STUDIES OF THE DISTRIBUTION OF RARE-EARTH ELEMENTS IN THE MINERALS OF LUNAR FERROAN ANORTHOSITES. Odette B. James*, Marilyn M. Lindstrom# and James J. McGee*, *U. S. Geological Survey, Reston, VA 22092, #NASA JSC, Houston, TX 77058

Our research is aimed at better understanding the petrogenesis of lunar ferroan anorthosites by establishing the exact nature and causes of compositional variations in the minerals of these rocks. Our results will help define the contents of minor and trace elements in ferroan-anorthosite parent magma(s). One aspect of our research consists of electron-microprobe (EMP) analysis of minor and trace elements in all the minerals of a large suite of ferroan anorthosites (preliminary results given by [1]). A second aspect consists of synthesis and evaluation of a large data base of chemical analyses of ferroan anorthosites (results reported by [2]). A third aspect consists of scanning electron microscope (SEM) and EMP studies of thin sections of splits previously analyzed by instrumental neutron activation (INAA) and use of the data to define the distribution of trace elements among the phases in the splits (results reported by [3] and herein).

Our initial combined INAA-SEM-EMP studies [3] were of a clast of troctolitic anorthosite from breccia 64435 that had relatively abundant and relatively magnesian mafic minerals for a member of the ferroan-anorthosite suite. We analyzed four splits from this clast by INAA: a plagioclase separate, a mafic-mineral separate, the residue from hand picking, and a whole-rock sample. The splits were thin sectioned, and modes of the mineral separates and the whole-rock sample were determined using the SEM. Because the plagioclase separate was nearly pure and the SEM mode permitted correction of the analyzed composition for the presence of minor mafic minerals, the composition of the pure plagioclase could be quite accurately determined.

Distribution coefficients from the literature were used to calculate the REE compositions of (1) the liquid in equilibrium with the plagioclase and (2) the mafic minerals that would be expected to have crystallized from that liquid. These data and the SEM modes were used to calculate the hypothetical REE compositions of the mafic-mineral separate and the whole-rock split. The calculated liquid had a nearly flat chondrite-normalized pattern of the trivalent REE and REE abundances about 11 times chondritic. The calculated patterns for the two splits had shapes that were very close to those of the measured patterns, but their abundances were low. If we assumed that the two splits contained small amounts of trapped equilibrium liquid, however, the measured REE patterns were readily duplicated (Fig. 1). The fit was best when the whole-rock split was assumed to contain 2.0 wt. % liquid and the mafic-mineral separate was assumed to contain 1.2 wt. % liquid.

We have begun similar studies of thin sections of separates of ferroan anorthosite 60025 previously analyzed by INAA. Thus far, an SEM mode has been completed for split ,699SM. This split consists almost entirely of olivine (44.6 vol. %) and orthopyroxene-augite intergrowths representing inverted pigeonite (total pyroxene 50.1 vol. %); plagioclase is minor (5.2 vol %). The olivine is $Fo_{65.5}$ and the orthopyroxene is $Wo_{2.1}En_{70.3}Fs_{27.6}$; the mg' (molar Mg/Mg+Fe) of these minerals is about 5% lower than that of the same minerals in the 64435 troctolitic anorthosite.

Using the same distribution coefficients for olivine and plagioclase as used in the 64435 study plus distribution coefficients for pigeonite [4], we have made a preliminary analysis of the REE distribution in the minerals in 60025,699SM. Unfortunately, at this stage, we are not certain that any of the analyzed 60025 plagioclase separates represent plagioclase in equilibrium with the mafic minerals in ,699SM, so we cannot define the composition of the equilibrium liquid as accurately as for the 64435 samples. Therefore, the analysis was done by (1) assuming a REE pattern for the liquid, using that determined for the 64435 troctolitic anorthosite as a starting point, (2) calculating the compositions of the minerals in equilibrium with this liquid using the distribution coefficients, and (3) calculating the composition of the split from the mineral compositions and SEM mode.

The best fit obtained thus far (Fig. 2) is based on an equilibrium liquid with a flat chondrite-normalized pattern of the trivalent REE (Eu was not calculated) and REE abundances slightly higher than those in the 64435 liquid. The calculated pattern duplicates the slope of the light REE in the observed pattern but has a much greater positive slope for the heavy REE. The greatest discrepancy between the calculated and observed patterns is in the region of Gd and Tb. The shape of the ,699SM pattern depends heavily on the Tb value, which is quite imprecise (20% 1σ uncertainty). A second split (60025,699LM) consisting of the same minerals but having slightly higher pyroxene/olivine has a pattern nearly parallel to that of ,699SM, except that its Tb content is much lower and the shape of the pattern is closer to that expected for a split dominated by pigeonite (Fig. 2b). A reduction by 1σ in the Tb value for ,699SM would lower it nearly to the value found in ,699LM and would make the calculated and observed patterns quite similar. It may also be possible to eliminate some of the discrepancy by a slightly different selection of distribution coefficients for olivine (a procedure that would also improve the fit to the 64435 data). The final set of distribution coefficients used will be that which provides the best fit to both the 64435 and 60025 data.

The data obtained thus far are consistent with the interpretation that the minerals in 60025,699SM are cumulus pigeonite and cumulus olivine crystallized from a liquid that had trivalent REE abundances similar to those in the equilibrium liquid of the 64435 troctolitic anorthosite. As has been indicated by other studies of ferroan anorthosites [3,5,6], the equilibrium liquid seems to have had a nearly flat chondrite-normalized pattern of the trivalent REE. This result supports hypotheses (such as the magma ocean theory) that the ferroan anorthosites crystallized from very primitive liquid(s) having nearly chondritic relative abundances of trivalent REE and resulting from melting of a large fraction of the Moon. Other analyzed separates from 60025 are currently being studied by the same techniques as 60025,699SM to refine our interpretation.

References: [1] McGee J.J., this vol. [2] James O.B. (1988) LPS XIX, 547. [3] James O.B., Lindstrom M.M. and Flohr M.K. (1989) PLPSC XIX, in press. [4] McKay G. et al. (1986) Geochim. Cosmochim. Acta 50, 927. [5] McKay G. (1982) LPS XIII, 493. [6] Palme H. et al. (1984) PLPSC 15, C3.

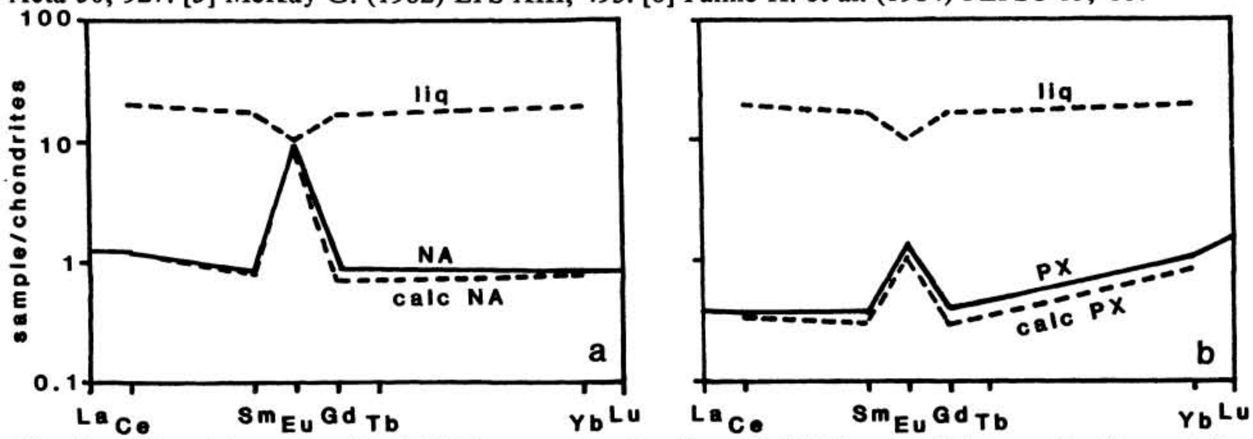

Fig. 1. Chondrite-normalized REE patterns of splits of 64435 troctolitic anorthosite and its equilibrium liquid (liq). INAA data shown by solid lines; calculated patterns shown by dashed lines. a) Actual and calculated compositions of whole-rock split NA. b) Actual and calculated compositions of mafic-mineral separate PX.

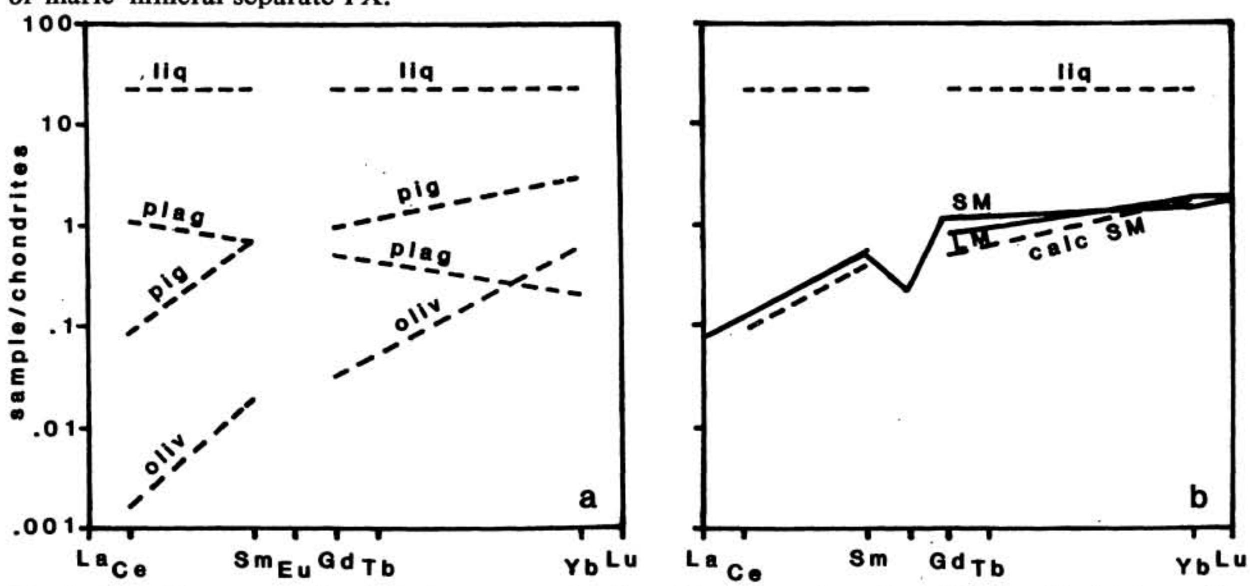

Fig. 2. Chondrite-normalized REE patterns of mafic splits, minerals, and equilibrium liquid for mafic anorthosite from 60025. INAA data shown by solid lines; calculated and assumed patterns shown by dashed lines. a) Compositions of minerals (pig = pigeonite; oliv = olivine; plag = plagioclase) calculated to be in equilibrium with assumed liquid (liq). b) Actual and calculated compositions of mafic-mineral split ,699SM and actual composition of mafic-mineral split ,699LM.