Metasomatic products of the lunar magma ocean: The role of KREEP dissemination

CLIVE R. NEAL and LAWRENCE A. TAYLOR

Department of Geological Sciences, University of Tennessee, Knoxville, TN 37996, U.S.A.

Abstract—The origin of the incompatible element-rich lunar component, KREEP, is in the Lunar Magma Ocean (LMO). The fractionated residual melt after crystallization of the LMO represents "urKREEP" (after WARREN and WASSON, 1979). The percentage of this residual melt is low enough to be within the realm of silicate liquid immiscibility (SLI). This process has the ability to split the KREEP signature into K- and REEP-Fractions, which are manifest as lunar granite (K) and phosphate phases present in highland lithologies or as quartz ferrotroctolite in lunar soils (REEP). We envisage this as a localized, but significant process since only a small portion of urKREEP undergoes SLI. Norms of experimental and Apollo 15 basaltic immiscible glasses suggest that the REEP-Fraction found in the lunar highlands has undergone post-SLI fractionation of at least fayalite. This significantly reduces the density of the REEP-Fraction and coupled with its low viscosity (10–15 poise), it can percolate upward, metasomatizing the lunar crust. The higher viscosity of the granitic melt (≅30000 poise) inhibits its mobility, and it forms "pods" in the lower crust (as required for VHK basalt petrogenesis).

With the identification of KREEPy components, the composition of urKREEP can be calculated. Using experimental evidence, the KREEP components may be recombined to give the pre-SLI composition, or liquid-liquid Kd's can be used to calculate a pre-SLI composition from lunar granite. Both calculated urKREEP compositions are lower in MgO and Al_2O_3 and higher in FeO and P_2O_5 than reported low- and high-K KREEP compositions. The calculated REE abundances are higher and the REE profiles are slightly more LREE-enriched than the previously reported KREEP compositions. However, the REE profile calculated using liquid-liquid Kd's is concave-upwards, compared to the LREE-enriched profile produced by recombining the KREEP components. Pre-SLI whitlockite/apatite fractionation occurred prior to immiscibility in order to generate the concave-upwards profile. The LREE-enriched profile represents the pre-SLI magma *prior* to phosphate fractionation. The presence of "superKREEPy" rock types can be accounted for by K- and REEP-Fraction assimilation, and the compositions of olivine vitrophyres can now be modeled using analyzed lunar rock types without the inference of a mythical "high-Mg" component.

Other, more widespread KREEPy rocks (*e.g.*, Apollo 14 breccias, Apollo 15 KREEP basalts, LKFM basalts) are produced by incorporation of the more widespread pre-SLI urKREEP component. The splitting of KREEP into identifiable lithological components allows the petrogenesis and role of KREEP in lunar evolution to be better understood.

INTRODUCTION

THE PETROGENESIS OF a widespread lunar component which is enriched in incompatible elements has been the subject of lively debate since the early 1970's. This component was first identified by MEYER and HUBBARD (1970) in Apollo 12 soils. Subsequently, it was given the acronym "**KREEP**" (HUBBARD *et al.*, 1971; MEYER *et al.*, 1971) to account for its elevated K, rare-earth element (REE), and P contents. Occurrences of KREEP have been documented from every landing site (*e.g.*, APOLLO SOIL SURVEY, 1971). Furthermore, a KREEPy component has been found in basalts (*e.g.*, IRVING, 1977; RYDER, 1987; SALPAS *et al.*, 1988; NEAL *et al.*, 1988a) and breccias (*e.g.*, McKAY and WEILL, 1977; SALPAS *et al.*, 1987), as well as soils (*e.g.*, MORRIS *et al.*, 1977; KOROTEV, 1981). It is interesting to note that a terrestrial analogue to KREEP may be found in kimberlites, which are considered to be the products of mantle melting and metasomatism (*e.g.*, WYLLIE, 1980).

There are two basic models proposed for the generation of KREEP, based upon the Lunar Magma Ocean hypothesis (LMO): 1) partial melting of an "ANT-suite" (Anorthosite, Norite, Troctolite) cumulate (*e.g.*, WALKER *et al.*, 1972; PRINZ *et al.*, 1973; NAVA and PHILPOTTS, 1973); or 2) as a residual magma after extreme fractional crystallization (*e. g.*, DOWTY *et al.*, 1976; SHIH, 1977; WARREN and WASSON, 1979; WARREN, 1985). As an offshoot of model 2), CRAWFORD and HOLLISTER (1977) suggested that the residual magma underwent liquid immiscibility, forming granitic and

high-Fe, KREEPy melts. WARREN and WASSON (1979) demonstrated that KREEP-normalized trace element patterns for a variety of "KREEPy" materials from different localities were essentially flat (*i.e.*, constant trace element ratios). They argued that this indicated a uniform, almost Moon-wide KREEP reservoir and concluded that KREEP could not be produced by partial melting. Based on this evidence, WARREN and WASSON (1979) argued for KREEP to be the residual from the LMO. They used the German prefix "ur" (meaning primeval) to describe KREEP produced in this way.

However, while we accept the essential features of WARREN and WASSON's (1979) model for urKREEP petrogenesis, we do not believe that it goes far enough in explaining many KREEP-related phenomena. For example, the geochemical modelling developed to account for the observed compositions of soils, breccias, and olivine vitrophyres (impact melts) requires the mixing of *three* major components by meteorite impact: anorthosite, KREEP, and a high-Mg rock-type (*e.g.*, WÄNKE *et al.*, 1976; WASSON *et al.*, 1977; ALLEN *et al.*, 1979; KOROTEV *et al.*, 1980; SHERVAIS *et al.*, 1988). It is well established that the lunar highlands are dominated by anorthosite, troctolite, and norite, but it appears that these lithologies cannot account for the high MG# of soils, breccias, and especially olivine vitrophyres (*e.g.*, WASSON *et al.*, 1977; SHERVAIS *et al.*, 1988). This is because *50 to 90% of a KREEP component* is required by such models *in order to generate the observed incompatible element abundances*. However, such large quantities of KREEP serve to greatly reduce the Mg content of the mixture. Therefore, in order to generate
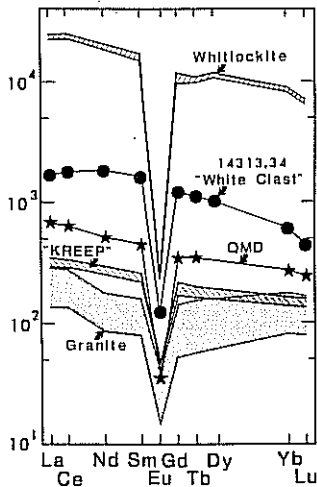
FIG. 1. Chondrite-normalized plot demonstrating the REE profiles and relative abundances of lunar granite (WARREN et al., 1983b, 1987; BLANCHARD et al., 1977; QUICK et al., 1977), high-K KREEP (WARREN and WASSON, 1979; VANIMAN and PAPIKE, 1980), the Quartz Monzondiorite (RYDER and NORMAN, 1978), the 14313,34 "white clast" (HASKIN et al., 1973), and whitlockites in highland samples (LINDSTROM et al., 1985).

the MG# of olivine vitrophyres, a "mythical" high-Mg component is required, such as "primary matter" (WÄNKE et al., 1976, 1977), "SCCRV" (WASSON et al., 1977), "MAF" (KOROTEV et al., 1980; KOROTEV, 1981), and "MAF-14" (SHERVAIS et al., 1988), depending on the designated model. Yet, these "high-Mg" components have not been observed in the lunar sample returns.

The existence of "super-KREEPy" rocks (Fig. 1) also is difficult to explain, even with the high-K KREEP composition defined by WARREN and WASSON (1979). The generally quoted range of high-K KREEP REE abundances (see WARREN and WASSON, 1979) is below that of the Apollo 15 quartz monzodiorite (RYDER, 1976; TAYLOR et al., 1980) and the "white clast" 14313,34 (HASKIN et al., 1973; SHIH et al., 1985). Although the "white clast" may be an unrepresentative sample of alkali norite (WARREN et al., 1983a), it has been demonstrated that the quartz monzodiorite cannot be generated from the high-K KREEP compositions by fractional crystallization or silicate liquid immiscibility (TAYLOR et al., 1980; NEAL and TAYLOR, 1988a).

A further problem in constraining KREEP petrogenesis is the difficulty in defining a pure, unadulterated KREEP composition. A consensus of opinion has emerged with regard to the petrogenesis of KREEPy samples, especially KREEP basalts. KREEP basalts may be either volcanic in origin (e.g., MEYER, 1972; BASU and BOWER, 1976; RYDER, 1976; DOWTY et al., 1976; IRVING, 1977; RYDER, 1987) or the product of an impact melt (e.g., SHIH, 1977; McKAY et al., 1978, 1979; TAYLOR, 1982; RYDER and SPUDIS, 1987). There is an inverse correlation between MG# and incompatible element concentration in KREEP basalts (SHIH, 1977), the opposite of what one would expect from a petrogenesis by fractional crystallization. WARREN and WASSON (1979), RYDER (1987), and WARREN (1988) concluded that the dichotomy between major and trace elements in KREEP basalts is due

to the incorporation of a possible urKREEP component into the basaltic signature during magma petrogenesis. DOWTY et al. (1976) suggested the reverse scenario. These authors used model and crystallization ages (i.e., ≅4.4 and 3.9 Ga, respectively) of a KREEP basalt to suggest the KREEP residual from the LMO crystallized in the ANT-dominated crust at ≅4.4 Ga. This primary KREEP was remelted at ≅3.9 Ga (due to the high concentration of Th, U, and K in KREEP), incorporating some of the Mg-rich ANT (Anorthosite-Norite-Troctolite) crust. HUBBARD and MINNEAR (1976) suggested that KREEP-rich liquids equilibrated with lower crustal materials which were highly depleted in incompatible elements, thus generating KREEP basalts. Whatever the intricacies of the process, the fact remains that practically all KREEPy samples are not pure KREEP.

The purpose of this paper is to extend the "urKREEP hypothesis" of WARREN and WASSON (1979) and WARREN (1985), by defining KREEP as specific (i.e., constrained) lunar components. These components are then used to demonstrate the petrogenesis of the "super-KREEPy" rocks present on the Moon. The modelling of olivine vitrophyre compositions is also undertaken, utilizing the defined components of KREEP. Since current KREEP compositions have been derived by various degrees of contamination of basaltic magmas by urKREEP, existing models for olivine vitrophyre petrogenesis have not used a pure KREEP component.

SUMMARY OF THE urKREEP HYPOTHESIS

The urKREEP hypothesis of WARREN and WASSON (1979) described the primary reservoir of KREEP as being the residual liquid (i.e., urKREEP) from the LMO. In an elegant description, these authors demonstrated that KREEP-normalized REE patterns of KREEPy materials exhibited little fractionation. In fact, the La/Lu ratio varied by <10%. Modelling of KREEP trace element profiles by partial melting of an "ANT suite" source yielded a ±20 to 25% variation in La/Lu ratio. Therefore, WARREN and WASSON (1979) suggested that the origin of KREEP by partial melting was unlikely. They concluded, from flat, unfractionated, KREEP-normalized trace element patterns of KREEPy materials, that a single major source was required. As such, this source must be able to provide KREEP to widely separate locations. This condition is satisfied by using the residual magma after fractionation of the LMO. This hypothesis is supported by LUGMAIR and CARLSON (1978) and HUGHES and SCHMITT (1985), who concluded that the narrow range of Sm-Nd evolutionary paths and the narrow range in Zr/Hf ratios in diverse KREEPy samples indicated a single KREEP source. The thickness of the urKREEP layer was <2 km, assuming the Moon had the composition of an H-group chondrite, depleted in Fe-Ni and FeS, and that half the incompatibles went into other phases apart from urKREEP (WARREN and WASSON, 1979; WARREN, 1985). In other words, the LMO residual or urKREEP represents ≅0.2% of the Moon and 0.5% of a 400 km deep magma ocean. However, the high MgO contents (10.62 wt%) and MG# (64.1) of the high-K KREEP composition reported by WARREN and WASSON (1979) is not consistent with it being the residual magma after ≅99% proposed fractionation of the LMO (WARREN, 1985), demonstrating that it is not pure KREEP.

ISOTOPIC CONSTRAINTS

The use of isotopes in constraining igneous fractionation and crystallization events is invaluable. The Rb-Sr, U-Pb, ^{39}Ar-^{40}Ar, and Sm-Nd isotope systematics for KREEP samples give similar results. Rb-Sr and Sm-Nd model ages generally cluster around 4.4 Ga (PAPANASTASSIOU and WASSERBURG, 1971; NYQUIST et al., 1972, 1973, 1974; SHIH, 1977; LUGMAIR and CARLSON, 1978; McKAY et al., 1979). In addition, the U-Pb data suggest that a major primary dif-

ferentiation occurred at ≅4.42 Ga, and another event opened the U-Pb system at ≅3.9 Ga (TERA and WASSERBURG, 1974).

The Rb-Sr and Sm-Nd *crystallization ages* yield 3.9 Ga (*e.g.*, MCKAY and WEILL, 1976; SHIH, 1977; LUGMAIR and CARLSON, 1978), which are roughly consistent with ages obtained by the ^{39}Ar-^{40}Ar method (*e.g.*, TURNER et al., 1973; SETTLER *et al.*, 1973). The initial isotopic ratios for individual KREEP samples are different at 3.9 Ga, but converge at 4.4 Ga. Furthermore, LUGMAIR and CARLSON (1978) demonstrated that KREEP samples have consistently negative C_{JUV} at 3.9 Ga. This indicates that the characteristic LREE-enriched pattern of KREEP was well established before this time, and led to the proposal of a single source for KREEP which formed at ≅4.4 Ga and underwent a significant remobilization at 3.9 Ga (*e.g.*, DOWTY *et al.*, 1976; SHIH, 1977; LUGMAIR and CARLSON, 1978). The nature of this 3.9 Ga remobilization event is considered to be the remelting of urKREEP (as this has concentrated U, Th, and K) and its extrusion (*e.g.*, DOWTY *et al.*, 1976) or the resetting of the isotopes by intense meteorite bombardment during the Imbrium basin-forming event (*e.g.*, TERA *et al.*, 1974). It is probable that a combination of these two processes accounts for the 3.9 Ga crystallization age.

IDENTIFICATION OF KREEP COMPONENTS

The dichotomy between major and trace elements in KREEP basalts highlights the problem of identifying a pure, pristine KREEP composition. Therefore, we have attempted to reduce the effect of contamination by *identifying possible KREEP components*. In order to do this, the *KREEP signature* must first be clarified. As suggested by its name, KREEP contains high abundances of K, P, and the REE. It has an LREE-enriched profile (*e.g.*, LUGMAIR and CARLSON, 1978; WARREN and WASSON, 1979), with a La/Lu ratio of 22 to 25 and a high concentration of incompatible elements. Therefore, a *KREEPy component* must contain one or more of these signatures.

The samples returned from the Moon include only one rock type which contains potassium in quantities greater than 2 wt% K_2O, and that is lunar granite (*e.g.*, BLANCHARD *et al.*, 1977; BLANCHARD and BUDAHN, 1979; WARREN *et al.*, 1983b, 1987). However, lunar granite contains lower REE abundances relative to the high-K KREEP composition (Fig. 1) of WARREN and WASSON (1979). Furthermore, the extremely high K/P ratios and low P_2O_5 abundances of lunar granite (relative to high-K KREEP) indicate that it cannot be a sink for phosphorus. Therefore, although a concentration of K can be accounted for in lunar granite, another component, enriched in P and the REEs above the high-K KREEP composition, is required. Likely candidates for part of this component are the highly evolved phosphates (whitlockite and apatite) which are present in primitive, Mg-rich highland lithologies (SHERVAIS *et al.*, 1984; LINDSTROM *et al.*, 1984). These phosphates (Fig. 1) are highly enriched in the REE → 10,000 times chondrite (LINDSTROM *et al.*, 1985).

While lunar granite and phosphate contain the essential elements for a KREEP signature, can they really be related to urKREEP? Some lunar granites contain phosphate phases (*e.g.*, WARREN *et al.*, 1983b), but phosphates found in primitive lunar highland lithologies are usually solitary or associated with minor plagioclase (LINDSTROM *et al.*, 1984; SHERVAIS *et al.*, 1984). It is generally regarded that lunar granite is a product of silicate liquid immiscibility (SLI: HESS *et al.*, 1975; RUTHERFORD and HESS, 1975; RUTHERFORD *et al.*, 1976; NEAL and TAYLOR, 1989). This led NEAL and TAYLOR (1988a) to conclude that *granite forms the K-Frac-*

tion of KREEP (high-SiO$_2$ melt produced by SLI) and the *apatite/whitlockite seen in the lunar highlands represents part of the REEP-Fraction* (high-Fe and PO$_4$ melt produced by SLI).

Compositions of both granitic and ferrobasaltic immiscible melt products of SLI have been analyzed from experiments (RUTHERFORD *et al.*, 1974; HESS *et al.*, 1975) and directly from the residual glasses of Apollo 15 mare basalts (*e.g.*, WEIBLEN and ROEDDER, 1973). Major element analyses of these immiscible melts are presented in Table 1, with the calculated norms. Because of the extreme compositions, CIPW norms would not be meaningful. Rather, the elemental abundances were converted to mole%, and normative mineralogies calculated stochiometrically (*i.e.*, one mole of FeO and one mole of TiO$_2$ in ilmenite). The results are interesting in that these extremely different bulk compositions have the same normative mineralogies but in different proportions. This observation supports the contention of HESS *et al.* (1978), demonstrating that the immiscible melts are in equilibrium with each other. Only when they have been separated will independent evolution occur. Furthermore, the ferrobasaltic assemblage (the quartz ferrotroctolite) reported by LU *et al.* (1989) may be further evidence of the presence of SLI products on the Moon. Although the quartz ferrotroctolite clast may be a nonrepresentative sample of a VLT basalt, it is too coarse-grained for a mesostasis assemblage (LU *et al.*, 1989). This clast consists of fayalite, ilmenite, plagioclase, and quartz and is considered to represent the REEP assemblage, consistent with the calculated normative mineralogy.

Normative mineralogies for the K-Fraction or granitic immiscible melt (Table 1) closely resembles observed lunar granite compositions (*e.g.*, WARREN *et al.*, 1983b, 1987; SHERVAIS and TAYLOR, 1983; SALPAS *et al.*, 1985). The presence of phosphate in the crystallized granitic melt was predicted by DICKENSON and HESS (1982, 1983), who concluded that the required level for phosphate saturation was much lower in a granitic melt (≅ half) than in a basaltic melt.

Table 1: Compositions with calculated norms and viscosities of analyzed immiscible melt glasses from experiments (Hess et al., 1975) and lunar basalts (Weiblen and Roedder, 1973).

	EXPERIMENTAL		BASALTIC	
SiO$_2$	74.3	38.4	75.6	44.6
TiO$_2$	0.70	3.10	0.60	3.25
Al$_2$O$_3$	11.1	6.73	11.6	4.82
FeO	6.86	33.1	3.17	32.4
MgO	0.05	0.51	0.04	1.67
CaO	2.07	11.3	1.46	11.4
Na$_2$O	0.42	0.17	0.29	<0.03
K$_2$O	4.17	0.57	7.26	0.19
P$_2$O$_5$	0.22	4.76	0.10	1.50
TOTAL	99.89	98.64	100.12	99.03
Or	21.4	2.3	36.6	0.8
Ab	3.1	1.0	2.1	0.2
An	7.0	15.5	3.8	4.4
Ilm	1.2	4.1	1.0	4.4
En	0.1	0.9	0.1	2.9
Wo	0.5	8.1	0.9	13.0
Fa	15.4	59.4	6.4	59.2
Phos	0.5	19.3	0.2	3.0
Qz	50.9	9.6	48.9	12.1
Viscosity (n)[*]	30,031	11	28,582	15

[*] calculations based upon the method of Bottinga and Weill (1972).

THE PROCESS OF SILICATE LIQUID IMMISCIBILITY

In the past, silicate liquid immiscibility has been a much maligned igneous process. However, since the discovery of granite in the essentially basaltic lunar environment, SLI is becoming accepted as a feasible geological process. Silicate liquid immiscibility splits a highly fractionated magma into a granitic (*i.e.*, K-Fraction) and a ferrobasaltic (*i.e.*, REEP-Fraction). This process is the only practical way granite can be formed from a basaltic parent without the generation of intermediate rock types (RUTHERFORD *et al.*, 1974; RUTHERFORD and HESS, 1975; HESS *et al.*, 1975, 1978). *The importance of SLI is that it can effectively split the KREEP signature into K- and REEP-Fractions* (NEAL and TAYLOR, 1988a).

The occurrence of immiscibility in magmas was discovered by ROEDDER (1951) at geologically feasible temperatures (1000–12000°C) in the system SiO_2-K_2O-FeO-Al_2O_3 (Fig. 2). The immiscibility field expands with addition of FeO until ≅43% FeO, after which it decreases (ROEDDER, 1978). The immiscibility field also increases with fO_2 (NASLUND, 1976) and CO_2-free total pressures of 1 to 5 Kb (WATSON and NASLUND, 1977).

Immiscibility only occurs after 90 to 98% fractionation, based upon experiments to determine the effects of extreme fractional crystallization (RUTHERFORD *et al.*, 1974; RUTHERFORD and HESS, 1975; HESS *et al.*, 1975; 1978) and the observations of ROEDDER and WEIBLEN (1970, 1971) and WEIBLEN and ROEDDER (1973). HESS *et al.* (1975) concluded that the fractionation path required for ultimate immiscibility of the residual is very similar to the "Fenner trend" (*i.e.*, concentration of Fe into the residual without significant silica enrichment). In addition, these authors also concluded that under conditions of low oxygen fugacity (such as in a lunar environment), there is a "thermal valley" which leads residual magmas towards Fe enrichment (*i.e.*, a ferrobasaltic composition). Furthermore, this type of fractionation does not produce intermediate rock types between basalt and granite.

The process of silicate liquid immiscibility entails preferential partitioning of certain elements into the respective melts. Whether an element is largely partitioned into the granitic or ferrobasaltic melt depends on the charge density of

the element and the polymerization of the respective melt (RYERSON and HESS, 1978). Highly charged cations (REE, Ti, Mn, P, U, Th, Zr, Hf, Sr, Y) are enriched in the ferrobasaltic melt. The ferrobasaltic melt is relatively depolymerized due to its low Si/O ratio (RYERSON and HESS, 1978). The granitic melt is highly polymerized (*e.g.*, KUSHIRO, 1975; RYERSON and HESS, 1978), and its melt structure can accommodate Al^{3+} in the tetrahedral sites in co-polymerization with Si^{4+}. This produces a local charge imbalance which is satisfied by a coupled substitution of alkalis. As such, Si, Al, Na, K, Rb, and Cs are enriched in the granitic immiscible melt (HESS and RUTHERFORD, 1974; HESS *et al.*, 1975; RYERSON and HESS, 1978). The partitioning of Ba may be into either the ferrobasaltic or granitic immiscible melts (NEAL and TAYLOR, 1989). If the molar (K + Na + Ba + Ca)/Al ratio is >1, Ba is partitioned into the ferrobasaltic melt; if this ratio is <1, Ba is partitioned into the granitic melt (NEAL and TAYLOR, 1989).

There is concrete evidence for the granitic melt portion of SLI (*i.e.*, K-Fraction) in the lunar regime. However, what of the ferrobasaltic melt or REEP-Fraction? HOLLISTER and CRAWFORD (1977) and CRAWFORD and HOLLISTER (1977) stated that the earliest Fe-rich immiscible melts are chemically similar to several groups of Fe-rich Apollo 12 and 15 mare basalts. These authors suggested that SLI may have played an important role in the formation of the source regions of Fe-rich mare basalts. HESS *et al.* (1978) concluded that the ferrobasaltic immiscible melt crystallized beneath the granitic melt (due to density considerations), forming the source region for high-Ti mare basalts. In a recent study of Luna 24 basalt particles, LU *et al.* (1989) described a plagioclase-quartz-ilmenite-fayalite-phosphate assemblage, which they termed a quartz ferrotroctolite. This assemblage was interpreted as being the ferrobasaltic product of SLI. In breccia 12013, QUICK *et al.* (1977) reported that SLI could account for the occurrence of light-colored high-SiO_2 and dark Fe-rich areas. Similarly, small clasts of a ferrobasaltic composition in breccia 77538 have also been interpreted as products of SLI (WARNER *et al.*, 1978a). Furthermore, WARREN *et al.* (1987) described the felsite 12033,517 which contained veinlets of brown glass. They attributed these veinlets to be the basic product of SLI which had permeated through the more viscous felsite.

WARREN and WASSON (1979) consider urKREEP to be approximately the final 0.5% residual magma remaining after the crystallization of the LMO. The LMO model has been refined since its conception (*e.g.*, WARREN, 1985), such that periodic replenishments of several smaller LMO systems have been inferred. However, we envisage that SLI occurs at the end of this process, as the last "replenishment" crystallizes. Such fractionation would be well within the operating limits of SLI, which occurs at >90% fractional crystallization (RUTHERFORD *et al.*, 1974; RUTHERFORD and HESS, 1975; HESS *et al.*, 1975, 1978). However, TAYLOR *et al.* (1980) concluded that SLI could not have been a major process at the end of the LMO crystallization, on the basis of elemental ratios in evolved lunar lithologies. The paucity of returned granite samples may support this contention. However, NEAL and TAYLOR (1989) suggested that SLI is critically dependent upon cooling rate, arguing that slow cooling rates are required
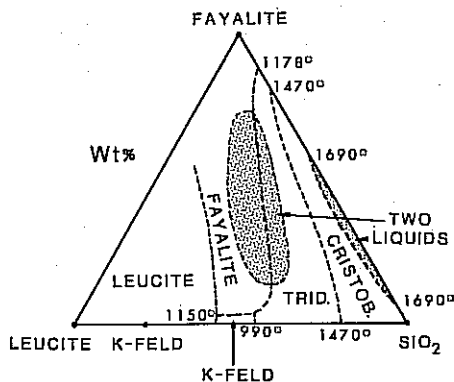

FIG. 2. Phase diagram of the system leucite-fayalite-quartz (after ROEDDER, 1978), demonstrating the presence of both high and low temperature immiscibility fields. Temperatures are in °C.

in order to achieve significant separation of immiscible liquids. These authors concluded that granite may only form in a plutonic or deep hypabyssal environment, beyond the reach of meteorite impact, excavation, and sampling. We consider that although SLI may not have been a major process at the conclusion of the LMO crystallization, it must have been significant. This contention is supported by the occurrence of Very High Potassium (VHK) basalts at the Apollo 14 site. Such basalts are generated by assimilation of lunar granite by a high alumina (HA) basalt magma (SHERVAIS *et al.*, 1985a; NEAL *et al.*, 1988b). Furthermore, the similarity of "KREEP" (NYQUIST *et al.*, 1972, 1973; LUGMAIR and CARLSON, 1978) and granite (SHIH *et al.*, 1985) Rb-Sr and Sm-Nd crystallization (3.9–4.1 Ga and 4.1 Ga, respectively) and model ages (4.3–4.4 Ga and 4.3–4.5 Ga, respectively) suggest a common source for both lithologies (*i.e.*, from the LMO).

A MODEL FOR urKREEP EVOLUTION

One of the significant implications of our model is that there is no distinction between "KREEP" and "urKREEP". In the following discussion, the terms are synonymous. However, a distinction must be made between "KREEP" (the residuum of LMO crystallization) and "KREEPy" rocks (*e.g.*, basalts containing high incompatible elements and high MG#, such as KREEP basalts). Unless KREEP is followed by a rock type, such as basalt, we use the term to mean the residual product of LMO crystallization.

The model proposed for KREEP petrogenesis involves the residual magma from the LMO undergoing SLI. Therefore, urKREEP represents the magma composition just prior to SLI. However, although the formation of urKREEP was extensive (WARREN and WASSON, 1979), SLI was more localized in extent (*e.g.*, TAYLOR *et al.*, 1980). Significant separation of these localized immiscible liquids will only take place at depth (NEAL and TAYLOR, 1989), which may be at the base of the ferroan anorthositic lunar crust (Fig. 3). We envisage that urKREEP was present as residual pockets in the LMO crystallate and locally underwent SLI. The granitic K-Fraction, although less dense than the ferrobasaltic REEP-Fraction, will not migrate far from the scene of SLI, because
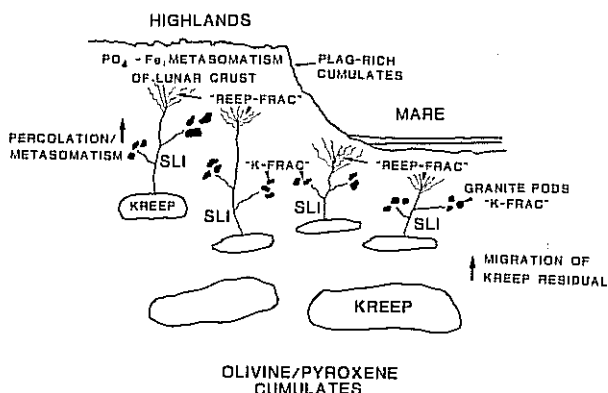

FIG. 3. The evolution of urKREEP represented in cartoon form. The highly viscous K-Fraction forms granite pods, whereas the less viscous REEP-Fraction percolates upwards, metasomatizing the lunar crust.

of its high viscosity (≅30000 poise; Table 1). This may explain the granite-KREEP relationship described by RYDER (1976) at the Apollo 15 site. However, it must be emphasized that most urKREEP does not undergo SLI. Evidence for this is that a "pre-SLI" KREEP composition is an important component required in HA basalt petrogenesis at the Apollo 14 site (NEAL *et al.*, 1988a) and of Apollo 15 KREEP basalts (*e.g.*, RYDER, 1987).

As the viscous granitic melt cannot readily disseminate, the formation of significant granite pods can occur, as required for VHK basalt generation (SHERVAIS *et al.*, 1985a; NEAL *et al.*, 1988b). However, the ferrobasaltic "REEP" melt (10–15 poise; Table 1) is less viscous by over 3 orders of magnitude such that it is likely to separate from the granitic portion. The density of this Fe-rich melt is relatively high (≅3.3 g/cm³) so it should readily separate from the granitic melt (≅2.7 g/cm³). However, after separation, it is the low viscosity of this water-like melt that will permit it to move independently of gravity, largely because of surface tension effects along grain boundaries. We suggest that portions of this melt migrated upward, *promoting the metasomatism of the lunar crust* by crystallizing the highly evolved phosphates noted by LINDSTROM *et al.* (1984) and SHERVAIS *et al.* (1984).

From the calculated norms of ferrobasaltic immiscible liquids (Table 1), we should expect to find a "REEP" assemblage of apatite/whitlockite, ilmenite, feldspar, pyroxene, quartz, but dominated by fayalite. In the lunar highlands, we find predominantly apatite/whitlockite with minor plagioclase, which would appear to negate our SLI model. However, just because a magma undergoes SLI does not mean that fractional crystallization ceases. It is perfectly feasible for this ferrobasaltic immiscible melt to undergo further fractionation. For example, comparison of mineral densities demonstrates that if fayalite (density = 4.14) crystallizes immediately after SLI, it will settle out from the residual liquid, promoted also by the melts' low viscosity. This will significantly reduce the density of the residual liquid, further promoting upward migration through and metasomatism of the lunar crust by grain boundary percolation. Therefore, post-SLI fractionation can account for the phosphate-dominated lithologies observed in the lunar highlands.

WARREN and WASSON (1979) noted that trace element ratios for KREEPy samples were consistent over wide areas of the Moon. Although SLI can alter some elemental ratios, the products of SLI have not, until now, been considered KREEPy in nature. We concur with TAYLOR *et al.* (1980) that SLI was probably a minor process on a Moon-wide scale, although it is locally significant. The pre-SLI melt, or ur-KREEP, imparts the KREEPy lithologies approximately constant trace element ratios. The recognition of KREEP components allows the nature of this urKREEP composition to be evaluated in a more quantitative sense.

THE "K-FRACTION/REEP-FRACTION" HYPOTHESIS IN ACTION

The ability of urKREEP, the LMO residual magma, to undergo SLI, is recognized to be a localized phenomenon. We consider that the LKFM compositions, Apollo 14 breccias, and Apollo 15 KREEPy basalts (for example), all with similar K/La ratios (WARREN and WASSON, 1979), can be

adequately explained by involvement of pre-SLI urKREEP in their respective petrogeneses. Because of the localized nature of SLI, the incorporation of KREEP components into lunar lithologies will be restricted. We have taken two examples of lunar rock types, whose petrogeneses cannot be adequately explained by simple fractional crystallization or assimilation of pre-SLI urKREEP, in order to test our K-Frac/REEP-Frac hypothesis.

1) Petrogenesis of the Quartz MonzoDiorite—QMD (15405)

The occurrence of lunar rocks with REE abundances greater than the high-K KREEP composition (Fig. 1) argues against assimilation by a basaltic magma of the high-K KREEP composition of WARREN and WASSON (1979). TAYLOR et al. (1980) argued against SLI involvement in the petrogenesis of 15405 (Quartz MonzoDiorite—QMD). However, NEAL and TAYLOR (1988a) concluded that simple fractionation of a high-K KREEP melt could not generate this composition. Clearly, the petrogenesis of 15405 QMD is difficult to define using the current KREEP compositions.

RYDER (1976) suggested that there was a KREEP-granite relationship at the Apollo 15 site. On the basis of our K-Frac/REEP-Frac hypothesis, this is certainly possible (see above). As a test of this model, we have attempted to generate the QMD composition (RYDER and NORMAN, 1978) by basaltic assimilation of our K- and REEP-Fractions. This modelling is intended to be illustrative rather than absolute in order to show the applicability of the K-Frac/REEP-Frac hypothesis to the generation of superKREEPy rocks. We have used the 12013 granite (QUICK et al., 1977), the Apollo 16 whitlockite 67975 (LINDSTROM et al., 1984, 1985), fayalite (NEAL et al., 1988b), ilmenite (HASKIN and KOROTEV, 1977; MCKAY et al., 1986), and evolved basalt 14321,1118 of NEAL et al. (1988a) as our modelling components (Table 2). Fayalite, ilmenite, and whitlockite represent the REEP-Fraction,

and granite represents the K-Fraction. The modelling undertaken involves simple bulk mixing (i.e., assimilation without any fractional crystallization) of these lithologies.

There is a high proportion of granite (33.85 → 33.9%) required in order to generate the high SiO_2, Al_2O_3, and K_2O contents of the QMD (Table 2). The REEP-Fraction required is 9.65 → 9.7% (1.65 → 1.7% whitlockite, 3% ilmenite, and 5% fayalite), with 56.5% evolved basalt 14321,1118. An evolved basalt is required primarily to generate the REE pattern (phosphate generates the REE abundances). Almost all elements of our modelled QMD are within 15% of the analyzed composition, except for MgO and P_2O_5. The high MgO content of our modelled composition may be rectified by the use of a basalt with lower MgO contents (i.e., more evolved), but no pristine examples of such a basaltic composition have been found. The high phosphorus content of our modelled composition (0.73 wt% P_2O_5) is from phosphate being used to generate REE rather than P_2O_5 abundances. However, the excellent match of most of the elements demonstrates the feasibility of generating the QMD by bulk assimilating different proportions of our K- and REEP-Fractions.

2) Petrogenesis of impact-generated olivine vitrophyres

There has been much debate in the literature concerning the petrogenesis of olivine vitrophyres. Olivine vitrophyres, as discovered and named (BASU et al., 1978; ALLEN et al., 1979), are distinguished from mare basalts by their high modal olivine, high MgO, high incompatible trace element abundances, and low CaO/Al_2O_3 ratios. ALLEN et al. (1979) concluded that olivine vitrophyres were impact melts of Mg-enriched highlands crust. It is now evident that a sub-population of these are formed by primary igneous processes (e.g., BASU et al., 1979), but the majority are in fact impact melts (BASU et al., 1978; WARNER et al., 1978b; ALLEN et al., 1979; GROVER et al., 1980; SHERVAIS et al., 1988). SHER-

Table 2: Modeling components and results of the Quartz MonzoDiorite (15405) composition. Major element oxides in wt% and REE in ppm.

	14321 PHOS.	AVERAGE GRANITE	ILM.	FAY.	BASALT 1118	MIX	15405[a] QMD	% DIFF.
% MIX	1.65	33.85	3.0	5.0	56.5			
SiO_2	----	73.0	----	33.2	49.3	54.23	55.4	2.1
TiO_2	----	0.6	50.5	----	1.91	2.80	2.6	7.6
Al_2O_3	----	11.9	0.4	----	14.5	12.23	11.9	2.8
FeO	1.16	0.9	40.4	51.1	14.8	12.45	14.1	11.7
MgO	2.97	0.7	6.3	15.0	7.0	5.18	3.8	36.3
CaO	40.1	1.4	----	----	11.7	7.75	8.9	13.0
Na_2O	----	1.4	----	----	0.52	0.77	0.81	5.2
K_2O	----	6.8	----	----	0.22	2.43	2.1	15.5
P_2O_5	44.1	---	----	----	----	0.73	0.4	81.5
La	10648	68	2.66	-----	30.6	216	210	2.9
Ce	28190	126	14.2	-----	82.9	555	560	0.9
Sm	4608	16	4.62	-----	15.3	90.2	93	3.0
Eu	70	2.54	0.43	-----	1.67	2.97	2.52	17.9
Tb	780	1.9	1.6	-----	3.32	15.4	19.7	21.6
Yb	3015	33.4	10.4	-----	9.72	66.9	65	2.9
Lu	353	5.1	1.59	-----	1.33	8.35	9.0	7.2

a = data from Ryder and Norman (1978).
Granite = Warren et al. (1983b, 1987); Blanchard et al. (1977); Blanchard and Budahn (1979); Quick et al. (1977). Phosphate = Lindstrom et al. (1985). Ilmenite = Haskin and Korotev (1977); McKay et al. (1986). Fayalite = Neal et al. (1988b). Basalt = Neal et al. (1988a).

VAIS *et al.* (1988) demonstrated that olivine accumulation was not consistent with observed quench textures and concluded that the discrepancy between observed and calculated olivine compositions was the result of two possible scenarios: 1) rapid quenching to form olivine microphenocrysts, preceded by a period of slower cooling; or 2) the earliest olivine was formed by disequilibrium crystallization, during which the olivine liquid Fe/Mg Kd was close to 0.5.

We are concerned herein with the olivine vitrophyres of impact origin. Our study (NEAL and TAYLOR, 1988b) involved the analysis of three new olivine vitrophyres from Apollo 14 breccia 14321. Based on our K-Frac + REEP-Frac ideas, we combined our whole-rock data with that previously reported for olivine vitrophyres, in order to generate a consistent model for the petrogenesis of this impact-generated rock type.

Whole-rock chemistry

The paradoxical problem with olivine vitrophyres is the "primitive" (high) MG# coupled with the "evolved" (high) incompatible element abundances. The olivine vitrophyres are LREE-enriched, with a general "KREEPy" REE pattern (Fig. 4), although La/Lu is slightly higher in our samples (25–26 *versus* 22 for the high-K KREEP composition of WARREN and WASSON, 1979). Other KREEPy incompatible elements (K, Hf, Th, U, P) show similar enrichments (Table 3). However, unlike KREEP, the compatible elements (Co, Sc, Cr, and V) are enriched in the vitrophyres, more akin to mare basalts. Nickel abundances are elevated above any pristine lunar composition (250–380 ppm), as are other siderophiles (Au and Ir), which supports an impact rather than a pristine igneous origin for these samples.

The three olivine vitrophyres are similar in major element compositions (Table 3) to those reported by SHERVAIS *et al.* (1988). The high MG# (molar [Mg/(Mg + Fe)]*100: 74.9–77.7) and the CaO/Al₂O₃ ratio (0.48–0.65) confirms the highland affinities of the olivine vitrophyres (SHERVAIS *et al.*, 1988). Although these vitrophyres contain approximately 0.5 wt% K₂O, they cannot be classified as very high potassium (VHK) basalts. The K/La and K₂O/Na₂O ratios (≅71 and ≅0.6, respectively) are too low and the MG# too high. We have taken an average whole-rock P₂O₅ value, calculated from
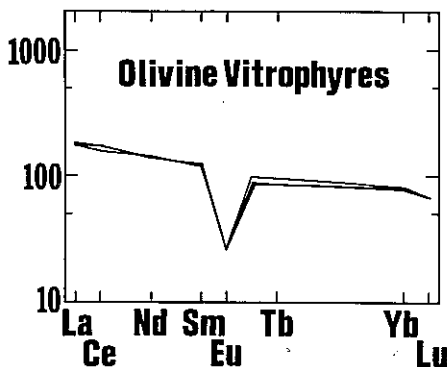
	.1416	.1439	.1539
SiO₂*	45.6	46.0	48.3
TiO₂	1.49	1.40	1.37
Al₂O₃	13.9	14.3	14.0
FeO	10.1	10.4	9.50
MnO	0.12	0.14	0.12
MgO	19.7	17.4	18.5
CaO	7.30	8.86	6.72
Na₂O	1.05	0.74	0.72
K₂O	0.49	0.48	0.53
P₂O₅ θ	0.27	0.27	0.27
MG#	77.7	74.9	77.6
CaO/Al₂O₃	0.53	0.62	0.48
K₂O/Na₂O	0.47	0.65	0.74
Sc	18.6	23.4	17.7
V	46	59	41
Cr	1550	1790	1450
Co	34.0	35.8	40.7
Ni	250	280	380
Cs	0.61	0.96	0.66
Ba	700	720	730
La	61.4	57.5	57.5
Ce	151	146	150
Nd	87	89	87
Sm	25.6	24.1	24.5
Eu	2.09	2.02	2.02
Tb	5.4	5.0	4.9
Yb	18.4	17.2	17.3
Lu	2.30	2.28	2.30
Hf	21.9	20.1	21.1
Ta	2.47	2.41	2.29
Th	12.1	10.8	11.6
U	3.6	3.3	3.4
La/Lu	26.7	25.2	25.0

* = SiO₂ by difference; θ = P₂O₅ calculated from glass analysis.

glass compositions, to be 0.27 wt%, by assuming a minimum of 50% opaque glass in the vitrophyres.

The dichotomy between major and trace elements (*i.e.*, high MG# and high incompatible element abundances) is the reason why, in previous geochemical models, a mythical high-Mg component was required: a large proportion of KREEP was required to generate the incompatible elements (*e.g.*, SHERVAIS *et al.*, 1988). But by adding a large proportion of KREEP, the overall MG# is too low, necessitating some fictitious "high-Mg" component to elevate the MG# to observed values.

Modelling of olivine vitrophyre compositions

The goals of the modelling were to use our K- and REEP-Fractions to significantly reduce the amount of KREEP required to generate the incompatible trace element abundances of olivine vitrophyres. This allows an increase in the amount of highland lithologies required to generate the high MG#. In our modelling, *we do not require any mythical "high-Mg" components in order to generate olivine vitrophyre compositions.* Rather, actual lunar compositions have been used, as reported in the literature (see below). We have mixed essentially four lunar components (Table 4): 1) *KREEP*—subdivided into granite (WARREN *et al.*, 1987), or the K-Fraction, and apatite/whitlockite (LINDSTROM *et al.*, 1984, 1985) and ilmenite (HASKIN and KOROTEV, 1977; MCKAY *et al.*, 1986), or the REEP-Fraction (fayalite was not used here because of the proposed post-SLI fractionation. Also, fayalite has not yet been observed with phosphate in highland lithologies); 2)

FIG. 4. Chondrite-normalized REE profiles of the three 14321 olivine vitrophyres.

Table 4: Components used in modeling olivine vitrophyre compositions. Major element oxides in wt%, trace elements in ppm.

	K R E E P			H I G H L A N D S		BASALT	METEORITE
	GRANITE	PHOS.	ILM.	TROCT.	DUNITE		
SiO$_2$	65.5	----	----	49.3	34.1	49.3	48.0
TiO$_2$	1.49	----	50.5	0.16	0.08	1.89	0.89
Al$_2$O$_3$	12.9	----	0.42	21.6	0.56	13.2	2.00
FeO	7.61	1.16	40.4	4.67	11.6	17.7	29.7
MgO	2.42	2.97	6.30	17.7	53.7	9.70	16.6
CaO	4.90	40.1	----	12.5	----	10.3	1.85
Na$_2$O	1.47	----	----	0.37	0.02	0.51	0.86
K$_2$O	2.96	----	----	0.07	----	0.14	0.09
P$_2$O$_5$	----	44.1	----	----	----	----	----
MG#	36.2	82.0	21.7	87.1	89.2	49.4	49.9
Sc	14.9	----	104	3.79	5.02	61.3	6.4
Cr	480	----	8689	933	522	3700	3000
Co	8	----	20.2	21	61.3	35	625
Ba	4540	----	----	238	24	210	2.9
La	82	7702	2.66	15.14	5.14	20.4	0.2
Ce	199	20624	14.2	38	13.5	51	0.6
Sm	27.7	3315	4.62	5.58	2.55	10.5	0.1
Eu	3.1	17.3	0.43	1.76	0.67	1.35	0.04
Tb	6.8	575	1.6	1.11	0.5	2.5	0.03
Yb	36.7	1903	10.4	3.35	1.98	6.6	0.13
Lu	5.8	224	1.59	0.55	0.39	0.92	0.02
Hf	36.8	0?	57.7	3.38	0.93	8.0	0.4
Ta	7.8	0?	----	0.31	0.1	0.91	0.017
Th	40	0?	1.23	0.71	0.71	2.1	0.075
Ni	22	----	----	30	40	70	14500

Granite = Warren et al. (1987); Phosphate = Lindstrom et al. (1985); Ilmenite = Haskin and Korotev (1977) and McKay et al. (1986); Troctolite and Dunite = Lindstrom et al. (1984); Basalt = Neal et al. (1988a); Meteorite = Boynton et al. (1975).

Highlands—subdivided into dunite and troctolite (LIND-STROM *et al.*, 1984), although a high-Mg norite may also be used, as this is the most common highlands lithology present at the Apollo 14 site; 3) *Mare Basalt* (SHERVAIS *et al.*, 1985b); and 4) *Meteorite* (BOYNTON *et al.*, 1975). The 14321 phosphate phases of LINDSTROM *et al.* (1984, 1985) was used here as we are dealing with 14321 olivine vitrophyres. Mare basalt is used as a modelling component because of the compatible element mare signature of the olivine vitrophyres. The modelling was undertaken for our three olivine vitrophyres, the Average Olivine Vitrophyre (AOV) of ALLEN *et al.* (1979) and the Preferred Average Olivine Vitrophyre (PAOV) of SHERVAIS *et al.* (1988). The proportions of components were adjusted iteratively until all elemental abundances were within approximately 10 to 15% of those analyzed (Table 5).

There is good agreement between the modelled and analyzed olivine vitrophyre compositions for our new samples, AOV, and PAOV. The new 14321 vitrophyres of this study can be generated by mixing 16.2% "KREEP" (14.43 → 14.4% K-Fraction, 1.77 → 1.8% REEP-Fraction), 57.1 → 57% highland lithologies, 25% mare basalt, and 1.7% of a meteoritic component. The AOV composition of ALLEN *et al.* (1979) can be generated by mixing 15.1% "KREEP" (15% K-Fraction, 0.1% REEP-Fraction), 58% highland lithologies, 27.4% mare basalt, and 2.5% of a meteoritic component. The high quantity of dunite (33.5%) required to generate the AOV of ALLEN *et al.* (1979) reflects the high MgO contents of this vitrophyre composition. This composition was calculated by modal mineralogy, rather than bulk rock analysis, and the high MgO contents may reflect an overcounting of olivine (SHERVAIS *et al.*, 1988). Therefore, although this AOV composition can theoretically be generated, we consider this an unlikely occurrence. The PAOV composition of SHERVAIS *et al.* (1988) can be generated by mixing 16.8% "KREEP"

(16.03 → 16% K-Fraction, 0.77% REEP-Fraction), 51.4 → 51% highland lithologies, 30% mare basalt, 1.8% of a meteoritic component. However, Na is consistently low in the modelled composition relative to our new samples, as well as the AOV and PAOV. Also, Eu, Th, Ta, and Hf are low in the modelled composition for both our new samples and PAOV (only major elements have been determined for AOV). In the modelled composition for PAOV, Sc and Co are a little high. It is possible that a greater proportion of plagioclase (albitic) could account for the low Na and Eu abundances, but not other elemental discrepancies. However, the Hf, Th, and Ta contents of apatite/whitlockite are unknown and have been taken to be 0. This is a gross oversimplification, as the phosphate phase is rich in incompatible elements. However, in the absence of precise data, we are unable to give abundances for these elements in apatite/whitlockite, but suggest they must be significant. The high Sc and Co abundances in the modeled PAOV composition could be explained by: 1) a higher proportion of mafic phases to feldspar in the highlands component; and 2) an as yet unanalyzed basalt containing greater abundances of the compatible elements. However, these minor discrepancies should not cloud the fact that the vast majority of elemental abundances in olivine vitrophyres can be generated by using observed lunar components in our model.

A RECALCULATION OF THE urKREEP SIGNATURE

Method 1

With the definition of the K- and REEP-Fractions, the composition of pure urKREEP can be back calculated. In this modelling, the major element and REE signatures of urKREEP are defined. As in any model, our hypothesis contains basic assumptions: 1) the average lunar granite REE

Table 5: Results of olivine vitrophyre modeling for the new data presented here, the "AOV" of Allen et al. (1979), and the "PAOV" of Shervais et al. (1988). Major element oxides in wt%, trace elements in ppm.

	NEW DATA			"AOV"			"PAOV"		
	MODEL	ACTUAL	% DIFF.	MODEL	ACTUAL	% DIFF.	MODEL	ACTUAL	% DIFF.
SiO_2	45.7	46.6	2.0	45.2	45.7	1.1	46.3	46.5	0.4
TiO_2	1.44	1.42	1.2	0.97	1.03	6.1	1.19	1.30	8.1
Al_2O_3	14.1	14.1	0.0	10.3	10.3	0.0	12.6	12.4	1.4
FeO	10.3	10.0	3.3	11.0	10.8	1.4	10.3	9.86	4.8
MgO	19.0	18.5	3.0	24.7	24.3	1.8	19.8	19.2	3.2
CaO	8.63	7.60	13.5	6.50	6.27	3.6	8.05	7.90	1.9
Na_2O	0.51	0.84	39.4	0.48	0.78	38.9	0.53	0.80	33.9
K_2O	0.49	0.50	1.5	0.51	0.46	9.8	0.55	0.51	6.9
P_2O_5	0.21	0.27	22.2	----	----	---	----	----	----
MG#	76.7	76.7	0.0	80.1	80.0	0.1	77.4	77.6	0.3
Sc	21.3	20.3	4.9				21.5	17.8	21.1
Cr	1625	1530	6.2				1362	1566	13.0
Co	39.3	35.7	10.0				42.2	35.5	18.9
Ba	809	717	12.8				868	767	13.1
La	60.2	58.8	2.4				62.3	58.2	7.0
Ce	156	142	10.0				162	158	2.2
Sm	25.0	24.7	1.1				25.8	25.3	2.0
Eu	1.61	2.53	25.3				1.49	2.01	26.0
Tb	4.87	5.10	4.6				5.05	6.05	16.5
Yb	17.7	17.6	0.7				18.5	19.8	6.4
Lu	2.43	2.30	5.6				2.55	2.64	3.5
Hf	9.60	21.3	54.9				10.3	22.0	53.3
Ta	1.50	3.00	50.1				1.59	2.56	38.0
Th	6.92	11.0	37.1				7.24	11.5	37.0
Ni	286	303	5.6				303	297	2.0
GRANITE		14.43			15.00			16.03	
PHOSPHATE		0.47			0.10			0.47	
ILMENITE		1.30			0.00			0.30	
TROCTOLITE		41.00			21.50			30.20	
DUNITE		16.10			33.50			21.20	
BASALT		25.00			27.40			30.00	
METEORITE		1.70			2.50			1.80	

pattern represents that of the high-SiO₂ (K-Fraction) immediately after SLI; 2) the phosphate phase in the REEP-Fraction contains all the REE; 3) the REE abundances of the REEP-Fraction are calculated using the average amount of phosphate in the norms calculated above for basic immiscible melts (≅3% apatite/whitlockite); and 4) major element concentrations are those determined for the immiscible liquids (HESS et al., 1975; WEIBLEN and ROEDDER, 1973).

In the modelling, we use the proportions of high-silica and high-Fe melts produced experimentally by HESS et al. (1975). These results indicate that the proportion of the ferrobasaltic melt exceeds that of the granitic melt, ranging from 75:25 to 85:15. We have taken the average ratio (80:20) and calculated an urKREEP composition. This ratio appears to be consistent for basaltic compositions, although it will change if the SiO₂ content of the system is increased or decreased. Two whitlockite REE compositions were used: 14321 (Model A) and 67975 (Model B) both from LINDSTROM et al. (1985). Average granite REE are calculated from WARREN et al. (1983b, 1987), BLANCHARD et al. (1977), and QUICK et al. (1977). Results are presented in Fig. 5 and Table 6.

An important result is that the REE abundances for both calculated urKREEP compositions far exceed the high-K KREEP composition of WARREN and WASSON (1979) (600 and 820 times chondrite La *versus* 340: Fig. 5), and any other reported KREEP composition. However, the negative Eu anomaly is deepened (Eu = 12 and 28 times chondrite *versus* 37). The actual REE patterns are similar, but the La/Lu ratio in both Model A and B are 32 and 29, respectively, greater than 22 of high-K KREEP. The compositions produced by models A and B probably represent the limits of urKREEP REE abundances. However, the high-K KREEP composition

of WARREN and WASSON (1979), intended to represent the lower limit of urKREEP, falls below these defined ranges (Fig. 5).

The major element composition of our calculated urKREEP composition is that of a ferrobasalt (Table 6), which is to be expected from SLI experiments (*e.g.*, RUTHERFORD et al., 1974; HESS et al., 1975). Our calculated urKREEP
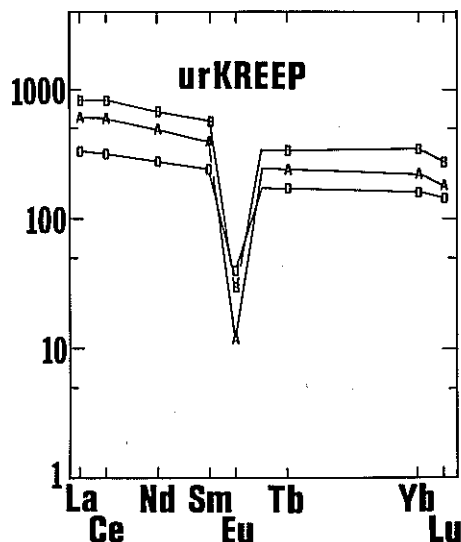

FIG. 5. Chondrite-normalized REE profiles of urKREEP compositions calculated by Method 1: A = results of Model A (14321 phosphate); B = results of Model B (67975 phosphate); 0 = high-K KREEP composition of WARREN and WASSON (1979).

Table 6: Modeling results of the urKREEP composition by back calculation from the K- and REEP-Fractions. Model A uses 14321 phosphate and Model B uses 67975 phosphate both from Lindstrom et al. (1985). Major element oxides in wt%, trace elements in ppm.

MIX	MODEL A			MODEL B			AVERAGE urKREEP	W&W '79 High-K KREEP
	REEP-Frac 80%	K-Frac 20%	Result	REEP-Frac 80%	K-Frac 20%	Result		
SiO_2	38.4	74.3	45.6	38.4	74.3	45.6	45.6	47.9
TiO_2	3.10	0.70	2.62	3.10	0.70*	2.62	2.62	1.65
Al_2O_3	6.73	11.1	7.59	6.73	11.1	7.59	7.59	16.6
FeO	33.1	6.86	27.8	33.1	6.86	27.8	27.8	10.6
MgO	0.51	0.05	0.42	0.51	0.05	0.42	0.42	10.6
CaO	11.3	2.07	9.42	11.3	2.07	9.42	9.42	9.52
Na_2O	0.17	0.42	0.22	0.17	0.42	0.22	0.22	0.86
K_2O	0.57	4.17	1.29	0.57	4.17	1.29	1.29	0.83
P_2O_5	4.76	0.22	3.85	4.76	0.22	3.85	3.85	0.78
MG#	2.7	1.3	2.6	2.7	1.3	2.6	2.6	64.1
La	231	64	198	319	64	268	233	110
Ce	611	158	521	846	158	708	615	270
Nd	369	77	310	512	77	425	368	180
Sm	96.1	21.2	81.1	138	21.2	115	98.1	49.0
Eu	0.49	2.59	0.91	2.10	2.59	2.20	1.56	3.00
Tb	16.3	5.15	14.0	23.4	5.15	19.8	16.9	10.0
Yb	55.6	29.1	50.3	90.5	29.1	78.2	64.3	36.0
Lu	6.63	4.46	6.20	10.6	4.46	9.36	7.78	5.00
La/Lu	34.8	14.4	31.9	30.2	14.4	28.9	29.9	22.0

K-Fraction = major elements from residual immiscible melts in Apollo 15 basalts (Weiblen and Roedder, 1973), REE from average lunar granite (Warren et al., 1983b, 1987; Blanchard et al., 1977; Quick et al., 1977). REEP-Fraction = major elements from residual immiscible melts in Apollo 15 basalts (Weiblen and Roedder, 1973), REE from Lindstrom et al. (1985). High-K KREEP from Warren and Wasson (1979).

major element compositions differ dramatically from the high-K KREEP of WARREN and WASSON (1979) (Table 6). The Ti, Fe, Mn, K, and P contents are much higher (*e.g.*, ≅27.8 *versus* 10.6 wt% FeO). The Si, Al, Mg, and Na contents of our modelled urKREEP composition are also reduced relative to WARREN and WASSON's (1979) high-K KREEP composition (*e.g.*, 7.59 *versus* 16.6 wt% Al_2O_3 and 0.42 *versus* 10.6 wt% MgO). This is what would be expected if plagioclase and olivine fractionation has occurred, as in the LMO hypothesis.

Method 2

Another approach to the calculating the urKREEP signature has been used by NEAL and TAYLOR (1989). An average lunar granite has been calculated from all reported lunar granite compositions and liquid-liquid *Kd*'s used to back calculate the "pre-SLI" magma composition. Liquid-liquid *Kd*'s were compiled from ROEDDER and WEIBLEN (1971), WEIBLEN and ROEDDER (1973), RUTHERFORD *et al.* (1974), HESS *et al.* (1975), WATSON (1976), RYERSON and HESS (1980), NEAL and TAYLOR (1989), RYDER (pers. commun., 1988). Liquid-liquid *Kd*'s (Table 7) are reported as the concentration of an element in the basic melt divided by the concentration of an element in the acid melt ($D_{b/a}$). Average $D_{b/a}$ values were used, except for barium, where controversy exists as to whether it partitions into the basic or acid melt. The $D_{b/a}$ barium calculated from immiscible basaltic glasses was used (≅0.5), and the proportion of basic to acid melt was also 80:20 (see above).

The composition of the pre-SLI magma produced by this method is representative of a residual magma after Fenner Trend fractional crystallization (Table 7). The major element composition of urKREEP calculated by this method is similar to that reported above: general ferrobasaltic composition;

high CaO contents: SiO_2 enrichment suppressed. Absolute abundances are similar, but not exactly the same (Table 7). By using liquid-liquid Kd's to calculate the pre-SLI melt (or urKREEP composition), more elements may be estimated than in the method above (Table 7). The trace element contents of the calculated pre-SLI magma are consistent with it

TABLE 7: Calculation of the pre-SLI melt for average granite. The pre-SLI melt composition is calculated from 20% granitic and 80% basic melt.

	$D_{b/a}$	LUNAR GRANITE			Pre-SLI Melt
		1	2	3	
SiO_2	0.61	69.2	70.8	43.3	48.5
TiO_2	4.20	0.68	0.69	2.91	2.42
Al_2O_3	0.60	13.2	13.5	8.06	9.15
FeO	6.70	3.68	3.75	25.2	20.9
MgO	4.72	0.20	0.20	0.96	0.80
CaO	4.55	3.37	3.45	15.7	13.1
Na_2O	0.44	0.88	0.90	0.40	0.50
K_2O	0.24	6.46	6.61	1.58	3.10
P_2O_5 @	18.5	0.10	0.10	1.89	1.53
TOTAL		97.77	100.00	100.00	100.00
Cr	3.99	410		1634	1389
Mn	5.12	114		582	488
Rb	0.24*	152		36.6	59.7
Sr	1.54	153		235	219
Cs	0.30	4.21		1.28	1.86
Ba	0.49	4450		2194	2645
La	5.29	61.2		324	271
Sm	4.42	19.7		87.2	73.7
Yb	4.18	27.5		115	97.5
Lu	5.66	4.00		22.6	18.9
Hf	2.44*	18.1		44.2	39.0
Ta	4.13	5.45		22.5	19.1
Th	2.44*	42.9		105	92.5
U	2.44*	12.5		30.5	25.1
Zr	2.44	1000		2435	2148

@ = maximum P_2O_5 wt% in granite calculated from modal % apatite/whitlockite; * = estimated $D_{b/a}$; 1 = average lunar granite; 2 = average lunar granite normalized to 100; 3 = calculated basic immiscible melt which compliments lunar granite.
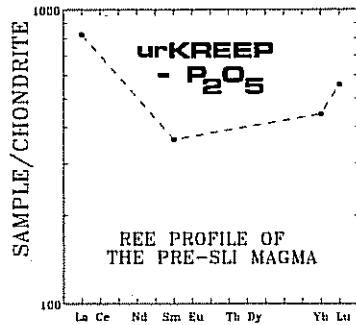
FIG. 6. Chondrite-normalized REE profile of urKREEP that has experienced phosphate fractionation, calculated by method 2. Liquid-liquid Kd's have only been calculated for La, Sm, Yb, and Lu, but the general concave-upwards REE pattern is evident.

being the residual from LMO crystallization. For example, the high field strength (Zr, Ta, Hf, U, Th)) and large ion lithophile (Cs, Ba, Sr, Rb) elements are enriched in this calculated melt, whereas the compatible elements (Mn, Cr) are reduced, relative to high-K KREEP.

The main difference in calculated urKREEP compositions using the two methods outlined above is seen in the REE contents (Figs. 5 and 6). In Fig. 5, KREEP possesses the normal LREE-enriched signature, whereas in Fig. 6, it has a concave-upwards pattern. The concave-upwards pattern has been produced by back calculating from lunar granite composition. Several authors have demonstrated that lunar granite petrogenesis requires some phosphate (apatite or whitlockite) fractionation in order to generate the general concave-upwards REE profile of lunar granite (DICKENSON and HESS, 1983; SALPAS et al., 1985; SHIH et al., 1985). However, whether this occurred before or after SLI was unclear. It is certainly feasible that the melt calculated by method 2 represents urKREEP minus whitlockite/apatite, and the melt calculated by method 1 represents urKREEP in toto.

The semi-quantitative modelling presented above is illustrative, in the sense that it is difficult to produce the melt calculated by method 2 by subtracting phosphate from the melt calculated by method 1. However, the modelling does illustrate that a KREEP or urKREEP signature can be readily estimated even though such a pristine composition has not as yet been found on the lunar surface.

CONCLUSIONS

The major problem in constraining KREEP petrogenesis is that no pristine KREEP composition has been identified. We support the conclusions of RYDER (1987) and WARREN (1988) who stated that KREEP basalts are not pristine KREEP compositions, rather they are basalts heavily contaminated with urKREEP. We also agree with the urKREEP hypothesis of WARREN and WASSON (1979) but do not believe that it goes far enough in describing KREEP-related phenomena. One important point that must be emphasized is that KREEP, as seen at the surface of the Moon, is not a rock type but a chemical signature, which may be composed of a variety of components. With this in mind, the following conclusions may be drawn:

1) The hypothesis of WARREN and WASSON (1979) requires extreme fractionation of the LMO, leaving an urKREEP residual. Such extreme fractionation required by this hypothesis puts the residual into the realm of silicate liquid immiscibility (SLI).

2) The process of SLI splits the KREEP signature into a K-Fraction (granitic) and a REEP-Fraction (ferrobasaltic/phosphatic). Although this only occurred locally, SLI allows the identification of specific KREEPy components, which are pure, undiluted KREEP products. Isotope systematics for granite and "KREEPy" materials support derivation from a common source.

3) The identification of these KREEPy components enables the generation of "superKREEPy" rocks and impact melts (olivine vitrophyres) to be modelled using observed, analyzed lunar components.

3a) The "superKREEPy" Quartz Monzodiorite composition can be generated by basalt assimilation of 33.85 → 33.9% of the K-Fraction and 9.65 → 9.7% of the REEP-Fraction.

3b) Olivine vitrophyre compositions are generated by mixing 14 to 18% "KREEP" (14–16% K-Fraction, 0.1–1.8% REEP-Fraction), 51 to 58% highland lithologies, 25 to 30% mare basalt, and 1.7 to 2.5% of a meteoritic component.

4) The K- and REEP-Fractions are real lunar components and may be used to calculate the composition of urKREEP, which is the composition of the melt just prior to SLI and the residual product of LMO fractionation. The results demonstrate that the major elements are more representative of a residual magma after fractional crystallization than the high-K KREEP composition reported by WARREN and WASSON (1979). The REE exhibit a deeper negative Eu anomaly, have higher abundances, and are slightly more LREE enriched than the high-K KREEP of WARREN and WASSON (1979).

The application of the K-Frac/REEP-Frac hypothesis allows several lunar petrogenetic problems to be resolved. By identifying KREEP components in this way, the importance of fractional crystallization and silicate liquid immiscibility in an evolving Moon is emphasized, and the nature of the pure urKREEP can be evaluated.

REFERENCES

ALLEN F. M., BENCE A. E. and GROVER T. L. (1979) Olivine vitrophyres in Apollo 14 breccia 14321: Samples of the high-Mg component of the lunar highlands. *Proc. Lunar Planet. Sci. Conf. 10th*, 695–712.

APOLLO SOIL SURVEY (1971).Apollo 14: Nature and origin of rock types in soil from the Fra Mauro formation. *Earth Planet. Sci. Lett.* **12**, 49–54.

BASU A. and BOWER J. F. (1976) Petrography of KREEP basalt fragments from Apollo 15 soil. *Proc. Lunar Sci. Conf. 7th*, 659–678.

BASU A., McKAY D. S. and FRULAND R. M. (1978) Clast-laden nature and the origin of Luna 24 olivine-vitrophyres. *Proc. Lunar Planet. Sci. Conf. 9th*, 535–546.

BASU A., MCKAY D. S., MOORE C. H. and NELSON N. R. (1979) A note on the Apollo 15 green glass vitrophyres. *Proc. Lunar Planet. Sci. Conf. 10th*, 301–310.

BLANCHARD D. P. and BUDAHN J. R. (1979) Remnants from the ancient lunar crust: clasts from consortium breccia 73255. *Proc. Lunar Planet. Sci. Conf. 10th*, 803–816.

BLANCHARD D. P., JACOBS J. W. and BRANNON J. C. (1977) Chemistry of ANT-suite and felsite clasts from consortium breccia 73215 and of gabbroic anorthosite 79215. *Proc. Lunar Sci. Conf. 8th*, 2507–2524.

BOTTINGA Y. and WEILL D. F. (1972) The viscosity of magmatic silicate liquids: A model for calculation. *Amer. J. Sci.* **272**, 438–475.

BOYNTON W. V., BAEDECKER P. A., CHOU C.-L., ROBINSON K. L. and WASSON J. T. (1975) Mixing and transport of lunar surface materials: Evidence obtained by the determination of lithophile, siderophile, and volatile elements. *Proc. Lunar Sci. Conf. 6th*, 2241–2259.

CRAWFORD M. L. and HOLLISTER L. S. (1977) Evolution of KREEP: Further petrologic evidence. *Proc. Lunar Sci. Conf. 8th*, 2403–2417.

DICKINSON J. E. and HESS P. C. (1982) Whitlockite saturation in lunar basalts (abstr.). *Lunar Planet. Sci. XIII*, 172–173.

DICKINSON J. E. and HESS P. C. (1983) Role of Whitlockite and Apatite in lunar felsite (abstr.). *Lunar Planet. Sci. XIV*, 158–159.

DOWTY E., KEIL K., PRINZ M., GROS J. and TAKAHASHI H. (1976) Meteorite-free Apollo 15 crystalline KREEP. *Proc. Lunar Sci. Conf. 7th*, 1833–1844.

GROVER J. E., LINDSLEY D. H. and BENCE A. E. (1980) Experimental phase relations of olivine vitrophyres from breccia 14321: The temperature and pressure dependence of Fe-Mg partitioning for olivine and liquid in a highlands melt-rock. *Proc. Lunar Planet. Sci. Conf. 11th*, 179–196.

HASKIN L. A. and KOROTEV R. L. (1977) Test of a model for trace element partitioning during closed-system solidification of a silicate liquid. *Geochim. Cosmochim. Acta* **41**, 921–939.

HASKIN L. A., HELMKE P. A., BLANCHARD D. P., JACOBS J. W., and TELANDER K. (1973) Major and trace element abundances in samples from the lunar highlands. *Proc. Lunar Sci. Conf. 4th*, 1275–1296.

HESS P. C. and RUTHERFORD M. J. (1974) Element fractionation between immiscible melts (abstr.). *Lunar Planet. Sci. V*, 328–330.

HESS P. C. RUTHERFORD M. J., GUILLEMETTED R. N., RYERSON F. J. and TUCHFELD H. A. (1975) Residual products of fractional crystallization of lunar magmas: An experimental study. *Proc. Lunar Sci. Conf. 6th*, 895–909.

HESS P. C., RUTHERFORD M. J. and CAMPBELL H. W. (1977) Origin and evolution of LKFM basalt. *Proc. Lunar Sci. Conf. 8th*, 2357–2373.

HESS P. C., RUTHERFORD M. J. and CAMPBELL H. W. (1978) Ilmenite crystallization in non-mare basalt: Genesis of KREEP and high-Ti mare basalt. *Proc. Lunar Planet. Sci. Conf. 9th*, 705–724.

HOLLISTER L. S. and CRAWFORD M. L. (1977) Melt immiscibility in Apollo 15 KREEP: Origin of Fe-rich mare basalts. *Proc. Lunar Sci. Conf. 8th*, 2419–2432.

HUBBARD N. J. and MINNEAR J. W. (1976) Petrogenesis in a modestly endowed Moon. *Proc. Lunar Sci. Conf. 7th*, 3421–3435.

HUBBARD N. J., MEYER C., GAST P. W. and WEISMANN H. (1971) The composition and derivation of Apollo 12 soils. *Earth Planet. Sci. Lett.* **10**, 341–350.

HUGHES S. S. and SCHMITT R. A. (1985) Zr-Hf-Ta fractionation during lunar evolution. *J. Geophys. Res.* **90**, D31–D45.

IRVING A. J. (1977) Chemical variation and fractionation of KREEP basalt magmas. *Proc. Lunar Sci. Conf. 8th*, 2433–2448.

KOROTEV R. L. (1981) Compositional trends in Apollo 16 soils. *Proc. Lunar Planet. Sci. Conf. 12th*, 577–605.

KOROTEV R. L., HASKIN L. A. and LINDSTROM M. M. (1980) A synthesis of lunar highlands compositional data. *Proc. Lunar Planet. Sci. Conf. 11th*, 395–429.

KUSHIRO I. (1975) On the nature of silicate melt and its significance in magma genesis: Regularities in the shift of the liquidus boundaries involving olivine, pyroxene, and silicate minerals. *Amer. J. Sci.* **275**, 411–431.

LINDSTROM M. M., KNAPP S. A., SHERVAIS J. W. and TAYLOR L. A. (1984) Magnesian anorthosites and associated troctolites and

dunite in Apollo 14 breccias. *Proc. Lunar Planet. Sci. Conf. 15th; J. Geophys. Res.* **89**, C41–C49.

LINDSTROM M. M., CROZAZ G. and ZINNER E. (1985) REE in phosphates from lunar highlands cumulates: An ion probe study (abstr.). *Lunar Planet. Sci. XVI*, 493–494.

LU F., TAYLOR L. A. and JIN Y. (1989) Basalts and gabbros from Mare Crisium: Evidence for extreme fractional crystallization. *Proc. Lunar Planet. Sci. Conf. 19th* (in press).

LUGMAIR G. W. and CARLSON R. W. (1978) The Sm-Nd history of KREEP. *Proc. Lunar Planet. Sci. Conf. 9th*, 689–704.

MCKAY G. A. and WEILL D. F. (1976) Petrogenesis of KREEP. *Proc. Lunar Sci. Conf. 7th*, 2427–2447.

MCKAY G. A. and WEILL D. F. (1977) KREEP petrogenesis revisited. *Proc. Lunar Sci. Conf. 8th*, 2339–2355.

MCKAY G. A., WIESMANN H., NYQUIST L. E., WOODEN J. L. and BANSAL B. M. (1978) Petrology, chemistry, and chronology of 14078: Chemical constraints on the origin of KREEP. *Proc. Lunar Planet. Sci. Conf. 9th*, 661–687.

MCKAY G. A., WIESMANN H., BANSAL B. M. and SHIH C.-Y. (1979) Petrology, chemistry, and chronology of Apollo 14 KREEP basalts. *Proc. Lunar Planet. Sci. Conf. 10th*, 181–205.

MCKAY G. A., WAGSTAFF J. and YANG S.-R. (1986) Zr, Hf, and REE partition coefficients for ilmenite and other minerals in high-Ti lunar mare basalts: An experimental study. *Proc. Lunar Planet. Sci. Conf. 16th; J. Geophys. Res.* **91**, D229–D237.

MEYER C. (1972) Mineral assemblages and the origin of non-mare lunar rock types (abstr.). *Lunar Planet. Sci. III*, 542–544.

MEYER C. and HUBBARD N. J. (1970) High potassium, high phosphorus glass as an important rock type in the Apollo 12 soil samples (abstr.). *Meteoritics* **5**, 210–211.

MEYER C., BRETT R., HUBBARD N. J., MORRISON D. A., MCKAY D. S., AITKEN D. A., TAKEDA H. and SCHONFIELD E. (1971) Mineralogy, chemistry, and origin of the KREEP component in soil samples from the Ocean of Storms. *Proc. Lunar Sci. Conf. 2nd*, 393–411.

MORRIS R. V., WARNER J. L., MCKAY D. S. and BROWN R. W. (1977) Nearly pure Apollo 12 KREEP: Soil sample 12023. *Proc. Lunar Sci. Conf. 8th*, 2449–2458.

NASLUND H. R. (1976) Liquid immiscibility in the system $KAlSi_3O_8$-$NaAlSi_3O_8$-FeO-Fe_2O_3-SiO_2 and its application to natural magma systems. *Carnegie Inst. Wash. Yearb.* **75** (for 1975–1976), 592–597.

NAVA D. F. and PHILPOTTS J. A. (1973) A lunar differentiation model in light of new chemical data on Luna 20 and Apollo 16 soils. *Geochim. Cosmochim. Acta* **37**, 963–973.

NEAL C. R. and TAYLOR L. A. (1988a) "K-Frac + REEP-Frac": A new understanding of KREEP in terms of granite and phosphate petrogenesis (abstr.). *Lunar Planet. Sci. XIX*, 831–832.

NEAL C. R. and TAYLOR L. A. (1988b) A re-evaluation of olivine vitrophyre petrogenesis. *Lunar Planet. Sci. XIX*, 839–840.

NEAL C. R. and TAYLOR L. A. (1989) The nature of barium partitioning between immiscible melts: A comparison of experimental and natural systems with reference to lunar granite petrogenesis. *Proc. Lunar Planet. Sci. Conf. 19th* (in press).

NEAL C. R., TAYLOR L. A. and LINDSTROM M. M. (1988a) Apollo 14 mare basalt petrogenesis: Assimilation of KREEP-like components by a fractionating magma. *Proc. Lunar Planet. Sci. Conf. 18th*, 139–153.

NEAL C. R., TAYLOR L. A. and LINDSTROM M. M. (1988b) The importance of lunar granite and KREEP in Very High Potassium (VHK) basalt petrogenesis. *Proc. Lunar Planet. Sci. Conf. 18th*, 121–137.

NYQUIST L. E., HUBBARD N. J., GAST P. W., CHURCH S. E., BANSAL B. M. and WIESMANN H. (1972) Rb-Sr systematic for chemically defined Apollo 14 breccias. *Proc. Lunar Sci. Conf. 3rd*, 1515–1530.

NYQUIST L. E., HUBBARD N. J., GAST P. W., BANSAL B. M., WIESMANN H. and JAHN B.-M. (1973) Rb-Sr systematics for chemically defined Apollo 15 and 16 materials. *Proc. Lunar Sci. Conf. 4th*, 1823–1846.

NYQUIST L. E., BANSAL B. M., WIESMANN H. and JAHN B.-M. (1974) Taurus-Littrow chronology: Some constraints on early lunar crustal development. *Proc. Lunar Sci. Conf. 5th*, 1515–1539.

PAPANASTASSIOU D. A. and WASSERBURG G. J. (1971) Rb-Sr ages of igneous rocks from the Apollo 14 mission and the age of the Fra Mauro formation. *Earth Planet. Sci. Lett.* **12**, 36–48.

PRINZ M., DOWTY E., KEIL K. and BUNCH T. E. (1973) Mineralogy, petrology, and chemistry of lithic fragments from Luna 20 fines: Origin of the cumulate ANT suite and its relationship to high alumina and mare basalts. *Geochim. Cosmochim. Acta* 37, 979–1006.

QUICK J. E., ALBEE A. L., MA M.-S., MURALI A. V. and SCHMITT R. A. (1977) Chemical compositions and possible immiscibility of two silicate melts in 12013. *Proc. Lunar Sci. Conf. 8th,* 2153–2189.

ROEDDER E. (1951) The system K₂O-MgO-SiO₂. *Amer. J. Sci.* **249,** 81–130.

ROEDDER E. (1978) Silicate liquid immiscibility in magmas and in the system K₂O-FeO-Al₂O₃-SiO₂: An example of serendipity. *Geochim. Cosmochim. Acta* **42,** 1597–1617.

ROEDDER E. and WEIBLEN P. W. (1970) Lunar petrology of silicate melt inclusions, Apollo 11 rocks. *Proc. Apollo 11 Lunar Sci. Conf.,* 801–837.

ROEDDER E. and WEIBLEN P. W. (1971) Petrology of silicate melt inclusions, Apollo 11 and Apollo 12 and terrestrial equivalents. *Proc. Lunar Sci. Conf. 2nd,* 507–528.

RUTHERFORD M. J. and HESS P. C. (1975) Origin of lunar granites as immiscible liquids (abstr.). *Lunar Planet. Sci. VI,* 696–698.

RUTHERFORD M. J., HESS P. C. and DANIEL G. H. (1974) Experimental liquid line of descent and liquid immiscibility for basalt 70017. *Proc. Lunar Sci. Conf. 5th,* 569–583.

RUTHERFORD M. J., HESS P. C., RYERSON F. J., CAMPBELL H. W. and DICK P. A. (1976) The chemistry, origin, and petrogenetic implications of lunar granite and monzonite. *Proc. Lunar Sci. Conf. 7th,* 1723–1740.

RYDER G. (1976) Lunar sample 15405: Remnant of a KREEP-Granite differentiated pluton. *Earth Planet. Sci. Lett.* **29,** 255–268.

RYDER G. (1987) Petrographic evidence for nonlinear cooling rates and a volcanic origin for Apollo 15 KREEP basalts. *Proc. Lunar Planet. Sci. Conf. 17th; J. Geophys. Res.* **92,** E331–E339.

RYDER G. and SPUDIS P. (1987) Chemical composition and origin of Apollo 15 impact melts. *Proc. Lunar Planet. Sci. Conf. 17th; J. Geophys. Res.* **92,** E432–E446.

RYDER G. and NORMAN M. (1978) *Catalog of Pristine Non-Mare Materials, Part 1.* Non-Anorthosites. JSC Publ. 14565. Johnson Space Center, Houston.

RYERSON F. J. and HESS P. C. (1978) Implications of liquid-liquid distribution coefficients to mineral-liquid partitioning. *Geochim. Cosmochim. Acta* **42,** 921–932.

RYERSON F. J. and HESS P. C. (1980) The role of P₂O₅ in silicate melts. *Geochim. Cosmochim. Acta* **44,** 611–624.

SALPAS P. A., SHERVAIS J. W., KNAPP S. A. and TAYLOR L. A. (1985) Petrogenesis of lunar granites: The result of apatite fractionation (abstr.). *Lunar Planet. Sci. XVI,* 726–727.

SALPAS P. A., TAYLOR L. A. and LINDSTROM M. M. (1987) Apollo 17 KREEPy basalts: Evidence for nonuniformity of KREEP. *Proc. Lunar Planet. Sci. Conf. 17th; J. Geophys. Res.* **92,** E340–E348.

SETTLER A., EBERHARDT P., GEISS J., GROGLER N. and MAURER P. (1973) Ar³⁹-Ar⁴⁰ ages and Ar³⁷-Ar³⁸ exposure ages of lunar rocks. *Proc. Lunar Sci. Conf. 4th,* 1865–1888.

SHERVAIS J. W. and TAYLOR L. A. (1983) Micrographic granite: more from Apollo 14 (abstr.). *Lunar Planet. Sci. XIV,* 696–697.

SHERVAIS J. W., TAYLOR L. A., LAUL J. C. and SMITH M. R. (1984) Pristine highland clasts in consortium breccia 14305: Petrology and geochemistry. *Proc. Lunar Planet. Sci. Conf. 15th; J. Geophys. Res.* **89,** C25–C40.

SHERVAIS J. W., TAYLOR L. A., LAUL J. C., SHIH C.-Y. and NYQUIST L. E. (1985a) Very High Potassium (VHK) basalt: Complications in mare basalt petrogenesis. *Proc. Lunar Planet. Sci. Conf. 16th; J. Geophys. Res.* **90,** D3–D18.

SHERVAIS J. W., TAYLOR L. A. and LINDSTROM M. M. (1985b) Apollo 14 mare basalts: Petrology and geochemistry of clasts from consortium breccia 14321. *Proc. Lunar Planet. Sci. Conf. 15th; J. Geophys. Res.* **90,** C375–C395.

SHERVAIS J. W., TAYLOR L. A. and LINDSTROM M. M. (1988) Olivine vitrophyres: A nonpristine high-Mg component in Lunar breccia 14321. *Proc. Lunar Planet. Sci. Conf. 18th,* 45–57.

SHIH C.-Y. (1977) Origins of KREEP basalts. *Proc. Lunar Sci. Conf. 8th,* 2375–2401.

SHIH C.-Y., NYQUIST L. E., BOGARD D. D., WOODEN J. L., BANSAL B. M. and WIESMANN H. (1985) Chronology and petrogenesis of a 1.8 g lunar granite clast: 14321,1062. *Geochim. Cosmochim. Acta* **49,** 411–426.

TAYLOR G. J., WARNER R. E., KEIL K., MA M.-S. and SCHMITT R. A. (1980) Silicate liquid immiscibility, evolved lunar rocks and the formation of KREEP. In *Proc. Conf. Lunar Highlands Crust* (eds. J. J. PAPIKE and R. B. MERRILL), pp. 339–352. Pergamon.

TAYLOR S. R. (1982) *Planetary Science: A Lunar Perspective.* Lunar and Planetary Institute, Houston, 481p.

TERA F. and WASSERBURG G. J. (1974) U-Th-Pb systematics on lunar rocks and inferences about lunar evolution and the age of the Moon. *Proc. Lunar Sci. Conf. 5th,* 1571–1599.

TERA F., PAPANASTASSIOU D. A. and WASSERBURG G. J. (1974) Isotopic evidence for a terminal lunar cataclysm. *Earth Planet. Sci. Lett.* **22,** 1–21.

TURNER G., CADOGAN P. H. and YONGE C. J. (1973) Argon selenochronology. *Proc. Lunar Sci. Conf. 4th,* 1889–1914.

VANIMAN D. T. and PAPIKE J. J. (1980) Lunar highland melt rocks: Chemistry, petrology, and silicate mineral chemistry. *Proc. Conf. Lunar Highlands Crust,* (eds. J. J. PAPIKE and R. B. MERRIL), pp. 271–337. Pergamon.

WÄNKE H., PALME H., KRUSE H., BADDENHAUSEN H., CENDALES M., DREIBUS G., HOFMEISTER H., JAGOUTZ E., PALME C., SPETTEL B. and THACKER R. (1976) Chemistry of lunar highland rocks: A refined evaluation of the composition of the primary matter. *Proc. Lunar Sci. Conf. 7th,* 3479–3499.

WÄNKE H., BADDENHAUSEN H., BLUM K., CENDALES M., DREIBUS G., HOFMEISTER H., KRUSE H., JAGOUTZ E., PALME C., SPETTEL B., THACKER R. and VILCSEK E. (1976) On the chemistry of lunar samples and achondrites. Primary matter in the lunar highlands: A re-evaluation. *Proc. Lunar Sci. Conf. 8th,* 2191–2213.

WARNER R. D., TAYLOR G. J., MANSKER W. L. and KEIL K. (1978a) Clast assemblages of possible deep-seated (77517) and immiscible-melt (77538) origins in Apollo 17 breccias. *Proc. Lunar Planet. Sci. Conf. 9th,* 941–958.

WARNER R. D., TAYLOR G. J., KEIL K., PLANNER H. N., NEHRU C. E., MA M.-S. and SCHMITT R. A. (1978b) Green glass vitrophyre 78526: An impact melt of very low-Ti mare basalt. *Proc. Lunar Planet. Sci. Conf. 9th,* 547–563.

WARREN P. H. (1985) The magma ocean concept and lunar evolution. *Ann. Rev. Earth Planet. Sci.* **13,** 201–240.

WARREN P. H. (1988) The origin of pristine KREEP: Effects of mixing between urKREEP and the magmas parental to the Mg-rich cumulates. *Proc. Lunar Planet. Sci. Conf. 18th,* 233–241.

WARREN P. H. and WASSON J. T. (1979) The origin of KREEP. *Rev. Geophys. Space Phys.* **17,** 73–88.

WARREN P. H., TAYLOR G. J., KEIL K., KALLEYMAN G. W., SHIRLEY D. N. and WASSON J. T. (1983a) Seventh foray: Whitlockite-rich lithologies, a diopside-bearing troctolitic anorthosite, ferroan anorthosites and KREEP. *Proc. Lunar Planet. Sci. Conf. 13th; J. Geophys. Res.* **88,** B151–B164.

WARREN P. H., TAYLOR G. J., KEIL K., SHIRLEY D. N. and WASSON J. T. (1983b) Petrology and chemistry of two "large" granite clasts from the Moon. *Earth Planet. Sci. Lett.* **64,** 175–185.

WARREN P. H., JERDE E. A. and KALLEYMEYN G. W. (1987) Pristine moon rocks: A "large" felsite and a metal-rich ferroan anorthosite. *Proc. Lunar Planet. Sci. Conf. 17th; J. Geophys. Res.* **92,** E303–E313.

WASSON J. T., WARREN P. H., KALLEMEYN G. W. MCEWING C. E., MITTLEFEHLDT D. W. and BOYNTON W. V. (1977) SCCRV, a major component of highlands rocks. *Proc. Lunar Sci. Conf. 8th,* 2237–2252.

WATSON E. B. (1976) Two-liquid partition coefficients: Experimental data and geochemical implications. *Contrib. Mineral. Petrol.* **56,** 119–134.

WATSON E. B. and NASLUND H. R. (1977) The effect of pressure on liquid immiscibility in the system K₂O-FeO-Al₂O₃-SiO₂-CO₂. *Carnegie Inst. Wash. Yearb.* **76** (for 1976–1977), 410–414.

WEIBLEN P. W. and ROEDDER E. (1973) Petrology of melt inclusions in Apollo samples 15598 and 62295, and of clasts in 67915 and several lunar soils. *Proc. Lunar Sci. Conf. 4th,* 681–703.

WYLLIE P. J. (1980) The origin of kimberlite. *J. Geophys. Res.* **85,** 6902–6910.