An REE-rich mineral, other than pyroxene or plagioclase, must be present in eucrites since their REE patterns usually cannot be reconstructed by combining REE analyses of these two major phases in a constant, mineralogically realistic ratio. The phosphate minerals have been suggested to be that phase (1). A systematic search for phosphates in monomict eucrites has been carried out and the abundances of Y and REE oxides (La,Ce,Sm,Yb) in these minerals has been determined. Phosphates have been found in all 13 eucrites studied so far. In most cases both fluorapatite and merrillite are present, but either may occur alone. Grain size varies from submicron up to about 50 μm and most grains are found in interstitial assemblages of these meteorites. Phosphate has been found included in pyroxene and, therefore, crystallized before the end of pyroxene crystallization.

Both F-apatite and merrillite contain significant minor components. F-apatite is fairly pure Ca₅(PO₄)₃F with up to 0.2% Cl. It has minor Fe and Mg with Mg/(Fe+Mg) =0.2. Merrillite, however, contains Y+REE, Na (-0.8%) and Fe+Mg (3-4%) with Mg/(Fe+Mg) =0.6. Y+REE, for merrillite, total -10% wt (see also 2,3). Y+REE analyses also show dramatic differences between the two phosphates. REE in F-apatite were below detection (-0.05%) in routine analysis and values of 250-300 ppm of Ce₂O₃ and La₂O₃ were obtained using high precision techniques, while Sm and Yb are below -150 ppm. F-apatite, therefore, contains about 500-1000 xCl abundances of LREE with lower levels of HREE. Merrillite contains much more abundant REE. Ce₂O₃ typically reaches 1.5 to 2% which represents an enrichment of 20-30,000 xCl. HREE enrichment factors vary from 5-10x10³. The phosphate REE patterns from eucrites show consistent light REE enrichment, perhaps because earlier pyroxene crystallization depleted HREE in the residual melts.

The phosphates are generally found in interstitial areas associated with silica, Ca-rich pyroxene, ilmenite and troilite. They are, therefore, late crystallizing phases that equilibrated with the incompatible-rich late melt phases. In rare instances merrillite is found included in pyroxene indicating that P₂O₅ saturation of the crystallizing melt occurred prior to the formation of the small interstitial areas. Large F-apatites have also been found in the cores of coarse feldspar grains from unbrecciated mafic clasts but these may be skeletal crystals that grew inward and outward, trapping late crystallizing apatite in their cores. It is texturally not clear whether the two phosphates crystallized together (no intergrowths have been found) or if one preceded the other. The bulk P₂O₅ and the silica contents of the eucrites (4-6) suggest that phosphate crystallization would have occurred late, near the solidus (<1000°C) when the bulk compositions of the remaining liquid had become silicic. Similarly, the low bulk P₂O₅ and the high solubility of apatite in mafic melts suggest that eucritic melts dissolved essentially all the phosphates in their source region (4).

Since the REE abundances of the two phosphate phases are quite different the reason for their coexistence rather than crystallization of a single phase is important. Possible reasons are: (A) Variation of the Ca/P ratio; (B) Concentration of F in the interstitial phases may have forced crystallization of apatite in preference to merrillite; (C) Alternately, concentration of Group IIIA elements in the interstitial liquid may have forced merrillite crystallization. None of these hypotheses can yet be tested but the presence or absence of the F seems likely to have had a profound influence on the types of phosphate present and hence on the concentration of REE elements in the phosphate.

Estimates of the distribution coefficients for REE between the silicate fraction and individual phosphates cannot be made since the composition of the equilibrium silicate melt is unknown. Comparison of the merrillite REE content with bulk
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eucrite REE content does not provide a useful estimate of Kd between bulk eucrite and merrillite since the phosphates crystallized from a fractionated, silica-rich liquid. Both merrillite and F-apatite appear to have fairly constant REE abundances in all eucrites. The data indicate that light REE are enriched in merrillite over apatite by factors of 30 to 100. Whether these factors represent equilibrium Kd is unknown. The results are very similar to F-apatite--merrillite pairs from lunar basalts (e.g.,7) indicating similarity of crystallization conditions.

In contrast to the eucritic phosphates, the abundant phosphates found in mesosiderites, which have basaltic achondrite silicates mixed with metal, are quite different. The mesosiderites also contain merrillite and F-apatite but merrillite is much more abundant, making up to 5% (vol) of some clasts. This merrillite differs from the eucritic merrillite as REE are below routine microprobe detection limits. REE-bearing phosphates have been found in mesosiderites but only by careful searching in the centers of very large mafic clasts (1) that have escaped much of the pervasive metamorphism so characteristic of these meteorites (8). The mesosiderite merrillite also contain significantly higher Fe+Mg (6-8%) than eucritic material and is more like merrillite from Angra dos Reis (3). The eucritic merrillite also differs significantly from chondritic merrillite (e.g., 9,10) which tends to have very similar REE contents to coexisting apatite. The chondritic phosphates of Bruderheim (9) are similar to mesosiderite phosphates suggesting that they were formed by comparable processes to the mesosiderite phosphates. There are, therefore, two quite distinct classes of achondritic merrillite (a) igneous merrillite containing REE found in eucrites and lunar basalts and (b) "metamorphic" merrillite that does not have the high REE signature of crystal-liquid fractionation such as that in mesosiderites. The low REE abundance of chondritic merrillites suggest that they are of metamorphic origin and perhaps formed by the types of metal-silicate reactions found in mesosiderites (11).

The presence of two REE-bearing phases other than pyroxene and plagioclase in the eucrites requires reinterpretation of REE bulk rock data. A minute amount of merrillite (~0.05% vol) can account for all the REE in many eucrites. Similarly about 0.5% (vol) of F-apatite in eucrites will significantly change the bulk REE pattern when compared to pyroxene or plagioclase REE patterns. Variable apatite/merrillite may cause significant variations in the REE abundances of these meteorites (for example clasts in Juvinas have REE abundances patterns ranging from 10x to 30x chondrites (12)). Most eucrites show a high temperature metamorphic overprint that might have mobilized the low-melting point in interstitial material without significantly affecting the major minerals. The evolution of the REE patterns in eucrites should, therefore, be based on variations of REE on mineral separates since these data are much more likely to vary systematically with fractionation indicators such as Fe/Mg or Ca/Na. The REE patterns of the phosphates may be used to constrain the later parts of the crystallization and metamorphic history of the eucrites.


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