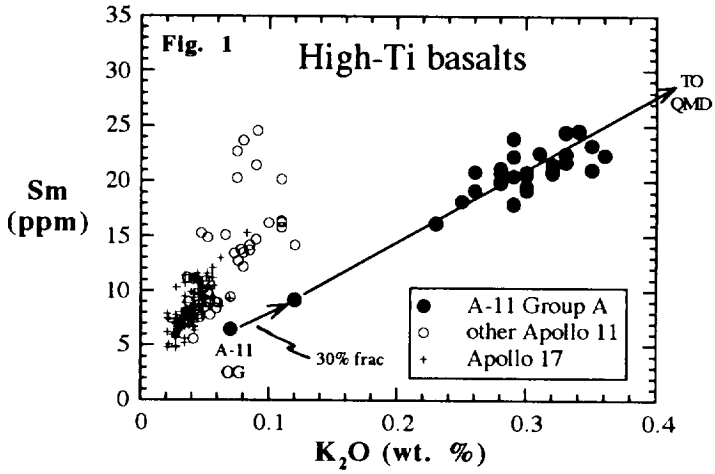
ON THE COMPOSITION OF *neu*KREEP: QMD CONTAMINATION AT APOLLO 11?

Eric A. JERDE, Gregory A. SNYDER, and Lawrence A. TAYLOR, Dept. of Geol. Sciences, University of Tennessee, Knoxville, TN 37996

APOLLO 11 GROUP A BASALTS: AN ANOMALOUS HIGH-Ti GROUP

The Group A basalts of Apollo 11 differ in many respects from other high-Ti basalts of the region. Chemically, they are the only high-K (> 2000 ppm K; [1]) variety of high-Ti basalt and are enriched in incompatible trace elements relative to other basalts from both the Apollo 11 and Apollo 17 sites (Fig. 1). In addition, Group A basalts are the youngest of all high-Ti basalts, with an age of 3.56 ± 0.02 Ga [2]. The cluster of compositions is consistent with the Apollo 11 Group A basalts representing a single flow (e.g., [3,4]). Papanastassiou et al. [5] have also indicated the uniqueness of these basalts, based particularly on relatively young Rb-Sr model ages (3.8 - 3.9 Ga). A model for the formation of the Group A basalts was presented by Jerde et al. [3,6], wherein the Apollo 17 orange volcanic glass is the parent liquid. Fractionation of this composition, coupled with the assimilation of incompatible-element-rich material, results in compositions akin to those of the Apollo 11 Group A basalt population. Orange glass of similar major-element composition is present at the Apollo 11 site as well [7], although complete trace element analyses are not available. New modelling results using the Apollo 11 orange glass major elements are grossly similar to those obtained using the Apollo 17 orange glass [e.g., 6], indicating ~30% fractionation (Table 1).



EVIDENCE OF KREEPy CONTAMINATION

Incompatible trace elements in Group A basalts were modelled by Jerde et al. [3], utilizing bulk partition coefficients calculated from the mineral assemblages indicated by fractionation calculations. The lack of trace-element data for the Apollo 11 orange glass precludes its use in modelling. However, the similarity in major-element composition of the Apollo 11 orange glass to that from Apollo 17 suggests that the trace elements follow suit (Delano, pers. comm.), and for the purposes of calculation, the Apollo 17 orange glass trace-element composition was used.

It is evident from the results (Table 1) that the incompatible-element abundances in Group A basalts are much too high (e.g., La = 26.5 ppm) to be explained by simple Rayleigh fractionation of the orange volcanic glass, which only leads to La = 8.8 ppm after 30% fractionation. The fact that K, P, and the REE are low in the calculated liquids suggests the addition of a KREEP component to obtain the basalts observed. In order to match the trace elements, ~20% of such a component (the high-K KREEP of Warren [8]) must be added, which would imply that the Apollo 11 Group A basalts are a young type of KREEP basalt. However, while this works chemically, isotopic considerations preclude it.

Table 1. Fractionation calculations.

	A11 OG	32% xtall'zd	10017
SiO_2	37.3	38.3	40.9
TiO_2	10.0	12.6	11.4
Al_2O_3	5.68	7.3	7.85
Cr_2O_3	0.63	0.12	0.35
FeO	23.7	23.9(21.3)	19.2
MnO	0.28	0.28	0.25
MgO	14.3	6.7(7.7)	7.78
CaO	7.62	10.2	10.4
Na_2O	0.31	0.43	0.49
K_2O	0.07	0.10	0.29
Total	99.89	99.93	98.91
La	6.2	8.8	26.7
Ce	19.0	26.9	80.1
Nd	17.8	25.2	65.6
Sm	6.5	9.2	21.0
Eu	1.8	2.55	2.26
Gd	8.5	12.1	(26.8)
Tb	1.65	2.34	4.63
Dy	9.4	13.3	30.9
Er	5.1	7.2	18.9
Yb	4.43	6.13	17.0
Lu	0.61	0.86	2.46

Oxides are in %, REE in ppm.
A-11 OG from [7].

Addition of 20% of an old KREEP component (~4.4 Ga with ε_{Nd} = -3 at 3.56 Ga) would overwhelm the LILE in the magma, yielding basalts with ε_{Nd} values <0. However, ε_{Nd} values of the Group A basalts of Apollo 11 fall in the range of +3 to +4. Therefore, any KREEPy assimilant could not have had an ε_{Nd} much less than +2 to +3. This KREEPy component must have been generated **after** complete crystallization of the LMO and represents the late-stage crystallization products of a magma melted from the depleted "adcumulate" mantle. However, such a late melting event must have occurred prior to the initiation of high-Ti basalt volcanism. We have termed the **post-LMO KREEPy component** which fits these parameters *neu*KREEP (new-KREEP) because of its young age relative to postulated *ur*KREEP (dregs of the LMO).

Table 2. neuKREEP.

		σ
La	164	10
Ce	504	34
Nd	377	21
Sm	110	6
Eu		
Gd	134	8
Tb	21.0	1.1
Dy	167	8
Yb	114	7
Lu	17.6	0.9
Hf	96.0	6.5
Ba	1375	128

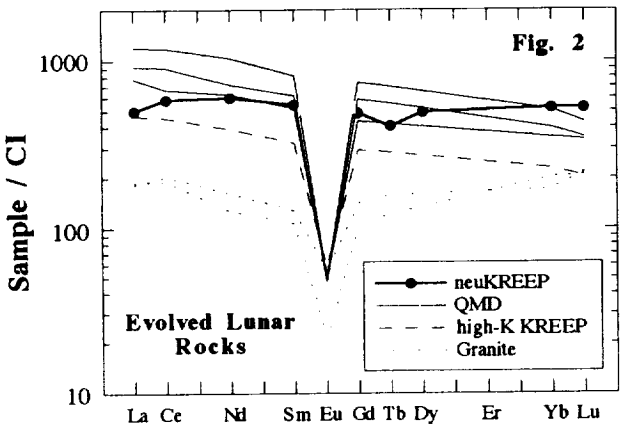
All concentrations are in ppm.

Mass-balance calculations were employed to determine a composition for *neu*KREEP from a set of twelve samples chosen from the suite of Group A basalts. These samples lie

along an assimilation line from the fractionated Apollo 11 orange glass composition through the array of Group A basalts (Fig. 1). Details of these calculations are given in Jerde et al. [6]. The results for some REE and other trace elements are given in Table 2. Approximately 7.5% (7.59 ± 0.18%) assimilation of *neu*KREEP is required to produce the baseline Group A basalt, and the entire array of Group A compositions can be generated by ~30% fractionation of the Apollo 11 orange glass coupled with 7.5 - 15% assimilation of *neu*KREEP with the composition in Table 2.

The major-element composition was determined through mass-balance using the assimilation values obtained from the REE. Sample 10017 was chosen as the target composition since it is a well-characterized Group A basalt. The trace-element abundances in 10017 indicate ~13% assimilation of the *neu*KREEP component, and the major elements were determined for *neu*KREEP using the mass-balance equation given above (Table 3).

COMPARISON OF *neu*KREEP WITH KNOWN LUNAR MATERIALS



The *neu*KREEP composition given in Table 2 and shown in Fig. 2 is more evolved than the postulated high-K KREEP composition given by Warren [8]. The major-elements are similar to those of the quartz monzodiorites (QMD) from Apollo 15 (e.g., [9]), although the chondrite-normalized REE slope is less than that of both high-K KREEP and QMD, more akin to some lunar granites (e.g., 73215c, 14321,1027 in [10]). The major-element composition given for *neu*KREEP is similar to that of QMD, suggesting that the Apollo 11 Group A basalts represent the fractionation product of a picritic glass along with the assimilation of a quartz monzodiorite component. The modelling is not as successful for Fe and Mg, with Fe overestimated and Mg underestimated in the fractionated orange glass, and not falling in the range of known lunar QMD. The fractionation program used for the calculations (MAGFOX; J. Longhi, pers. comm.) underestimates the K_d for olivine crystallization, using 0.26. If a more realistic K_d is used (i.e., 0.3), the Fe and Mg results match more closely (see the values in parentheses in Tables 1 and 3). Taking into account incomplete fractional crystallization and perhaps crystallization of some native iron and chromite may resolve remaining discrepancies in the composition of *neu*KREEP.

Warren et al. [10] noted the possibility that some lunar granites may be the late-stage remnants of younger, smaller intrusions formed through partial melting of the deep interior, which is essentially what we envisage as the origin of *neu*KREEP. Assuming that this melt, indeed, was originally derived from the depleted cumulate mantle and that it crystallized with a $^{147}Sm/^{144}Nd$ greater than, but similar to, KREEP (= 0.168), an age of 4.15 Ga can be calculated. This calculated model age is similar to the measured age (4.08 ± 0.07 Ga) of a KREEP basalt from Apollo 17 [11]. Furthermore, Shih et al. [11] suggested that other KREEPy rocks (including basalts, granites, troctolites, and norites) from various landing sites also may be cogenetic with this Apollo 17 KREEP basalt. This could further indicate that a Moon-wide melting event occurred at this time which fused only the most evolved rocks. Internal isochrons for granite 14321,1027 give ages of 4.09 ± 0.11 Ga and 4.11 ± 0.20 Ga from Rb-Sr and Sm-Nd, respectively [12], coinciding with our estimated age of *neu*KREEP of 4.15 Ga.

Table 3. neuKREEP major-elements.

	neuKREEP	QMD
SiO_2	60.0	(55)
TiO_2	2.6	2.6
Al_2O_3	11.9	11.9
Cr_2O_3	2.04	0.1-0.2
FeO	(3.8)	10.8-15.1
MnO	0.03	---
MgO	(8.4)	3.8
CaO	11.9	8.6- 11.3
Na_2O	0.9	0.79-1.01
K_2O	1.7	1.4-2.1

QMD values are from [9].

References:

[1] Neal C. R. and Taylor L. A. (1992) GCA, 56, 2177-2211; [2] Snyder G. A., Lee D.-C., Taylor L. A., Jerde E. A., and Halliday A. N. (1992) LPS XXIII, 1321-1322; [3] Jerde E. A., Snyder G. A., and Taylor L. A. (1992) LPS XXIII, 609-610; [4] Beaty D. W. and Albee A. L. (1980) Proc., LPSC, 11, 23-35; [5] Papanastassiou D. A., DePaolo D. J., and Wasserburg G. J. (1977) Proc., LPSC, 8, 1639-1672; [6] Jerde E.A., Snyder G.A., and Taylor L.A. (1992) In: Workshop on geology of the Apollo 17 landing site, [G. Ryder, H. H. Schmitt, and P. D. Spudis, ed.], LPI, Technical Report 92-09, 21-24; [7] Delano J.W. (1986) Proc., LPSC, 16, D201-D213; [8] Warren P. H. (1989) In: Workshop on Moon in transition: Apollo 14 KREEP, and evolved lunar rocks, [G. J. Taylor and P. H. Warren, ed.], LPI, Technical Report 89-03, 149-153; [9] Marvin U. B., Lindstrom M. M., Holmberg B. B., and Martinez R. R. (1991) Proc., LPSC, 21, 119-135; [10] Warren P. H., Taylor G. J., Keil K., Shirley D. N., and Wasson J. T. (1983) EPSL, 64, 175-185; [11] Shih C.-Y., Nyquist L. E., Bansal B. M., and Wiesmann H. (1992) EPSL, 108, 203-215; [12] Nyquist L., Shih C.-Y., Bansal B., Weismann H., and Wooden J. (1983) LPS XIV, 576-577.