Plutonic Rocks

The photograph of the back side of the Moon (fig. 34) illustrates how thoroughly the lunar highlands have been cratered. From this, it is easy to see why it has proven difficult to obtain many unaltered samples of the early lunar crust. It is safe to say that all samples from the lunar highlands must have undergone several cratering events.

The main criteria for identification of lunar plutonic rocks has been for homogeneous mineral chemistry combined with very low Ir and Au concentrations. For this, electron microprobe and instrumental neutron activation analyses have proven to be the most useful analytical tools of the lunar program. Coarse grain size and/or distinctive polygonal texture also are used (*see* last figure in appendix 2). Other criteria were given by Warren and Wasson 1977 and Warner and Bickel 1978.

Most plutonic rock fragments were found at the Apollo 16 and Luna 20 sites on the lunar highlands or at the Apollo 15 and 17 sites adjacent to the highlands. Table V is a list of the some of the "pristine" fragments of the original lunar crust. Plutonic samples mainly are mainly found enclosed as clasts in breccia samples from these sites, and most of them have crushed and/or annealed textures. Thin sections of anorthosite 60025 and norite 78235, included in this study set, illustrate the rather severe effects of shock, granulation and annealing that have modified these rock and made it difficult at best to date and or model their origin.

The lunar highlands contain an abundance of anorthositic material without a significant complementary, mafic component. Although many large anorthosite samples were returned, only one large dunite (72415) and one

Figure 34 - Back side and west limb of the Moon as photographed by the Apollo 16 metric camera (no. 3021) as the crew headed home. Note that heavily cratered highlands cover most of back side.

large troctolite sample (76535) were found. This observation has led to the interpretation that the Moon originally had an anorthositic crust. This crust must be relatively thick, otherwise the large basin's would have yielded numerous mafic fragments along with the abundant anorthositic material.

Lunar anorthosites have relatively high Fe/Mg ratios and are termed ferroan anorthosites. Two additional suites of plutonic rock, Mg-norite and Mg-gabbronorite, have been identified (James and Flohr 1983), but they have a different trend of Fe/Mg ratios in the mafic minerals with increasing Na in the plagioclase (fig. 35). Apparently, the Mg-norites and Mg-gabbronorites did not form during the initial differentiation which produced lunar anorthosite. Instead, they probably crystallized from mafic parent magmas that were generated after the primordial anorthositic lunar crust was formed. It is thought that the norites formed in layered intrusions that formed from basaltic magma generated by partial melting of subcrustal rocks.

Table V. – Pristine Plutonic Fragments of the Original Lunar Crust

Sample	Rock Type	Weight, grams	Age / Technique million years		Special Features
72415	Dunite	55	4450 ± 100	Rb/Sr	symplectite
76535	Troctolite	155	4260 ± 60	Sm/Nd	old Rb/Sr age
78235	Norite	400	4340 ± 40	Sm/Nd, Rb/Sr	
77215	Norite	846	4370 ± 70	Sm/Nd, Rb/Sr	
73255,27	Norite	clast	4230 ± 50	Sm/Nd	
72275	Norite	10	4080 ± 50	Rb/Sr	
76255	Norite	300			
15455	Norite	200	4480 ± 120	Rb/Sr	
72435	mafic clast				cordierite
15405,57	quartz monzodiorite (e)		4294 ± 26	U/Pb	zircon
15455	mafic clast				cordierite
15445,17	Norite clast (b)		4460 ± 70	Sm/Nd	
15445,247	Norite clast (b)		4280 ± 30	Sm/Nd	
15455,228	Anorthositic norite (b)		4530 ± 290	Sm/Nd	
67435	Troctolite	2			Mg spinel
15405,57	Monzodiorite	3	4320 ± 20	U/Pb	zircon
14321,1027	Granite (e)	clast	3965 +20/-30	Rb/Sr, U/Pb	pyrochlore
14303,209	Granite (e)	clast	4308 ± 3	U/Pb	zircon
14306,60	Ferrogabbro (e)	clast	4200 ± 30	U/Pb	zircon
15362	Anorthosite	4			
15415	Anorthosite	269			"Genesis rock"
60025	Anorthosite	1836 (d)	4440 ± 20	Sm/Nd, U/Pb	
67016,328	Ferroan noritic anorthosite (f)		4562 ± 68	Sm/Nd	
67075	Anorthosite	219			
67667	Lherzolite		4180 ± 70	Sm/Nd	
78155	Granulite	401	4200	U/Pb	
62236	Ferroan anorthosite (a)		4294 ± 58	Sm/Nd	
67215	Ferroan noritic anorthosite (c)		4400 ± 110	Sm/Nd	
Y86032GC	Ferroan anorthosite		4490 ± 90	Sm/Nd	meteorite clast

references: (a) Borg *et al.* 1999, (b) Shih *et al.* 1993, (c) Norman *et al.* 2003, (d) Carlson and Lugmair 1988, (e) Meyer *et al*. 1996, (f) Alibert *et al*. 1994

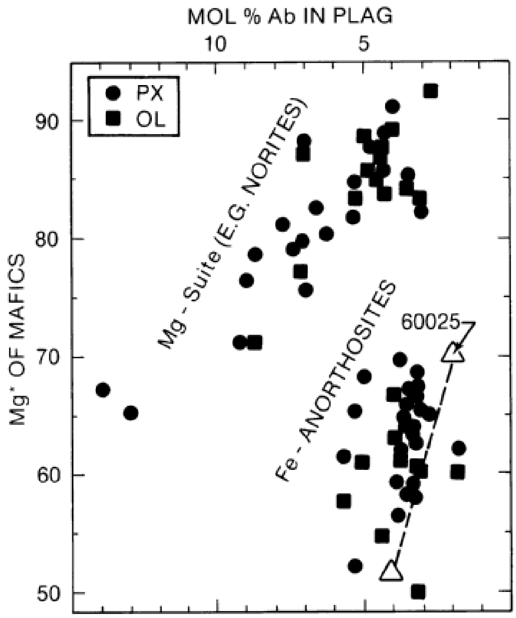

Figure 35 - Chemical composition of co-existing plagioclase and mafic minerals in pristine plutonic lunar rocks. The Mg-norites and Fe-anorthosites have different trends and are presumed to be from unrelated series of rocks. Note that the mafics in 60025 vary widely (from Ryder 1982).

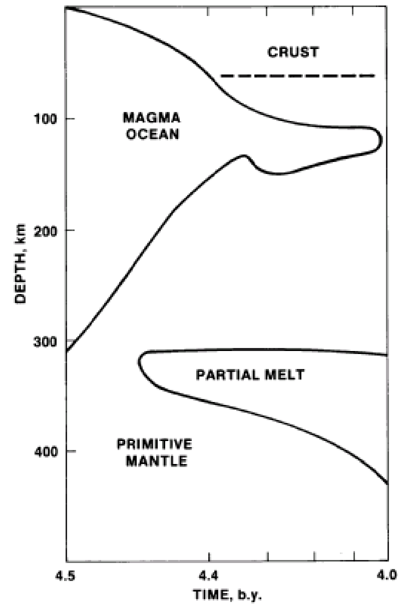

Figure 37 - Simplified thermal model of the Moon illustrating the depth of the magma ocean as a function of time (after Solomon and Longhi 1977). Radioactive decay of U extends the life of the magma ocean and initiates partial melting of the primitive interior.

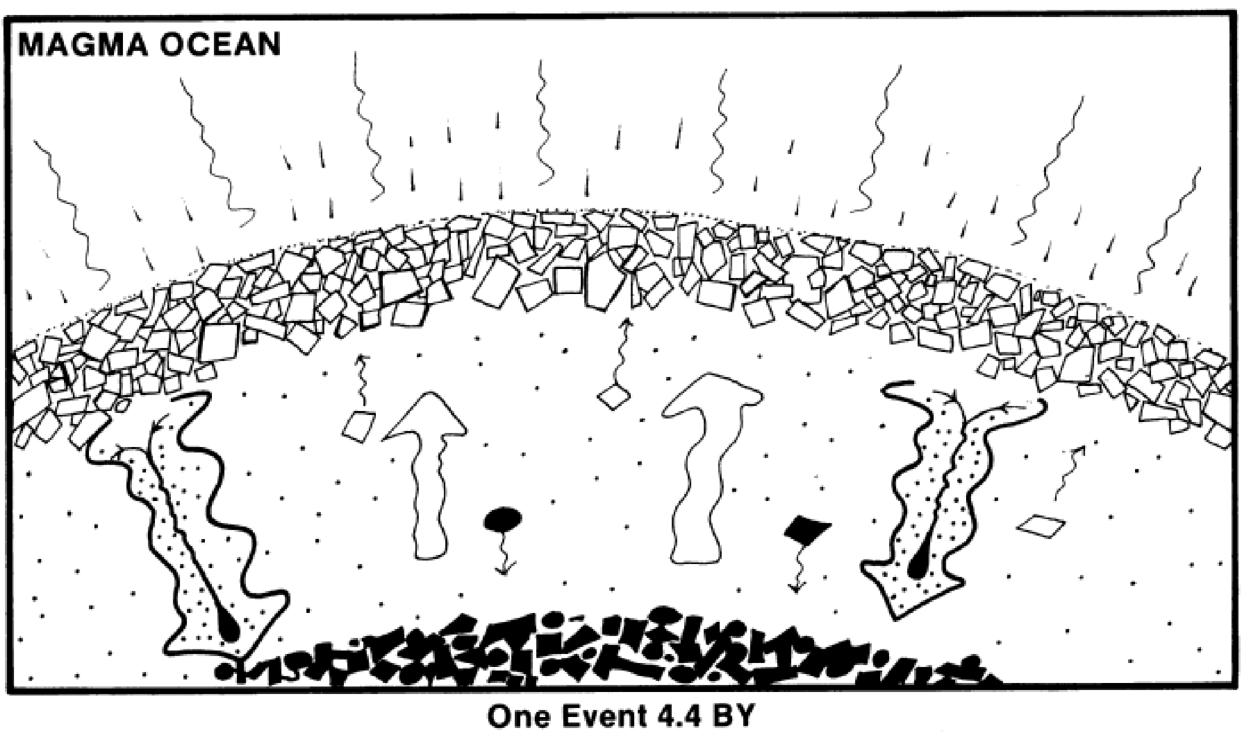

Figure 36 - Cartoon of lunar magma ocean (after Walker 1983). In this model, mafic minerals sink as “density masses” and plagioclase crystals float or are formed at the surface. This model has been used to explain the apparently thick feldspar-rich original crust of the Moon. Convection is required to remove heat rapidly so that there is a rigid crust by the time of the basin-forming events.

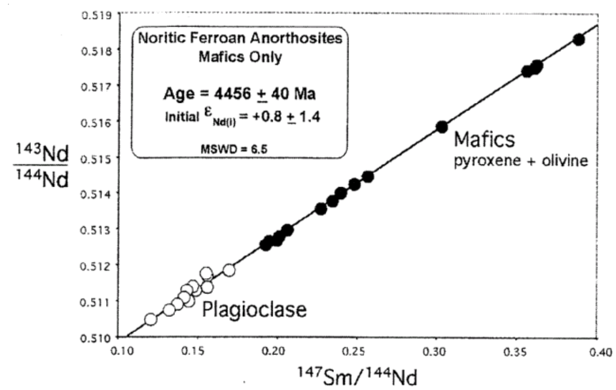

Figure 38 - Model age for formation of lunar crust based on mafic minerals from ferroan anorthosites (Norman *et al.* 2003, MAPS **38**, 659).

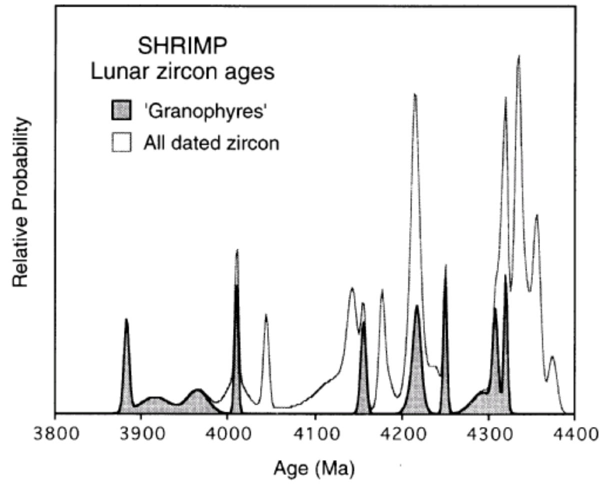

Figure 39 - Summary of ages of lunar zircons (from Meyer *et al*. 1996, MAPS **31**, 383). Some zircons are from "granophyre" but others are from norite and other plutonic rocks.

The global distribution and high chemical purity of lunar anorthosite has led to the model of a global lunar magma ocean hundreds of kilometers thick (Warren 1985). It is apparent that Ca-rich plagioclase (anorthite with a density of 2.7 g/cm^3) floats in anhydrous magma of bulk lunar composition (Walker and Hays 1977). Figure 36 illustrates the flotation of plagioclase and sinking of mafic minerals in a lunar magma ocean. The initial heat source for this magma ocean was the rapid terminal accretion of the outer part of the Moon. Figure 37 illustrates one of the early thermal models for the solidification of such a magma ocean, but perhaps you can see what is obviously wrong with such a model! There are many alternatives to this simplified model (*see* Proceedings of the Lunar and Planetary Science Conferences).

Tremendous effort has been invested to radiometrically date fragments of lunar plutonic rocks and determine their initial isotopic composition (see summary Table V). Some samples, like troctolite 76535, have yielded "discordant" ages by different techniques! Much work remains to be done in the isotopic study of old lunar rocks, and we have learned that it needs to be led by careful petrography. Figure 38 is an "isochron" of mafic fractions of various anorthosites and perhaps represents the best way to obtain the age of the original anorthositic crust of the moon. Figure 39 is a summary of the ages obtained U/Pb ion microprobe dating of lunar zircons. New techniques need to be developed and applied.