite is texturally early, before spinel. The texturally inferred crystallization sequence for the inclusions is hibonite, grossite, perovskite, spinel and melilite. Except for the absence of the very rare phase CaAl$_2$O$_4$ and the reversal of the order of melilite and spinel appearance, this resembles a portion of the predicted equilibrium condensation sequence for a cooling gas of solar composition at $10^{-3}$ atm (Grossman 2010). Those calculations predict that grossite should form as a result of reaction between hibonite and gaseous Ca. The serrated contacts between hibonite and grossite in 59-2 and 59-6 could be evidence of this reaction.

Simon et al (2001) found that the inclusions they studied had isotopically heavy Mg, implying that they had undergone evaporation while at least partially molten. It is not known if either 59-2 or 59-6 have heavy Mg as well, but an interpretation similar to that of Simon et al. (2001) is indicated here. The corroded spinel and adjacent or enclosed grossite, hibonite and perovskite are likely relict, condensate phases enclosed in later-formed, once-molten melilite. Inclusions 59-2 and 59-6 may be fragments of inclusions similar to the Type A Allende inclusions reported in Simon et al. (2001).

Both Weber and Bischoff (1994) and Krot et al. (2004) cite irregular shapes and high porosity as evidence for a condensation origin for grossite-bearing inclusions they studied. Among the present samples, inclusion 59-1 (Fig. 3b) is the grossite-bearing inclusion with the highest porosity. It has minor hibonite and grossite, and is dominated by rounded, anhedral spinel grains that have rims of melilite. The rimming of individual grains is most easily explained by reaction between the oxide grains and Si in the nebular gas, as predicted to occur below 1575K at a total pressure of $10^{-3}$ atm (Grossman 2010), prior to agglomeration of them.
into the inclusion. The preservation of gaps between the grains indicates that the inclusion was not subsequently melted after formation of melilite.

Inclusion L5-1 (Fig. 3c) is an irregularly-shaped, loose aggregate of hibonite laths with interstitial grossite and alteration products. Texturally, these features are consistent with formation by gas-solid condensation, but detailed interpretation is not straightforward. Calculations (Ebel and Grossman 2000; Grossman 2010) show that for grossite to form by equilibrium condensation from a gas of solar composition at $10^{-3}$ atm, it must do so by reaction of hibonite with gaseous Ca, because ~90% of the Al in the system condenses into hibonite prior to grossite formation. In L5-1 the hibonite-grossite contacts are straight and smooth, however, not indicative of a reaction relationship. The hibonite in this inclusion is unusual, however, in having Fe contents that are correlated with Ti contents (Fig. 9d) and anticorrelated with Al. This suggests that, in this occurrence, the Fe entered the hibonite in a coupled substitution with Ti for Al at the time of hibonite formation, and not by secondary replacement of Mg. Conditions under which Fe-bearing hibonite would form in a nebular setting are unknown; a system enriched in Fe and/or O relative to a system of solar composition would probably be required. Perhaps, in the system in which L5-1 formed, grossite condensation occurs with sufficient Al remaining in the vapor that it can do so without consuming hibonite.

Another grossite-bearing inclusion is L5-2 (Fig. 3h). It has an outer shell of spinel that appears to have grown inward, enclosing a grossite-rich core. Based on the bulk composition (Table 5), spinel is the liquidus phase, followed by grossite. This is consistent with the observed textural relationship of these phases, but neither corundum nor hibonite, which are enclosed in grossite, are predicted. If this inclusion formed from a liquid, either the small corundum and hibonite grains are relict, or the bulk composition obtained from the exposed plane is not representative of the inclusion. On the other hand, with corundum, hibonite, grossite, perovskite and spinel present, the interior of this inclusion does consist of an assemblage of phases predicted to condense from a gas of solar composition (Grossman 2010). The smooth alignment of the outer edges of the spinel grains, however, suggests inward growth from a melt-vapor interface, and spinel is the predicted liquidus phase; this makes a molten origin more likely for this inclusion than formation by gas-solid condensation.

Formation of complex inclusion 59-3

This inclusion consists of a relatively fine-grained, porous main mass that partially encloses a coarser, more compact clast (Fig. 4). Part of the fine-grained area is spinel-dominated and part is hibonite-dominated (Fig. 4c). During cooling of a gas of solar composition, hibonite is predicted to react with gaseous Ca to form grossite (Grossman 2010) but spinel is known to form directly from hibonite instead, in some cases pseudomorphically replacing it (MacPherson et al. 1984; Simon et al. 2006). The retention of hibonite in 59-3 indicates that only partial replacement of hibonite by spinel occurred, as in Murchison inclusion SH-6 (MacPherson et al. 1984). Hibonite replacement was followed by melilite formation; the hibonite and the spinel grains have melilite rims. Melilite is predicted to condense before spinel but commonly does not, possibly due to unfavorable kinetics relative to formation of spinel from hibonite (Simon et al. 2006). As in 59-1, there are many gaps between the grains, indicating that the inclusion was not subsequently melted after the melilite rims formed.

In addition to the textural differences, the composition of hibonite in the clast is MgO- and TiO$_2$-poor compared to that in the host (Fig. 13), suggesting that they had different origins.
Despite these differences, hibonite in the clast has the same Fe content as that in the host (Fig. 13). This implies that Fe was added after incorporation of the clast into the host. As in typical Acfer hibonite, Mg contents correlate with Ti + Si and Fe contents do not. The coarse, compact texture and curved edge of the clast suggest that it was once molten, in contrast to the porous host. The host and clast are intergrown at the contact, so there may have been some reaction between them when they came into contact with each other, indicating that one or both of the objects was hot at the time.

On the other hand, could the apparent clast/host boundary instead be a reaction front, with the clast a remnant of the primary inclusion and the fine-grained material around it reaction products? This cannot be ruled out but it seems unlikely. To form the fine-grained hibonite-perovskite-spinel assemblage from the melilitel-rich, Ti-poor coarse material would require addition of Ti, to account for the abundance of perovskite and relatively high Ti content of the fine-grained hibonite, and a temperature increase sufficient to vaporize Si, mobilize Ti and stabilize hibonite, followed by re-formation of melilite upon cooling. It seems more likely that this object contains at least three generations of material and records the following series of steps in its formation.

First, the clast, a once-molten hibonite-spinel-melilite spherule, formed. Formation of the host inclusion began with condensation of hibonite and partial reaction of the grains with the nebular gas to form spinel. This was followed by further reaction between grains and gas, forming melilite rims on both hibonite and spinel. Melilite is predicted to begin forming from the aluminates prior to spinel (Grossman 2010), but the melilite rims on spinel grains indicate that spinel formed before melilite. The clast may have been partially molten when incorporated, as it is intergrown with host phases along its outer edge. The clast could have been incorporated during the gas-grain reactions that formed either spinel or melilite, assuming the clast did not cut off access of the gas to the interior of the inclusion, and prior to deposition of the melilite, anorthite and diopside rim layers. The inclusion was eventually broken and deposited on the Acfer 094 parent body.

**Distribution of CAIs in Acfer 094**

A comparison of the CAI population found in thin section with that found in the disaggregated material can provide an indication of its variability within Acfer 094, as these materials are from different, probably non-adjacent subsamples. Of the inclusions found in the disaggregated material: 94% have assemblages found in the thin section; three of the four most common assemblages (Sp+Mel±Pv; Sp+Pv; An+Pyx) are also among the four most common in the thin section; the most common assemblage, An+Pyx, at 20.9% is much more abundant than in thin section (9.7%), while the assemblage most common in the thin section, Sp+Mel±Pv, has similar percentages in the two suites: 22.5% of the CAIs in the section, 19.4% in the disaggregated material. The proportions of hibonite- and of grossite-bearing inclusions in the disaggregated material, 14% and 9%, respectively, are slightly higher than those seen in thin section in the present study, 13 and 5%, respectively, and not very different from those found by Krot et al. (2004), who found 10 and 10%. There is no evidence for strong disparities between the CAI populations of different subsamples of Acfer 094.

**CONCLUSIONS**
1) The Acfer 094 refractory inclusion population is dominated by small, melilite-bearing inclusions and is somewhat similar to those in CO chondrites, as found in previous studies (Weber 1995; Krot et al. 2004).

2) Inclusions like those found in CV and CM chondrites are present but are very rare. Abundances of secondary phases are low.

3) Most inclusions have rims of melilit, aluminous diopside, or both. The common occurrence of melilit rims indicates that many Acfer 094 inclusions, including hibonite-bearing ones, encountered a region of the solar nebula where melilit was condensing.

4) FeO contents seen in primary phases are unusually high. They appear to be pre-accretionary but to account for them in a nebular setting would require unusual conditions, such as enrichment in dust relative to gas.

5) Acfer 094 contains a distinctive population of refractory inclusions. They exhibit a wide variety of mineral assemblages and record different histories from one another.

ACKNOWLEDGMENTS

We thank G. MacPherson and the Smithsonian Institution for allocation of the thin section and A. Nguyen and E. Zinner for the aliquot of disaggregated material. A. Fedkin, L. Keller and K. Nakamura-Messenger provided helpful information. This work was supported by NASA through grant NNX08AE06G (LG), and funding is gratefully acknowledged.

REFERENCES


Table 1. Mineralogy of the most abundant Al-rich objects found in thin section USNM 7233-1. Only assemblages with four or more occurrences are listed.

<table>
<thead>
<tr>
<th>Mineralogy</th>
<th>No. of objects</th>
<th>% of objects</th>
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<tr>
<td>Sp+Mel±Pv</td>
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<td>Sp+Pv</td>
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</tr>
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<td>Sp</td>
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</tr>
<tr>
<td>An+Pyx</td>
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<td>Sp+An+Diop</td>
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<td>2.8</td>
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<td>Gro+Sp+Pv</td>
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</table>

Sp: spinel; Mel: melilite; Pv: perovskite; An: anorthite; Pyx: pyroxene; Hib: hibonite; Diop: diopside; Tpyx: Ti-bearing pyroxene; Gro: grossite. “Pyx” indicates that some members of the group contain diopside and others contain Tpyx.
Table 2. Mineralogy of the least abundant (three or fewer occurrences) Al-rich objects found in thin section USNM 7233-1.

<table>
<thead>
<tr>
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<td>Gro+Sp+Mel+Pv</td>
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<td>Mel+Pv+An</td>
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</tr>
<tr>
<td>Sp+Mel+Diop+An</td>
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</tr>
<tr>
<td>Tpyx+Diop+Pv</td>
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<td>Hib+Sp+Fo</td>
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</tr>
<tr>
<td>Hib+Mel</td>
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<tr>
<td>Sp+Tpyx+An</td>
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<tr>
<td>Sp+Mel+Diop+Pv</td>
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</tr>
<tr>
<td>Sp+Mel+Fo+FeS+Diop</td>
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<td>Mel+Pv</td>
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<tr>
<td>Mel+Diop+Fo</td>
<td>1</td>
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</tbody>
</table>

Abbreviations as in Table 1, plus: Cor: corundum; Fo: forsterite.
Table 3. Electron probe analyses of hibonite in Acfer 094 inclusions.

<table>
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<th>1.</th>
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<td>MgO</td>
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<td>Al$_2$O$_3$</td>
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<td>88.92</td>
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<td>8.42</td>
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<td>V$_2$O$_3$</td>
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<tr>
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Cations per 19 oxygen anions

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Sample numbers: 1.: 18-1; 2.: ACM4; 3.: L5-1; 4.: 59-2; 5.: 59-6; 6., 7.: 59-3; 8.: 27-3.
Table 4. Altered spinel in L5-1 and L5-2.

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<td>TiO₂</td>
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Cations per 4 oxygen anions

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<td>0.023</td>
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<tr>
<td>Cr</td>
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<td>0.051</td>
<td>0.037</td>
<td>0.041</td>
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<td>0.001</td>
<td>0.002</td>
<td>0.002</td>
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<tr>
<td>Mn</td>
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<td>0.019</td>
<td>0.014</td>
<td>0.016</td>
<td>0.018</td>
<td>0.020</td>
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<tr>
<td>Fe</td>
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<td>0.258</td>
<td>0.188</td>
<td>0.212</td>
<td>0.240</td>
<td>0.263</td>
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<td>Tot. cat.</td>
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<td>2.970</td>
<td>2.934</td>
<td>2.944</td>
<td>2.942</td>
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</table>

Mg/(Mg+Fe)  0.679  0.707  0.687  0.698  0.706  0.697

1., 2.: L5-1; 3.-6.: L5-2. In all analyses contents of V₂O₃ are below the detection limit of the electron probe, 0.03 wt% V₂O₃.
Table 5. Bulk major element contents of grossite-bearing inclusions, obtained by modal recombination.

<table>
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<tr>
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<th>59-2</th>
<th>59-6</th>
<th>L5-2</th>
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<tr>
<td>MgO</td>
<td>9.2</td>
<td>11.3</td>
<td>5.6</td>
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<td>Al₂O₃</td>
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<td>50.2</td>
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<td>SiO₂</td>
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<td>10.6</td>
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<td>CaO</td>
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<tr>
<td>TiO₂</td>
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<td>4.6</td>
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<tr>
<td>FeO</td>
<td>0.5</td>
<td>1.1</td>
<td>4.7</td>
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</table>
FIGURE CAPTIONS

Fig. 1. Backscattered electron images of the most abundant inclusion types. a) Inclusion 1-1, a spinel-melilite inclusion with spinel poikilitically enclosed in melilite, with rim layers of anorthite and diopsite. b) Inclusion 28-4, a nodular spinel-melilite-perovskite inclusion. c) Inclusion 32-3, a spinel-perovskite inclusion, melilite rim. d) Inclusion 22-7, a fine intergrowth of anorthite and diopsite. e) Inclusion 19-3, a spinel-pyroxene inclusion. An: anorthite; Diop: diopside; Mel: melilite; Pv: perovskite; Sp: spinel; Tpyx: Ti-bearing pyroxene.

Fig. 2. Backscattered electron images of hibonite occurrences in Acfer 094. a) Inclusion 18-1, a hibonite-spinel-perovskite spherule with a melilite rim. b) Inclusion ACM4, an aggregate of hibonite laths with interstitial perovskite. c) Inclusion 19-1, a relatively large hibonite plate with fine inclusions of perovskite and Zr-, Y-rich oxides. Hib: hibonite; other abbreviations as in previous figure.

Fig. 3. Backscattered electron images of grossite-bearing inclusions in Acfer 094. a) Inclusion 34-1, a typical occurrence with a massive grossite-perovskite core, a discontinuous layer of spinel, and a melilite rim. b) Inclusion 59-1, a porous inclusion with anhedral grossite, hibonite and spinel. Individual grains have melilite rims. c) Inclusion L5-1, consisting of hibonite laths with interstitial grossite and alteration products. Outer margins of the hibonite laths have been converted to spinel. d) Inclusion 59-2. Note the straight, crystallographically controlled hibonite-spinel contacts and the corroded contacts between melilite and spinel and between hibonite and grossite. e) Inclusion 59-2, higher magnification view of contacts between hibonite, spinel and grossite. f) Inclusion 59-6, a spherule with a core of hibonite, grossite, perovskite and spinel enclosed in melilite. As in 59-2, spinel-melilite and hibonite-grossite contacts are irregular while hibonite-spinel contacts are straight. g) Inclusion 59-6, higher magnification view. h) Inclusion L5-2, consisting of a grossite-rich interior with a large perovskite grain and smaller, sparse corundum and hibonite grains, enclosed in a layer of altered spinel. Gro: grossite; other abbreviations as in previous figures.

Fig. 4. Backscattered electron images of compound inclusion 59-3. a) View of the entire inclusion fragment, showing the coarse-grained clast, fine-grained host, and rim layers. b) View of clast and adjacent, spinel-rich host. Note the arcuate contact between clast and host, intergrowth of phases along it, and melilite (light) rims on spinel grains. c) View of hibonite-rich (right) and spinel-rich (left) parts of host. Abbreviations as in previous figures.

Fig. 5. Backscattered electron image of inclusion 27-3, a perovskite-rich inclusion with interstitial hibonite and spinel, enclosed in a melilite rim. Abbreviations as in previous figures.
Fig. 6. Backscattered electron image of inclusion 23-3, probably a fragment of a Type B coarse-grained refractory inclusion. The unrimmed fragment consists of euhedral spinel partially enclosed in fassaite. Abbreviations as in previous figures.

Fig. 7. Histograms of compositions of melilite in rims and mantles (a) and in melilite-rich inclusions (b). The rim and mantle melilite is generally more gehlenitic than melilite in the interiors of inclusions.

Fig. 8. Plots of FeO contents vs. åkermanite contents for melilite from a) rims and mantles on inclusions in Acfer 094; b) in melilite-rich inclusions in Acfer 094; and c) mantles of two Type B1 inclusions from Allende. The Acfer data show no correlation between FeO and Åk contents, whereas in the Allende inclusions the most gehlenitic melilite, which occurs at the edges of the inclusions, is the most FeO-rich.

Fig. 9. Analyses of hibonite in Acfer 094 inclusions. a) Mg vs. Ti + Si cations per 19 oxygen anions. Most analyses plot on or near the 1:1 reference line, except for those from inclusion L5-1. b) Mg + Fe vs. Ti + Si, cations per 19 oxygen anions. Most analyses plot above the 1:1 reference line. c) Fe vs. Mg cation contents in hibonite. Fe contents are not correlated with Mg. Most Fe contents fall within a narrow range, except for those from ACM4 (low) and L5-1 (high). d) Fe vs. Ti + Si cations per 19 oxygen anions. No correlation is seen except for hibonite in L5-1.

Fig. 10. Minor element contents in spinel in spinel+melilite±perovskite (SMP) and in hibonite-bearing inclusions from Acfer 094 and from Murchison. a) Wt% V₂O₃ vs. TiO₂ in SMP inclusions. b) Wt% Cr₂O₃ vs. FeO in SMP inclusions. c) Wt% V₂O₃ vs. TiO₂ in hibonite-bearing inclusions. d) Wt% Cr₂O₃ vs. FeO in hibonite-bearing inclusions.

Fig. 11. Oxide-oxide plots for the unusual, spinel-like phase in inclusions L5-1 (solid symbols) and L5-2 (open symbols). a) Wt% FeO vs. MgO. b) Wt% Cr₂O₃ vs. MgO + FeO. c) Wt% TiO₂ and MnO vs. MgO + FeO. d) Wt% CaO vs. MgO + FeO. e) Total cations vs. Ca cations per four oxygen anions. f) Total cations vs. Mg + Fe cations per four oxygen anions.

Fig. 12. Plot of Al₂O₃ vs. TiO₂^tot (all Ti as TiO₂) contents in pyroxene in the spinel-pyroxene inclusion 19-3, shown in Fig. 1e. Both Ti-bearing and Ti-poor (aluminous diopside) pyroxene is present.

Fig. 13. Compositions of hibonite in the clast and host, inclusion 59-3. Hibonite in the clast is Mg- and Ti-poor compared to that in the host, but they have similar Fe contents.
Acfer rim and mantle melilite
Rims: 22 analyses
mean Åk = 8.8
Mantles: 103 analyses
mean Åk = 9.1

Melilite-rich
Acfer inclusions
132 analyses
average Åk = 14.0
std dev = 7.9

Fig. 7
Fig. 8a, b
Fig. 8c
Fig. 9a, b
Fe cations per 19 Ox vs Mg cations per 19 Ox

Fe = Ti + Si

Fig. 9c, d
Fig. 10
Fig. 11a, b
Fig. 11c, d
Fig. 11e, f
Hibonite in 59-3

- **Mg clast**
- **Mg host**
- **Fe clast**
- **Fe host**

Cations per 19 Ox

Ti + Si cations per 19 Ox

Fig. 13