MORPHOLOGY AND STRUCTURE OF THE TAURUS-LITTROW HIGHLANDS (APOLLO 17): EVIDENCE FOR THEIR ORIGIN AND EVOLUTION

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Abstract. The Taurus-Littrow region (Apollo 17 landing area) is located in the northeastern quadrant of the Moon in the mountainous area on the southeastern rim of the Serenitatis basin. The highlands in the Taurus-Littrow region can be divided into three broad terrain types. (1) *Littrow massifs* – massive, 10–20 km diam, steep-sloped (20°–30°), highland blocks often bordered by linear graben-like valleys. (2) *Littrow sculptured hills* – a series of closely spaced 1–5 km diam domical hills occupying broad highland plateaus which have been cratered and block faulted. Sculptured hill units stretch along the eastern edge of Serenitatis from the Apollo 17 area north to Posidonius. (3) *Vitruvius front and plateau* – a long irregular but generally north-trending scarp (occasionally rising over 2 km above the surrounding terrain) and its associated uplifted plateau to the east. This terrain is composed of hills ranging from 2–7 km diam, whose morphology is intermediate between the sculptured hills and the massifs.

It is concluded that the highland units in the Taurus-Littrow region are primarily related to the origin of the Serenitatis basin because of their marked similarity to more well-preserved basin-related deposits in the younger Imbrium and Orientale basins: (1) the massifs and sculptured terra are morphologically similar to the Imbrium basin-related Montes Alpes and Alpes Formation, (2) the relative geographic position of the Taurus-Littrow highlands and Montes Alpes/Alpes Formation is the same, forming the second ring and spreading distally, and (3) the structures are similar in orientation and development (e.g., massifs are related to radial and concentric structure; Alpes Formation/sculptured terra are not).

Interpretation of the massifs and sculptured hills as Serenitatis impact-related deposits lessens the possible role of highland volcanism in the origin and evolution of the Taurus-Littrow terrain, although extensive pre-Serenitatis volcanism cannot be ruled out. The preserved morphology of the sculptured hills suggests that the thickness of post-Serenitatis large basin ejecta (from Imbrium, for instance) is small, compared to the total highland section. This implies that the primary contributions to the highland stratigraphy are from Serenitatis and pre-Serenitatis events. The highland surface, however, may be dominated by ejecta from the latest nearby large event (formation of the Imbrium basin).

Structural elements mapped in the Taurus-Littrow area include lineaments, the Vitruvius structural front, two types of grabens, and scarps. The majority of lineaments, as well as some grabens, appear to be related to a dominant NW trend and subordinate N and NE trends. These trends are interpreted to be related to a more regional lunar grid pattern which formed in the area prior to the origin of the Serenitatis basin, causing distinct structural inhomogeneities in the highland terrain. The Serenitatis event produced radial and concentric structures predominantly influenced by this pre-existing trend. Younger grabens are generally circumferential to the Serenitatis basin and appear to be related to readjustment of Serenitatis-produced structures; those that are oblique to Serenitatis follow the pre-Serenitatis structural grain. No obvious structural elements can be correlated with the post-Serenitatis, Nectaris and Crisium basins. It is believed that the origin and hence the geographic concentration of the Littrow massifs is related to the fact that Serenitatis radials in the massif area coincide with lines of pre-existing structural weakness along a general lunar grid direction (NW). Pre-existing structurally weak lunar grid trends seem to have been structurally reactivated by Serenitatis radials, causing preferential uplift of large blocks in this area. Elsewhere in the region radials would be oblique to this direction. Since Serenitatis and Imbrium radials coincide in the massif area, the post-Serenitatis Imbrium event may have reactivated Serenitatis radial fractures, possibly rejuvenating the massif terrain.

The geologic and tectonic history of the Taurus-Littrow highlands began prior to the origin of

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Serenitatis in Tectonic Interval I. The strong NW trending structural elements are believed to have formed as part of a global stress pattern (possibly shear) sometime during this period of probable crustal formation and fragmentation. Tectonic Interval II was initiated by the origin of the Serenitatis basin. The basic topography and morphology of the region and most large grabens resulted from this event and their orientations show that they were controlled at least in part by the pre-existing grid. No other large basins forming during this interval appear to have had a major effect on the area. Tectonic Interval III is dominated by the formation of narrow grabens following structural patterns circumferential to the Serenitatis basin and tangential to it where they coincide with pre-existing grid directions. Serenitatis isostatic rebound or early mare fill may have produced this stress system. The scarp in the vicinity of the Apollo 17 landing site is the youngest obvious structural element.

1. Introduction

Apollo 17 visited a complex highland region at the southeastern edge of Mare Serenitatis (Figures 1, 2). The purpose of this paper is to present the results of an analysis of the morphology and major structural trends in the Taurus-Littrow region and to outline the bearing of these features on the origin and subsequent history of this area of the highlands. The analysis is complicated by the fact that in old complex lunar terrain, many of the morphologic forms which characterize distinct geologic units have been subdued or destroyed (e.g., compare the structures around the relatively

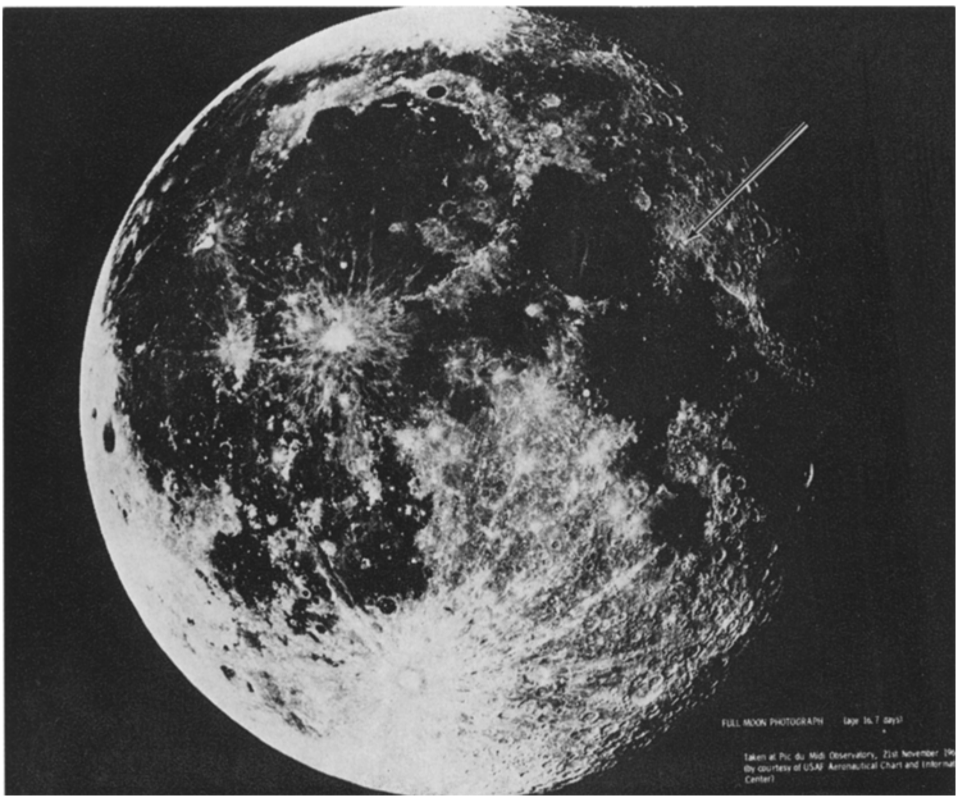


Fig. 1. Full Moon photograph. Arrow designates Apollo 17 region.

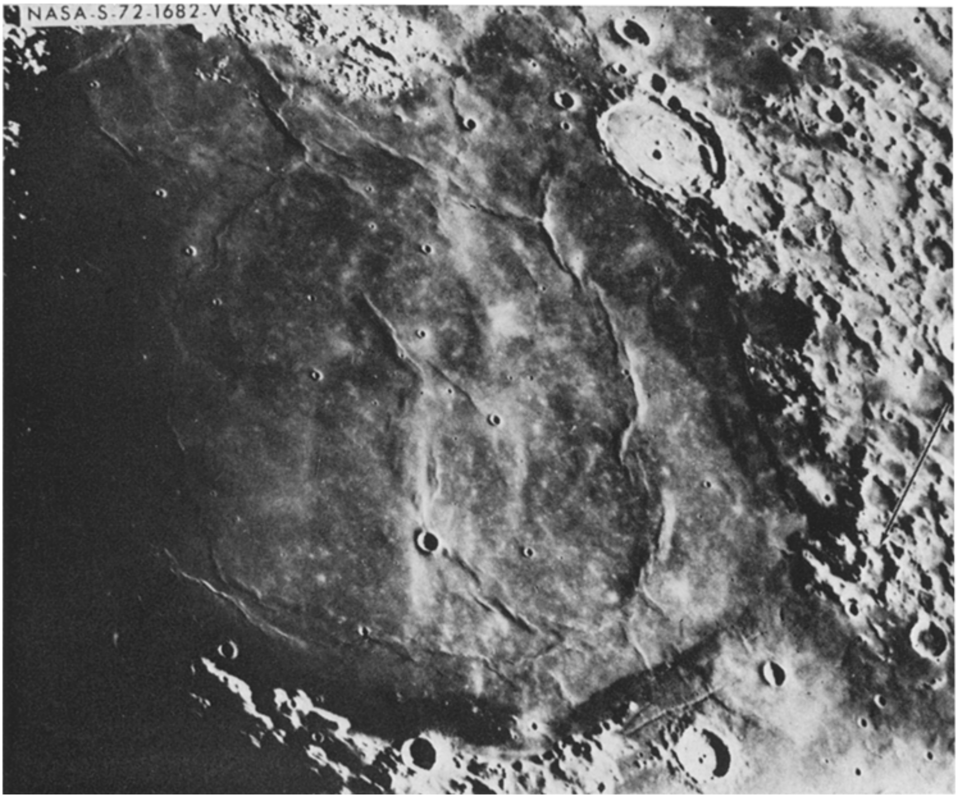


Fig. 2. Telescopic view of the Serenitatis basin with Apollo 17 landing area designated.

young Orientale basin and the older Serenitatis basin). In many cases, the only remaining evidence of a previous period of history may lie in degraded morphologic units and in distinct or indistinct structural elements. Furthermore, due to multiple events, such a wide variation in structural grain may exist that no distinctive trends are obvious at first glance.

The sources of data for this study (Table I) include the appropriate Lunar Orbiter 4 and 5 photography, Earth-based telescopic photography, and a variety of photographs obtained on the Apollo 15 mission. In particular, the Apollo 15 panoramic and metric camera photography served as the primary source and most of the measurements were made on an area centered on metric camera frame 0971.

Throughout this study the term 'basin' will be used to refer to the generally circular topographic and structural features which form depressions that are often subsequently filled with mare material. Thus, the Serenitatis basin is a structure which has been flooded by mare material forming a surface known as Mare Serenitatis.

Data were obtained by mapping structures in the Taurus-Littrow area (valleys, rilles, lineaments, crater chains, scarps, linear crater walls, etc.) and measuring the azimuths of features or regional groups of these features. Care was taken to avoid

TABLE I

Sources of photographic data for the Taurus-Littrow region

Apollo 15 panoramic camera	9260–9300 9530–9565		
Apollo 15 metric camera	0385–0395 0555–0566 0830–0839	0965–0975 1105–1118 1397–1408	1515–1520 1648–1655 1792–1798
Apollo 15 hasselblad	10945 11695–11696 11704–11714	12398 12765–12774 12842–12847	
Lunar Orbiter 4	H 73, 74, 78, 79 M 86, 91, 98		
Lunar Orbiter 5	H 66–69 M 66–69		
Earth-based telescopic photography			

spurious results from lighting artifacts (Howard and Larsen, 1972) mainly by measuring only prominent topographic features, many of which could also be verified on topographic maps (U.S. Army Topographic Command, 1972). Additional data were obtained by compiling hypsographic maps and profiles from existing topographic maps. Most of the data are presented in the form of azimuth frequency diagrams.

2. Major Lunar Structural Elements

Regional structural elements on the Moon usually fall into one of several categories which often define linear elements. These include: (1) faults and linear scarps such as Rupes Recta, (2) rilles, both straight and sinuous, such as Hyginus and Hadley, (3) crater chains, such as Davy, and (4) structures associated with multi-ringed basins such as mountain fronts, linear and concentric down-faulted rilles, fractures, and valleys, and other crater-related structures. Global lunar structural grains, primarily composed of these elements, have been described and mapped by Strom (1964) and Fielder (1963) and have been called the lunar grid. Although often coinciding with multi-ringed basin structural systems, the majority of global lineaments appear to form an essentially independent fracture system generally oriented in a NW–SE, NE–SW direction. Offield (1966) studied structural patterns in the central portion of the lunar nearside and failed to detect strong indications of the lunar grid directions which were obvious from much larger samples (Strom, 1964). Offield's results suggest that the regional structure in the lunar equatorial belt may be different than that in other lunar nearside regions.

In addition to the initial variety of structural elements, there may also be an aging

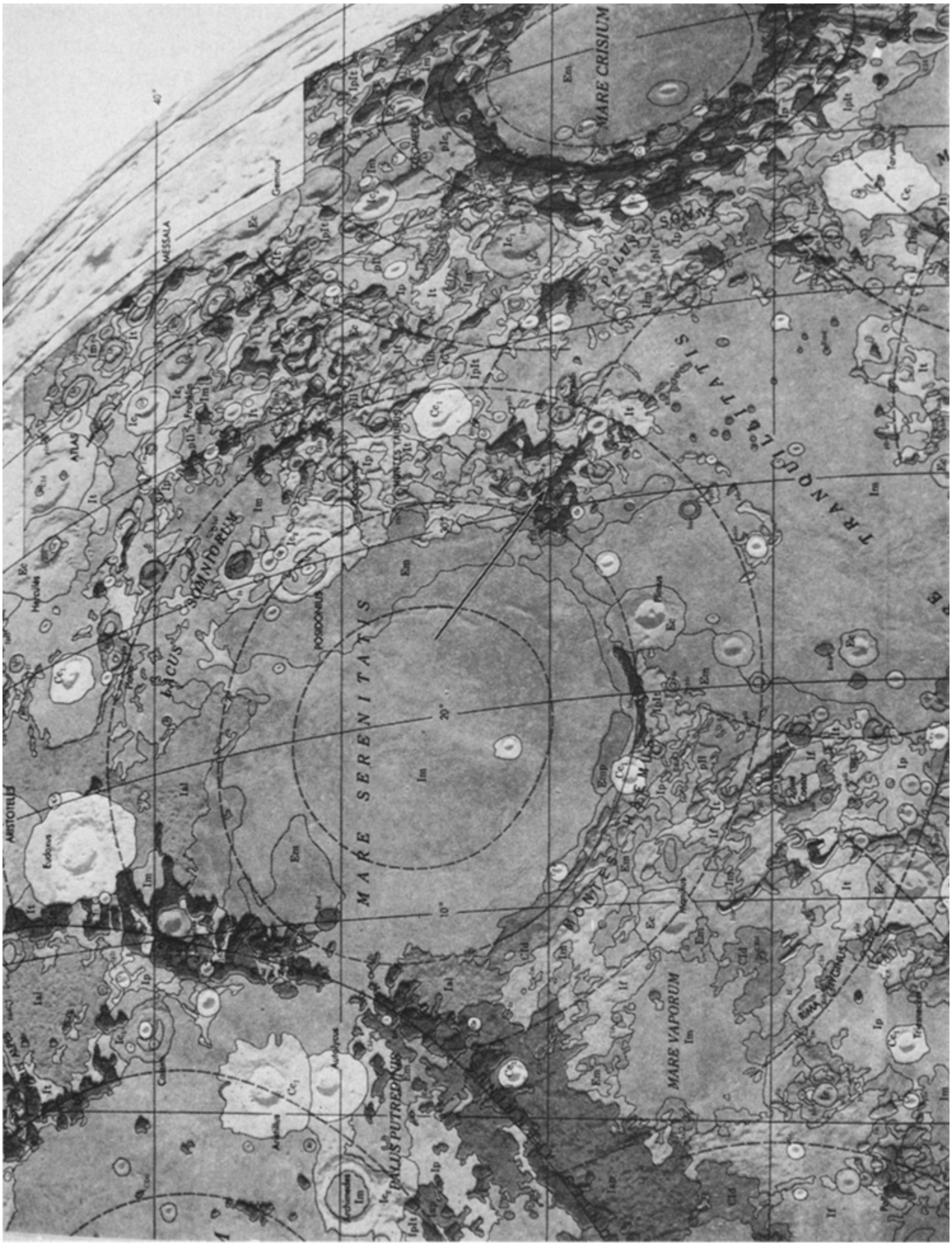


Fig. 3. Geologic map of Serenitatis and adjacent areas (from Wilhelms and McCauley, 1971).

effect due to factors such as structural readjustment (rejuvenation) or impact modification (erosion, subduing, and destruction). This might explain the differences in sharpness and indeed the presence or absence of many structures associated with different multi-ringed basins. For instance, the Imbrium basin is known to overlap and thus is younger than the Serenitatis basin. Radial and concentric structures are much sharper and more distinct around the Imbrium basin than around the older Serenitatis basin.

3. General Basin Terrain Morphology – The Imbrium Basin Example

It is worth describing circum-Imbrium basin materials in some detail since their well-preserved nature will aid in the recognition of similar units in the older and more subdued Serenitatis basin and because in part, their deposition has greatly modified Serenitatis deposits. The interior, or first ring of the Imbrium basin now remains as a discontinuous series of peaks protruding through the mare fill and forming a generally circular outline (Figures 3 and 4). Montes Teneriffe are the most prominent peaks in

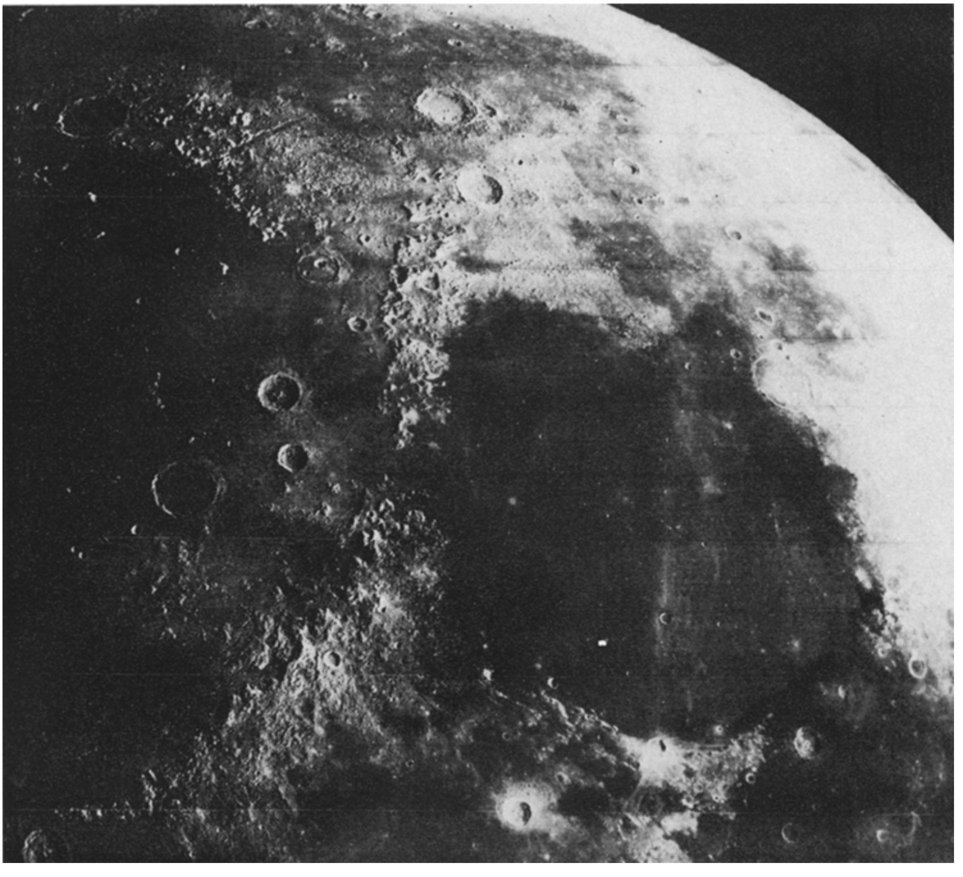


Fig. 4. Eastern Mare Imbrium (left) and Serenitatis (right; about 500 km diam) LO IV–109M.

this ring. The second, or intermediate ring, is most prominent in the area of Montes Alpes and is defined there by the basinward scarp of this range (Figures 3 and 4). The third, or outer ring, is dominated by Montes Carpatus, Montes Apenninus, and Montes Caucasus. The Apennines and Caucasus (Figure 4) are subdivided into four broad units as discussed by Wilhelms and McCauley (1971):

(1) pIr (pre-Imbrian rugged material), characterized by "rugged blocks most commonly 10 to 30 km across, generally with rectilinear outlines; forms highest and most rugged parts of arcuate raised ridges in and around major circular multi-ringed basins; most extensive and rugged around Imbrium, more subdued

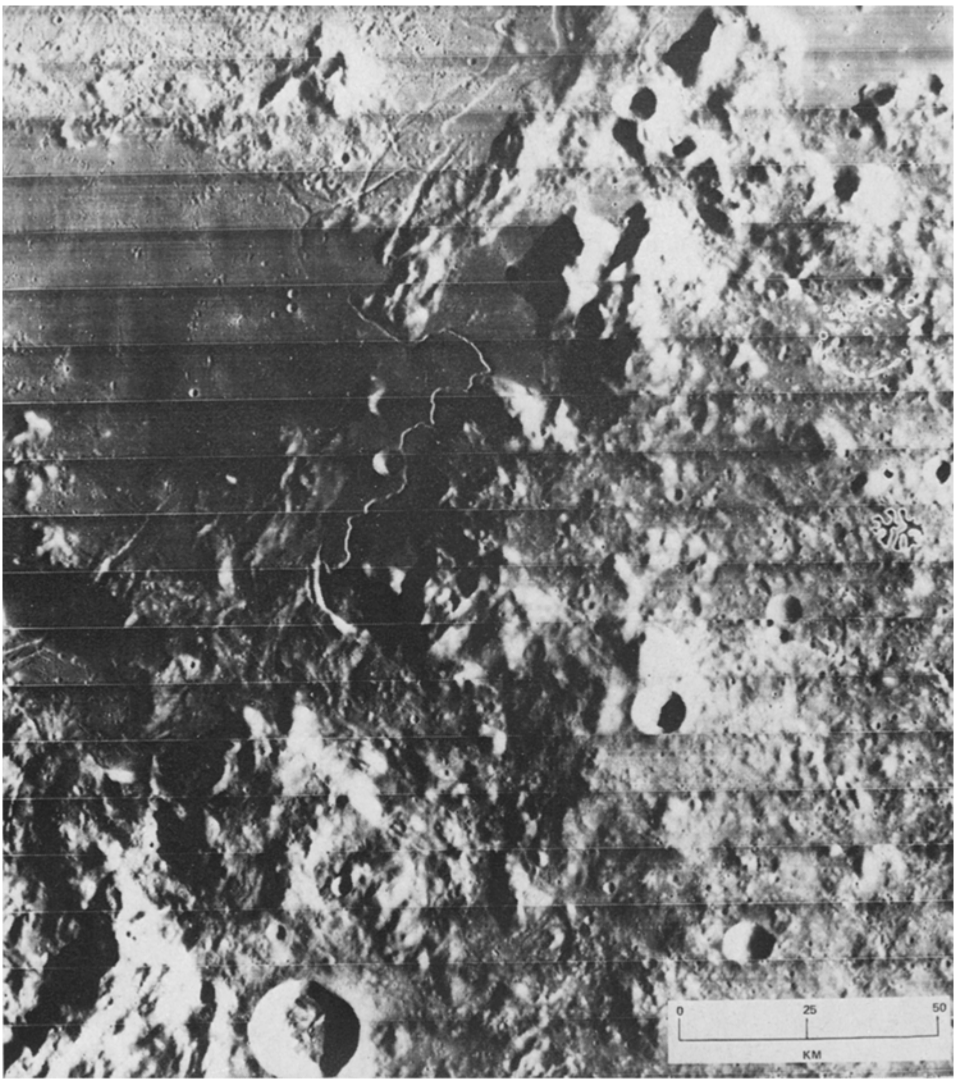


Fig. 5. Pre-Imbrian rugged material (pIr) in the Apennine Mountains of the Imbrium basin (LO IV–102H3).

elsewhere. Slopes steep, smooth, and bright at Orbiter 4 scale. Gradational contacts with adjacent low terrain, or bordered by apron of material that encroaches on adjacent materials" (Figure 5).

Mount Hadley is the type area for this unit which is interpreted to be composed of pre-basin rocks uplifted by the impact forming the basin. Some post-impact tectonic rejuvenation is suggested in certain areas and some of the more subdued blocks might possibly have been formed or modified by volcanism (Wilhelms and McCauley, 1971).

(2) Iap (material of the Apennine Mountains), characterized by "rough coarse blocks of material having elongate rectilinear outlines parallel to Apennine scarp bordering Imbrium basin, and smooth to undulating interblock materials. Blocks gradational in size with Alpes Formation (finer) and pre-Imbrian rugged material (coarser)" (Figures 5 and 6).

Wilhelms and McCauley (1971) interpret this unit as probably bedrock which was fractured at the time of the Imbrium impact. They interpret inter-block materials as possibly basin ejecta.

(3) Ial (Alpes Formation), characterized by "blocky or knobby but smooth-surfaced, closely spaced hills 2–5 km diam without conspicuous preferred orientation or lineation. Occurs both within Apennine ring, as at type area, and beyond, as near Kepler" (Figure 7).

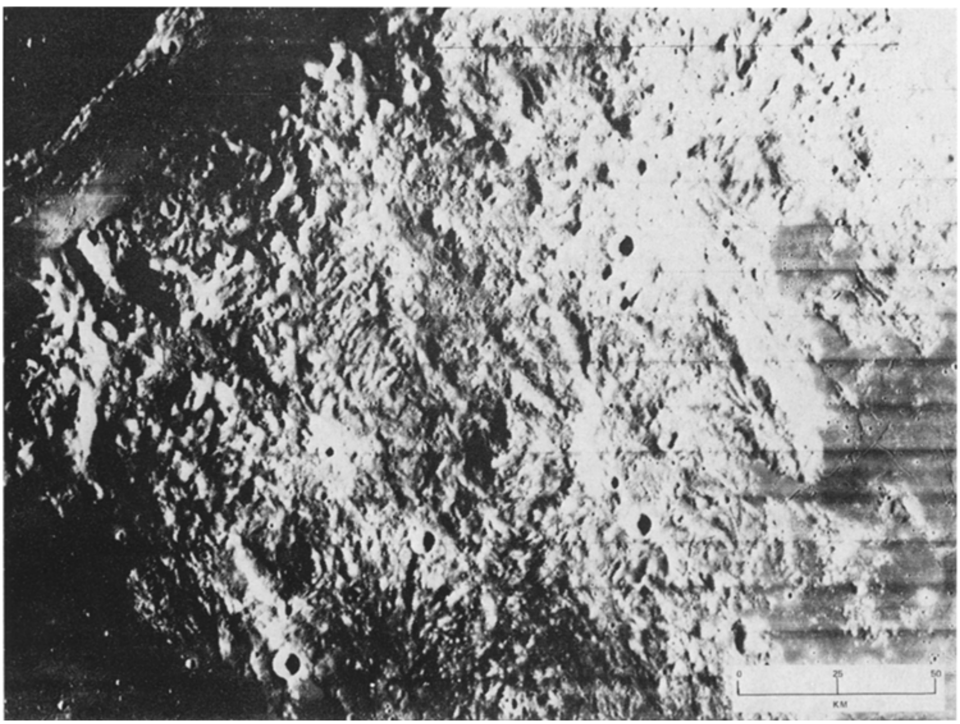


Fig. 6. Material of the Apennine Mountains (Iap) northeast of Sinus Aestuum at the edge of the Imbrium basin (LO IV–109H2).

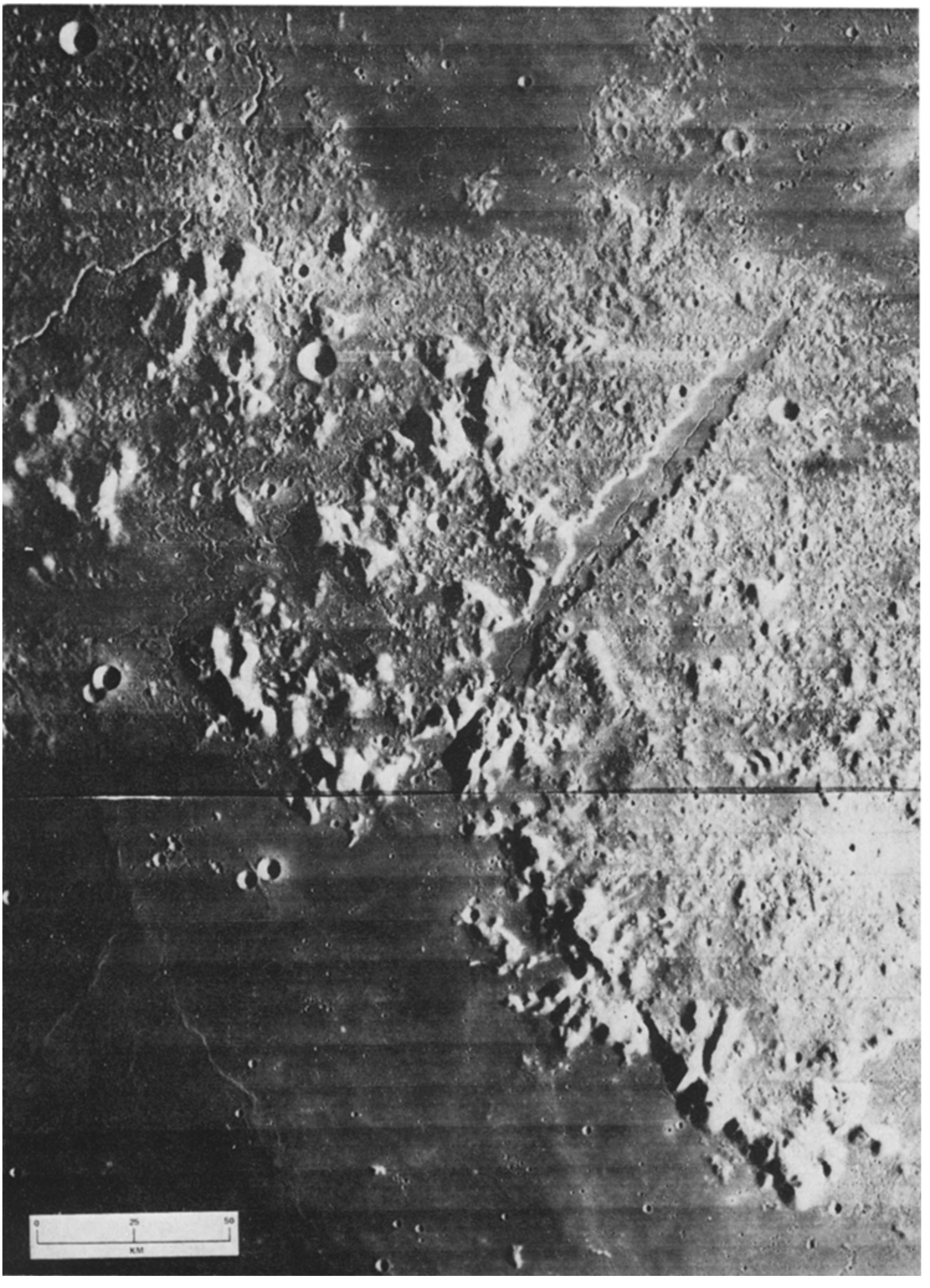


Fig. 7. Material of the Alpes Formation (Ial) along the Alpes Mountains in the Imbrium basin (LO IV–115H).

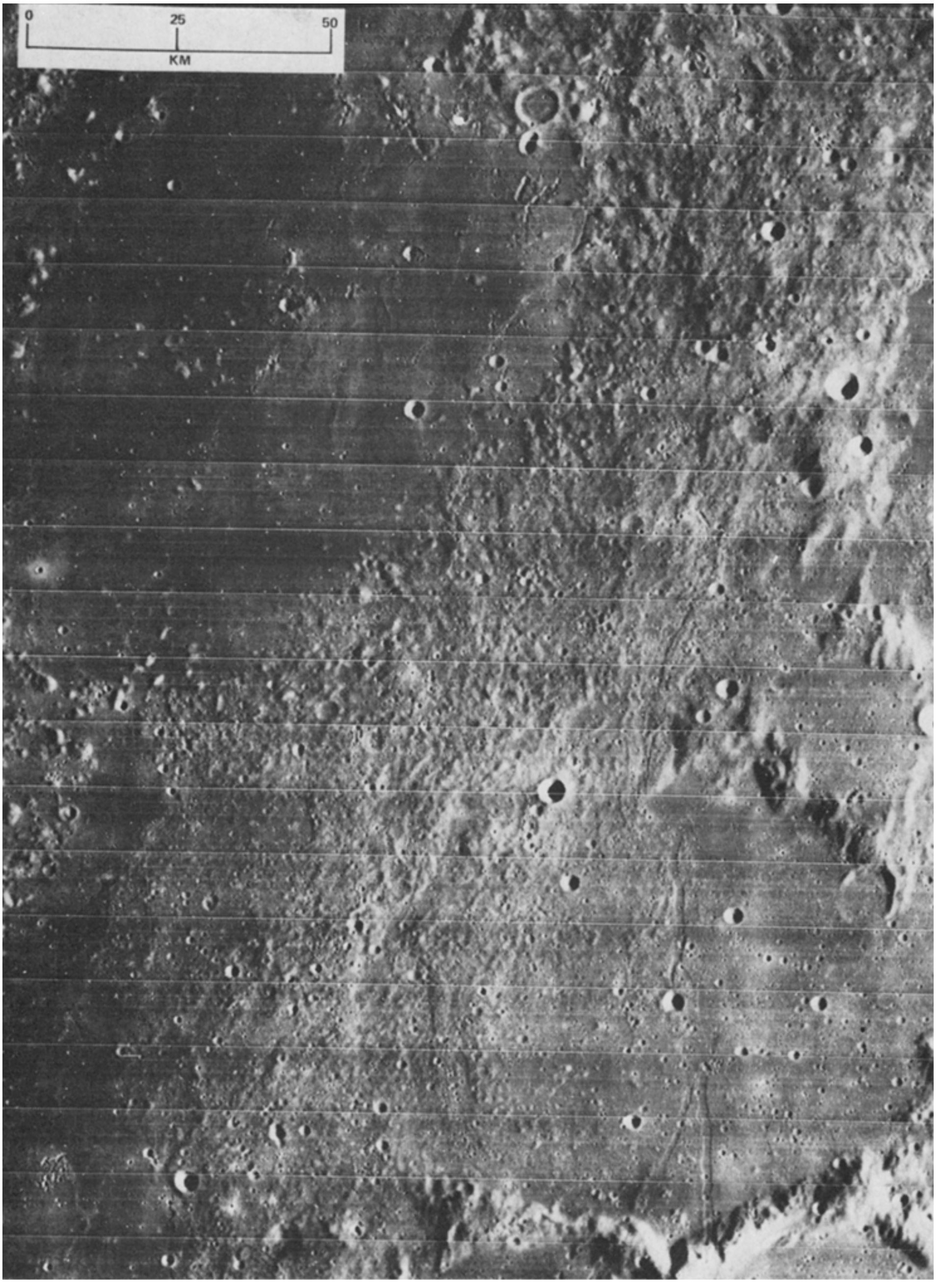


Fig. 8. Fra Mauro Formation (If) south of the Imbrium basin near the crater Fra Mauro (LO IV–120H3).

This unit is related to the Imbrium basin and according to Wilhelms and McCauley may be erosionally degraded ejecta, or pre-basin bedrock which has been structurally deformed, or both.

(4) If (Fra Mauro Formation), characterized by "sinuous to straight, smooth textured ridges or elongate hummocks typically 2–4 km across and 5–7 km long, oriented radially and subradially to the Imbrium basin" (Figure 8).

This unit is interpreted to be the impact ejecta of the Imbrium event and was sampled on Apollo 14 (Wilshire and Jackson, 1972).

A summary of these basin related facies emphasizing their associated structures is shown in Table II. In general, there appears to be a direct relationship between topographic prominence and number of radial structures and increasing distance from the basin while there is an inverse relationship between increasing distance and concentric structures. Many exceptions to this exist, particularly around basin rings,

TABLE II

Comparison of concentric and radial structures in units of the Imbrium basin

Geologic unit and occurrence (in general order away from basin margin)	Concentric structures	Radial structures
(1) pIr (Pre-Imbrian rugged material) Forms second and third rings.	S Basin facing scarp usually defines major basin rings	S–M Blocks are usually rectilinear; part of their definition is the radial component. Often define short radial grabens.
(2) Iap (material of the Apennine Mountains) Associated with the third ring on both sides.	S Rectilinear blocks are elongated parallel to basin-defining scarps.	M Occurs primarily as discrete regional fractures, usually strong, but widely spaced.
(3) Ial (Alpes Formation) Between second and third ring. Outside, but near the third ring.	W No conspicuous preferred orientation or lineation.	W–M No conspicuous preferred orientation or lineation. Some radial structure may be a reflection of underlying topography.
(4) If (Fra Mauro Formation) Outside the third ring.	W Very inconspicuous.	S Occasionally very strong; comprised of ridges generally oriented radially.

S – strong
M – moderate
W – weak

where radial structures are often strong. The Alpes Formation is also anomalous in that it shows little pervasive structural grain although nestled among strongly lineated terrain.

4. Regional Setting

The Taurus-Littrow region is located in the northeastern quadrant of the Moon in the mountainous region of the eastern and southerstern rim of the Serenitatis basin. The Apollo 17 landing site lies on plains nestled between mountains at the edge of the Serenitatis basin (Figure 2). Geologic maps of this region have been compiled at various scales by Carr (1966), Scott and Carr (1972), Scott and Pohn (1972), Lucchitta (1972), and Wolfe and Freeman (1972). Since the area not only lies at the edge of the Serenitatis basin, but also in close proximity to the Imbrium, Tranquillitatis, and Crisium basins, the majority of structural elements in the region might reasonably be expected to be related to concentric and radial elements of these basins. Figure 3 illustrates the position of mapped concentric rings associated with these basins.

In terms of lunar cratering history, the Serenitatis basin is relatively old, with Tranquillitatis and Fecunditatis the only discernible nearby eastern hemisphere basins pre-dating its formation (Table III). Subsequent to Serenitatis, the Nectaris,

TABLE III

Relative ages of formation of major nearside circular basins[a]

Basin	Coordinates
Orientale	S20 W95
Imbrium	N37 W19
Crisium	N17 E59
Humorum	S24 W39
Nectaris	S16 E34
Serenitatis	N26 E19
Fecunditatis	S03 E51
Tranquillitatis (W)	N09 E27
Tranquillitatis (E)	N11 E38
Nubium	S19 W17

[a] From Stuart-Alexander and Howard (1970). Hartmann and Wood (1971), place the same basins prior and subsequent to Serenitatis, although their order differs.

Crisium and Imbrium basins formed in that order in this region of the Moon (Stuart-Alexander and Howard, 1970). A quantitative model of ejecta contributions from the various large impact structures (and the resulting stratigraphy) in the Taurus-Littrow region has been derived (McGetchin *et al.*, 1973). This paper concentrates on terrain morphology and the structural contributions from basins and other sources. It is clear from the foregoing discussion that two factors should weigh heavily in an

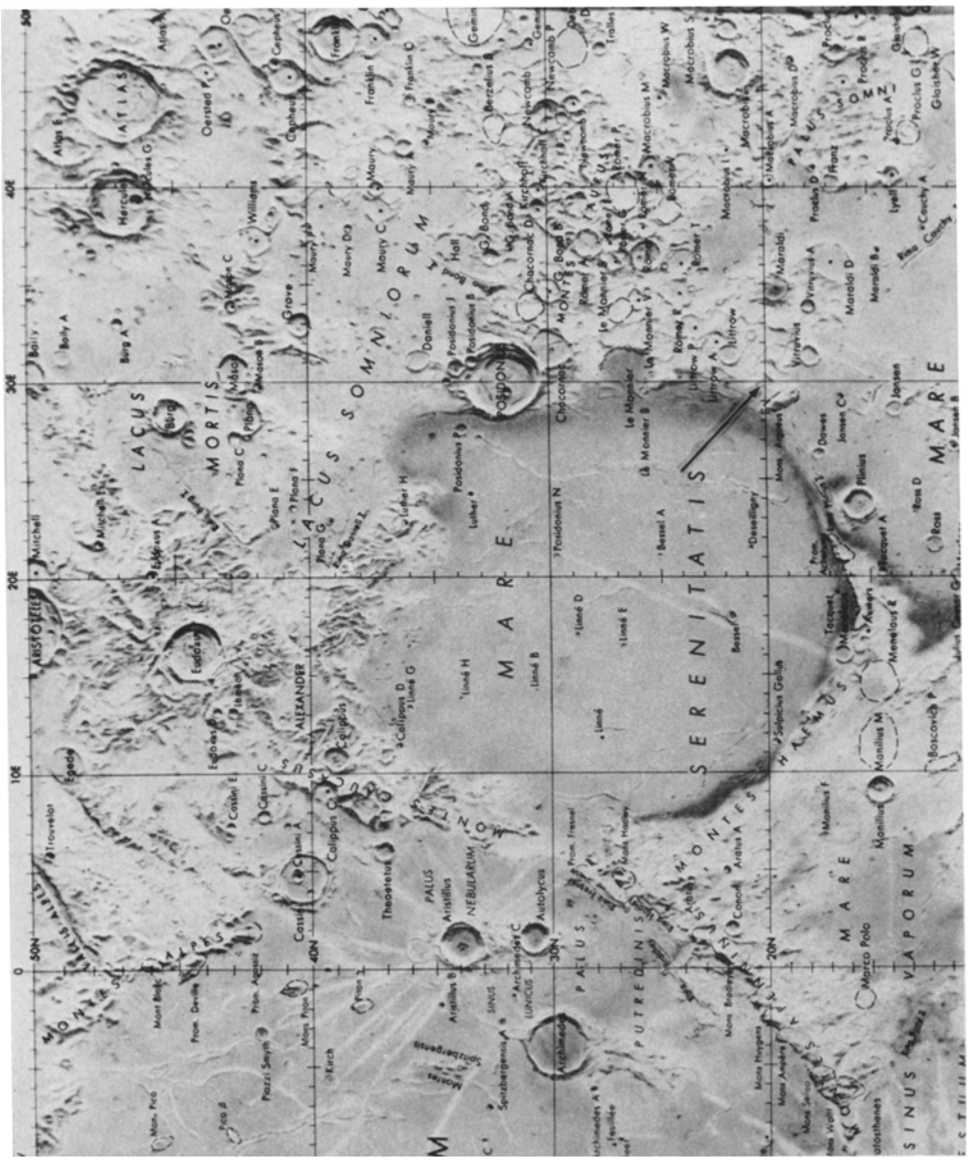


Fig. 9. Chart of the Serenitatis region with Apollo 17 landing area designated (portion of Lunar Earth-side chart LMP-1).

analysis of the origin of the present morphology of the Serenitatis basin: the relatively old age, and thus the expected subdued nature of Serenitatis morphologic units and concentric and radial structures, and secondly, the proximity of other large relatively younger multi-ringed basins, such as Imbrium, which may have heavily modified the Serenitatis basin in both a structural and stratigraphic sense.

The highland areas surrounding Mare Serenitatis and making up the rim of the Serenitatis basin were formed earlier than those of younger basins such as the Imbrium Apennine Mountains. Along the western margin of Serenitatis, the effects of the Imbrium event dominate. Both the Apennine and Caucasian Mountains, which form the third ring of the Imbrium structure, topographically replace what must have been the eastern upraised third ring of the Serenitatis basin (Figures 3, 4, 9). Imbrium-related deposits of pre-Imbrian rugged terrain, Alpes Formation, and materials of Montes Apenninus are the units which form these mountain ranges (Wilhelms and McCauley, 1971).

In addition to the two distinct mountain chains forming the western border of the Serenitatis basin, other terrain types characterize large portions of the basin rim. One of these is the Haemus Mountains (southwest Serenitatis), dominated by the grooved and furrowed structure of the Fra Mauro Formation and several portions of topographically high, undivided terra material, particularly around Menelaus. To the north in the area to the east of the Caucasus Mountains and to the southeast of Eudoxus, the closely spaced hills of the Alpes Formation dominate, rather than the elongate ridges of the Fra Mauro as in the Haemus Mountains (Figures 3 and 4). The western edge of the Serenitatis basin (dominated by Imbrium basin deposits) is seperated from the eastern portion, both to the north and to the south. In the south, a broad channel of flat mare terrain exists between Acherusia Promintory and the Vitruvius-Littrow area, connecting Serenitatis and Tranquillitatis maria. To the north, a similar terrain exists between Mare Serenitatis and Mare Frigoris as a more extensive yet congested flat mare channel, in the form of Lacus Somniorum (Figures 3, 4, and 9). The eastern portion of the Serenitatis basin rim stretches from Posidonius south through the Taurus Mountain area, to the Vitruvius region. Although apparently not dominated by effects of the Imbrium basin (whose center is over 1300 km away), this part of the Serenitatis basin is in close proximity to the Crisium, Tranquillitatis, and Fecunditatis basins. Structural and depositional effects from these basins, as well as the lunar grid in general, have probably complicated this region. Highland units mapped in this region are dominated by pre-Imbrium rugged terrain, pre-Imbrian-Imbrian hilly terrain, and undivided upland terrain (Wilhelms and McCauley, 1971; Scott and Pohn, 1972; Figure 3).

5. Local Setting and Terrain Morphology

The highlands in the Taurus-Littrow region are subdivided into three broad morphologic types: (1) massifs, (2) sculptured hills, and (3) the Vitruvius front and plateau (Figure 10).

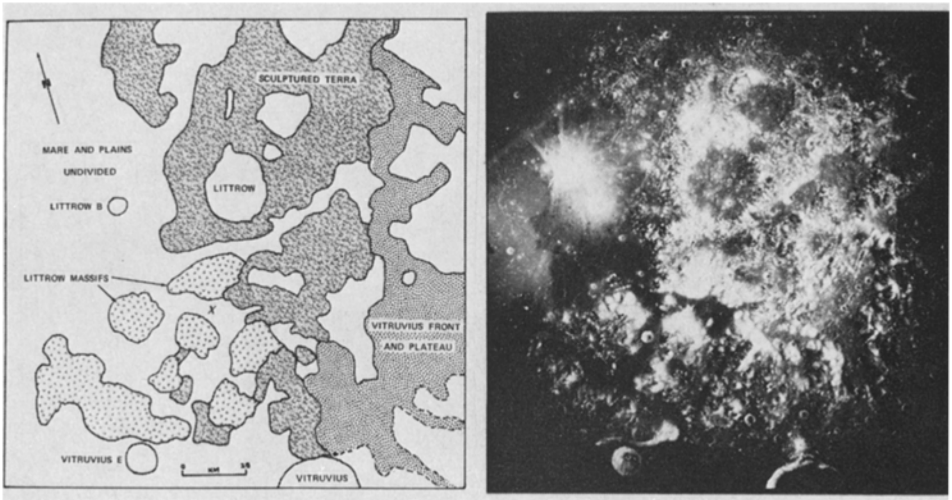


Fig. 10. Sketch map of terrain types in part of the Taurus-Littrow highlands and Apollo 15 metric camera frame 0971. X denotes the Apollo 17 target point.

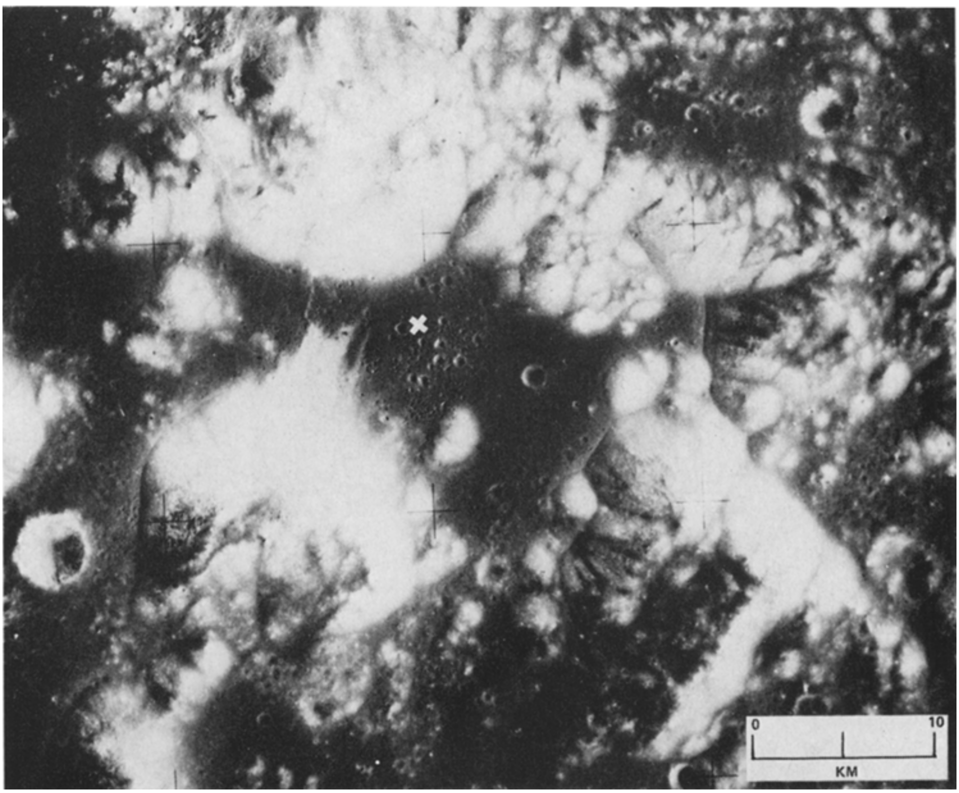


Fig. 11. Apollo 17 landing area (X) showing massifs and related units (portion of AS–15–0970).

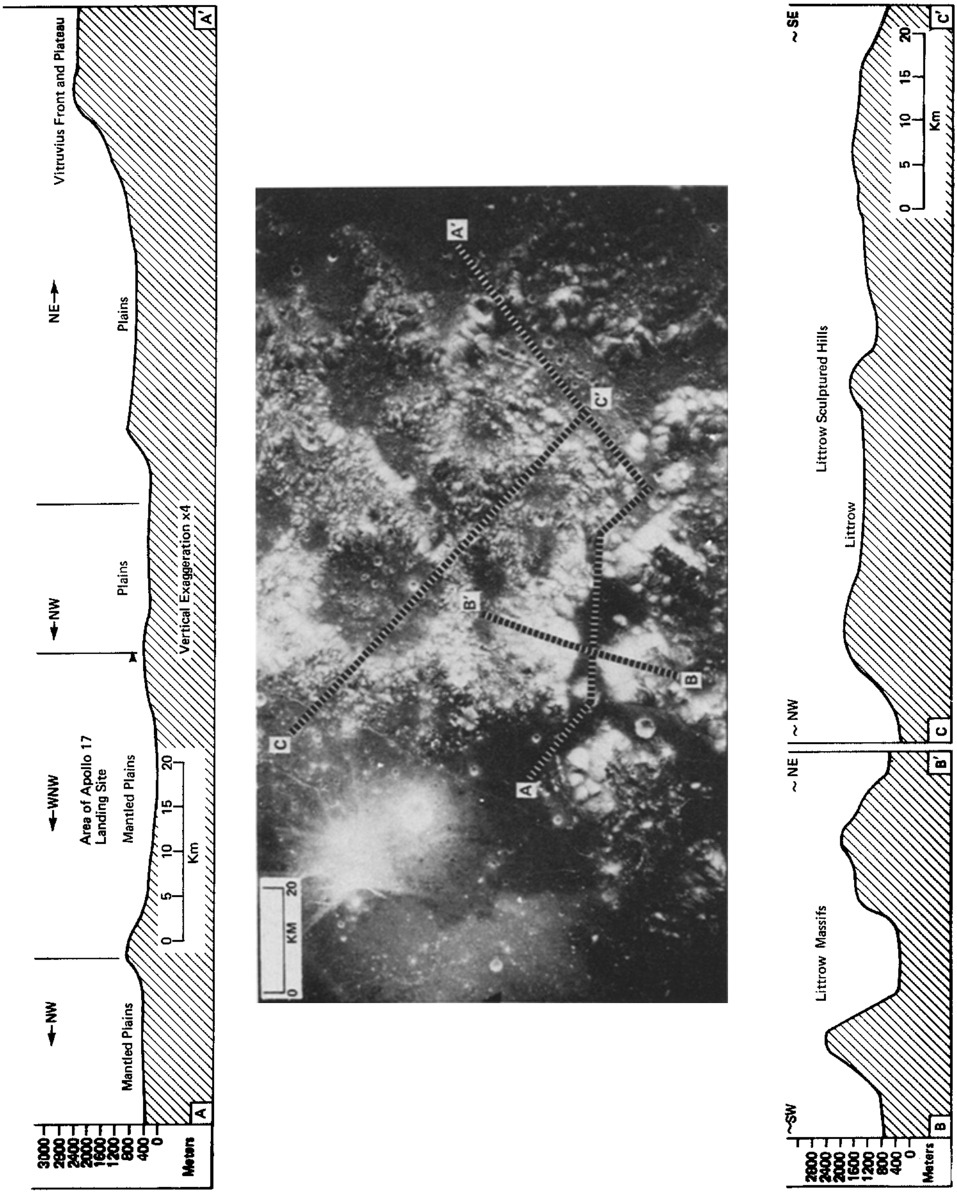


Fig. 12. Topographic profiles in the Taurus-Littrow area.

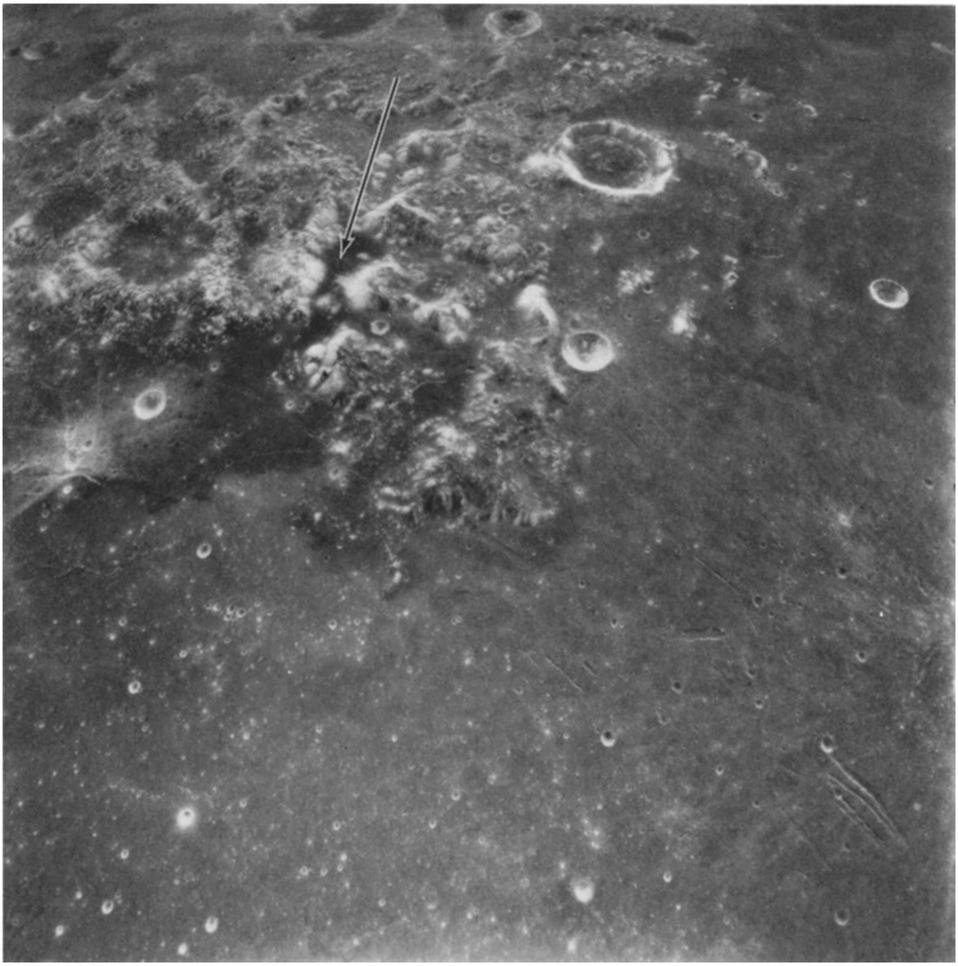


Fig. 13. Oblique view (looking east) of the Taurus-Littrow region (Apollo 17 landing region is designated) (AS-15-1404).

Littrow massifs – This name is informally applied to a group of seven relatively distinct highland structures clustered around the Apollo 17 landing site. The Littrow massifs are usually composed of one or several large hills and are defined by their rather massive character, averaging 10–20 km diam, and steep high-albedo slopes ranging up to 20–30°. It is the isolated and massive nature of these structures, as well as their steep-sloped faces, that delineates them as a distinct morphologic type in this area (Figure 11). Bordering grabens and fewer small scale structural lineations in the massifs suggest that these units may have behaved as massive blocks during structural deformation of the region, in contrast to other areas which may have been more finely divided by structural effects. A topographic profile of the Littrow massif unit is shown in Figure 12 and illustrates the generally flat plains between massifs.

These probably represent grabens which at least in the landing area were subsequently filled by mare basalts (ALGIT, 1972). The Littrow massif region sits at the southeast edge of a more massive highland block, the 'Littrow-Maraldi uplands', at the junction of two major basins, Serenitatis and Tranquillitatis (Figure 13). The

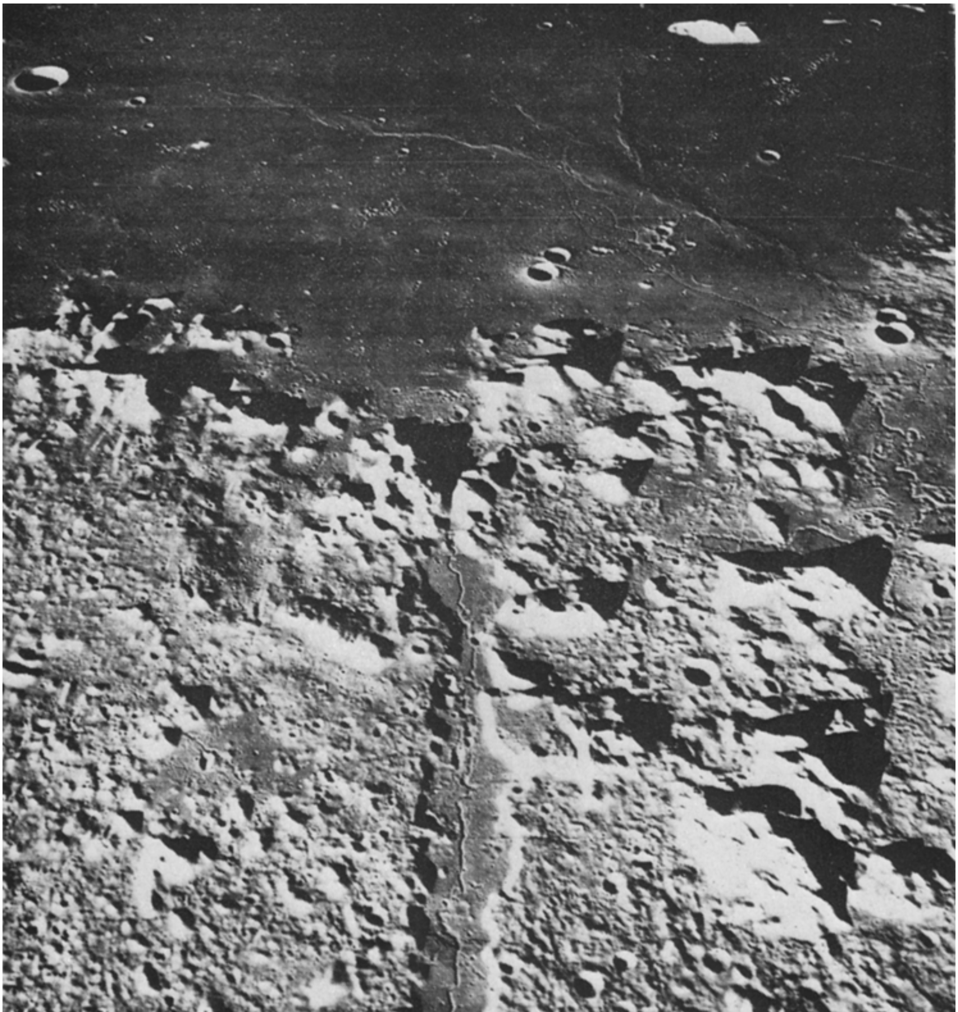


Fig. 14. Oblique view toward Mare Imbrium (looking southwest) of the Alpes formation, Alpine Valley (8 × 150 km), and Montes Alpes (LO V–120M).

massif-bounding grabens are oriented generally NW–SE and NE–SW, approximately radial and circumferential to the Serenititatis basin at this point.

The Littrow massif area defines a roughly pentagonal region bounded on the southwest by Mons Argaeus, the largest massif, and Vitruvius *L*, and bounded to the north by the massif just north of the landing site (Figure 10). The concentration of massifs in this particular region is striking and may indicate that the pentagonal area was a discrete highland block which was subsequently broken up into its present form.

Littrow sculptured hills – This name is informally applied to a group of closely-spaced highland domical hills occupying cratered plateaus and stretching from Vitruvius northward to LeMonnier and from the edge of the Serenitatis basin eastward

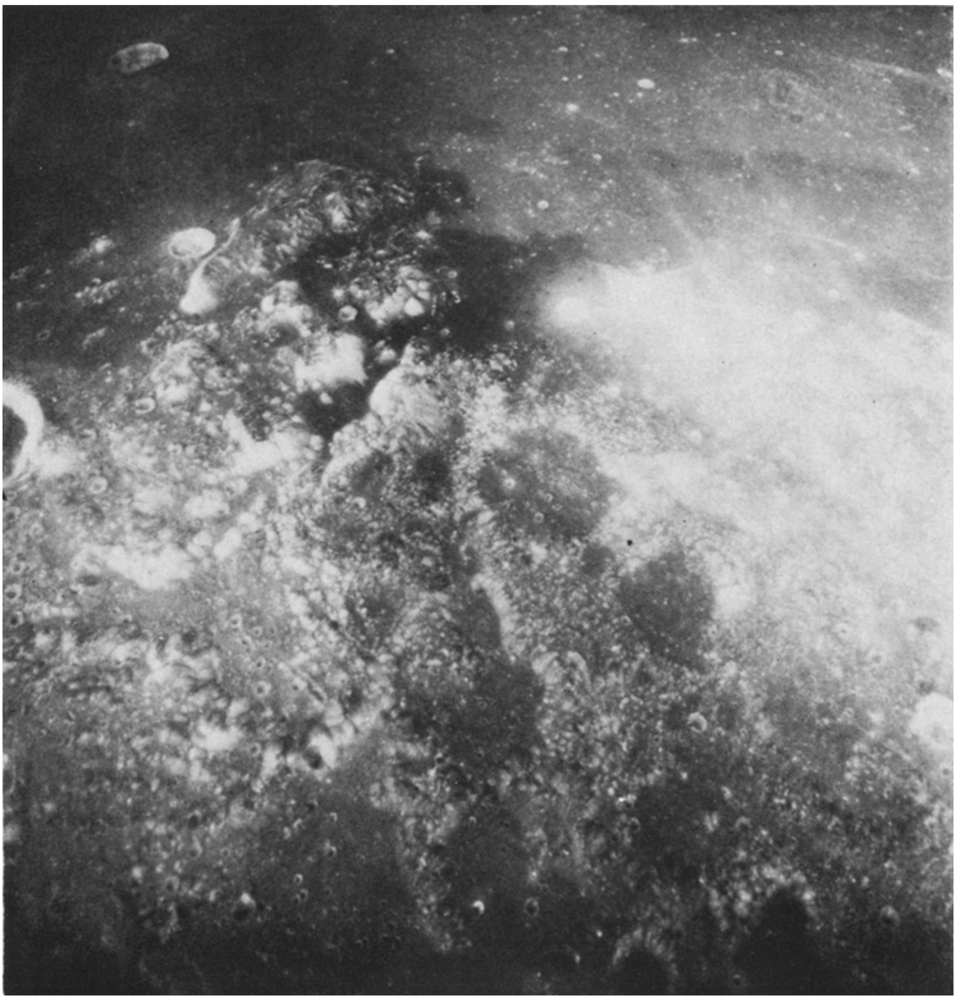


Fig. 15. Oblique view toward Mare Serenitatis (looking west-northwest) of the Taurus-Littrow region (AS-15-0835).

to the Vitruvius front and plateau (Figures 10 and 13). The sculptured terra is defined by a series of closely-spaced hills ranging from 1–5 km diam. These hills occupy broad highland plateaus (see Figure 12 for topographic profile) which have been block-faulted and cratered. They form the rims of old craters (Littrow, Littrow A) as well as intercrater areas. Relatively smooth plains units occur within this sculptured terra and fill in both the floors of large old craters (such as Littrow) and the floors of graben-like blocks. The borders of these closely-spaced domical hills give the Littrow sculptured terra plateaus a distinctive 'corn-on-the cob' texture which contrasts sharply with the large rugged rectilinear Littrow massifs. The borders of the closely-spaced hills are often aligned to give the Littrow sculptured terra a lineated pattern which is variable in direction over the area.

It is interesting to note the distribution of this unit in relation to the Serenitatis basin as a whole. The eastern edge of Mare Serenitatis marks the position of the second ring and the remnants of the third ring form a series of structures stretching from just west of Römer north to Lacus Somniorum (Wilhelms and McCauley, 1971). The Littrow sculptured terra thus occupies a position very similar to that of the Alpes Formation in the Alpine Valley region of the Imbrium basin (Figure 7). In addition to its similar position, the Littrow sculptured terra units also share many of the morphologic characteristics of the Alpes Formation (Figures 14 and 15 and Table II).

Vitruvius front and plateau – This name is informally applied to a significant north-trending scarp and its associated uplifted plateau which stretches from Vitruvius northward to the vicinity of Römer *R* (Figures 10, 12 and 13). The hills that form the scarp of the Vitruvius front and associated plateau are intermediate in size between the Littrow massifs and the components of the sculptured terra, ranging about 2–7 km diam. The scarp forming the front occasionally rises over 2 km above the plains and domical hills of the Littrow sculptured terra (Figures 12 and 13). Locally the trend of scarp is somewhat irregular but the overall trend in this region is distinct, approximately N–S in orientation.

The Vitruvius front lies approximately half-way between the third ring of the Serenitatis basin (Wilhelms and McCauley, 1971), which has been mapped just east of Römer and Maraldi about 40 km to the East, and the edge of Mare Serenitatis to the West (Figure 3). Although secondary sets of peaks exist in the Imbrium basin between the second and third ring (Alpes Mountains; Figures 7 and 14), they are much more irregular and more discontinuous than the Vitruvius front. Other basins, such as Orientale, also do not show distinct analogs to the Vitruvius front.

5.1. Discussion

Setting and morphology of Taurus-Littrow highlands deposits – The deposits described in the preceding sections lie at the eastern edge of the Serenitatis basin between the intermediate or second basin ring (the edge of Mare Serenitatis) and the outer or third ring (Figure 3). It is concluded that the basic landforms in this region are

TABLE IV

Comparison of analogous Imbrium and Serenitatis basin deposits

	BASIN DEPOSITS	
	IMBRIUM	SERENITATIS
CHARACTERISTICS	MASSIFS	MASSIFS
Size	10–30 km diameter	10–20 km diameter
Shape	Massive, generally rectilinear	Massive, curvilinear to rectilinear
Location	Generally associated with mountain fronts forming basin rings	Along edge of Mare Serenitatis at second basin ring (Wilhelms and McCauley, 1971; also Figure 3)
Structure	Strong concentric, moderate to strong radial structures; usually defines massive block	Defined by structures which are concentric and radial to Serenitatis
CHARACTERISTICS	ALPES FORMATION	SCULPTURED TERRA
Size	2–5 km diam	1–5 km diam
Shape	Blocks of knobby smooth-surfaced closely spaced hills	Smooth-surfaced closely spaced hills
Location	Between second and third rings and beyond third ring	Between second and third rings of Serenitatis (Figure 3)
Structure	No conspicuous preferred orientation or lineation	Structural elements variable, but are oblique to concentric and radial trends

analogous to those seen in similar geographic settings in younger multi-ringed basins (e.g., Imbrium, Orientale) and that these basic units were formed coincident with the Serenitatis basin. In addition to the similarity of the geographic setting, the following points support this conclusion:

(1) Although the older Serenitatis basin has undergone more modification, the similarity between these deposits and the Alpes Mountains (between the second and third ring of the Imbrium basin) is nonetheless striking (compare Figures 7 and 10). The mountains forming the Alpes chain are similar in size, morphology, and distribution to the massifs of the region around the landing site. The Alpes Formation (Figures 7 and 14; Table II), here lying between the second and third rings of the Imbrium basin and generally northeast of the main massifs, is also strikingly similar in size, morphology, and distribution to the sculptured hills and terra of the Serenitatis basin (Table IV and Figures 14 and 15). Relationships similar to those seen at Imbrium and Serenitatis also occur in the Orientale basin between the Rook (second ring) and Cordillera (third ring) Mountains (Figure 16).

(2) A structural similarity exists between these deposits in addition to the geographic and morphologic comparisons. In the Imbrium basin, and in the Alpes Mountain

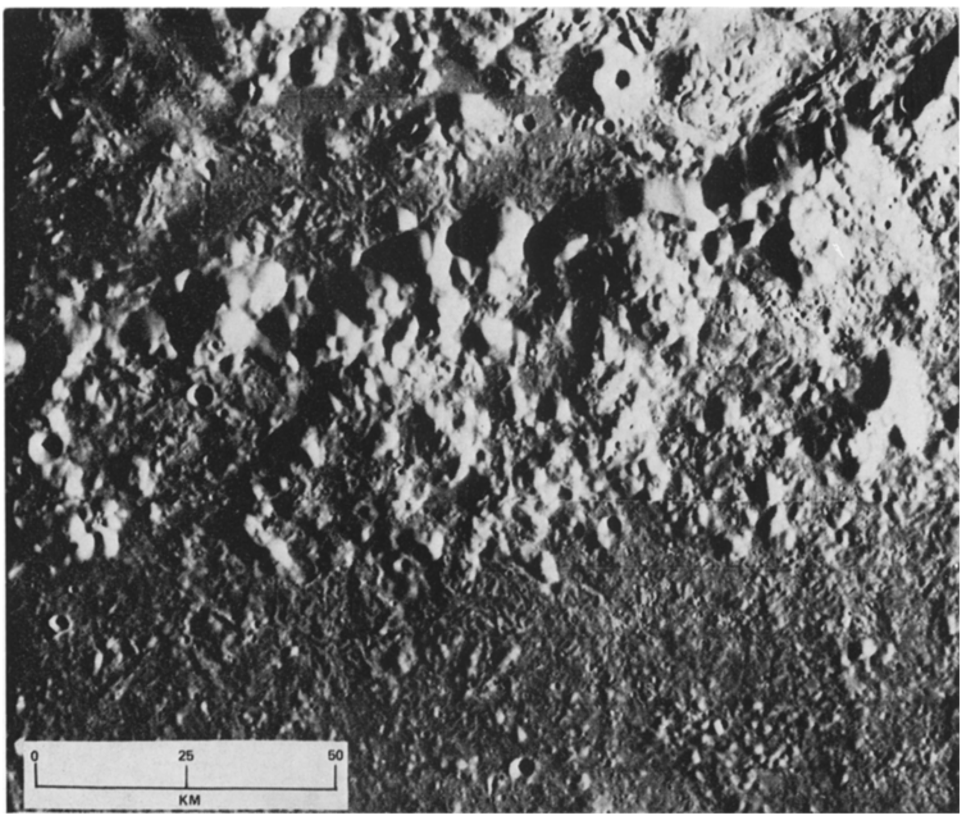


Fig. 16. The Orientale basin between the second and third ring showing similarities to analogous Serenitatis and Imbrium units (LO IV–195H1).

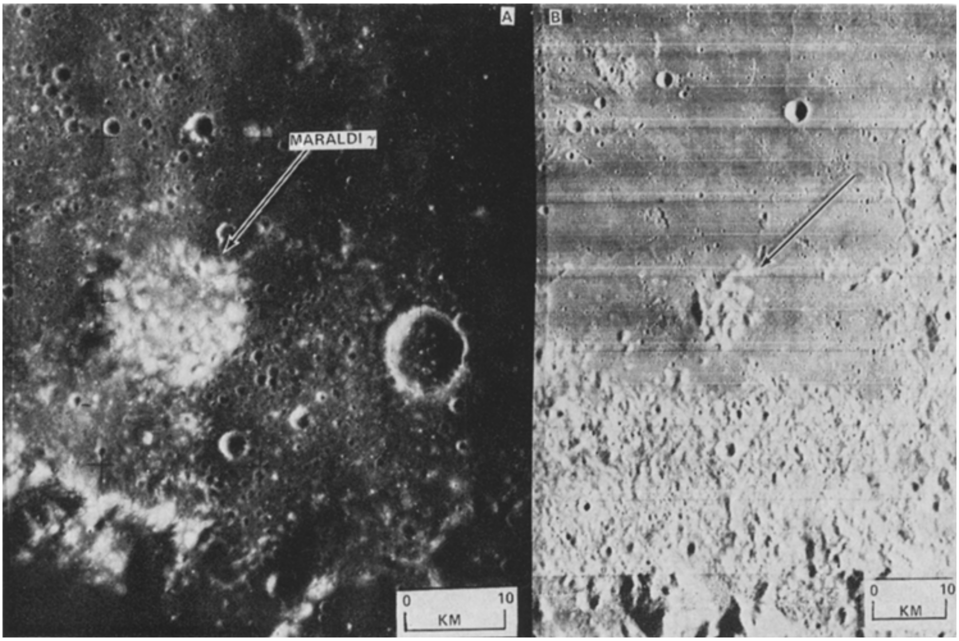


Fig. 17. Domical structures in the Taurus-Littrow region (Maraldi γ) (A: portion of AS-15-0562), and near Montes Alpes in Imbrium (B: portion of LO IV–1154).

area in particular (Table II), the massifs in the vicinity of the second ring show moderate to strong concentric and radial structures (Figure 7). In fact, these structures often border and define the massifs themselves. The Alpes Formation, on the other hand, shows only weak to moderate concentric and radial structures (Figure 7). Again, this situation is analogous to the Taurus-Littrow region of Serenitatis, where massifs show pronounced trends concentric and radial to Serenitatis, while concentric and radial trends are subdued or absent in the sculptured hills or terra (Figures 10 and 18).

Implications for the role of volcanism – Much of the sculptured hills terrain in the Taurus-Littrow region resembles other areas of the Moon that have frequently been interpreted as varieties of volcanic domes or some type of volcanic deposit. However, the similarity of the sculptured hills to other more obviously basin-related deposits such as the Alpes Formation (morphology, structure, and geographic position) argues that the basic landforms are not volcanic in origin. This conclusion does not of course rule out the possibility of volcanic deposits within the sculptured units or as a thin veneer. Nor does it rule out the possibility that the sculptured hills may be related in some way to a possibly fluidized phase of the poorly understood process of multi-ringed basin formation.

The generally smooth plains units, such as those filling craters and valleys, are of volcanic origin in at least some areas. The plains that occur in the graben-like valleys (such as the valley containing the landing site, Figure 11) are generally smooth but are populated by numerous isolated and discontinuous hills reminiscent of structures in the adjoining highlands. These similarities suggest that the hills may be part of the upper surface of a downdropped block (graben). However, the intervening smooth plains are generally smoother than the surrounding highlands. Basalt samples of the plains (subfloor unit) collected by the Apollo 17 crew in the area of the landing site

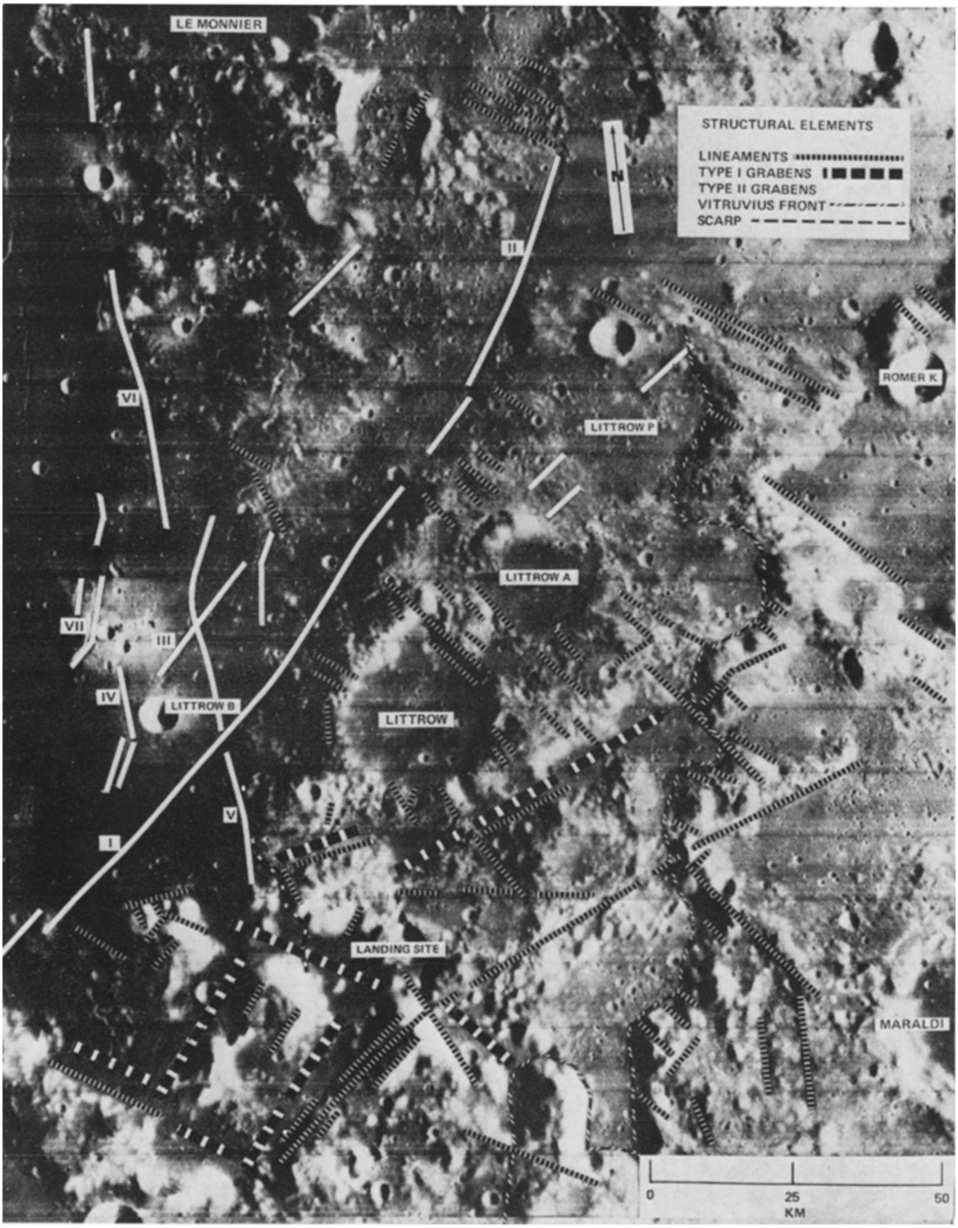


Fig. 18. Structural element summary for the Taurus-Littrow region (base is LO IV–78–79H).

indicate that at least in this area a volcanic flooding has occurred (Apollo Lunar Geology Investigation Team, 1972). Again, the poorly understood process of multi-ringed basin formation leaves much room for the possibility of an associated non-volcanic smoothing phase for plains units outside the landing area.

The massive nature, steep slopes, and shapes of the Littrow massifs (Figure 11) are reminiscent of many terrestrial extrusive acidic volcanic domes (in particular see Green and Short, 1971, plate 65A–B). However, the distinct relationship of their boundaries with Serenitatis basin-related structures (outlined in detail in the section on structure), and their similarity to concentric massifs in other basins, suggest that they are more likely related to tectonic processes associated with impact basin formation than to volcanism.

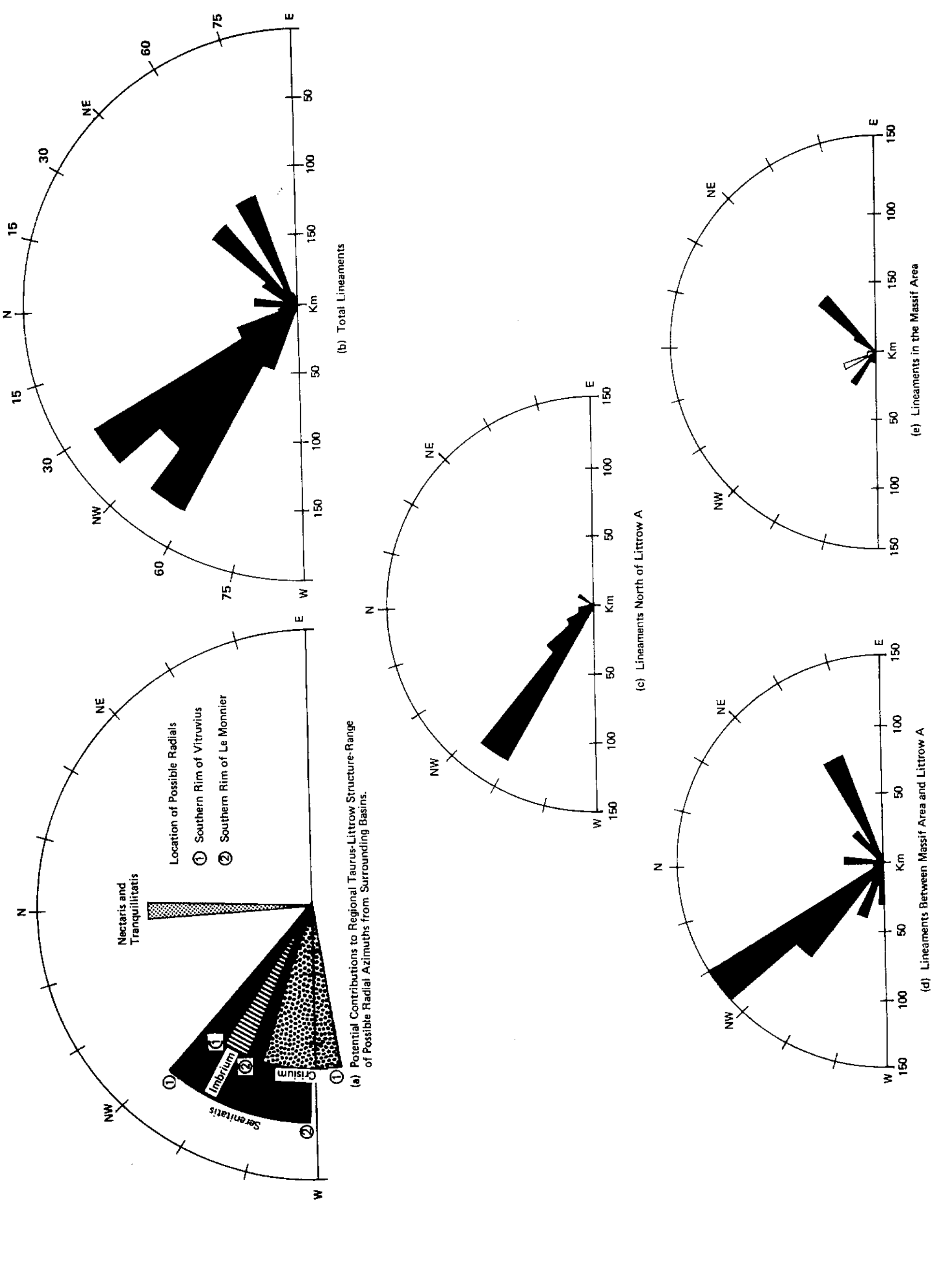
An isolated structure (Maraldi γ) (Figure 17a) a few kilometers northeast of Maraldi has been mapped as a dome and interpreted as possibly volcanic in origin or related to degraded basin ejecta (Wilhelms and McCauley, 1971; Scott and Pohn, 1972). Although the morphology and isolated nature of this structure is suggestive of volcanic terrain, its similarity and proximity to the sculptured hills terrain argues that it may be related to deposits of the Serenitatis basin, and isolated by later deposits. Indeed, a very similar structure can be seen in the analogous Alpes deposits of Mare Imbrium (Figure 17b).

It is concluded that the major highland landforms in this region are related to the Serenitatis basin-forming process rather than to extensive volcanism.

6. Structural Geology

A variety of structural elements exists in the area and includes lineaments (defined by ridges, furrows or alignments of hills), a variety of grabens, and long continuous scarps of varying elevation (Figure 18). Possible factors in the origin of these structural elements exist in the form of potential radial and concentric structural contributions from nearby basins (e.g., Serenitatis, Crisium, and Imbrium), from global tectonic patterns as described by Strom (1964), or possibly from previously unknown factors. Potential radial contributions from basins surrounding the study area are shown in Figure 19a; Figure 19–bm shows the cumulative lengths of the various linear elements plotted in 10° segments. Structural elements are discussed in general order of decreasing age.

Lineaments – These elements are defined by elongate furrows, ridges, and scarps up to 30 km in length. In the sculptured hills region in particular, lineaments 2–10 km in length are formed by the coincidence of boundaries of closely-spaced hills and appear to be more than superficial in nature since they are readily visible where they intersect crater walls or scarps. Their vertical and near-vertical appearance in these places and their straightness over varying elevations suggests a near-vertical orientation for these structural elements. Lineaments occur over the whole study area but are more abundant in the sculptured hills terrain than in the Littrow massif region (Figure 18). No evidence of lateral offset was seen along any lineaments.



Figs. 19a–e. (a) Potential contributions to regional structure from radial elements of surrounding basins; (b–e) cumulative lengths of various linear elements plotted in 10° segments.

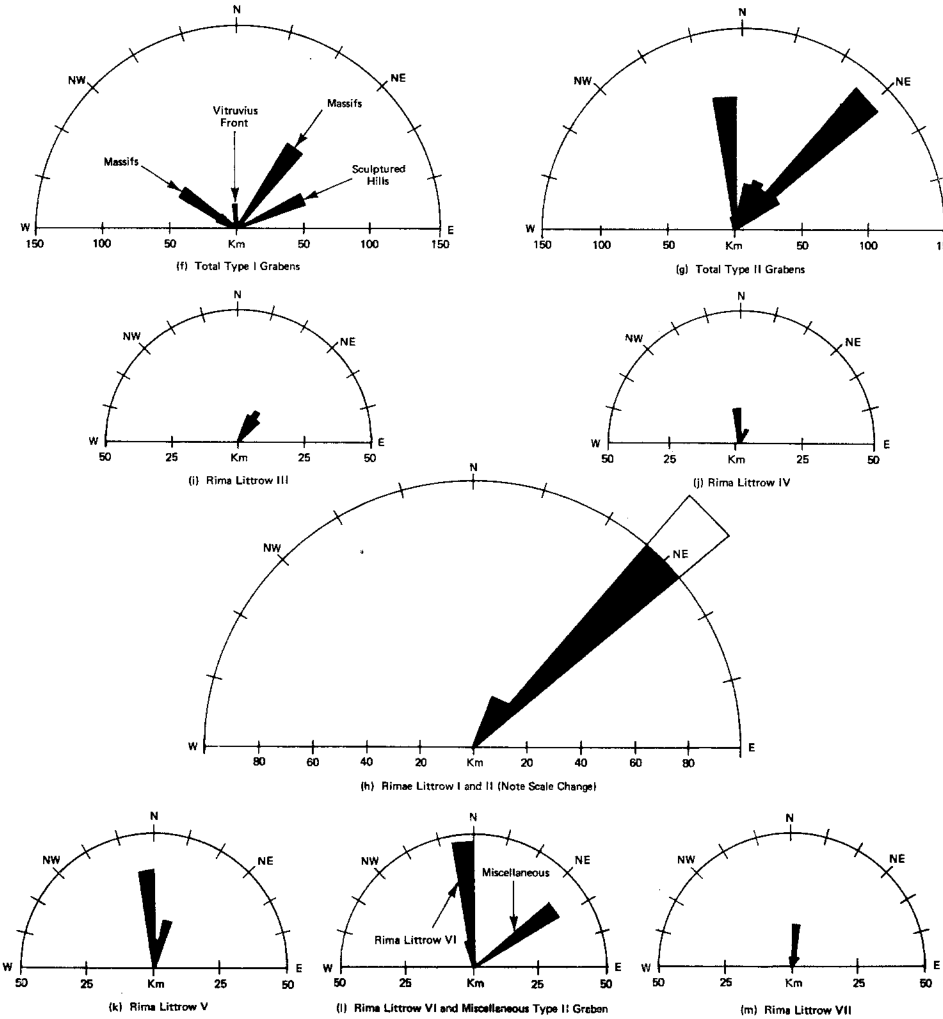


Fig. 19f–m. Cumulative lengths of various linear elements plotted in 10° segments.

The cumulative length of lineaments is plotted in 10° azimuth intervals in Figure 19b. For all lineaments measured in the study, the dominant trend is clearly in the range N30–60°W, centered on N45°W. Other less significant trends occur in the N40–50E and N60–70E segments. As a whole, the total lineament system does not seem to correspond to any radial or circumferential system related to surrounding basins (Figure 19a). It does, however, show a preference for NW and NE lunar grid directions described by Strom (1964). The depression of the NW trend in the N40–50W segment suggests that there might be two components forming this broad maximum. This primary NW trending lineament system is readily visible (Figure 18) and it is also obvious that there is a broadly systematic lineament azimuth variation over the study area. In the area north of Littrow A the major trend lies in the N50–60W

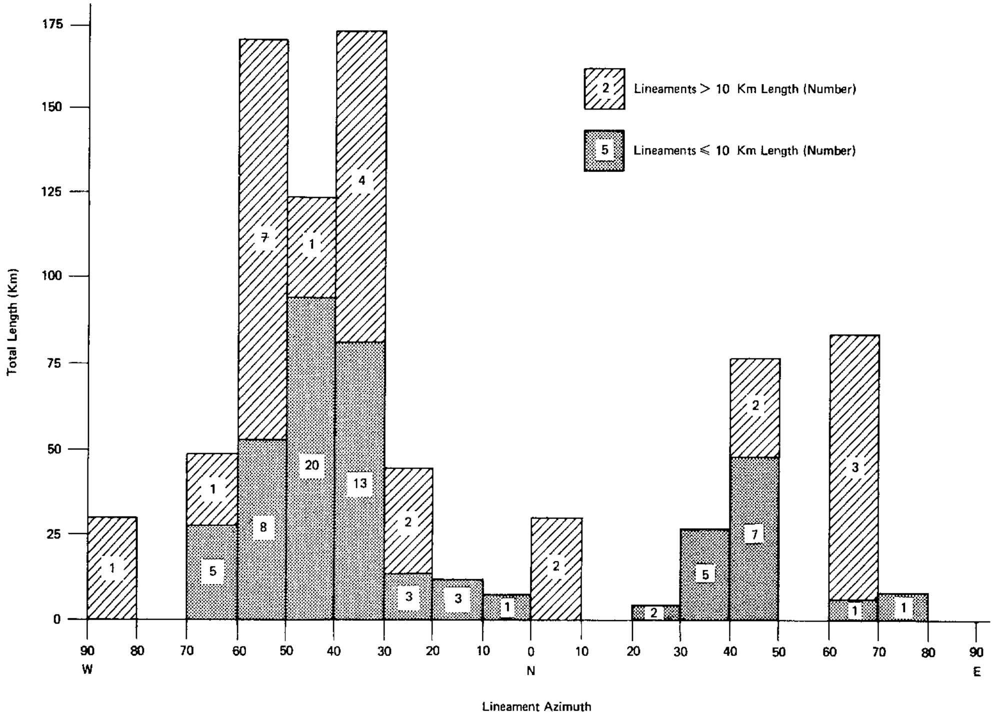


Fig. 20. Relationship of lineament length to Azimuth.

direction. Although this coincides with part of the general Serenitatis arc (Figure 19a, c), it does not coincide with that portion expected in the region between Littrow A and the southern rim of LeMonnier (≈N79–89W). This structural trend also appears to be independent of radial and concentric contributions from other nearby basins (Figure 19a). Between the massif area and Littrow A the dominant trend has rotated slightly clockwise to the N30–50W direction and a number of subordinate azimuths become apparent, the most obvious one being in the N60–70E direction (Figure 19d). As to the north, these major directions do not correspond to potential major contributions from surrounding basins (Figure 19a). An additional variation is the increase in the population of shorter (≤10 km) lineaments and decrease of longer (>10 km) lineaments in this area as compared to the north (Figure 20). Lineaments are much less prominent in the massif area (Figures 10, 18, and 19e) and the only notable trend is N40–50W.

In summary, lineaments in the study area are most prevalent in the sculptured hills terrain and show a dominant NW trend and subordinate NE trends and near-vertical orientation. Although the major direction of lineament development in the study area seems to vary rather systematically clockwise from N60W to N30W from north of Littrow A southward, there appears to be little relationship to potential structural contributions from nearby lunar basins (Figure 19a–e). McGill (1972) also found NW and NE lineament trends for a larger area extending east to the vicinity of Crisium and also reported little evidence of major structural influence from surrounding basins.

These lineaments may be related to structural trends from ancient, subsequently obliterated basins. However, the bulk of the lineaments seem more likely to be related to lunar grid patterns described by Strom (1964) and Fielder (1963), who interpreted them to be the manifestation of a stress field with a N–S oriented maximum principal stress axis. Other maxima in the area (Figure 19b) might be the result of second and third order shear patterns (Moody and Hill, 1956).

Structural fronts – These are defined as major regional topographic scarps and the Vitruvius front (Figures 10, 13, and 18) is the only major one in the area. Its radical elevation change over a short distance suggests a steeply dipping fault plane. Although locally variable, the Vitruvius front average trend is about N09E and with the possible exception of Tranquillitatis, appears to be unrelated to any local basin structure. This trend is generally coincident with the N–S global trend of Strom (1964) and Fielder (1963).

Grabens (Type I) – These structures are linear troughs generally 5–10 km in width and of variable length (Figure 18). The linear and steep-sided nature of the bordering highlands suggests that these are fault-bounded valleys and they are therefore referred to as grabens. The numerous steep walls and scarps along the graben edges imply steeply dipping boundary faults. Type I grabens are particularly prominent in the Littrow massif area where they form flat-floored valleys bordering the massifs (Figure 11) and they also occur in the sculptured hills area although they are less visible there. Although graben floors are occasionally very rough, many seem to have undergone some smoothing process (basaltic lava flows in the Apollo 17 landing valley) to produce a relatively smooth plains-like surface on the valley floor. This lies in contrast to the general domical nature of the surrounding uplands. Nowhere in the area have Type I grabens been found to transect plains units. Thus, graben formation would seem to have taken place no later than the plains formation.

Type I graben azimuths show three major trends, two of which (N50–60W; N30–40E) dominate the structure in the Littrow massif area and which are normal to each other (Figure 19f). The N50–60W lineaments, while falling within the general NW total lineament trend (Figure 19b), differ slightly in length and orientation from lineaments in the massif area and adjoining portions of the sculptured hills. In these areas lineaments trend slightly more northerly (in the N30–50W range) and the majority of lineaments are less than 10 km in length (Figure 20). Lineaments of lengths and orientations similar to the N50–60W Littrow massif trend do occur, however, north of Littrow A (Figures 19c and 20), where they form some of the most prominent lineaments in the study area (Figure 18).

In summary, the Type I grabens in the Littrow massif area appear to be related to radial and concentric azimuths of the Serenitatis basin and to the general NW regional lineament trend. In the sculptured hills area Type I grabens are generally parallel and normal to the lineament trends.

Grabens (Type II) – These structures are shallow linear troughs less than 3 km in width and of variable length and orientation (Figure 18). As with Type I grabens, the flat floors and linear walls suggest that these are fault-bounded down-dropped blocks or grabens and their generally constant width over different topographic levels indicates steep dips. Type II grabens are always narrower and shallower than Type I grabens. Type II grabens transect highland units and plains and are flooded by mare material. They are therefore thought to be younger than the highland units, Type I grabens, and the plains, and older than the mare surface at the eastern edge of Serenitatis. Type II grabens occur predominantly in the plains along the eastern edge of Serenitatis and in the adjacent highlands. These structures are also called arcuate rilles (Strom, 1964), and are often found around the perimeters of circular basins. The rilles in this area are known as Rimae Littrow.

Virtually all Type II grabens plot between N10W and N60E (Figure 19g) and the most striking correlation is with the range of azimuths concentric to the Serenitatis basin in this region (Figure 19a; N–S in the north near LeMonnier ranging to N43E in the south near Vitruvius). Indeed, the Type II grabens in the northern part of the area (Rima Littrow VI and parts of IV, V and VII; Figures 18 and 19i–m) trend generally northward, while the southern grabens (Rima Littrow I and parts of III; Figure 19h–i) trend generally northeastward. However, it is obvious from Figure 18 that the grabens do not simply follow the edge of the basin. There are numerous local irregu-

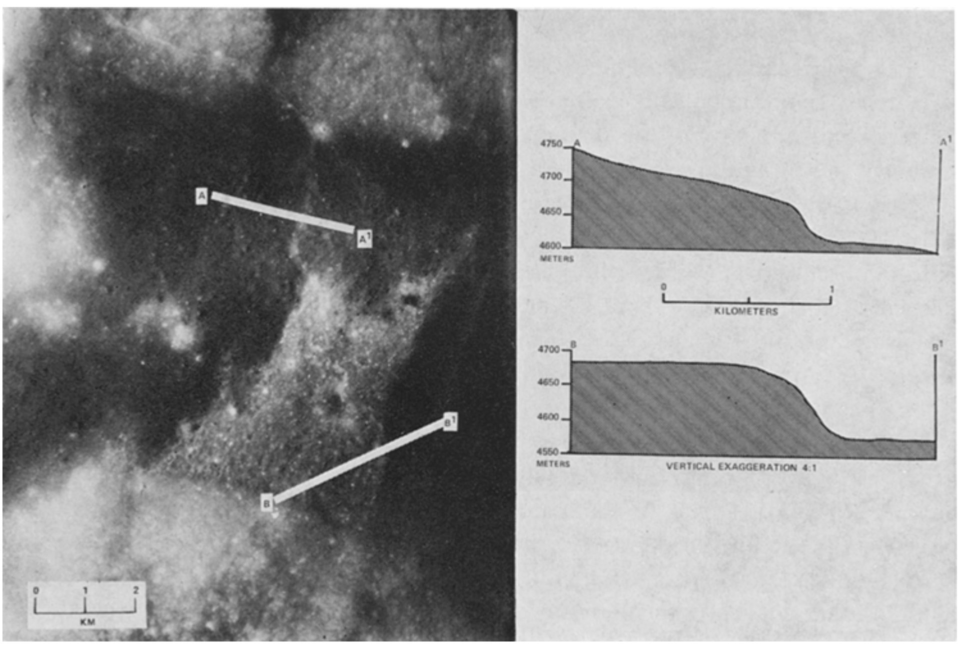


Fig. 21. Topographic profiles of the scarp in the Apollo 17 landing region.

larities probably related to underlying local variations (for instance, Rima Littrow VII is irregular in the area just SW of Littrow BA; the 18 km ghost crater there may be responsible for these variations). A striking regional variation is seen in Rimae Littrow I–II which in the south are broadly circumferential (continuing the trends of Rimae Plinius in southern Mare Serenitatis) but at the eastern edge of Serenitatis strike off into the uplands in a direction parallel to pre-existing lineament patterns (Figure 19b and h).

Therefore, Type II grabens appear not only to be related to patterns circumferential to the Serenitatis basin, but also to pre-existing local irregularities and more regional lineament systems.

Scarp – A single discontinuous east-facing scarp stretches at least 30 km from the vicinity of the Apollo 17 landing site northward (Figures 18 and 21). In the Type I graben in which the landing site lies, the scarp in general separates an upper relatively flat western valley floor from a similar eastern floor downdropped by about 50–90 m (Figure 21). In detail on the valley floor, the scarp is made up of a series of small coalescing scarps and elongate ridges over an area 100–400 m wide. The scarp changes direction as it passes into the adjacent highlands where it becomes a single scarp and discontinuously winds its way northward where it appears to merge with Rima Littrow V just west of the large crater due west of Littrow BC. The scarp transects plains units and adjacent upland talus and appears fresher than the Type II grabens, suggesting a relatively younger age.

The scarp trend shows variable azimuths perhaps reflecting both changes in strike of the subsurface plane and changing topography. The scarp strikes about N26W in the southern half of the plains, changes to N27E in the middle of the plains and continues part way up the side of the north massif with this strike. From that point on it winds its way discontinuously around the North Massif often changing apparent strike until it appears to merge with Rima Littrow V. The orientation of the fault trace suggests two possibilities: (a) that it may be a shallow, variably dipping normal fault in this area with only moderate changes in strike (in this case, a fault plane solution where the scarp intersects the north massif indicates a strike of N27E and a dip of 17°SE); or (b) that it is a steeply dipping (perhaps reverse) discontinuous fault which is constantly changing strike and is primarily related to reactivation along older structural trends.

Although showing variable azimuths, the major trend of the scarp trace falls in the N00–30W direction. This differs from lineament and Type I graben trends (Figures 19b, f) but coincides with a Type II graben trend which is formed from components of Rimae Littrow IV, V and VI (Figure 19g, j, k, 1). Although the scarp differs from Type II grabens in age and form, it appears to merge with one of these structures and also parallel important Type II graben trends, suggesting a tectonic relationship. Local changes in fault trace may reflect a changing strike caused by encounter with different materials or older structural elements. For instance, the fault trace near the base of the north massif seems to be related to the trend of the Type I graben which defines the valley.

6.1. Discussion

Role of multi-ringed basin structure – No obvious concentric or radial structures associated with the pre-Serenitatis basins, such as Tranquillitatis, exist in the study area (Figure 19a–m). Although several multi-ringed basins postdate the origin of the Serenitatis basin and its associated deposits (Nectaris, Crisium, and Imbrium), there is little evidence for any structures within the Taurus-Littrow region which might be attributed to the Crisium and Nectaris events (Figure 19). In the southwestern part of this area, radials from the Imbrium basin coincide with Serenitatis radials (Figure 19a), and it is therefore difficult to assess contributions from this source. The Imbrium event, however, may have caused movement along structural elements coincident with radial directions (such as the graben bounding the Littrow massifs), producing some rejuvenation. In general, structural effects from multi-ringed basins surrounding Serenitatis appear to have had a minor influence on the structural evolution of the Taurus-Littrow highland study area. McGill (1972) has reached a similar conclusion for an area extending east to the Crisium basin.

Origin of massifs – Although very similar to the massifs of the Alpes Mountains, the massifs described in the southeast portion of the Serenitatis basin (Figures 3, 10, and 14) are striking in that they are confined to a narrow portion of this quadrant and are absent elsewhere along the eastern edge of Mare Serenitatis. Since the massif boundaries coincide with Serenitatis radial and concentric structures, the distribution of massifs might be expected to be more widespread. The absence of the massifs elsewhere along the eastern edge of Mare Serenitatis suggests that their origin and the control of their location may be due to more than simply the presence of Serenitatis concentric and radial structures. A generalized map diagram of the regional structures (Figure 18) illustrates an additional factor. Directly to the east of Mare Serenitatis the regional structural trends average predominantly NW–SE (Figures 18 and 19a, c), roughly coincident with lunar grid directions. Any radial fracture originating from Serenitatis would intersect such pre-existing structures obliquely. Along the southeastern edge of the basin, however, radial fractures would *coincide* with such pre-existing structures (Figure 19a) and might tend to reactivate old tectonic trends and preferentially uplift highland blocks in this area of coincidence. Examination of other multi-ringed basins suggests that coincidence of radial fractures with lunar grid quadrants may be responsible for the distribution and morphology of many massifs composing these rings. As mapped by Wilhelms and McCauley (1971), the distribution of massif material around the Humorum, Nectaris, and parts of the Imbrium basins tend to support this hypothesis. In addition, Strom (1964, p. 207) has noted a coincidence of prominent radial lineaments and global lineament directions in parts of the Humorum and Nectaris basins. For the specific case of the second basin ring, the Imbrium basin also provides supporting data in that the two most prominent areas of massif development, the Alpes Mountains (NE) and the area south of Archimedes (SE) correspond to the lunar grid (Figures 1, 3 and 4). In addition, the morphology of massifs within the mountain ranges is often controlled by an apparent

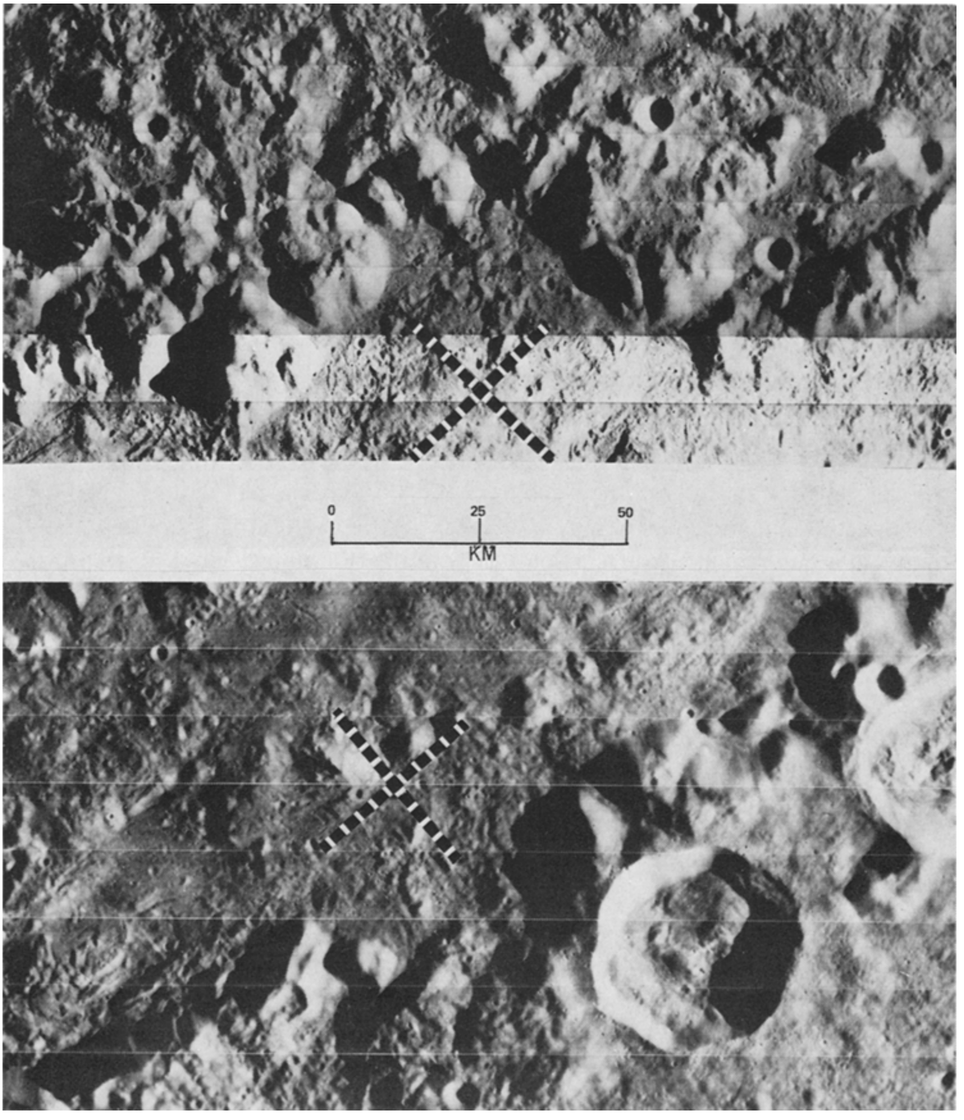


Fig. 22. Orientale basin: structural boundaries in massif blocks related to the lunar grid (LO IV–195H2; 187H1). Top is the northern part of Montes Rook; bottom is southeastern part of Montes Cordillera. X shows NE and NW azimuths in each area.

pre-existing grid as in the Orientale Basin (Figures 16 and 22). In Orientale, for instance, the intersecting grid patterns cause massifs along the north edge of the basin to have a saw-tooth pattern, while massifs in the grid quadrants tend to parallel the scraps of the ring.

These factors strongly suggest that the topographic prominence of the Serenitatis massifs (Figures 10, 11, and 12) may be due to enhancement of tectonic movement caused by the coincidence of Serenitatis radial fractures with pre-existing structural lunar grid directions. Furthermore, additional tectonic enhancement may have occurred because of the proximity of the Tranquillitatis basin. The massif region lies between the discrete Taurus Mountain highland block to the north and northeast and the topographically low area where the Serenitatis basin overlaps the Tranquillitatis basin to the southwest (Figures 3 and 13). Tectonic effects may have been marked in this intermediate area due to this juxtaposition of strong and weak areas and this may have added to the structural evolution of the massifs. Figure 3 also shows that the area of massifs coincides with a postulated ring of the Tranquillitatis basin. Since the existence of multiple rings around this basin has not been proven, and since the massifs do not coincide in detail with postulated Tranquilitatis concentric structure (Figure 19a), contributions to the structure from this source seem unlikely.

Since radials from the Imbrium and Serenitatis basins coincide in the massif area, it is possible that the massifs may have been jostled and perhaps uplifted and rejuvenated along radial fractures associated with the Imbrium event. The steep slopes and apparent freshness of the massif faces, the scarp, and the presence of apparently recent landslide deposits (Lucchitta, 1972), suggest that some massif movement may have taken place.

Stratigraphic implications – The still-distinct morphology of the sculptured hills (in spite of their association with the older Serenitatis event) and their similarity to younger analogous Imbrium deposits (Figures 7 and 10) suggests that the terrain may have been rejuvenated in some way, or that post-Serenitatis deposits are thin enough so that they have not totally obscured the characteristic morphology of this unit. Two factors suggest that major rejuvenation of the sculptured hills has not taken place; (1) although marked where they occur, the structural lineations do not define the majority of boundaries of the sculptured hills. Therefore, many of these boundaries may be depositional rather than tectonic, and not as readily rejuvenated; (2) the absence of marked structural elements in the sculptured hills attributable to post-Serenitatis basin formation (such as Crisium and Imbrium, Figure 19) suggests that these major events had no radical effect on this terrain. If major rejuvenation of these structures has not occurred since their origin, then post-origin deposition could probably not have left deposits over 100–200 m in thickness. Estimates of ejecta contributions to Taurus-Littrow highland stratigraphy from major multi-ringed basins (McGetchin *et al.*, 1973) indicate a post-Serenitatis cumulative thickness similar to this. If rejuvenation has not occurred and the ejecta thickness estimates are anywhere near correct, then the primary contribution to the Taurus-Littrow highland stratigraphic section is from Serenitatis and pre-Serenitatis events rather than post Serenitatis events.

The distinctly different morphology of the sculptured hills and the Littrow massifs suggests different modes of phases of origin for these units, and thus the possibility of different compositions.

TABLE V

Geologic and structural history of the Taurus-Littrow region

GEOLOGIC PERIOD	GEOLOGIC EVENTS	STRUCTURAL ELEMENTS	TECTONIC INTERVAL AND TAURUS-LITTROW AREA TECTONIC ENVIRONMENT	
COPERNICAN ERATOSTHENIAN IMBRIAN	? Dark Mantle ? ? Mare ? ? Plains ?	Scarp ?Type II Graben - post-plains pre-latest mare?	TECTONIC INTERVAL III	Regional stresses from (1) redistribution associated with possible generation of mare basalt magmas and mare flooding, and (2) isostatic readjustment of basin.
PRE-IMBRIAN PERIOD OF INTENSE BOMBARDMENT	IMBRIUM BASIN FORMATION - Deposition of ejecta in area plus possible structural rejuvenation. CRISIUM BASIN FORMATION - NECTARIS BASIN FORMATION - SERENITATIS BASIN FORMATION Deposition of ejecta blanket, formation of massifs and sculptured hills.	No major structures definitely attributable to these events Type I Graben - generally coincident with Serenitatis basin formation	TECTONIC INTERVAL II	Regional stresses associated with large basin formation.
	FORMATION OF FECUNDITATIS AND TRANQUILLITATIS BASINS - Possible deposition of ejecta blankets in Littrow region	Lineament system probably formed early in this period	TECTONIC INTERVAL I	Regional stresses associated with large basin formation. Global stress fields possibly related to: ·internal convection ·crust formation ·recession from vicinity of earth ·etc.

7. Geologic and Tectonic History

Tectonic Interval I (Table V) – This period spans the time prior to the formation of the Serenitatis basin. Geologically, this was the period of crustal formation and fragmentation. The lunar surface was being impacted by a spectrum of objects ranging in size up to those that produced the major multi-ringed basins and a thick deposit of impact ejecta blankets was being accumulated (Short and Forman, 1970).

The lunar grid in general and the NW trending lineament system in the Taurus-Littrow region in particular, are believed to have originated during this interval (Table V). In the study area the lineament system appears to pre-date the Serenitatis event because Serenitatis-related structures are enhanced wherever they coincide with the lineament system. Possible causes for the parts of the lineament system that transect younger highland terrain include structural control from underlying basement fractures and structural rejuvenation along these planes of weakness.

Fielder (1963), Strom (1964), and Elston *et al.* (1971), have discussed the global lineament systems and have concluded that they represent a stress field with the maximum principal stress axis oriented N–S with strike-slip movement developed 45° to the E and W and tension fractures developed N–S, producing the primary grid patterns. A major problem with this interpretation is the lack of widespread evidence for strike-slip dislocations which should be associated with shear. Although Fielder (1965) has presented examples of local apparent strike-slip movement, the general lack of such evidence in the lineament systems is striking (Mutch, 1970). Two possible explanations seem likely: (1) the grid system may well have had associated strike-slip movement but may have been produced so early in lunar history that any evidence of this lateral offset has since been destroyed or blanketed by the products of early intense bombardment. In this model, overlying highland deposits would be influenced by or would inherit the basement fault pattern. This inheritance is quite common terrestrially where zones of Precambrian structural weakness control subsequent deformation patterns (Spencer, 1959; Wise, 1964; Spencer and Kozak, 1965; Hoppin and Palmquist, 1965). Lack of evidence of regional strike-slip movement in the lineaments of these younger deposits would suggest that the overlying units are influenced by the faults but not the sense of shear. This in turn would suggest that by this time (still very early in lunar history) the stresses causing global shear had relaxed (e.g., the Moon receding from the vicinity of the Earth), leaving an intensely sheared basement which would greatly influence subsequent lunar structure; (2) the grid system may actually represent a global series of fractures or joints along which lateral movement did not originally take place. This might be due to stress patterns caused by early convection and formation of the lunar crust or to characteristics of the lunar crust itself. Origins of similar terrestrial patterns are not well understood. Subsequent lunar events (major impacts, etc.) may have activated these fractures, causing inheritance of the pre-existing patterns by later deposits.

In addition, stresses derived from the constant Earth-Moon tidal interaction may also have been (and still be) a significant factor in the activation of a previously formed lunar grid system, regardless of its origin. On Earth, regional joint systems are often found which appear to bear no relation to regional stress fields (Hodgson, 1961). It has been suggested (Kendall and Briggs, 1933; Price, 1966) that such joint systems might be fatigue phenomena resulting from alternating torsional stresses. Lunar gravitational attraction would cause semi-diurnal tidal action responsible for such stress systems. Blanchet (1957) has mapped fracture patterns in the Canadian shield that bear no relation to Precambrian tectonic trends. These patterns are also found in the overlying sedimentary cover, even in young, unconsolidated glacial sediments. Blanchet believes that the stress field was derived from tidal motion of the Earth's crust. Indeed, recent studies of lunar seismic data (Latham *et al.*, 1971; Hamilton, 1972; Lammlein *et al.*, 1972) conclude that many moonquakes are triggered by tidal stresses (anomalistic and/or latitudinal tides). Therefore, in addition to local rejuvenation by specific major events, lunar tides may have provided a source for accentuating ancient trends on a longer term and more regional basis.

Whatever its cause, a global lunar grid pattern was probably produced during tectonic interval I. In the study area the dominantly NW trending lineament system and subordinate N and NE trends are thought to be a surface manifestation of this global system of basement structural elements.

Tectonic Interval II – In the Taurus-Littrow region (Table V) this period begins with the formation of the Serenitatis basin and associated deposits and ends with Imbrium basin formation. The topography forming the lineament systems may have been enhanced at this time as a result of reactivation of the global system formed in tectonic interval I. In the study area, structural elements radial to Serenitatis are pronounced only along Type I graben boundaries in the Littrow massif area where the radials coincide with the NW lineament direction. Other Type I grabens are concentric to Serenitatis or are normal to the NW grid direction. The Vitruvius front may also have been formed in association with the Serenitatis event, having been formed along the global N–S segment of the grid system.

It is generally agreed that the violently released stresses accompanying the formation of large lunar impact basins will produce radial and concentric fractures around the basin. What is not generally agreed upon is the process of formation and its relative and absolute time scales (Hartmann and Wood, 1971). Estimates range from fracturing and faulting accompanying the event (Baldwin, 1949, 1963; Van Dorn, 1968; and Chadderton *et al.*, 1969) to fracturing accompanying the event and major faulting occurring later at the time of mare flooding (reviewed in Hartmann and Wood, 1971, pp. 6–7). Data from this study indicate that Type I grabens were formed prior to the plains and thus close to if not coincident with the formation of the Serenitatis basin.

Tectonic interval II thus appears to be characterized by formation of Type I graben radial and circumferential to the Serenitatis basin and by the possible reactivation of a pre-existing regional lineament system, both related to the formation of the Serenitatis basin. The formation of the Crisium and Imbrium basins toward the end of interval II may also have reactivated pre-existing structural elements although large scale rejuvenation is not obvious. Coincidence of radials from Imbrium and

Serenitatis and the NW grid direction in the Littrow massif area may have caused some rejuvenation in that region.

Tectonic Interval III – This period is dominated by Type II grabens which formed subsequent to the deposition of most, if not all, plains units in the Taurus-Littrow area and prior to at least the latest mare (Table V). The structural elements associated with this interval are generally characterized by pairs of steeply dipping faults forming grabens which are generally circumferential to the Serenitatis basin. The additional N–S trend (Figure 19g) may be related to and possibly inherited from the N–S element of the grid pattern which Fielder (1963) and Strom (1964) interpreted to be derived from E–W tension.

McGill (1971) and Baldwin (1971) have discussed the orientation and nature of fractures bounding lunar linear and arcuate rilles. McGill shows that the rilles he considered are true grabens (bounded by inward dipping normal faults) and that a vertical maximum principal stress axis characterized the stress system that produced them. In the Littrow region the coincidence of these rilles with Serenitatis basin concentric structures suggests that sagging of the Serenitatis basin interior may have been responsible for the stress field producing the grabens. This might have been caused by isostatic readjustment or by early lava infill.

The scarp in the vicinity of the Apollo 17 landing point formed in this interval, is regionally parallel to Rima Littrow V, and may also represent adjustment of the region to isostatic rebound and mare fill.

Finally, Littrow *BA*, a fresh crater chain which has been interpreted to be volcanic in origin (Carr, 1966), is oriented almost E–W and is not parallel to any significant structural trend.

8. Conclusions

(1) The Taurus-Littrow highlands, lying along the eastern edge of the Serenitatis basin, can be divided into several distinct morphologic terrain types. From comparisons to the morphology and geographic position of basin-related deposits of the Imbrium basin, the Littrow massifs are shown to be analogous to the massifs forming portions of the Imbrium basin second ring, and the Littrow sculptured terra is shown to be analogous to the Imbrium basin Alpes Formation. These relationships strongly suggest that the basic landforms in the Taurus-Littrow highlands are basin-related deposits formed coincident with or only shortly after the origin of the Serenitatis basin.

(2) Interpretation of the basin highland landforms as related to the impact origin of the Serenitatis basin lessens the possible role of volcanism in forming these morphologic units. In particular, the domical nature of the sculptured terra appears to be more closely related to a poorly understood basin-forming process than to subsequent widespread volcanism. The possibility of volcanic deposits within or as a veneer on this unit cannot be ruled out.

(3) Structural elements mapped in the Taurus-Littrow area include lineaments, structural fronts, two types of grabens, and scarps. The majority of lineaments, as

well as some grabens, appear to be related to a dominant NW trend and subordinate N and NE trends. These trends are interpreted to be related to a more regional lunar grid pattern (Strom, 1964; Fielder, 1963) which formed in the area prior to the origin of the Serenitatis basin, causing distinct structural inhomogeneities in the highland terrain.

(4) No obvious concentric or radial structures associated with pre- or post-Serenitatis major basins were detected in the area. With the possible exception of the Imbrium basin, structural effects from multi-ringed basins surrounding Serenitatis appear to have had a minor influence on the structural evolution of the Taurus-Littrow highland area.

(5) The confinement of Littrow massifs to the SE portion of the eastern edge of the Serenitatis basin and the coincidence of their boundaries with both the regional lineament pattern and Serenitatis concentric and radial structures, suggests that during the Serenitatis event, the massifs were uplifted preferentially where Serenitatis structures coincided with pre-existing crustal inhomogeneities. Some topographic rejuvenation may have occurred as result of the Imbrium event.

(6) The distinct morphology of the sculptured hills suggests that, barring major rejuvenation, extensive regional mantling of the area by younger ejecta (e.g., Imbrium, Crisium) has not occurred. This implies that the primary contribution to the Taurus-Littrow highland stratigraphic section is from Serenitatis and pre-Serenitatis events rather than post-Serenitatis events, although Imbrium ejecta deposits may dominate the surface.

(7) The geologic and tectonic history of the Taurus-Littrow highland region can be divided into three periods. *Tectonic Interval I* covers the period between the origin of the Moon and just prior to the Serenitatis basin formation and includes lunar crustal formation and fragmentation. The strong NW trending structural trends (and subsidiary associated trends) are believed to have formed during this period and to have controlled much of the subsequent structural evolution of the area. These trends are thought to be part of more regional lunar grid patterns which may have been caused by global shear, and possibly rejuvenated throughout lunar history by regional tidal stresses and specific local events. *Tectonic Interval II* begins with the formation of the Serenitatis basin and associated deposits. The basic topography and morphology of the Taurus-Littrow region was formed as a result of this event. Most large grabens (Type I) were formed at this time and pre-existing regional fractures may have been rejuvenated. The Crisium and Imbrium basins formed later in this period but appear to have had little major effect on this area. *Tectonic Interval III* is dominated by the formation of narrow (Type II) grabens occurring primarily in the plains and following structural patterns circumferential to the Serenitatis basin. Pattern variations may be related to underlying grid trends. The stress system producing these structures may have been caused by Serenitatis basin isostatic readjustment or early volcanic infilling. The scarp in the vicinity of the Apollo 17 landing site is the youngest obvious structural element and appears to be an eastward shallow dipping normal fault or a high-angle variably striking fault indicating adjustment of the region to isostatic rebound and mare fill.

(8) Based on these observations and conclusions, the Littrow massifs should be composed of a sequence of breccias primarily derived from Serenitatis ejecta and uplifted pre-Serenitatis deposits. Although a thin mantle of Imbrium ejecta was probably deposited in the area, it is anticipated that post-Imbrium events (such as talus accumulation, impact cratering, and debris slides) will have made pre-Imbrian materials accessible to the Apollo 17 astronauts. No difference in composition between massifs and sculptured terra can be proven from this study. However, the distinct morphologic differences suggest that even if they are of similar bulk composition, the two terrain types may represent different phases of a basin forming process.

(9) The Apollo 17 landing site is interpreted to lie in a graben bounded by steeply dipping normal faults trending radial to the Serenitatis basin and parallel to a more regional NW pre-Serenitatis structural pattern. The valley is believed to have formed at the time of the Serenitatis event in an area where radial Serenitatis fractures encountered pre-existing parallel regional structural inhomogeneities. The scarp which crosses the valley of the landing area may represent a variably striking, high-angle fault or alternatively, a shallow eastward dipping normal fault. Based on the latter model, the fault plane should lie between 0–2 km in depth where it exists beneath the traverse area. Evidence for its presence and geometry may be obtained from geophysical experiments carried out on Apollo 17.

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