A CHEMICAL AND PHYSICAL MODEL FOR THE GENESIS OF LUNAR ROCKS:
PART I. CRUSTAL ROCK TYPES. Norman J. Hubbard, TN/Geochemistry Branch,
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The four known major lunar rock types (chemical groupings) can be pro-
duced by a single general model that meets essentially all known chemical and
physical constraints. The rock types to be explained are: 1) crustal (non-
mare) rocks of anorthositic composition, 2) crustal (non-mare) rocks of
basaltic composition (KREEP, etc.), 3) Apollo 12 and 15 mare basalts and 4)
Apollo 11 and 17 mare basalts. Only the crustal rock types are considered
here. As presented here this model is essentially descriptive even though
the model has been designed to meet quantitative constraints, when they can
be developed and defended. This model is primarily a result of attempting
petrogenesis within the framework of workable thermal models. This model
incorporates, in modified form, the lunar thermal model of Toksoz and
Johnson (1) and the lunar bulk composition model, also modified, of Ganapathy
and Anders (2). The experimental petrologic studies of Walker et al. (3) and
Kushiro and Hodges (4) on plagioclase rich compositions provide a framework
of pressure, temperature and bulk composition for crustal rock types. The
major chemical systematics of crustal rocks are described in Hubbard et al.
(5) and can be explained as follows: 1) the chemical composition and inter-
element ratios of crustal basaltic rocks can be explained by the pseudoter-
nary diagram (SiO2, olivine and plagioclase) used by Walker et al. and
equilibrium batch partial melting models, and 2) many of the chemical vari-
ations within the anorthositic group of rocks are correlated with plagioclase
content, i.e., variations in plagioclase/liquid ratios are a primary, but not
sole, cause of variations in bulk chemical composition.

Thermal and bulk composition models are the source of the following fea-
tures of this model: 1) the heat to drive the chemical differentiation is
derived from accretional melting of the outer portion of the Moon, 2) tempera-
atures of this outer, initially molten, zone decline with time and are accom-
apanied by downward migration of a partially molten zone, 3) cooling rates are
a few °C per 10^6 years and are much slower than the rate of chemical reactions
so that unzoned mineral assemblages occur at a shallow depth below the surface
and are typical of the regions where the petrogenesis of crustal rock types
occurs, 4) the initial bulk composition is somewhat Al2O3 rich (>11.0%) and
very MgO rich (~28.0%) with a MgO/FeO ratio greater than 4.0. The thermal
model is modified by reducing the initially molten zone to no more than 400
km in order to avoid the embarrassment of a thick layer of extensively molten
material at the time of mare basalt genesis. The bulk composition model is
modified such that the REE and Ba abundances in the high temperature conden-
sate reflect the higher U/REE ratio of the Moon relative to Allende refrac-
tory inclusions, resulting in almost 2 fold greater REE content. The relative
REE abundances are taken as that of basaltic lunar crustal rocks, except
for Eu, instead of that of chondritic meteorites because of the difficulty of
significantly altering the relative abundances of trivalent REE in lunar
crustal compositions by less than extremely small degrees of partial melting
or extremely large degrees of fractional crystallization. The resultant
abundances range from near 10 fold chondritic for La to about 5 fold for Lu.
The critical features of crustal rocks that have to be matched by this, or
A CHEM AND PHYSICAL MOD FOR THE GEN. OF LUNAR ROCKS: PART I

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any other model, are: 1) anorthositic rocks with MgO/FeO between 0.8 and 1.5, i.e., no extreme FeO enrichment (FeO>MgO) accompanying enrichment of Al₂O₃ to at least 26.0%, and 2) large enrichments of lithophile trace elements (REE, etc) in the crustal basaltic rocks with only minor interelement fractionation of lithophile trace elements, other than Eu and Sr, and no extreme FeO enriched compositions.

The genesis of crustal rock types is limited to the upper part of the initially totally molten zone. The neterogenetic steps in the model are: 1) initial crystallization of MgO rich olivine, 2) sinking of the MgO rich olivine to leave the upper region of the initially molten zone with up to 2 fold enrichment in Al, REE, alkalies, etc., 3) extensive crystallization of plagioclase in the upper region to produce a non-sinking mineral "meshwork" that greatly retards further removal of olivine or other minerals from this region, 4) once fractional crystallization has become "closed system" crystallization due to the meshwork of non-sinking plagioclase crystals, slow cooling and the presence of silicate liquid results in equilibrium crystallization producing a spectrum of equilibrium assemblages of solid plus liquid, except perhaps for incomplete equilibrium of plagioclase, on a scale large enough to produce essentially unzoned mineral assemblages, 5) at ~80 to ~95% solidified the liquid will have the chemical composition of various subtypes of crustal basaltic rock types and be chemically identical to the results of equilibrium batch partial melting and be on the plagioclase-olivine or plagioclase-pyroxene cotectic, 6) clean separation of these liquids will produce simple examples of these rock types, 7) preimpact protoliths for many of the "polymict" breccias can be produced by incomplete separation of liquid from solid, with or without complete equilibrium of plagioclase, or by veining of previously solidified material by the liquid, 8) residues from the separation of liquid and solid will be troctolitic and complementary to the liquid removed, 9) the somewhat higher average MgO/FeO ratios of crustal basaltic rocks relative to anorthositic rocks represent secondary accumulation of olivine that occurred after the plagioclase meshwork largely stopped the sinking of olivine and before almost total crystallization of plagioclase effectively stopped further bulk fractionation, i.e., this region contains more olivine, 10) any siderophile elements present in the original lunar material and that remain trapped in the plagioclase meshwork will participate in the genesis of crustal rocks and may provide an indigenous siderophile component in anorthositic and crustal basaltic rock types, 11) the total solidification of the upper region stops the production of crustal rock types and is followed by a period of solid state thermal metamorphism, and 12) further petrogenesis occurs at deeper levels.

The chemical zonation of the outer ~50 km of the initially molten zone, produced during the genesis of crustal rock types, is gradational and as follows (see Figure 1): A) a "skin" of solidified material that formed when falling temperatures and consequent crystallization increased viscosities enough so that convection could no longer bring hotter material to the surface, B) a layer of anorthositic rocks that represent maximum plagioclase enrichment, and C) a layer of material that produced crustal basaltic rocks by separation of liquid and solid as described above. The final position of crustal
basaltic rocks is not specified in this model, i.e., it is not specified if they are extrusive or plutonic. The production of crustal rocks is proposed to have occurred within the first $300 \times 10^6$ years, or less, of lunar history and was finished by $4.2-4.3 \times 10^9$ years ago. Further zonation established by the end of crustal petrogenesis is: D) a continuation of layer C that provides physical and chemical isolation of layer C from FeO, alkali and trace element enriched residual liquids forming below, 3) a layer of FeO, alkali and trace element enriched liquid, F) a cumulate layer, predominantly of MgO rich olivine, and G) a zone, below the initially molten zone, where partial melting of hitherto unmelted lunar material is occurring.

References:

Figure 1. Zonation* Produced During the Genesis of Crustal Rock Types
A. "skin" - best example of pre-"closed system" composition: depleted in olivine: very probably destroyed by impacts.
B. Crustal rocks of anorthositic chemical composition: $\text{Al}_2\text{O}_3 > 26.0\%$.
C. Source region for crustal rocks of basaltic or noritic chemical composition (KREEP, VHA, etc.), also troctolites, some anorthosites, and dunites.
D. An extension of layer C that provides insulation of layer C from E.
E. Source for 14053 type materials?
F. Residual liquid enriched in FeO, alkalies, REE, etc.
G. Olivine cumulate.

* This sequence is viewed as highly gradational.