HIGHLAND CRUST AT THE APOLLO 14 SITE: A REVIEW

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Recent petrologic studies of pristine nonmare samples from the Apollo 14 site have demonstrated the unique character of the western highlands crust. Many of the lithologies which occur here are not found at other highland sites or represent unique variations of more common lithologies. Rare highland samples found at the Apollo 12 site have petrologic and geochemical affinities with the Apollo 14 highland suite and the two sites taken together constitute what can be called the Western Highland Province. Rocks of the Western Highland Province are geochemically distinct from similar lithologies found at eastern highland sites (Apollo 15, Apollo 16, Apollo 17, and the Luna sites) -- a fact which adds further complications to current petrogenetic models for the lunar crust (e.g., [1]; [2]; [3]). Nonetheless, an understanding of how the Western Highlands Province formed and why it differs from highland crust in the east is crucial to our overall understanding of primordial lunar differentiation and petrogenesis.

OCCURRENCE: Highland plutonic rocks at the Apollo 14 site occur only as clasts in the crystalline-matrix Fra Mauro breccia (e.g., 14304, 14305, 14321) or in younger regolith breccias (e.g., 14312, 14318). Many of these clasts have rims of an older, dark breccia matrix attached, which shows that these rocks have been effected by at least two or three episodes of brecciation. Texturally the clasts vary from cataclasites with no surviving primary textures, to texturally pristine clasts with well preserved igneous textures. The texturally pristine clasts are generally chemically pristine as well, unless they have been invaded by thin glass veins of melt rock. Many texturally pristine clasts are known only from thin section and electron microprobe study, and no chemical data are available. Pristinity of the cataclasites must be evaluated chemically using siderophile element concentrations and the cut-off values for siderophile contamination suggested by Warren and Wasson [4].

LITHOLOGIES: Three distinct suites of plutonic rock are important at the Apollo 14 site: the Magnesian suite, the Alkali suite, and a variety of evolved lithologies. The Magnesian suite can be further subdivided into the olivine-bearing magnesian troctolite association (which includes troctolite, anorthosite, dunite, and pyroxene-bearing troctolites) and the less abundant magnesian norite association (which includes norites, olivine norites, gabbronorites, and ilmenite gabrros/norites). Ferroan anorthosites ("FAN"), which dominate highland suites in some eastern provinces (Apollo 15, Apollo 16) are rare in the Western Highland Province. Each of these suites, including FAN, will be considered here in order of their relative abundance.

MAGNESIAN SUITE

Magnesian Troctolite Association: The magnesian troctolite association includes a variety of olivine-bearing rocks characterized by relatively calcic plagioclase compositions (An93-96) and a range in olivine compositions (Fo75-90). *Troctolite* is the most common lithology in this association, with modes around 30-40% olivine and 60-70% plagioclase ([1]; [5]; [2]; [6]; [7]). More mafic compositions with 50-60% olivine are less common (e.g., [7]; [11]), but troctolitic anorthosites with 10-15% olivine and 85-90% plagioclase are widespread ([5]; [8]; [9]). A few troctolites also contain minor enstatite and diopside. Other important members of the Apollo 14 magnesian troctolite association include magnesian anorthosite, dunite, and pyroxene-rich troctolite.

Magnesian anorthosites are relatively new additions to the Mg-rich suite ([9]; [7]). These rocks are characterized by plagioclase-rich modes (90-99% plagioclase) with mineral compositions similar to the Mg-troctolites: An94-97 plagioclase with minor Fo84-90 olivine. An REE-rich Ca-phosphate phase (probably whitlockite) forms a large, 500 x 120 micron, anhedral grain in one of these anorthosites ([7] [19]) and may contain almost all of the REE found in this samples.

Dunite is another rare but important member of the magnesian troctolite association. Two small dunite clasts have been found to date: one in breccia 14321 ([7]), the other in breccia 14304 ([11]). Both consist of nearly pure Fo88-89 olivine with almost no compositional variation either within or between the two clasts.

Two *pyroxene-rich troctolite* clasts have also been found. One is an anorthositic troctolite with 80% plagioclase, 15% olivine, and 5% diopside, the other is a mafic troctolite with 46% plagioclase, 47% olivine, 7% enstatite, and minor Cr-pleonaste [8,9,10]. Mineral compositions are similar in both, with An94-95 plagioclase, Fo88-89 olivine, and pyroxene Mg#s (= 100*Mg/[Mg+Fe]) of 90. The Mg-rich compositions of the olivines and coexisting pyroxenes indicates that the parent magmas reached pyroxene saturation early in their fractionation history, prior to extensive olivine fractionation. In addition, the stable coexistence of olivine-enstatite and enstatite-spinel (both in discrete grains and in enstatite-spinel symplectites) indicates that crystallization occurred relatively deep in the crust, where the four-phase assemblage ol-plg-opx-sp was stable [8,9,10].

Hunter and Taylor [5] were first to notice a compositional gap between two troctolite subgroups (figure 1). Group I troctolites tend to have more mafic-rich modes and more magnesian phase compositions (olivine Fo85-90); Group II troctolites are more felsic modally and have more Fe-rich mineral compositions (olivine Fo74-81). All of the minor lithologies discussed above plot with the Group I troctolites. Only one sample of Group II troctolite has been analyzed chemically (14321 c2 -- [2]). Its incompatible element abundances are in the same range as the more numerous Group I troctolites.

Magnesian Norite Association: The magnesian norite association contains a diverse assemblage of rocks referred to as ilmenite gabbros, ilmenite norites, and gabbronorites [3,5,8,11]. Only four clasts have been described so far that can be considered unequivocably part of the Mg-suite: norite 14063 ,61 [5], gabbronorite 14304 ,125 [11], olivine norite 14318 ,149 [6], and olivine norite 14305 ,489 [12]. These rocks have modes with subequal portions of plagioclase and pyroxene -- generally pigeonite with minor augite. Ilmenite is a common accessory phase in some of these clasts, along with Ti-spinel, Fe-metal, and troilite. Plagioclase compositions are around An87-90 and mafic silicates have Mg#s between 70-75. One a plot of An content of plagioclase versus Mg# of mafic silicate (figure 1), these rocks plot between rocks of the magnesian troctolite association and the alkali suite.

Several clasts in breccias 14303, 14304, and 14305 are gabbronorites with An90-95 plagioclase and relatively Fe-rich mafic silicates with Mg#s 65-70 [8,11,12]. These rocks generally have orthocumulate or mesocumulate textures, with primocrysts of plagioclase and pigeonite surrounded by post-cumulus feldspar, pigeonite, augite, ilmenite, and Ti-spinel. Their modes are similar to the magnesian norites described above, but they plot *below* the Mg-suite field on an An-Mg# diagram, between the magnesian norites and the ferroan anorthosite field (figure 1). This is the same region where Apollo 14 mare basalts plot, suggesting that some of these gabbronorites may be cumulates derived from aluminous pigeonite basalts (e.g., [8]). Potential mare cumulates are characterized by high modal ilmenite and Ti-rich (TiO_2 > 0.5 wt%) cumulus pigeonites. These rocks also fall on calculated fractionation trends for Mg-suite parent magmas [13] and may be related to the Group II troctolites by fractional crystallization. Gabbronorites with Ti-poor pigeonite and low modal ilmenite may thus be related to more magnesian members of the Mg-suite.

ALKALI SUITE

Alkali Anorthosite/Norite Association: The Alkali suite was first recognized by Warren and Wasson [4] and subsequent studies established it as the second most common highland rock association at the Apollo 14 site [2,5,6,8,9,10]. This suite was once thought to be unique to the Western Highlands Province, but similar alkali gabbronorites are now known from the Apollo 16 site [7,14]. The most common lithologies are anorthosite and norite or gabbronorite; olivine norites are rare.

Alkali anorthosites were the first alkalic highland lithology recognized [1]. Seven true alkali anorthosites are known from Apollo 14 [1,5,9,10,11]. These rocks are characterized by modes of 95-100% plagioclase (An76-86) with minor pigeonite, augite, K-feldspar, ilmenite, silica, whitlockite, and Fe-metal. Mafic silicates have Mg#s 50-70, with the higher Mg#s being augite. Plagioclase primiocrysts are up to 1.5 mm across; accessory phases are generally much smaller. Whitlockite (an REE-rich Ca-phosphate) occurs either as interstitial grains or as small inclusions in plagioclase primocrysts (indicating co-saturation) and may comprise up to 2% modally.

Alkali norites are another common alkalic lithology -- at least six clasts are currently recognized [5,6,8,10,11]. These rocks typically contain 75-85% modal plagioclase (An80-85), but more mafic clasts with 14-40% plagioclase are known. Pigeonite or hypersthene are the most common mafic phases, and may occur either as cumulus primocrysts or as post-cumulus crystals interstitial to plagioclase. Augite, K-feldspar, ilmenite, and whitlockite are common post-cumulus accessory phases; Mg#s in the mafic silicates are typically the same as in the alkali anorthosites (53-63 in pigeonite, 64-68 in augite). Whitlockite is found in most alkali norites and may comprise up to 35% of the mode [10]. As a result, REE in these clasts exhibit a wide range in concentrations.

Two *alkali olivine norites* have been described [12,14]. These rocks contain about 65% modal plagioclase, 25% orthopyroxene or pigeonite, and 5-10% olivine modally, with minor ilmenite, whitlockite, and troilite. Plagioclase compositions are typical of the alkali suite (An78-83), but the mafic silicate compositions are Mg-rich compared to typical alkali norites and anorthosites, with olivine Fo70-80 and pyroxene Mg#s 75-85 (figure 1).

EVOLVED LITHOLOGIES

The most common evolved lithology at Apollo 14, commonly referred to as "lunar granite", is a granophyric intergrowth of quartz and alkali feldspar, either alone, with sodic plagioclase (An60-80). The alkali feldspar vary from nearly pure orthoclase (Or95 Ab5) to a ternary feldspar (Or45 Ab25) which plots in the forbidden zone in a feldspar ternary [15,16,27]. In one small granite clast orthoclase and ternary feldspar both occur as granophyric intergrowths with quartz [27]. Accessory minerals include pigeonite, augite, ferroaugite, fayalite, ilmenite, zircon, and Ca-phosphates (apatite, whitlockite). Variations in mineral assemblages and in mineral compositions (e.g., BaO in alkali feldspars, Mg# in mafics) indicate that at least four distinct parent magmas are involved.

The only age data available at the Apollo 14 site on highland lithologies are from lunar granite 14321, 1027 [16,28]. This granite has been dated at 4.1 Ga using Rb/Sr isochron techniques [28]. Its $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios are the highest yet measured on any lunar material [28].

Granite clasts are relatively common at the Apollo 14 site, which suggests that granite differentiates of mafic plutons are a common and important crustal component in the Western Highlands Province. Based on the abundance of K,Si-rich glasses in Apollo 14 soils and regolith breccias, granites are estimated to comprise 0.5% to 2% of the crust here [17,27].

FERROAN ANORTHOSITES

Ferroan anorthosites are rare at the Apollo 14 site. Only one clast of ferroan anorthosite has been characterized chemically and petrographically [6]. This clast is a monomict cataclasite which consists of nearly 100% plagioclase (An95.5) with relict grains up to 1.3 mm across. Olivine (Fo69) is the only mafic phase.

GEOCHEMISTRY OF THE WESTERN HIGHLANDS PROVINCE

Plutonic rocks of the Western Highlands Province are characterized by high concentrations of incompatible trace elements compared to their eastern counterparts. This characteristic applies to the only FAN clast analyzed to date, as well as to rocks of the magnesian and alkali suites [6]. Despite the fact that whole rock analyses of Apollo 14 plutonic rocks are very sensitive to accessory mineral contents due to the small size of most analyzed samples (< 100 mg), the observed enrichment of incompatible elements in these rocks appears to reflect a fundamental geochemical characteristic of the Western Highlands Province, and is not a spurious effect of sampling problems.

Troctolites, anorthosites, and dunites of the magnesian suite are characterized by a wide range in REE concentrations, with La ranging from 15x to 700x chondrite (figure 2). The highest REE concentrations are found in magnesian anorthosites that contain abundant whitlockite [7,19]. More realistic estimates of crustal composition may be obtained from rocks with the lowest REE contents, but even these are much more enriched than comparable Mg-suite rocks from the east. In addition, parent magma REE concentrations of 3000x (for La) to 1500x (for Lu) chondrite are implied by whitlockite/liquid partition coefficients and the high REE concentrations found in the accessory whitlockite [7,19]. The calculated parent magma REE concentrations are about 10x KREEP --- far to high to have precipitated the observed primitive mineral compositions [7,9,19]. Lindstrom and others [7,19] suggest that the whitlockites may not be in equilibrium with the Mg-suite parent magma. They envisage formation of the phosphates after crystallization from metasomatic fluids which penetrate the rock from below. The source of this fluid and its physical nature (aqueous ? magmatic ?) is not yet resolved.

Rocks of the alkali anorthosite suite are characterized by a similar wide range in REE concentrations, with La from 35x to 600x chondrite (figure 3). As noted in the Mg-suite plutonic rocks, the highest incompatible element concentrations seem to occur in samples with high modal whitlockite and apatite (e.g., [10]). REE concentrations in accessory Ca-phosphate phases are similar to those observed in the Mg-suite rocks -- about 10,000x chondrite. Again, the parent magma composition implied by these concentrations is unrealistically high. In addition, major element compositions of the minerals in the alkali suite are much more evolved than minerals in the Mg-suite rocks, but their accessory phases have nearly identical trace element contents. Clearly, there is no simple explanation to this apparent paradox.

Chemical differences between rocks of the Western Highlands Province and nonmare plutonic rocks from the east are clearly illustrated by a plot of Sm (an incompatible MREE) and Eu (an MREE which is compatible with plagioclase under the reducing conditions found on the moon). Figure 4 shows data for ferroan anorthosites, eastern Mg-suite rocks, western Mg-suite rocks, and western alkalic rocks. Ferroan anorthosites and eastern Mg-suite rocks are characterized by low concentrations of Eu (.5 to 1.0 ppm) and a wide range of Sm concentrations, with Sm in FAN < 0.3 ppm and Sm in the eastern Mg-suite rocks > 0.5 ppm (figure 4). Western Mg-suite rocks have a range in Sm similar to the eastern troctolites (from 2 to 100 ppm Sm) but are enriched in Eu relative to the eastern rocks. Alkali anorthosites are even richer in Eu, with 2 to 10 ppm Eu in rocks with the same Sm content as the Magnesian suite.

ORIGIN OF THE WESTERN HIGHLAND PROVINCE

The high Sm concentrations which characterize plutonic rocks of the Western Highland Province also result in low Ti/Sm and Sc/Sm ratios [1]. These ratios are sub-chondritic, as in KREEP, and suggest derivation of western plutonic suites from an evolved crustal or upper mantle source. Alternatively, these low ratios may reflect the assimilation of residual urKREEP by magmas parental to Mg-suite rocks (e.g., [20]). However, if the incompatible element-rich magnesian suite troctolites, anorthosites, and dunites of Apollo 14 crystallized from Mg-rich magmas that were severely contaminated with urKREEP [20], where did the alkali suite magmas come from ??

Several scenarios can be envisioned for the origin of the western magnesian and alkali suite highland rocks. All of these models have certain attractive features, but none are entirely consistent with what we currently know about the western highland suite. Some possibilities include:

(1) The Mg-suite and alkali suites represent distinct parent magmas, derived from different parts of the lunar mantle, each of which assimilated variable amounts of urKREEP prior to crystallization. This model begs the question of ultimate source, and does not address why there are two distinct parent magmas. It does seem consistent with the gap between the alkali suite and troctolites of the Mg-suite, and with the steep apparent fractionation trends seen in the magnesian troctolite association and in the alkali suite (figure 1). This steep trend in the alkali suite is accentuated by the recent discoveries of primitive olivine norites with typical alkalic plagioclase compositions.

(2) The alkali suite represents Mg-suite magma which has evolved by AFC processes; its high alkali and trace element contents are attributed to relatively large fractions of assimilation. This model has the advantage of one parent magma, and seems in general consistent with the overall trend of the Mg-suite in figure 1. It does not explain, however, why both suites have the same range in trace element concentrations, or why the alkali suite has higher Eu concentrations than either the Mg-suite or KREEP -- fractional crystallization of plagioclase and KREEP assimilation should both act to lower Eu in a residual magma derived from the Mg-suite. It is also puzzling why there are so few Mg-suite norites intermediate to the alkalic rocks and the Mg-troctolites (figure 1). If variable contamination of a single magma was operative, a continuous trend in compositions would be expected.

(3) The alkali suite represents cumulate rocks which crystallized from a KREEP parent magma. This magma was assimilated by Mg-suite parent magmas before they crystallized, or penetrated already crystallized Mg-suite plutons to enrich them metasomatically. It is not clear if the alkali suite cumulate rocks are consistent with this origin, but it does offer an attractive explanation to the contrasts in major and trace element compositions observed between the two suites.

The origin of the evolved lithologies cannot be established with any certainty [15,16,17,27]. Lunar granites are characterized by V-shaped REE patterns with LREE and HREE concentrations 100-200 times chondrite, MREE 100 times chondrite, and significant negative Eu anomalies [15,16,17]. Dickinson and Hess [29] have shown that lunar granites cannot form from KREEP parent magmas because overall REE concentrations are too low in the granites, and because KREEP has a steep negative HREE slope, while granites have a shallow positive slope. Other potential parent magmas include mare basalt, the alkali suite parent magma, and the Mg-suite parent magma [15,16,17,30,31]. The V-shaped REE patterns have been attributed to apatite fractionation [17], but fractional crystallization alone cannot create the observed major and trace element characteristics. In particular, the high K/La ratios of lunar granites seem to require silicate liquid immiscibility at some point in the fractionation history [15,16,17,27,30,31].

WHERE DO WE GO FROM HERE ?

Despite the tremendous increase since 1980 in geochemical and petrologic data on the Western Highlands Province, there are still large gaps in our understanding of how the western crust formed, and why it is different from the eastern crust. Since much of this uncertainty revolves around KREEP, a major priority should be detailed studies which focus on the origin of KREEP, its geochemistry, and its phase relations. In addition, age data is virtually nonexistent on highland lithologies at Apollo 14. Age data are critical to understanding how the alkali suite and Mg-suite rocks are related to one another, and to the aluminous mare basalts which are common at this site (e.g., [21,22,23]. The Apollo 14 aluminous mare basalts range in age from 3.75 to 4.3 Ga -- the same age inferred for many highland crustal rocks [24,25,26]. The relationship between this early mare volcanism and crust forming-processes needs to be thoroughly explored. In addition to these efforts, more data are needed on the variety of highland rock types present at the Apollo 14 site, with special emphasis on integrating whole rock chemistry with phase chemistry (e.g., [19]). The question of possible metasomatism must be addressed, including the specific transport mechanism and the source of the metasomatic fluid.

The unique nature of the highland suite at Apollo 14 provides an exciting opportunity to investigate variations in the lunar crust which formed during the earliest stages of lunar differentiation and perhaps earlier, during accretion. Understanding the origin of these primordial variations in the lunar crust will increase our understanding of how planetary crusts form and evolve, and should give us important insights into the early evolution of the Earth as well.

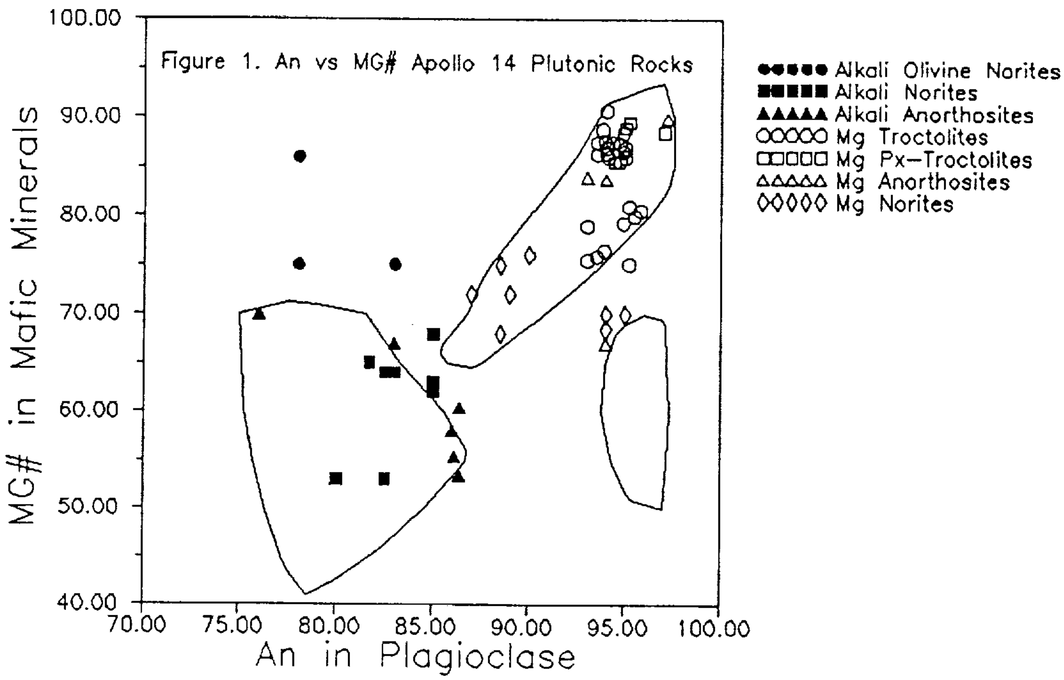

Figure 1. An in plagioclase versus MG# in mafic mineral for plutonic rocks from the Apollo 14 site. Mg-suite rocks are shown in open symbols, as are norites which plot between the Mg-suite data field and the FAN data field. Alkali suite rocks are shown in filled symbols.

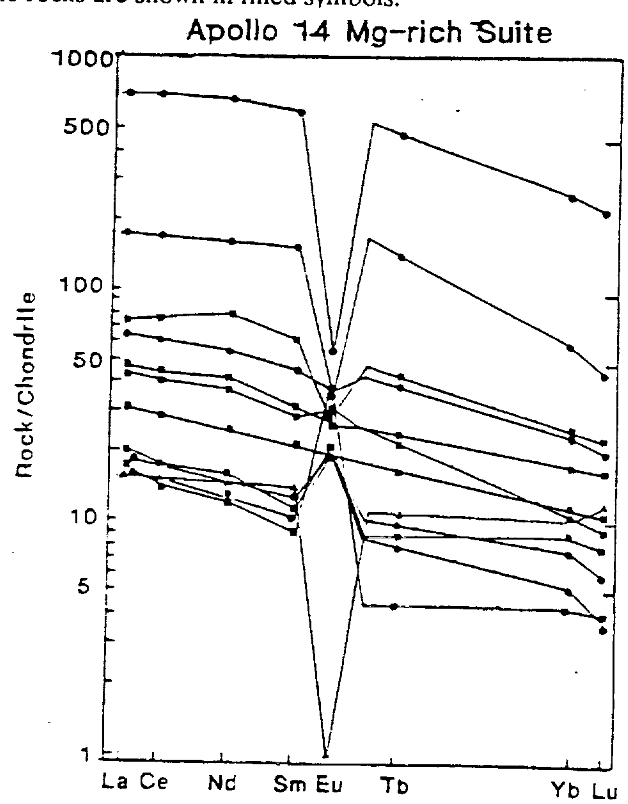

Figure 2. Chondrite-normalized REE patterns for Magnesian suite troctolites (squares), anorthosites (circles), and a dunite (triangle). After Shervais and Taylor, 1985.

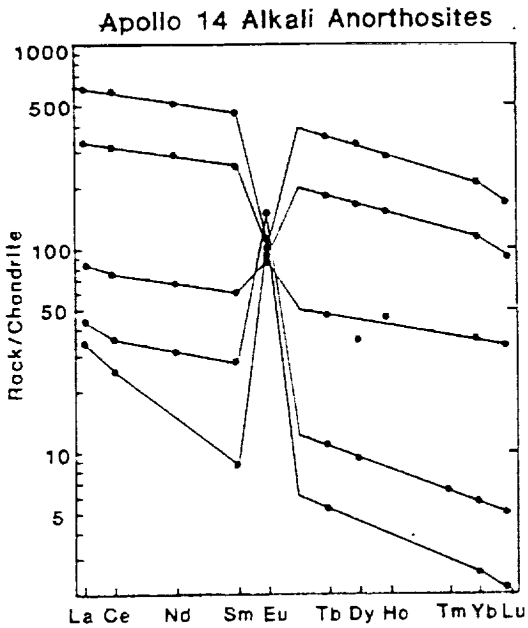

Figure 3. Chondrite-normalized REE patterns for representative alkali suite anorthosites and norites. After Shervais and Taylor, 1985.

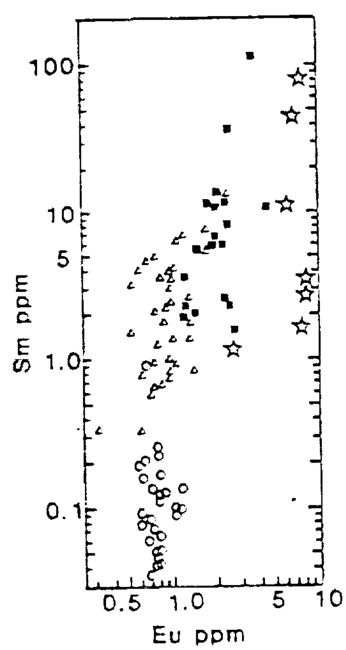

Figure 4. Sm vs Eu plot, with data for eastern ferroan anorthosites (open circles), eastern Mg-suite rocks (open triangles), western Mg-suite rocks (filled squares), and western alkali suite rocks (Stars). Western rocks are characterized by higher concentrations of Eu relative to Sm than equivalent eastern rocks.

REFERENCES

[1] Warren P.H. and Wasson J.T. (1980) Further foraging for pristine nonmare rocks: Correlations between geochemistry and longitude. *Proc. Lunar Planet. Sci. Conf. 11th*, pp. 431-470.

[2] Warren P.H., Taylor G.J., Keil K., Marshall C., Wasson J.T. (1981) Foraging westward for pristine nonmare rocks: Complications for petrogenetic models. *Proc. Lunar Planet. Sci. 12B*, pp. 21-40.

[3] Shervais, J.W. and Taylor, L.A. (1986) Petrologic constraints on the origin of the Moon; in W.K. Hartman, R.J. Phillips, and G.J. Taylor (eds) Origin of the Moon, LPI Houston, 173-202.

[4] Warren P.H. and Wasson J.T. (1977) Pristine nonmare rocks and the nature of the lunar crust. *Proc. Lunar Sci. Conf. 8th*, pp. 2215-2235.

[5] Hunter, R.H. and Taylor, L.A. (1983) The magma ocean from the Fra Maurto shoreline: An overview of the Apollo 14 crust; Proc. 13th Lunar and Planet. Sci. Conf., J. Geophys. Res. Supl., 88, A591-A602.

[6] Warren P.H., Taylor G.J., Keil K., Kallemeyn G.W., Rosener P.S., and Wasson J.T. (1983a) Sixth foray for pristine nonmare rocks and an assessment of the diversity of lunar anorthosite. *Proc. Lunar Planet. Sci. Conf. 13th*, in *J. Geophys. Res., 88,* A615-A630.

[7] 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. 15th Lunar and Planet. Sci. Conf., J. Geophys. Res. Supl, 89, C41-C49.

[8] Shervais J.W., Taylor L.A., and Laul J.C. (1983) Ancient crustal components in the Fra Mauro breccias. *Proc. Lunar Planet. Sci. Conf. 14th*, in *J. Geophys. Res., 88,* B177-B192.

[9] 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*, in *J. Geophys. Res., 89,* C25-C40.

[10] Warren, P.H., Taylor, G.J., Keil, K., Kallemeyn, G.W., Shirley, D. and Wasson, J.T. (1983b) Seventh foray: whitlockite-rich lithologies, a diopside bearing troctolitic anorthosite, ferroan anorthosites, and KREEP, Proc. 14th Lunar and Planet. Sci. Conf., J. Geophys. Res. Supl., 88, A615-A630.

[11] Goodrich C.A., Taylor, G.J., Keil, K., Kallemeyn, G.W., and Warren, P.H. (1986) Alkali norite, troctolites, and VHK mare basalts from breccia 14304. *Proc. Lunar Planet. Sci. Conf. 16th*. In *J. Geophys. Res. 91,* D305-D318.

[12] Neal C.R., Taylor, L.A., and Lindstrom, M.M. (1987) Petrology and geochemistry of highland clasts from Apollo 14 breccias 14303, 14305, and 14321, *Proc. Lunar Planet. Sci. Conf. 18th*, pp. 709-711.

[13] Longhi, J. (1982) Effects of fractional crystallization and cumulus processes on mineral composition trends of some lunar and terrestrial rock series, *Proc. Lunar Planet. Sci. Conf. 13th*, in *J. Geophys. Res., 87,* A54-A64.

[14] James O.B., Lindstrom M.M., and Flohr M.K., (1987) Petrology and geochemistry of alkali gabbronorites from lunar breccia 67975, *J. Geophys. Res., 92,* E314-E330.

[15] Warren, P.H., Jerde E.A., and Kellemeyn G.W., (1987) Pristine moon rocks: A "Large" felsite and a metal-rich ferroan anorthosite, *J. Geophys. Res.*, 92, E303-E313.

[16] Warren P.H., Taylor G.J., Keil K., Shirley D.N., and Wasson J.T. (1983c) Petrology and geochemistry of two large granite clasts from the moon. *Earth Planet. Sci. Lett., 64*, 175-185.

[17] Salpas P. Shervais J.W., and Taylor L.A. (1985) Petrogenesis of lunar granites: The result of apatite fractionation (abstract). In *Lunar and Planetary Sciences XVI*, pp. 726-727. Lunar and Planetary Institute, Houston.

[18] Jerde, E., Warren, P.H., Morris, R.V., Heiken, G. and Vaniman, D.T. (1987) A potpourri of regolith breccias: "New" samples from the Apollo 14, 16, and 17 landing sites; Proc. 17th Lunar and Planet. Sci. Conf., J. Geophys. Res. Supl., 92, E526-E536.

[19] Lindstrom M., Crozaz G., Zinner E., (1985) REE in phosphates from lunar highlands cumulates: an ion probe stude (abstract), in *Lunar and Planetary Science IVI*, pp. 493-494, Lunar and Planetary Institute, Houston.

[20] Warren P.H. (1988) The origin of pristine KREEP: Effects of mixing between UrKREEP and the magmas parental to the Mg-rich cumulates, *Proc. 18th Lunar and Planetary Sci. Conf.*, pp. 233-241.

[21] Dickinson T., G.J. Taylor, K. Keil, R.A. Schmitt, S.S. Hughes, and M.R. Smith, (1985) Apollo 14 aluminous mare basalts and their possible relationship to KREEP, *Proc. Lunar Planet. Sci. Conf. 15th*, in *J. Geophys. Res., 90*, C356-C374.

[22] Shervais J.W., L.A. Taylor, and M.M. Lindstrom (1985a) Apollo 14 mare basalts, petrology and geochemistry of clasts from consortium breccia 14321, *Proc. Lunar Planet. Sci. Conf. 15th*, C-375-395.

[23] Shervais J.W., L.A. Taylor, and J.C. Laul (1985b) Mare basalt petrogenesis: an important link in very high potassium (BHK) basalt, *Proc. Lunar Planet. Sci. Conf. 16th*, in *J. Geophys. Res., 90*, in press.

[24] Shih C.-Y, Nyquist I.E., Bogard D.D., Bansal B.M., Weismann H., Johnson P., Shervais J.W., and Taylor L.A. (1986) Geochronology and petrogenesis of Apollo 14 Very High Potassium mare basalts. *Proc. Lunar Planet. Sci. Conf. 16th*, in *J. Geophys. Res., 91*, D214-D228.

[25] Shih C.-Y, Nyquist I.E., Bogard D.D., Dasch E.J., Bansal B.M., and Weismann H. (1987) Geochronology of high-K aluminous mare basalt clasts from Apollo 14 breccia 14303. *Geochim. Cosmochim. Acta*, in press.

[26] Taylor L.A, J.W. Shervais, R.H. Hunter, C.Y. Shih, L. Nyquist, B. Bansal, J. Woden, and J.C. Laul (1983) Pre-4.2 AE mare basalt volcanism in the lunar highlands, *Earth Planet. Sci. Lett., 66*, 33-47.

[27] Shervais, J.W. and L.A. Taylor (1983b) Micrographic granite: more from Apollo 14 (abstract), in *Lunar and Planetary Science XIV*, pp. 696-697, Lunar and Planetary Institute, Houston.

[28] Shih, C.-Y., L.E. Nyquist, D.D. Bogard, B.M. Bansal, H. Weismann, J.W. Shervais, and L.A. Taylor, Age and petrogenesis of VHK basalts, *Proc. Lunar Planet. Sci. Conf. 16th*, in *J. Geophys. Res., 90*, in press, 1985.

[29] Dickinson, J.E. and P.C. Hess (1983) Role of whitlockite and apatite in lunar felsite. *Lunar and Planetary Science XIV*, pp. 158-159, Lunar and Planetary Institute, Houston.

[30] Neal, C.R. and L.A. Taylor (1987) Lunar granite: an enigma with a new perspective. *Lunar and Planetary Science XVIII*, pp. 704-705, Lunar and Planetary Institute, Houston.

[31] Taylor, G.J., R.D. Warner, K. Keil, M.S. Ma, and R.A. Scmitt (1980) Silicate liquid immiscibility evolved lunar rocks and the formation of KREEP. *Proc. Conf. Highlands Crust*, Merrill and Papike, eds, pp. 339-352, Pergamon, New York.