IMPACT INDUCED FRACTIONATION IN THE HIGHLANDS. J.L. Warner, NASA Johnson Space Center, Houston, TX 77058, C.H. Simonds, Lunar Science Institute Houston, TX 77058 and W.C. Phinney, NASA-JSC

Petrologic processes on the Moon are not necessarily the same as those on Earth. We suggest that total and partial melting during impact events, a process insignificant on Earth, is important in the petrogenesis of the lunar highlands. The following considerations drive us to that conclusion.

1. Why are about 85% of the non-mare rocks polymict breccias?
2. Why do the bulk rocks at each landing site display a wide range of compositions whereas the soils show a narrower range (Table 1)?
3. Why do all breccias have a significant meteorite component (1)?
4. Why do about half the non-mare breccias have melt-derived matrices (2)?
5. How can a "primitive" (old) rock survive multiple impacts?

The answers to these questions have important petrologic implications.

1. Most non-mare rocks are impact-produced breccias that have undergone multiple impact events, evidenced by common breccia-in-breccia texture. The compositional range of the lithic and mineral clasts is a measure of the amount of mixing that each rock has undergone.
2. Assuming that rocks represent local bedrock, and that, to a first approximation, soils are derived by crushing of bedrock during impact events, the restricted range of soil compositions at each site reflects the mixing efficiency of impact processes.
3. Meteorite components are additional evidence that all breccias have been mixed with the regolith (this relies on assumed base level abundances (1)).
4. Apparently portions of ejecta and fall-back blankets reached melting temperatures, and the large fraction of non-mare breccias involved, suggest that melting processes on the lunar surface are potentially important. Total melting will have the effect of mixing, but partial melting may produce differentiation. Fractional crystallization would also produce differentiation, but rapid cooling and high clast contents make this process unlikely.
5. A rock with high melting temperature has the best probability to survive. The few identified "primitive" rocks are high melting-temperature cumulates.

This evidence of mixing and melting leads to the expected conclusion that non-mare rocks have recorded the intense impact history that is evident from photogeology. A straightforward prediction from these concepts is that all breccias within a "region of mixing" should be of almost constant composition. The "region of mixing" is defined by the saturation-crater size in the highlands: at least 50 km in diameter, yielding a region of 7500 km^2 that is up to 10 km deep. However, in the area of one landing site which is two orders of magnitude smaller than the "region of mixing," the rocks do not have a constant composition, indicating that the above prediction is wrong.

This apparent paradox may be resolved if the diversity of highland breccia compositions may somehow be ascribed to the same impacts that tend to homogenize compositions. Impact partial melting, accompanied by separation of melt and residue, is such a process. The following points test the geochemical data in the context of impact partial melting. Soils are used as an example of bulk composition of parental material within ejecta and fall-back blankets.

6. Why do impact melts at each landing site show a definite pattern in composition from KREEP through VHA basalt to Highland basalt (2), even though the "average" (soil) composition at each site is different?

7. Why do all non-mare breccias (including impact melts) have the same slope to their REE distributions (3), and an inverse correlation between Al_2O_3 and many trace element (e.g., Sm) contents (Table 1)?

8. Why do most crystallization ages of highland rocks fall between 3.85 and 4.05 AE, with a few as old as 4.25 AE (4,5,6)?

9. Why can the whole rock Rb-Sr data be approximated by a 4.6 AE, I_{Sr}= 0.6990 line for low Rb samples, and a 4.26 AE, I_{Sr}=0.69925 line for moderate and high Rb samples (4,6,7)?

These questions may be answered with quite reasonable assumptions that suggest the nature of the partial melting.

6. Phase equilibrium relations (8) show that it is possible to generate: KREEP by small (10-35%) amounts of partial melting of almost any highland soil; VHA basalt by large (ca. 60%) amounts of partial melting of a feldspathic (Apollo 16 type) highland soil, or by small (<20%) amounts of partial melting of a feldspathic spinel troctolite (phase equilibria cannot distinguish between these two sources for VHA basalt); and Highland basalt (or higher Al_2O_3 compositions such as 68415/416) by nearly total melting of feldspathic (Apollo 16 type) highland soils.

7. The REE data for highland and mare samples considered together demand that KREEP and VHA basalt are partial melts (3). Since the REE, derived mainly from accessory phases, are enriched in the first extracts of partial melts, they will be inversely correlated with the amount of partial melting, and phase equilibria relations show that Al_2O_3 from feldspar grains is directly correlated with the amount of partial melting. Hence the REE slope and Al_2O_3 correlation of KREEP and VHA may be generated by partial melting of local soil.

Since a significant meteorite component has been found in all analyzed non-mare melt rocks (1), and most contain shocked clasts, none of them is a pure partial melt from the lunar interior. There are three possible schemes to account for the data: (i) a partial melt from the lunar interior that has been contaminated with regolith on its way to the surface, (ii) a total impact melt of a mixture of volcanic rock plus regolith, and (iii) a partial to total impact melt of regolith or bedrock plus regolith. For schemes (i) and (ii), if the volcanic rocks were young (3.9-4.1 AE), we would expect to find fragments with primary textures (which we don't), and, if the volcanic rocks were old, they would have been obliterated in the mixing of subsequent impacts. Although scheme (iii) requires physical separation of a partial melt within an ejecta or fall-back blanket, the separation distance need be only in the order of meters (the size of the largest known masses of KREEP and VHA basalt), and terrestrial impact melts do separate.

8. The spectra of crystallization ages and the lack of older dates have been used as evidence of a lunar-wide cataclysm at about 3.9 AE (6). The data are also consistent with a continuum of smaller impact events of sufficient

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intensity and frequency to reset the radiometric clocks with a half-life of about 100 million years. This implies that few highland rocks will age in ejecta for more than 200 million years before being remelted. The impacts capable of resetting ages and remelting materials seem to have stopped by 3.85 AE.

9. These relations do not suggest a unique geologic process. Consider Rb-Sr evolution by partial impact melting starting at 4.6 AE with an average highland composition ($^{87}Rb/^{87}Sr=0.05$, $I_{Sr}=0.6990$); at 100 million year intervals from 4.6 to 3.9 AE iterate the system by aging, mixing, and partial melting; from 3.9 AE to the present the system is only aged. This model adequately matches the data.

The following model (Fig. 1) accounts for the observed relations. Early in the Moon's history intense cratering continuously crushed and mixed most material on the lunar surface to a depth of at least 10 kilometers while simultaneously generating impact melts in ejecta and fall-back blankets. These events continued from the formation of the moon to 3.85 AE, with a thermal cycle of 100 to 200 million years. The observed diversity of highland rock compositions (excluding the "primitive" cumulates) is largely due to partial melting of surface materials during impact events.

Residue from this partial melting process must meet well-defined chemical criteria: (i) Al_2O_3 and CaO higher than the parent (local soil), (ii) MgO greater than FeO, (iii) TiO_2, K_2O, and REE lower than the parent. Uncertainty about the residue texture of an impact partial melt allows several alternatives: 61016 is a high ^{87}Sr cataclastic anorthosite; 67955 is a light matrix breccia; 61295 is a glassy to melted matrix breccia; and 68815 is a devitrified glass. We favor cataclastic anorthosites as the residue since they are the white material in the migmatitic black and white rocks (2). Other workers have suggested that there are two series of anorthosites (9). Perhaps one of these is derived from the moon's original crust and the other from the residue of impact partial melting.

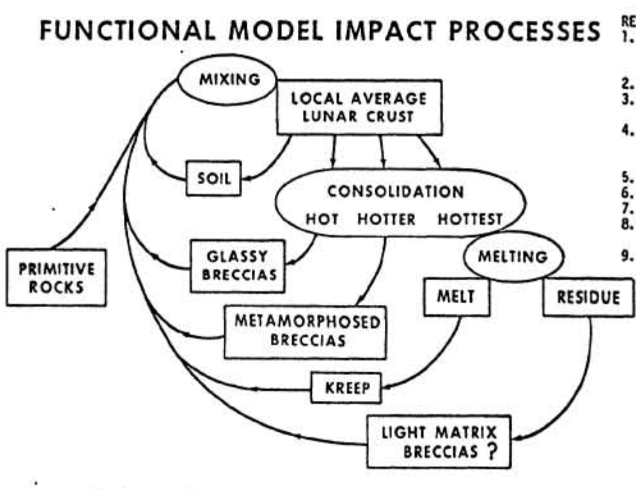

FIGURE 1

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TABLE 1. RANGE OF COMPOSITIONS - APOLLO 16

	Rocks	Soils	KREEP	VHA
Al_2O_3 (%)	16.4-35.2	24.2-28.2	16.4-19.5	22.4-24.4
FeO (%)	.7-10.5	4.0-6.0	8.6-10.5	5.3-7.8
K_2O (%)	.03-.39	.07-.13	.34-.39	.14-.28
Sm (ppm)	.04-27.1	3.1-7.0	20.0-27.1	4.5-10.0

Data from (3) and Curator's Data Base