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SEARCHING FOR *neu*KREEP: AN EMP STUDY OF APOLLO 11 GROUP A BASALTS

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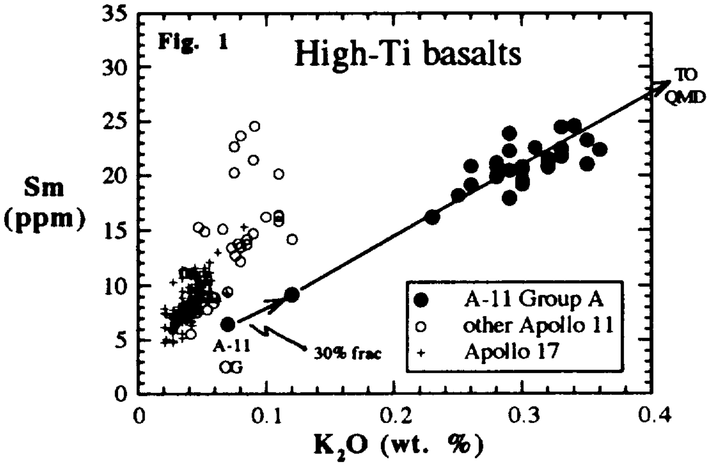
The Apollo 11 and 17 landing sites are characterized by the presence of high-Ti basalts (TiO2 > 6%). The Group A basalts of Apollo 11 have elevated K compositions (> 2000 ppm; [1]) and are enriched in incompatible trace elements relative to the other types of high-Ti basalt found in the region (Fig. 1). These unique basalts also are the youngest of all high-Ti basalts, with an age of 3.56 ± 0.02 Ga [2]. Recent modelling of the Apollo 11 Group A basalts by Jerde et al. [3] has demonstrated that this unique variety of high-Ti basalt may have formed through fractionation of a liquid with the composition of the Apollo 11 orange glass, coupled with assimilation of evolved material (dubbed *neu*KREEP, and having similarities to lunar quartz monzodiorite). Assimilation of this material would impart its REE signature on the liquid, resulting in the elevated REE abundances observed. Minerals such as whitlockite which contain a large portion of the REE budget can be expected to reflect the REE characteristics of the assimilant. To this end, an examination of the whitlockite present in the Apollo 11 Group A basalts was undertaken to search for evidence of the *neu*KREEP material assimilated.

THE NATURE OF *neu*KREEP

The evolved *neu*KREEP component must have been generated after complete crystallization of the LMO and represents the late-stage crystallization product of a magma melted from the depleted "adcumulate" mantle. 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** [4]. This calculated model age is similar to the measured age (4.08 ± 0.07 Ga) of a KREEP basalt from Apollo 17 [5]. Furthermore, Shih et al. [5] 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.



The composition calculated for this evolved component [3] is similar to that of the quartz monzodiorites (QMD) summarized by Marvin et al. [6] from Apollo 15 (Table 1), although with a chondrite-normalized REE slope that is shallower than that of the previously described QMD's. It is envisaged that such material was assimilated into a magma of Apollo 11 orange glass composition undergoing fractionation. Approximately 7.5% 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 7.5 - 15% assimilation of *neu*KREEP with the composition in Table 1. The major-element composition (Table 1) was determined through mass-balance using the assimilation values obtained from the REE.

However, no rocks akin to QMD have been recognized in the material returned from the Apollo 11 site. Assimilation of QMD-like material with the composition of *neu*KREEP would greatly increase the REE abundances in the liquid, imparting the REE signature of *neu*KREEP to the magma. We have undertaken a search for REE-rich phases (namely whitlockite and apatite; no zircons were found) in the Apollo 11 Group A basalts. Since whitlockite will hold the majority of the REE, the chondrite-normalized patterns can be expected to reflect those of the liquid in which it crystallized.

For this search, Apollo 11 Group A basalts with high abundances of REE were chosen since these would likely harbor the greatest amounts of whitlockite. The mesostases of these rocks were examined for the presence of phosphates using the electron microprobe (EMP), which was also used to analyze the observed grains. Counting times of 60 seconds were used for the REE during analysis to enhance the counting statistics. REE oxides analyzed in the whitlockites are all present in amounts >0.3 wt.%. In apatite, the most abundant REE analyzed (Ce) was present in amounts only ~0.3 wt.%. Due to the low REE abundances in apatite, we concentrated mainly on whitlockite in our analyses.

Table 1. neuKREEP

SiO_2	60.0
TiO_2	2.6
Al_2O_3	11.9
Cr_2O_3	2.04
FeO	---
MnO	0.03
MgO	---
CaO	11.9
Na_2O	0.9
K_2O	1.7
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

Oxides in percent, all others are in ppm.

QMD values are from [5].

WHITLOCKITE CHARACTERISTICS

The majority of the phosphates are small and irregular, with the greatest dimension being approximately 50 μm. However, the grains are seldom more than 10 μm wide. In many cases, the grains are composite with both whitlockite and apatite forming portions with sharp interfaces between the two minerals. Examples of apatite rods with whilockite ends and whitlockite rods with apatite ends both exist. Zoning is also common, with some grains exhibiting order-of-magnitude variations in REE abundance, essentially varying from apatite to whitlockite. Where strong zoning exists, we utilized the high-REE analyses from the zoned grains for our discussion.

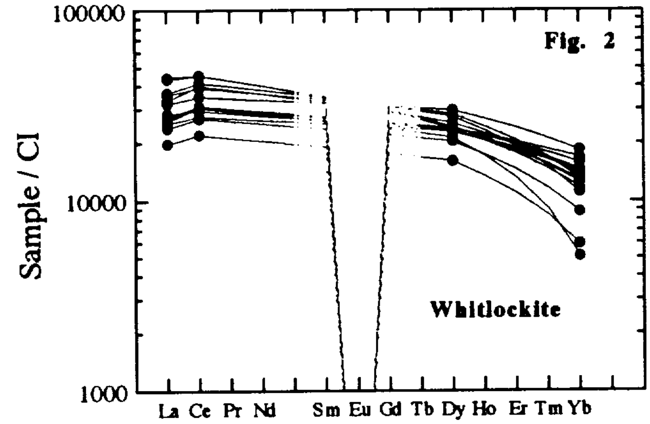


Fig. 2

Whitlockite REE patterns obtained for three Apollo 11 Group A basalts are shown in Fig. 2. While outwardly similar to REE patterns for whitlockite from other lunar basalts, the whitlockite in Apollo 11 Group A basalts generally has a shallower chondrite-normalized REE pattern. Chondrite-normalized Ce/Dy ratios in whitlockites from lunar basalts tend to be >1.7 (data in Neal and Taylor [7]), while in our "Group A" whitlockites, the normalized Ce/Dy ratios are usually <1.6. This suggests that the liquid from which the Apollo 11 whitlockite crystallized had a shallower slope as well, relative to other lunar basalts. Indeed, the calculated *neu*KREEP composition (Table 1; [3]) has a shallower REE slope than other evolved materials such as KREEP. Assimilation of *neu*KREEP would dominate the REE budget and, presuming constant partition coefficients, whitlockite forming from the *neu*KREEP-dominated liquid would be expected to have a shallower REE slope than that crystallizing from a KREEP-dominated liquid.

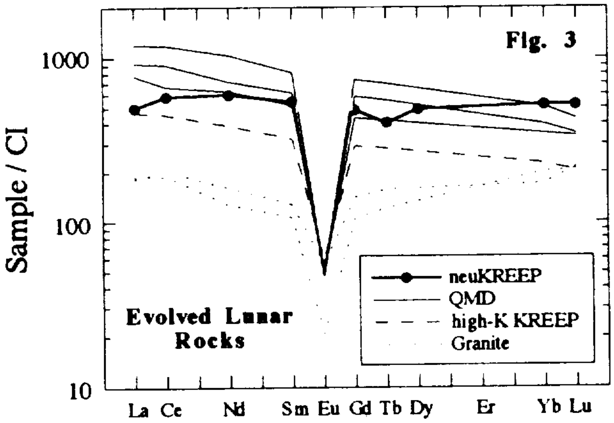


Fig. 3

An additional feature present in the whitlockites analyzed from the Apollo 11 Group A basalts is the "kink" (reversed slope) in the pattern at Ce (Fig. 2), the result of a slight depletion in La. A pronounced kink is not characteristic of whitlockites in basalts from other missions (e.g., [7]), or in other whitlockite analyzed by our group (e.g., [8]), but is present in all analyzed to date from Apollo 11 Group A basalts. The calculated ***neu*KREEP** material (Fig. 3) is slightly depleted in La, resulting in a **similar kink in the REE pattern at** Ce. This suggests a link between the supposed *neu*KREEP composition and the whitlockites actually observed in the basalts. This high point at Ce is akin to, although smaller than, the positive Ce anomalies observed in some zircons due to preferential takeup of Ce^{4+} in the mineral (e.g., [9]). However, no similar Ce peak is seen in other lunar whitlockites, and it is unlikely that sufficient oxidizing conditions existed in the lunar environment to create significant amounts of Ce^{4+}.

***neu*KREEP is more evolved than the postulated high-K KREEP composition** given by Warren [10], with the major-elements similar to those of quartz monzodiorites from Apollo 15 (e.g., [6]). The chondrite-normalized REE slope is less than that of both high-K KREEP and the quartz monzodiorites, however, pointing to slightly different material. The subtle differences in whitlockite compositions in the Apollo 11 Group A basalts relative to whitlockites from other lunar basalts suggest a connection to the calculated *neu*KREEP component, additional evidence for the existence on this new lunar component.

References:

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