

FORSTERITE-BEARING TYPE B REFRACTORY INCLUSIONS: EVOLUTION FROM AGGREGATES TO VOLATILIZED MELT DROPLETS. E. S. Bullock¹, G. J. MacPherson¹, K. Nagashima², A. N. Krot², M. Petaev³ and S. B. Jacobsen³. ¹Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, DC, USA. Email: BullockE@si.edu. ²Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Mānoa, Honolulu, HI 96822, USA. ³Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA.

Introduction: Forsterite-bearing Type B CAIs (FoBs) are igneous inclusions found only in CV chondrites [1–4]. They remain enigmatic yet important among all refractory inclusions because: (1) many show significant mass-dependent isotopic fractionation in magnesium, silicon and oxygen [5, 6]; (2) their forsterite-rich compositions are unlike (i.e. less refractory than) all other refractory inclusions yet are similar to but do not overlap those of Al-rich chondrules [7, 8]; and (3) many show clear evidence of melt evaporation from their outer regions, which is consistent with their fractionated isotopic compositions. Through our continuing work on these objects, we can now recognize clear chemical and mineralogical patterns that reveal an evolutionary, petrogenetic sequence among the FoBs. In fact, this sequence is more clearly delineated than for any other variety of refractory inclusions.

Analytical Method: Bulk compositional data and high-resolution back-scattered electron images for polished sections of six FoBs (Allende *ALVIN*; Allende *SJ101*; Allende *TS35*; Efremovka *E60*; Efremovka *E64* and Vigarano *3137-2*) were obtained using a FEI NOVA NanoSEM 600 scanning electron microscope, operated at 15keV with a sample current of 2-3 nA and a Thermo-Noran energy dispersive X-ray analytical system. Mineral compositions were measured with a JEOL JXA-8900 5-spectrometer wavelength-dispersive electron microprobe, operated at 15 keV and 15-20 nA beam current.

Results: FoBs exhibit a range of mineral compositions that correlates with overall structure and texture of the individual inclusions. The essential structure of a typical FoB consists of an olivine-bearing core (forsterite, åkermanitic melilite, pyroxene, spinel) surrounded by an olivine-free mantle (gehlenitic melilite, spinel, anorthite), but the relative proportion of the two varies greatly from object to object. In the simplest cases, the olivine-bearing core occupies all but the outermost few hundred microns of the inclusions (e.g., *ALVIN*). In more complex examples, such as *TS35*, the cores represent 50% or less by volume of the inclusion.

The cores consist of forsterite (invariably containing 0.8 to 2 wt% CaO), aluminous pyroxene, spinel that is unevenly distributed, and a minor amount of very Mg-rich melilite ($\sim \text{Åk}_{80-90}$). The mantles are olivine-free and contain spinel, pyroxene that is more Al- and Ti-rich than that in the cores, anorthite, and alu-

minous melilite with a wide range of compositions (Åk_{6-70}). When the bulk compositions of the inclusions are plotted on appropriate phase diagrams (e.g., Fig. 1, anorthite-gehlenite-forsterite diagram, after [9]), along with the separate compositions of core and mantle, the trends cut across major liquidus boundaries. Thus the olivine-free mantles cannot be related to the cores by fractional crystallization. The progression from simplest to most complex FoBs, outlined above is paralleled by a progressive change in the range of melilite compositions (Fig. 2). The simplest objects, *SJ101* and *ALVIN*, have nearly monomodal melilite compositions at Åk_{80-90} , all of which occurs in the olivine-bearing lithology. With increasing thickness of the aluminous (olivine-free) mantles, the melilite composition histograms extend to much more gehlenite-rich compositions ($\sim \text{Åk}_6$ in the mantle of *TS35*). The fact that the melilite compositions in objects such as *TS35* extend across the binary minimum in the melilite liquidus reinforces the idea that the olivine-bearing cores and the olivine-free mantles cannot be related by any igneous crystallization processes. We interpret the mantles to be the result of evaporative magnesium and silicon loss during very rapid melting events, with no diffusive equilibration between core and mantle.

Discussion: One property of FoBs that has remained a perplexing puzzle is the invariable gross heterogeneity in the distribution of spinel relative to olivine in the cores, previously described by us as spinel-rich and spinel-free islands [8]. Now however, the newest of the FoB samples in our study, *SJ101*, provides what we think is the key to understanding not only this property but also to the evolutionary sequence of FoBs in general, as discussed below.

From the perspective of mantle thickness and mineral chemistry (especially melilite composition), *SJ101* is the simplest of all FoBs that we have observed. It differs from the others also in that the heterogeneity of spinel and olivine distribution takes the form of sinuous bands of forsterite separating pyroxene + spinel regions, rather than more equant “islands” [10]. The internal textures and grain size within *SJ101* are also highly variable, suggesting a very low degree of melting and homogenization. This is reinforced by Mg, Si and O isotopes, which show little or no mass-dependent fractionation [10, 11]. The form of the heterogeneity suggests the nature of the precursors to the

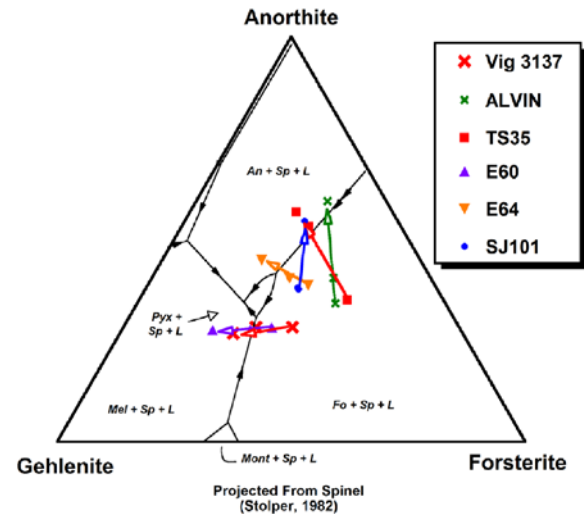
FoBs: a sinuous aggregate such as an amoeboid olivine aggregate with numerous enclosed spinel-pyroxene-rich refractory nodules [12, 13].

Inclusions such as *ALVIN* and *E64* show the next step in the evolution of FoB. These inclusions underwent more thorough melting, as indicated by their coarser-grained and more uniform textures relative to *SJ101*, thin forsterite-free mantles, and minor mass-dependent fractionation in oxygen [8].

The inclusions that show the greatest effects of both melting and evaporation, *E60*, *3137-2* and especially *TS35*, have extensive forsterite-free mantles, which we interpret to be the result of major evaporative loss of magnesium and silicon when the inclusions were molten. Yet even in the most extensively modified object, *TS35*, spinel-rich and forsterite-free islands are preserved. These three inclusions show mass-dependent fractionation in oxygen, but not to any greater degree than in the other FoBs in this study. In all cases, the isotopic fractionation is no greater in the mantles than in the cores. This implies that although magnesium elemental equilibration between core and mantle was not maintained, oxygen isotopic equilibration largely was maintained.

The following sequence of FoB evolution can be suggested. The most 'primitive' FoB, *SJ101*, appears to be a sintered or barely melted aggregate of fine-grained spinel-rich 'proto-CAIs' (pyroxene + spinel + melilite), surrounded by forsterite-rich rims. With increased degree of melting, the 'typical' FoB petrographic textures witnessed in the other five FoBs are produced. Intense and probably very brief (flash) melting events resulted in the formation of forsterite-free outer mantles owing to evaporative loss of magnesium and silicon. The different chemical evolution trends from core to mantle, shown on Fig. 1, reflect different evaporating ratios of Si to Mg (and therefore differing Mg and Si partial pressures in the ambient gas [14]).

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Core – Mantle Trends of FoB CAIs

Fig. 1. Compositions of FoB CAIs plotted on the ternary projection forsterite-gehlenite-anorthite (after [9]). Arrows extend from the core through the bulk to the mantle compositions for each CAI.

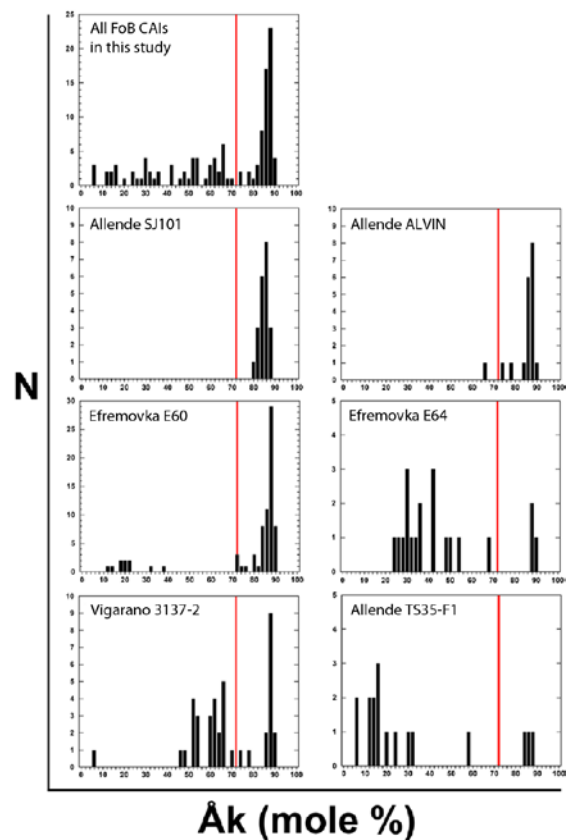


Fig. 2. Compositions of melilite within each FoB CAI in this study. Red vertical lines mark the position of the binary minimum in the liquidus for the pure system åkermanite-gehlenite.