

**EVOLUTION OF THE MOON IN LIGHT OF EUROPIUM ANOMALIES AND ABUNDANCES OF LANTHANIDE AND OTHER LITHOPHILE TRACE ELEMENTS IN APOLLO RETURNED LUNAR SAMPLES.** John A. Philpotts, 11515 Catalpa Ct., Reston, Virginia 20191; j\_philpotts@yahoo.com

**Pre-Mission Research and Development:** The Apollo program has been a major boon to lunar science and associated fields commencing well before the first sample return and continuing to the present day. The prospect of working on lunar samples stimulated our small group at NASA/Goddard Space Flight Center to develop a technique for high quality determinations of lanthanide (REE) abundances in geologic samples by mass spectrometric isotope dilution [1], to determine a comprehensive set of mineral/melt partition coefficients for lanthanide and other lithophile trace elements (LTE) in rock forming minerals for use in quantitative modelling of igneous differentiation [2, 3], and to model generation of europium (Eu) anomalies in basalt owing to fractionation of plagioclase [4, 5], among other studies.

**Early Mission Analysis and Interpretation:** These preparations were opportune inasmuch as REE abundances were proved to be one of the more powerful tools for interpreting lunar igneous differentiation by many investigative teams (P. Gast, L. Haskin, R. Schmitt, among others). Further, negative Eu anomalies were found to characterize the basalts from Apollo 11 [6, 7] and every subsequent sample return mission. Based on the pronounced positive Eu anomaly observed in plagioclase/melt partition coefficients there seemed to be a reasonable possibility that the negative lunar basalt anomalies could be explained in terms of fractionation of feldspar during partial melting or crystallization events. Results from calculated  $\text{Eu}^{2+}$  and  $\text{Eu}^{3+}$  abundance estimates indicated that Eu anomalies should be larger for lunar samples than terrestrial samples, for similar type and extent of differentiation, likely due to more reducing conditions [8]. Supported by results from Surveyor VII, proposals were early made for the lunar highlands being created by flotation accumulation of plagioclase [9, 10]. Based on LTE data for partition coefficients and for mineral separate abundances that we obtained for each of the Apollo returns, such proposed highland material would be expected to have high enrichments of Eu, an expectation subsequently borne out by analyses of lunar anorthosites [11, 12]. Eu enrichments in the highlands appeared to offer a reasonable complement to Eu depletion in lunar basalts. However, whereas Eu anomalies in feldspathic basalts can be modified during melting or subsequent differentiation, many lunar basalts were reported to lack feldspar on the liquidus [13]. Such basalts cannot have been in equilibrium with a feld-

spathic residue or have been crystallizing feldspar. The difficulty was how then to account for their negative Eu anomalies. Due to this complication a number of investigators proposed that the Eu anomalies were due to minerals other than feldspar or to other processes. However, the apparent obstruction may have served as a clue to a better-informed understanding of lunar evolution. The lack of feldspar on the liquidus was a problem for a feldspar fractionation explanation of the Eu anomalies only if generation of the basalts were viewed as a single step process. However, some of the Apollo 11 and Apollo 12 basalts were noted to have REE abundance patterns appropriate to cumulates [6, 7, 14]. A multi-stage origin for at least the basalts lacking feldspar on the liquidus offered a solution to the problem. The basalts could have acquired their Eu-depletion from parental materials that were cumulates in prior, perhaps primordial, differentiation that did involve feldspar fractionation [6, 7, 14, 15]. Melting of cumulates also came under consideration by a number of other investigators based on different and various reasons [9, 10, 16, 17]. The cumulate melting scenario was also found to be generally consistent with a growing body of data reporting sample isotopic ages.

**Current Research:** Eu anomalies continue to hold promise for better understanding the evolution of the Moon. LTE abundances in lunar samples, like reported isotopic ages, are quantized to some extent by landing site. The survival of this quantization places limits on the amount of inter-site material exchange that can have occurred after emplacement of the igneous rocks. Most impact gardening appears to be localized in extent, an observation supported by the close compositional similarity of regolith, breccia, and igneous rocks within many individual sites. The clustering of ages for some landing sites further suggests consanguinity of melting events which would be expected to apply also for the compositional groupings. The author has argued for homogeneous accretion of the Moon based on the limited range observed for K/Ba abundance ratios [15]. If this is the case, lack of appropriate modes in LTE abundances appears to indicate that little if any primary material survived intact at the surface of the Moon. Complete melting and differentiation of at least the outer portions of the Moon or melting and intimate mixing of surface products via impact events, may have erased the primordial signature. This also relates to Eu anomalies. Based on anomalies observed in lunar samples, primordial lunar material may well have had the

same relative abundance of Eu as found in chondritic meteorites and many achondrites [7, 10]. Few lunar samples now show this relative abundance and many of those that do appear to have an excess of feldspar. However, data on mineral separates permit identification of a possible primary liquid descent line for lunar igneous rocks. Projection of compositional trends to Eu-anomaly values of zero may provide useful independent estimates of LTE concentrations in primordial lunar material and perhaps the bulk Moon.

**References:** [1] Schnetzler C.C. et al. (1967) *Analytical Chem.* 39, no. 14, 1888-1890. [2] Philpotts J.A. and Schnetzler C.C. (1970) *GCA* 34, 307-322. [3] Schnetzler C.C. and Philpotts J.A. (1970) *GCA* 34, 331-340. [4] Philpotts J.A. and Schnetzler C.C. (1968) *Chem. Geol.* 3, 5-13. [5] Philpotts J.A. and Schnetzler C.C. (1969) *Chem. Geol.* 4, 461-465. [6] Philpotts J.A. and Schnetzler C.C. (1970) *Sci.* 167, 493-495. [7] Philpotts J.A. and Schnetzler C.C. (1970) *Proc. Ap. 11 LSC* 2, 1471-1486. [8] Philpotts J.A. (1970) *EPSL* 9, no. 3, 257-268. [9] Anderson A.T., Jr., et al. (1970) *Sci.* 167, 587-590. [10] Wood J.A. et al. (1970) *Sci.* 167, 602-604. [11] Philpotts J.A. et al. (1973) *Proc. Fourth LSC, GCA Suppl.* 4, 2, 1427-1436. [12] Hubbard N.J. et al. (1971) *EPSL* 13, 71-75. [13] Ringwood A.E. and Essene E. (1970) *Proc. Ap. 11 LSC* 1, 769-799. [14] Schnetzler C.C. and Philpotts J.A. (1971) *Proc. Second LSC* 2, 1101-1122, MIT Press. [15] Philpotts J.A. et al. (1972) *Proc. Third LSC* 2, 1293-1305, MIT Press. [16] Gast P.W. et al. (1970) *Proc. Apollo 11 LSC* 2, 1143-1163. [17] Haskin L.A. et al. (1970) *Proc. Apollo 11 LSC* 2, 1213-1231.