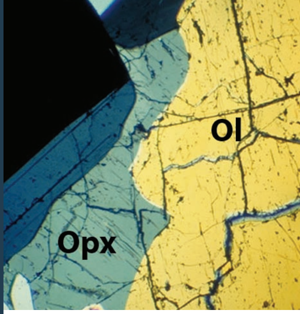

Ancient Lunar Crust: Origin, Composition, and Implications

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1811-5209/08/0005-0017$2.50 DOI: 10.2113/gselements.5.1.17

Samples from the Apollo (USA) and Luna (Soviet) missions and from lunar meteorites, coupled with remote sensing data, reveal that the ancient highlands of the Moon are compositionally diverse. The average surface material contains 80 vol% plagioclase. A major suite of rocks, the ferroan anorthosites, averages 96 vol% plagioclase. The feldspathic composition reflects plagioclase flotation in a magma ocean. Late-stage REE-rich magma pooled in the Procellarum region of the lunar nearside. The concentration of heat-producing elements in this region triggered mantle melting and overturn of the cumulate pile, forming two more suites of chemically distinct highland rocks, the magnesian and alkali suites.

Keywords: lunar highlands, anorthosite, magma ocean, lunar composition, KREEP, Mg-suite

THE BATTERED ASYMMETRIC MOON

The Moon is lopsided. The first images of the farside of the Moon, taken by the Luna 3 spacecraft in October 1959, showed far fewer dark maria than on the familiar Earth-facing hemisphere. The crust is thicker on the farside than on the nearside (e.g. Neumann et al. 1996), and post-Apollo orbital remote sensing data show dramatic chemical differences between hemispheres (Fig. 1). Jolliff et al. (2000) identified three major geochemical provinces. The nearside contains most of the maria (dark lava plains with high FeO content) and hosts a large area strikingly enriched in Th, named the Procellarum KREEP Terrane (PKT). Sample analysis shows that this area has high concentrations of incompatible lithophile elements that correlate with Th, including **K**, the rare earth elements (**REE**), and **P**, giving the acronym KREEP. The farside is dominated by Fe-poor, Al-rich feldspathic rocks generally low in Th, in an area called the Feldspathic Highlands Terrane. The farside is also the site of the huge South Pole–Aitken (SPA) impact basin (2500 km in diameter), which contains more Fe and Th than the rest of the farside, but less than in the PKT.

The highlands were battered by impacts during the Moon's first 600 My or so, creating a jumbled pile of debris. Primary igneous rock bodies were broken, mixed, and melted as impacts stirred the upper several kilometers. Rarer enormous impacts (e.g. South Pole–Aitken basin) excavated the entire crustal column and might even have mixed mantle rock into their ejecta, converting the highland crust into a huge rubble pile. Fortunately, chunks of igneous rocks survived the bombardment and are preserved as clasts inside highland impact breccias. A major achievement by Warren and Wasson (1978) was to devise a set of rules to distinguish an igneous rock from one produced by impact. They dubbed the igneous survivors *pristine* rocks. The criteria for the recognition of igneous rocks include coarse-grained igneous textures, uniform mineral compositions, and low concentrations of siderophile elements such as iridium and silver (siderophile elements tend to concentrate in metallic iron), which were added to breccias by impacting projectiles rich in siderophile elements.

A lot of work has led to the identification of about a hundred pristine rock samples from the highlands (Warren 1993). Some are in the kilogram range, many are small chips, and some are only found in thin sections. This modest rock collection is extremely valuable, however, especially when put in the context of the bulk compositions of breccias and global remote sensing data.

PRISTINE NONMARE IGNEOUS ROCKS

Lunar geochemists generally divide pristine nonmare rocks into three main categories (see reviews by Warren 1993; Papike et al. 1998; and Jolliff et al. 2006). The major groups are the *ferroan anorthosite suite*, the *magnesian suite*, and the *alkali suite*. Modal data and mineral compositions below are from summaries in Jolliff et al. (2006), unless stated otherwise. Most sample data are from Apollo samples, all of which were collected in the Procellarum KREEP Terrane. Meteorites provide information on other areas, especially the farside highlands (Korotev 2005).

Ferroan Anorthosite Suite (FAN Suite) and the Magma Ocean Concept

Ferroan anorthosites were first observed as small rock fragments in the Apollo 11 regolith, which is composed mostly of underlying mare basalt lava flows. Boldly stepping outside the box, Wood et al. (1970) proposed that the fragments came from the highlands, that the highlands were composed mostly of anorthosite, and that the only way such a huge volume of plagioclase-rich rock could form was by accumulating it at the top of a globe-encircling magma. The concept soon acquired the name *magma ocean* and became a central tenet of lunar science. Our view of it became more sophisticated with time, of course (see Jolliff et al. 2006 for summaries of models). Calculations (e.g. Snyder et al. 1992) of the chemical evolution of the magma ocean suggest that the last product was a residual magma charged with trace elements, identified as the KREEP component that characterizes the Procellarum KREEP Terrane.

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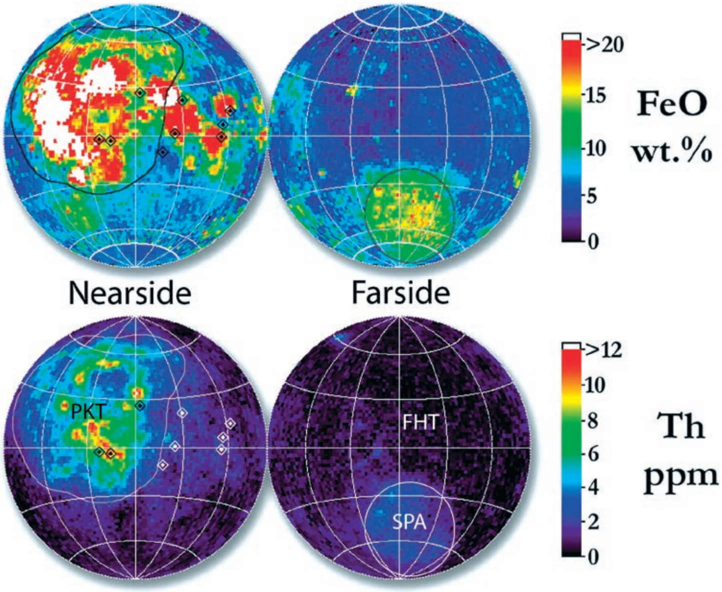

FIGURE 1 Distribution of FeO and Th on the lunar nearside and farside, determined by the Lunar Prospector Gamma-Ray Spectrometer. Three major regions stand out (Jolliff et al. 2000): the high-FeO, high-Th area on the nearside, called the Procellarum KREEP Terrane (PKT); the low-FeO, low-Th areas in the highlands (southern nearside and most of the farside), called the Feldspathic Highlands Terrane (FHT); and the moderate-FeO and moderate-Th South Pole–Aitken Terrane (SPA) on the farside. Diamonds show Apollo and Luna landing sites. MAP COURTESY OF JEFFREY GILLIS-DAVIS (U. HAWAI'I)

Bulk chemical compositions show that the anorthosites are chemically distinct from the other pristine rocks (FIGS. 2 AND 3). As their name implies, they are rich in plagioclase, averaging about 96 vol% plagioclase (see Table 3.2 in Jolliff et al. 2006). FAN suite rocks have high Al_2O_3 concentrations and low molar Mg/(Mg+Fe) (Mg#) and Na/(Na+Ca). The low Mg# for the anorthosites led to calling them *ferroan anorthosites* (FAN suite), while the more magnesian and less feldspathic rocks were classified as the *magnesian suite* (Mg-suite). The FAN suite also contains distinctly lower concentrations of incompatible lithophile elements like La and Th (FIG. 3). Thus, a distinct geochemical bimodality exists among pristine rocks, with ferroan anorthosites constituting one group and everything else making up the other. Along with the geochemical bimodality comes an inferred petrogenetic bimodality: ferroan anorthosites originated from the magma ocean and the others from subsequent magmatic activity.

In spite of the pervasive impact brecciation, surviving textures suggest that FAN rocks are plagioclase cumulates (FIG. 4A). They consist of equant plagioclase crystals up to about 4 mm across with interstitial, locally poikilitic, orthopyroxene or pigeonite (usually inverted) and olivine. Augite generally occurs as exsolution lamellae inside orthopyroxene.

Petrologists subdivided the FAN suite into four subgroups, showing that the FAN suite is complicated, as were the processes than led to its formation. The subgroups are ferroan anorthosites (the most abundant, with a plagioclase composition of $An_{>95}$), sodic anorthosites (An_{92-95}), mafic ferroan rocks (plagioclase abundance is still high, typically >80%, with $An_{>95}$), and mafic magnesian rocks (plagioclase abundance is >75%, with $An_{>95}$). This range in composition suggests that the rocks formed at different stages of crystallization of a chemically complicated magma ocean. However, things may be even more complicated. Takeda et al. (2006) describe a chip of magnesian anorthosite in lunar meteorite Dhofar 489 (sample d2, FIGS. 2 AND 3). The sample has the same low concentrations of incompatible elements and low Na/Ca as the ferroan anorthosites but has a much higher Mg#.

A great advance since the original characterization of pristine rocks is the ability to measure trace-element abundances in individual minerals by ion microprobe analysis (e.g. Shearer and Floss 1999 and references therein). These informative datasets allow us to calculate the trace-element concentrations in the parent magmas from which the FAN suite rocks crystallized. Calculating a parent magma composition from cumulus minerals gives uncertain results because the minerals might have cooled slowly enough for the major and trace elements to redistribute and because of uncertainties in distribution coefficients. Nevertheless, ratios of the compositions of plagioclase to those of coexisting mafic minerals are not far off the ratios of their experimental crystal–liquid distribution coefficients, indicating that the minerals have preserved the record of their crystallization, hence the compositions of their parent magma. Parent magma compositions calculated from plagioclase crystals in FAN rocks (FIG. 5) range from roughly chondritic abundances (ferroan anorthosite subgroup) to progressively more light-REE enriched in the order sodic anorthosites, mafic magnesian, mafic ferroan. This impressive range can be interpreted as indicating multiple parent magmas or just the complexities expected in a fractionating global magma ocean.

FAN rocks have been difficult to date (Norman et al. 2003). Impact events haphazardly heated them, affecting all isotopic systems to some degree. They also contain such small amounts of mafic minerals that it is difficult to obtain an isochron because the range in parent/daughter ratios of mineral separates is limited. Thus, geochronologists have focused on a few regions using a small number of samples that are relatively rich in pyroxene. Sm–Nd isochrons have given a range in ages from 4.29 to 4.54 Ga. This is too large a range for a set of rocks that crystallized from an early, relatively short-lived magma ocean, suggesting instead that a series of magmas led to the formation of the FAN suite. However, Norman et al. (2003) showed that pyroxene data from four FAN rocks fall on a precise isochron of 4.456 ± 0.040 Ga. In contrast, plagioclase data are scattered because plagioclase is much less resistant than pyroxene to isotopic exchange during heating events.

Global remote sensing data show that the highlands crust is not composed of vast areas of anorthosite (Lucey et al. 1995; Prettyman et al. 2006), although most of the farside and southern highlands on the nearside are quite aluminous (FIG. 2B). The largest areas containing over 90% plagioclase are the rings around huge impact basins (Hawke et al. 2003). This suggests that a layer of anorthosite underlies the uppermost highlands crust and that the original crust has been modified by the addition of more-mafic materials on top, either by impacts excavating mafic intrusions and/or by volcanism.

Mg-Suite and the KREEP Connection

KREEP was identified at the Apollo 12 site, which was located in a mare. Besides the mare basalts present, geochemists found breccias decidedly rich (compared to the Apollo 11 materials and Apollo 12 basalts) in K, rare earth elements, phosphorus, and other incompatible trace elements; this elemental assemblage was dubbed KREEP. Eventually it became clear that KREEP is a chemical component that occurs in a variety of rocks, including the Mg-suite, the alkali suite, and some mare basalts. It has a characteristic rare earth element pattern of continuously decreasing abundance from La to Lu, with a chondrite-normalized La/Lu value of 2. Using concentrations in Apollo 14 samples as a guide, Warren and Wasson (1979) estimated the chemical composition of the KREEP component, which they called "urKREEP"; by this term they meant that the component represents the residual liquid left over from crystallization of the lunar magma ocean.

The Mg-suite is enriched in KREEP compared to the ferroan anorthosite suite (Fig. 3). It thus has the unusual attribute of having high concentrations of trace elements coupled with relatively high Mg#. In other words, the major-element fractionation index suggests primitive magmas, but the trace elements indicate evolved magmas. This odd decoupling of major and trace elements is an essential characteristic of the Mg-suite of lunar nonmare rocks and plays a central role in models for the genesis of Mg-suite magmas. Mg-suite rocks are composed of cumulates of plagioclase (typically 50–65 vol%, but up to 80 vol%) and a mafic silicate, either olivine (troctolites, Fig. 4b) or orthopyroxene (norites, Fig. 4c), with a few samples containing augite plus or minus pigeonite (gabbronorites); a few dunites also occur. All the rocks are clearly chemically distinct from FAN rocks (Figs. 2 and 3).

The chronology of the norites and troctolites is not straightforward because of shock events around 3.9 Ga. Only one troctolite has been dated, sample 76535 (Fig. 4b). Except for an older Rb–Sr age, isotopic systems converge on an age of 4.26 Ga (age data are summarized in chapter 5, table 5.6 of Jolliff et al. 2006.). Norites range in age from 4.5 Ga, as old as the FAN suite, down to about 4.1 Ga, indicating a protracted period of Mg-suite magmatism. Thus, the Mg-suite consists mostly of cumulate norites and troctolites that range in trace-element concentrations and age, indicating derivation from numerous magmas.

Ion microprobe measurements of trace elements in individual mineral grains in Mg-suite rocks demonstrate the KREEP connection. Calculated parent-magma compositions (using plagioclase for consistency with FAN suite rocks) generally have the typical downward-sloping REE patterns characteristic of urKREEP (Fig. 5). In addition, some magmas appear to have had REE contents much greater than the hypothetical urKREEP component, yet still retain their magnesian character.

Mg-suite rocks appear to be restricted to the Apollo landing sites, all of which are in or close to the Procellarum KREEP Terrane. Meteorites from the lunar highlands do not appear to contain Mg-suite rocks (Korotev et al. 2003; Korotev 2005), but KREEP-poor varieties from otherwise similar magmas might be present in the highlands (see below). The strong link between the compositions of the Mg-suite parent magmas and their locations in the Procellarum KREEP Terrane suggests that KREEP plays a major role in the origin of the Mg-suite.

The petrogenesis of the Mg-suite has been reviewed by Shearer and Floss (1999) and Shearer and Papike (2005). Several ideas have been proposed, but most investigators focus on two of them. Both hypotheses address the paradoxical combination of high Mg# and high trace-element concentrations. An assimilation model solves the problem by calling on decompression melting of rising, low-density early-magma-ocean cumulates with high Mg#, after which the melt product assimilates the late-magma-ocean product urKREEP. This requires that the Mg# of the resultant magma be high so that the magma is still capable of precipitating magnesian olivine (Fo_{90} or so) after assimilation accompanied by fractional crystallization. If so, the Mg-suite systematically formed from the lowermost part of the

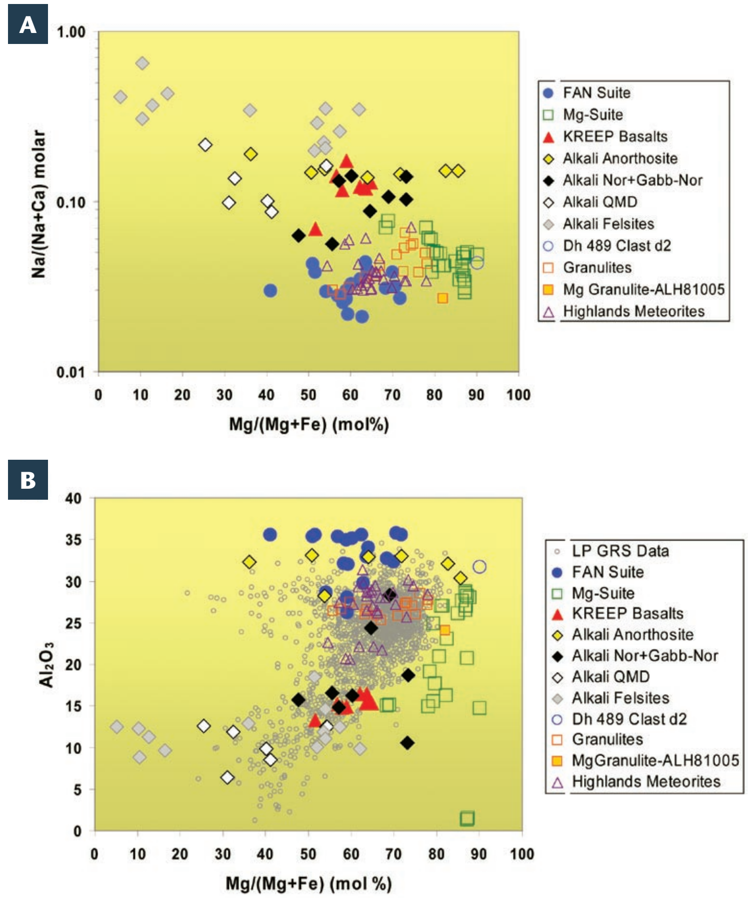

Figure 2 Pristine highland rocks can be distinguished by differences in bulk-rock compositions. Ferroan anorthosites (FAN suite) show a wide range in Mg/(Mg+Fe), though their Mg# values are generally lower than those of the Mg-suite rocks. FAN samples have high Al_2O_3 (**B**) and low Na/(Na+Ca) (**A**) compared to other suites of pristine igneous rocks, indicating that they formed in a different magmatic system. A sample of magnesian anorthosite from lunar meteorite Dhofar 489 (Takeda et al. 2006) plots along an extension of the FAN suite, but at much higher Mg/(Mg+Fe). Granulitic breccias from the Apollo collection and meteorites from the lunar highlands tend to plot between the main groups of pristine rocks, suggesting that they are mixtures of them, but they more likely represent an average highland rock type somewhat more mafic and magnesian than the FAN suite. Abbreviations: KREEP = K-REE-P-rich component; Nor = norite; Gabb-Nor = gabbronorite; QMD = quartz monzodiorite; LP GRS = Lunar Prospector gamma-ray spectrometry data; Anor = anorthosite; Dh = Dhofar 489. Data from Papike et al. (1998), an updated version of Table 2.1 in Jolliff et al. (2006) (supplied by Randy Korotev), Meyer (2008), and Maloy et al. (2005); GRS data from Prettyman et al. (2006)

magma-ocean cumulate pile. An interesting ramification is that magnesian magmas rising on the farside hemisphere would not have KREEP to assimilate (assuming it is concentrated in the Procellarum KREEP Terrane), suggesting that there might be low-KREEP magnesian mafic rocks on the farside of the Moon; the only possibility discovered so far is a spinel-bearing troctolite in lunar meteorite Dhofar 489 (Takeda et al. 2006).

The other model depicts formation of mantle sources that consist of magma-ocean cumulates mixed with late-stage residuum (urKREEP). The deep, low-density, olivine-rich cumulates would rise as the urKREEP sank during a massive overturn of the mantle, forming an olivine–urKREEP hybrid. The resulting hybrid sources would have been heated by the high K, Th, and U concentrations in the KREEP component, causing partial melting. In principle, this process would have been most efficient in the region of the mantle beneath the Procellarum KREEP Terrane.

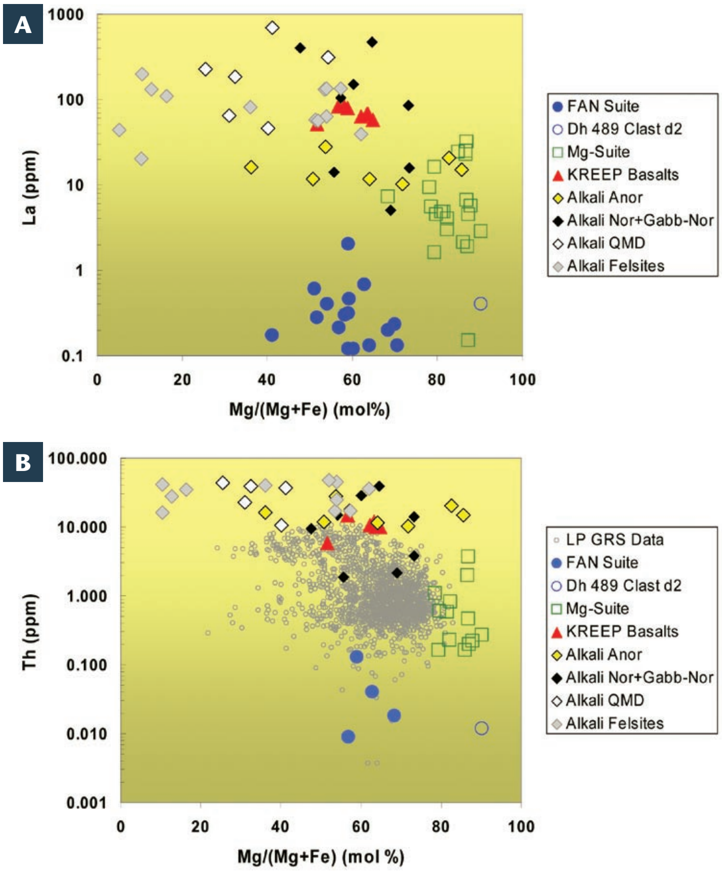

FIGURE 3 Suites of pristine highland rocks differ from each other in their abundances of trace elements. FAN suite rocks and a magnesian anorthosite from Dhofar 489 have low concentrations of La (**A**) and Th (**B**). As in Figure 2, granulites and lunar-highland meteorites plot in between groups of pristine rocks and might represent a reasonable average composition of the ancient lunar highlands. DATA SOURCES LISTED IN THE CAPTION TO FIGURE 2

Alkali Suite and Its Record of Extensive Fractionation

The alkali suite is a catchall for rocks generally enriched in alkalis (by lunar standards; see FIG. 2A). Rock types include KREEP basalts, alkali anorthosites, alkali gabbronorites, quartz monzodiorites, and felsites (also called granitic rocks, although they are not the familiar coarse-grained rocks of terrestrial batholiths); see chapter 4 of Jolliff et al. (2006) for a summary. KREEP basalts are central to understanding this extensive set of rocks. These basalts, found mostly at the Apollo 15 and 17 sites, average about 50 vol% plagioclase, with somewhat less pyroxene (pigeonite and augite) and lesser amounts of a host of minor minerals (K-feldspar, phosphates, ilmenite, zircon, silica polymorphs, and others). They are the closest in appearance and composition to typical terrestrial basalts (FIG. 4D), with subophitic to intersertal textures, Al_2O_3 contents of 13–16 wt%, and Mg# of 52–65 (FIGS. 2 AND 3). REE are high, and the pattern has the typical KREEP La/Lu slope of 2 (chondrite normalized). Some authors (see review by Shearer and Papike 2005) have suggested that KREEP basalts could represent the parent magma for Mg-suite and other alkali suite rocks.

Alkali suite rocks have distinctly higher Na/Ca, La, and Th than other highland igneous rocks, and they have a large range in Mg# (FIGS. 2 AND 3). The general view is that magmas similar to KREEP basalts fractionated to form a series of differentiated rocks and cumulates: alkali anorthosites as plagioclase cumulates ($An_{76–88}$), norites and gabbronorites as pyroxene–plagioclase cumulates, and quartz monzodiorites and felsites as highly fractionated residual magmas. Particularly strong evidence exists that the Apollo 15 quartz monzodiorites formed by fractional crystallization from KREEP basalt magma. Even the Mg-suite norites and troctolites could fit into this picture as cumulates, though a lack of olivine suggests that KREEP basalts do not have olivine on their liquidi. Calculated parent magmas of the alkali suite (determined from ion microprobe analyses of plagioclase) indicate a kinship with urKREEP (FIG. 5) in that they have high REE concentrations and in general a sloping REE pattern.

The felsites (FIG. 4E) provide particularly interesting examples of extensive fractional crystallization; see chapter 4 in Jolliff et al. (2006). The largest sample weighs only 1.8 grams, so felsites might represent late-stage segregations in basaltic magmas, rather than fragments of large differentiated rock bodies. The felsites sometimes occur with FeO-rich portions, suggesting that silicate liquid immiscibility might have played a role in their formation. An important issue is the scale of separation of immiscible melt pairs. Some authors (e.g. Neal and Taylor 1989) argue that the high viscosity of high-Si melts would have made it difficult for them to separate and form large bodies.

Crystallization ages of alkali suite rocks range from 4.3 to 3.8 Ga, thus overlapping those of the Mg-suite but extending to younger ages. KREEP basalts from Apollo 15 are the youngest samples, 3.86–3.82 Ga; KREEP basalts found in Apollo 17 breccias range from 4.08 to 3.93 Ga. Like the Mg-suite, alkali-rich rocks are apparently also confined to the Procellarum KREEP Terrane. Sample studies show that they are not abundant, an observation supported by their high Th concentrations compared to Lunar Prospector gamma-ray spectrometry (GRS) data (FIG. 3B).

CRYPTIC IGNEOUS ROCKS

Two other groups of rocks bear significantly on our understanding of the composition of the ancient highlands crust: granulitic breccias and meteorites from the lunar highlands. All are breccias, but their bulk compositions cannot be explained by mixtures of known pristine rocks (e.g. Korotev et al. 2003), showing that we have not identified all varieties of lunar highlands igneous rocks.

The granulites occur in both the Apollo and Luna samples and in lunar meteorites (Lindstrom and Lindstrom 1986). They tend to have granulitic (metamorphic) textures (FIG. 4F), with high two-pyroxene equilibration temperatures, 1100 ± 50°C. They have a large range in bulk-rock Mg#, from 55 to 78 mol% among Apollo samples (FIG. 2) and up to 82 mol% among clasts in lunar meteorites (Maloy et al. 2005). Equilibration temperatures do not correlate with Mg#. Granulitic breccias are intermediate in trace-element concentrations between FAN suite rocks and Mg-suite rocks. Their high Al_2O_3 contents (averaging about 27 wt%, implying ~75% plagioclase), however, suggests that the dominant protolith was a feldspar-rich norite (leuconorite), possibly representing an important primary highland rock type (Lindstrom and Lindstrom 1986). A magnesian granulite in lunar meteorite ALH 81005 has low La (Maloy et al. 2005), indicating little contribution from Mg-suite rocks. It is possible that many granulites are cumulates from magnesian magmas much poorer in REE than those making up the Mg-suite from the nearside Procellarum KREEP Terrane. The highly magnesian anorthosite sample from Dhofar 489 (FIGS. 2 AND 3) suggests that such trace-element-poor feldspar-enriched protoliths exist on the farside (Takeda et al. 2006). The variation in Mg# in the farside highlands, as shown by the variation in Mg# among granu-

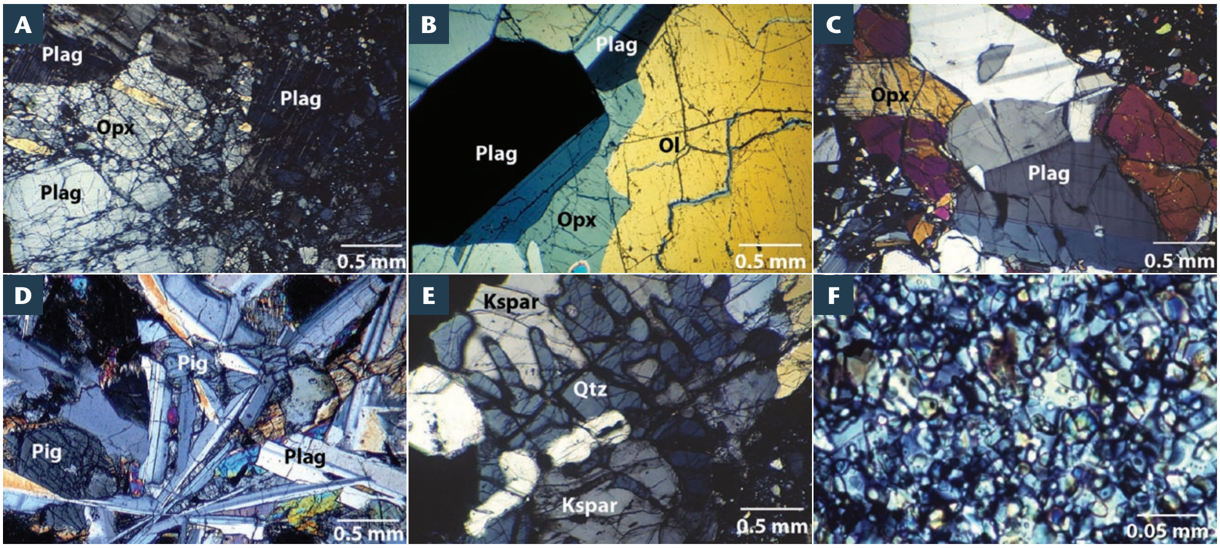

Figure 4 Photomicrographs of pristine highland rocks and a granulite. (**A**) FAN sample 62236,5 is a plagioclase cumulate with intercumulus orthopyroxene (with augite exsolution lamellae). This area is particularly rich in pyroxene; plagioclase comprises 85% of the bulk sample. (**B**) Mg-suite troctolite with cumulate olivine and plagioclase; sample 76535. (**C**) Unbrecciated clast of Mg-suite norite; sample 76255,73. (**D**) KREEP basalt with a subophitic texture characteristic of crystallization in a basaltic lava flow; sample 15386. (**E**) Felsite, showing a graphic intergrowth of quartz and K-feldspar; sample 14321,1047. (**F**) Granulitic breccia consisting of an assemblage of very fine-grained plagioclase, olivine, and orthopyroxene crystals with a hornfelsic texture; sample 79215,71. Abbreviations: Plag: plagioclase; Opx: orthopyroxene; Pig: pigeonite; Qtz: quartz; Kspar: potassium feldspar.

lites, lunar meteorites, and Lunar Prospector GRS data (Fig. 2), suggests that a range of magma types is represented in the highlands. Did all of these magmas originate in the magma ocean, as suggested by Arai et al. (2008)? If such magnesian rocks are endemic to the lunar highlands, the conventional view of the magma ocean as a global process may not be correct or at least is more complicated than we think (e.g. Arai et al. 2008). Or, did some granulite protoliths form after magma-ocean crystallization? Or, did almost all the crustal rocks we have sampled, even the ferroan anorthosites, form after a magma-ocean event (e.g. Longhi 2003)?

Korotev et al. (2003) and Korotev (2005) emphasize the possibility that magnesian, feldspathic rocks are common on the farside. Bulk lunar highland meteorites (defined here as those with >20 wt% Al_2O_3) vary in Mg# as widely as do the granulites and trend to lower trace-element concentrations (Fig. 3). Their average Al_2O_3 content is 28.5 wt%, somewhat more than the granulites, corresponding to ~80 wt% plagioclase. It seems clear that feldspathic rocks with a wide range in Mg# and relatively low concentrations of incompatible trace elements dominate the farside highlands. It is not clear, however, whether these represent magma-ocean cumulates, cumulates from trace-element-poor magnesian mafic magmas, or complicated impact-induced mixtures of assorted magnesian lithologies.

IMPLICATIONS FOR CRUSTAL EVOLUTION AND LUNAR BULK COMPOSITION

Data obtained from lunar samples and remote sensing clearly point towards formation of a primary crust by plagioclase flotation in a magma ocean. Besides the important arguments summarized in Warren (1985), such as the Eu anomaly in mare basalts, current data indicate that the highlands average about 80% plagioclase, at least in the upper several kilometers. Large outcrops of anorthosite in basin rings indicate that the crust is probably richer in feldspar at depth (e.g. Hawke et al. 2003). Thus, the entire crust has an excess of plagioclase over typical cotectic basaltic magmas, a compositional feature most easily explained by accumulation of plagioclase in a global magma ocean, with corresponding mafic cumulates forming the mantle. Existence of a magma ocean implies a hot origin for the Moon, consistent with the giant impact hypothesis (e.g. Hartmann and Davis 1975).

While we do not understand all the processes that could have operated in such a huge magma system, it seems clear that the magma ocean set the stage for all subsequent magmatic activity on the Moon. It led to formation of the

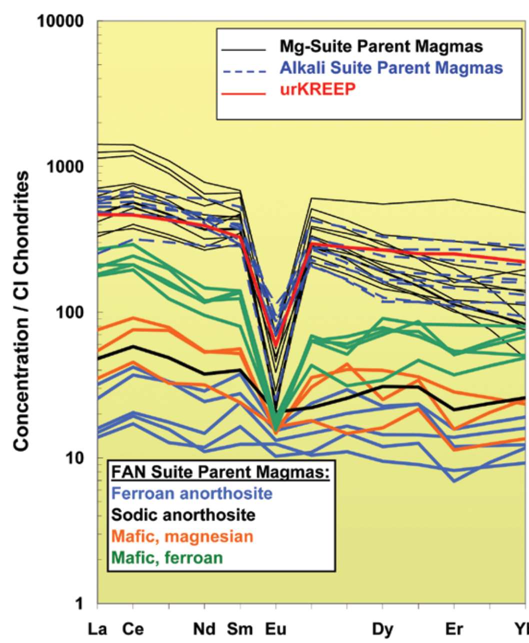

Figure 5 REE concentrations in parent magmas calculated from ion microprobe analyses of plagioclase in the four subgroups of the FAN suite, in Mg-suite rocks, and in alkali rocks, with the urKREEP pattern shown for comparison. The original plagioclase data are in papers cited by Shearer and Floss (1999) and Shearer and Papike (2005). Except for the mafic, ferroan subgroup of the FAN suite, the parent magmas of the remainder of the FAN suite appear to have had roughly chondritic abundances and only small Eu anomalies. The parent magma of the mafic ferroan subgroup is more evolved. Mg-suite and alkali suite parent magmas appear to have a kinship with KREEP.

source regions in the mantle for the other types of highland rocks and for the mare basalts. Although we do not know what caused the asymmetric distribution of KREEP, the magma ocean almost certainly played an important role. In turn, the regional concentration of radioactive elements affected the course of magmatism beneath the Procellarum KREEP Terrane (e.g. Wieczorek and Phillips 2000), yet another contribution of the magma ocean to lunar geochemical evolution.

The magmas associated with the Procellarum KREEP Terrane were diverse in composition, as shown most prominently by the variation in Mg# and concentrations of incompatible elements among Mg-suite and alkali-suite samples. PKT magmatism was as diverse as mare basalt magmatism. The nearside lunar mantle—the complex cumulate pile formed from the magma ocean and then probably overturned—was (and is) heterogeneous on a large scale. It seems likely that the mantle beneath the farside highlands is different from the nearside mantle, certainly in the abundances of incompatible elements. It is not certain if mafic intrusions are abundant in the farside feldspathic highlands (a rare example is a spinel troctolite in a lunar meteorite; Takeda et al. 2006), but if not, why was magma generation in the farside mantle so unproductive? Formation of primary planetary crust and its complementary mantle is a complicated and messy business.

The high Al_2O_3 content of the lunar highlands is an important data point in estimating the lunar bulk composition (crust plus mantle), especially in trying to assess whether the Moon is enriched in refractory elements compared to the bulk silicate Earth. Estimates fall into two categories (summarized by Taylor et al. 2006): no enrichment, or enrichment by at least 50%. This is important for understanding the processes that might have operated during planetary accretion and in the proto-lunar disk surrounding the Earth after the Moon-forming impact. While the thickness of the crust is uncertain, the high Al_2O_3 content of the highlands requires that the mantle contain no more than 1 wt% Al_2O_3 if the Moon is not enriched in refractory elements (Taylor et al. 2006). On the basis of geochemical signatures in some mare volcanic glasses, Neal (2001) postulated that the lunar mantle below ~500 km contains 2–3% garnet, which has implications for the bulk lunar Al_2O_3 content. This may be testable with a global seismic network.

ACKNOWLEDGMENTS

I thank Randy Korotev for an updated compilation of lunar meteorite compositions, Randy Korotev, Chip Shearer, and Clive Neal provided useful and insightful reviews. Supported by NASA grants NNG05GF68G to K. Keil and NNX08AY88G to G. J. Taylor.

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