

## Geology of the Imbrium Basin Apennine Mountains and relation to the Apollo 15 landing site

P. SPUDIS and J. W. HEAD

Department of Geological Sciences, Brown University, Providence, Rhode Island 02912

**Abstract**—Detailed mapping of the Imbrium Basin Apennine Mountains has emphasized several important factors in the geologic evolution of this region. Pre-Imbrian topography was composed of two types of landforms: (1) the nearby Serenitatis, South Imbrium, Aestuum, and Vaporum basins which produced widely spaced regional lows and a sequence of basin deposits; (2) Pre-Imbrian craters that reworked existing basin deposits and produced local topographic lows. The sequence of events during the Imbrium impact can be summarized as follows: Intensive structural uplift along the Apennine Front occurred prior to the emplacement of ballistic ejecta. Ejecta became more discontinuous toward the backslope and produced radial texture by sedimentary erosional and depositional processes. Post-ejecta-emplacement downfaulting exposed pre-Imbrian deposits along the front and caused severe seismic disturbances that reworked many of the previous units and accentuated pre-basin structures. Tectonic mapping and orbital geophysical data support the idea that little structural modification has occurred in the Apennines since their formation 3.9 b.y. ago. The extensive exposure of pre-Imbrian deposits during the formation of the Apennine Front suggests that talus slopes at the bottom of the massifs may be dominated by this material. Samples collected during Apollo 15 are derived from this unit, and Imbrium ejecta may constitute a relatively minor fraction of this suite.

### I. INTRODUCTION

THE APENNINE MOUNTAINS form the southeast portion of the third (outer) ring of the Imbrium Basin and are part of the most prominent topography associated with this impact basin. The Apennine region (Fig. 1) was heavily influenced by the Imbrium event, which was responsible for the emplacement of an extensive ejecta deposit and the formation of the Apennine scarp (Wilhelms and McCauley, 1971; Hackman, 1966; Carr and El-Baz, 1971). In spite of the extensive effects of the Imbrium ejecta emplacement, pre-Imbrian material may be exposed at the surface in this region due to such factors as: (1) structural uplift and exposure (Hackman, 1966), (2) uplift and shedding of Imbrium ejecta (Carr and El-Baz, 1971), and (3) mixture of pre-Imbrian material with Imbrium ejecta during deposit emplacement (Morrison and Oberbeck, 1975; Hawke and Head, 1977b). The Apollo 15 mission explored the base of the Apennines (Swann *et al.*, 1972) and collected a suite of highland samples. Detailed geologic mapping of this area has been undertaken to address the following problems: (1) What are the origins of the major geologic units and structure and how are they related to the Imbrium basin event? (2) What are the characteristics and origin of pre-Imbrium topography and how did it influence the Imbrium Basin deposits and structure? (3) What effects do these factors have in determining the provenance of highland samples collected during Apollo 15?

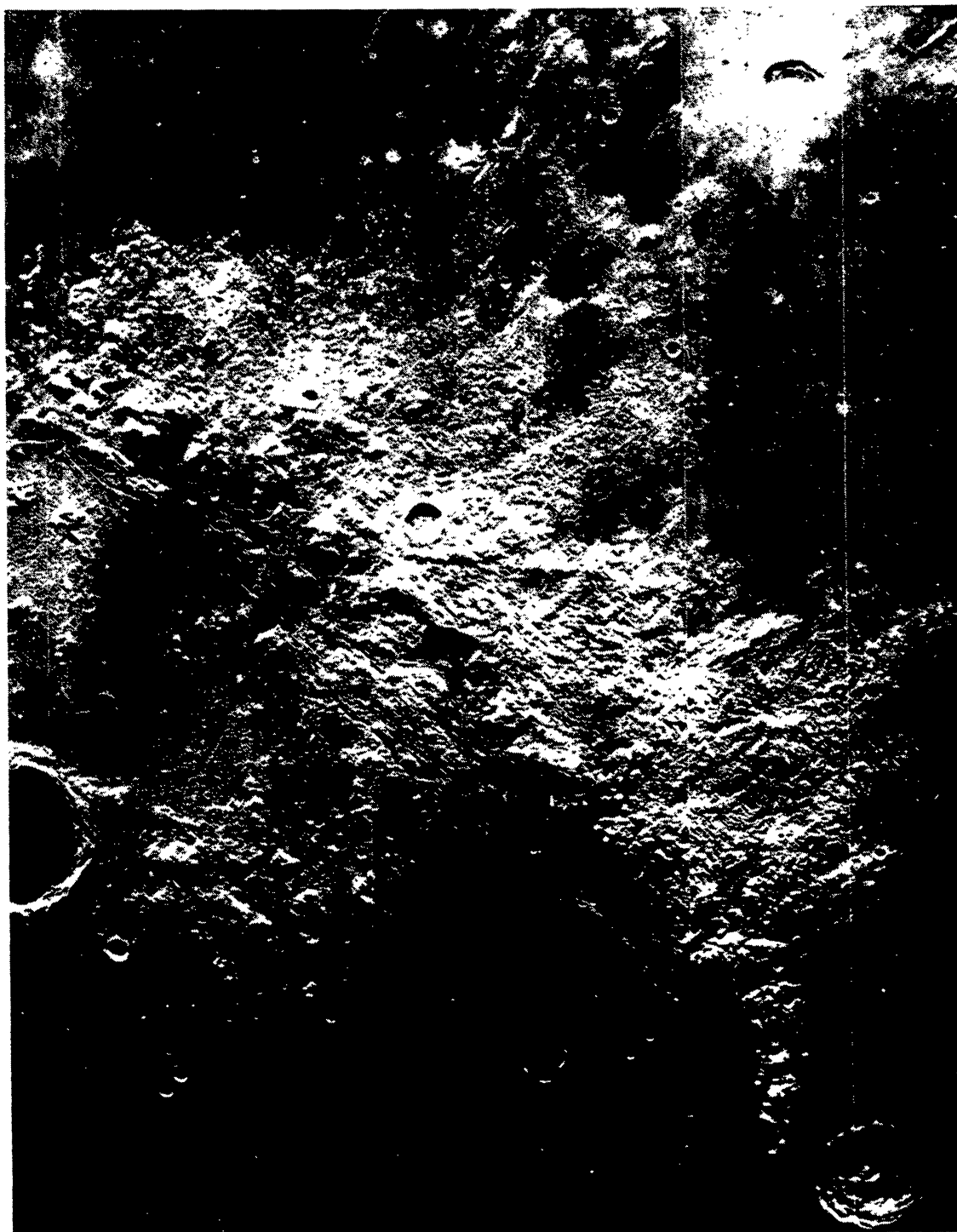


Fig. 1. The Apennine Mountains (enlargement of LO IV-102M).

## II. GEOLOGY

The Apennine Mountains contain several morphologically distinctive units (Figs. 2 and 3).

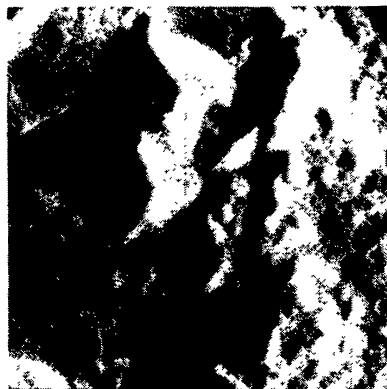
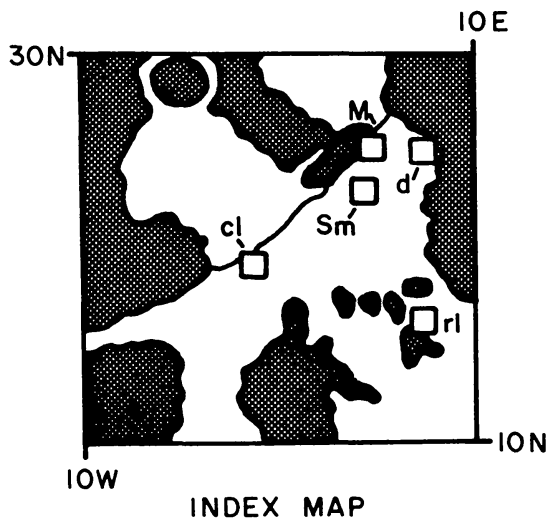
*Massifs* are large positive relief structures that are equant to elongate in plan view and greater than 20 km in average dimension (Type area: 26°37'N, 4°7'E; Hadley Lunar Topographic Orthophotomap (LTO) 41B4). They are concentrated on or near the Apennine Front and stand distinctly higher than surrounding terrain. They define the Apennine scarp or front and rise up to 4 km above the terrain inside the basin and often stand 1–1.5 km above the adjacent Apennine backslope (Fig. 4). The topographic distinctiveness and prominence of the massifs and their concentration along, and association with, the Apennine scarp, are evidence for an origin related to structural uplift and Imbrium Basin formation.

*Sub-massifs* are positive relief features that are notably smaller than the massif units (4–20 km) (Type area: 25°15'N, 3°33'E; Hadley LTO 41B4). Sub-massifs are equant to elongate in shape and occur throughout the Apennines but are concentrated near the front. Most of the sub-massifs are correlative with mapped pre-Imbrian craters (see Fig. 6) and appear to represent remnants of pre-Imbrian crater rim crests. In some cases, particularly near the scarp, the sub-massifs may represent fault blocks similar in origin to massifs but of smaller dimension.

*Concentrically lineated* terrain is comprised of linear ridges parallel and subparallel to the Apennine Front. Ridges vary from 1 to 3 km in width and 2 to 12 km in length (Type area: 21°30'N, 1°20'E; Conon LTO 41C1). Most concentrically lineated terrain is concentrated at or near the Apennine Front. The concentric lineations are formed by the margins of terrace-like segments producing “stairstep” topography extending away from the front in both directions. On the basis of these characteristics and the association with uplifted massifs and zones of major basin deformation (Head, 1976b), parts of this unit are interpreted as slump blocks that developed in association with the formation of the Apennine Front.

*Radially lineated* terrain typically occurs within the Apennine backslope, usually more than 100–200 km from the front (Type area: 18°30'N, 9°E; Bowen LTO 41C3). This unit consists of parallel to sub-parallel linear ridges similar in size to the concentrically lineated unit but oriented in a direction radial to the Imbrium Basin (normal to the Apennine scarp). This unit primarily represents the product of sedimentary erosional and depositional processes associated with the emplacement of basin ejecta (Moore *et al.*, 1974; Morrison and Oberbeck, 1975; Head, 1976a). In some areas of radially lineated texture, the subdued remnants of elongate basin secondaries can be recognized and these crater rim remnants make up the ridges that have a pronounced radial orientation. Although some radial ridges may represent fractures associated with basin formation, no such examples could be positively identified.

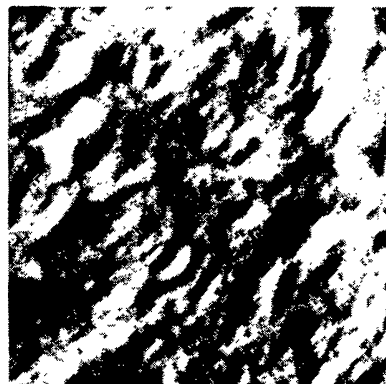
The *domical terrain* is the most extensive unit exposed in the Apennine backslope (Type area: 26°30'N, 7°30'E; Joy LTO 41B3). Relief is moderate to low



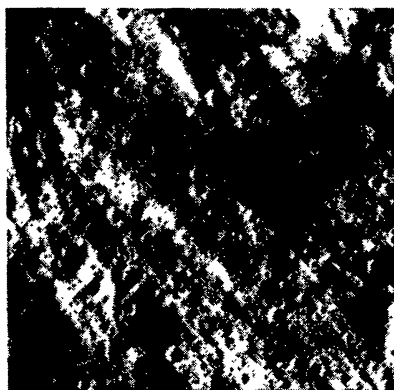
M - MASSIF



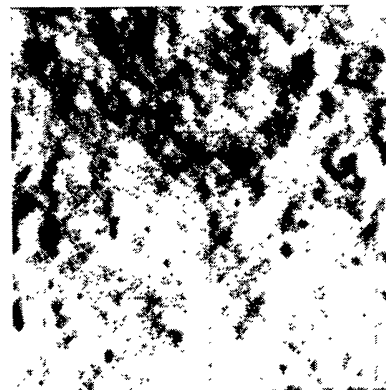
Sm - SUB-MASSIF



cl - CONCENTRICALLY  
LINEATED



rl - RADIALLY LINEATED



d - DOMICAL

Fig. 2. Type areas for geologic map units described in text. Photo scale is approximately 45 km on each side (Apollo 15 and 17 metric photos).

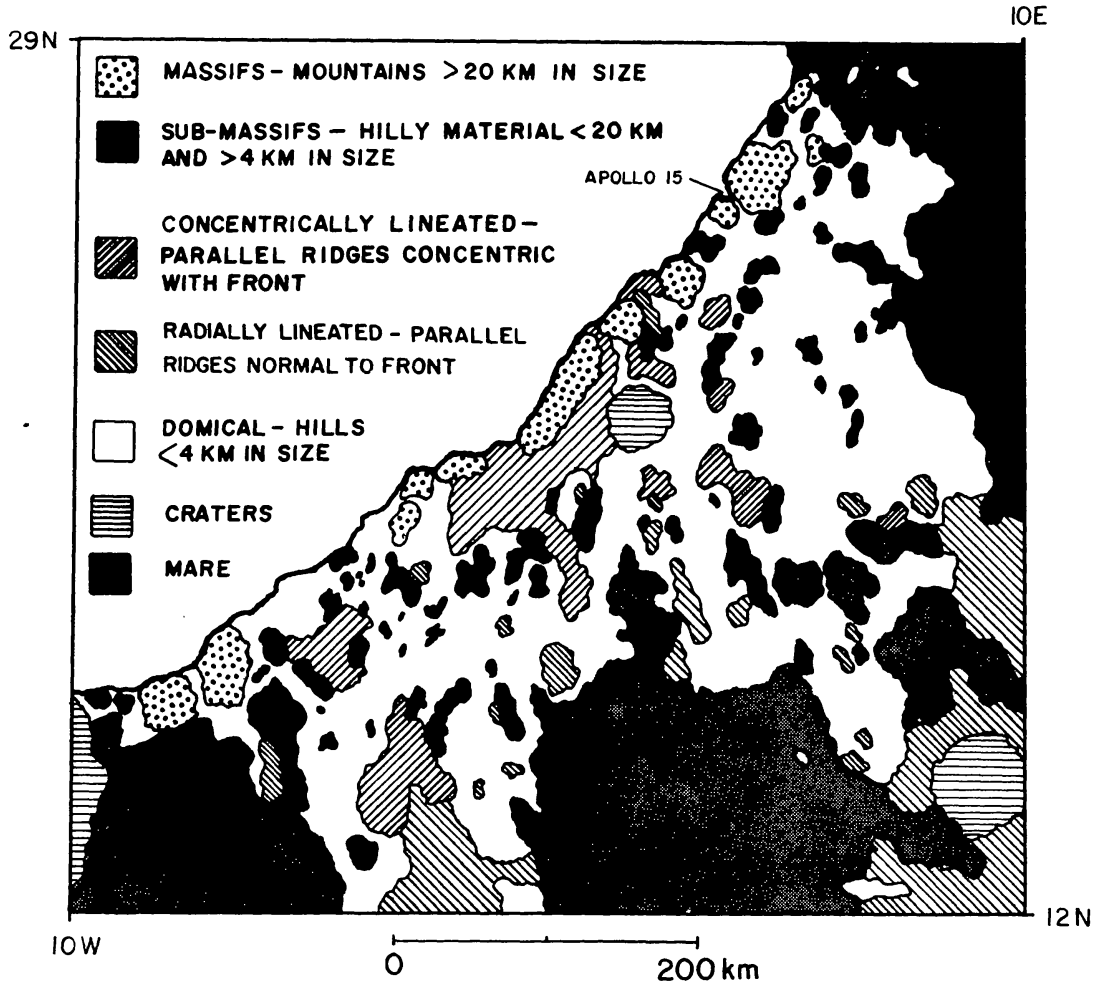


Fig. 3. Geologic map of the Apennine Mountains. The Apennine Front is shown by the heavy, irregular line. Units are not in stratigraphic order.

(less than several hundred meters) and morphology is generally domical. The domes are typically on the order of 2–5 km in size. This unit is gradational in many places with other units, particularly the sub-massif unit and morphologically resembles the Alpes Formation (Page, 1970; Wilhelms and McCauley, 1971). Domical terrain is particularly prominent in the northern Apennines near Mare Serenitatis. Several origins have been proposed for terrain characterized by a domical surface texture. Wilhelms and McCauley (1971) interpreted the Alpes Formation as erosionally degraded ejecta, structurally deformed pre-basin bedrock, or both. Head (1974a) interpreted materials of similar morphology between the outer Rook and Cordillera rings of the Orientale Basin as basin rim radial ejecta that had been modified by slumping and formation of a basin megaterrace. In this case, movement of surface deposits during and just after

their emplacement was one important factor in producing the domical texture. Moore *et al.* (1974) interpret the same material in Orientale to be of impact melt origin. No evidence was found to support an impact melt origin for the domical facies in the Apennine area. The following observations support an origin related to processes closely associated with basin formation and accompanying terrain modification, as opposed to long-term degradational processes: (1) topographic prominence of domes, (2) preservation of fine elements of radial texture, (3) association of similar facies with fresher (Orientale) and more degraded (Serenitatis; Head, 1974b) basins, and (4) distribution patterns related to basin and pre-basin topography.

Several of the geologic units recognized in the Apennines have analogous counterparts in the Orientale Basin region (Moore *et al.*, 1974; Head, 1974a). As in the Apennines, concentrically lineated terrain is intimately associated with the outer basin ring and the massif units that occur along the Cordillera scarp. The concentrically lineated terrain grades into radially textured facies away from the scarp in both basins, but the transition is better preserved in the younger and fresher Orientale Basin. Elongate secondary craters and crater chains radial to the basin are also encountered at both basins in this region. A notable difference between Imbrium and Orientale is the distribution of domical terrain. The domical facies at Orientale (Head, 1974a) is found primarily between the middle (Outer Rook) and outer (Cordillera) basin rings. At Imbrium, domical terrain is distributed there (Alpes) but is also abundant along the Apennine backslope (Fig. 3).

Figure 4 shows three topographic profiles across the Apennine Mountains (topographic data taken from Lunar Topographic Orthophotomaps). Profile A-A' distinctly shows the plateau character of the northern Apennines. This plateau is bounded by the third Imbrium Basin ring and the second Serenitatis Basin ring, and this fact strongly suggests that pre-existing Serenitatis Basin topography has strongly influenced the present topographic configuration of the Apennines in this area. The greater than 4 km relief of the Apennine Front strongly argues for original exposure of pre-Imbrium Basin deposits, at least near the base of the front. Profile B-B' does not display the plateau character of profile A-A', since the second Serenitatis ring is not crossed. A very subdued topographic break seen in this profile corresponds well with the location of the third Serenitatis Basin ring (Wilhelms and McCauley, 1971; Reed and Wolfe, 1975). In general, the third basin ring of Serenitatis does not appear to have been as well developed initially as the corresponding structure in the Apennines (Wilhelms and McCauley, 1971; Head, 1974b). An increase in slope toward the Haemus Mountains reflects the approach to the Serenitatis second ring. Profile C-C' clearly shows the topographic break that corresponds to the edge of the Mare Vaporum crater (see Fig. 6). Topographic depression in the Apennine backslope are in part correlated with the presence of pre-Imbrian craters (Fig. 6). These topographic data support the idea that pre-existing topography (particularly the Serenitatis Basin) had a profound influence on the distribution of morphologic facies in the Apennine backslope.

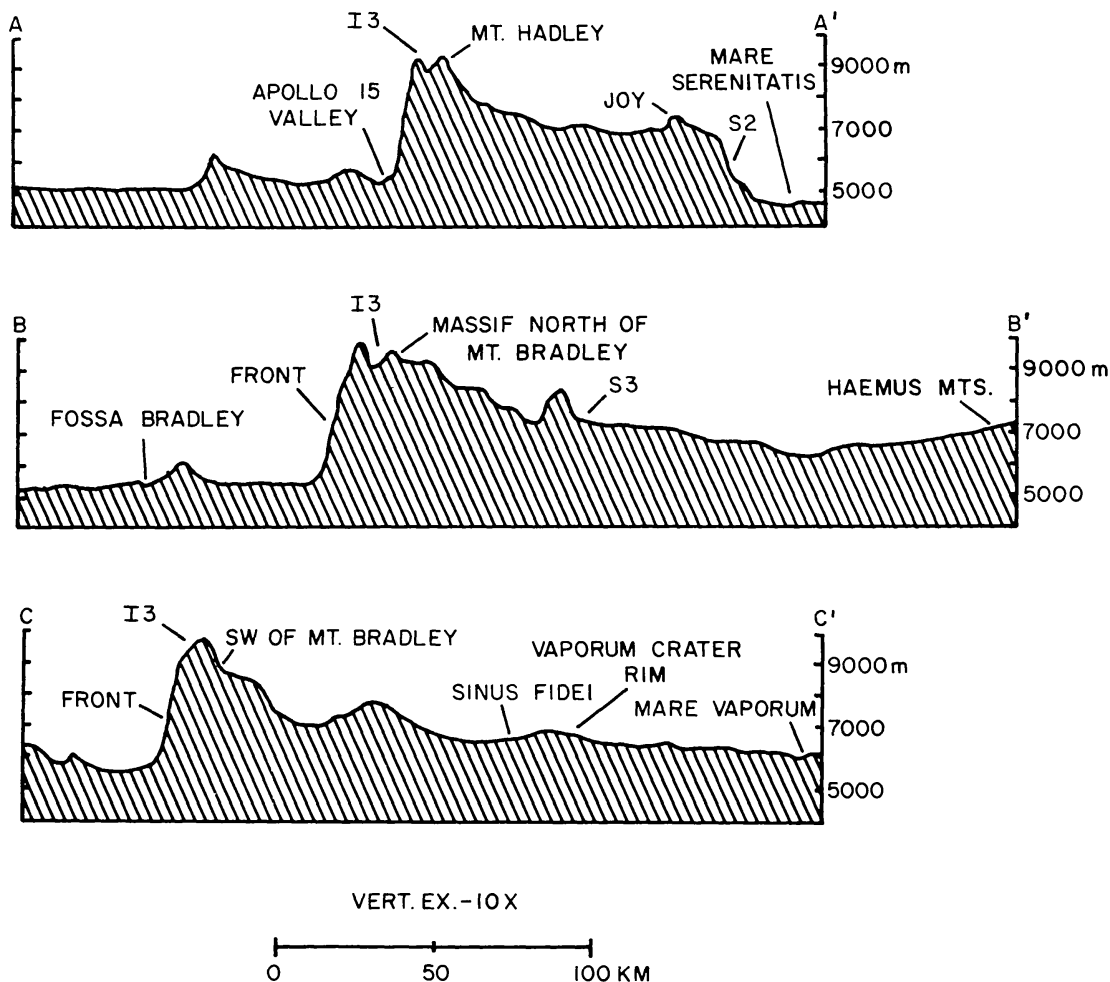


Fig. 4. Topographic profiles along section lines shown in Fig. 6. The symbols "I3" refer to the third Imbrium Basin ring; "S2" and "S3" refer to the second and third Serenitatis Basin rings, respectively.

### III. STRUCTURE

The major lineaments visible in the region are shown in Fig. 5. In general, most lineaments appear to be radial to or concentric with the Imbrium or Serenitatis basins. Recent reduction of orbital gravity data acquired by radio tracking of the Apollo 15 CSM suggest that the Apennine Mountains are isostatically uncompensated (Ferrari *et al.*, 1977). This implies the lunar lithosphere has been sufficiently rigid for the past 3.9 b.y. to support this crustal load and argues against extensive post-Imbrium Basin structural adjustment continuing up until the present.

### IV. PRE-IMBRIAN TOPOGRAPHY AND STRUCTURE

Several large craters and basins formed in pre-Imbrian time and exerted a marked influence on subsequent events and facies distribution (Fig. 6). The

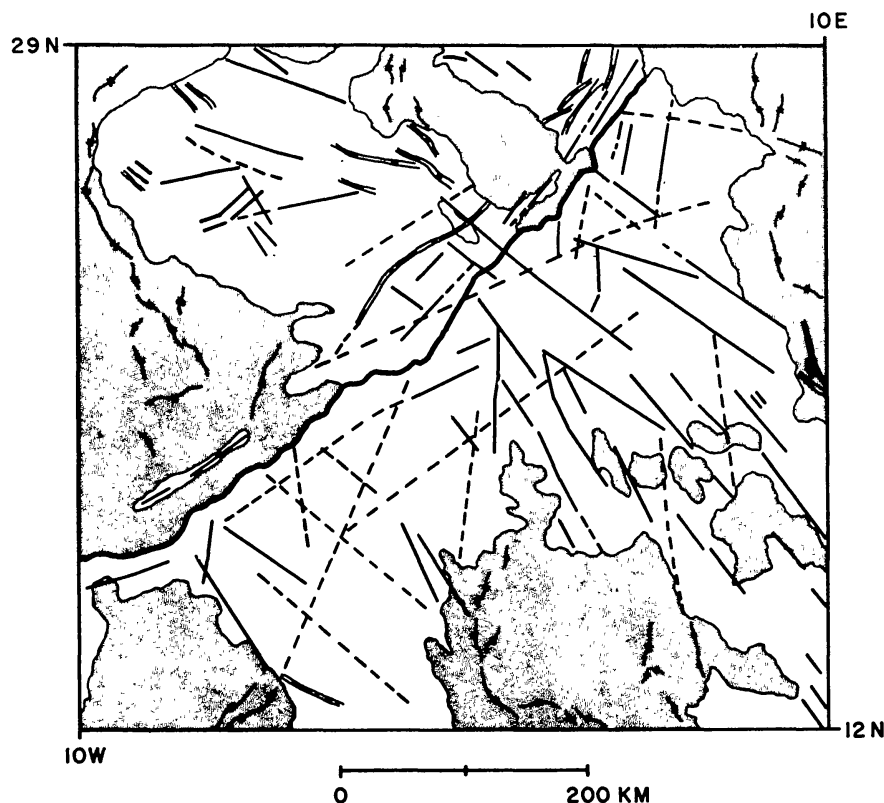


Fig. 5. Lineament map of the Apennine Mountains. Heavy lines are prominent lineaments, dashed lines represent subdued lineaments. Graben are shown by the line and ball symbol. Shaded areas are mare materials and mare ridges are shown by the doubly hatched line.

topographic prominence of the Apennine region is in part due to the preservation of a positive terrain segment between depressions produced by pre-Imbrian events. The large basin centered near Copernicus (Wilhelms and McCauley, 1971) is the oldest major feature detected in that area. This basin produced the regionally low topography near Copernicus (Hawke and Head, 1977a) and in the western Apennines, where the trace of an outer ring of the basin has been mapped (Wilhelms and McCauley, 1971). The abrupt contact between mare and uplands within Imbrium to the southwest of Archimedes (Fig. 6) may be explained by the extension of this basin ring and its influence on the Imbrium event (Head, 1977, Fig. XIV-1). The Aestuum Basin (Wilhelms, 1968) has accentuated this depression in the southwest part of the area. A similar regional depression has also been produced by the Vaporum crater. The eastern Apennine area was radically affected by the formation of the Serenitatis Basin which created a large, multi-ringed depression, and emplaced a significant ejecta deposit. Much of the eastern map area lies between the second and third rings of Serenitatis and outside the Imbrium Basin third ring (Apennines). Abundant smaller pre-Imbrian craters have been mapped in the Apennines and a decrease in density of these features toward Serenitatis may be attributable to the effects of ejecta from the Serenitatis event. Just prior to the formation of the Imbrium

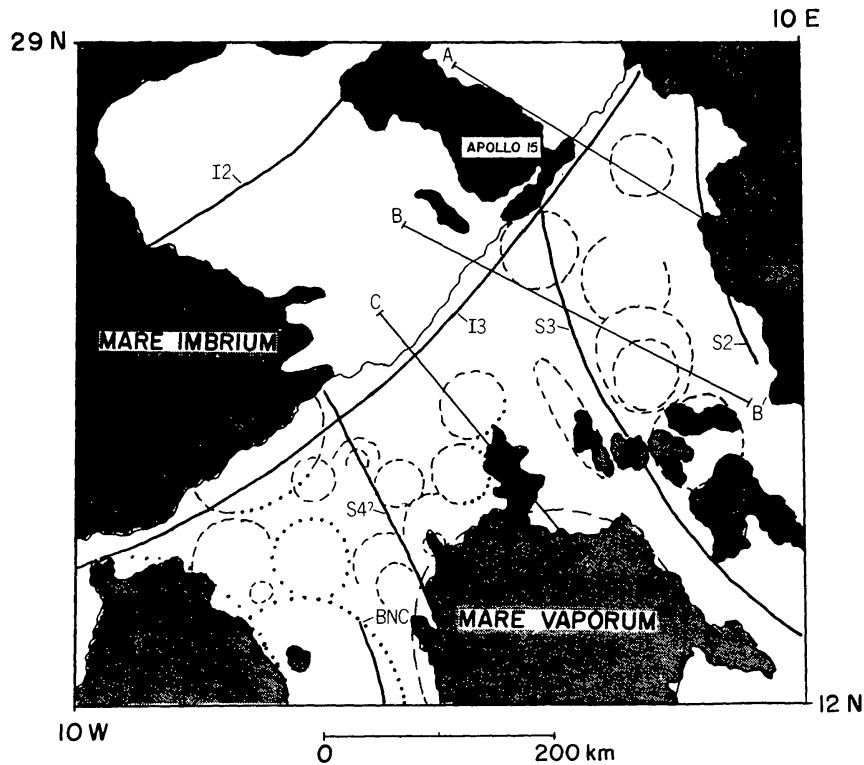


Fig. 6. Basin rings and pre-Imbrian craters in the Apennine Mountains. Dashed lines indicate a higher degree of certainty than dotted lines. Topographic profiles shown in Fig. 4 are taken along the lines designated with letters. Basin rings are designated by letter (I = Imbrium; BNC = Basin near Copernicus (Wilhelms and McCauley, 1971); S = Serenitatis), and number [e.g. "I3"—third Imbrium Basin ring (Apennine scarp)]. Basin ring locations taken from Wilhelms and McCauley (1971) and Reed and Wolfe (1975).

Basin, the Apennine area was a cratered highland region surrounded by and strongly influenced by large crater and basin-related depressions, and dominated by the deposits and topography of the Serenitatis Basin.

## V. DISCUSSION AND CONCLUSIONS

The following factors have been important in influencing the characteristics and distribution of the geologic units shown in Fig. 3: (a) Concentration of massif and sub-massif units in the southwest Apennines appears to be due to the concentration of pre-Imbrian cratered highland topography there. (b) The more subdued morphology of the northeastern Apennines (primarily domical facies) appears to be due to the influence of the Serenitatis event in smoothing out previously cratered topography. (c) The plateau-like topography and regional slope reversals seen in the northeast reflect both Imbrium and Serenitatis related topography. (d) The more even decay of backslope topography in the central and southern regions reflects the effects of other, more subdued pre-Imbrian topography (Vaporum, Aestuum) on the Imbrium event. (e) Many of the sub-massifs

are the remnants of pre-Imbrian crater rims (cf., Figs. 3 and 6). (f) The topographic prominence of the massifs along the front, the characteristics and distribution of the concentrically lineated terrain, the truncation of a large crater along the front, and the abundance of pre-Imbrian craters support a model of basin formation where the outer basin scarp (Apennines) has been formed by downfaulting of a megaterrace along the base of intense basin rim uplift at a distance of 1.2 to 1.5 crater radii from the crater rim crest (Head, 1976b).

Detailed study of the geologic units of the Apennine Mountains has provided additional information on Apollo 15 highland sample provenance. The importance of major structural uplift associated with formation of the Apennine Front is further emphasized by the geologic mapping and topographic data. The same information, in combination with mapping of pre-Imbrian topography, shows that the Serenitatis Basin was a dominant factor in the morphologic and petrologic characteristics of the Apollo 15 site just prior to the formation of the Imbrium Basin. Detailed knowledge of the provenance of the highland samples collected by astronauts Scott and Irwin requires an improved understanding of lunar slope processes, since the samples were obtained from talus at the base of massifs. However, the regional characteristics and setting of the site can provide important guidelines for models of sample provenance. On the basis of the preliminary results of this study, the following points argue for the importance of factors in addition to material derived from the Imbrium Crater: (1) The Apennine Mountain scarp appears to mark the location of a ring formed outside of the Imbrium Crater rim (see Head, 1974a, 1976b) and is thus not the crater rim itself. The mass of crater ejecta falls off exponentially from a maximum near the crater rim crest. Therefore, less material derived from the crater would be expected at this distance. (2) Higher velocities are required to transport material greater distances from the crater rim crest. As a consequence, ejecta impacts at a higher velocity and incorporates higher proportions of local material into the resulting ejecta deposits (Morrison and Oberbeck, 1975; Hawke and Head, 1977b). (3) Intensive structural uplift associated with massif formation raises pre-Imbrian material to surface and near-surface levels. (4) Downfaulting associated with basin megaterrace and outer ring (Apennine) formation produces a scarp whose relief is locally in excess of 4 km. This value is considerably greater than estimates of Imbrium ejecta thickness in this area (see McGetchin *et al.*, 1973) implying exposure of a considerable thickness of pre-Imbrian deposits. Primary sources of pre-Imbrian material at the Apollo 15 site include: (1) Serenitatis Basin ejecta deposits (the Apollo 15 site is located on the third ring of the Serenitatis Basin), (2) local crater deposits (see Fig. 6), and (3) Pre-Imbrian basin deposits (Vaporum, Aestuum, basin near Copernicus).

The characteristics of surface deposits are important in the interpretation of remote sensing spectral data (Charette *et al.*, 1977). Massif and sub-massif units in the northern Apennines probably represent pre-Imbrian deposits associated with the Serenitatis Basin. These same units in the southern Apennines will contain more local non-Serenitatis material since they are further removed from the Serenitatis Basin. Massifs and sub-massifs in this area probably represent

reworked local materials produced by pre-Imbrium Basin cratering and basin deposits of the South Imbrium, Aestuum, and Vaporum basins. Domical terrain is most likely to consist of Imbrium ejecta near the Apennine Front, local components becoming more important toward the backslope. Radially lineated terrain probably contains a significant fraction of locally derived material. Care should be taken in interpreting spectral information in the northern Apennines since the domical terrain here is discontinuously mantled with a dark mantling deposit. This dark mantle may be pyroclastic material deposited during the early stages of mare emplacement (Carr and El-Baz, 1971).

On the basis of the foregoing discussion and conclusions, the following sequence of events in the Apennine region is suggested. The Apennine region just prior to the Imbrium event was strongly dominated by the presence of the Serenitatis Basin in the east and the South Imbrium and Aestuum basins in the southwest. During the impact of the Imbrium projectile, pronounced structural uplift occurred from the crater rim crest out to the area that was later to become the Apennine Front. The pre-Imbrian rocks in this area were uplifted, and the massif units are remnants of the outer edges of that early episode of uplift. Strong seismic disturbance (Schultz and Gault, 1975) accompanied uplift. Ballistic ejecta was emplaced during the later stages and after structural uplift. The effect of this ejecta was to: (1) mantle pre-existing topography near the front, and (2) mix with pre-existing local material further out along the backslope. Sub-massif units for the most part represent pre-Imbrium topography that protrudes above the mantling Imbrium ejecta and are remnants of pre-Imbrium crater rim crests. The domical terrain near the front consists of Imbrium ejecta that contains progressively more local material away from the front. Radially lineated terrain formed during the interval of ballistic sedimentation by erosional secondary chain cratering, deposition of ejecta "filaments", and radial flow of material. Formation of the Apennine scarp or "megaterrace" (Head, 1976b) occurred shortly after ejecta emplacement. The rapid downfaulting of the scarp produced most of the concentrically lineated terrain by *en echelon* movement of material along the zones of earlier structural disturbance. Extensive slumping also occurred along the front during this interval (Carr and El-Baz, 1971). Modification of emplaced Imbrium ejecta by seismic activity produced some of the subdued domical morphology seen in the Apennine backslope and helped shed ejecta emplaced on pre-Imbrian material during the sedimentation interval. Almost all structural adjustment occurred during this period of megaterrace formation. This interval of intense seismic disturbance following ejecta emplacement helped to accentuate pre-Imbrium Basin structural and topographic features that might otherwise be obscured by the effects of Imbrium Basin formation. Following formation of the Apennine Front, geological activity was primarily concerned with post-basin volcanism. Later cratering in the Apennines (e.g., Conon) has redistributed some material, but this is a relatively minor effect.

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