PERVASIVE LAYERING IN THE LUNAR HIGHLAND CRUST: EVIDENCE FROM APOLLOS 15, 16, AND 17

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Abstract

This paper presents results of a photogeologic reconnaissance of 70 mm photographs taken on the lunar surface during the Apollo 15, 16, and 17 missions, whose primary objective was to investigate the lunar highland crust. Photographs at all three sites, notably the Apennine Front, show pervasive layered structure. These layers are easily distinguished from lighting artifacts, and are considered genuine crustal structures. Their number, thickness, and extent implies that they are lava flows, not ejecta blankets or intrusive features. They appear to be the upper part of the earliest lunar crust, possibly forming a layer tens of kilometers thick. Remote sensing studies (X-ray fluorescence and reflectance spectroscopy), indicate that the highland crust is dominantly a feldspathic basalt. It is concluded that the highland layers represent a global crust formed by eruptions of high-alumina basalt in the first few hundred million years of the Moon's history.

Introduction

The primary scientific objective of the last three Apollo missions was to investigate the nature and origin of the lunar highland crust, the first three landings having been on maria (Apollo 11 and 12) or ejecta from the Imbrium Basin impact (Apollo 14), the Fra Mauro formation. As part of the surface exploration, the astronauts took hundreds of 70 mm terrain photographs. Many of these were not given intensive study before the end of the Apollo Program. We have selected three sets of photographs from Apollos 15, 16, and 17, showing highland structure, and carried out a photogeologic study of them. This paper reports results of this study, which has fundamental implications for the nature and origin of the oldest lunar crust. A preliminary report was presented (Lowman ,2005) at the 36th Lunar and Planetary Science Conference.

Methods

Suitable 70 mm surface photographs were selected from the Apollo 15, 16, and 17 Preliminary Science Reports, and from catalogues of Apollo photographs compiled by the National Space Science Data Center. Black-and-white high-contrast 9 x 9 prints were prepared and used with transparent overlays. The specific objective was to produce quantitative measurements of the number and thickness of apparent structural layers at each of the sites. Hand-drawn sketch diagrams of the best photographs were prepared.

The approach was similar to that used in photogeologic lineament mapping, except that the "lineaments" mapped were seen horizontally, in cross section. Standard photogeologic practice was followed. Only actual visible lineaments were shown, and there was no attempt to interpolate between probably continuous segments. Except for the Silver Spur exposure, for which an 800 meter height had been previously measured by the Apollo geology team (Swann et al., 1972), photo scales were estimated on the basis of camera focal length and estimated distance to the area being sketched. After the sketch maps were prepared, lineaments were counted along traverses normal to the apparent dip; results are presented in Table 1.

This investigation should be considered strictly preliminary. Measurements of range, especially at St. George Crater, are averages only. Photographs used were on high-contrast paper, but no digital enhancements could be made. Future studies should use digitized versions of these scenes, and precise photogrammetric measurements of range and height made. This study is essentially a retrospective photogeologic reconnaissance, done more than three decades after the pictures were taken.

Apollo 15: Apennine Mountains

The Apollo 15 spacecraft landed at the base of the Apennine Mountains, the uplifted rim of the Imbrium Basin (Fig. 1), a site chosen to investigate the structure and composition of the pre-Imbrian crust (Allen,1972; Spudis and Ryder, 1985). The Apollo 15 mission commander, D.R. Scott, took a panoramic series of 70 mm photographs from the hatch of the Lunar Module shortly after landing.

The mountains of the Apennine Front showed conspicuous layers, evident at once to the crew (Scott et al., 1972). The view to the northeast, showing Mount Hadley, was strongly lineated (Fig.2). This picture was taken with grazing incidence illumination, and it was shown by Wolfe and Bailey (1972) that the steeply-dipping set is a lighting artifact. Their interpretation has been generally accepted, and is in fact beyond dispute. However, as noted by Apollo 15 geology team, there is another set of lineaments, more nearly flat-lying, visible in close-up photographs of Mount Hadley (Fig. 3) taken under the same illumination. These are undoubtedly genuine structures, termed "regolith-covered benches" by the Geology Team (Swann et.al., 1972). We did not measure this set, but they provide a good example of the layering seen elsewhere.

Views to the southeast provide the best look at structures of the Apennine Front. A wide-angle view (Fig. 4) shows the regional context of Hadley Delta, Silver Spur (Fig. 5 ,6) and St. George Crater (Fig.7,8). Detailed interpretation will be deferred at this point. However, it should be pointed out that the wide-angle view shows the regional extent and thickness of the layers (as they will henceforth be termed). They are consistently parallel to the east-dipping topography, and are clearly dip slopes similar to terrestrial cuestas or hogbacks.

Petrologic interpretation of the Apennine Front layers will be presented later, but some structural and geophysical aspects should be discussed here. First, it appears that the inclinations of the Silver Spur and St. George layers from the horizontal are roughly true dips in the structural sense, i.e. the maximum dips in the planes being measured. However, determination of true dip requires measurements on at least two different separate exposures, not possible here since the pictures were taken from a single point,the landing site.

The layers exposed at Silver Spur and St. George Crater are not a thin surficial deposit, whatever their nature. The total number of layers in this part of the Apennine Front, from the mare surface (Palus Putredinus) to the crest of the Apennines, is probably in the low hundreds. Hadley Delta and Silver Spur together have over 4 kilometers of relief, and the **exposed** stratigraphic thickness, assuming a 30 degree true dip, is probably over 3.5 km. Furthermore, since the base of this section is not exposed, this figure cannot be assumed to be a maximum. The Apennine Front section could be just the upper part of a much thicker sequence, as will be discussed further.

Apollo 16: Descartes Area

The Apollo 16 landing site, near the crater Descartes, was chosen as representative of the true lunar highlands, so to speak (England, 1972; Hinners, 1973). As recounted by Wilhelms (1998), the mission was extremely productive scientifically, one reason being that it almost immediately overturned pre-mission geologic interpretations of the local geology. The main mapped units, in particular the Cayley Formation, had been considered volcanic, from their relative ages and geomorphology(Muehlberger, et al., 1972). However, the Apollo 16 crew (Young et al., 1972) discovered at once that the local rocks were overwhelmingly breccias. This was subsequently confirmed by sample analysis.

The Descartes area, intensely cratered highland terrain, proved to be, as expected, heavily cratered and rough, with little obvious expression of underlying structure as exposed at the Apollo 15 site. However, close examination of the photographs taken during EVA in particular showing South Mountain (Figs. 9,10), reveals subtle but distinct subhorizontal linear features. As at the Apollo 15 site, only one photographic station was possible,and the attitude of these features is only an apparent dip in a structural sense; they could in principle be dipping steeply away from the line of sight. However, South Mountain does not form a cuesta, suggesting that the apparent dip (near-horizontal) is close to the true dip.

The Apollo 16 astronauts sampled South Mountain,mapped as the Descartes Formation, but found little but regolith breccias (Young et al., 1972). The Descartes Formation, mapped at South Mountain, has been interpreted as ejecta from Mare Nectaris to the south, analogous to the interpretation of the lineaments of the Apennine Front. There are several other basins in the area: Serenitatis, Tranquillitatis, and Fecunditatis, for example, so the ejecta interpretation is a reasonable one for the Apollo 16 site.

Apollo 17: Taurus-Littrow Valley

A re-examination of the surface EVA photographs taken on the Apollo 16 and 17 missions shows that these two highland sites also have layered structures.The Taurus-Littrow Valley is radial to the Serenitatis Basin (Head, 1974), and hence is analogous to the Apollo 15 landing site. The valley is bordered by highland terrain, the South Massif and, to the north, the North Massif and the Sculptured Hills (Fig.11). The crew observed roughly horizontal "source crops" for various boulders visited (Schmitt and Cernan,1973; Schmitt, 1973). These were sketched and measured,but those of the North Massif are not well-defined in photographs and will not be reproduced here .

In contrast, the Sculptured Hills (Fig. 12) show distinct layers in high-contrast pictures with grazing incidence sunlight. There appear to be at least 20 layers, with an average thickness of about 70 meters (Fig.13). Furthermore, the easterly dips obvious in the nearest exposure appear parallel to those in the distance (center and extreme right), and to some in the North Massif (not shown). The structures visible here thus may represent a much larger area than previously realized, and the apparent dip strengthens the analogy with the Apennine Front layers previously discussed. The Sculptured Hills layers also appear to be topographically expressed as dip slopes inclined away from, in this case, the Serenitatis Basin.

Interpretation

The quantitative results of the study to this point, for the best-exposed areas, are shown in Table 1. It is clear that at all three Apollo landing sites, chosen explicitly for study of the lunar highland crust, there are structural layers, resembling terrestrial sedimentary strata. Water- or air-deposited rocks are obviously out of the question for the Moon. There are three general possibilities for the nature and origin of the pervasive layering described here.

The majority opinion is that the layers are superimposed overlapping ejecta blankets from mare basins. There are at least 43 basins, defined as impact craters over 300 km wide (Zuber et al., 1994;Spudis et al, 1994;Petro and Pieters, 2005), generally believed to have formed a layer, or megaregolith, tens of kilometers thick (Horz et al.,1991). Petro and Pieters show that the ejecta from the South Pole Aitken Basin alone could have blanketed the entire lunar surface.

This explanation for the layers illustrated here is contradicted by several lines of evidence, some from post-Apollo programs such as Clementine and Lunar Prospector. There is no sharp distinction between mare basins and impacts craters such as Copernicus. At the best exposed lunar crust area, the Apennine Front, we have mapped roughly 100 layers, of similar thickness, forming a continuous stratigraphic sequence. This is far too many for the ejecta blanket interpretation. An obvious explanation is that each ejecta blanket is stratified when deposited. However, the Fra Mauro Formation showed no such stratification detectable by seismic methods (Kovach et al.,1971), and the formation was at the Apollo 14 site only about 70 meters thick, similar to the low-velocity layer (Cayley Formation) at the Apollo 16 site (Kovach et al., 1973). Formation of large impact craters and basins may well have been a complex,long-lived process after the initial impact, but the evidence in hand does not support the interpretation of the highland crust layers as impact ejecta blankets.

A second possibility, discussed by Short and Forman (1972), is that the layers, in particular those of Silver Spur, are magmatic, analogous to those of layered mafic intrusions such as the Bushveld Complex. This interpretation cannot be easily dismissed. Apollo missions returned samples of anorthosites, norites, and troctolites (ANT) , best interpreted as formed by magmatic differentiation, e.g., crystal fractionation. The generally-accepted "magma ocean" could be considered a global magma chamber, from which ANT rocks formed. However, reasoning by analogy with terrestrial igneous features is disputable. The Bushveld Complex, for example, is a Precambrian structure formed at depth and now exposed by billions of years of fluvial or marine erosion (Wager, 1968). The lunar highlands as exposed on the Apennine Front cannot be interpreted this way. Radiometric dates show that the highland rocks have ages between 4 and 4.5 Ga. There was no older crust for them to be intruded into; they **are** the older crust.

We interpret the pervasive highland layers as lava flows, analogous to those of the Columbia Plateau (Fig. 14), on the basis of thickness, number, and structure. Plateau basalts as typified by those of the Grande Ronde River exposures are characterized by thickness (15-39 meters) (Hooper, 1981, 1997), great horizontal extent, and generally low dips where undisturbed by later tectonism. They are agreed to have been formed by fissure eruptions. However, basaltic lava flows of the central eruptive type, as seen in Hawaii (Figs. 15,16) have comparable thickness and collectively number in the thousands. The layers of the highland crust are thus similar in major structural respects to terrestrial lava flows.

Not to overlook the obvious, basaltic lava flows are exposed in Hadley Rille, and were photographed by the Apollo 15 crew (Swann et al., 1972.) These were flat-lying thin layers, unfortunately largely covered by talus. They appeared structurally similar to the Silver Spur layers and those of the Grande Ronde Gorge, with alternating hard and soft layers, in one interpretation, expressed as "benches and inflections" in the walls. In Hawaii, lava flows are frequently surfaced by aa basalt, formed by cooling as the flow advances. This is illustrated on a small scale (Fig. 16) by alternating layers.

A discussion of lunar petrology would be beyond the scope of this paper. However, a few main points should be made. First, the widely-accepted view that the lunar highlands are anorthosite was disproven by the Apollo 15 and 16 X-ray fluorescence surveys (Adler at al., 1971, 1972; Yin et al., 1993), showing that the exposed crust along the flight path was chemically anorthositic gabbro or feldspathic basalt (Lowman, 1972). Analyses of soil from the Apennine Front were dominantly low-potassium Fra Mauro basalt (Reid, 1974), a finding supported by XRF data specifically over the Apollo 15 site (Clark and Hawke, 1981). Post-Apollo investigations, in particular those using earth-based reflectance spectroscopy (Pieters, 1985, 1993) , show that anorthosite is a subordinate and probably deep-seated component of a "noritic" highland crust. Reflectance data from Clementine (Cahill et al.,2005) showed lunar surface compositions dominated by pyroxene, plagioclase, and olivine.

The recognition of wide-spread "cryptomaria," i.e. pre-basin basalts, indicates that high-alumina (i.e., feldspathic) basalts make up much of the original lunar crust, formed in the first differentiation or in later magmatic events (Kramer et al.,, 2004;Kramer and Neal,2005; Hawke et al., 2005; Neal et al., 2005). Schultz and Spudis (1979) have shown that the abundant dark-halo impact craters imply widespread pre-basin basaltic volcanism. Feldspathic lunar meteorites were considered representative of the lunar highland crust by Joliff and Gillis (2002).

Multispectral imagery from the 1990 Galileo Earth-Moon flyby gave a look at the western limb and far side, previously not covered (Belton et al., 1992). The highlands west of Oceanus Procellarum appear compositionally similar to the highland areas of the Apollo 15, 16, and 17 sites. They support the existence of cryptomaria, indicating that the Orientale ejecta covers an area of older mare (i.e., basaltic) volcanic rock. Collectively, the evidence now available suggests that the lunar highland crust is essentially basaltic.

Summary and Conclusions

We have found that, at all three of the highland landing sites, the highland crust shows a layered structure easily distinguished from lighting artifacts. These layers, best exposed along the Apennine Front, are collectively several kilometers thick. Since their base is not exposed, they may be only the upper part of a lunar crust several tens of kilometers thick, as in fact inferred from geophysical data (Zuber et al., 1994; Weiczorek and Phillips, 1997). If correct, our interpretation implies that the first differentiation of the Moon was an era of global volcanism in which hundreds of high-alumina basaltic lava flows erupted in the first few hundred million years of the Moon's history.These flows were presumably accompanied or followed by intrusive magmatic processes, during which anorthosites, norites, troctolites, and KREEP were formed (Spudis and Davis, 1986).

This interpretation is a radical one, directly contrary to the widely-accepted magma ocean/anorthosite concept (e.g., Schmitt, 1999). However, it is based on surface investigations at three widely-separated sites, seismic data, remote sensing, and returned sample analyses. It can be tested by further remote sensing studies and eventually by renewed surface and subsurface investigations on the Moon's surface. Further study of the photographs used here by digital enhancement and precise photogrammetric measurements would be an obvious first step.

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Illustrations

14. Lava flows of Columbia River Basalt in canyon walls of Grande Ronde River, southeastern Washington. Twenty major flows, each about 15-20 meters thick.
15. Mauna Loa basaltic lava flows on Hawai'i; road cut on Rt. 11, southwest coast south of Captain Cook. Two flows completely exposed; lower portion of each is gray, upper portion (original surface) is brown.
16. Mauna Loa 1859 basaltic lava flow front, Waikoloa, Hawai'i.

Table 1 Statistics of layers mapped on Apollo photos.

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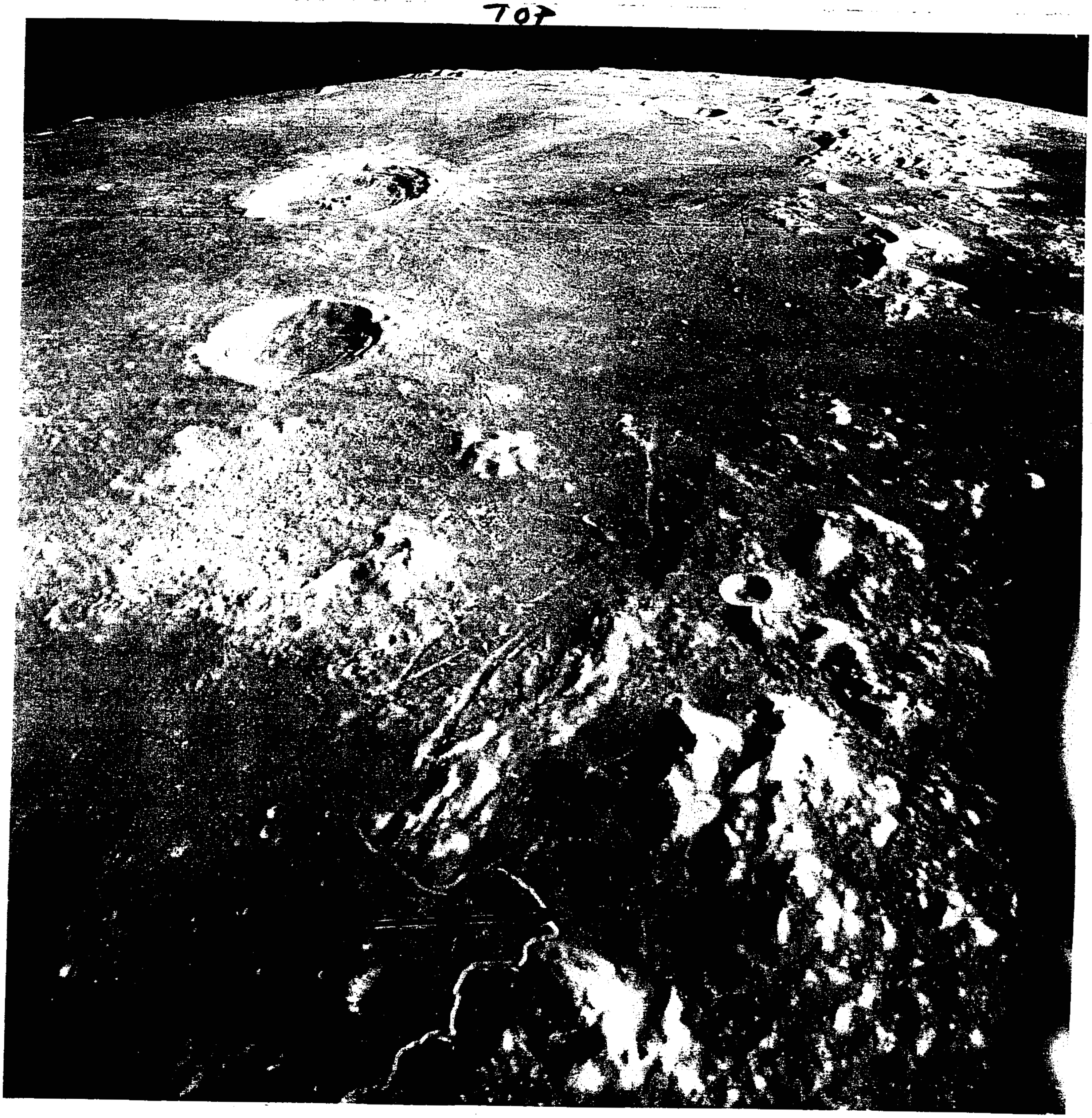
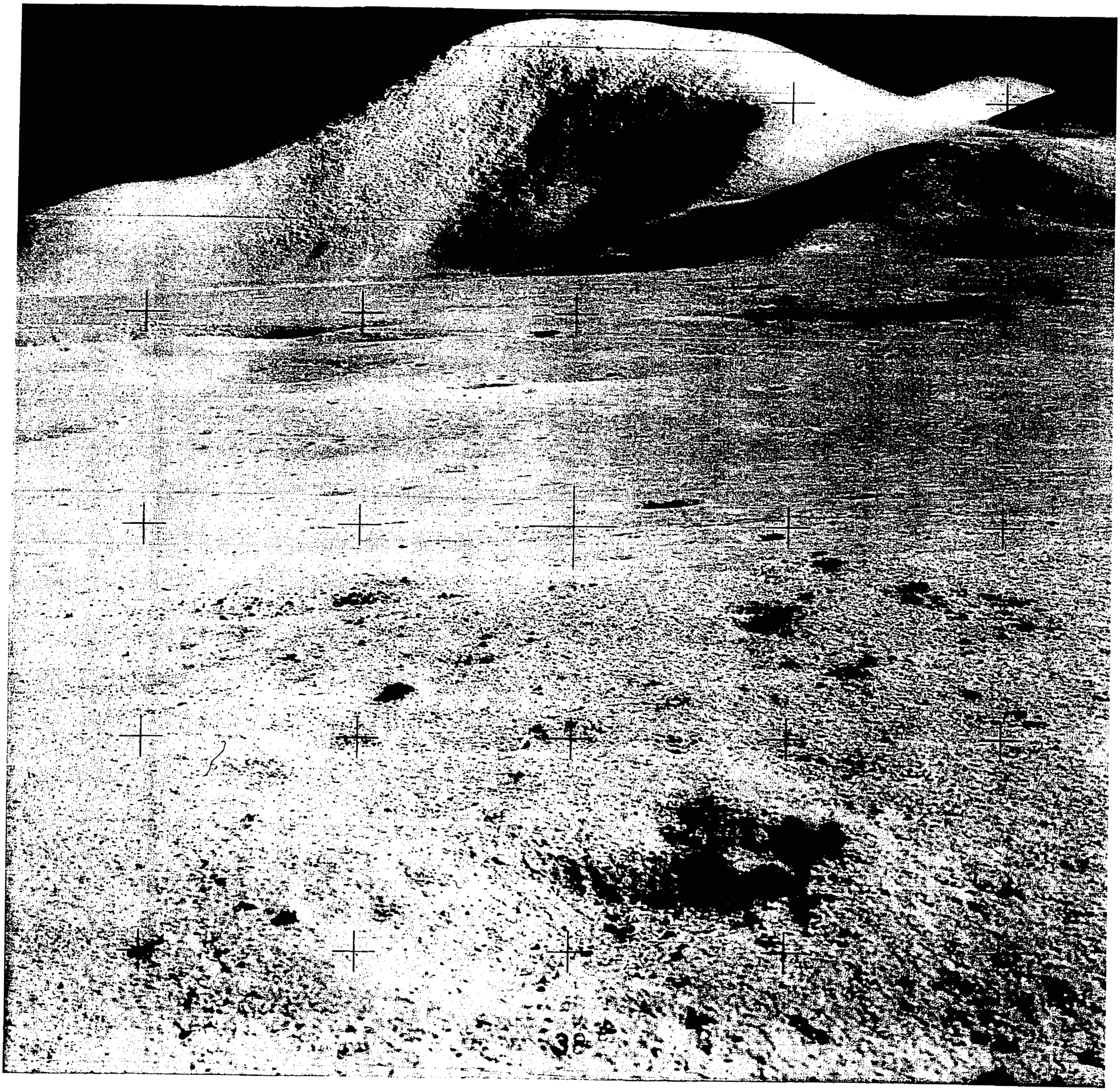
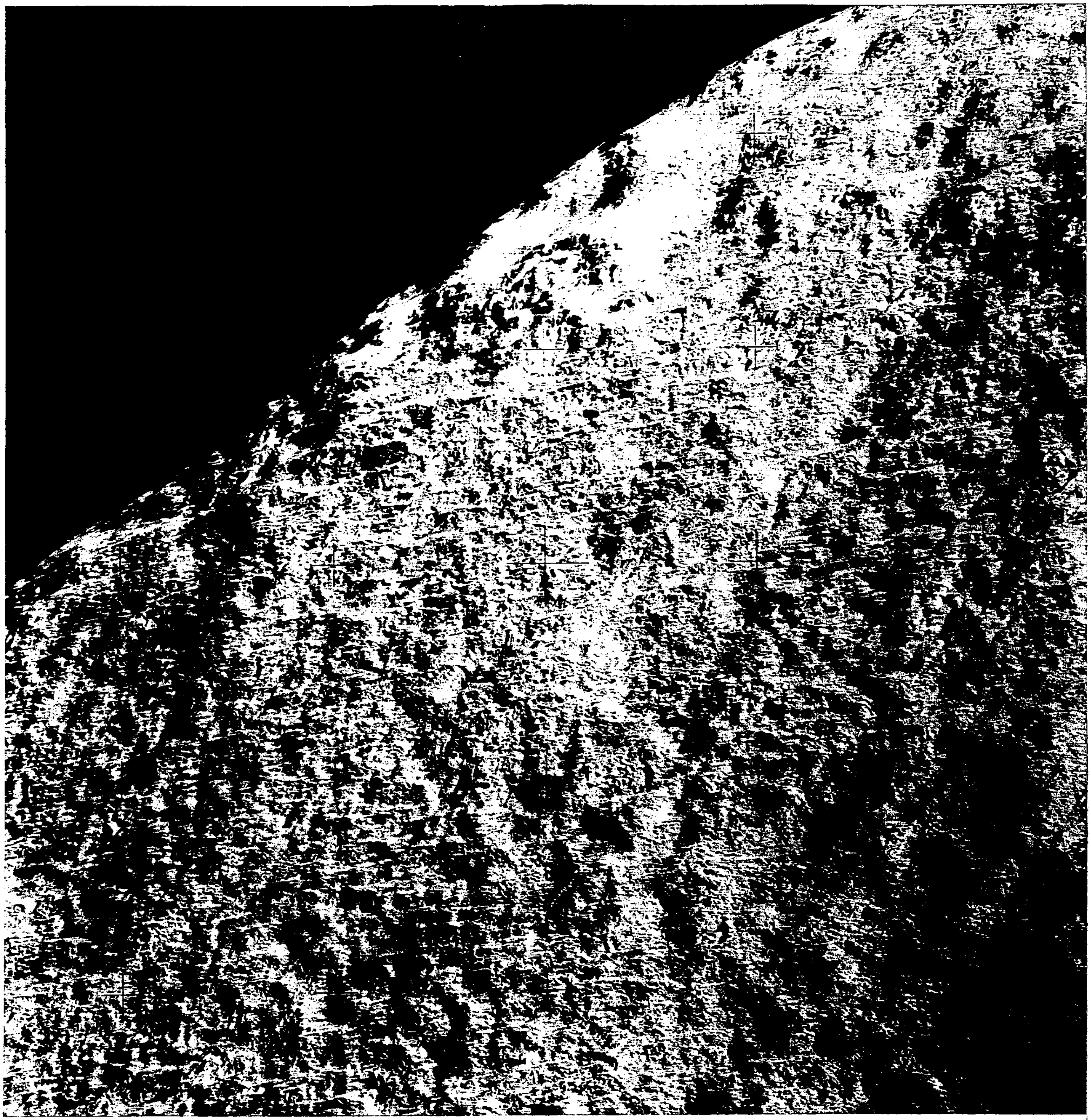


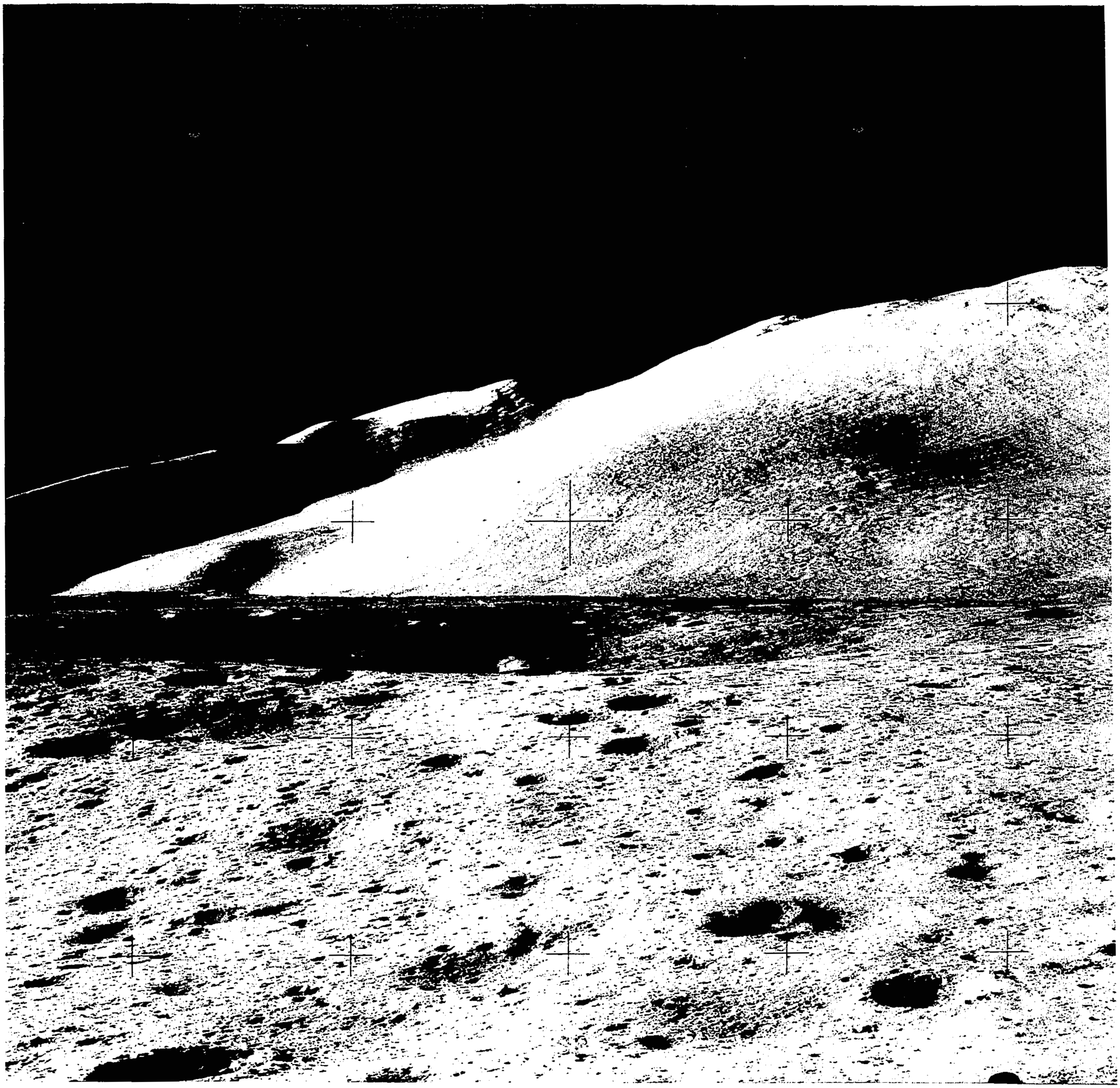
1. Oblique view of Apollo 15 landing site, looking north,taken with metric camera from Apollo 15 spacecraft. (Photo AS15-1537(M))



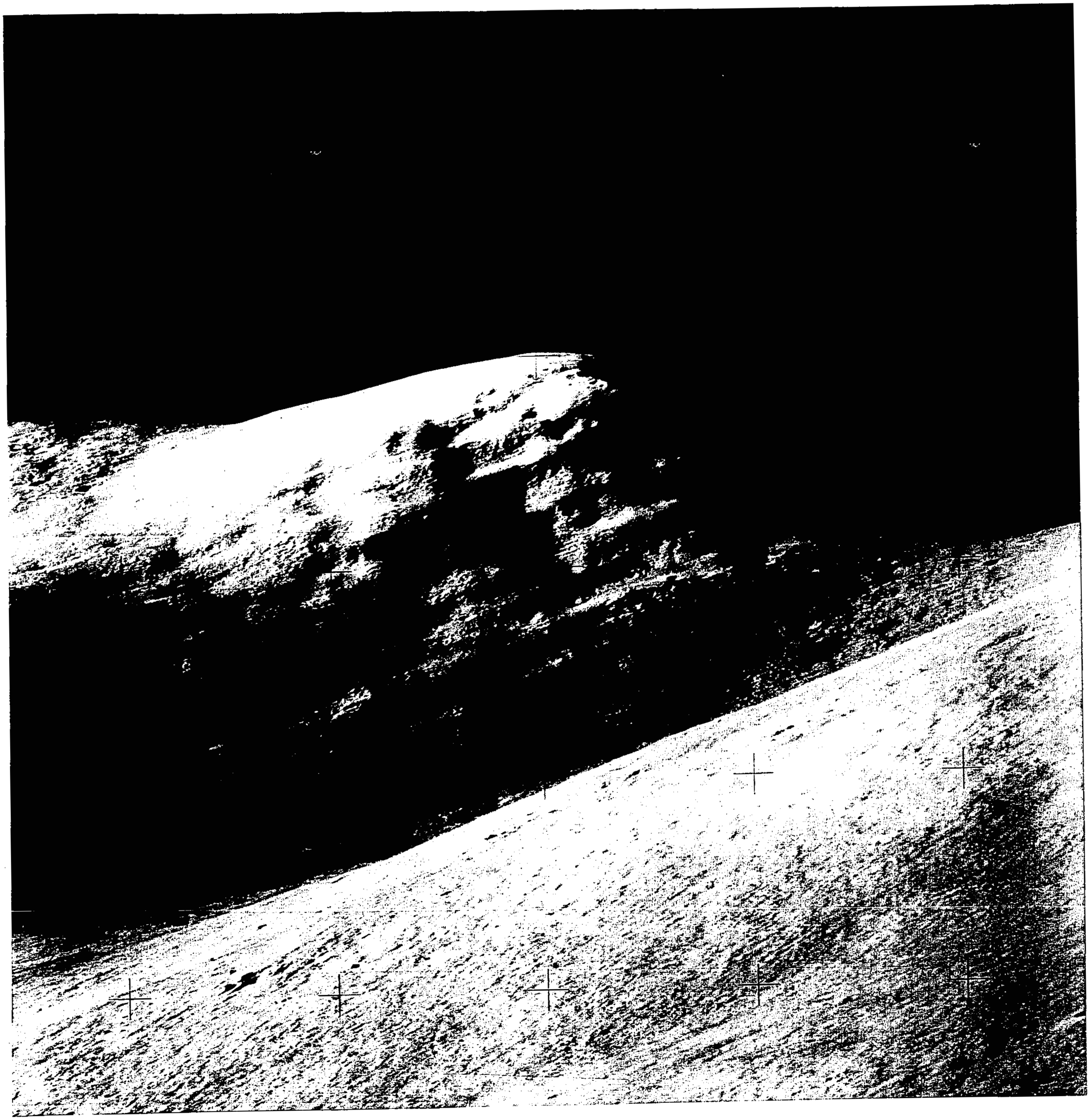
2. Apollo 15 EVA photo, looking NE to Mount Hadley (about 4.5 km high) Lineaments dipping to left interpreted as lighting artifacts produced by grazing incidence light. (PhotoAS15-90-12208)



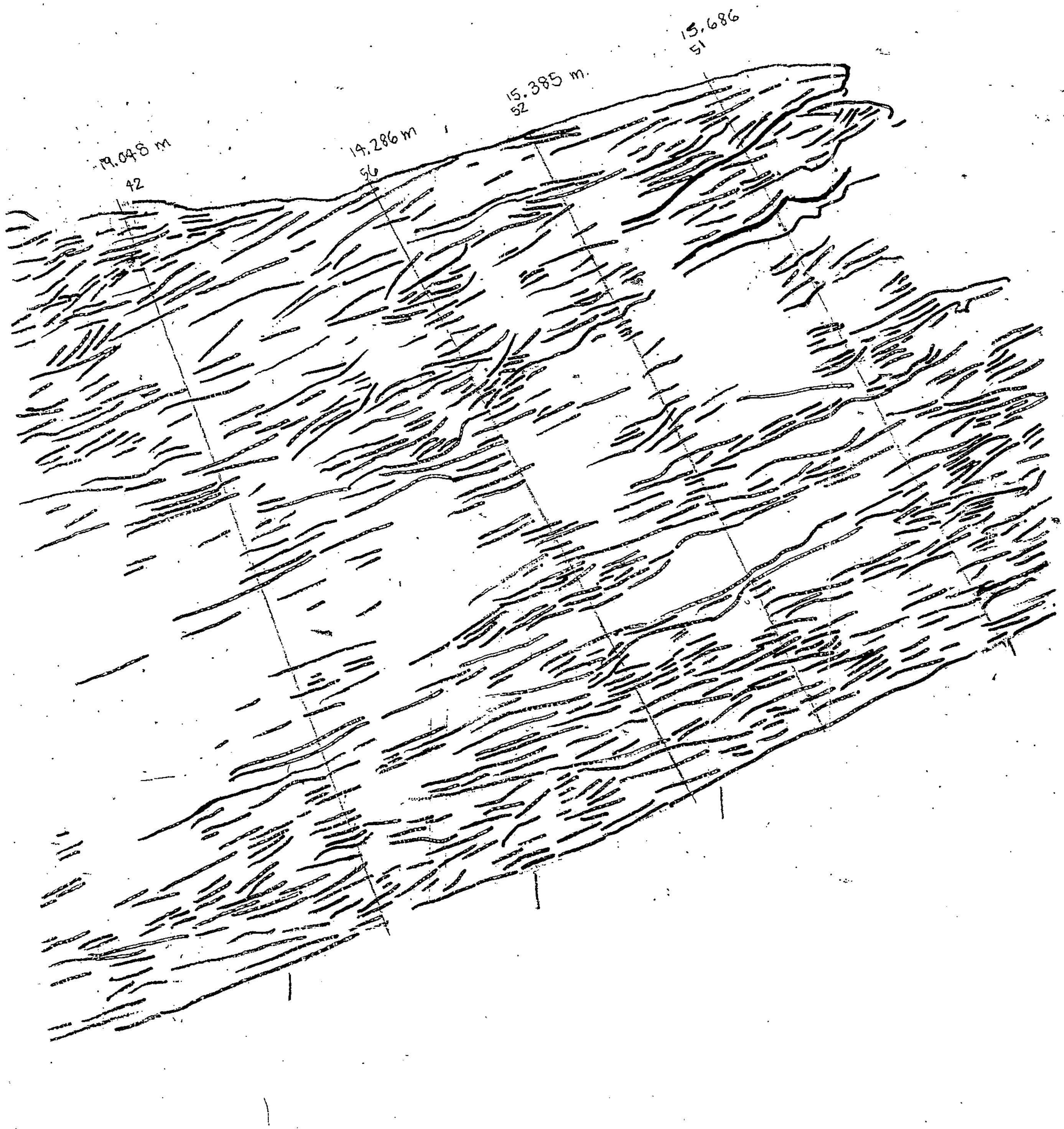
3. Apollo 15 EVA photo, 500 mm lens, looking NE to Mount Hadley. Lineaments dipping to left are lighting artifacts; nearly horizontal ones considered true structural benches. (Photo AS15-84-11321)



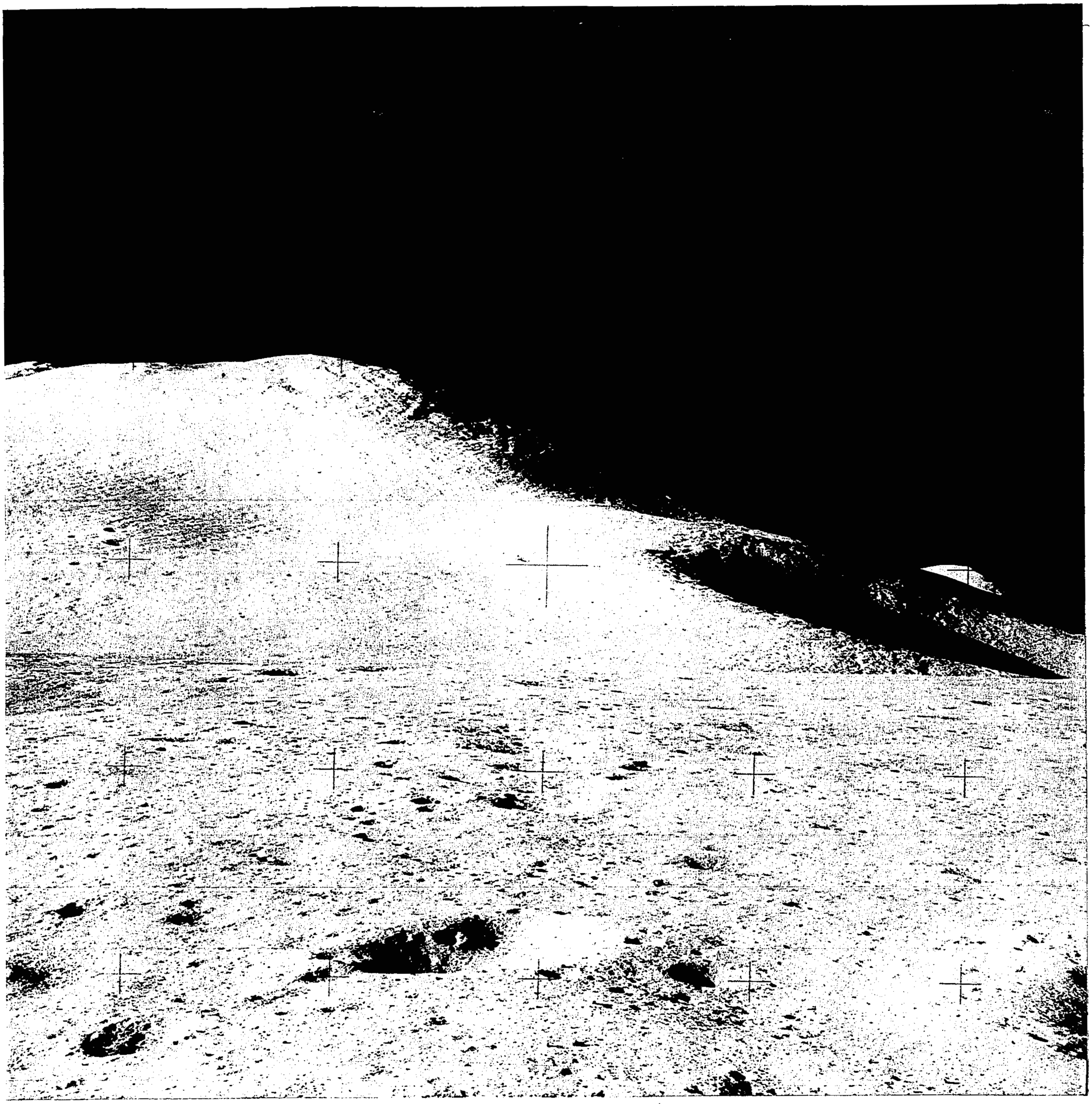
4. Apollo 15 EVA photo, looking S to Hadley Delta (right) and Silver Spur (left center). Distance to Silver Spur crest about 20 km. Hadley Delta is about 3.5 km high.



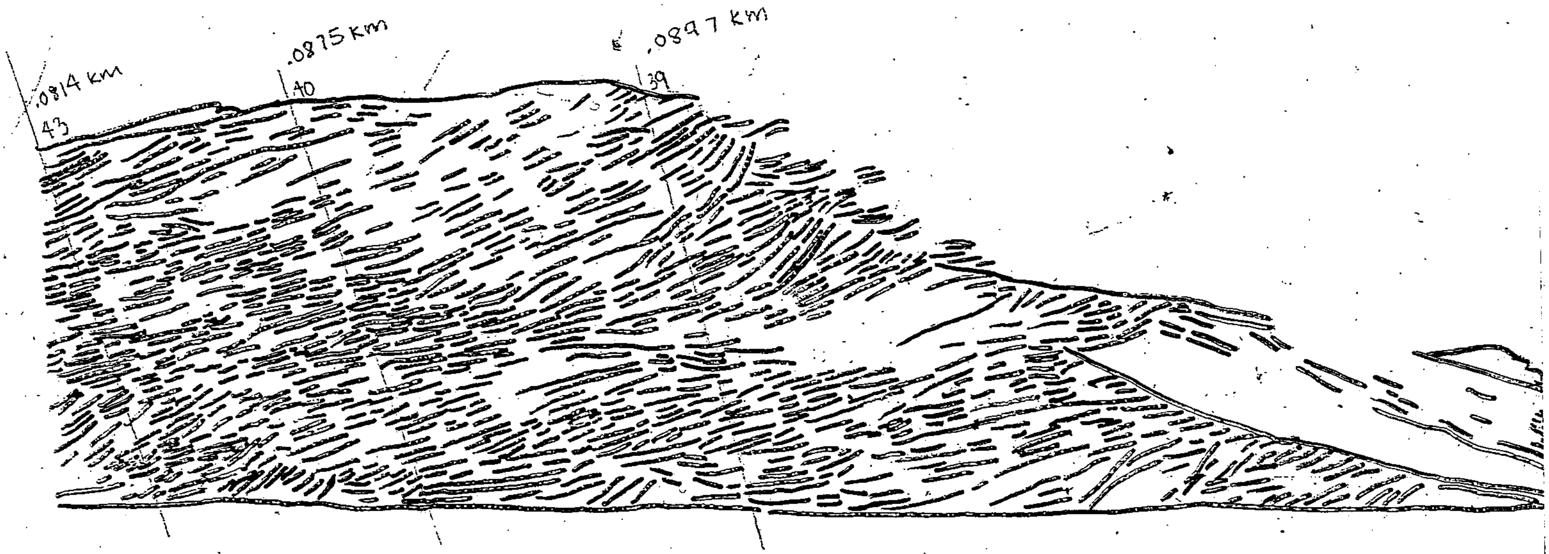
5. Apollo 15 EVA photo, 500 mm lens, looking S toward Silver Spur. Steep face of Silver Spur about 800 m high. (Photo AS15-84-11250).



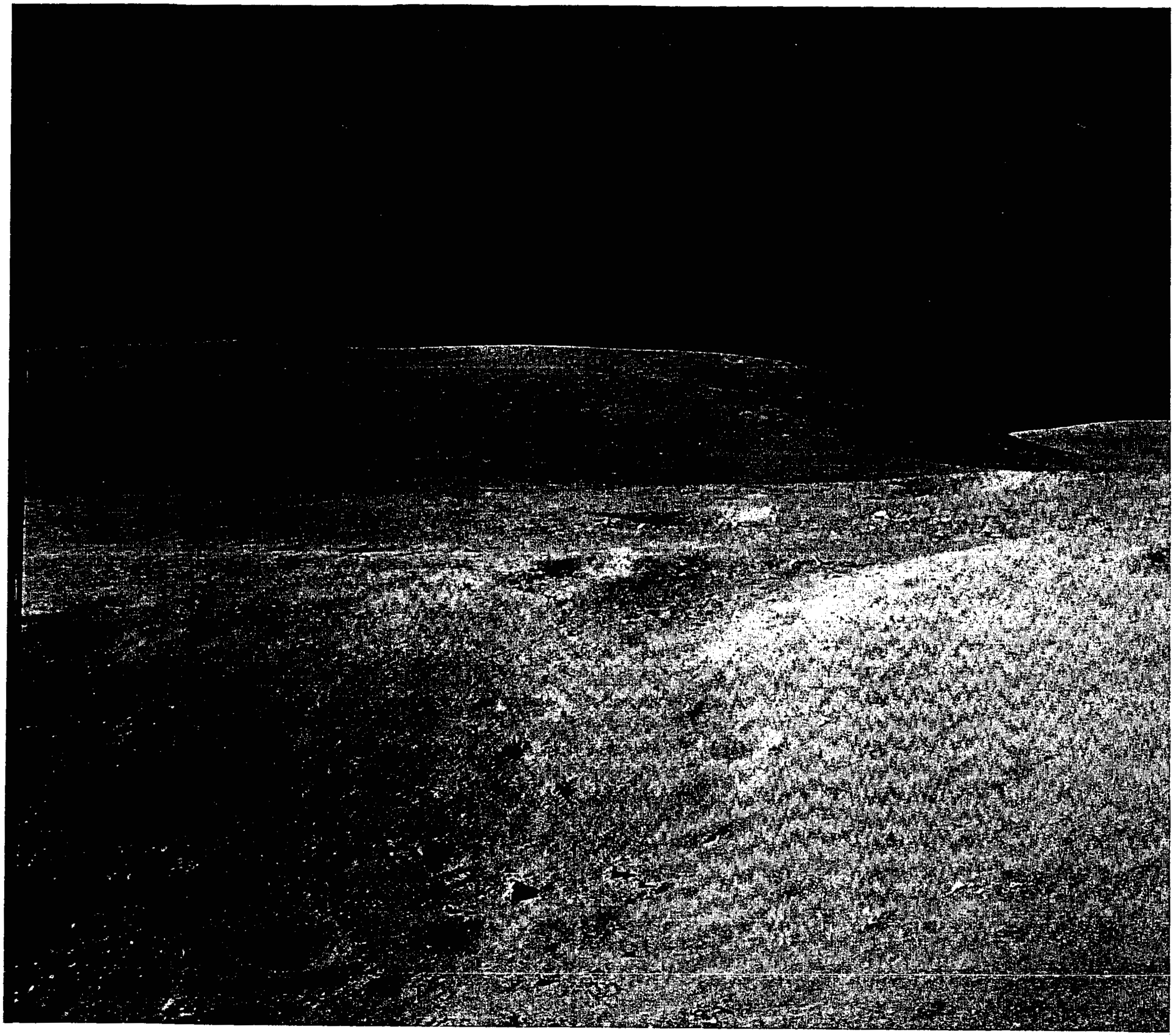
6. Sketch map of Fig. 5, showing traverses and numbers of layers counted.



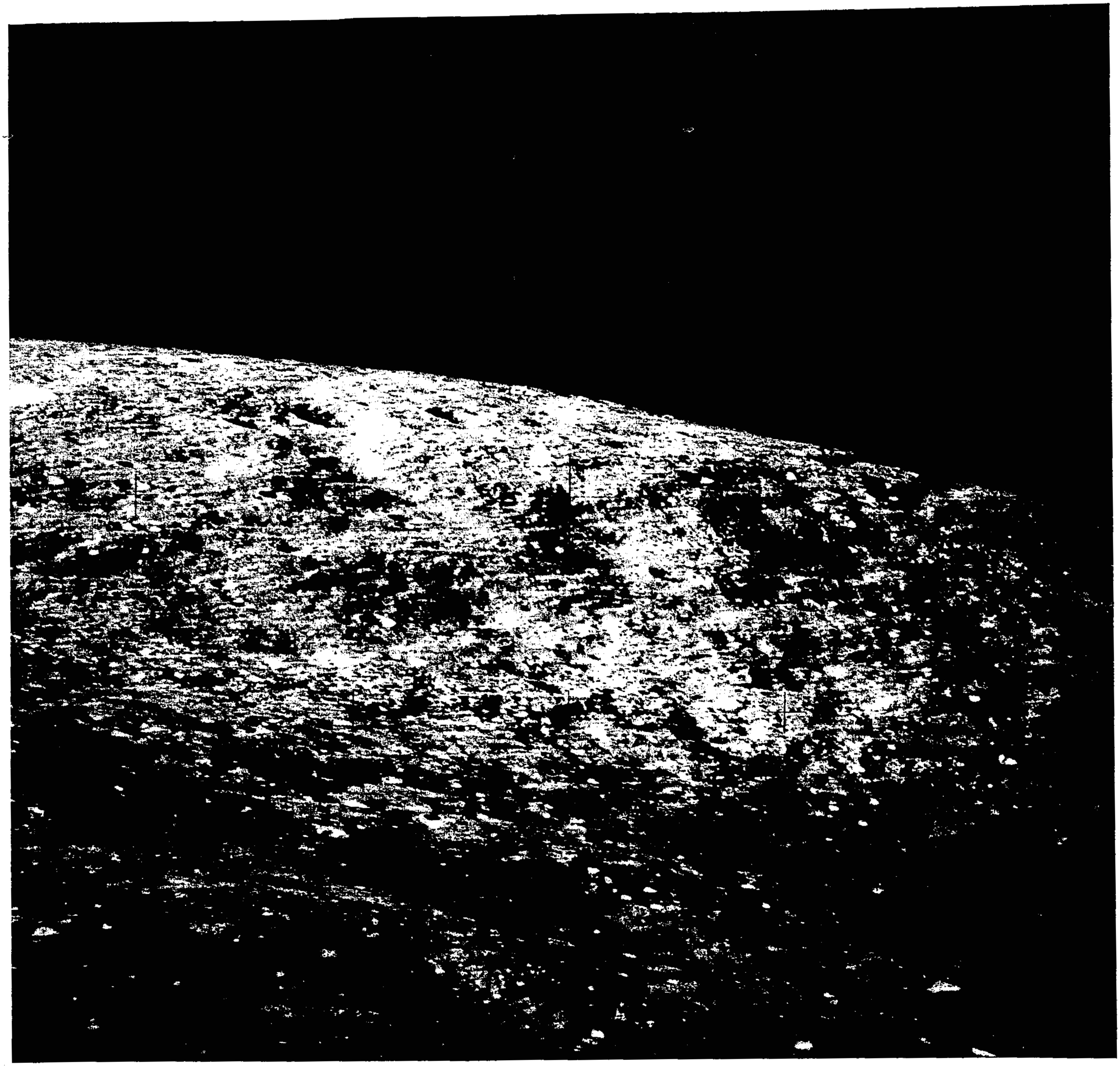
7. Apollo 15 EVA photo, looking S toward Hadley Delta (about 3.5 km high) and St. George Crater (Photo AS15-85-11374)



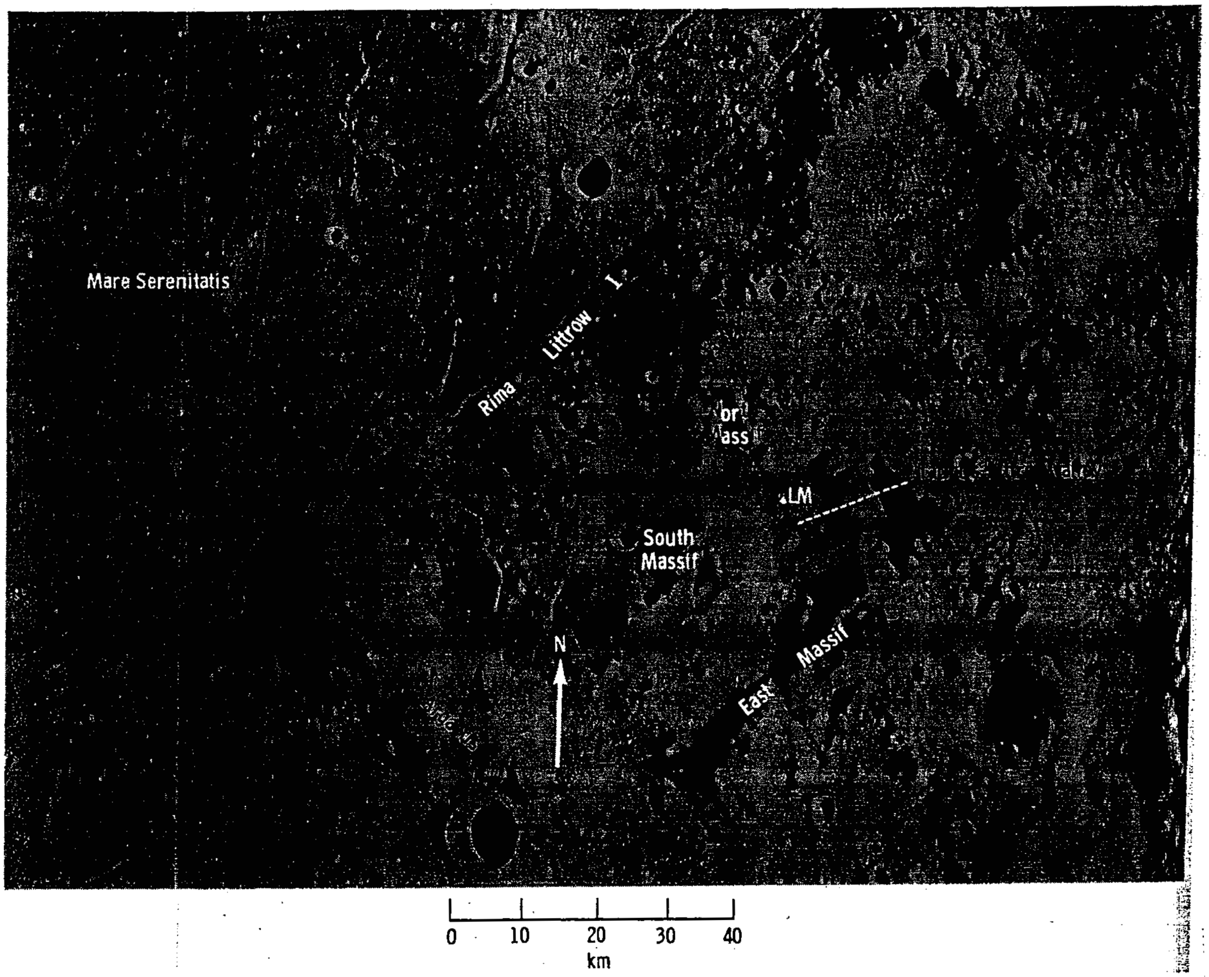
8. Sketch map of Fig. 7, showing traverses and numbers of layers counted.



9. Apollo 16 EVA photo, looking S toward Stone Mountain (Photo AS16-113-18325).

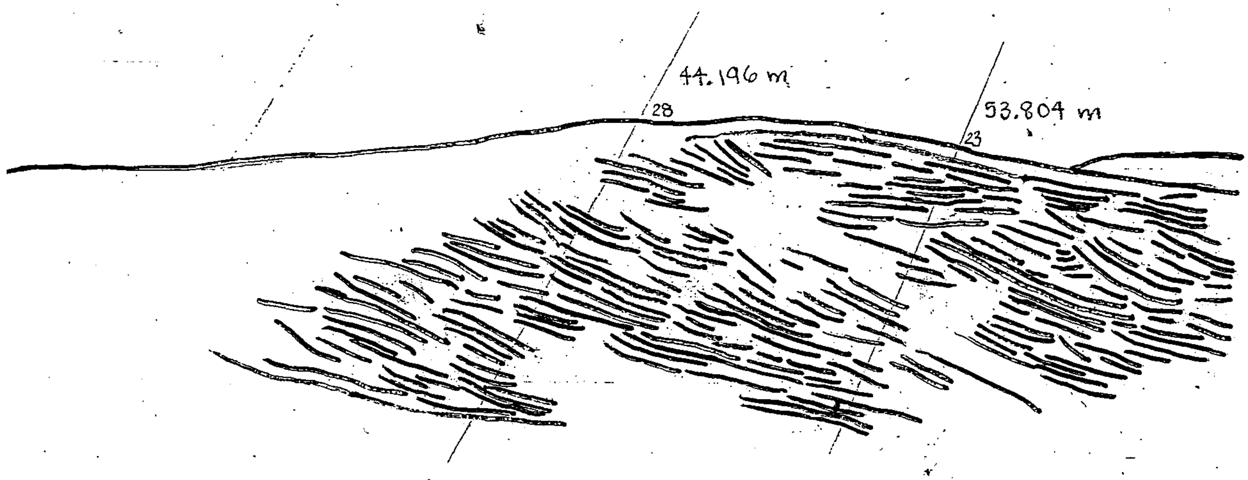


10. Apollo 16 EVA photo, showing crest of Stone Mountain (Photo AS16-112-18217). Lineaments in lower half of photo are probably lighting artifacts produced by grazing incidence illumination; Those at top, roughly horizontal, are considered real structure.



11. Map of Apollo 17 site and adjacent region, from Apollo 17 Preliminary Science Report.

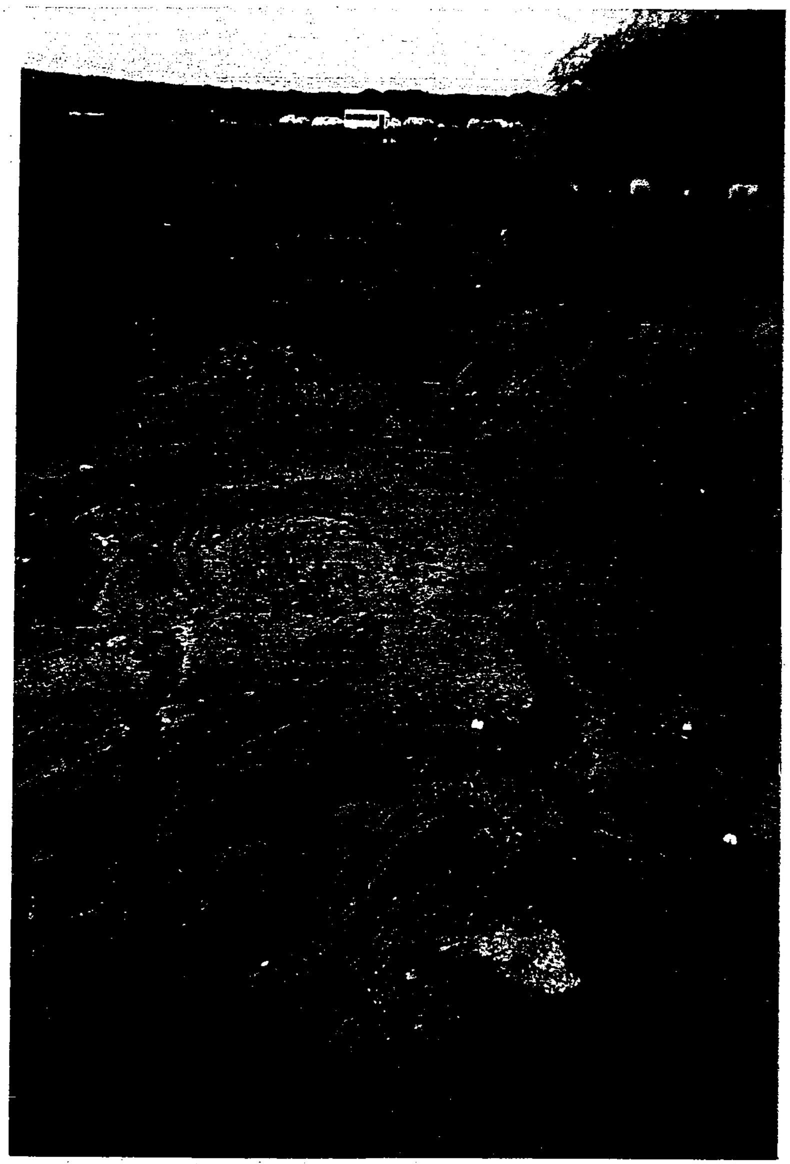
12. Apollo 17 EVA photo, looking NE toward North Massif (left), Wessex Cleft (center), and Sculptured Hills (right). Note parallel layers in line with Wessex Cleft on horizon and at extreme upper right on horizon. (Photo AS17-136-20695)



13. Sketch map of Fig. 12, showing traverses and numbers of layers counted.

14. Lava flows of Columbia River Basalt in canyon walls of Grande Ronde River, southeastern Washington. Twenty major flows, each about 15-20 meters thick.

15. Mauna Loa basaltic lava flows on Hawai'i; road cut on Rt. 11, southwest coast south of Captain Cook. Two flows completely exposed; lower portion of each is gray, upper portion (original surface) is brown.



16. Mauna Loa 1859 basaltic lava flow front, Waikoloa, Hawai'i.

Results/ Conclusions

Silver Spur	4	42, 56, 52, 51	19, 14, 15, 16
St. George Crater	3	43, 40, 39	81, 88, 90
Sculptured Hills	2	21, 14	56, 84
North Massif	2	28, 23	44, 54

Table 1 Statistics of layers mapped on Apollo photos.