THE OLD IMBRIUM HYPOTHESIS. E. Schonfeld and C. Meyer, Jr., NASA Manned Spacecraft Center, Houston, Texas 77058.

An understanding of the early stratigraphy and history of the moon requires the determination of the ages of the Imbrium impact event. The ejecta blanket produced by the Imbrium impact has been mapped on the basis of its hummocky morphology radial to Imbrium and is called the Fra Mauro Formation (1).

The Apollo 14 samples are supposed to represent excavated Fra Mauro material (2) and their age of \( \approx 3.9 \) AE has been interpreted as the age of the Imbrium event (3). This interpretation we call the "orthodox" hypothesis. In this hypothesis the formation or initial extrusion time of the KREEP basalt precedes the formation of the Imbrium basin, since the Apollo 14 samples are very rich in KREEP. However, there is a variety of data from the Apollo missions that appear inconsistent with the above "orthodox" interpretation; we therefore propose an alternative hypothesis on the age of the Imbrium event.

The data from the orbital gamma ray experiment of Apollo 15 and 16 (4) suggest that there is an asymmetric distribution of KREEP basalt in the region of Imbrium ejecta and that there is a relatively large amount of KREEP basalt within the Mare Imbrium. In order to explain this distribution of KREEP basalt we propose that the order of lunar events was such that the Imbrium event predates the extrusion of KREEP basalt (5). We have previously interpreted the model ages of KREEP materials to mean that their "formation age" (time of extrusion of volcanic rock) is about \( 4.4 \pm 0.1 \) AE (6). Thus the Imbrium event may have occurred before approximately \( 4.4 \) AE. If the proposed hypothesis is correct, then KREEP materials sampled at the Apollo 14 site may not represent Imbrium ejecta. The extremely complicated, brecciated textures and multiple, reset, crystallization ages of KREEP and other materials may instead be the result of extensive bombardment by smaller post-Imbrium but pre-mare projectiles from about \( 4.4 \) to \( 3.8 \) AE.

A large number of craters such as Plato, Archimedes and Sinus Iridum are found in or on the borders of the large circular mare basins. These Archimedian craters are younger than the big circular basins and older than the mare lavas which fill or bury them. The large number of such craters demonstrates that a significant time elapsed between formation of the mare basins and eruption of the mare lavas.

This post-Imbrium, pre-mare cratering interval may have produced a relatively thick pre-mare regolith covering the Fra Mauro Formation but not obscuring its topography. If KREEP basalt had flooded the Imbrium-Procellarum area soon after our postulated pre-\( 4.4 \) AE Imbrium event, then this cratering between \( 4.4 \) and \( 3.8 \) b.y. would have formed a blanket of brecciated KREEP material covering much of the adjacent terra regions around the Imbrium and Procellarum basins. Later flooding by mare basalt obscures much of the original surface covered by KREEP basalts, but does not cover all of the surrounding terra that was coated by the brecciated KREEP blanket at the Archimedian stage.

Lunar material may be subdivided into three main types: mare basalts, KREEP basalt, and gabbroic anorthosite. We have shown previously that the
composition of many lunar soils can be matched to a first approximation by a mixture of different proportions of these three lunar rock types (6). Other rock types are present, but these can be considered as minor in amount. This simplified classification is consistent with the data of the orbital geo-chemical experiments (4). Mixing model calculations of lunar soil compositions show that high concentrations of Th in soils are caused by large amounts of KREEP basalt as a component and vice versa. Petrological examination of the soils supports these calculations.

Little Th, and hence, KREEP basalt, was seen from lunar orbit in the region of the Haemus Mountains south of Mare Serenitatis. This region is clearly sculptured by Imbrium ejecta, as is the Fra Mauro region (1), but is more anorthositic and less KREEP-rich in composition. It is possible that Imbrium ejecta may consist of different materials in different directions, but we believe this is an important anomaly to current interpretations of the Fra Mauro Formation.

It is important to observe that the gamma ray experiments found relatively high concentrations of Th everywhere inside the Imbrium basin (5). This may mean that a relatively large amount of KREEP basalt was extruded into the Imbrium basin prior to mare filling. Thus if there is no KREEP in the Imbrium ejecta and if it is found inside the Imbrium basin, then it is not unreasonable to propose the hypothesis that the Imbrium event may predate the extrusion of KREEP basalt.

One of the inherent difficulties with the interpretation that Apollo 14 breccias are Imbrium ejecta is that there are few recognizable anorthositic (or non-KREEP) clasts in the matrix of these complex breccias. Analysis of the plagioclase, in such anorthositic clasts that do exist shows that these have high BaO and K2O contents in the plagioclase unlike anorthosite from Apollos 11, 15, or 16 and are derived from KREEP (7). Also chemical mixing model calculations of most Apollo 14 breccias indicate only a minor anorthositic component (6). On the other hand, the orbital x-ray experiments of Apollo 15 and 16 (8) indicate that plagioclase-rich rock similar to "anorthosite" comprises the bulk of the terra surface. Thus, it is reasonable to assume that much of the Imbrium ejecta might also be anorthositic in composition.

There are a substantial number of "white rocks" on the rim of Cone Crater which are presumably the deepest material excavated at the Apollo 14 site. These include samples 14063 and 14083 (chipped from a large boulder) which are much higher in anorthositic material. These may be better candidates for Fra Mauro materials. The plagioclase-rich samples from the Apennine Front (Apollo 15) are another likely choice for Fra Mauro material. However, the brown glass microbreccias which are so abundant on the Apennine Front (9) may be part of the Archimedian blanket of regolith breccias and may have had a history similar to that of the Apollo 14 samples. In this case they may be mixtures of anorthositic Imbrium ejecta and post-Imbrium KREEP basalts.

There appears to be a spread in the crystallization ages of the Apollo 14 samples of about 0.1 AE. If such a spread is real there is a difficulty in explaining such a spread with the single impact orthodox hypothesis.
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the other hand in the case of the present hypothesis one would except a spread in ages.

The age of some of the Apollo 16 samples is ~3.9 AE (10). If these samples are typical of the lunar "plains" or Cayley Formation, then there is another discrepancy in the "orthodox" interpretation of the age of Imbrium, because the Cayley Formation is interpreted to be younger than the Fra Mauro Formation (11).

Yet another difficulty with the "orthodox" age of Imbrium is that it requires Imbrium sized planetisimals to be stored somewhere for 0.7 AE and then released to impact the moon.

We conclude that the KREEP rich samples from the Apollo 14 site may not be of the Fra Mauro Formation and may not date the Imbrium event. Possibly other samples of more anorthositic composition will provide an age of the Imbrium event, or possibly the intense cratering rate of the early moon may have reset all of the older crystallization ages. Finally, although this Old Imbrium Hypothesis is not yet proven, it may explain more of the basic observations of lunar scientists than the orthodox hypothesis.

(3) Lunar Sample Analysis Planning Team (1972) Science 176, pp. 975-981.