

## Composition and origin of the Apennine Bench Formation

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**Abstract**—The Apennine Bench Formation is a pre-mare light plains unit that crops out along some of the margins of the Imbrium basin and near the Apollo 15 landing site. These plains embay terra of the Imbrium basin but pre-date Imbrian age craters and mare materials. Although the surface of the Apennine Bench Formation is heavily fractured and modified by extensive secondary cratering, detailed comparison of the surface morphology of basin impact melt deposits and the Apennine Bench Formation suggest the two units are not related in origin. The chemical composition of the Apennine Bench Formation as determined from a variety of remote sensing data is that of medium-K Fra Mauro (KREEP) basalt. Detailed petrographic and chemical studies of samples returned by the Apollo 15 mission indicate the KREEP basalts in the Hadley-Apennine region are of volcanic origin and are chemically distinct from Imbrium basin impact melt, which has low-K Fra Mauro basalt composition. Integration of the morphologic, stratigraphic and geochemical data suggest that the Apennine Bench Formation consists of post-Imbrium basin, pre-mare volcanic KREEP basalt flows. This unit may represent the largest surface exposure of highland (non-mare) volcanism preserved on the lunar surface and, as such, provides valuable insight into early lunar crustal processes.

### INTRODUCTION

The Apennine Bench Formation (Imbrian age; type area: 24°–25°N, 356°–358°E) was defined as materials comprising moderately high albedo plains near the crater Archimedes (Hackman, 1966; Wilhelms, 1970) and west of the Apollo 15 landing site. 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. Pre-Apollo studies suggested these plains were remnants of pre-mare volcanic flows (Hackman, 1966; Carr and El-Baz, 1971). Several post-Apollo studies of lunar basins and their deposits (Head, 1974; Howard *et al.*, 1974; Moore *et al.*, 1974) have emphasized the importance of the production of impact melts during basin formation. Based in part on analogy to Orientale deposits, a current photogeologic interpretation of the Apennine Bench Formation holds its origin as Imbrium basin impact melt (D. E. Wilhelms, pers. comm., 1977). 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.



Fig. 1a. Regional view of the northern Apennine and Caucasus Mountains showing the moderately high albedo Apennine Bench Formation plains (portion of LO IV-109M).

#### REGIONAL GEOLOGIC SETTING OF THE APENNINE BENCH FORMATION

The Apennine Bench Formation is located primarily between the second (Archimedes) and third (Apennine) rings of the Imbrium basin (Fig. 1). The light plains are found in close association with Imbrium basin related terra and crop out at topographic levels intermediate between mare and highlands. Hackman (1966) recognized that the Apennine Bench Formation is the oldest post-Imbrium basin geologic unit, as it clearly pre-dates the Imbrian age crater Archimedes. The

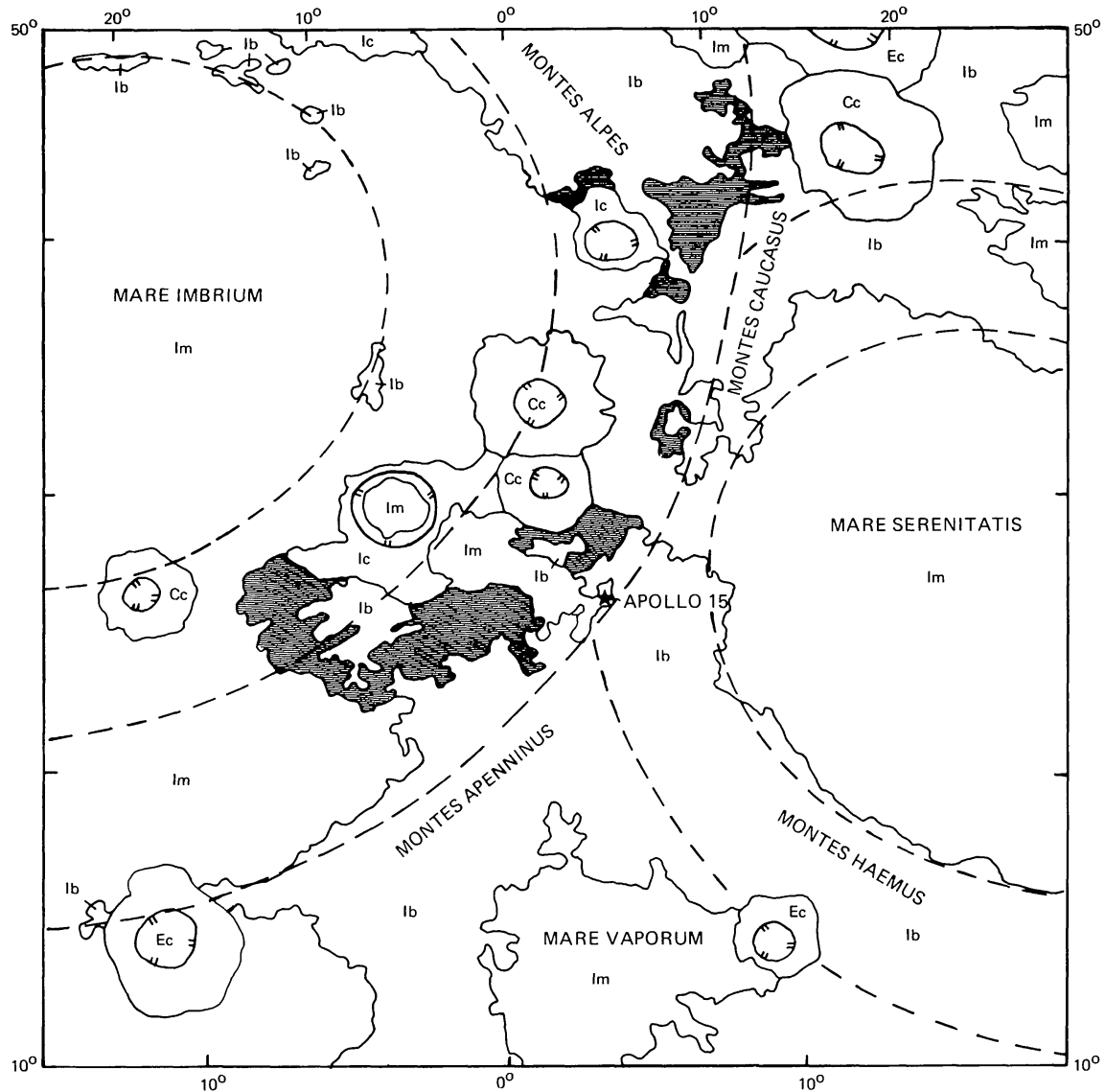


Fig.1b. Regional geologic map showing distribution of the Apennine Bench Formation (shaded). Geologic units: Ib—Imbrium basin terra; Im—mare material; Ic, Ec, Cc—crater materials. Basin ring locations and geologic units other than the Apennine Bench Fm. adapted from Wilhelms and McCauley (1971).

largest areal exposure of the Apennine Bench Formation occurs south of Archimedes and the deposits and secondaries of this crater have severely altered primary surface textures in this region. In addition, the Copernican age formation of the craters Aristillus and Autolycus (Fig. 2) are both likely to have excavated Apennine Bench materials and degraded surface textures in exposures north of the Apollo 15 landing site. Thus, regional geologic events have strongly influenced surface morphology of the plains, and hence make the photogeologic interpretation of the Apennine Bench Formation difficult.



Fig. 2. Oblique views looking north toward the Copernican age craters Aristillus (top) and Autolycus (below) showing the effects of extensive secondary cratering on the morphology of the Apennine Bench Formation (AB). Arrow points to the Apollo 15 landing site (portion of AS15-1538).

COMPARATIVE MORPHOLOGY OF IMPACT MELT DEPOSITS  
AND THE APENNINE BENCH FORMATION

Detailed study of the morphology of impact melts has been related largely to the study of the deposits in and around fresh lunar craters. Criteria for the recognition of deposits produced by impact melting have been described in detail by Shoemaker *et al.* (1968), Howard and Wilshire (1975), and Hawke and Head (1977). Melt deposits typically occur on crater floors and rims and display ponding, flow lobes, complex fracturing and other evidence of a previously fluid condition. Most importantly, impact melts typically mantle pre-existing topography and show evidence for flow off local topographic highs (Fig. 3). This is considered to be an argument against a volcanic origin for these lava-like deposits (Howard and Wilshire, 1975; Hawke and Head, 1977).

Current understanding of the morphology and regional setting of multi-ring basin impact melt deposits is based primarily on the study of the relatively unflooded Orientale basin. Moderately high albedo smooth plains (Maunder Fm. of Scott *et al.*, 1977) occur near the center of the basin, with the largest continuous exposures concentrated around the inner Rook ring (Fig. 4). These plains contain numerous graben and fractures and appear to mantle rugged terra associated with basin ring structures (Moore *et al.*, 1974; Head, 1974). There is little evidence for large scale surface flow, but some surface features attributable to local flow have been described (Greeley, 1976). The smooth plains deposits of the inner basin grade into a fissured facies that is concentrated between the inner and outer Rook rings. In this region, underlying basin topography is visible and thick accumulations of ponded melt are not seen. These deposits grade abruptly into more rugged knobby or domical texture between the outer Rook and Cordillera rings (Montes Rook Fm. of Scott *et al.*, 1977). This texture has been interpreted as representing melt with large amounts of included clastic debris (Moore *et al.*, 1974) or as consisting primarily of clastic debris that has been seismically modified during the final stages of basin ring formation (Head, 1974). 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 and melt probably occurs as isolated pools or pods within the clastic debris.

The surface morphology of the Apennine Bench Formation superficially resembles the Maunder Formation, but the Apennine Bench plains occur near the second (Archimedes) ring of Imbrium, where knobby or domical materials dominate at Orientale (Outer Rook ring). The Apennine Bench plains are fractured and graben-like cracks and subsidence depressions have extensively modified the smooth plains in addition to extensive secondary cratering (Fig. 5). A notable difference from the Orientale melt sheet is the lack of evidence for flow off local topographic highs, a morphology that is distinct from local areas of Imbrium melt pools (Fig. 6) as described by Wilhelms *et al.* (1977). In this region, the Apennine Bench Formation apparently embays rather than mantles the basin terra materials and exhibits a smooth planar surface in contrast to the rough, hummocky, fissured appearance of the impact melt deposits of Orientale and other large craters. No unequivocal volcanic landforms have been identified on the Apennine Bench

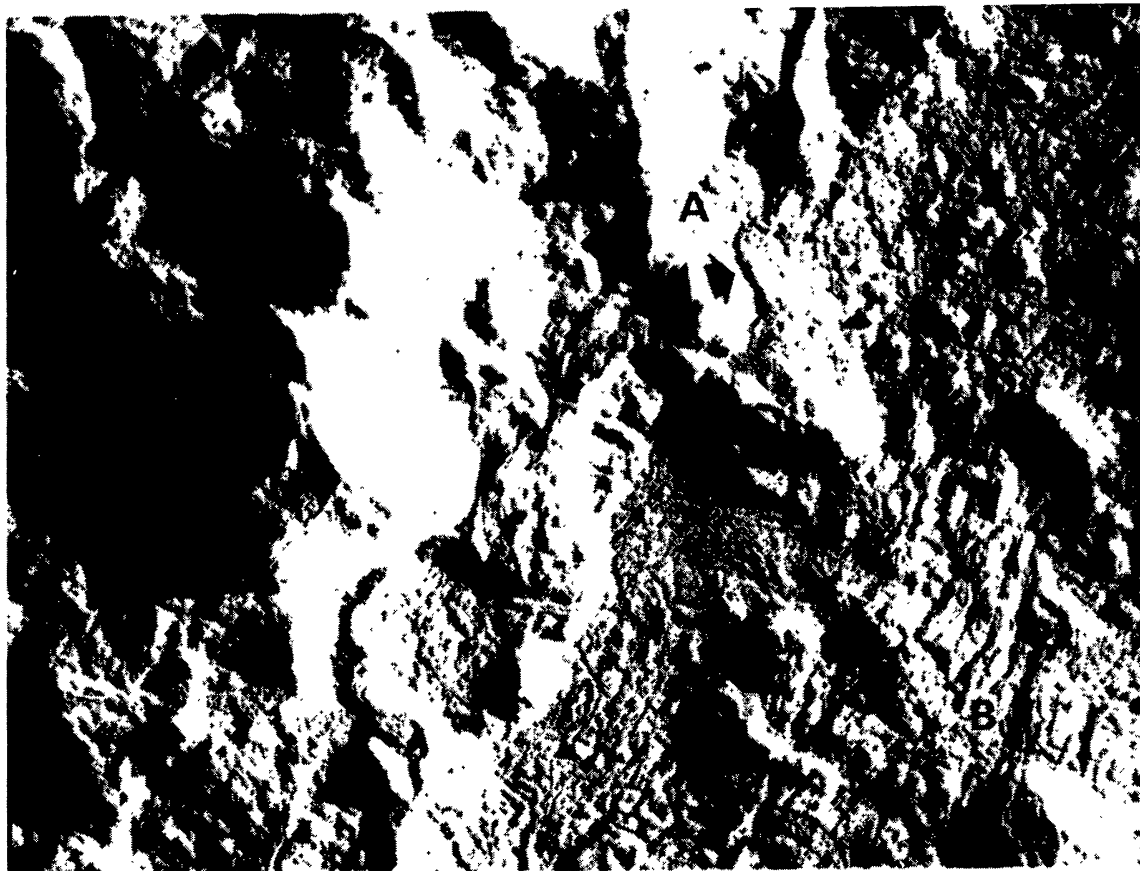


Fig. 3. Portion of the floor of the crater Tycho showing a lobe of viscous melt (arrow) that has probably flowed off the local topographic high (A). Note the fissured appearance of a melt mantling deposit (B). Area shown is 4.3 by 5.5 km; portion of LO V-125H<sub>2</sub>.

plains, indicating that if the Apennine Bench Formation is volcanic, it may have been emplaced by flood-type volcanism.

The photogeologic evidence seems to suggest that the Apennine Bench Formation is not related to Imbrium basin impact melt deposits. The morphology, geologic setting and stratigraphic relationships of the Apennine Bench Formation are all consistent with the original interpretation of Hackman (1966) that these plains consist of pre-mare volcanic flows.

#### APOLLO 15 LUNAR SAMPLE DATA IN RELATION TO THE APENNINE BENCH FORMATION PROBLEM

The Apollo 15 mission to the Hadley-Apennine region of the moon may hold important clues to the nature of the Apennine Bench Formation. Since the landing site was near large areas of Apennine Bench materials (Fig. 1b), it may be expected that this unit would be sampled in the Apollo 15 collection. Candidates

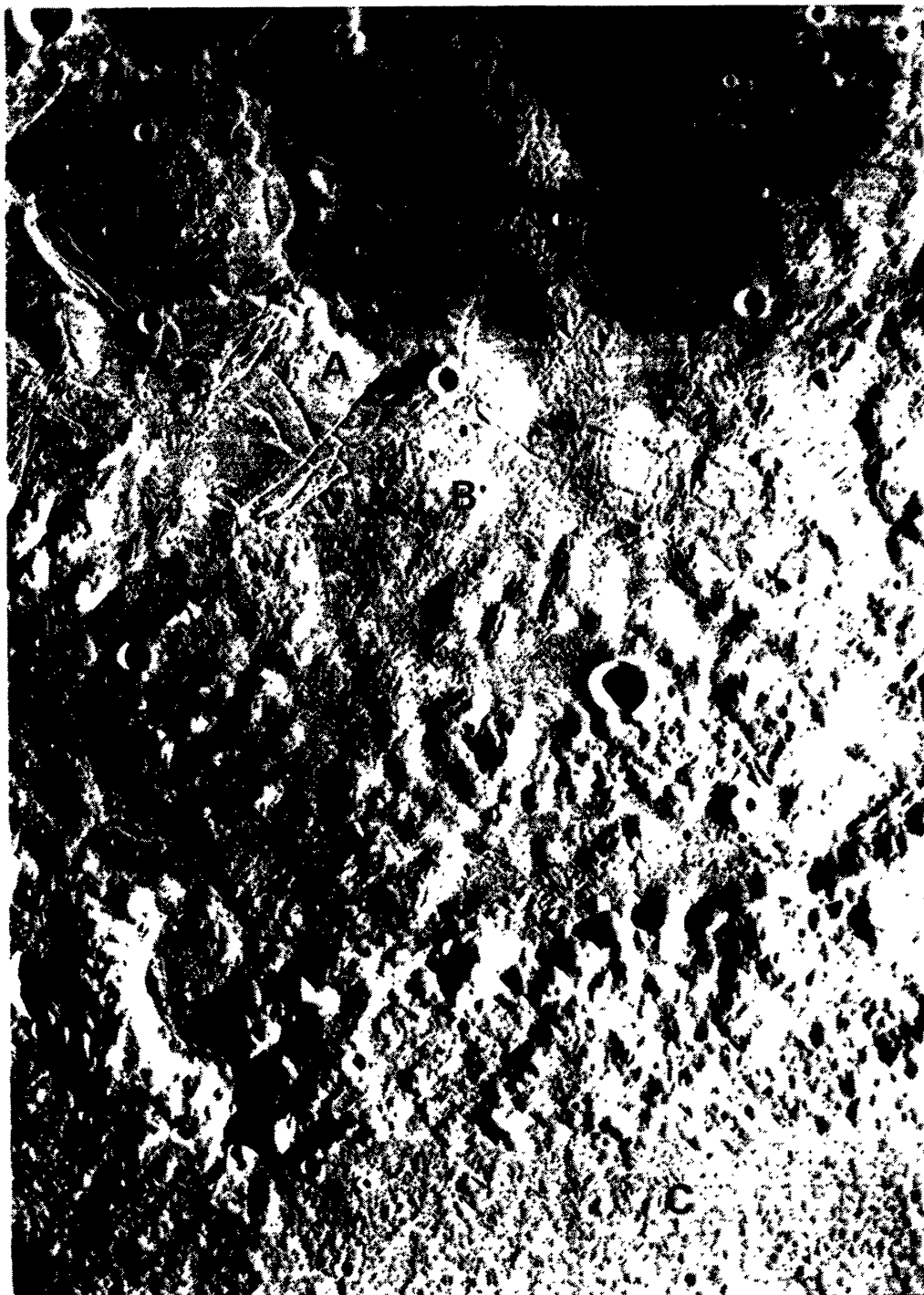


Fig. 4. Melt deposits of the Orientale basin displaying thick accumulation of ponded melt (A) grading into a fissured, mantling facies through which pre-existing topography is visible (B). Knobby textured materials (C) probably contain a lower volume fraction of melt than the plains deposits. Area shown is 160 by 300 km; portion of LO IV-195H<sub>1</sub>.

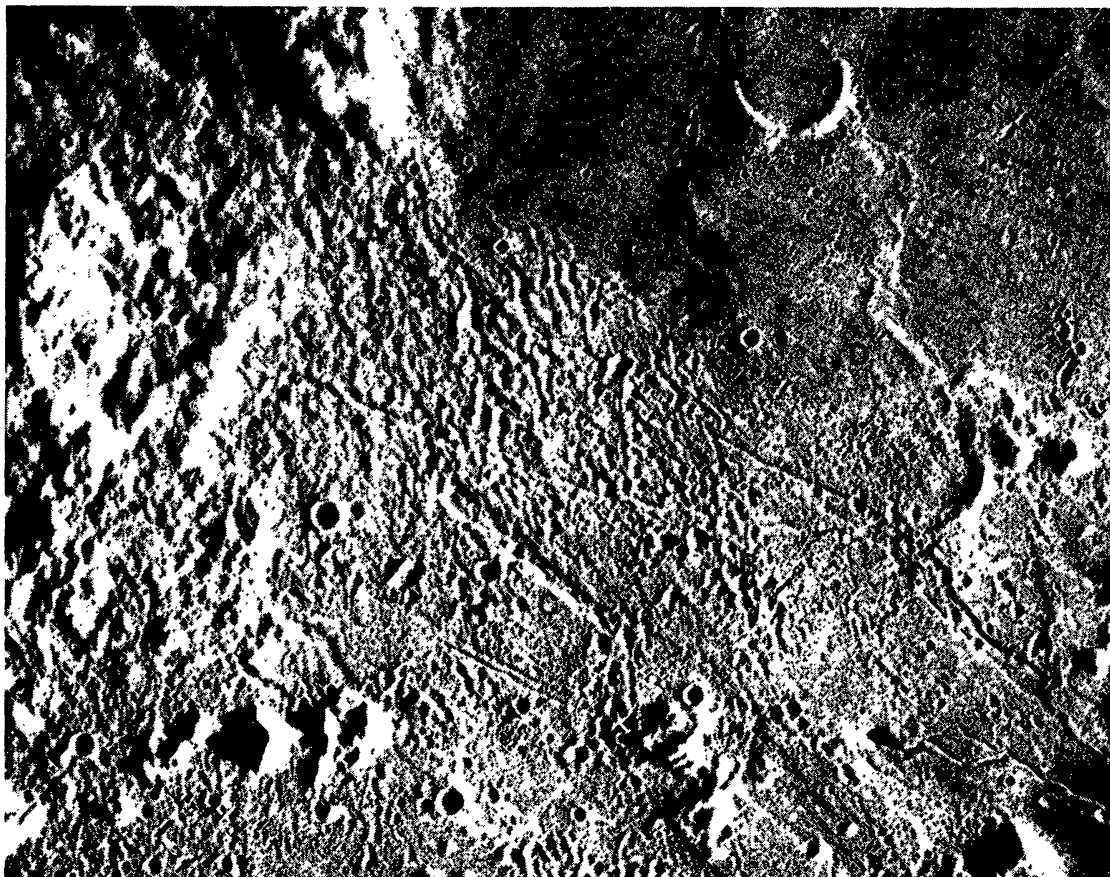


Fig. 5. Apennine Bench Formation southeast of the crater Archimedes showing the effects of Archimedes continuous deposits (A) and secondary craters (B). Graben (C) are approximately radial to the Imbrium basin. Irregular plateaus (D) may represent Apennine Bench Formation primary surface textures thinly mantled by mare basalt flows. Area shown is 100 by 135 km; portion of AS15-418.

for this material would be found in the non-mare component distributed throughout the site, but sampled mostly near the Apennine front.

One of the most important rock types returned from the Apollo 15 landing site was a variety of igneous textured non-mare basalt with KREEP chemistry (LSPET, 1972). Systematic study of these KREEP basalt fragments in Apollo 15 soils and rake samples has strongly suggested that most of these fragments are of volcanic origin (Ryder and Basu, 1976; Basu and Bower, 1976; Dowty *et al.*, 1976; Irving, 1977). 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 (Irving, 1977). These KREEP basalts typically have grossly similar bulk chemistry but vary widely in abundance in soil samples collected around the landing site (Basu and Bower, 1976). Their presence and distribution in the Apollo 15 collection argues strongly for the existence of volcanic KREEP basalt flows somewhere in the vicinity of the landing site (Ryder and Basu, 1976; Spudis, 1978).



Fig. 6. Differences in surface morphology of the Apennine Bench Formation (A) and probable Imbrium basin impact melt (B and C). The Apennine Bench light plains show a smooth, planar surface that embays Imbrium basin terra deposits, similar to contact relationships seen at mare-highland boundaries. Flow lobe at (B) has drained from the topographic high; deposits at (C) mantle the terra material and display a heavily fissured appearance. Compare these melt deposits with those in Fig. 3. Area shown is 140 by 140 km; portion of AS17-2110.

One of the prime sampling objectives at the Apennine front was the acquisition of Imbrium basin ejecta. Absence of identifiable lunar mantle fragments on the surface of the moon and theoretical considerations of cratering suggest basins excavate mostly crustal materials (Taylor, 1975; Head *et al.*, 1975). Impact melts will homogenize layered target media (Dence, 1971) and a sample of basin impact

melt should represent an average of the lunar crustal column sampled in the basin target area (Dence *et al.*, 1976). Petrographic investigations of the Apollo 15 "black and white" breccias 15445 and 15455 (Ryder and Bower, 1977) have produced compelling evidence for an impact melt origin of the black matrix; based on analogy and similarities with the Apollo 17 "melt" sheet (Wood, 1975; Winzer *et al.*, 1977) as well as considerations of lunar crustal bulk composition, these rocks have been interpreted as fragments of the Imbrium basin impact melt sheet (Ryder and Bower, 1977; Ryder and Wood, 1977). The matrices of the black and white breccias have a low-K Fra Mauro (LKFM) basalt composition and probably represent a column of lunar crustal materials that was sampled by the Imbrium impact. The production of a basin melt deposit by large scale vertical mixing of crustal materials as described by Dence *et al.* (1976) was challenged by Ryder and Wood (1977) who instead proposed the Imbrium melt was ejected as a roughly continuous "stream," variable in composition. In this manner, the more anorthositic component was ejected farther than the Apollo 15 position and hence, the melt at the site has a LKFM composition, reflecting derivation from deeper crustal levels. However, geochemical studies of Apennine Front material (Taylor *et al.*, 1973) and regional Apennine mountain materials by remote sensing methods (Hawke, 1978) strongly suggest that the dominant highland component in the Apennine and Haemus Mountains is of LKFM composition. Thus, the presumed anorthositic component may have been thin or discontinuous in the Imbrium target site and the melt matrix of the black and white rocks may represent a pre-Imbrian crustal average in this region where the crust was composed mainly of the LKFM basalt.

The clear implication of the Apollo 15 sample studies is that the volcanic KREEP basalts, which have medium-K Fra Mauro (MKFM) basalt chemistry, cannot represent Imbrium basin impact melt which has LKFM composition. This is supported by recently revised values of heat flow from the Apollo 15 landing site (Langseth *et al.*, 1976) which constrain the amount of U and the associated KREEP component to a layer of LKFM no thicker than 20 km (Ryder and Wood, 1977). Thus a large impact such as that which produced the Imbrium basin could not produce a melt with MKFM composition as this would require a thick KREEP-rich crustal target which in turn would increase heat flow values by substantial amounts.

#### COMPOSITION OF THE APENNINE BENCH FORMATION BY REMOTE SENSING METHODS

The Apollo 15 CSM carried instruments that enabled remote measurement of lunar surface geochemistry (Adler and Trombka, 1977). These data have been greatly refined in the years since the Apollo missions to the point where nearly complete major element chemistry and partial trace element information may be determined for specific regions of the lunar surface. One such region for which this information is available is the area just south of Archimedes, a region almost completely dominated by the Apennine Bench Formation. Thus, the chemistry of

Table 1. Chemical Data for Imbrium Basin Impact Melt, Apollo 15 Volcanic KREEP, and the Apennine Bench Fm.

Oxide	A	B	C	D
SiO <sub>2</sub>	43.6	52.4	50.83	51 ± 4
TiO <sub>2</sub>	1.34	1.78	2.23	—
Al <sub>2</sub> O <sub>3</sub>	20.5	17.8	14.77	19 ± 7
Cr <sub>2</sub> O <sub>3</sub>	0.17	0.21	—	—
FeO	8.1	8.6	10.55	9 ± 2
MnO	0.08	0.10	0.16	—
MgO	14.0	7.1	8.17	6.0 ± 1.0
CaO	10.8	9.9	9.71	—
Na <sub>2</sub> O	0.58	0.96	0.73	—
K <sub>2</sub> O	0.14	0.57	0.67	0.4 ± 0.1
P <sub>2</sub> O <sub>5</sub>	0.2	0.55	0.70	—
Th (ppm)	5.3	10.5	—	7.1 ± 0.7
U (ppm)	1.1	3.10	—	—
MgO/MgO + FeO	0.63	0.45	0.44	0.43 ± 0.03

A—15455 matrix—Imbrium basin impact melt (Ryder and Bower, 1977; Ryder and Wood, 1977)

B—15382 volcanic KREEP basalt (Dowty *et al.*, 1976)

C—15386 volcanic KREEP basalt (Rhodes and Hubbard, 1973)

D—Apennine Bench Fm., using orbital geochemical data and earth-based remote sensing data (Bielefeld *et al.*, 1976; Adler and Trombka, 1977; Frontispiece, 1977; Charette *et al.*, 1977)

the Archimedes region seen from orbit will be largely controlled by the composition of the Apennine Bench light plains. In addition, a recently developed earth-based technique to determine the bulk FeO content of mature highland soils by spectral reflectance (Charette *et al.*, 1977) provides control for the total Fe content of the region. This is important since Fe data obtained from the Apollo orbital gamma-ray spectrometer may be as much as 25% low for KREEP-rich areas (Bielefeld *et al.*, 1976). Thus, integration of all sources of remote sensing information provides fairly accurate major element chemistry for the Apennine Bench Formation.

Chemical data for Apollo 15 volcanic KREEP basalts, Imbrium basin impact melt and the Apennine Bench Formation are given in Table 1. Comparison shows that the Apennine Bench Formation 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 (K, Th). In short, the Apennine Bench Formation is MKFM while Imbrium impact melt is LKFM composition. This is in agreement with the idea that an Imbrium melt sheet with total KREEP contents similar to that of the Apennine Bench Formation 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 (Langseth *et al.*, 1976; Ryder and Wood, 1977). This observation supports the idea that the Apennine Bench Formation is represented in the Apollo 15 sample collection by the volcanic KREEP fragments and that the Apennine Bench Formation consists of volcanic KREEP basalt flows. Similar conclu-

sions were reached by Schonfeld and Meyer (1973) and Hawke and Head (1978). Spectral data from earth-based color difference photography (Whitaker, 1972; Whitaker, pers. comm., 1977) show that Apennine Bench materials have a distinctly red appearance that previous studies (Malin, 1974; Wood and Head, 1975) have associated with pre-mare KREEP volcanism, although the relationship between red spectral reflectance and KREEP has not been conclusively established.

As closely as the Apennine Bench Formation resembles MKFM basalt, there are suggestions in the data of some mixing process. The two variation diagrams of Fig. 7 show that while the calculated composition of the Apennine Bench Formation falls very close to the MKFM field, it lies on a mixing line between MKFM and anorthositic lithologies, not LKFM. This is in agreement with the orbital chemical mixing model results presented by Hawke (1978). Since this region is near the second (Archimedes) ring of the Imbrium basin, one would expect the non-Apennine Bench component of the chemistry of this region to be derived from deep crustal levels and hence, to be non-anorthositic. One possibility is that this component is not anorthositic but is derived from KREEP-poor granitic lithologies. However, the origin of the contamination of the Apennine Bench MKFM remains an unsolved problem.

#### AGE RELATIONSHIPS

Age relationships between Apollo 15 volcanic KREEP and Imbrium basin impact melt as determined by radiometric dating methods are not clear. Two Rb-Sr internal isochrons for Apollo 15 KREEP yield values of  $3.90 \pm 0.02$  AE ( $I = 0.70024 \mp 0.00012$ ) for 15382 (Papanastassiou and Wasserburg, 1976) and  $3.94 \pm 0.04$  AE ( $I = 0.70038 \mp 0.00010$ ) for 15386 (Nyquist *et al.*, 1975). Argon ages for 15382 yield values of  $3.90 \pm 0.05$  AE (Stettler *et al.*, 1973) and  $3.91 \pm 0.05$  AE (Turner *et al.*, 1973). These data strongly suggest extrusion of the KREEP lava flows around 3.90 AE.

Unfortunately, the age of the Imbrium event is known with less precision. One  $^{39}\text{Ar}$ - $^{40}\text{Ar}$  age has been obtained for the black portion of 15455 (Imbrium melt) and this gave an ill-defined plateau at  $3.92 \pm 0.04$  AE (Alexander and Kahl, 1974). If this date accurately represents the age of the Imbrium basin, then the Apennine Bench KREEP basalts were emplaced nearly 200 m.y. after the basin formed. However, the error bar overlap of the KREEP basalts and Imbrium melt rock is considerable and no firm conclusion can be drawn regarding their relative age. It is possible that portions of the Apollo 15 KREEP basalt collection were extruded at different times and the fact that at least one KREEP sample 15434,73, has a different initial Sr ratio ( $I = 0.70070$ ) than 15382 indicates more than one magma was involved in the production of Apollo 15 KREEP basalts (Meyer, 1977). In any case, the age dating of Apollo 15 materials demonstrates that the formation of the Imbrium basin and extrusion of Apennine Bench KREEP basalts were closely spaced in time, a conclusion that is in accord with photogeologic data which suggest the Apennine Bench Formation is the oldest post-Imbrium unit in this

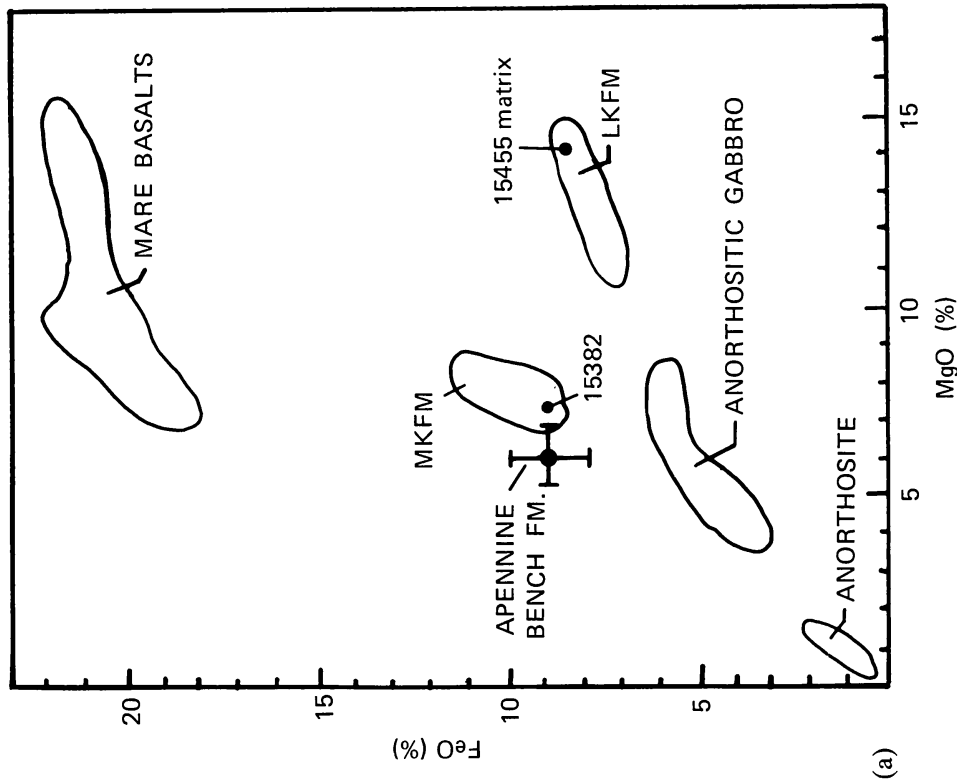
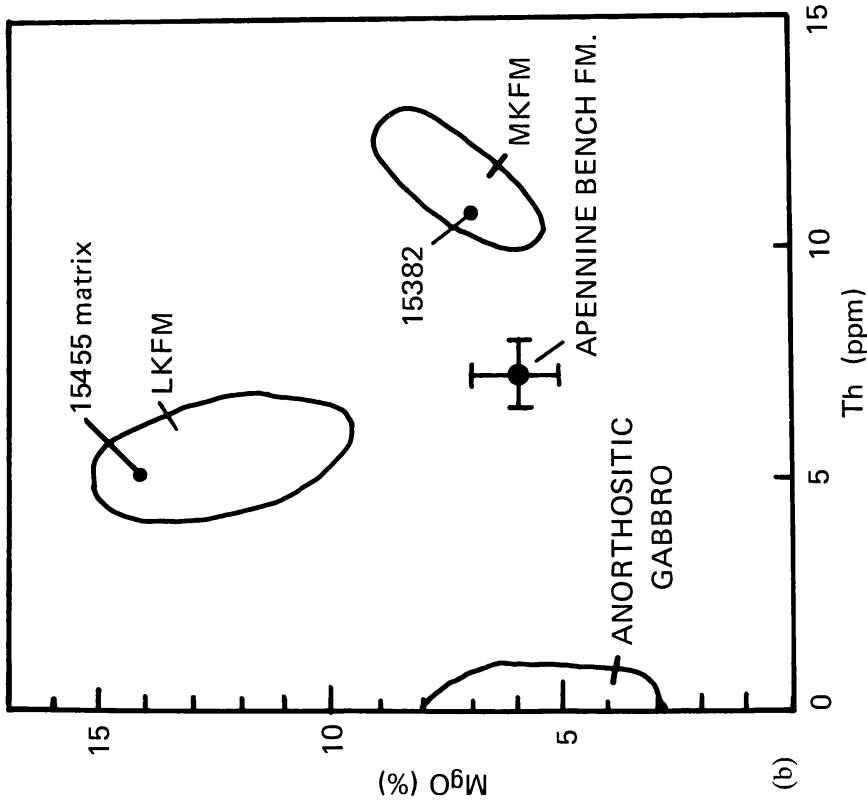


Fig. 7a. Variation diagram of FeO-MgO for lunar rock types showing the composition of the Apennine Bench region as determined by remote sensing methods. The plains plot very close to the MKFM (KREEP basalt) field. Location of 15382 (Apollo 15 volcanic KREEP) and 15455 matrix (Imbrium basin impact melt) are also shown. Field boundaries modified from Schonfeld (1977). Fig. 7b. Variation diagram of MgO-Th for lunar rock types. The Apennine Bench region falls on a mixing line between MKFM and "anorthositic" compositions. Location of 15382 (Apollo 15 volcanic KREEP) and 15455 matrix (Imbrium basin impact melt) are also shown. Data for field boundaries taken from Taylor (1975) and Meyer (1977).

region. This is in agreement with earlier suggestions that KREEP volcanism was active in pre-Imbrian time (reviewed in Meyer, 1977) and subsurface magma reservoirs were probably in existence during formation of the last of the large, young lunar basins.

### CONCLUSIONS

Integration of stratigraphic relationships, geologic setting, surface morphology and remote sensing data suggest that the Apennine Bench Formation is composed of post-Imbrium basin volcanic KREEP basalt flows. This KREEP volcanism occurred 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 earth-facing west side of the moon (Adler and Trombka, 1977) and the lack of KREEP basalt fragments younger than about 3.9 AE (Meyer, 1977) suggest this type of volcanism was uncommon after the formation of the youngest large lunar basins. Thus, the Apennine Bench Formation may represent the largest surface exposure of highland (non-mare) volcanism preserved on the lunar surface and as such, provides valuable insight into early lunar crustal processes.

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