ORIGIN OF APOLLO 15 OLIVINE- AND QUARTZ-NORMATIVE BASALTS

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Introduction: The Apollo 15 Mission to the Moon collected a large suite of low-Ti mare basalts. The whole-rock chemistries of these rocks led to their division into Olivine-Normative Basalts (**ONB**s) and Quartz-Normative Basalts (**QNB**s) [1,2]. The relationship of these two groups has been the subject of some debate. Are they directly related or do they represent melting of different sources in the lunar mantle? Chappell and Green [1], and Rhodes and Hubbard [2], using least-squares calculations, concluded that these basalts cannot be related by any process of near-surface fractional crystallization. Vetter *et al.* [3] added a significant number of trace-element analyses, new ONB and QNB compositions, and an intra-group classification system to these investigations. Many of the trace-element trends are similar in both rock types - the REE, Hf, Sm/Eu values all increase with decreasing MgO (Fig. 1). Still, many differences occur, made evident by the QNBs, such as near-constant Co concentrations and decreased Sc concentrations with decreasing MgO. However, a plot of La/Yb vs. Mg# (Fig. 2) shows there is a great deal of ambiguity in the chemistry of these rock types that needs to be addressed (i.e., the ONB-QNB division is not obvious).

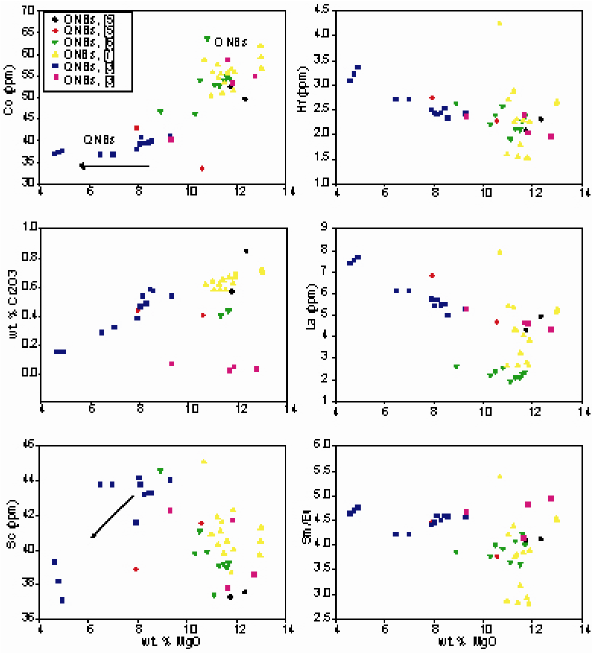

Fig. 1. Trace Element Variations in Apollo 15 Basalts, using MgO as a fractionation index, after [3].

In previous studies [1-3], primitive basalt compositions were considered to be representative of parental-magmas, however, based on fractionation trends this may not be accurate. The present study addresses the relationship of Apollo 15 ONBs and QNBs using whole-rock data, and an in-situ mineralogic approach (EMP + LA-ICP-MS), to understand the causes of chemical dispersion, and the relationships between these two groups. We have chosen to calculate a set of mineral-melt distribution coefficients (D) for the Apollo 15 basalts using a raster analysis of the quenched matrix of vitrophyric QNB 15499. These D-values, along with experimental D-values (e.g., [4]) can be used to calculate the parental-melt compositions of low-Ti mare basalts.

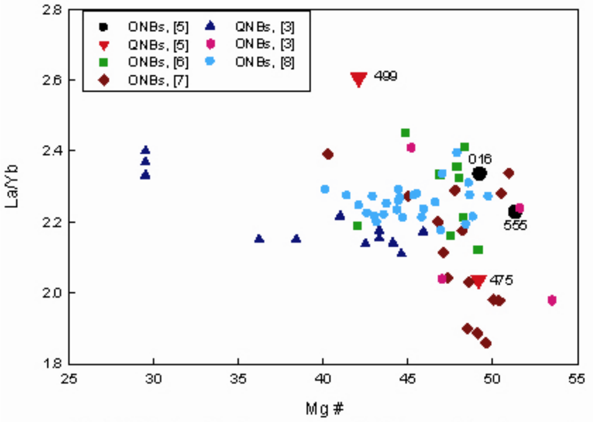

Fig. 2 Whole-Rock Data comparison of Olivine- and Quartz-normative basalts from past and present studies. Both basalt types trend from primitive to evolved compositions.

Methods: Mineral major-element compositions were measured using an automated CAMECA SX-50 electron microprobe (EMP). Mineral trace-element compositions were measured by LA-ICP-MS at the Australian National University, Canberra. Whole-rock major- and trace-element analyses are from Day *et. al* [5].

Results: Olivine-normative basalts possess olivine with Fo_{25-60}, and pyroxenes compositions ranging $Wo_{10-42}En_{10-59}Fs_{22-55}$. The QNBs have olivine compositions of Fo_{44-69}, and pyroxene in the range of $Wo_{5-40}En_{13-67}Fs_{25-43}$, consistent with previously published data [6,8]. Representative pigeonites from each of the basalt types have near-identical rare-earth-element (REE) patterns (Fig. 3). The overall abundances of REEs in the pyroxenes of QNBs are greater than that of the ONBs. Chapell and Green [1] have considered this to be due to a higher degree of partial melting of the QNB source compared to the mantle source of ONBs. The REE profile for the raster analysis (Fig. 4) is relatively flat compared with pyroxene analyses, and between 100 to 10×CI Chondrite.

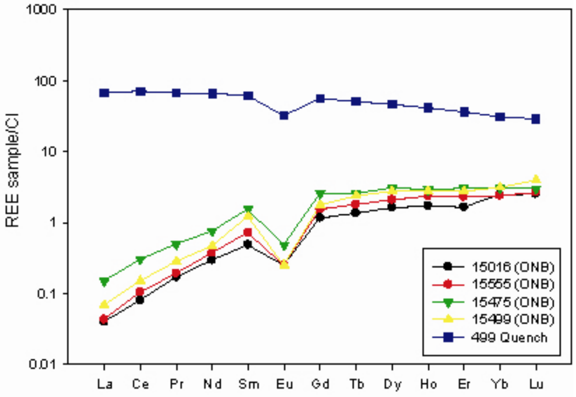

Fig. 3 Rare Earth Element patterns normalized to chondrite for representative pyroxenes from each basalt type. Data from a raster analysis of the quenched matrix in vitrophyre 15499 is also plotted.

We have also analyzed trace elements in plagioclase, olivine, spinel, and ilmenite in these rocks. The LREE abundances of plagioclase from both sets of rocks are generally ~1 x CI Chondrite. HREE abundances in plagioclase are generally below detection limits.

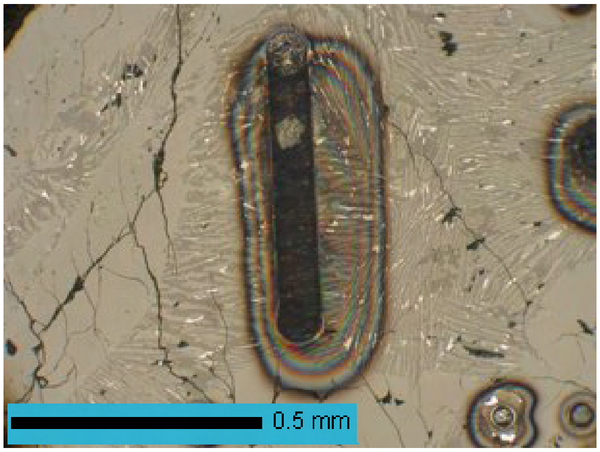

Fig. 4 Image showing the area of raster analysis of the quenched matrix of 15499.

Discussion: Apollo 15 ONB and QNB mare basalts have identical crystallization ages (~3.3±0.1 Ga [10,11,12]), and similar whole-rock and pyroxene rare-earth-element patterns. Analysis of photographs and astronaut's accounts of the western wall of Hadley Rille revealed the presence of three separate flows, with the ONBs overlying the QNBs [12]. Therefore, regardless of the genetic relations between these two basalt types, the ONBs must be younger than the QNBs.

Distribution coefficients were calculated using the general formula $D = Conc_{Px}/Conc_{Quenched\ Matrix\ of\ 15499}$. The distribution coefficients calculated by this method are in excellent agreement with those from Norman *et al.* [14] for Hawai'ian basalt glasses (Fig. 5).

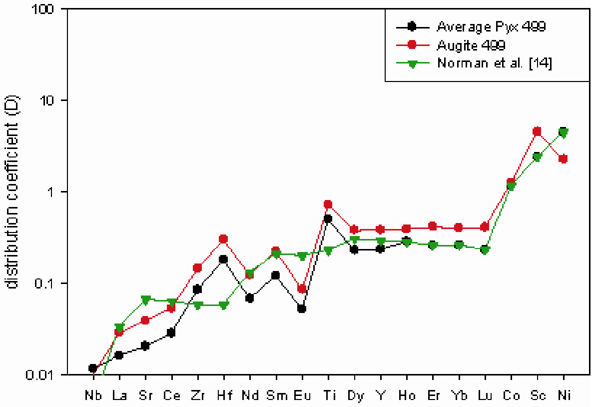

Fig. 5 Comparison of calculated distribution coefficient values with those of Norman et al. [14].

One set of D-values was calculated using an average composition for all the pyroxenes analyzed, the other from the composition of an augite. These calculated distribution coefficients enable successful modeling of parental-melt compositions for low-Ti basalts.

The large set of internally consistent LA-ICP-MS data for ONB and QNB samples reveals important new insight into their petrogenesis. On the basis of our ongoing studies, it is apparent that fractional crystallization is an significant factor in the origin of these basalts. However, the large range in whole-rock trace-element and isotope compositions (e.g., [5]) requires some inherent variation in their mantle sources. This study places important limitations on the degree of mantle source heterogeneity permissible, and suggests an important genetic relationship between QNBs and ONBs.

[1] Chappell, B. W. and Green, D. H. (1973) *Earth and Planet. Sci. Letters*, 18, 237-246; [2] Rhodes, J. M. and Hubbard, N. J. (1973) *Proc. Lunar Sci. Conf. 4th*, 1127-1148; [3] Vetter, S. K., Shervais, J. W. and Lindstrom, M. M. (1973) *Proc. Lunar Planet. Sci. Conf. XVIII*, 255-271; [4] McKay, G. (1986) *Geochim. Cosmochim. Acta.* 50, 69-79; [5] Day J.M.D. *et al.* (2006) *LPSC XXXVII*, this volume; [6] Ryder, G. and Steele, A. (1988) *Proc. Lunar Planet. Sci. Conf. XVIII*, 273-282; [7] Shervais J.W. *et. al.* (1990) *Proc. Lunar Planet. Sci. Conf. 20th*, 109-126. [8] Ryder, G., and Shuraytz, B. C. 2001, *Journal of Geophys. Research*, 106, 1435-1451; [9] Ryder G. (1985), *Catalog of Apollo 15 Rocks*, pp. 1296; [10] Nyquist, L. E., Shih, C. Y. 1992. *Geochim. Cosmochim. Acta*, 56, 2213-2234 [11] Snyder G.A. *et al.* 1997. *Lunar Planet. Sci. Conf. XXVIII*, 1347-1348; [12] Snyder G.A. *et al.* (1998) *Lunar Planet. Sci. Conf. XXIX*, abstract #1141; [13] ALGIT (1972) *Science*, *175*, 407-415; [14] Norman, M. D., Garcia, M. O. and Bennett, V. C. (2004) *Geochim. Cosmochim. Acta.*, 68, 3761-3777.