FELDSPATHIC, GRANULITIC IMPACTITES THAT PRE-DATE THE FINAL LUNAR BOMBARDMENT. J.L. Warner¹, C.E. Bickel², W.C. Phinney³ and C.H. Simonds⁴ (¹NASA Johnson Space Center, Houston, TX 77058; ²San Francisco State University, San Francisco, CA 94132; ³Lunar Science Institute, Houston, TX 77058)

Among the Apollo collections we recognize a petrographically and chemically distinct suite of impactites that probably formed in the interval after the early differentiation that solidified the lunar crust about 4.4 AE, but before the final lunar bombardment that started about 4.0 AE. This suite of "Early Impactites" consists of at least 5 large rocks (67955, 76230/76235, 77017(?), 78155 and 79215) and scores of fragments that occur as clasts in breccias and as fragments in regolith samples from all missions, including many of the anorthosites of Wood et al. (1).

Petrographically these samples are granulites (2-7). Crystal forms are anhedral and equant; boundaries form smooth curves and meet at 120° triple junctions. The texture is granoblastic in all but 76230 and 77017 which are poikiloblastic. The interpretation that these samples are impactites is based on their texture and trace element composition. All display mineral clasts characteristic of the clast-matrix structure of breccias: 67955 and 78155 even contain clasts of several rock types. All contain high abundances of trace siderophile elements (8-10) that suggest meteorite contamination and are a fingerprint of materials that have had a surface history. The Early Impactites display precisely homogeneous mineral compositions over distances of a millimeter, feldspar mineral clasts commonly have olivine necklaces, and melt inclusions in feldspar are not observed. Annealing of the Early Impactites is less than in 15415 and 76535 where mineral compositions are homogeneous over distances of a centimeter and there is near-perfect approximation to textural equilibrium, and more than in the lunar breccias and impact-melt rocks where mineral compositions are not homogeneous and igneous textures are common.

Chemically the Early Impactites approximate anorthositic norite or troctolite (Table 1); they have the composition of the lunar crust. They are similar to lunar plutonic rocks in that their trace lithophile element contents are low and only slightly fractionated with respect to chondrites (13,14). Rare earth element distribution patterns are not similar to the constant negative slope patterns typical of lunar breccias and impact-melt rocks. These data suggest a low to negligible KREEP component in the Early Impactites.

Only fragmentary data exists on the age of these samples. 78155 has an Ar-plateau age of 4.22 AE (15) that has been confirmed by a Pb isotopic study (16). All the other measured samples (76230 and 77017) have Ar-plateau ages of about 3.9 AE (17-19). Bickel et al.(7) have argued that 79215 must predate the final bombardment based mostly on the unique spectrum of meteoritic trace siderophile elements.

The age of the Early Impactites is crucial to our discussion. Our speculations rely on the 4.22 AE age of 78155 and the interpretation that the other Early Impactites originated after the consolidation of the lunar crust and before the start of the final lunar bombardment that produced the lunar breccias and impact-melt rocks contained in the Apollo collection. The younger ages cited above may represent resetting by impact or excavation from depth. This is surely the case for 76230, a 0.5 m clast in an impact-melt rock with the same age.
The existence of this suite of Early Impactites provides our only record of lunar surface evolution before the final bombardment. Several implications are discussed:

Granulite Metamorphism. The granulitic texture of the Early Impactites does not occur in breccias and impact-melt rocks formed during the final bombardment, except as clasts in those breccias (20). This suggests that the high temperatures and prolonged heating required to develop these textures was only achieved earlier in lunar history than the start of the final bombardment. If such conditions were achieved more recently, these granulites were not sampled by the Apollo program. Formation of granulitic textures under dry conditions where there is no evidence for a vapor or a melt requires extensive volume diffusion of Si and Al in plagioclase. Such diffusion processes are inferred to be ineffective at less than 1000°C. Evidence for temperatures in excess of 1100°C are inferred from coexisting uninverted pigeonite and low-Ca augite in 78155 (6). Maintenance of these high temperatures for prolonged periods does not appear to occur in the larger terrestrial impact structures (e.g., Manicouagan) or typically in the lunar impact-melt rocks. We suggest that these conditions can only be achieved by burial of several kilometers and only when the 1000°C isotherm is relatively shallow. These conditions could have been achieved early in lunar history when there was a higher impact flux and a higher heat flow, and still hot impactites could have been buried by layers of younger ejecta that were themselves hot. Following this model the observed Ar-plateau ages are likely to represent the time of excavation.

Chemical Composition of the Lunar Surface and Age of KREEP. The chemical composition of the lunar surface, as recorded by impactites, appears to have undergone a major change at about the time of the start of the final bombardment. Impacts produce violent and extreme mixing and it is inferred that impactites record the average composition of the target material from any given impact (21). The composition of Early Impactites (assuming they are not allochthonous blocks that formed in the far side highlands or some other trace element-poor region of the lunar surface) suggests that the pre-bombardment crust was essentially KREEP-less. In contrast, KREEP composition material dominates the chemistry of rocks that formed during the final bombardment. The time of arrival of KREEP material onto the lunar surface must be after the formation of the Early Impactites and approximately coincide with the start of the final bombardment. This age for KREEP agrees with the crystallization age for both igneous and brecciated KREEP (22). If KREEP originated as a volcanic rock, its interval of eruption corresponds with the interval of the final bombardment. On the other hand, if KREEP is a late differentiate within the lunar crust, its arrival onto the lunar surface coincides with the final bombardment because the multi-ringed basins formed by the final bombardment were required to excavate it.

Volcanic History of the Moon. If KREEP is a volcanic, as its peritectic-like composition suggests, further speculations may be made about the Moon's volcanic history. The three types of volcanics returned from the Moon include KREEP (the oldest), Hi-Ti, Hi-Fe mare basalts (intermediate in age), and Lo-Ti, Hi-Fe mare basalts (youngest). The young, Hi-Ti basalts predicted for Western Procellarum based on crater morphology and reflectance spectra (23) were not identified among the Apollo 12 coarse fines (24) and may not exist. This picture of lunar volcanic activity is remarkably simple and is not much more complex than...
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the pattern that existed in 1971 when Warner (25) first suggested that the depth to the source region of lunar volcanics increases with time. Such a "zone refinement" also appears to be the case for Mars (26), and is probably to be expected in the future history of the Earth.

References

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| TABLE 1. COMPOSITION OF EARLY IMPACTITES (References 7, 11 and 12) |
|-----------------|-------------|-------------|-------------|-------------|
|                 | 67955       | 76230       | 77017       | 78155       | 79215       |
| SiO₂            | 45.0        | 44.5        | 44.1        | 45.6        | 43.8        |
| TiO₂            | .3          | .2          | .4          | .3          | .3          |
| Al₂O₃           | 27.7        | 27.0        | 26.6        | 25.9        | 27.7        |
| Cr₂O₃           | .1          | .1          | .1          | .2          | .2          |
| FeO             | 3.8         | 5.1         | 6.2         | 5.8         | 4.6         |
| MnO             | .05         | .06         | .08         | .1          | .06         |
| MgO             | 7.1         | 7.6         | 6.1         | 6.3         | 6.3         |
| CaO             | 15.5        | 15.2        | 15.4        | 15.2        | 15.9        |
| Na₂O            | .4          | .4          | .3          | .3          | .5          |
| K₂O             | .03         | .06         | .06         | .08         | .1          |
| P₂O₅            | .05         | .03         | .04         | .04         | .4          |
| Total           | 99.9        | 100.3       | 99.4        | 99.7        | 99.9        |

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