COMPOSITION AND ORIGIN OF THE APENNINE BENCH FORMATION,

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The Apennine Bench Formation (Imbrian; type area: 24°–25°N, 356°–358°E) was defined as materials comprising moderately high albedo plains near the crater Archimedes and west of the Apollo 15 landing site (1, 2). These plains pre-date the formation of both the crater Archimedes and mare materials, but appear to post-date and embay rugged terra associated with materials of the Imbrium basin (1). Early studies (3) suggested this unit may represent impact melt of the Imbrium basin, but later pre-Apollo studies suggested the plains were remnants of pre-mare volcanic flows (1, 4). Several post-Apollo studies of lunar basins and their deposits (5, 6) have emphasized the importance of the production of impact melts during basin formation and based in part on analogy to Orientale deposits, a current photogeologic interpretation of the Apennine Bench Fm. holds its origin as Imbrium basin impact melt (7). It is suggested here that Apollo 15 data show these plains to be volcanic in origin and to represent a major surface expression of pre-mare KREEP volcanism on the Moon. This hypothesis is based on photogeologic evidence, Apollo 15 lunar sample information, and remote sensing data that have been integrated to produce a model for the geologic evolution of this region.

Morphology of the Apennine Bench Fm. Current understanding of the morphology and regional setting of basin impact melt deposits is based primarily on the study of the relatively unflooded Orientale basin. Moderately high albedo smooth plains (Maunder Fm., (8)) occur near the center of the basin, with the largest continuous exposures concentrated around the inner Rook ring. These plains contain numerous graben and fractures and appear to mantle rugged terra associated with basin ring structures (5, 6). There is little evidence for large scale surface flow, but locally, flow is discernible as mobile material has preferentially moved off topographic highs to fill local depressions. These relations closely resemble smaller scale structures in fresh lunar craters, such as Tycho and King, that have been interpreted as impact melts (9). These smooth deposits grade abruptly into more rugged knobby or domical texture between the outer Rook and Cordillera rings. This texture has been interpreted as representing melt with large amounts of included clastic debris (5) or as consisting primarily of clastic debris that has been seismically modified during the final stages of basin ring formation (6). In either case, the total volume fraction of melt at this radial distance from the basin center has decreased to the point where a continuous sheet of clast-free melt is no longer present.

The surface morphology of the Apennine Bench Fm. superficially resembles the Maunder Fm., but the Apennine Bench plains occur near the second ring of Imbrium, where knobby or domical materials dominate at Orientale. The plains are heavily fractured and graben-like cracks and subsidence depressions have extensively modified the smooth plains. A notable difference from the Orientale melt sheet is the lack of clear evidence for flow off local topographic highs. No unequivocal volcanic landforms have been identified on the Apennine Bench, but some highly degraded possible volcanic structures appear to be masked by secondary craters. Typically, the plains appear to embay terra associated with the Imbrium basin and evidence for emplacement as a mantling deposit is ambiguous.

Studies of terrestrial craters indicate that increasingly larger impacts will produce progressively larger volumes of melt (10). It may be argued that the larger Imbrium impact would produce much larger melt volumes than Orientale and the presence of the Apennine Bench Fm., if it is impact melt, between the Imbrium second and third rings is a reflection of this increased melt volume. However, although the Apennine Bench region is inside the Imbrium topographic basin, it is a topographically *high* area outside the Imbrium "transient cavity," due to the presence of local pre-existing basins and craters (11). Study of melt deposits around lunar craters (12) indicate ponding and accumulation of fluid melt deposits in topographic *lows* outside of craters, suggesting the Apennine Bench region would be an unlikely site for major accumulation of a fluid, mobile melt sheet. Such a melt sheet at this range from the basin center would probably be manifested as melt-mantled terra material, such as the fissured Maunder Fm. (8), or corrugated facies (6), at Orientale. The photogeologic evidence alone is ambiguous and inconclusive in regard to the origin of the Apennine Bench Fm.

APENNINE BENCH FORMATION

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Apollo 15 Lunar Sample Data and Composition of the Apennine Bench Fm. by Remote Sensing Methods. Apollo 15 lunar sample data may hold clues to the nature and origin of the Apennine Bench Fm. Systematic study of KREEP basalt fragments in Apollo 15 soils has demonstrated that most of these fragments are of volcanic origin (13, 14, 15, 16). Among the criteria leading to this conclusion are extremely low concentrations of meteoritic siderophile trace elements, lack of "cold clast" inclusions, and phase relationships suggestive of igneous fractionation processes (16). The KREEP basalt fragments show little variation in bulk chemistry, but vary widely in abundance in soil samples at stations around the Apollo 15 landing site (14). Petrographic investigations of the Apollo 15 "black and white" breccias (17) have produced compelling evidence for an impact melt origin of the black matrix and based on analogy and similarities with the Apollo 17 "melt sheet" (18, 19), as well as considerations of lunar crustal bulk composition (20), these rocks have been interpreted as fragments of Imbrium basin impact melt (17, 20).

Absence of identifiable lunar mantle fragments on the surface of the Moon and theoretical considerations of cratering suggest basins excavate mostly crustal materials (21). Impact melts will homogenize layered target media (22) and a sample of basin impact melt should represent an average of the lunar crustal column sampled in the basin target area (20). The matricies of the black and white breccias have a low-K Fra Mauro basalt composition and probably represent a column of lunar crustal materials. Recently revised values of lunar heat flow rates (23) constrain the amount of U and associated KREEP component in the Moon, and indicate that a layer of low-K Fra Mauro material no thicker than approximately 20 km probably occurs near the base of the crust (20). This would suggest that Imbrium basin impact melt should be a homogenized mixture of ANT suite and low-K Fra Mauro rocks and thus should be depleted in the KREEP component.

The Apollo 15 CSM carried instruments that enabled remote measurement of lunar surface geochemistry. Best available reduction of these data (24, 25, 26) have been used to produce a model composition of the Apennine Bench Fm. shown in column D, Table 1. Table 1 also shows compositions of Imbrium basin impact melt, as determined from Apollo 15 sample study, a well documented sample of volcanic KREEP basalt, and an average of nine KREEP basalt fragments from Apollo 15 soils. Comparison shows that the Apennine Bench Fm. closely resembles Apollo 15 volcanic KREEP basalt but *not* Imbrium basin impact melt; specifically, the basin melt has a higher MgO/MgO + FeO ratio as well as being significantly depleted in the KREEP component (alkalis, P_2O_5, Th). This is in agreement with the idea that an Imbrium melt sheet with total KREEP contents similar to that of the Apennine Bench Fm. would require a zone of KREEP-enriched material at depth; such a layer would produce much higher heat flow values than those observed on the Moon (20, 23). This observation supports the idea that the Apennine Bench Fm. is represented in the Apollo 15 sample collection by the volcanic KREEP fragments and that the Apennine Bench Fm. consists of volcanic KREEP basalt flows. Ages for a clast-laden Imbrium melt rock (15455) and a volcanic KREEP basalt (15382) (Table 1; 27, 28) show considerable overlap, which suggests that the volcanic episodes emplacing the KREEP basalt flows occurred contemporaneously with or soon after formation of the Imbrium basin. This is in agreement with earlier suggestions that KREEP volcanism was active in pre-Imbrian time (29, 30, 31) and subsurface magma reservoirs were probably in existence during the formation of the large, young lunar basins. Spectral data from Earth based color difference photography (32) show that Apennine Bench materials have a distinctly red appearance that previous studies (30, 31) have associated with pre-mare KREEP volcanism. Viewed against the "ground truth" provided by the lunar sample studies, the remote sensing data in this region of the Moon support a volcanic origin for the Apennine Bench Fm.

Summary and Conclusions. Integration of stratigraphic relationships, geologic setting, and remote sensing data suggest that the Apennine Bench Fm. is composed of post-Imbrium basin volcanic KREEP basalt flows. This KREEP volcanism occurred at or shortly after the time of Imbrium basin formation and may have been triggered by the large basin impact which could have provided the structural "plumbing" through which magma could reach the surface. It is not known how pervasive this pre-mare KREEP volcanism was, but the limited distribution of the KREEP component, concentrated mainly on the west side of the Moon (24, 25), and the lack of KREEP basalt fragments younger than about 3.9 by (29) suggest this type of volcanism was uncommon after the formation of the youngest large lunar basins. The fact that the Apennine Bench Fm. is probably not Imbrium basin impact melt suggests that basin melt at the Apollo 15 range and position (third ring of basin) probably occurs as "pods" and isolated "pools" randomly dispersed in mostly clastic debris and precludes the existence of an extensive melt sheet as seen at the Apollo 17 site (18).

TABLE 1. CHEMICAL AND AGE DATA FOR IMBRIUM BASIN IMPACT MELT, APOLLO 15 VOLCANIC KREEP, AND THE APENNINE BENCH FM.

Oxide %	A	B	C	D
SiO_2	43.6	52.4	51.0	47–55
TiO_2	1.34	1.78	1.22	.....
Al_2O_3	20.5	17.8	19.1	19–23
Cr_2O_3	0.17	0.21	0.19	.....
FeO	8.1	8.6	6.5	7–9
MnO	0.08	0.10	0.09	.....
MgO	14.0	7.1	6.7	6.0
CaO	10.8	9.9	11.1	.....
Na_2O	0.58	0.96	0.98	.....
K_2O	0.14	0.57	0.69	0.4
P_2O_5	0.2	0.55	0.38	.....
Th (ppm)	5.3	10.5	....	7.1
U (ppm)	1.1	3.1	....	.....
MgO/MgO + FeO	0.63	0.45	0.51	0.4–0.46
Age (by)	3.92 ± 0.04 (27)	3.90 ± 0.05 (28)	....	.....

A – 15455 matrix - Imbrium basin impact melt (17, 20)
B – 15382 volcanic KREEP basalt (13, 29)
C – Average of nine Apollo 15 KREEP basalt fragments (14)
D – Model composition of Apennine Bench materials, using orbital geochemical data (24, 25, 26)

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