
Samples returned from the lunar surface provide clear evidence that the moon underwent chemical differentiation by internal melting and upward movement of silicate liquids during the first billion years of lunar history. Whole rock Rb/Sr ages, particularly on KREEP basalts, clearly indicate that this differentiation started with the formation of the planet or very shortly (100-200 million years) thereafter (1).

The chemical composition of silicate liquids brought to the surface have two common characteristics; i.e. all are depleted in volatile elements relative to chondrites, as is evidenced by their low K/U ratios; and all are depleted in siderophile elements. In addition, the dark-colored basalts of the mare region appear to be readily distinguished from other basaltic rocks or their derivatives by a number of chemical characteristics. Mare basalts consistently have: 1) high FeO contents and high FeO/MgO ratios, 2) low, but variable, Al₂O₃ contents, 3) high and variable TiO₂ contents, and 4) low, but variable, large ion lithophile element contents.

To a first approximation, these basalts appear to be formed by moderate (3-10%) to extensive (20-30%) partial melting of a pyroxene-rich source. In addition, there is strong trace element evidence for the occurrence of plagioclase in this source.

The number of samples from highland regions is limited, and the chemical and textural character of these samples is inferred rather than directly observed. Nevertheless, it is clear that the highlands probably contain a wide variety of basaltic rocks. Inferrer primary basaltic liquids differ widely in the range of trace element characteristics. All, however, appear to be rich in plagioclase. In addition, plagioclase-enriched rocks (anorthosites) may be common in highland areas. It may be inferred that the rocks from the highlands are, in general, higher in Al₂O₃ and lower in FeO than the mare basalts. The difference in Al₂O₃ content is dramatically demonstrated by the x-ray fluorescence experiment (2).

The variation in LIL element abundances in very old (approximately 4.5 billion years) lunar basaltic liquids poses a major problem for the origin of these liquids. The KREEP basalts appear to require small degrees of partial melting of a plagioclase-rich source. The LIL element abundance patterns in these basalts imply that they are derived from a source with U, Th, Ba, REE, and Sr concentrations at least 5 times those of average chondrites. The origin of LIL element-poor liquids is less well-defined. If they are formed by very extensive, perhaps complete, melting of the outer shell of the moon, they require that this shell be extensively enriched in Ca, Al, and refractory LIL elements. These inferred concentrations and the inferred abundance of plagioclase suggests that the moon had an outer shell rich in refractory
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...elements very early in its history. It is suggested that this shell was produced by the accretion of materials that were enriched in refractory elements during condensation from a hot solar nebula. The depletion in volatile elements obviously is concordant with this suggestion.

It has been shown (3, 4) that the whole moon cannot be as rich in aluminum as the outer shell here inferred. The inversion of Ca/Al-rich assemblages to eclogite at modest pressures thus requires that the primitive moon had a more ferro-magnesium interior composition. It is suggested that this interior accreted from material that separated from the solar nebula at lower temperatures. It may, in fact, approach chondrites in many of its chemical characteristics. The high Fe/MgO ratio of the mare basalts, as well as the LIL element abundance patterns, provide further evidence for the chemical heterogeneities already inferred.

The chemical structure for the primitive moon inferred from the surface chemistry can also explain the relatively high heat flow (5) and thermal history inferred from the ages of igneous rocks (1). Extensions of earlier thermal model calculations (6) using uranium concentrations that decrease from 0.1 ppm in the outer 200 kilometers to 0.02 ppm in the inner 1,000 kilometers and initial temperatures that decrease from 1200°K at the surface to 273°K at the center of the primitive moon predict that melting of the interior of the moon begins 100-200 million years after formation of the moon beginning at a depth of ~100 kilometers, proceeding to depths of 200-400 kilometers 1-1.5 billion years after formation of the moon. However, the present predicted heat flow for these models is still less than 3/4 of that reported for the Apollo 15 site. The present temperature predicted by these models does not exceed the basalt solidus but is substantially higher than that inferred by Sonett, et al. (7).

In summary, we suggest that many of the chemical and thermal characteristics of the moon can be consistently explained if the moon accreted as a heterogeneous body in which refractory elements are enriched in the outer 30-20% of the mass of the moon.

REFERENCES: