GLOBAL CONTEXT FOR LUNAR NONMARE ROCK TYPES: SAMPLE AND REMOTE-SENSING PERSPECTIVES.

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Results of recent lunar orbital remote sensing missions provide new perspectives on the lateral and vertical distribution of lunar rock types. Global data on FeO and Th concentrations permit subdivisions of the Moon's surface into geochemical terranes [1] that correspond in part to specific rock types and to previously noted east-west differences in the distribution of rock types according to sampling site longitude [e.g., 2,3]. Thus, rock types rich in KREEP come mainly from the Th-rich Procellarum-Imbrium region (Procellarum KREEP Terrane or PKT [1,4,5]). The global geochemical data reveal a vast region of the lunar far side that is highly feldspathic and low in both FeO and Th contents. The feldspathic lunar meteorites share these traits and so may provide samples from this vast region, nearly uncontaminated by mafic and Th-rich basin ejecta, which is common at all Apollo landing sites.

Of central importance to understanding the Moon's crust and the differentiation that produced it is the variation of rock types and composition with depth. Previous and ongoing work on thermobarometry [6], cooling rate indicators (and, by inference, depth of origin) [7,8] and on investigating rocks at depth through impact ejecta and uplift structures [9-11] continue to provide new information that must be integrated with global remote sensing and with geochemical and isotopic constraints [e.g., 12-13]. In this abstract, we discuss a model for the distribution of nonmare rock types that is consistent with available constraints.

In the following discussion, we draw upon previous classifications of rock types [14-16] and we defer to [16] for descriptions of specific rock types. For petrologic context, the main igneous rock types are consistent with a magma-ocean framework wherein the ferroan-anorthositic-suite (FAS) rocks result primarily from accumulation of plagioclase and buoyant enrichment within the crust. The magnesian-suite rocks do not appear to be related directly to formation from the magma ocean but were instead derived from early remelting and mixing of magma-ocean cumulates and residua, and crustal assimilation prior to intrusion into the crust. Mg-suite rocks have higher Mg/Fe ratios and are more mafic, on average, than FAS rocks. The alkali suite of rocks and volcanic KREEP basalt bear petrologic, geochemical, and spatial relationships to many of the magnesian-suite rocks (see below).

Evidence from samples and sampling-site locations coupled with global remote sensing lead to the conclusion that the major suites of igneous rocks are not distributed uniformly around the Moon, but are distributed instead according to a strong global asymmetry. What was recognized early in sample studies as an east-west dichotomy relative to landing-site longitude is consistent with the abundance of highly feldspathic rocks that characterize the lunar highlands on the eastern lunar near side and central part of the feldspathic highlands terrane (FHT), which dominates the northern lunar far side. Alkali- and magnesian-suite rocks are common at the western landing sites, but the presence of ferroan anorthosite (FAN) at Apollo 15 and magnesian suite rocks at Apollo 17 complicate a simple east-west landing site dichotomy. Nevertheless, associations of clasts in breccias and relationships inferred from petrology and geochemistry such as the apparent derivation of many members from KREEP-enriched parent melts [17] link many of the magnesian- and alkali-suite rock types to an origin within the PKT.

<u>Ferroan Anorthositic Suite</u>. Although present in Apollo 15 highland rocks, FAS rocks are most abundant in the Apollo 16 samples, especially among ejecta from North Ray Crater. Ferroan anorthosite and anorthositic norite share the low FeO and Th concentrations that characterize the FHT. Feldspathic fragmental breccias, which are rich in ferroan anorthositic components, and "genomict" FAS breccias resulted from impacts into regions devoid of magnesian lithologies and KREEP. The anorthositic central regions of the FHT, with FeO as low as 3–5 wt.% and Th <1.5 ppm, make up >25% of the Moon's present surface [1]. Because the FHT is such a large proportion of the Moon's surface and because of its highly feldspathic makeup, it is the most likely source of the feldspathic lunar meteorites, which, except for ALHA81005, are dominated by FAS components and lack KREEP. Even basin impacts into the FHT did not exhume significantly more mafic rocks, indicating that the highly feldspathic character extends to a significant thickness, at least ~30 km.

Isotopic systematics are mostly consistent with an early, magma-ocean derivation of FAS rocks; however, geochemical and petrologic properties reflect complex post-crystallization processes. Although age determinations are difficult, most FAS rocks are extremely ancient (>4.4 Ga), but the 4.36 Ga age of 62236 [18] and 4.40 Ga age of 67215 [19], and disturbed Rb-Sr systematics of some samples reflect a prolonged and more complex history than a single-stage flotation-cumulate origin. The positive ε_{Nd} of 67215 indicates derivation from an LREE depleted source, which is not expected for a magma-ocean origin [19]. Sample textures of many FAS rocks reflect recrystallization and subsolidus reequilibration, and minerals record slow cooling, with depths of formation in the upper crust, but none >25 km among those studied [7,8]. All of these features are consistent with prolonged cooling and perhaps density-driven readjustment within the thick, feldspathic parts of the early crust [e.g., 20,21] such that mafic FAS rocks are probably more abundant deep within the FHT, but deep enough that they remain largely unsampled by basin impacts.

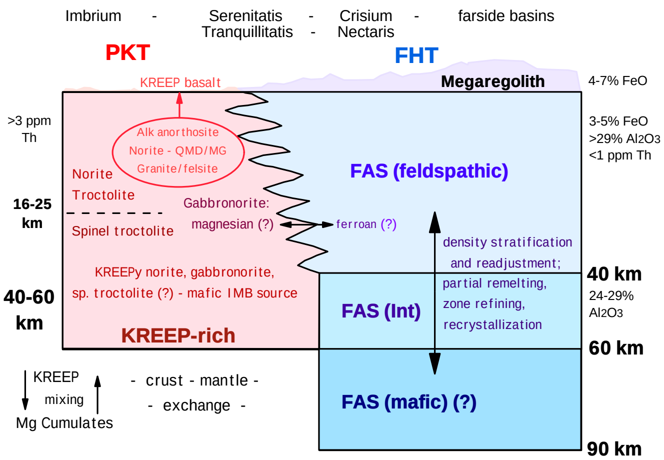

Figure. Schematic relationships between rock types and terranes, including inferred depths and locational relationships of selected basins.

Magnesian and alkali suites. Rocks of these suites are compositionally and lithologically more variable than FAS rocks. The Mg-suite includes mafic lithologies such as norite, gabbronorite, troctolite, spinel troctolite, and rare ultramafic types such as dunite, harzburgite, and pyroxenite. The alkali suite includes alkali anorthosite, alkali gabbronorite, sodic ferrogabbro, quartz monzodiorite (QMD), monzogabbro (MG), and granite (or felsite). The majority of these rocks contain plagioclase and pyroxene, and the compositions of coexisting plagioclase and pyroxene lie generally along a crystallization trend. Indeed, some can be related to others through crystallization of a KREEP-like parent magma [17], and many lie along a linear ε_{Nd} array [12]. Relationships are not all simple, however, and it is not clear whether or how, for example, the troctolites, dunites, or gabbronorites are related to the other rock types.

The major new evidence bearing on the origin of these groups is the nearly complete confinement of KREEP-rich surface exposures to the PKT as revealed by the Lunar Prospector Th map [22]. Other parts of the Moon may contain KREEP-rich material emplaced from the PKT mainly by the Imbrium impact [5]. A strong inference that can be drawn from the "east-west dichotomy" and the uniqueness of the PKT is that the magnesian and alkali suites may mostly restricted in origin to the PKT. This model accommodates several outstanding problems such as the age of some Mg-suite rocks that appear to be as old as the oldest FAS rocks, and the prolonged intrusive activity indicated by the range of crystallization ages for other Mg- and alkali-suite rocks, which, unlike the FAS, extends to the time of the cataclysm [reviewed by 16]. This model also explains the association between Mg-suite rocks and KREEP-bearing melt breccias and, importantly, the lack of Mg-suite rocks in the feldspathic lunar meteorites.

Except for the spinel troctolites, whose mineral assemblage indicates depths of origin 16–25 km [6], and troctolites bearing chromite-augite-Opx symplectites, formed at >40 km depth [6], most Mg- and alkali-suite rocks formed in shallow intrusions, judging by pyroxene exsolution and cation ordering [8], and mineral compositions such as CaO in olivine [e.g., 23].

Evidence of deeper, more mafic and KREEP-rich lithologies comes from the mafic impact-melt breccias, which are thought to be basin melts. Compositional variations among melt-breccia groups reflect variable mixing of predominantly KREEPy norite to gabbronorite precursors with a source of magnesian olivine, providing genetic relationships with troctolite or dunite, and a potential link to mantle-derived, cumulus magnesian sources [24,25].

Although the magma-ocean concept provides a useful framework, a number of questions and problems remain. A most challenging and important problem in understanding the distribution of lunar crustal rock types and early lunar differentiation is the extraction of urKREEP residual melt from late magma-ocean pyroxene and plagioclase cumulates, and its strong concentration into the PKT. Isotopic data indicate that the differentiation and sequestration of magma-ocean residual melt occurred very early (model ages constrain KREEP relative abundance pattern to have been established ~4.36-4.42 Ga [12]). A key problem is how the PKT and FHT became separated. Did a mega-impact of which no memory remains strip anorthositic upper crust from the PKT, or did the magma ocean solidify such that an anorthositic "protocontinent" developed with residual-melt accumulation in the intervening sea where the concentration of radioactive elements further sustained magmatic activity? What role did early thermal insulation of a nonuniformly thickening anorthositic crust play? Did late-stage ilmenite and ferropyroxene cumulates mix with magnesian cumulates raised by gravitational instability [e.g., 26] and were such processes confined mainly to the PKT?

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