The mineral hosts and locations of many incompatible elements such as Ba, P, Zr, Nb, Th, Pu and the Rare Earth Elements (REE’s) can be elegantly mapped with high sensitivity and micrometer spatial resolution by the fission track print technique which U acts as a tracer for the other incompatible elements. The information so gained about host mineral compositions is invaluable in understanding the mineralogical controls on these trace elements' behaviour. One of the additional benefits is that various U-Th-Pb-system age determinations can be made by ion², or even electron³, microprobe on the located mineral grains. Fission track maps of 16 coarse-grained Allende Ca-Al-rich inclusions (CAI’s) have revealed the following:- (1) in CAI’s of Grossman’s Type A⁵ the sole U-Th-REE-bearing accessory mineral is perovskite. (2) in Type lb CAI’s, U is very evenly distributed as in a glass and no incompatible-element-rich accessories are found. (3) Type B⁶ CAI’s range from those having uniformly dispersed U to those in which up to 85% of the total U resides in “stars”, i.e. µm-sized U-Th-REE-rich grains. In this latter group of CAI’s, which include the known isotopically anomalous Cl and EK-1-4-1, seven different accessory phases were found and are described below.

The compositions of these phases, whose average grain sizes range from 0.7μm to 2.5μm, were deduced from multiple, ZAF-corrected, electron microprobe and SEM analyses. The former distinguished overlapping X-ray lines (e.g. from Ba and Ti) while the sharply defined beam of the latter minimized X-ray generation in surrounding materials. This X-ray "contamination" was estimated, taking account of the different excited volumes for Mg, Si, Ca, etc., from the differences between SEM analyses at 10kV and at 15kV. The fact that in each case a number of different grains yielded consistent energy-dispersive X-ray spectra is taken to mean that definite mineral species were analysed. The quality of the analyses varies considerably with the size, shape and neighbours of each grain and it is difficult to assess uncertainties except by noting the consistency between analyses. Our best estimates of the compositions, normalized to total 100, are shown in Table 1. The 3 significant figures arise from the normalization and do not imply this accuracy. The amounts of radiogenic Pb (up to 20%) have been recalcuated back to the original composition at the time of crystallization. In the absence of structural data, mineral names have been suggested from compositions alone.

Phase I Ca (REE, Th) Silicate 5 grains of mean size 1.4μm were found whose composition approximates formula $M_2O_{31}$, $M_4O_{3}$, or $M_5O_{15}$. We could find no suitable analogs of $M_2O_{31}$ or $M_4O_{3}$. However, we are grateful to Dr. A. F. Reid of C.S.I.R.O. for pointing out to us that the apatite structure $M_2O_{32}$ (or $M_4O_{3}$) tolerates a very wide range of substitutions including Si for P coupled with Th, REE, etc. for Ca. Thus, for example, Ca$_{26}$P$_{26}$ might become (Ca, REE, Th)$_{20}$Si$_6$O$_{26}$ which approximates the mean Phase I formula (Table 1) of Ca$_{44}$REE$_{24}$Th$_{24}$Si$_6$O$_{26}$. Given that the Si and Al analyses could well be overcorrected for matrix Si and Al "contamination", the tentative assignment of Phase I as a substituted apatite structure appears plausible. But whatever its structure and exact composition, this material appears to be a definite, and probably new, mineral phase.

Phase II Pyrochlore 55 grains of mean size 1.7μm were found of this mineral whose composition resembles a 5μm "pyrochlore" found in lunar troctolite 76535. The Pyrochlore has the formula $A_{2-z}B_{2}O_{6}$ (0, OH, F)₁₋₉ where A = Ca, REE, Th, etc. and B = Al, Ti, Nb, etc., to which the mean Phase II analysis (Ca, REE, Th)$_{1.62}$ (Nb, Ti, Zr, Al)$_{0.98}$O$_7$ conforms very well, even to the usual A-site deficiencies.

Phases III and IV Thorianite ? (Th, U)O$_3$; Baddeleyite ? (Zr, Ti)$_2$O$_3$. These mineralogical names are assigned here only on the basis of composition. 12 small 0.8μm grains of the former and only 1 grain of the latter were found.

Phase V Calcio-celsian ? (Ba, Ca), Al$_6$Si$_6$O$_{22}$ Terrrestrial occurrences of barium feldspar often contain K; its absence in the volatile-poor Allende CAI’s is not surprising. The 12 2.5μm grains of this phase were frequently associated with Pyrochlore.
TABLE 1

SEM AND MICROPROBE ANALYSES OF SIX ACCESSORY ALLENDE MINERALS

(WEIGHT PERCENT AND FORMULA)
Phase VI Nb-rich Perovskite (Ca, REE)₆(Ti, Nb)₂O₁₂. Simple Nb-poor perovskite is ubiquitous in and below the rims. However, only eleven 2.4μm grains of Nb-REE-Th-rich perovskite were found (in two Type B CAI's which did not contain Phase I).

Phase VII Apatite No analyses are given of this phase, only 3 small grains of which were found, reflecting the strong depletion of P in Allende CAI's.

It is not certain that the analyses in Table I are primary compositions. However the 4.56 b.y. U-Th-Pb age¹ of these accessory phases indicates that no detectable Pb loss or, presumably, alteration took place later than 200 m.y. after formation even in the notoriously alteration-prone¹ niobates. The pyrochlore, perovskite and "Phase I" are more enriched in light than heavy REE's. While this is the common crystal chemical preference of perovskite, the niobates at least seem to accept¹ either heavy or light REE's. One possible explanation for the light REE abundance in the accessories follows from the hypothesized¹² subcooled liquid origin of Type B CAI's. Early-formed Ti-pyroxene may have depleted the heavy REE's before pyrochlore and "Phase I" crystallized. This would also be consistent with the predominant association of accessories with, or interstitial to, spinels and the most Mg-rich, least refractory (and last crystallizing?) melilite.

A final tentative observation based on a study of the only four CAI's found to contain accessories (excluding Cl and EKI-4-1) is that the CAI subtypes B₁ and B₂ may have different suites of accessories. Thus, small 2- or 3-grain clumps of pyrochlore, calcio-celsian and "Phase I" are the predominant accessories in Type B₁ CAI's whereas thorianite, baddeleyite, apatite and niobian perovskite are found mainly in Type B₂.


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