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THE WESTERN HIGHLAND PROVINCE AT THE APOLLO 14 SITE

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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. 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 (e.g., [1-3]).

MAGNESIAN SUITE: The Magnesian suite consists of two distinct groups, 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). The magnesian troctolite association includes a variety of olivine-bearing rocks; troctolite is the most common lithology, but troctolitic anorthosites and anorthosites are also widespread [1-9]. Mafic compositions are rare: only two dunites and a few small mafic tractolites have been found, as well as two pyroxene-rich troctolites have been found. The magnesian norite association contains a diverse assemblage of rocks referred to as ilmenite gabbros, ilmenite norites, and gabbronorites. Only four clasts have been described so far that can be considered unequivocal part of the Mg-suite. Other gabbronorite clasts have mineral compositions that plot below the Mg-suite field on an An-Mg# diagram (figure 1), in the same region where Apollo 14 mare basalts plot [7,8,10].

ALKALI SUITE: The Alkali suite was first recognized by Warren and Wasson [1] and subsequent studies established it as the second most common highland rock association at the Apollo 14 site. 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. The most common lithologies are anorthosite (7 clasts) and norite or gabbronorite (6 clasts). Two olivine norites have been found; these may represent primitive cumulates from the alkali suite parent magma [1,4,8,9,10].

EVOLVED LITHOLOGIES: The most common evolved lithology at Apollo 14 is a granophyric intergrowth of quartz and alkali feldspar commonly referred to as "lunar granite". Accessory minerals include pigeonite, augite, ferroaugite, fayalite, ilmenite, zircon, and Ca-phosphates. Variations in mineral assemblages and in mineral composition (e.g., BaO in alkali feldspars, MG# in mafics) indicate that at least four distinct parent magmas are involved. 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.

FERROAN ANORTHOSITES: Ferroan anorthosites are rare at the Apollo 14 site. Only one clast of ferroan anorthosite has been characterized chemically and petrographically.

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 [1-10]. Chemical differences between rocks of the Western Highlands Province and nonmare plutonic rocks from the east are clearly illustrated by Sm and Eu. 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 (Sm=2 to 100 ppm) but are enriched in Eu relative to the eastern rocks (Eu=1-5 ppm). Alkali anorthosites are even richer in Eu (Eu=2 to 10 ppm) in rocks with the same Sm content as the Magnesian suite.

ORIGIN OF THE WESTERN HIGHLAND PROVINCE: The high Sm concentrations with characterize plutonic rocks of the Western Highland Province also result in low Ti/Sm and Sc/Sm ratios. 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 of Mg-suite rocks [9]. 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, 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 questions 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 an 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 that 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 represent 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.

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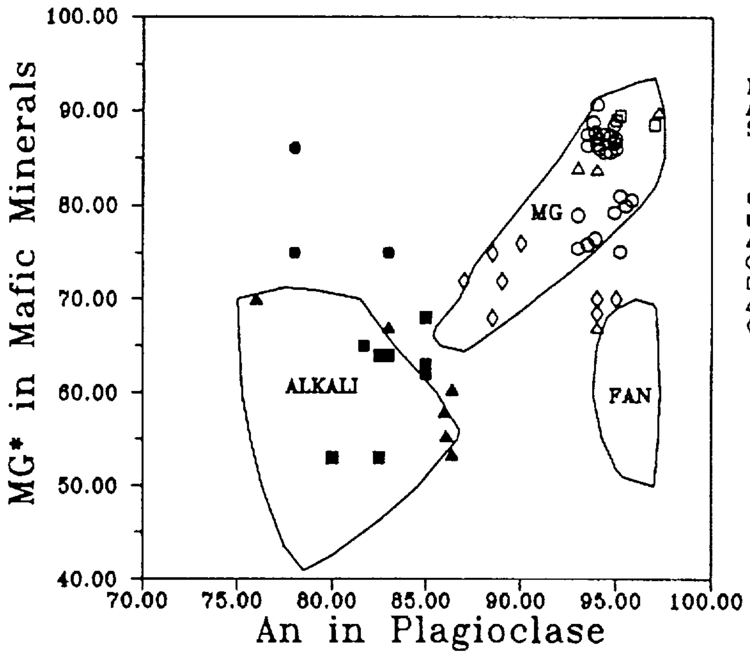

Figure 1. An vs MG* for Apollo 14 plutonic rocks. Symbols:

●●●●● Alkali Olivine Norites
■■■■■ Alkali Norites
▲▲▲▲▲ Alkali Anorthosites
○○○○○ Mg Troctolites
□□□□□ Mg Px-Troctolites
△△△△△ Mg Anorthosites
◇◇◇◇◇ Mg Norites