Origin and Evolution of the Moon:
Apollo 2000 Model

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Introduction: A descriptive formulation of the stages of lunar evolution [1] as an augmentation of the traditional time-stratigraphic approach [2] enables broadened multidisciplinary discussions of issues related to the Moon and planets. An update of this descriptive formulation [3], integrating Apollo and subsequently acquired data, provides additional perspectives on many of the outstanding issues in lunar science.

- Stage 1: Beginning (Pre-Nectarian) – 4.57 b.y. before present
- Stage 2: Magma Ocean (Pre-Nectarian) – 4.57 - 4.2(?) b.y.
- Stage 3: Cratered Highlands (Pre-Nectarian) – 4.4(?) - 4.2(?) b.y.
- Stage 4: Large Basins–(Pre-Nectarian - Upper Imbrium) – 4.3(?) - 3.8 b.y.
  - Stage 4A: Old Large Basins and Crustal Strengthening (Pre-Nectarian) – 4.3(?) - 3.92 b.y.
  - Stage 4B: Young Large Basins (Nectarian - Lower Imbrium) – 3.92 - 3.80 b.y.
- Stage 5: Basaltic Maria (Upper Imbrium) – 4.3(?) - 1.0(?)
- Stage 6: Mature Surface (Copernican and Eratosthenian) – 3.80 b.y.- Present.

Lunar Origin: Increasingly strong indications of a largely undifferentiated lower lunar mantle and increasingly constrained initial conditions for models of an Earth-impact origin for the Moon [4,5,6,7] suggest that lunar origin by capture [8] of an independently evolved planet should be investigated more vigorously. Capture appears to better explain the geochemical and geophysical details related to the lower mantle of the Moon and to the distribution of elements and their isotopes. For example, the source of the volatile components of the Apollo 17 orange glass apparently would have lain below the degassed and differentiated magma ocean [3] in a relatively undifferentiated primordial lower mantle. Also, a density reversal from 3.7 g/cm^3 to approximately 3.3 g/cm^3 is required at the base of the upper mantle to be consistent with the over-all density of the Moon. Finally, Hf/W systematics allow only a very narrow window, if any at all, for a giant impact to form the Moon [3,9,10].

Origin of the Oldest Mg-suite Rocks: Continued accretionary impact activity during the crystallization of the magma ocean would result in the "splash intrusion" of residual liquids into the lower crust of the Moon as soon as the crust was coherent enough to resist re-incorporation into the magma ocean. For Mg-suite rocks with crystallization ages greater than about 4.4 b.y., impact-dominated dynamics of crustal formation resulted in the injection of liquids from the magma ocean into the crust. Such a process probably helps to account for the apparent increasingly mafic character of the crust with depth [11,12]

Thermal Requirement for Re-melting the Magma Ocean Cumulates: Creation of a megaregolith during the Cratered Highland Stage constituted a necessary pre-requisite for the later re-melting of magma ocean cumulates to produce mare basalt magmas. The increasingly insulating character of the pulverized upper crust would slow the cooling of the residual magma ocean. It also would have allowed the gradual accumulation of radiogenic heat necessary to eventually partially re-melt the source regions in the upper mantle that produced the mare basalts and related pyroclastic volcanic eruptions. The reverse wave of heating would proceed downward into the upper mantle from the still molten and significantly radioisotopic urKREEP residual liquid zone at the base of the crust.

Heterogeneous vs. Homogeneous Early Moon: The potential effects of a giant, Procellarum basin-forming event ~4.3 b.y. ago [2] and of a geographically coincident Imbrium event ~3.87 b.y. ago [2] can explain the surface concentration of KREEP-related materials in the Procellarum region of the Moon [13]. Lunar Prospector gamma-ray spectrometer data indicates that the Procellarum event excavated only relatively small amounts of material related to KREEP. This strongly suggests that urKREEP magmas had yet to move into the Moon's lower crust. The extensive movement of such liquids across and possibly along the crust-mantle boundary region to beneath Procellarum, however, may well have occurred in response to the regional reduction in lithostactic pressure. The coincidental formation of another large basin, the 1160-km diameter Imbrium basin, near the center of Procellarum resulted in the redistribution of KREEP-related materials roughly radial to the younger basin. This scenario may make unnecessary recent proposals of a chemically asymmetric Moon [14,15,16,17,18] to account for the surface concentration of KREEP-related material around Imbrium.

Geochemical Dichotomy Between The Lunar Near And Far Sides: The timing of the giant, South Pole-Aitken basin-forming event at the end of the Cratered Highland Stage (~4.2 b.y. ago [3]) can account for the lack of both extensive KREEP-related material [13] and basaltic maria [19] associated with South Pole-Aitken. The absence of an Imbrium-size event in South Pole Aitken would have kept hidden any KREEP-rich crustal province. As would be expected with the removal of most of the insulating upper crust, relatively little mare basalt has erupted in South Pole-Aitken [19] except possibly in its northern portions [20].

Source of Large Basin-Forming Objects: After the Cratered Highlands Stage and before the Basaltic Maria Stage, objects from a discrete source region formed about 50 large basins on the Moon over approximately 400 million years. Four possibilities for sources of the impactors of the Large Basin Stage appear plausible at this time [21,22,23,8]. Of these possibilities, the initial breakup of the original Main Belt planetesimal would appear to be the best present choice as a discrete impactor source.

UrKREEP Mobilization: The striking differences between young, mascon basins (~3.92-3.80 b.y.) and old, non-mascon basins (~4.2-3.92 b.y.) indicate that the older, isostaticly compensated basins triggered the regional intrusion, extrusion, and solidification of mobile urKREEP-related magmas prior to the formation of the younger, uncompensated basins [24]. This suggests that the fracturing of the lunar crust by the older basin forming events permitted urKREEP liquids to migrate into the crust, removing the potential for rapid, post-basin isostatic adjustment by urKREEP magma movement at the crust-mantle boundary.

Cryptomaria: The clear stratigraphic correlation of cryptomaria [25,26,27,28,29] with the Old Large Basin Substage suggests that these units are related to KREEP basalts or to partially melted, low titanium, late cumulates of the magma ocean. They underlie ejecta from the young large basins and may be represented in the Apollo samples by basalts of ages clearly greater than 3.92 b.y. [30,31] or by KREEP-related basalts with model ages of 4.2-4.4 b.y. [32].

Core Formation: The association of lunar magnetic anomalies with the antipodes of post-Nectaris basins [33,34] and the initially low accretion temperature of the lower mantle suggest that the $Fe_xNi_yS_z$ liquid separated from the early magma ocean did not coalesce into a circulating core until about 3.92 b.y. ago. As anomalies do not appear to be antipodal to the Nectaris basin, and are apparently of lower intensity antipodal to Orientale, then a dipole field may have been active only between about 3.92 and 3.80 b.y., the respective apparent ages of these basins.

Vesicles in Crystalline Melt Breccias: Remobilized solar wind hydrogen imbedded in the megaregolith of the cratered highlands probably was the dominant component of the fluid phase that formed vesicles in crystalline melt breccias produced by large basin forming events [35].

Vesicles in Mare Basalt Lavas and Volatiles Associated with Pyroclastic Eruptions: Remobilized hydrogen, derived from the decomposition of primordial water presumably was the dominant component of the fluid phase associated with mare basalt vesicles [36] and pyroclastic eruptions. The total absence of any indication of water associated with this fluid phase demonstrates that all primordial water in the source materials for the magma ocean has been lost to space or decomposed by $Fe_xNi_yS_z$ liquid separation [37] and migration.

Hydrogen Concentrations at the Lunar Poles: The probability is high that the epithermal neutron anomaly detected over the lunar poles [38] is largely if not entirely the consequence of concentrations of solar wind hydrogen rather than cometary water ice [38,39]. Hydrogen and other solar wind volatiles can be expected to be concentrated in permanently shadowed areas [41]. A continuous blanket of cometary water ice, unless fortuitously covered by protective ejecta from larger, but very infrequent impacts probably would erode [3] and be lost in a geologically short interval.

References: [1] Schmitt, H. H., (1991) *Am. Min.76,*773-784. [2] Wilhelms, D. E. (1987) *USGS Prof. Paper 1348.* [3] Schmitt, H. H., (in press), in H. Marks, Ed., *Encyl. of Space*, Wiley. [4] Halliday, A. N., and Drake, M. J. (1999) *Science 283,*1861-1863. [5] Cameron, A. G. W. (1999) *LPI XXX Abst. 1150.* [6] Agnor, C. B., and co-workers (1999) *LPI XXX Abst. 1878.* [7] Jacobsen, S. B. (1999) *LPI XXX Abst. 1978.* [8] Alfven, H., and Arrhenius, G. (1972) *The Moon 5,* 210-225. [9] Lee, D., and co-workers, (1997) *Science 278,*1098-1103. [10] Palme, H. *LPI XXX Abst. 1763.* [11] Kahn, A. and Mosegaard, K. (1999) *LPS XXX, Abst. 1259.* [12] Pieters, C. M., and Tompkins, S. (1999) *LPS XXX, Abst. 1286.* [13] Lawrence, D. J., and co-workers (1998) *Science 281,* 1484-1485. [14] Haskin, L. A. and co-workers (1999) *LPS XXX, Abst. 1858.* [15] Feldman, W. C., and co-workers (1999) *LPS XXX, Abst. 2056.* [16] Wieczorek, M. A., and co-workers (1999) *LPS XXX, Abst. 1548.* [17] Korotev, R. L. (1999) *LPS XXX, Abst. 1305.* [18] Jolliff, B. L., and co-workers (1999) *LPS XXX, Abst. 1670.* [19] Feldman, W. C., and co-workers (1998) *Science 281,*1489-1493. [20] Blewett, D. T., and co-workers (1999) *LPS XXX, Abst. 1438.* [21] Morbidelli, A. (1998) *Science 280*, 2071-2073. [22] Murray, N., and Holman, M. (1999) *Science 283,* 1877-1881. [23] Fernandez, J. A. (1999) in P. R. Weissman and co-workers, Eds., *Encyl. of the Solar System*, Academic Press, 554-556. [24] Schmitt, H. H. (1989) in G. J. Taylor and P. H. Warren, Eds., *Workshop on Moon in Transition, LPI Tech. Rept. 89-03,* 111-112. [25] Hawke, B. R., and co-workers (1999) *LPS XXX, Abst. 1956.* [26] Bell, J., and Hawke, B. R., *JGR 98,* 6899-6910. [27] Clark, P. E., and B. R. Hawke (1991) *Earth, Moon, Planets 53,* 93-107. [28] Head, J. W., and co-workers (1993) *JGR 98.* 17, 165-17, 169. [29] Williams, D. A., and co-workers (1995) *JGR 100,* 23, 291-23299. [30] Taylor, L. A., and co-workers (1983) *EPSL 66,* 33-47. [31] Heiken, G. H., and co-workers (1991) *Lun. Sourcebook*, 209. [32] Heiken, G. H., and co-workers (1991) *Lun. Sourcebook*, 218-219. [33] Lin, R. P., and co-workers (1998) *Science 281,* 1481. [34]] Lin, R. P., and co-workers (1999) *LPS XXX, Abst. 1930.* [35] Schmitt, H. H. (1973) *Science 182,* 682. [36] Schmitt, H. H., and co-workers (1970) *LPS I,* 11-13. [37] Agee, C. B., (1991) in C. B. Agee and J. Longhi, Eds., *Workshop Phys. Chem. Magma Oceans*, LPI, 11-12. [38] Feldman, W. C., and co-workers (1998) *Science 281,*1496-1500. [39] Nozette, S., and co-workers (1999) *LPS XXX, Abst.1665.* [41] Watson, K., and co-workers (1961) *JGR 66,* 3033.

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