Global Petrologic Variations on the Moon: A Ternary-Diagram Approach

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Approach. We have used the ternary-diagram approach outlined herein in an attempt to show on a single map as much detailed geochemical information indicating petrologic variations within the lunar crust as possible. We confine the presentation of our ternary-diagram analysis and subsequent discussion of the results to use of the Fe (wt%) versus $(Th/Ti)_c$ variation diagram, because these data include only the Apollo gamma-ray orbital data, which have more global coverage (about 19%) than that of the X-ray orbital data (about 9%). The $(Th/Ti)_c$ ratio represents the observed Th/Ti ratio normalized to Cl chondrite values. We produced an error database for Fe and $(Th/Ti)_c$ by the standard method of determining error from counting statistics to take into account the analytical errors associated with the Fe and $(Th/Ti)_c$ data in the present analysis.

The method starts by establishing a ternary reference diagram whose three sides are each divided into eight segments. Each ternary subdivision is assigned a distinct color; the colors represent a spectral continuum from red to green to blue to red. The center of the diagram is a trianglar area representing approximately equal proportions of each apex, and it is thus assigned a gray color. Assignment of rock end-member compositions to the three apexes allows rock or soil compositions that are binary or ternary mixtures of these three end members to be represented as continuous colors in the visible spectrum.

Each of the end-member Fe and $(Th/Ti)_c$ compositions is an average calculated from values reported in the literature. The Mg-suite (troctolite and norite) and KREEP rocks are represented by the red apex, the mare basalt by green, and the ferroan anorthosite by blue. Thus, we can now assign a color from the ternary reference diagram to each pixel in the orbital geochemical databases, using the Fe-concentration and $(Th/Ti)_c$-ratio values of the pixel and the ternary apexes. The relative proportion of each of the three compositional end members (apexes) needed to produce the observed composition of a particular pixel is determined trigonometrically. Once the pixel's location within the diagram has been determined, the color at that location is assigned to that pixel's position in a new image or map file. This process is then repeated for every pixel within the orbital databases. Also, the frequencies of occurrence of pixels at a particular ternary composition are accumulated within a ternary scattergram.

Certain pixels within the Fe and $(Th/Ti)_c$ databases have high uncertainties, mostly because of their low orbital accumulation times. To determine the effects of these errors on the areal abundance of units within the classification map, we decreased by increments the amount of error that pixels could have in terms of Fe and $(Th/Ti)_c$ before being excluded from the classification map. The following discussion pertains to the classification map (not shown) in which pixels that have errors greater than 75% are excluded. This level of error exclusion provides a reasonable amount of certainty for the remaining unit pixels and their areal abundances.

Discussion. Examination of the classification map allows easy determination of (1) the global spatial distribution of end-member compositions, (2) the transitional spatial relations between end-member compositions, and (3) quantitative estimates of the relative proportions of each end member at each pixel location within the orbital groundtracks. The use of elemental ratios in our analyses, instead of the commonly used elemental bivariate diagrams

[1,2], shows geologic information that is otherwise hidden in individual elemental databases.

The Apennine Bench region is shown to have a composition corresponding to a mixture of KREEP and mare basalt, which is consistent with the results of previous studies [3,4]. Other areas of Mg-suite/KREEP material are in the farside highlands near Van de Graaff (18°-29°S, 175°-171°W), within the Hertzsprung basin (3°-5°S, 125°-130°W), and south of Mare Smythii and west of Pasteur Crater (7°-15°S, 76°-98°E). The first two of these KREEP-rich highland areas coincide with areas of highland crustal thinning [5,6] that are covered by the orbital gamma-ray data. An inverse relation between Th concentration and highland crustal thickness has been reported by [7]. The preliminary elemental concentrations obtained by [8] suggest that the Van de Graaff region may have a "granitic" rock composition, similar to that of sample 12013. Generally, the average composition of lunar granites is lower in Fe, Ti, and Mg and significantly higher in K and Th than that of KREEP basalts. The Fe and Ti concentrations of these three highland areas are indeed lower than that at any of the three nearside high-KREEP areas, possibly because of the proximity of maria to the KREEP-rich areas; however, the three highland KREEPy areas do not appear to be associated with extensive mare deposits. For K, [9] have presented preliminary gamma-ray data showing the Van de Graaff region to have only 880 ppm K, whereas they report the Fra Mauro region as having 2680 ppm K. This significantly lower K value for Van de Graaff strongly suggests that these KREEP/Mg-suite highland areas (at least those near Van de Graaff) are not composed of "granitic" rock. They are most likely either "KREEPy basalts" [10] resulting from volcanism propagated by crustal thinning in these areas, or the remnants of an Mg-suite pluton exposed by an early impact event (such as the South Pole-Aitken basin; [11]).

Our classification map also shows that, at the spatial resolution (about 100 km) of the gamma-ray instrument, the central regions of most major maria have relatively pure mare-basalt compositions. Only Mare Tranquillitatis appears to have compositions transitional between mare basalt and ferroan anorthosite, which is probably the result of the addition of underlying anorthositic highlands debris to mare-basalt regoliths by vertical mixing through relatively thin, young, blue mare-basalt flows [12,13]. At Aristarchus, the unit map indicates a mixture of KREEP, mare basalt, and ferroan anorthosite, which grades into a more KREEP- and mare-basalt-rich unit at the north border of the groundtrack. The presence of these two units can be attributed to the relatively thin, young, blue mare-basalt flows in these two areas [14] that mixed with underlying KREEP- or Mg-suite-rich highland terrain. This underlying material is present at relatively shallow depth, as indicated by its exposure within Aristarchus Crater [15,16].

A series of relatively young lava flows with well-developed flow fronts occur in southwestern Mare Imbrium [17]. In addition to their striking morphological development, remote-sensing data indicate that these lava flows are rich in Ti [14], relatively rich in Th (8.0 ppm; [18]), and young (less than 2.0 b.y. old; [19]). These high-Ti, KREEP-rich lavas are represented on our petrologic map by two units of mostly mare basalt with some KREEP component.

Another interesting area is within and near the Balmer basin on the lunar eastern limb (10°-15°S, 75°E). The position of this zone correlates with the light plains fill of the Balmer basin, which has been described previously as KREEP-rich, mare-like deposits [10,20]. Our classification map shows these plains to represent roughly an equal mixture of anorthosite, mare basalt, and KREEP/Mg-suite material. The identification of dark-halo craters in this region [20,21] supports the suggestion that light plains in the region thinly mantle buried, KREEP-rich mare-basalt flows. These basalt flows are probably older than 3.9 b.y. because they are buried by highland plains of Imbrian to Nectarian age [22]. It thus appears that the ancient lunar maria (older than 3.9 b.y.) had a diversity of chemical compositions, ranging from "normal" chondritic Th/Ti values to more KREEP-rich varieties.

The lunar surface represented by the Apollo orbital groundtracks is shown to consist of 8.4% relatively pure (85%) ferroan anorthosite, even though pixels that have high compositional uncertainties were excluded. Deleting the maria from these data raises this value to 12.9%. Most of the lunar highlands is composed of four units. Considering the areal percentages of the groundtracks and the modal amounts of the end-member components for these four units results in an average highland composition of 68% ferroan anorthosite, 29% mare basalt, and 3% KREEP/Mg-suite rocks. This resultant rock composition approximates that of "anorthositic gabbro" and is consistent with our previous analyses [23]. This composition may represent the average composition of the upper half of the highlands crust [24].

Significant amounts of mare basalt (21.1% of the Apollo groundtrack) occur within the highlands (mostly on the eastern limb and farside highlands), as indicated by the areal distribution of a unit composed of 65% ferroan anorthosite, 3% KREEP/Mg-suite, and 32% mare basalt. Its areal distribution coincides with mapped occurrences of highland plains that display dark-halo craters [19,21], for which spectral data indicate the presence of excavated mare basalt [25]. This coincidence suggests that mare volcanism occurred within these highland areas before the end of the final heavy bombardment. We do not, however, dismiss the possibility that this unit may represent some type of highland gabbro or a mixture of Mg-suite rocks with an as-yet-unsampled mafic rock type that has a subchondritic Th/Ti ratio.

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