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LUNAR ANALOGS OF FLUVIAL LANDSCAPES: POSSIBLE IMPLICATIONS

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INTRODUCTION

The subject of possible fluid erosion on the moon is a topic of continuing interest. Much of the interest has stemmed from the presence of lunar[1] rilles some of which do not lend themselves readily to tectonic interpretation. The advent of relatively large scale Lunar Orbiter photography in the last few years has stimulated speculation because of the remarkable meandering patterns of some sinuous[2] rilles.

In seeking an explanation for sinuous rilles it is understandable that the possibility of fluid flow should have received considerable attention. If, for example, the Moon is a small scale analog of the Earth with a comparable early record of degassing, considerable quantities of water vapor should have been emitted. Whether the liberated water vapor, or any other vapors for that matter, could be retained considering the low gravity of the Moon and the high temperatures during lunar days, has been warmly debated. We will consider some of the current views later. The present approach is primarily geomorphic and concentrates on the problem of whether any features of the lunar landscape require fluid erosion.

The sculpturing of the lunar highlands, hitherto somewhat neglected, will also be considered. In many areas, the sculpturing suggests fluid erosion at an early stage in lunar history. If this proves to be true, the products of this erosion may lie buried under the later deposits of the lunar maria. The post-mare meandering rilles, on the other hand, are sparsely distributed and largely confined to the lunar maria. If due to fluid erosion, this activity was very localized in post-mare time. Localized fluid erosion is also suggested by terrestrial-type valleys on the inner and outer flanks of both pre- and post-mare craters.

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[1] Some investigators prefer the spelling "rill". This seems unfortunate inasmuch as lunar rilles are far greater in magnitude than earthly rills, and almost certainly different in origin.

[2] The term "sinuous" connotes a winding course without technical restriction on degree of sinuosity. Sinuous and meandering, however, are not necessarily synonymous. A meandering course is a sinuous course in which the limbs of many of the repetitive curves are parallel or exceed parallelism. A sinuous course may have meanders only locally. A stream is not generally referred to as meandering if only an occasional curve is meander-like, but is ordinarily so designated if many of the curves are of this character. We shall use the term open meanders for those curves in which the limbs are parallel, and closed meanders for those whose limbs are curved inward toward each other.

It should be pointed out that only the landscape of the near side of the moon is considered because of 1) the abundance of high quality photographs over much of the area, 2) the availability of geologic maps prepared by the U.S. Geological Survey, 3) the availability of lunar charts, many with contours, and 4) the greater expanses of territory not completely cratered. The most comprehensive coverage of the near side of the moon is provided by the Lunar Orbiter IV photography taken in 1967. Although generally excellent, the photos are somewhat blurred in some areas and details are obscured. Thus, general statements on the topography of the near side of the moon are qualified to the extent that perhaps 5 to 10 percent of the area could not be examined in the same detail as the remainder.

SINUOUS RILLES

We are herein concerned primarily with those sinuous rilles whose characteristics indicate the possibility of fluid erosion. Because of inability to distinguish sufficient detail, we will disregard rilles less than two inches in length (about 20 miles at the scale of the Lunar Orbiter IV photographs), and will disregard larger rilles if detail is obscure. A few simply curving rilles have been included because of special characteristics.

The locations of selected rilles, and of areas in which groups of rilles occur, are shown in Figure 1. The areas outlined at localities 1 and 2 are the Aristarchus and Alpine Valley regions within which there are too many rilles to be plotted separately. Elsewhere, large rilles are drawn in completely, and the sites of small rilles or groups of small rilles, are indicated by an X. The Apollo 11 and 12 landing sites are included for general information. Only the rilles of the Aristarchus and Alpine Valley regions are described in detail. The characteristics of all others are listed in Table I.

One of the listed properties is sinuosity. This is expressed as the ratio of the length of the curving channel to either the length of the valley within which it occurs, or - if on a plain - to the length of the line passing through the midpoints of all curves. The sinuosity of a stream with curves having parallel limbs is 1.5. This is considered to be a meandering stream, as are all streams with greater sinuosities. A straight stream has a sinuosity of 1.0. Intermediate types have sinuosities between 1.0 and 1.5. It should be pointed out, however, that meandering streams may have long stretches in which the sinuosity is less than 1.5. The Mississippi River, for example, has a sinuosity of 1.61 for about 288 miles from Cairo, Illinois to Greenville, Mississippi. In the first 25 miles south of Cairo, however, the index is only 1.21; for 33 miles south of Caruthersville, Arkansas it is 1.47; and for 80 miles south of New Orleans it is only 1.06. Lunar rilles, too, vary in sinuosity along their course.

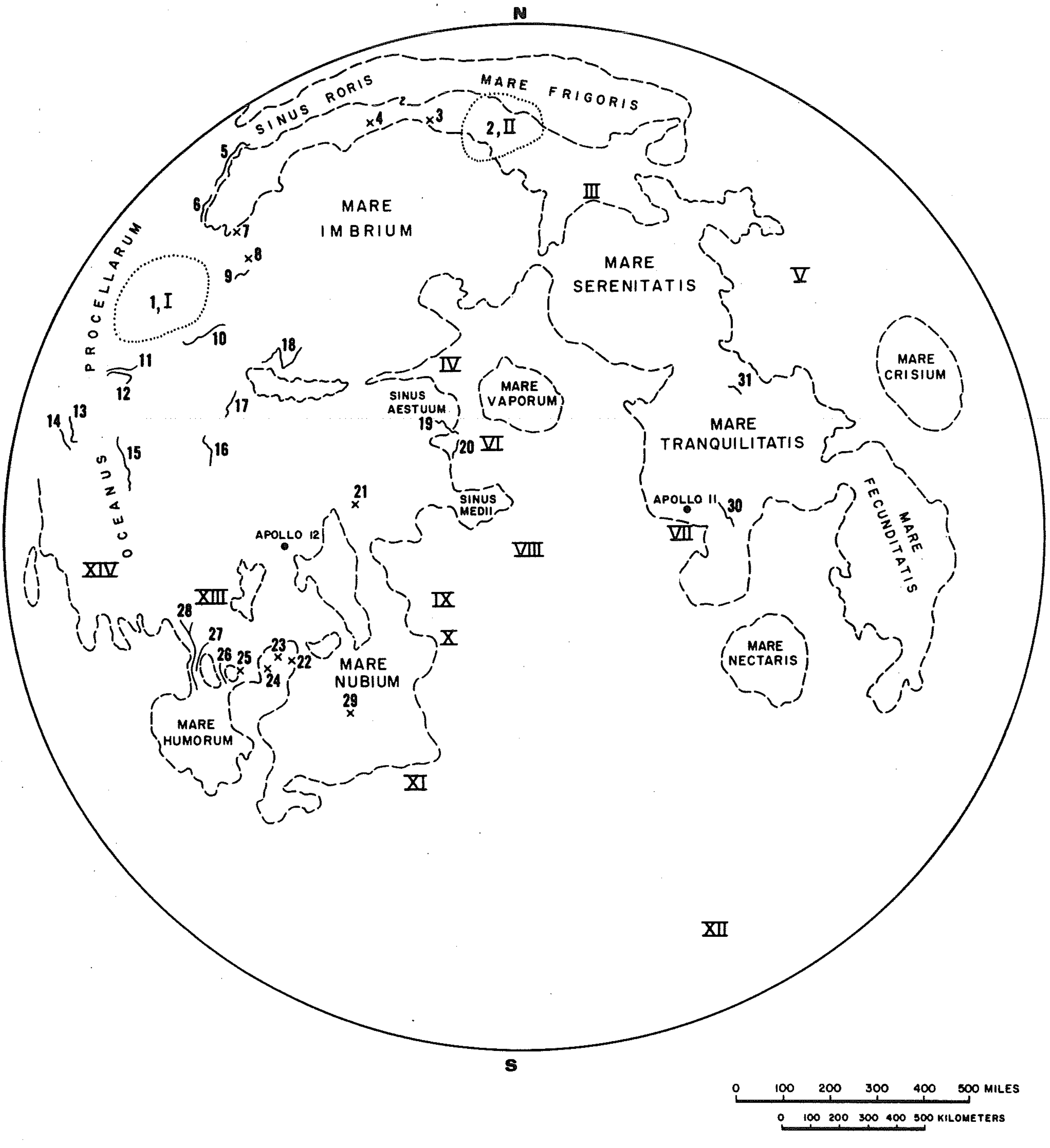

Fig. 1. Map of rille and terra sites. Small numbers, rille localities; roman numerals, terra localities.

TABLE I. CHARACTERISTICS OF SELECTED SINUOUS RILLES

Notes: For location of rilles, See Fig. 1.
LO IV HR: Lunar Orbiter IV High Resolution on photos. Scales 1:600,000 to 1:680,000
Sin. ratio: Sinuosity ratio; ratio of length of channel to either length of valley or length of line through midpoints of curves. Sinuosity index numbers in parentheses.

Rille number, name, or region	LO IV HR photos	Approx length (mi) and sin. ratio	Crater at head	Description Note: LAC = Lunar Aeronautical Chart
1 Aristarchus Region	144,145 150,151 157,158			See text
2 Alpine Region	122,127			See text
3 West Flank Plato	127	40 Trench (1.19) Rille (1.25)	Yes	Curving graben-like trench, about 1.6 mi wide near its head, extending about 18.6 mi to the shore of Mare Imbrium. Width decreases little in this distance, but depth decreases to zero. Trench contains inner rille whose sinuosity only slightly greater than that of trench. Rille continues additional 21 mi largely on mare surface, but close to terra shore. At widest, rille is 2000 ft across, but narrower in some reaches. Termination abrupt, not tapering. At head of trench and rille is double crater each about 2.5 mi across.
4 NW border M. Imbrium	139	a. 25 (1.24) b. 39 (1.06)	Yes Yes	a. Eastern of two rilles. 4300 ft wide at head; narrower downvalley. V-shaped profile. Appears to terminate in small elliptical crater. Crater at head only slightly larger than width of rille. b. Companion rille about 20 mi west. Maximum width about 4600 ft in midcourse. Also deepest here where crosses low ridges. Small crater north end about 1.5 mi across. Rille intersects flat floor of 2.1 mi wide crater at south end.

Rille number, name, or region	LO IV HR photos	Approx length (mi) and sin. ratio	Crater at head	Description Note: LAC = Lunar Aeronautical Chart
5 Rima Sharp	151,158	214	No	One of longest rilles on Moon. Changing characteristics permit division into four sections. Because rille broadens to south, north end will be considered head for convenience in discussion. Headwater section, about 19 mi. long, is the narrowest, only 1000 ft wide in the northwest. Extends between two promontories and sweeps well into intervening bay. Most sinuous of four sections but sinuosity does not approach meandering. V-shape cross profile. Second section, 17 mi. long, double width of first section and low sinuosity. At southwest end hangs above floor of crater about 1.6 mi long. V-shape profile. Third section, starts at same crater with depth equal to that of crater. Uniform promontories. Negligible sinuosity, V-shape profile. Fourth section, about 137 mi long extends south in broad sweeping curve well out from mainland. Shallow, angular U in cross profile. Width of 2600-2950 ft constant for all but one stretch of 16 mi where creases toward south until rille merges with mare surface. Low sinuosity.
6 Immed. S. of Rille 5	151,158	68 (1.16)	No	Sinuosity very low and largely accounted for by a few broad curves in lower half of course. Rille width at limit of visibility at N. end but broadens to 3000 ft. at S. end. Flat floor in lower course. Parallels terra margin touching at peninsulas and filtering behind terra islands. Abrupt S. termination in 2 aligned craters no wider than rille.
7 NW border M. Imbrium	145	40 (1.03)	No	Sinuosity very low. Rille width 1050 ft at S. end but increases to about 2100 ft within 1 mi of S. end. Rille feathers into Mare at N. end. Flat floor near central part of rille.

Rille number, name or region	LO IV HR photos	Approx length (mi) and sin. ratio	Crater at head	Description Note: LAC = Lunar Aeronautical Chart
8. E. Border M. Imbrium	139	25 (1.08)	No	SW end of rille begins in a deep, V-shaped, forked, elongate depression. Rille is shallow relative to the depression and is extremely faint adjacent to depression. Rille straight for about 3.7 mi from depression but sinuosity increases and depth decreases toward NE end. Merges with mare surface at N. end.
9. E. border M. Imbrium	139	110 (1.02 to 1.2)	Yes	Rille heads in irregular shaped crater, about 1.2 mi wide, northwest of Crater Diophantus. It trends northeastward, parallel with the regional slope (LAC 39), in bold arcuate sweeps, containing many true meander-like curves in the western half, sinuosity ratio 1.2 to 1.3, but very low sinuosity (1.02) in northeastern half. Between 10 mi and 47 mi from W. end, rille occupies swale formed by ejecta from Craters Delisle and Diphantus. 2000 ft wide at W. end; gradually decreases in width and depth northeastward and feathers into mare at north end.
10. SE, M. Imbrium	138,144	a. 59 (1.15) b. 181 (1.06)	No	Two rilles head on a wrinkle ridge at N. edge of Crater Brayley. a) Western Rille - 59 mi long with sinuosity ratio about 1.15, locally more sinuous. b) Eastern Rille - Divided into one long and two short distal segments. Main segment more sinuous near crater. Some definite meander-like curves in W. half, east of here sinuosity very low. Sinuosity of distal segments less than main segment.
11. S. of Aristarchus	150	115 (Variable)	No	Intermittent stretches, totaling perhaps 40% of length, sinuosity probably approaches 1.3 or 1.4 with many meander-like curves. Accurate measurement of highly crenulate sinuous course impossible. Crosses two low wrinkle ridges. Fairly constant average width of about 1000 ft but broadens at E. end where merges with mare surface. Very shallow and uniform depth.

Rille number, name, or region	LO IV HR photos	Approx length (mi) and sin.ratio	Crater at head	Description Note: LAC = Lunar Aeronautical Chart
12. Rima Marius	150,157	158 (1.12)	No	For a distance of about 16 mi near tapered western end the sinuosity is considerably greater, probably approaching 1.3. Near head about 3300 ft wide and relatively deep and V-shaped profile. Both width and depth diminish toward W. end where rille pinches out. Extremely steep head. Trend of rille approximately contours slope (LAC 38, 39,57).
13. Central Oceanus Procellarum	157,162	106 (1.03)	No	Moderately sinuous with a few meander-like curves for about 31 mi. from SE end. About 31 mi. from NW end rille bifricates into 2 branches. Each branch in turn locally bifricates. Near SE end about 2000 ft wide V-shaped profile and relatively deep. Width and depth decreases toward NW end where rille pinches out in mare material. Trends subparallel with faint topographic break near SE end.
14. About 50 km S. of #13	157	47 (low)	Yes	Composed of 4 segments which might be continuous but indistinct on photos. Each segment low sinuosity, shallow, U-shaped profile. Segment at NW end very faint, may terminate in elongate depression.
15. E. border Oceanus Procellarum	144,150	140 (1.04)	No	Maximum width near center about 2000 ft. Narrow, shallow, U-shaped profile entire length. Moderately sinuous with meander-like curves in NW 47 mi. NW end terminates in tiny crater, SE end pinches out between two wrinkle ridges. Trend subparallel to east side of long wrinkle ridge (LAC 57)
16. E. of Kepler	133,138	71 (1.08)	No	Intermittent stretches have sinuosity approaching 1.2 or 1.3 with numerous meander-like curves. At N. end straight and crosses wrinkle ridge in moderately deep depression. Near center rille trends through a swale between isolated knobs of terra and from there is moderately sinuous and parallel with terra-mare contact. 18.6 mi from S. end, rille occupies an irregular shaped depression. Maximum width about 2000 ft at N. end, U-shaped profile. Depth and width decrease southward and rille pinches out in mare at S. end.

Rille number, name, or region	LO IV HR photos	Approx length (mi) and sin. ratio	Crater at head	Description Note: LAC = Lunar Aeronautical Chart
17. SW of Montes Carpatus	133	37 (1.1)	No	Rille heads in fan-shaped depression at N. end. Maintains uniform width, about 1600 ft, and depth entire length. Appears to be deflected by knob of terra about 9 mi from S. end. Ends in narrow NW trending, 1.9 mi long depression at S. end.
18. N. of Montes Carpatus	126,133	149 (1.03)	Yes	Low sinuosity. About 1 mi wide in western 35 mi but decreases to 1000 ft at E end. Near center the trend obliterated by several relatively deep elongate depressions. E. half more sinuous with a few meander-like curves. Subparallel to slope around Prom. Banat. E. and W. ends terminate in small elongate crater. May originate near center and tend E. and W. from this point.
19. Rima Bode 1	109	51 (1.15)	No	Trend is subparallel to mare-terra contact within a large reentrant. Moderately sinuous with many meander-like curves throughout entire length. Near W. end rille appears to be controlled for a short distance by a very straight fracture (?) that crosses rille at right angles. E. of this point rille aburptly widens, to a maximum of about 3000 ft, is relatively deep with a U-shaped profile. Decreases in width and depth toward E. Near E. end occupies a swale between terra knobs. Pinches out at E. end.
20. S. of #19	109	39 (1.2)	Yes	Elongate crater at S. end. Rille about 1 mi wide, relatively deep and U-shaped in profile at S. end by decreases to 2000 ft wide and becomes shallow at N. end. Short stretches near center may have sinuosity ratio of about 1.3 or 1.4. Near center occupies double crater, but depth of rille remains constant. At N. end crosses wrinkle ridge in deep V-shaped depression (or gorge?). N. end is about 17 mi from E. end of No. 19. Faint discontinuous depression suggest these two rilles might have been connected at one time.

Rille number, name, or region	LO IV HR photos	Approx length (mi) and sin. ratio	Crater at head	Description Note: LAC = Lunar Aeronautical Chart
21. SE of Copernicus	121	31 (1.04)	No	Low sinuosity. N. end begins abruptly at wrinkle ridge. S. end pinches out in mare.
22. NW border M. Nubium	125	32 (1.02)	No	Very low sinuosity. 1000-1150 ft wide, V-shaped profile entire length. S. end begins in elongate depression. N. end terminates near rim of buried crater.
23. W. of #22	125,132	34 (1.08)	No	Low sinuosity but short stretches with meander-like curves. Occupies reentrant in terra material and is subparallel with terra-mare contact. W. end trends through swale in terra and pinches out in mare.
24. E. border M. Nubium	125,132	29 (1.02)	No	N. end originates in mare material within a partially buried crater. About 5 mi from N. end breached E. rim of buried crater then parallels rim. S. end in mare between knob of terra and wrinkle ridge. Rille entirely in mare material and maintains uniform width of about 1000 ft.
25. NE of M. Humorum	132	32 (1.06)	No	Very low sinuosity. Trend of rille parallels junction of dark mare and light terra material. U-shaped profile, maximum width about 1000 ft. Pinches out at both ends.
26. NE of M. Humorum	137	38 (1.03)	No	Low sinuosity except near north end where a few meander-like curves. Confined to mare. Maximum width of about 1000 ft, pinches out at terminal ends.
27. NE of Crater Garsendi	137	a) 16 (1.01) b) 26 (1.02) c) 48 (1.05)	No	Rille discontinuous and for convenience divided into 3 segments which are, from N to S, a) gently curving very low sinuosity. N. end originates at doming around crater. S. end terminates at N. margin of wrinkle ridge. b) W. end originates at S. margin of wrinkle ridge and separated from (a) by about 1 mi. Low sinuosity but meander-like curves near center. S. end occupies swale between knobs of terra.

Rille number, name, or region	LO IV HR photos	Approx length (mi) and sin.ratio	Crater at head	Description Note: LAC = Lunar Aeronautical Chart
27. continued				c) N. end originates on W. edge of terra knob 7 mi. W. of termination of (b). Low sinuosity but several meander-like curves near N. end. S. one-half of rille sinuosity is very low. U-shaped profiles with maximum width about 2000 ft. Pincjes cout at S. end. Companion to rille #28 and is included here for comparison purposes.
28. E. and NE of Gassendi	137	140 (1.01 to approx. 1.3)	Yes	Sinuosity ratio approaches 1.3 (est.) in N. half but ratio changes rather aburptly to about 1.01 in the S. half. 47 mi. from N. end a very sinuous branch, about 17 mi long, joins main rille at accute angle. N. end of branch rille is in an elongate depression that connects two wrinkle ridges. N. end of main rille connects with a 12 mi E-W trending sinuous rille atop a wrinkle ridge. Just S. of the junction of the branch and main rilles are several features similar to cut-off meanders of earthy streams. Southward the rille extends between two promontories and occupies a wide V-shaped depression through the tip of one of the promontories. From there, the rille crosses a flat mare area and impinges against the E. rim of Crater Gassendi, trends parallel to the rim and pinches out about 14 mi south.
29. Center of M. Nubium	120	35 (1.05)	Yes	Low sinuosity but short stretches have meander-like curves. Locally small craters obliterate rille but craters are obviously post-rille in age. N. end originates in crater which is about 2000 ft in diameter. Pinches out at S. end.

Rille number, name or region	LO IV HR photos	Approx length (mi) and sin.ratio	Crater at head	Description Note: LAC = Lunar Aeronautical Chart
30. S. Central M Tranquilitatis	77,78	83 (1.01 or less)	Yes	Two segments with extremely low sinuosity. Southern segment about 52 mi long with broad sweeping meander-like curve near S. end and obliterated by elongate crater near center. S. end originates at lip of crater. Northern segment originates in double crater. This segment may have been continuous with southern segment. Minor gentle curves near center. This rille may have tectonic origin.
31. NE border of M. Tranquilitatis	78	29 (1.02)	Yes	Extremely low sinuosity ratio. Grossly arcuate in plan with broad meander-like curve near S. end. Maximum width about 1 mi at S. end. Depth and width decreases northward. N. end deflected by very faint rim of mare-filled circular crater(?). May have tectonic origin.

The characteristics of the selected sinuous rilles are summarized below. The numbers correspond to those in Figure 1 and Table I.

Length and Continuity

Lengths vary from the arbitrarily selected minimum of about 20 miles to a maximum of 214 miles (Rima Sharp, No. 5).

Some rilles are discontinuous, consisting of several aligned segments.

Some rilles are interrupted by wrinkle ridges.

Other rilles cross wrinkle ridges without interruption.

Widths vary from 1000 feet to about 4 miles (Schröter's Valley, No. 1).

Widths may decrease progressively with decreasing depth, may increase with decreasing depth, may remain constant for long distances, or may vary along the course.

Depth

Depths relative to width vary from extremely shallow to deep.

Depths are generally independent of length.

Depths may be greatest at one end and shallower toward the other. This change may be independent of variations in width.

Depths may be greatest in midcourse rather than at either terminus.

Depths may change independent of changes in cross-profiles.

Cross-profile

Cross-profiles include both V and U shapes. U shapes may be shallow or deep relative to width.

Cross-profiles may change gradually or abruptly along the course of a rille. Rima Sharp (No. 5) displays abrupt changes.

A few rilles and valleys have an inner rille incised within their flat floors. (Schröter's Valley, Alpine Valley, and Rille No. 4).

Association with Craters

A crater is present at the heads of some rilles, particularly those that rise in terra areas.

Many rilles lack craters at either end. Particularly true of rilles restricted to mare surfaces.

Craters are scattered along the course of some rilles. Their confinement within the rilles suggest a genetic relationship.

Some craters breach the rims of rilles and probably represent coincidental meteoritic impacts.

Sinuosity

Overall sinuosities of the selected rilles is consistently below 1.5, the minimum index for meanders. However, sinuosities indicative of meandering are found along segments of many rilles (See Table I). Some rilles have only isolated meander-like curves.

Sinuosities that can be adequately explained by tensional tearing do not in themselves provide evidence of fluid flow although they do not disprove this. Interlocking meander curves, however, do suggest fluid flow.

The distribution of the sinuous rilles is obviously related to the distribution of the maria. Sinuous rilles, for example, are non-existent within the central highlands and throughout the southern hemisphere below latitude 25° south. A secondary problem concerns the scarcity of sinuous rilles in the eastern maria as compared to the western. These problems are outside the scope of the present investigation. In searching for apparent explanations, however, the possibility was considered that the distribution is apparent rather than real and due to variations in photo quality, to the arbitrary basis of rille selection, and to inconsistencies in the selection procedure itself - for example - in determining which rilles are sinuous enough for inclusion in the map. With a few exceptions on the eastern limb of the moon, the Lunar Orbiter IV photographs are of high quality and can not account for the unequal distribution pattern. To determine whether the arbitrary minimum length of rilles selected presented a true picture of sinuous rille distribution or merely recorded the distribution of large rilles, all sinuous rilles smaller than the cut-off size were counted in the eastern and western halves of the visible face of the moon. The proportions were essentially the same as for the larger rilles. The possibility that photos on a larger scale than the Lunar Orbiter IV photographs might reveal still smaller rilles in a different distribution pattern, is not borne out in the restricted areas covered by the large scale Lunar Orbiter I, II, III, and V photographs. As for the selection of a rille as sinuous enough, in whole or part, to merit the inclusion in the figure, the determining factor was the presence of curves comparable to those in terrestrial channels.

The distribution of sinuous rilles is therefore real, not apparent. The explanation of the unequal distribution must await answers to the problem of the unequal distribution of the maria themselves.

Schröter's Rille and Alpine Rille are discussed in detail on the premise that if fluid erosion can be substantiated for either of these rilles, the probability that it may apply to other rilles will be enhanced.

These two rilles are confined to two well-known lunar valleys, Schröter's Valley and Alpine Valley. The valleys themselves will be described in detail because they provide the setting for the inner rilles and because their origin may have bearing on the origin of the rilles.

Schröter's Valley and Rilles of the Aristarchus Region

Many of the rilles in this region have been given names (Lunar Aeronautical Charts 38 and 39) depending on whether they are more closely associated with the Aristarchus Plateau or with Prinz Crater to the northeast (Fig. 2). All of the former bear the group name Rima Aristarchus and are distinguished from each other by roman numerals from I to VIII. Only two of the rilles associated with Prinz Crater are named: Rima Prinz I and Rima Prinz II.

Schröter's Valley

Prior to the advent of the relatively large scale Lunar Orbiter IV photography in 1967, Schröter's Valley appeared in photographs simply as an unusually large sinuous rille. The Orbiter IV photography, however, revealed the presence of an inner, narrow meandering rille incised in the floor of the valley. To avoid confusion, we shall continue to refer to the larger feature as Schröter's Valley and will reserve the term Schröter's Rille for the inner meandering channel.

Schröter's Valley is a broad flat-floored, steep-sided trough. For the first 10 miles from the crater known as Cobra Head it is 3 1/2-4 miles wide and as much as 4000 feet deep. Its width decreases to about 2 1/2 miles where the valley leaves the slopes of Herodotus and the depth decreases to about half that at the Cobra Head. Its width remains essentially constant for the next 65 miles, although the trench becomes progressively shallower. At the end of this 65 mile stretch, the trough turns westward for 3-4 miles before ending aburptly with very little diminution in width. I shall refer to this westerly termination as The Toe (Fig. 2 and 16). Schröter's Rille, the inner channel, does not turn west into The Toe but continues southwesterly for another 30-35 miles eventually dying out on the mare surface about 10 miles offshore. The overall length of Schröter's Rille is thus about 110 miles exclusive of the sinuous curves. Had the presence of this remarkable rille been known prior to the advent of Lunar Orbiter photography, it might have induced some modification in proposed theories of origin of the valley itself.

Schröter's Valley lies within the Vallis Schröteri Formation of the Aristarchus Plateau. Moore (1965, 1967) has subdivided this formation into several members each of which has different surface characteristics. He believes that the Vallis Schröteri Formation, as well as the deposits of Oceanus Procellarum, consist of volcanic ash flows, ash falls, and lava flows.

The general configuration of Schröter's Valley, exclusive of the inner rille, suggests fracture control. The suggestive evidence includes the angular U-shape cross-profile, the parallel sides, the angular turns in

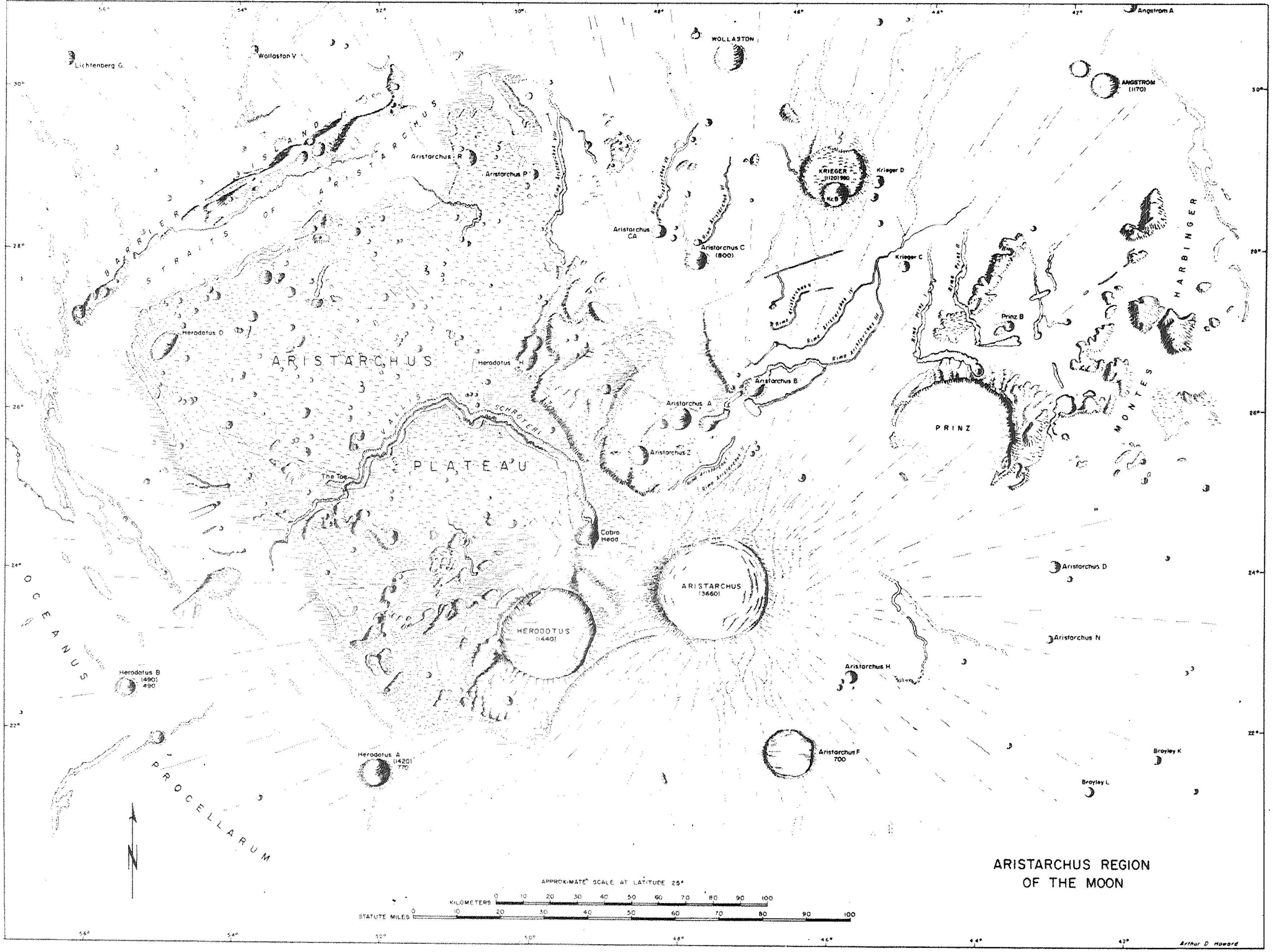

Fig. 2. Physiographic diagram of the Aristarchus region. The interrupted radial lines are rays from Aristarchus. Numbers in parentheses indicate depths of craters below rims. Other numbers indicate elevation of crater rims above surroundings.

parts of its course, and the parallelism of parts of its course with the major fracture directions of the plateau. The simplest fracture explanation would seem to be that of a graben. Although this is probably true, it does seem unusual that the trench should start full-fledged at a crater and diminish in dimensions more or less continuously downvalley. If the graben resulted from the meteoric impact that created the crater, why were not fractures created in other directions as is true of Hyginus Rille (See Fig. 14). Lunar Aeronautical Chart No. 39 shows only one interruption in the downslope gradient of the valley, at a point about 8 miles from Cobra Head. If, however, as mapped by Moore (1965, 67) and concurred in by the writer, the mare-like material forming the flat floor of the trench is later than the trench itself, it may hide an irregular valley floor below. An alternative to the graben hypothesis is that Schröter's Valley started as a simple tension crack and that its flat-floored graben-like appearance is due to the later filling of mare-like material. An original tension crack more than 3 miles wide at the crest would be unusual. Perhaps the crack was narrow at first, but deep enough to accommodate the products of mass movement responsible for its present great width. If considerable widening by mass movements had taken place, however, it is unlikely that the remarkably parallel sides would have persisted. I believe that an origin by downdropping of a sliver of the crust prior to the inner fill is the more likely of the direct fracture origins.

An indirect fracture-control hypothesis of the valley would involve fluid erosion, with the crater as the source of the fluid which at first spilled across the plateau guided by fracture-controlled swales. One difficulty is the abrupt termination of the flat-floored valley at The Toe, whereas the inner rille continues on. Another difficulty concerns the ultimate fate of the vast quantity of material that presumably would have been eroded from the valley. There is no evidence of it at present on the mare surface at the terminus of the valley. We would thus have to assume that the valley is older than at least part of the mare deposits and its debris is hidden under the mare surface. Yet the relative freshness of the trench compared to the worn appearance of the rest of the topography of Aristarchus Plateau suggests recency. This is supported to some extent by the continuation of the inner rille out onto the mare surface. In the author's opinion, the evidence favors the view that Schröter's Valley (not Rille), from Cobra Head to The Toe, is a graben rather than an erosional feature and that it was occupied shortly after formation by the mare-like material which forms its flat-floor. Early filling seems required to explain the preservation of the essentially parallel valley sides. Evidence to be presented later indicates that the amount of time after deposition of the fill was also too short for significant modification of the trench walls.

Cameron (op. cit., p. 2424), in rejecting a fault origin for Schröter's Valley, states that some expression of the responsible faults ought to be found on the upland beyond sharp bends, and the principal directions of the rille ought to be repeated in the pattern of intersecting ridges and valleys in the immediate vicinity. If we consider some of the long reaches of the trench itself, we find that the southwesterly lower course of Schröter's Valley does indeed parallel one of the major inferred fracture directions, although the valley locally deviates from this trend. Small segments of the upper course trend northwest, parallel to a second major fracture direction, but the overall trend is irregular. The situation is no different than that encountered on Earth where fractures do not necessarily conform to a few major trends; considerable divergence is common. Relative to Cameron's comment that evidence of fractures should be visible beyond sharp bends, it might be noted first that the relatively small scale of the photos may conceal subtle fracture traces, and secondly, that the mechanics of faulting may determine whether or not fracture traces are expectable outside the confines of the valley. If, for example, one side of the valley merely pulled away from the other, the resulting fracture might be quite irregular but with little effect beyond the fracture. Or, if the valley subsided as a graben, there need be no significant fracturing outside the trench so formed. Cameron's objections, therefore, do not disprove a fault origin for the main trough of Schröter's Valley. The highly sinuous inner rille, however, unknown until recently, can hardly be attributed to fracture control alone, regardless of how the fractures are arranged or how they were generated.

Prior to recognition of the inner rille, Cameron (1964) had suggested that Schroter's Valley, which descends uniformly to the west, might have been eroded by nuées ardentes-type flows. The material within the valley would presumably represent these pyroclastic deposits. Moore and Cattermole (1967, p. 136) point out that pyroclastics are typically acidic in composition with much higher albedo than that shown by the material within Schröter's Valley. Aside from this, however, the fact that Schröter's Valley terminates abruptly in a blank wall at The Toe, weakens the analogy made by Cameron with the channel of an historic ignimbrite flow in Japan which is open downvalley. Furthermore, if an ignimbrite flow had started on the plateau surface prior to erosion of the vally, why the sharp curves at this level prior to downcutting? As for the inner rille, the possibility of a narrow, stream-like ignimbrite flow following a tightly meandering course on the level valley floor before incision seems even more remote.

Moore (1967) suggests that Schröter's Valley is either a graben or "a channel produced by flow of volcanic material". Based on terrestrial analogs, lava is not an effective eroding agent and hardly capable of eroding deep valleys. If, as seems to be true, the trench material is actually younger than the plateau materials above, then a further objection to an erosional origin whether by lava or any other agency, concerns the fate of the large amount of material that would have been eroded from Schröter's Valley. The amount has been estimated at 100 km^3 (24 miles^3) by Cameron (1964, p. 2428). If the mare surface were already in existence, the products of erosion should have covered it beyond the mouth of the valley. There is no evidence of such deposits. The difficulty might be circumvented by assuming either 1) the debris was scattered thinly and long enough ago to have allowed darkening to the tone of the surrounding mare surface, or 2) the sediments are interbedded with the mare deposits. If Schröter's Valley is a graben, and if it formed later than the mare surface as suggested by evidence to be presented shortly, then the problem of disposing of huge quantities of erosional debris is avoided.

If the valley is in truth a graben, the level trough floor into which the inner rille is incised could conceivably be the downdropped surface of the plateau or a later filling. Moore (1965, 1967) differentiates this valley-bottom material on the basis of its higher albedo from the somewhat similar-appearing plateau material bordering the valley along much of its upper course. He concludes that the trench filling is younger than the plateau material above. In places along the lower course of the valley, the plateau surface is hummocky and quite different in appearance from the smoother, lighter, mare-like material within the trench itself. The contrast confirms that the trench material is not a downdropped segment of the plateau surface, but is younger. A younger age is also suggested by the lesser cratering of the mare-like filling as compared to the superficially similar parts of the plateau above.

If the graben hypothesis is true, there is evidence that the mare-like trench filling was emplaced shortly after the graben was formed. The evidence is simply that there appears to have been insufficient time for mass movements to destroy the parallelism of the valley sides prior to occupation by the valley floor fill.

Moore (1967) interprets the plateau materials as volcanic and believes that the material within the valley is at least veneered with volcanic deposits. The resemblance of the fill to part of the plateau materials above supports this interpretation. That the surface of the fill is not an alluvial surface is suggested by the absence of channels or meander scars. Perhaps the filling is gas-fluidized debris.

Schröter's Rille

Figure 3 is a stereopair of part of Schröter's Valley and Rille prepared from Lunar Orbiter V Photography. The viewer will undoubtedly be distracted by the apparent offsets in relief between adjacent photographic strips. The offsets are due to the electronics of scanning and transmitting the individual strips back to Earth. The viewer should examine the three-dimensional picture within each narrow strip independently of the offset strips above and below.

The meanders of Schröter's Rille are faithful analogs of incised earthly meanders. The meander belt itself, in the few places where it can be measured, is between 1 and 1 1/2 miles wide, and the radius of curvature of individual meanders is 1/2 mile or less.

In incised meandering valleys on Earth, numerous meander spurs are asymmetric, with the steeper slope on the upstream or undercut side, and the gentler, on the downstream or slip-off side. Unfortunately, because of the black shadows on the lunar photos, it is impossible to discern the base of the slopes on the shady side to compare with the slope on the opposide. I am unable, therefore, to say whether any of the meander spurs along Schröter's Rille are asymmetric. Should this eventually be demonstrated, a fluid agency would, in my opinion, be established beyond reasonable doubt.

A few observations bearing on time of formation may be in order. If one carefully examines Figures 3 and 4, he will note that where the inner rille is crowded against the sunlit, southern side of the trench, the trench

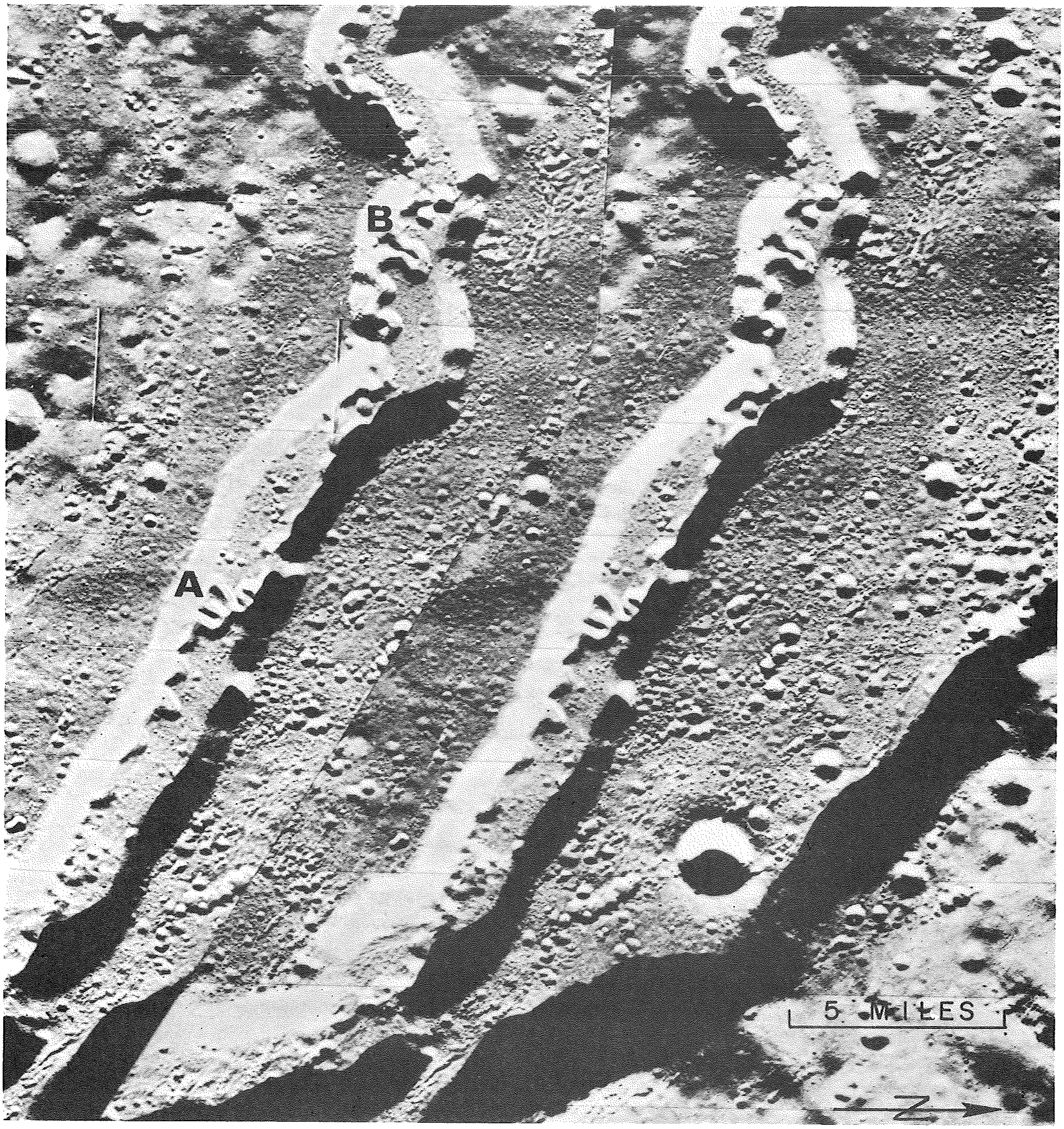

Fig. 3. Schröter's Valley and Rille, Aristarchus region. Note the interlocked meanders at A and B. Note the probable cutoff at A and the incipient cutoff at B. The horizontal framlets are offset vertically as a result of electronic transmission techniques.

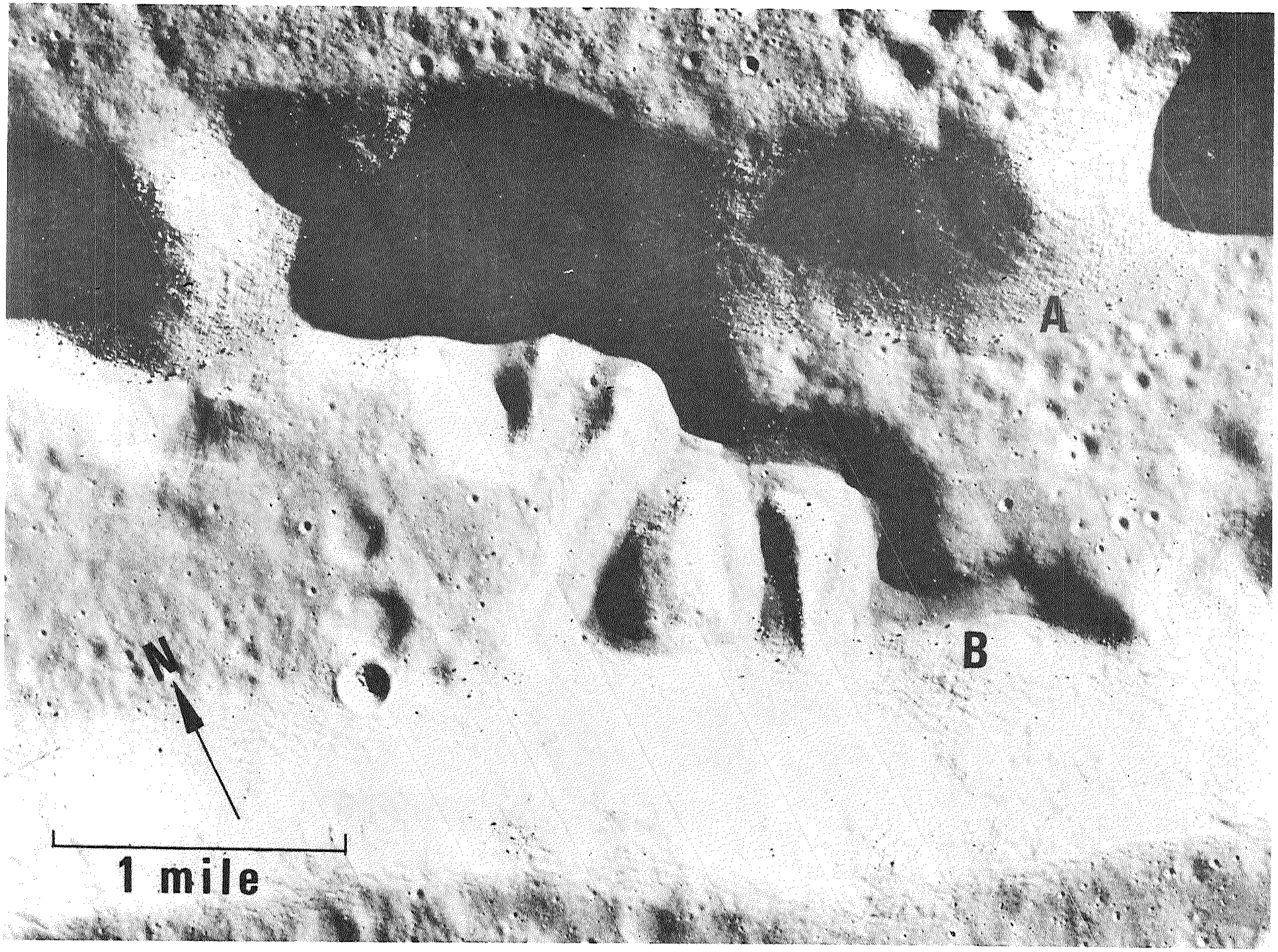

Fig. 4. High resolution view of part of Schröter's Valley and inner meandering rille. Note accumulation of fragments at foot of north slope of valley at A, and encroachment of slope debris into rille channel at B and at tight meander to the left. The encroachment indicates cessation of rille erosion some time in past. The large meander may be completely cut off. High resolution Lunar Orbiter V photograph.

wall seems to truncate the meanders. The effect is not optical, that is, it is not due to concealment by glare of portion of the wall. If one projects with a pencil the probable continuations of the meanders into the light areas, he will find that there should be numerous places around the curves for shadows to outline the course. The truncations of the meanders is an actuality; the valley side actually comes down to, and encroaches into the meanders. Note in Figure 4 that accumulations of rock fragments, including one fragment 100 feet across, occur at the foot of the valley slopes, both where these meet the terrace surface and where they extend to the bottom of the channel. The larger fragments are generally at greater distances from the foot of the slope than the smaller, a situation also true on Earth. It appears, therefore, that incision of the meandering channel took place sufficiently long ago to allow for encroachment of slope debris into the no-longer active channel.

The bedrock exposures upslope may seem to contradict the suggestion of a debris slope, at least for those portions of the southern slope that encroach into the channel. A possible explanation is provided by relations on the north side of the valley. Here bedrock is exposed on slopes only in those reaches where the channel is across the valley, that is, the bedrock slopes descend only to the level of the fill terrace, not to channel level. It seems possible, therefore, that debris slopes occur only where valley sides have been oversteepened by erosion of the channel. As long as the channel was being actively eroded, the bulk of the debris was presumably removed from the foot of the steepened slopes as rapidly as it accumulated, although the large blocks may have had to await comminution. When the agency responsible for channel erosion ceased to operate, the debris from the oversteepened slopes accumulated and encroached into the channel. The same situation probably applies where the channel impinges against the north wall, but the details are hidden in the strong shadows.

Other Rilles of the Aristarchus Region

Within a fan-like area extending northwest to northeast of Aristarchus are eight rilles bearing the names Rima Aristarchus I to VIII, while due north of Prinz are two rilles named Rima Prinz I and II (Fig. 2). Other unnamed rilles are scattered about the region. Although only a few of the rilles may be termed sinuous, some of the others will be briefly discussed because of interesting relationships which may bear on their origin.

Perhaps the most striking feature of the eastern group of Aristarchian rilles (Rimae) and the Prinz rilles to the east is the preferred orientation of certain rectilinear segments clearly indicating tectonic control at least in part (Fig. 5). Tectonic control is also indicated by faint rectilinear tonal lineaments, with the same general trend, that cross the rilles, by similarly oriented linear trends in the upland northwest of Aristarchus, by rectilinear segments of Schröter's Valley to the southwest, and by the angular patterns, on a smaller scale, of the walls of some of the rilles such as Rima Prinz II and Rima Aristarchus V. A second tectonic orientation in the rilles is less obvious, consisting of straight reaches up to several miles in length oriented northwest-southeast, approximately at right angles to the more prominent northeasterly trend. This northwest trend is prominently represented by the scarp trending southeast from

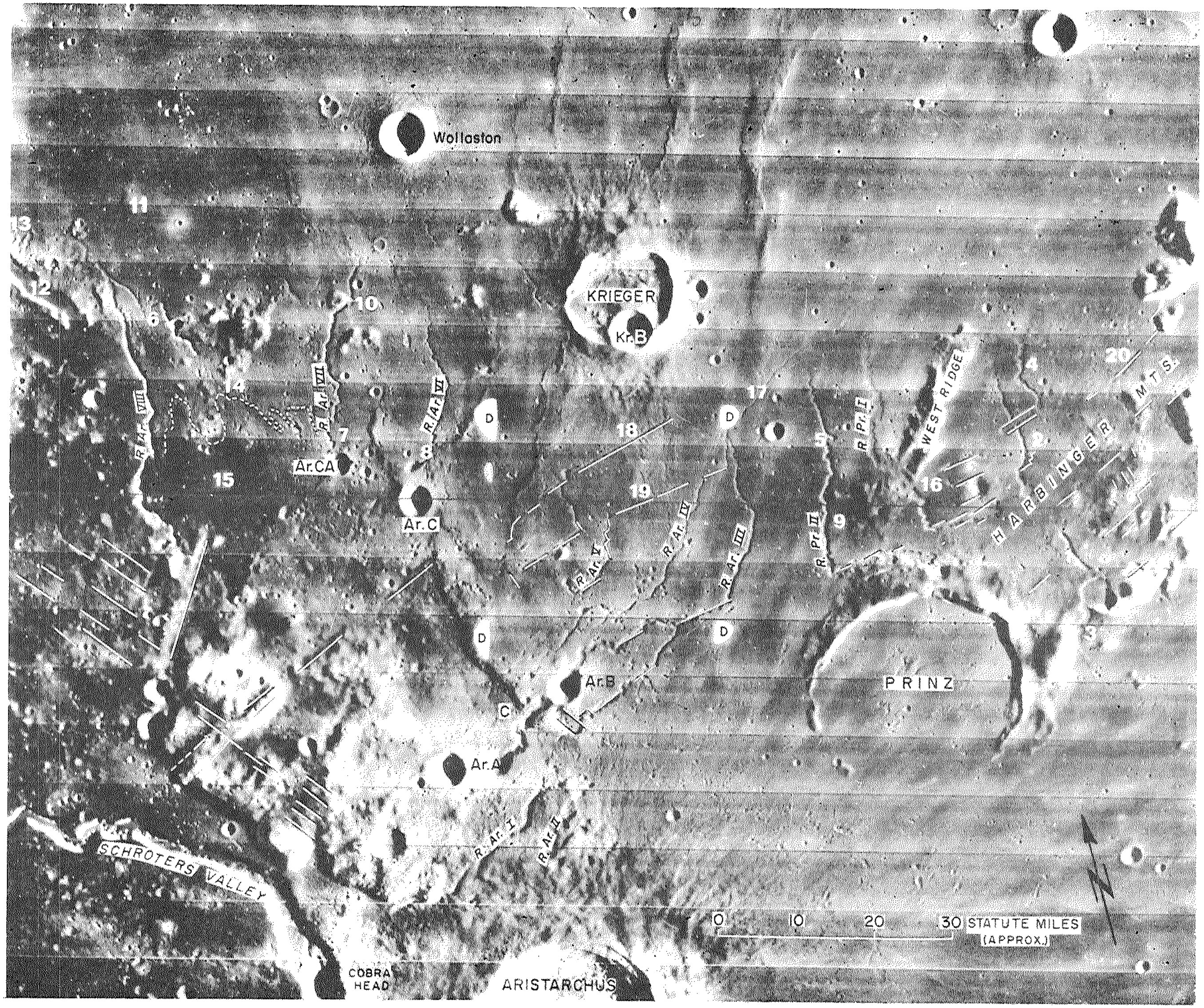

Fig. 5. Rilles of the Aristarchus-Prinz region. Numbers and letters refer to localities discussed in text. White areas labelled D are defects in the photograph. Lines indicate fractures less obvious than those represented by major scarps. R-Rima; Ar - Aristarchus; Pr - Prinz.

Aristarchus C and by the bold scarp northeast of Schröter's Valley (Fig.2). Numerous parallel, but less obvious lineaments are present both in the Aristarchian upland as well as in the adjoining maria. Because of the regional curvature of the fracture trends, their exact compass directions change laterally. In general, however, both directions accord with the rectangular outlines of the Aristarchus plateau as a whole. A third tectonic direction, north by northeast, may be indicated by rectilinear segments in some of the rilles but the indications are not as convincing as the others. The north wall of Rima Prinz I, immediately north of crater Prinz, is angulate in pattern and clearly indicates control by the fracture sets described.

The variation in the types of rille heads is interesting. Rima Aristarchus I is a gently curving linear depression without any clear crater at its head and shows no obvious tendency to narrow or become shallower in one direction or another. A short rille at 1 (Fig.5), northeast of Prinz, is also of this type. The rilles at 2 and 3, northeast of Prinz, as well as Rima Prinz I and the southern branch of Rima Aristarchus III, start at flat-floored depressions of different shapes. The flat floor of each of these depressions, except that at the head of the south branch of Rima Aristarchus III, continues down the rilles to varying distances. The rest of the rilles in Figure 4 appear to start in or next to craters.

Many of the rilles become narrower and shallower away from their source (ex. Aristarchian rilles III and IV), others become broader (ex. Rima Prinz I and the rille at 4). Those that become broader have flat floors to their very ends, whereas those that become narrow, are V-shaped toward their terminus.

Practically all of the rilles of Figure 5 are sinuous to some extent but most of the curves are of the open type and are as easily explained by tensional tearing of the crust as by other processes. There are exceptions, however. The curve at 5 (Fig. 5 and top of Fig. 6) is more like an incised meander than a fracture feature, as are the meanders of Schröter's Valley. A few of the rilles have interruptions along their course. This is true of the eastern tirbutary of Rima Aristarchus VIII at 6, of Rima Aristarchus VII at 7; of Rima Aristarchus VI at 8, and perhaps one or two other less obvious sites along other rilles.

A different type of interruption occurs along the rille north of the number 2 in Figure 5 and just to right of the center of Figure 6. A segment of the surface has obviously dropped down here, yet only the faintest trace of a channel is recorded in the graben even in the Lunar Orbiter V photographs (Medium Resolution, Frame 189). A possible explanation is that the graben was subsequently flooded by material which effectively conceals the rille. The significance of the faint channel-like trace across the floor of the graben is not clear. It is unlikely that it is a true channel since it can not be traced into the flat depression at the head of the rille. Perhaps a recurrence of fracturing is indicated. If so, the fracture is traceable within the rille for several miles north and south of the graben. The material of the flat-floored depressions at the heads of some of the neighboring rilles may also be a later filling.

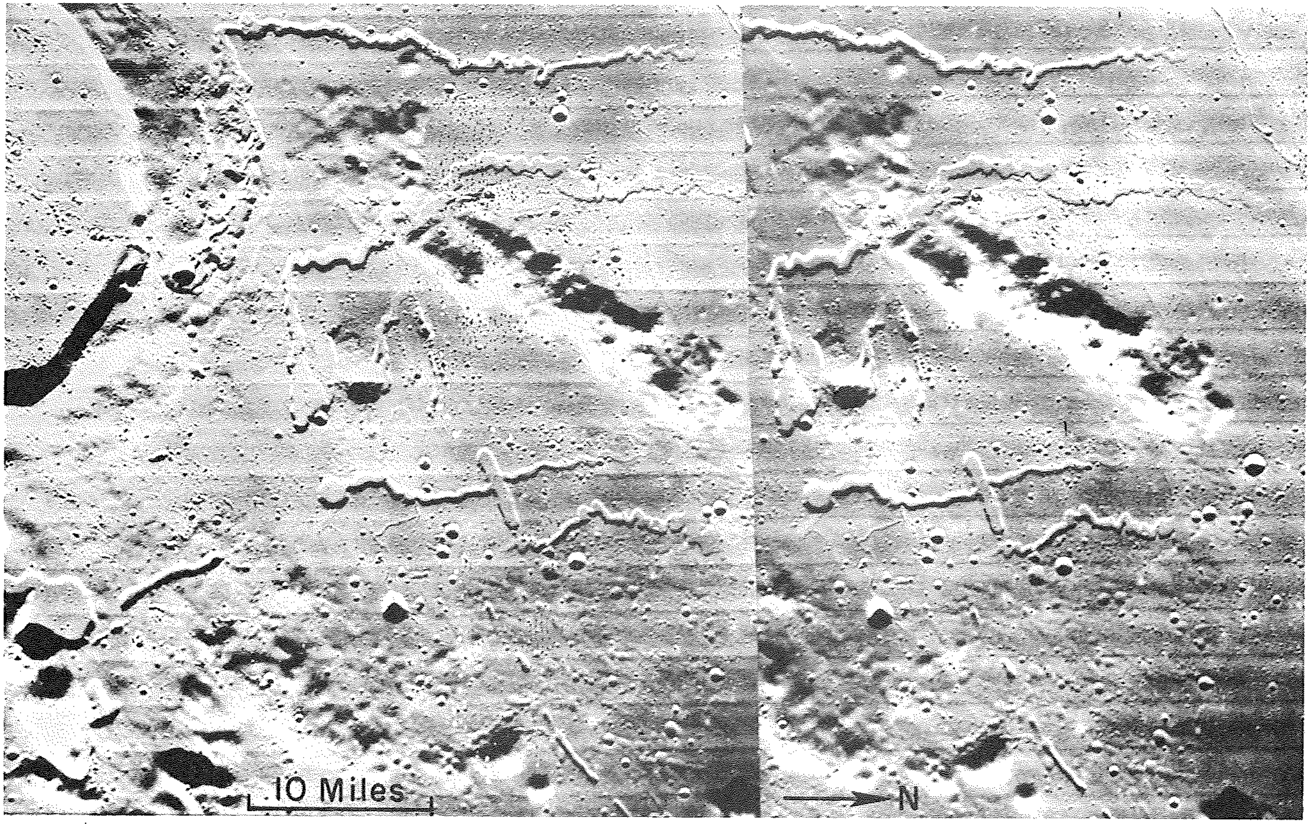

Fig. 6. Rilles of the Prinz region. Crater Prinz in upper left. Harbinger Mountains to north and northeast. For names of features refer to Figure 5. Rectilinear segments and angular turns indicate fracture control of many rilles. Note 1) isolated meander in uppermost rille (Rima Prinz II), 2) transection of the terra ridge (West Ridge) by next Lower rille (Rima Prinz I), 3) spatula-like depression along course of third rille from top with faint rille crossing floor of depression, and 4) broad terminations of some of rilles.

A few additional observations within the area of the figures are worthy of note. Frame 189 of the Medium Resolution, Orbiter V photography clearly shows a terrace within Rima Prinz II at locality 9 (Fig. 5) and at the top of Figure 6. This one occurrence, however, provides little basis for speculation on its origin. At locality 10, debris from a circular hill (volcanic dome?) has spilled into Rima Aristarchus VII indicating that this rille at least is not the latest landform in the area. Another dome appears at 11, near the terminus of Rima Aristarchus VIII. At locality 12 is a textbook example of a graben while at 13, an intricately embayed shoreline appears. The broken line at site 14 outlines a faint pattern, best seen under magnification, which represents the lobate fronts of earthly lava flows. The dark area to the south at 15, the so-called Woodspot, may be a lava plain. Note that Rima Prinz II cuts across West Ridge of Harbinger Mountains at locality 16. If a fluid origin of the rille were established, we might be justified in examining the possibilities of superposition or antecedence. Both of these possibilities require long-term, even though intermittent erosion, and the superposition theory, in addition, would require evidence of a higher surface from which superposition occurred. The alternative is that a low place existed here that offered no obstruction to fluid passage.

About 7 miles north of the junction of Rima Aristarchus III and IV (site 17), the combined rille splits with a smaller distributary taking off to the north. At the point of departure, the distributary hangs above the main channel. About 3 miles down this distributary there appears to be another distributary splitting off from this branch and there may be still another near its terminus. The main distributary is interrupted in at least two places by small swarms of craters indicating that the distributary, if due to fluid erosion, has not recently been eroded. The distributary rille pattern is reminiscent of that on fans and deltas on Earth, but no evidence of associated deposits is visible. Nor is there recognizable evidence of deposits at the termini of the other rilles in this region including those (ex. Prinz I and II) that retain full width to their termini.

The presence of distributary rilles is, of course, inconclusive as far as demonstrating fluid flow. The writer has observed similar distributary patterns in sinuous tensional cracks in cement and concrete (Fig. 7).

The rectilinear cross rilles at 18 and 19 (Fig. 5), and the interrupted rille at 20, are clearly fracture controlled but the exact mechanism by which they were created presents a problem. In the absence of recent fluid erosion - and there is no evidence of such in these three rilles - the furrows may represent either open cracks resulting from tension at the surface, or narrow collapse features resulting from tension below the surface. The remarkable linearity for great distances suggests the possibility of strike slip faulting, although there is no independent evidence of this. The broad interrupted rille at site 20, with the abrupt terminations at both ends of each segment, is reminiscent of collapse features above buried faults. In a sense, its segments are small narrow replicas of the spatula-like graben along the rille at locality 2. If strictly due to tensional tear at the surface, we might expect each segment to have tapered rather than abrupt ends. The floors of many rilles

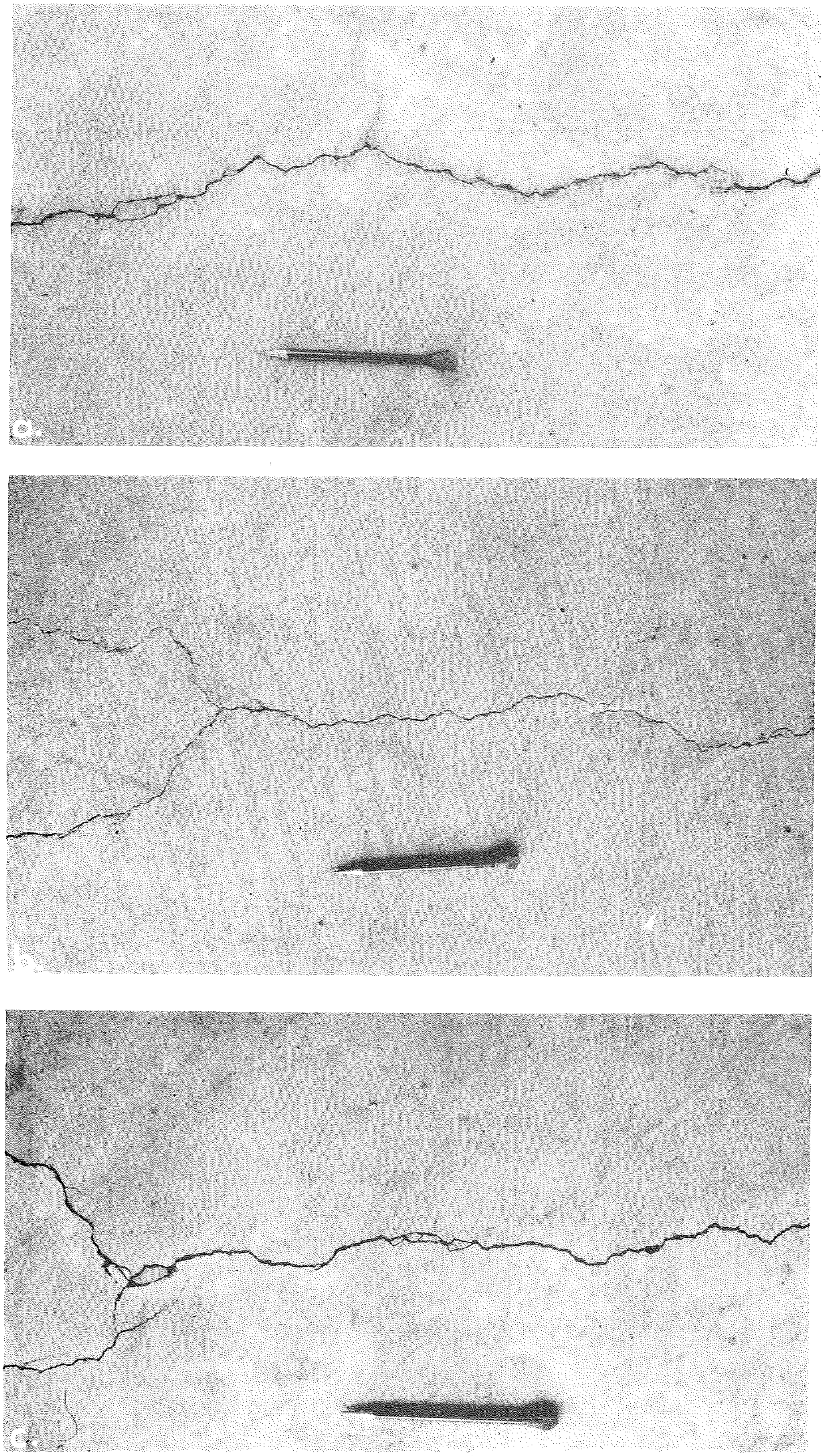

Fig. 7. Tension cracks in cement. a. This crack has the highest sinuosity ratio (1.06) of the three shown. Note local braiding and right-angle tributary. b. Acute angle tributaries. Note overlapping offsets along main crack and lower tributary. c. Tributary feathering out toward main crack. Local braiding. None of dozens of cracks observed show meander-like curves.

are occupied by mare-like material similar to that in many broad depressions. A broad sinuous rille (3, Fig. 5) extends southward from such a depression. Although 4000-5000 feet wide, the rille is only about 8 miles long to the point where its floor merges with the mare surface beyond. The impression is strong that the depression and rille were once considerably deeper, that the rille once had a much greater length, but that mare material, perhaps both from the depression at its head and the mare basin beyond, flooded the rille and submerged its lower course.

The situation here may provide a possible explanation for the contrast in terminations of sinuous rilles. Those that decrease in size and feather out on the mare surface are V-shaped, at least in their lower courses, and mare-like material does not extend to their terminuses. Fluid erosion prior to filling of their upper reaches may be indicated. This suggestion would be enhanced if we could find evidence of fan-like deposits at the channel mouths. Such deposits have not yet been identified. The sinuous rilles that retain full width to their ends, such as Rima Prinz I and II, display a mare-like filling throughout their length. This material, therefore, may conceal erosional debris at the channel mouths, and may itself be difficult to detect on the mare surface if it is identical in characteristics and origin to the mare materials. If the rilles antedate the latest mare deposits, the latter may bury earlier erosional deposits.

A number of other sinuous rilles in the Aristarchus region outside the area of Figure 5 merit brief consideration. Several of these are shown in Figure 8. The broad, deep, rapidly tapering rille south of Aristarchus R reveals clear evidence of fracture control in the sharply angular bends in the valley in the east-west section of its course and the fact that the two walls dovetail exactly. Within the upland, and for a short distance beyond, the rille is essentially V-shaped in cross profile, but the profile changes to a progressively shallower channel out toward the terminus. The rille, which is about a mile wide at its head, starts abruptly within a mile of a crater approximately 1 1/2 miles in diameter. The rille displays no details that demand consideration of an origin other than tensional, but the abrupt beginning, and the distribution of the tensional loci present problems. The rille pattern in the upland, if tensional, would seem to require a foundering of the area within the main bend of the rille, but why the abrupt head? Perhaps the head actually is a small crater, no wider than the rille, from which a fluid moved down the rille. If so, why no modification of the angular valley-side projections in the east-west section? Could the downwarping have torn the head of the rille apart by strike-slip movement along the lineament expressed by the wrinkle ridge in the Straits of Aristarchus and its more subtle continuation on land. It is obvious that we can only present problems here; there is no basis for answers. There are many other lunar rilles with abrupt heads where no trace of associated lineaments have been observed.

The most interesting of the rilles in Figure 8 is that at the foot of Barrier Island and which, for convenience, we will refer to simply as

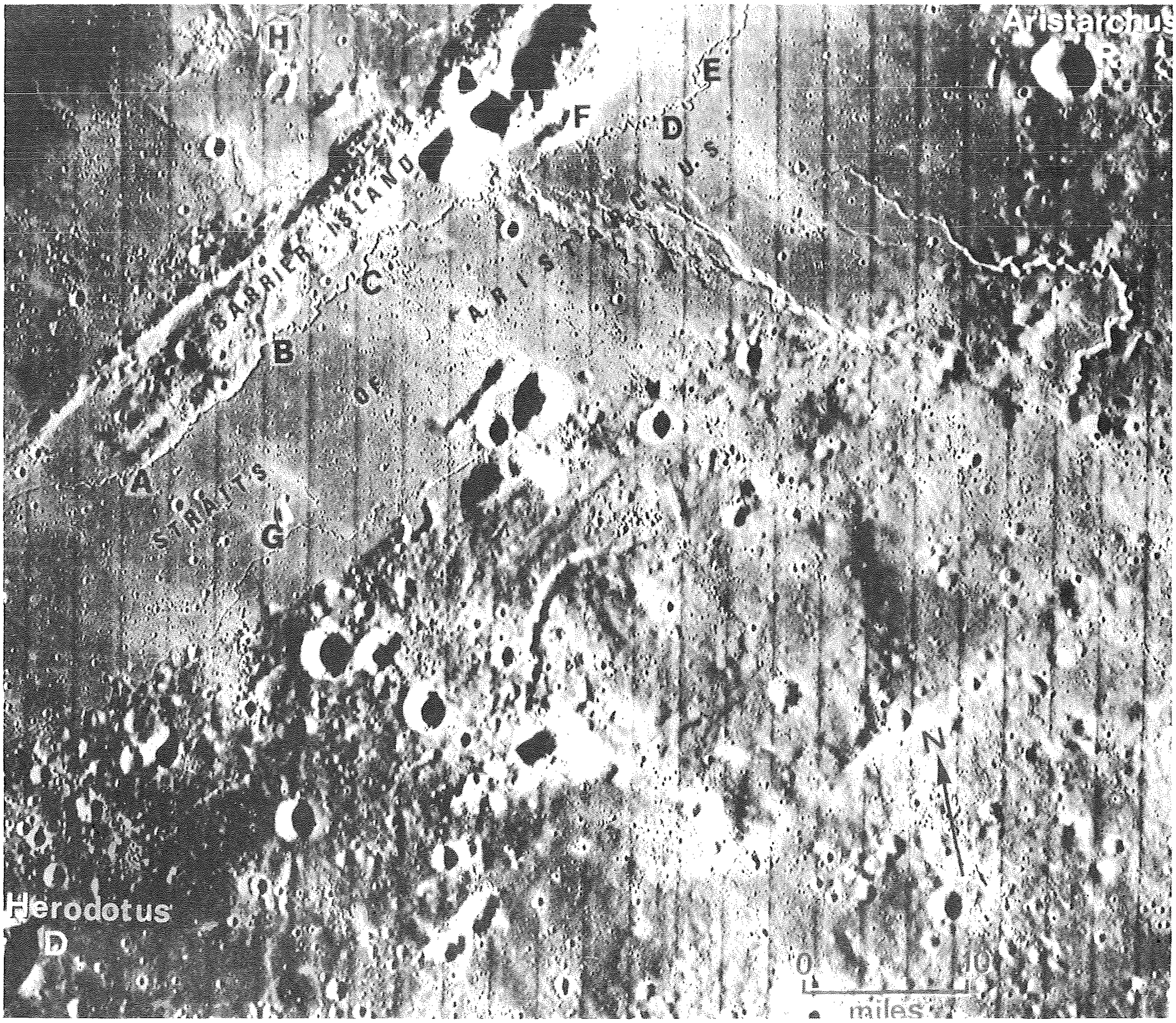

Fig. 8. Rilles of northwestern portion of Aristarchus region. The long sinuous rille at the foot of Barrier Island shows interlocking meanders from B to C and D to E. The rille actually consists of two separate rilles, one extending north and one extending south from the prominent wrinkle ridge. For description of other rilles, see text.

Barrier Rille. This 60-mile long feature, which extends beyond the limits of the figure, is interrupted only at the wrinkle ridge that crosses the Straits of Aristarchus and at site F where slope debris has apparently crowded into the rille. The rille hugs the base of Barrier Island for about 10 miles between A and B and for about 3 miles at locality F. The rille feathers out at both the northern and southern extremities (Fig. 2) but for most of its course appears to be fairly constant in width and depth. At its north end it seems to terminate in a small, faint crater; at its south end, it turns westward through an interruption in Barrier Island and dies out immediately on the far side.

The rille cannot be traced across the wrinkle ridge in its mid-course. Perhaps the ridge came into being later and dismembered the rille, aided perhaps by the creation of the clusters of small craters in this area. Or, conceivably, we are actually dealing with two rilles which have their sources at the wrinkle ridge and flow away from each other. This might explain the tapered ends to the north and south. Although there is a crater about 500 meters in diameter on the south side of the wrinkle ridge immediately adjacent to the source (?) of the southern rille, there is only a cluster of smaller craters at the source (?) of the northern rille. Lunar Aeronautical Chart No. 38 shows the wrinkle ridge as a divide across the Straits of Aristarchus with the terrain sloping away to the north and south. Thus, the general topography seems to support the suggestion provided by the tapered termini of the rille to the effect that we are dealing with two rilles heading, full-fledged, at the wrinkle ridge.

It is unlikely that the rille can be explained throughout its length as a simple tensional crack because of the interlocking meander-like curves between B and C, and D and E. Fluid erosion or fluid modification of a ragged fracture, seems indicated. The intersection of the eastern fault of Barrier Island and the line of weakness suggested by the wrinkle ridge may have provided the avenue of escape for fluid from below. That the wrinkle ridge may follow an en echelon set of fractures is suggested by northwest-southeast offsets along its course.

In those places where the rille hugs the slopes of Barrier Island, a tensional fracture seems indicated. If fluid actually emerged at the wrinkle ridge, perhaps it followed tectonic lines wherever these were available. Another curving rille appears on the opposite side of the Straits of Aristarchus (Figs. 2 and 8,G). It has no tight curves hence could be a simple tensional crack. This is supported to some extent by the interruptions along its course and the rectilinearity of its northernmost segment. If these two parallel rilles are directly or indirectly related to faults, the broad intervening tract, Straits of Aristarchus, may represent a pre-mare graben.

There are a number of other curving rilles in the Aristarchian region but these add nothing to the problem of genesis. One of the larger appears just southwest of the center of Figure 8. It is short relative to its breadth and depth, and - whether by design or accident - has a crater at its head. It shallows to the north, but there is little indication of narrowing. It appears to be a simple graben that was either 1) caused by the meteorite impact that created the crater, 2) happened to terminate in a crater at one end, or 3) that had a "blow-out" at one end. There is no reason to suspect a fluid agency in view of the abruptness with which the feature terminates.

Another similar curving rille occurs on the plateau northwest of Herodotus (Fig. 2). It rises in a crater and continues generally northward for 16-18 miles. It is interrupted in midcourse by a pair of overlapping craters whose rims block the rille indicating that the craters are post-rille. North of the craters, the rille diminishes steadily in width and depth until it is lost in the plateau surface. Although it shows no meander-like curves, it resembles Schröter's Valley in that its source is in a crater and it tapers out toward the distal end.

The rille at H in Figure 8 is a broad, angular, parallel-sided, flat-floored feature probably of tectonic origin.

In the far west-center of Figure 2 is an interesting curving rille with many small rimless craters along its course. A reasonable interpretation is that the craters are gas vents along a tensional fracture, a common situation on Earth.

In brief, the rilles of the Aristarchus-Prinz region vary in characteristics and probably in origin. A few, including Schröter's Rille, seem to require a fluid medium, others are obviously tensional fractures, and still others may involve fluids whose paths were in part fracture controlled.

Alpine Valley and Rilles of the Alpine Region

Alpine Valley

Alpine Valley (Fig. 9) extends some 90 miles across the Alpine range from Mare Frigoris on the northeast to Mare Imbrium on the southwest. Its trend is about N 60°E. For convenience in description we shall refer to the opposite sides of Alpine Valley as the north and south sides rather than northwest and southeast sides. The valley is a steep-sided trough with a maximum width of about 9 miles in its midcourse and averaging 5 to 6 miles for the greater part of its extent. Starting about 20 miles inland from Mare Frigoris it grows shallower and narrower in that direction. It dies out about 5 miles from Mare Frigoris while still about 2-1/2 miles wide. In the Mare Imbrium direction, it pinches to a gap, herein referred to as The Collar, 25 miles northeast of the broad midpoint. The valley then flares abruptly to a width of 8 or 9 miles in a distance of only 4 miles, finally terminating at a constriction in the mountain mass which we shall refer to as The Gorge. There is no evidence of a valley floor in this 4-5 mile gorge. Beyond the gorge is the embayment of Mare Imbrium referred to herein as Alpine Bay. The overall length of Alpine Valley, if we include Alpine Bay, is about 100 miles.

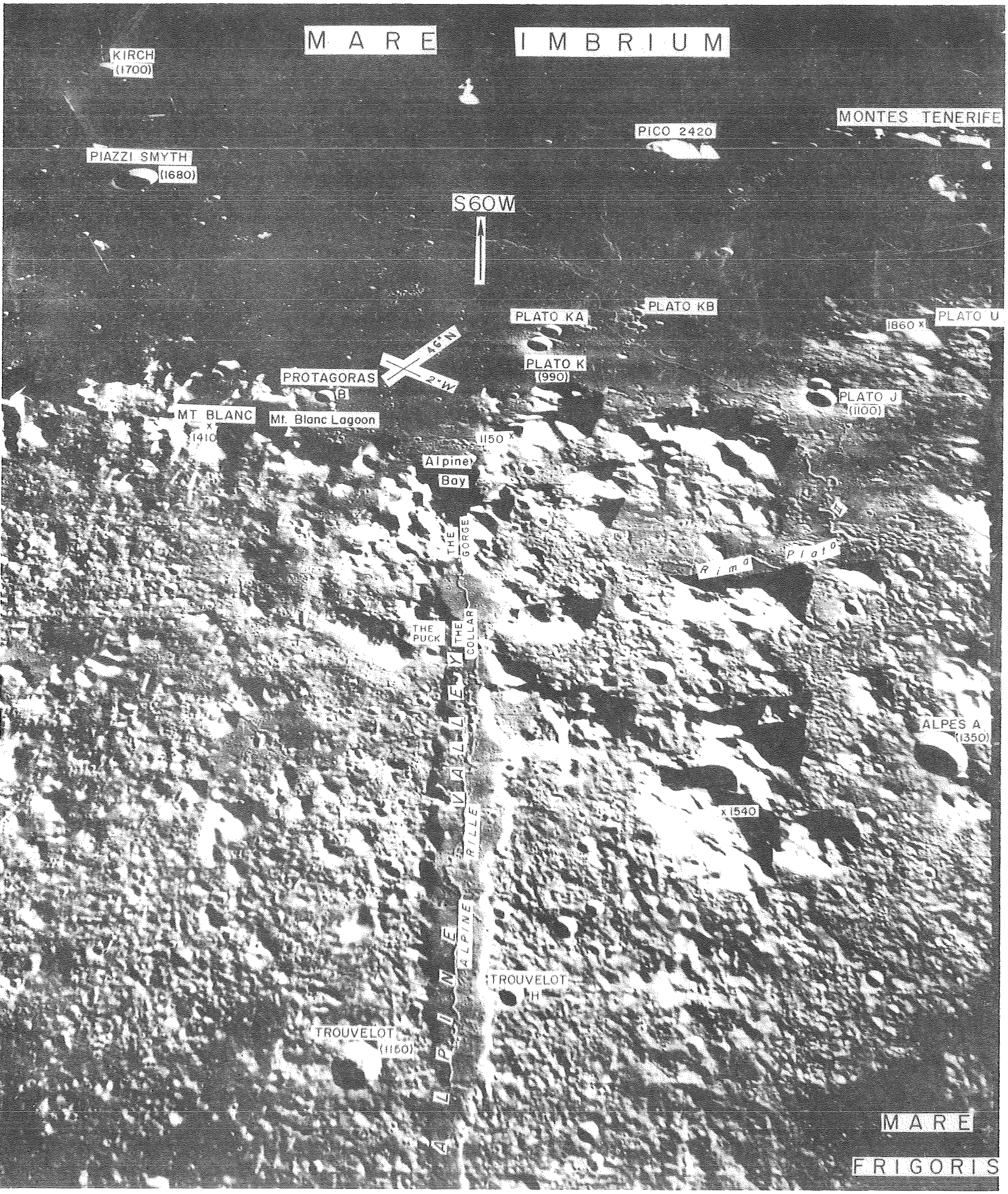

Fig. 9 Oblique view of Alpine Valley region. Note contrast between massive angular mountain blocks and knobby plateau. For fracture patterns, see Figure 11.

The floor of Alpine Valley, exclusive of the inner rille, is essentially flat. It consists of dark mare-like material with a considerable sprinkling of small craters most of which are 1/4 of a mile or less in diameter. The largest clearly discernible crater is about 1 1/2 miles across, but there are only a few that exceed 1 mile in diameter.

The north side of Alpine Valley is somewhat more sinuous than the south side, with several large scallops. It is much smoother in detail, however. The south side reveals about a dozen narrow peninsula-like projections extending as much as 4 miles into the valley. Most of these extend obliquely into the valley in a northerly direction. If one neglects these peninsulas, the south side of the valley is remarkably rectilinear with only a slight bow outward. A few of the peninsulas just upvalley from The Collar seem to separate craters along the south wall, suggesting the possibility that the peninsulas are rims between contiguous craters. There is little or no evidence of rims on the valley floor, however, so that the rim explanation is not entirely convincing. Certainly many of the peninsulas further northeast can not be so explained; they do not appear to be associated with craters.

In the broadest part of the valley, an isolated hill about a mile across at the base, rises above the valley floor at a distance of 2-3 miles from the south wall. A much smaller hill is about 5 miles to the northeast, within 2 miles of the north wall.

The valley-floor mare-like material meets the south and north walls in sharp contact. It intimately embays the reentrants between the peninsulas of the south wall. Clearly Alpine Valley had essentially its present configuration prior to the mare-like filling; the south side had long descending spurs whereas the north side was mildly sinuous without notable spurs.

The occurrence within Alpine Valley of mare-like material apparently identical to the surface materials of Mare Imbrium in both albedo and low frequency of large craters, suggests that Alpine Valley is older than at least the last phase of Imbrium filling.

It has been suggested (Fielder, 1965, p. 107) that Alpine Valley follows a left-lateral (sinistral) strike-slip fault. The principal evidence presented is the apparent offset of the range front at the mouth of the valley, an offset said to amount to 32 km (20 miles). Other evidence cited consists of "two horst lineaments ... displaced sinistrally for 20 km; and a short dip-slip fault - probably of recent origin - bends across the Valley ... in a manner that can be explained if it developed during a phase of sinistral movement along the axis of the valley". None of the modern large scale photographs of this region were available at the time of Fielder's comments. Examination of Lunar Orbiter IV and V photos fails to verify the observation on the displaced horsts and the dip-slip fault. On the assumption that the mountain front was displaced sinistrally 32 km (20 miles), the situation prior to the displacement has been restored in Figure 10,B. Note that the restoration, except along the Imbrium shore, results in a poorer fit of the northwest-

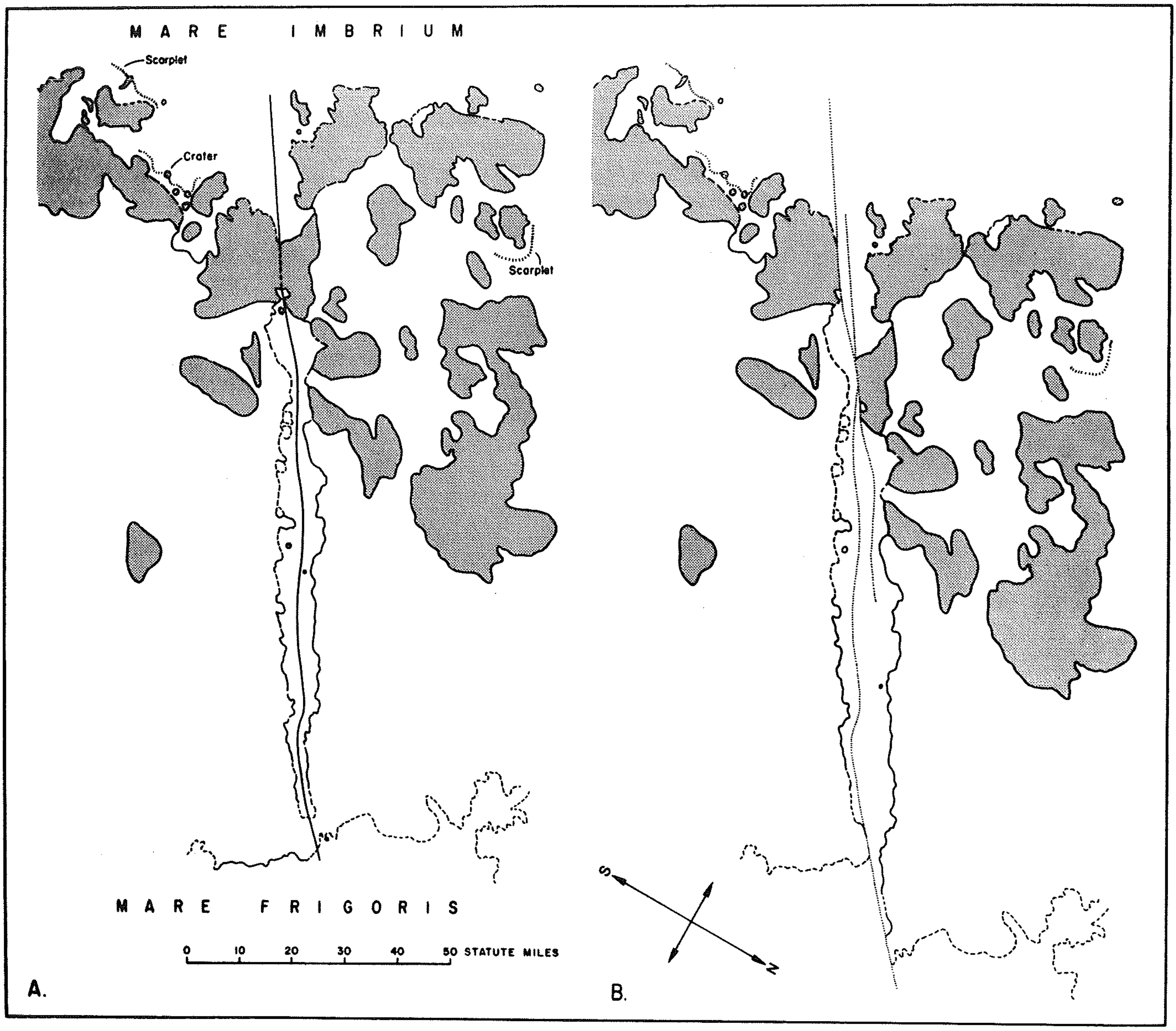

Fig. 10. Diagram illustrating proposed strike-slip displacement along Alpine Valley. A. Present distribution of mountain masses north and south of Alpine Valley. A left-lateral offset of 20 miles has been suggested. B. Distribution of mountains masses prior to suggested offset. Note poorer fit of mountain groups and offset of Mare Frigoris coast.

trending mountain groups than before, and the shoreline on the Mare Frigoris side is now offset. Note, too, that even though the assumed offset at the mouth of Alpine Valley is eliminated by the restoration, an equally prominent offset in the mountain front still remains some 20 miles to the south. The width of the valley in the restored version appears greater because no attempt was herein made to close the spaces resulting from the movement along the necessarily curvilinear fault. If we assume a shear couple to have been responsible for the strike-slip movement, these openings would, of course, be closed.

Thus there appears to be no convincing evidence of the suggested strike-slip movement. There is, however, convincing evidence of dip-slip faulting in the region. Probably the most striking evidence is afforded by 1) the "precipitous" front of the Alpine Range overlooking Mare Imbrium, particularly in the area south of Alpine Bay, 2) the remarkably linear trend of the scarp, and 3) its planar faces descending toward Mare Imbrium. These characteristics suggest a major dip-slip fault which will be referred to for convenience as the Mount Blanc Fault (Fig. 11). The Mount Blanc Fault appears to truncate the obliquely trending mountain groups inland and these same mountain groups are probably truncated by a major fault at their north end, a fault parallel to Alpine Valley. Between the Mount Blanc Fault and Mare Imbrium, is a discontinuous belt of mountains up to about 25 miles wide. The segment of the belt north of Alpine Bay in particular is rectangular in shape and clearly divided into segments by fractures parallel to the Mount Blanc Fault. The trends of the fractures are indicated by straight and planar scarps, and by tonal traces with the same orientation crossing the individual mountain masses. The north end of this rectangular mountain area is sharply truncated along a line roughly parallel to Alpine Valley, almost certainly the site of another major fault. A fault scarplet encircles the northeast corner of the block. The mountain groups farther inland also terminate approximately along this line although the presence of a parallel fault is possible.

The segment of the belt south of Alpine Bay is smaller and more ragged than that to the north but the same preferred orientation of trends is visible. Locally, there is an even more pronounced blocky topography than in the northern segment.

In seeking an analogy for these major topographic configurations, one need only turn to the margins of some of the large craters, such as Copernicus, or to the margins of other circular mare. Many of the craters show clear evidence of peripheral faulting with concentric segments which have been downdropped in progressively greater amounts toward the center of the depression. The downdropping is not uniform, however; some parts of an arcuate sliver may hang back at higher levels, other portions may subside to considerably greater depths. Backward rotation during downdropping of mare margins may account for flooding between the crest of the subsided block and the main scarp, or the fragmentation of the block during subsidence may provide low areas for flooding. Thus, farther south, along the southeast shore of Mare Imbrium northeast of Crater Eratosthenes, a long rugged sliver of land lies, like an offshore

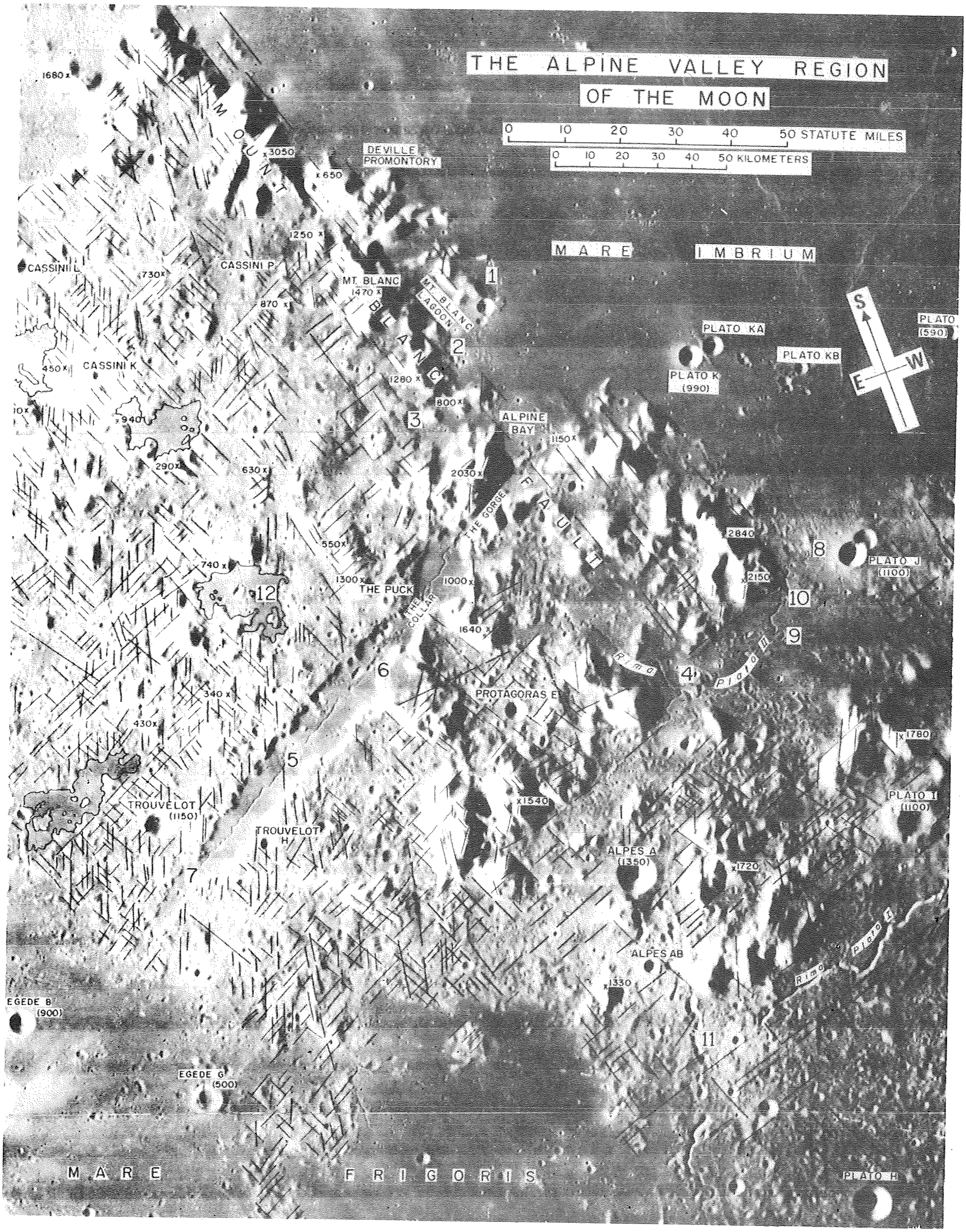

Fig. 11. Fracture patterns of the Alpine Valley region.

bar, some 15 to 20 miles off the bold Apennine coast (Fig. 12). Except for a few much smaller elongate islands, it is separated from the linear scarp of the Apennines by a broad lagoon of mare material. Local offsets of the coast appear to be due to intersecting faults, as suggested by the angular offsets of the faceted mountain front. Supporting evidence for a fault origin of this segment of the Apennine coast is the presence of parallel graben in the belt of land separating this portion of Mare Imbrium from Palus Putredinus to the northeast. In the case of the Mount Blanc front, the southern segment of the offshore belt is still connected to the mainland for half its length, the remainder being separated by a lagoon of the mare. That dip-slope faulting has continued until recently, or may still be active, is indicated by the curving scarplets in the mare extending south of crater Protagorus B (Fig. 10, and Locality 1, Fig. 11) and others at the foot of the main scarp at 2, in the same vicinity. There are suggestions of scarplets elsewhere along this segment, but not as clearly defined. The high curving scarp at 3 may represent an earlier stage of foundering.

The broad embayment and lagoon that has led to the suggestion of strike-slip movement at the mouth of Alpine Valley may merely indicate differential subsidence of the linear block seaward of the Mount Blanc Fault, greatest toward the mouth of Alpine Valley. The rectangular segment to the right of the mouth of the Valley, which preseumably was left standing as the former continuations on either side subsided, is surrounded on the north and east by mare material, and recent faulting is suggested by the rectangular scarplet at the northeast corner (4). An additional suggestion of recency, is the fact that the scarplet at the foot of the main scarp at 2 appears to cut a fresh crater on the surface of the mare.

In brief, although there is no convincing evidence of significant strike-slip displacement in the Alpine Valley region, there is convincing evidence of dip-slip movement. The apparent offset at the mouth of the valley appears reasonably explained by differential down-faulting of the broad sliver of land seaward of the Mount Blanc Fault, the depression being greatest at the mouth of Alpine Valley and on the far side of the rectangular segment across Alpine Valley. The faulting parallel to the Alpine front may, except for scale, be similar to that responsible for the multiple rims of craters and other circular marias, namely slumping (faulting) in toward the center of the depressions.

This brings us to the question of the origin of Alpine Valley proper, involving such problems as its configuration, the presence of the peninsulas on the south side, and the central rille.

The steep-sided, canoe-shaped configuration of the valley seems simply explained on the basis of a graben origin. The contrast in the two walls, however, is striking. The south wall is the more regular of the two as far as gross configuration is concerned. Its trend describes a shallow arc for 70 miles from near Mare Frigoris to The Collar. The simplicity of this simple arc is modified, however, by the many peninsulas that project from the valley wall. The north wall, on the other hand, is regionally more irregular with a number of small and large

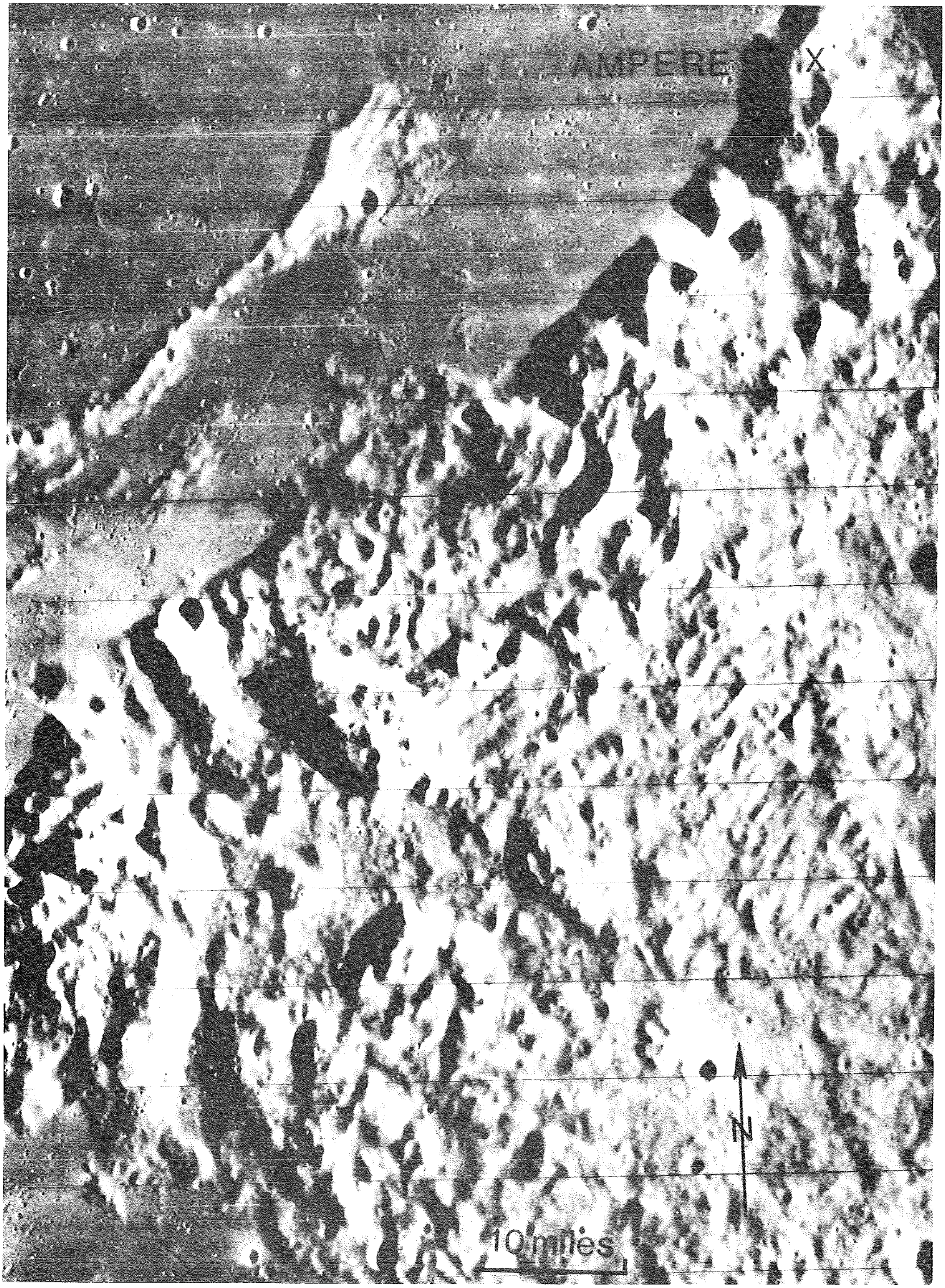

Fig. 12. Southeast coast of Mare Imbrium. The bold, linear, facetted mountain front is a fault scarp similar to the Alpine front (Fig. 11).

scallops. It is at the large scallops that the valley reaches its greatest width. In detail, however, the north wall appears to be smoother than that on the south, except for a cluster of parallel protuberances a short distance upvalley from Crater Trouvelot (Fig. 9).

In order to determine if the contrast in detail of the two walls is solely due to the shadowing effects resulting from the direction of incidence of the sun's rays in the photos,the author shaded the north wall as it might appear if the light were coming from the north. No narrow peninsulas, such as mark the south side, appeared, but the absence may be due to the crudity of the method employed. Because the contrast in detail poses secondary problems with the graben hypothesis, another possible explanation was considered. It will be noted (Fig. 11) that in the southwestern half of the valley, at least a half dozen craters occur along the base of the south wall. Two or three of the peninsulas appear to lie between adjacent craters. This suggests the possibility that the peninsulas represent the common rims of adjacent craters. The craters display no rims, however, on the valley floor: the craters appear as pits below the mare-like filling. Furthermore, some of the peninsulas, including the longest one of all, reveal a layering similar to that of the upland blocks. In deference to the last observation, we might suppose that the peninsulas represent projecting slivers of the upland that separated an earlier generation of aligned craters, and that these older craters were subsequently submerged by the mare-like material and later reopened. The distribution of the craters may indicate a major fracture at the base of the south wall below the valley fill. The complete, or nearly complete absence of rims suggests subsidence rather than explosion.

The obliquely-trending peninsulas in the upstream half of the valley, however, are clearly fracture-controlled, and have no obvious craters associated with them. This raises an important question: how were these peninsulas etched out prior to the valley fill, when the valley was deeper than now? Are they merely residual features left as the central area dropped, creating ragged tears in the intricately fractured valley side? If so, why wasn't the opposing valley side similarly affected? Or, are the spaces between the peninsulas the sites of pre-fill landslide scars? Again why the difference in the two valley sides? We might suppose that the original slab of upland dropped differentially, a greater amount on one side than the other. Perhaps the major fault is on the simply curved south side of the valley where the aligned craters are. Although it seems possible that differential subsidence of the graben might account for the contrasted appearance of the two sides, I am at a loss to explain the development of the details.

If we assume that the original valley wall once followed the ends of the peninsulas, we are then faced with the problem of explaining how the reentrants were "eroded" back, and furthermore why the reentrants combined to form a simple curvilinear trend. If we consider the great length of the scarp, perhaps this difficulty is more imaginary than real: reentrants of 2-4 miles along a 75-mile long linear scarp do not seriously detract from the simple regional configuration.

In brief, until there is evidence to the contrary, it will be assumed that Alpine Valley is a graben, formed by subsidence of a sliver of the Alpine upland prior to at least the latest episode of mare filling, that the depth of the graben was greater than now and was subsequently reduced by invasion of the mare-like material.

Alpine Rille

Running down the center of Alpine Valley is Alpine Rille which, except for a few irregularities, is remarkably rectilinear (Fig. 9). The existence of this rille was known prior to advent of Lunar Orbiter photography but details were lacking. The rille is shown on the preliminary geologic map of the Plato quadrangle (M'Gonigle and Schleicher, 1966). The rille averages about a half mile in width from rim to rim. The mare-like surface below which it is etched is densely pitted with small craters the largest of which, with a few exceptions, are about a half mile across. The floor of the inner rille appears flat over long stretches (Fig. 13) and consists of material somewhat lighter in tone and with fewer craters than the graben floor material above. The larger craters in the graben floor are occupied by similar-appearing material. In one place the inner fill of Alpine Rille extends laterally into a breached crater indenting the side of the rille. The above relations clearly indicate that after the mare-like filling of the graben, the rille was created on its floor, and the rille as well as some of the larger craters were occupied by material whose surface is smoother than that of the graben floor material above. The sharp junction of this inner material with the sides of the rille makes it seem unlikely that it is mass movement material from the sides of the rille. Possible explanations are lava or gas-fluidized deposits.

The origin of the rille itself is obscure. The following facts are relevant:

1. The rille, with a few local deviations, is remarkably straight in the 60 miles from The Collar to the latitude of the upland crater Trouvelot.
2. At two places between The Collar and the latitude of Trouvelot, there are local wrinkle-like departures from the rectilinear course of the rille. The largest departure amounts to 2-2 1/2 miles (5, Fig. 11).
3. The rille width of about 1/2 mile is constant, with only local variations.
4. The rille does not continue through the gorge into Mare Imbrium (Fig. 13, A).
5. The rille is interrupted at a number of places along its course, in some placed by craters (Fig. 13, C), in others, by extension of the surface of the graben fill across the rille to form dam-like barriers (D). The latter may indicate subsidence of the rille along a subsurface fracture, rather than direct tearing of the surface.

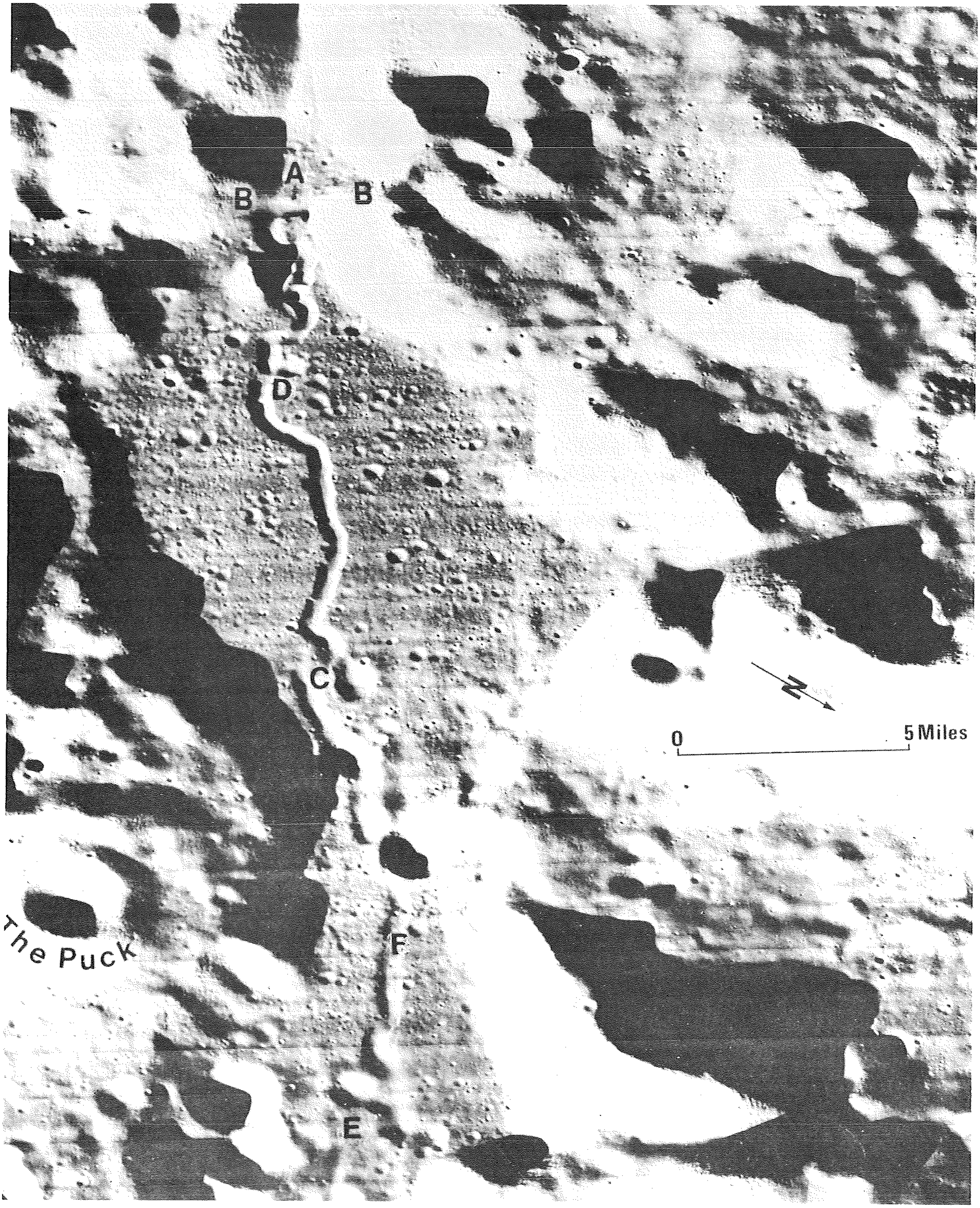

Fig. 13. Southwest terminus of Alpine Rille. Note that the rille does not continue beyond A. Bedrock extends unbrokenly across the gorge beyond A and is almost continuous from B to B. The rille is interrupted at several places (C, D, and E). Its floor is flat and occupied by lighter material than the pitted surface above.

6. Craters are aligned along the rille for about 15 miles starting from a point about 6 miles upvalley from The Collar. At least three of these craters form a continuous chain (6, Fig. 11).

7. In the vicinity of the deviation at 5 (Fig. 11), approximately north-south lineaments, in part consisting of small aligned craters, cross the graben floor obliquely and align with fracture traces on the adjacent uplands.

8. At locality 7 (Fig. 11), near crater Trouvelot, the valley appears offset dextrally. A lineament (furrow?) crosses the valley floor at this point. The rille, much less prominent beyond here, is displaced in the same direction as the valley as a whole. Another small offset in the rille, about 4 miles downvalley, is also associated with a faint lineament on the valley floor parallel to that at 7.

9. There are few pronounced curves along the course of the rille, and only one or two in which the limbs approach parallelism.

In the author's opinion, all of these observations are satisfactorily explained on the assumption that the rille is a fracture representing a renewed splitting of Alpine Valley. The interruptions along its course are expectable according to this hypothesis. Figure 7,b is a tensional fracture in cement showing such an interruption, and all three fracture illustrations show sinuosity and tributary fractures.

The local deviations from the rectilinear trend may be related to the configuration of the bedrock below the graben fill. Note that the deviation at 5 (Fig. 11) occurs at the site of a protuberance of the north wall and a reentrant in the south wall, although closely-spaced cross-faults may also have had some influence. As for the alignment of craters along fractures, there are numerous earthly analogs. None of the curves of the rille have meander-like necks; hence present no difficulty for the tensional spreading hypothesis.

There arises then the question of whether the rille, after opening as a fracture, might not have served as a channel for a fluid. Objections to this are the interruptions in the rille and its absence in The Gorge. The aligned craters could, of course, have come into existence at any later time.

In summary, the evidence suggests that Alpine Valley is a graben and that after its occupation by the mare-like filling a continuation of the distensive forces resulted in the new fracture represented by Alpine Rille. Subsequently, more mare-like material occupied considerable parts of the rille floor.

Other Rilles of the Alpine Region

Rima Plato II: The most remarkable of the neighboring rilles is Rima Plato II north of Alpine Valley (Figs. 9 and 11). The rille is about 87 miles long, about 2800 feet wide at its head, and about 1000 feet wide at its termination.

Interesting aspects of this rille are its twin headwater branches which, for convenience, we will refer to as South and East forks, its sinuous pattern, and its decrease in size as it flows out over Mare Imbrium. Except at localities 4 and 8 (Fig. 11), the rille flows on the surface of fresh-looking mare material which has only scattered small craters. South Fork occupies a broad lowland whose linear margins suggest fault control. The western margin may be the site of the Mount Blanc Fault. East Fork and the course of the main rille into Mare Imbrium, are parallel to the bold linear mountain front which extends inland from Mare Imbrium. Fault control of the lowlands is strongly indicated.

Superficially at least, Rima Plato II seems to support the hypothesis of fluid erosion; it has headwater branches, a locally, highly sinuous course, and continues randomly out over the neighboring mare surface. The difficulties with the simple fluid erosion hypothesis are: 1) the abrupt beginnings, particularly of East Fork, 2) the crossing of the low neck of upland at locality 4 (Fig. 11); 3) the passage across the low area of upland at locality 8; and 4) the interruptions in the course, at localities 4 and 8. Although the situation at the head of South Fork is not entirely clear, the fork seems to originate in an irregular depression some 2 1/2 - 3 miles across, whose floor is below the mare surface into which the rille is incised. To this extent, South Fork resembles many other rilles that rise in depressions. For most of its 30-mile course toward the junction with East Fork it is highly sinuous, although long segments of the course are essentially straight. South Fork becomes narrower, shallower, and less sinuous as it progresses northward. Its faint channel seems to overhang East Fork at the junction.

East Fork is only 9-10 miles long, roughly the maximum extent of the mare embayment it occupies. About 5 miles beyond its junction with South Fork, it terminates in a crater 1 1/2 miles in diameter. Between the junction and the crater, the rille is incised in two large meander-like curves across a low neck of the upland at 4 (Fig. 11).

There is no connection immediately beyond the crater with the main part of Rima Plato II. The first clear indication of the beginning of the main rima is about 4 miles beyond. As nearly as can be determined, the rille continues with one possible interruption to locality 8 (Fig. 11) where an apparent interruption occurs. It is possible, however, that the rille wanders across a level lowland here and is difficult to detect. From locality 8, the rille can be traced across the surface of Mare Imbrium for about 50 miles. An angular pattern in its distal portion, and the angular pattern of a nearby rille indicate fracture control. Fracture control may also be indicated by straight sections and right angle bends in both South and East Forks.

Difficulties with the hypothesis that the rille system represents tensional cracking of the lowlands in which they occur are these: 1) the origin of South Fork in a depression, 2) the highly sinuous course and the general lack of "match" of the opposing valley sides, 3) the termination (source?) of East Fork in a crater, and 4) the highly sinuous course of Rima Plato II beyond the crater.

The major difficulties with the fluid-erosion hypothesis are the interruptions along the course of the rille. Perhaps the actual connection at 4 is underground, or perhaps the fluid dissipated by evaporation or seepage just before reaching East Fork. As for the interruption at locality 8, faint surface indications suggest that there may actually be a connection here. Assuming the connections exist, superimposition as an explanation of the crossing of these low, oldland areas may not be necessary. The upland surface is practically at mare level at these sites and the rille may have been able to wander around among the low hummocks maintaining a consistently downhill gradient. The problem of the crater at one termination of East Fork remains.

Although Rima Plato II presents certain difficulties, the weight of evidence supports the former presence of a flowing fluid. Parts of its course may follow fracture traces, but the sinuosity even along these relatively straight stretches, and the extreme sinuosity between localities 4 and 8, cannot be explained by simple distension. Even disregarding the meander-like curve at site 9 which seems to follow around a low knob, the tight meanders at site 10, with a probable meander core in one of them, renders the distension origin practically impossible.

In brief, the available evidence suggests that a fluid was involved in the excavation of Rima Plato II, although parts of its course may have been originally determined by fractures.

Rima Plato I: Rima Plato I, incised entirely in the hummocky Alpine Plateau, is a deep rille, V-shaped in cross-profile, with a uniform width of about 1 1/4 - 1 1/2 miles for the 50 miles of its course shown in Figure 11 (lower right). It displays one large and several smaller curves, all open and in no way resembling meanders. Its talweg is clearly irregular, that is, it does not descend uniformly in one direction. Locally the interruptions within the rille rise almost to the level of the upland. Except for its greater breadth, and its development in the "basement" rocks of the plateau rather than in mare material, Rima Plato I resembles Alpine Rille in general characteristics. There is no reason for suspecting other than a fracture origin.

Rille, Site 11 (Fig 11): Eleven or twelve miles east of Rima Plato I at locality 11 is a broad, beaded curvilinear lineament consisting of a chain of craters which, after an interruption of a few miles, becomes a continuous V-shape rille. The latter becomes narrower and shallower toward the shore of Mare Frigoris where the rille fades out. The head of the rille is a crater of the same magnitude as those forming the chains at 11. The chain seems reasonably explained as a string of blowouts along a fracture; the continuous section may represent the fracture with only a single vent at its head.

Although there are a few meander-like curves near the terminus of the continuous rille, the curves are open and could have resulted from tensional rupture. Thus, there is no clear evidence to indicate whether or not a fluid was involved in the fashioning of this continuous rille.

Rille, Site 12 (Fig. 11): South of Alpine Valley, a relative small rille with V-shape profile follows a rectilinear course out of a mare pool and across an island-like outlier of the mountainous terra. Its head appears to be a string of craters. On the far side of the terra island it braids in a simple pattern. Beyond here, there appear to be several faint branches extending among the low knobs of the plateau surface. However, the situation is hazy at best. The rectilinear path of the greater part of the rille, as well as its path across the terra island, suggest a fracture origin. The simple braiding could conceivably be of fracture origin, but does not seem too likely. The distributary (?) pattern beyond here is not amenable to fracture interpretation. Although the rille is small, and some of the details difficult to make out, it may well be that a fluid followed the fracture and debouched in the area of the distributaries. The vermicular-like texture in the area of the distributaries is different from that of the surroundings and tempts the conclusion that we are actually dealing with a site of deposition. As far as the writer is aware, no clear evidence of deposition has been found at the termini of rilles anywhere, suggesting either that no deposition has taken place, or that the deposits are too thin and widespread to distinguish at the scale of the photos.

Origin of Sinuous Rilles

We have already noted that most of the highly sinuous rilles are located around the border of the mare basins or associated with island-like or peninsula-like areas surrounded by mare materials (Fig. 1). We also noted that they appear to be concentrated in the western half of the near face of the moon where greater areas of mare are found.

The various proposed theories of rille origin will be considered and additional suggestions will be offered. Of all the sinuous rilles, Schröter's Rille with its remarkable incised meanders is probably the most spectacular and informative. For this reason, Schröter's Rille will receive special attention.

General Considerations

We have already considered the improbability that Schröter's Valley could have been eroded by lava or ignimbrite flows. The prospects for such origin are even more remote for the highly sinuous inner rille. The principal objections are the improbability that volcanic flows would meander on a flat surface or erode meandering courses.

A variety of the lava erosion hypothesis would have the rilles form by collapse of lava tunnels. Aside from the magnitude of the tunnels that would be required, there is no record of collapse features on Earth with highly meandering courses. Furthermore, collapse valleys generally have irregular widths and their floors are a series of basins. This is not to say that collapsed lava tunnels do not exist on the moon, but only that they can not explain the extreme sinuosity and the great dimensions of the sinuous rilles.

If volcanic fluids, either lava or ignimbrite flows, are unacceptable, what fluid media remains? A number of investigators have suggested the possibility of erosion by running water, either at the surface (Gilvarry, 1969) underground (Firsoff, 1960[1]), or more complicated processes involving permafrost (Gold, 1964; Lingenfelter, Peale, and Schubert, 1968). We will consider these suggestions in reverse order. I should like to emphasize again that the present analysis is primarily geomorphic: it seeks to determine whether the observed landforms are reasonably explained by the suggested processes, especially as these would be affected by the influence of the lesser gravity of the moon.

Subsidence above Sub-permafrost Rivers

Gold (1964, p. 253-54) has postulated the presence of a thick permafrost layer on the moon starting at a depth of about 100 meters and with water trapped below it. The presence of subterranean water is attributed to radioactive heating. Gold suggests that when the permafrost layer is breached by a crater, the water shoots out and boils off. He proposes a subterranean system of rivers under the permafrost running toward the point where the water can escape freely. This would be analagous to groundwater drawdown at an earthly well. Gold suggests that these subterranean streams are forced up against the underside of the permafrost by hydrostatic pressure causing them to wear a pattern by melting the ice. As the subterranean river courses become large enough, the surface subsides to provide replicas of the subsurface river channels. Gold states that rilles commonly converge on craters in flat ground. The suggestion of permafrost is intriguing, but it is most unlikely that the sinuous rilles can form as suggested. In the first place, many rilles do not have craters; secondly, craters occur at the "upstream" end of many rilles and would more reasonably appear to be the source rather than the terminus of any fluid flows; and thirdly, the surface rilles, including Schröter's Rille, do not have the highly variable width and irregular floors that characterize subsidence valleys on Earth.

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[1] This publication is referred to by Cameron (1964) but could not be located by the present writer.

Surface Erosion by Crater-liberated Sub-permafrost Water

Lingenfelter, Peale, and Schubert (1968) follow Gold in his suggestion of a permafrost layer that may be breached by cratering to liberate entrapped water. They, however, propose surface erosion. They infer a permafrost layer one kilometer thick and require a crater at least one kilometer in diameter for the necessary breaching. To circumvent rapid evaporation in the lunar vacuum they visualize the sequence of events as follows (p. 267):

> "As the water welled up within the crater, the exposure to near-vacuum would cause it to boil, the latent heat being supplied from the water - principally through the formation of surface ice. Boiling would continue in the liquid below until the weight of the ice layer was sufficient to maintain the triple-point pressure (37 g/cm^2 under lunar gravity). Sublimation would occur at the ice surface at a rate depending on how rapidly energy was supplied to the surface. Liquid would continue to freeze at the ice-water interface. The ice would thicken until an equilibrium was established in which the upper surface mass-loss rate by sublimation ... balanced the rate of mass gain at the bottom ..."

These authors believe that lunar diurnal variations in the thickness of the ice would be small. For the formations of the rilles themselves they suggest:

> If the water breached the crater wall, it would flow down the slope (boiling and freezing where exposed to vacuum), quickly covering itself with a blanket of ice. Since the appearance of the rills [rilles] indicates that the rivers were hundreds of meters wide -- large relative to the equilibrium thickness of the ice blanket -- we would not expect the ice to restrict the river's course or hinder the development of meanders; cracks in the ice would be rapidly repaired by the freezing of water exposed to the vacuum and the supercooled ice.

The authors further believe that if the lunar surface material is a loose aggregate, disintegrated by meteoritic impacts, it would be easily erodible down to the permafrost level, about 100 meters.

To explain the groupings of sinuous rilles they postulate that only certain areas of the moon had sufficient subsurface water pressure to overflow the threshold-size craters. The lack of rilles associated with all craters of the proper size in a group is taken to mean that some of the craters were formed after pressure had been depleted by prior rupture of the permafrost.

I will leave to others, more competent in these matters, the analysis of the arguments for the presence of permafrost. For the sake of the geomorphic analysis, we will assume that it exists and that it can be breached as suggested to provide routes to the surface for waters trapped below. We will assume that the ice cover of the rising water column in the crater will be maintained by accretion from below as the surface wastes by evaporation as suggested by Lingenfelter et al. It must be assumed of course that the ice cover itself will be raised bodily, probably with fragmentation, if the water level is to rise in the crater.

The first important observation to be made is that not all sinuous rilles rise in craters, and of those that do, not all rise in craters deep enough to breach the postulated thickness of permafrost. The sinuous rille off the northwest coast of Aristarchus Plateau, at the foot of Barrier Island, is an example (Figs. 2, 8). The rille is interrupted in mid-course; the northern and southern segments appear to start independently at a wrinkle ridge which connects the island to the mainland. Each segment becomes narrower and shallower away from the ridge and from each other. Lunar Aeronautical Chart No. 38, with contours, shows the wrinkle ridge to be a divide with the ground falling away both to the north and south. Although a tiny crater appears at the end of the northern segment, it appears to be at the terminus, not at the head of the rille. It is unlikely that the wrinkle ridge is a later feature which arose across the path of a formerly continuous rille, because the two segments taper in both directions away from the ridge.

Other examples of rilles without craters at their heads are listed in Table I. These include some of the longest rilles on the moon. It is interesting to note that the longest sinuous rilles observed, beside lacking craters at their heads,are narrower and shallower, relative to their length, than those with prominent craters. Their width remains fairly constant for long distances. The longest of these are found in the maria, and because some are narrow and shallow, are often easily overlooked. As we shall see shortly, the absence of craters at the heads of many sinuous rilles is not fatal to the breached permafrost hypothesis.

It should perhaps be pointed out at this time, that Adler and Salisbury (1969), as a result of their vacuum-chamber experiments, concluded that ice readily forms in a vacuum to sufficient thickness to allow liquid water to exist beneath it, but that the water does not erode rille-like channels. Instead it percolates through the soil following the greatest pressure gradient, only here and there momentarily breaking through explosively to the surface before the exit is again sealed off.

We might suppose that sinuous rilles represent collapse over the subterranean courses demonstrated in the experiments of Adler and Salisbury (1969). I am unaware of any earthly analog of tightly meandering caverns whose collapse might furnish surface features such as Schröter's Rille, but we cannot be sure how the difference in lunar parameters would affect subsurface fluid behavior. The arguments against collapse, however, are the same as for collapsed lava tubes, the uniform width of the rilles and their more or less continuous downslope gradients.

Let us assume, however, that ice-covered rivers such as suggested by Lingenfelter et al. can indeed exist on the moon. Can such rivers develop meandering courses? Will they erode incised courses? Any difficulties that appear will, of course, apply also to sinuous rilles without craters at their heads.

Lingenfelter et al. (p. 267-268) dismiss the problem of the development of sinuosities with the statement:

> Since the appearance of the rills [rilles] indicates that the rivers were hundreds of meters wide -- large relative to the equilibrium thickness of the ice blanket -- we would not expect the ice to restrict the river's course or hinder the development of meanders; cracks in the ice would be repaired by the freezing of water exposed to the vacuum and the supercooled ice.

The authors go on to say that the

> boiling water, when it first encountered the very porous and weakly bonded material on the slopes ... would churn the surface and produce a slurry of mud and ice.

Let us concentrate our analysis for the moment on Schröter's Rille. Evidence has already been presented indicating that the broad trough of Schröter's Valley within which the rille is incised, is a graben. It could be argued that the meteorite impact that created the Cobra Head, was also responsible for the creation of the graben. If permafrost-entrapped water was liberated by the impact, it flowed down Schröter's Valley prior to the mare-like filling which - it will be recalled - is probably younger than the trench itself. The pre-fill stream presumably escaped from the closed end of the graben, perhaps along a tensional fracture rather than by overflow. One question that immediately arises is why - after original breaching of the permafrost by a crater and subsequent emplacement of the mare-like fill - a second period of water emission took place to erode the inner rille itself. We could become involved in a complicated, relatively unrewarding series of speculations at this point. Let us instead, concentrate solely on the proposition that the post-fill escaping waters eroded the incised meandering channel.

Lingenfelter et al proposed that, as the escaping water flowed away from the crater, it was protected from rapid evaporation by an ice cover that extended itself forward with the stream. I assume that a partial earthly analog would be an Arctic river whose surface freezes but which may still confine water in depth. The difference, of course, is that the Arctic river is already there and simply freezes over, whereas the lunar river grows forward building an ice carapace as it progresses. Because of the fundamental difference in the origin of the ice cover, plus the mitigating influence of the lunar vacuum, earthly analogs are probably of only limited value although suggestive. The lesser lunar gravity should not be an overriding consideration because, while the absolute value of the component of gravity on the slope down which the water flows is less than that on Earth, the density of the water is also reduced.

One observation on cold-climate earthly streams that seems pertinent is that shallow, sluggish streams freeze sooner than deeper, swifter ones. Yet some of the longest meandering rilles on the Moon, such as the one just north of Rima Marius (Fig. 1, No. 12), are narrower and shallower than broad, deep sinuous rilles. By analogy one would expect the latter to be the longest. Next, in the freezing of Arctic and Subarctic rivers, ice may form not only on the surface of the water but on the channel floor as well (Muller, 1947, p. 24). This is <u>bottom-ice</u> or <u>anchor-ice</u>. Such ice may appear even before surface ice develops. Whether bottom-ice forms or not, however, the river becomes increasingly constricted as freezing continues, and the resulting hydrostatic pressure forces the water into the alluvium on both sides of the river. The pressure may be relieved by eruption of the entrapped water to the surface through the river ice itself or through the neighboring ground. I am unaware of any descriptions of orderly lateral erosion by ice-capped rivers. Nor am I aware of meandering eskers indicative of meandering in glacially-encased streams. As far as earthly analogs are concerned, therefore, there seems to be no basis for assuming that ice-capped lunar rivers would engage in orderly development of meanders.

If we examine the situation in Schröter's Valley, we find that there is no evidence that the meanders of Schröter's Rille grew from simple curves on the surface of the graben fill.There is no evidence of a floodplain on the surface of the fill; no crescentic bars and swales, no cut-offs, and no meander scars in the valley sides. The pitted surface of the fill is everywhere uniform in appearance from the valley sides to the very brink of the incised rille. It seems unlikely that the small scattered craters could have completely eliminated all record of former floodplain features, but I hesitate to say unequivocally that this could not have happened. To strengthen the ice-capped river hypothesis, however, we might assume that the meanders are initial, rather than the product of evolutionary growth from simple curves. Earthly streams that come into being on level surfaces, such as exposed lake bottoms or the surface of valley fills, may meander from inception. The question is, would ice-encased streams do likewise? I suspect that, like an encrusted lava flow, an ice-encased stream under hydrostatic pressure would break out of its confining shell at different places, starting new branches, rather than engaging in orderly lateral shifting of its carapace and enlargement of curves. Above all, there is the difficulty of explaining the accretionary growth of slender threads of ice with constant widths for distances of 100 miles and more. Wasting should have been very rapid away from the source of supply. Furthermore, the ice carapace would have had to persist long enough to permit the water below to erode vertically hundreds of feet. Lingenfelter el al suggest that the water would form an easily transportable slurry with the loose lunar materials. This may be true, but in Schröter's Valley at least, there are ledges of solid rock in the valley walls, rock firm enough to roll down the long slopes and persist as blocks up to 100 feet across at the foot of the slopes. If the meanders of Schröter's Rille are original and represent the wanderings of an ice-capped stream on the surface of the valley fill, we might ask where such a presumably sluggish stream would derive the energy for vigorous downcutting. There are several possibilities: 1) the hydrostatic pressure under the confining ice cover might permit a high rate of flow even in a meandering course, provided break-outs did not occur, 2) a steeper gradient downstream might result in a wave of rejuvenation extending upstream, or 3) favorable tilting might increase the velocity. The incision of the rille, then, is not in itself a serious objection to the ice-carapace hypothesis. The other difficulties mentioned, however, render unlikely the "crater-breached permafrost, ice-covered river" hypothesis of rille origin. The vacuum chamber experiments of Adler and Salisbury (1969) also fail to support the view that locally released subsurface water, would provide continuous surface streams. The devastating argument against *crater-breaching* of permafrost to account for *all* rilles of possible fluid origin is that many sinuous rilles do not head in craters.

In spite of the objections to the ice-covered river hypothesis, the proposal that some sinuous rilles are eroded by water locally derived from the subsurface is compatible with available geomorphic evidence including the long downslope gradients, the uniform widths, the meandering patterns, and imminent cutoffs. The problem then is to obtain water from below and make it available for rille erosion in such a way as to overcome the objections raised above.

Before considering alternate possibilities involving water, I should like to call attention to an interesting series of experiments by Schumm (1969) designed to demonstrate that "some lunar sinuous rilles could have formed as a result of fluidization of loose surface materials by gases vented from lunar crustal fractures". Many features created in the experiments have analogs on the lunar surface, such as linear crater chains resembling Hyginus Rille (Fig 14), interrupted rilles, and sinuous rilles. Differences concern the invariable development of rims along the experimental rilles in contrast to the great majority of lunar rilles, the scalloped sides of many of the experimental rilles as compared to the smooth parallel sides of most lunar sinuous rilles, the absence of V-shaped cross profiles in the experimental rilles, the failure of the experimental rilles to feather out toward their termini in contrast to many lunar sinuous rilles, and the absence of experimental meander patterns comparable to those of Schröter's Rille. Although Schumm's experiments do not duplicate the meandering type lunar rille with which we are concerned, the other analogs of lunar features suggest that gas emission may be locally important. The experiments also suggest the possibility that the level fills of some rilles may consist of gas fluidized debris which flowed down the rilles even though the latter were formed by some other process.

Alternate Possibilities for Liberation of Sub-permafrost Water

The presence of sinuous rilles without craters at their heads does not negate the possibility of origin by permafrost-entrapped waters. It may merely mean that the permafrost was breached by other than crater impact. We know that on Earth, artesian water is commonly emitted along fractures. We know that post-mare faulting is common on the moon, witness the "Straight Wall", 75 miles long and 1000 or more feet in height in the southeastern corner of Mare Nubium, and the recent fault scarps in the Alpine Valley region referred to in this report. Surely if permafrost

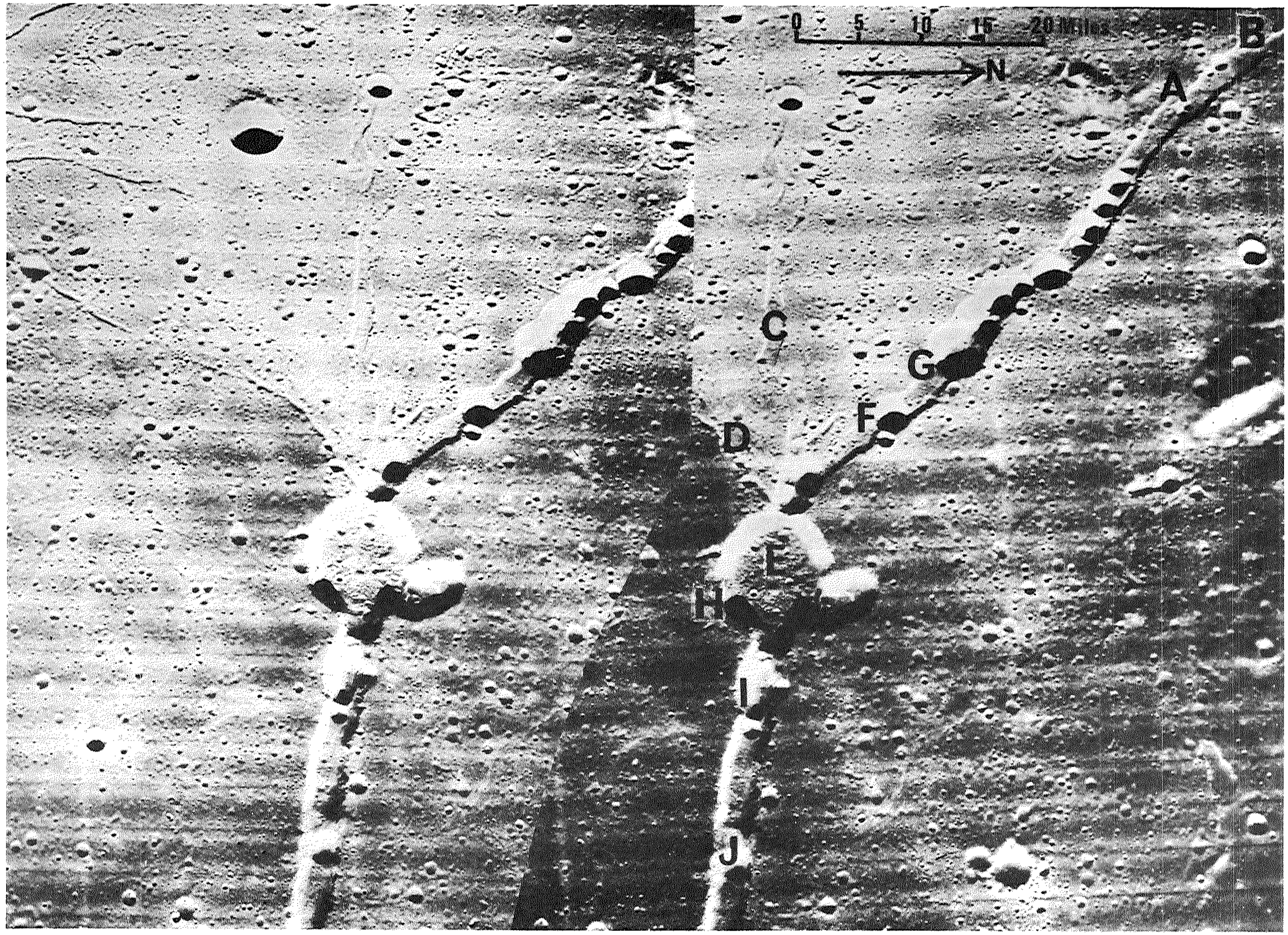

Fig. 14. Hyginus Rille. In addition to the prominently cratered fractures extending to the northwest and east, other faint fractures (C and D) radiate in other directions from Hyginus crater (E). The main branches are graben which have localized rimless craters of internal origin (F, G). An exception is the crater (I) which appears to be rimmed. A small crater (H) indents the rim of Hyginus crater. A remnant of the upland which failed to subside along the graben is indicated at J. A fault splinter and a fault terrace are indicated at A and B respectively.

is present, it would be breached by faults or by simple tensional tear fractures. It is also well known that artesian water does not rise everywhere along a fracture but only in those places where favorable passageways exist. The appearance of water at spotty intervals along a tensional fracture would overcome one objection to the hypothesis of rille origin by Lingenfelter el al, namely the preservation of long, narrow ice-capped rivers fed from a single source.

Conceivably, too, a permafrost layer might be breached locally by eruptive gas vents with or without associated fractures. Unless the vents are close together, however, or lined up along a linear depression, it is difficult to explain a continuous rille in this fashion.

Volcanic Vapors and the Origin of Rilles

If the pre-incision curves of Schröter's Rille were original rather than the result of slow accretion growth on a floodplain, we avoid the problem of explaining the change in behavior from a laterally eroding stream during meander development to a vertically-downcutting stream during the period of incision. If erosion by ice-covered streams seems inadequate to explain sinuous rilles and yet water seems the most likely agent of erosion, the problem of preservation of streams over long distances under approximately present lunar conditions remains.

We do know that crater Aristarchus and the Cobra Head are the scenes of recurrent transient events consisting of flashes, glows, and hazy obscurations (Middlehurst et al, 1968). We also know that there are debris and lava flows on the slopes of Aristarchus. If these are at least in part volcanic manifestations, then a volcanic source of water for rille erosion seems possible. The presence of great gaseous clouds, largely water vapor, during volcanic eruptions on Earth is a well-known phenomenon. The question is could these persist for any length of time in the present near-vacuum conditions on the moon. Again it seems to be a question of rate of supply versus rate of loss. If emissions are copious enough to make up for the escape loss, clouds might persist and provide rain for nourishment of streams. Nourishment would have to be plentiful to provide a continuous supply of water to the streams and to compensate for evaporation, assuming that vapor pressure at the water-air boundary was not great enough to provide equilibrium conditions. It is interesting to note that because of the absence of wind, a volcanic cloud might hover longer over the volcanic vent, localizing rains more than on Earth. In the absence of wind drift, such clouds would presumably dissipate only by escape of substance to space. Some of the transient "obscurations" reported by Middlehurst et al (1968) may be ephemeral clouds. We are still faced with the problem of how rivers generated by such volcanic rains could extend themselves 100 miles or more away from their source of supply in spite of rapid evaporation. The supply of water could be increased greatly if permafrost were locally melted by the volcanic activity and, together with entrapped water below, converted to steam and incorporated in the volcanic clouds. Even assuming, however, that enormous quantities of water might be made available in volcanic eruptions we might expect that channels formed by the resultant streams would diminish rapidly in size away from their source of sustenance. Yet this is not true for many sinuous rilles, including Schröter's Rille. Furthermore, we might reasonably expect to find other rilles radiating outward from the source area rather than, as is often the case, a single rille.

Perhaps part of the answer to the problem of sustained flow is emission of volcanic fluids at many places along fractures. The suggestion that craters aligned along graben-like features, such as Hyginus Rille, are volcanic vents has been made by a number of investigators. Middlehurst and Kuiper (1963, p. 34-35) suggest that volcanism may have been triggered by the impact that created Hyginus Crater. The idea that volcanism may occur along lunar fractures is thus not new. There seems to be no logical reason why emissions may not take place without the aid of craters, that is, simply as fissure emissions. It is interesting to note that a transient event observed by Greenacre and Barr at Lowell Observatory on November 28, 1963 (Middlehurst et al, 1968),consisted of a pinkish streak in Schröter's Valley 12 miles long, 1 1/2 miles wide, and 1 1/4 hours in duration. The alignment of hot springs and fumaroles along fractures is, of course, common on Earth. If such emissions were to occur at intervals along a ragged fracture on the Moon, fluid flow might be sustained for considerable distances and at different places along the fracture, during different episodes of volcanic activity. Fluid erosion, plus movement of material down the valley sides, could then account for the elimination of the original raggedness. In this view, the sinuous meanders start as ragged cracks along which volcanic emissions occur and provide water for fluid modification.

There may be some advantages to a fracture source of fluids rather than a source in volcanic craters. Crater Posidonius (Fig. 15), on the northeast coast of Mare Serenitatis, may offer some light on the subject. The crater floor displays a number of rilles all but one of which are linear, with angular bends, and clearly fractures. The exception is a highly sinuous rille which hugs the west wall of the crater. The eastern, fractured half of the crater floor is generally higher than the western half. The latter appears to be drowned in fresh mare material. The linear fractures do not penetrate the western mare area the material of which is presumably later than the higher, fractured area. The sinuous rille on the west side of the crater floor begins abruptly at the crater wall where it is V-shape in cross-profile and relatively deep. It is broader and shallower at its north end where it fades out. Presumably the flow of any involved fluid was to the north. If the sinuous rille was eroded by a stream formed by rains from volcanic clouds, it is difficult to understand why only this one sinuous rille resulted, why it has no tributaries, and why it has so abrupt a beginning. If the fluid was emitted at the south end of a fracture, these difficulties disappear. Relative to fracture control, it is interesting to note that the trends of the two major segments of the rille conform to fracture directions to the east.

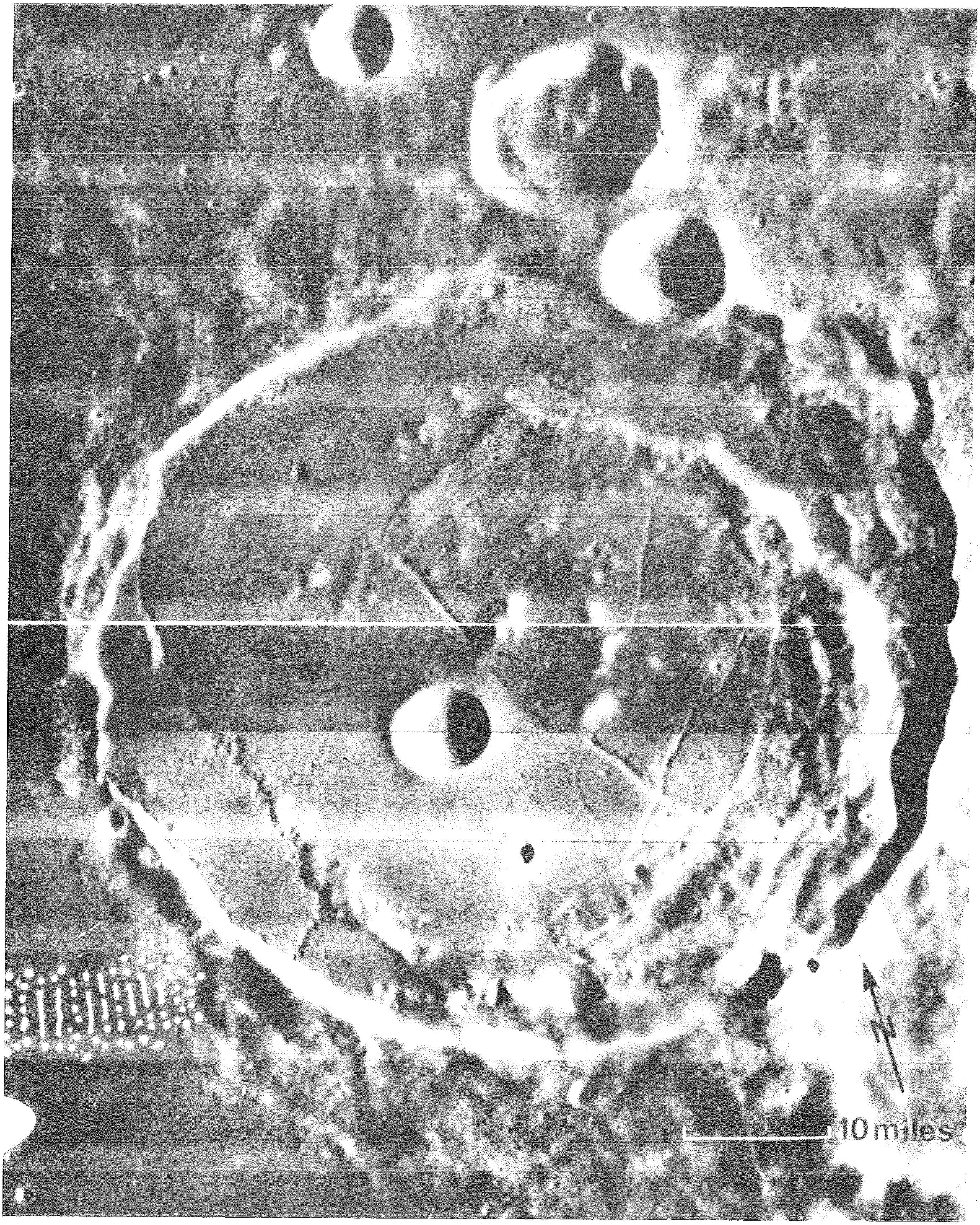

Fig. 15. Crater Posidonius on northeast coast of Mare Serenitatis. The highly sinuous rille at left contrasts with rectilinear rilles to the right.

In brief it would appear that either permafrost-entrapped water, or volcanic waters, or a combination of both, might explain the development of sinuous rilles. Emissions along fracture seem to be required for long sinuous rilles. Incised meandering rilles, because of lack of evidence of a floodplain at which incision started, suggest an original curving course. The two requirements, multiple emissions along the rille and an original irregular course, are met by assuming an original, irregular fracture subsequently modified by fluid flow. A single fluid source might still apply to relatively short sinuous rilles heading in craters.

Although I believe that water-modification of irregular tensional fractures offers less difficulty than other suggestions offered, I do not think that the problem of rapid evaporation of water as it reaches the surface can be casually dismissed. It is precisely this difficulty that Lingenfelter et al sought to circumvent by proposing an ice-cover for the surface streams. Yet we have seen that there are objections to this concept. I should like to suggest a possible way out of the dilemma for consideration by those more versed in the chemical and physical limitations than I am.

Let us consider first sinuous rilles heading in craters. The difficulty with crater-breaching or permafrost to provide surface water is that it is a one-shot mechanism: the entire length and depth of great rilles like Schröter's Rille must somehow result from this single impact event. In contrast volcanic events can be repetitive and may also involve the permafrost. The basic requirement would be that water vapor be emitted in such quantities over the vent as to create a volcanic cloud and maintain it in spite of rapid loss to space. If such events were in progress while the terminator was in the area, the mild temperatures would at least reduce temperature-induced evaporation, and conditions would be somewhat better suited for rains and surface streams. Another possible favorable factor would be that the volcanic clouds, in the absence of wind, might tend to hover over the vent rather than drift away. Because favorable temperature conditions would follow the terminator and return only at two-week intervals, the amount of erosion at any one time might be severely limited. Hence, erosion of long lunar rilles, particularly those that are deeply incised, may be a long-continued but intermittent process resuming whenever chance combinations of prolific volcanic eruptions and favorable temperatures occurred.

That "local atmospheres" could maintain themselves over vapor-emitting segments of fractures, is much less likely because of the narrow source. In either case, the maintenance of streams of water for long distances is still a disturbing factor. It seems necessary to radically reduce the evaporation rate as well as "increase" the supply of water. Perhaps the reduction in evaporation rate can be explained by a high sediment content in the water, but not high enough to prevent erosion.

Rille Terminations and Rille Origin

This brings us to the problem of the contrast in rille terminations. Many, like Schröter's Rille, gradually become smaller and eventually die out. An earthly analogy is afforded by streams that extend from humid source areas into drier regions. Such streams lose substance by evaporation and infiltration. Other sinuous rilles, including several north of crater Prinz, while becoming shallower outward, maintain or even increase their width. We have already noted the fracture control of at least portions of the courses of these rilles. The rilles are occupied by mare-like material which seems to merge with the surface of the mare beyond. In brief, considerable portions of these rilles may be buried under the latest materials of the mare basin. Although sinuous, the rilles may well be simple tensional fractures whose flat floors are occupied by mare-like material or fluidization debris. At least one rille provides evidence that the surface of the inner mare-like material is actually a fill and not a downdropped part of surrounding surface. The rille with circular head just below the center of Figure 5 is interrupted by a spatula-like depression in midcourse. If the rille had originally continued uninterruptedly to the north, and the transverse depression had dropped across its path, the deep rille ought to be visible in the graben. Instead we find only a faint depression crossing the graben and dying out a few miles up and down valley. We can only assume that the essentially smooth floor of the graben, and of the rille up and down valley, represents later material which buried the downdropped segment of the rille, and that the faint depression across the graben represents a rejuvenation of the original rille fracture.

TERRA SCULPTURE

Fourteen areas have been selected to illustrate the wide range of sculptural detail in terra landscapes (Fig. 1). The unequal distribution is due in part to variation in quality of the photographs and in part to the similarity of the topography over considerable areas. In these latter areas, a single representative photo suffices.

Even cursory examination of the photographs of the near side of the Moon reveal striking differences in the appearance of the terra uplands in different regions. Thus, the mountains along the eastern border of Mare Imbrium are lofty, and present bold linear escarpments overlooking the mare surface; the uplands bordering much of Oceanus Procellarum, on the other hand, are relatively low with ragged borders; and the terra of the central highlands between Mare Nubium and Mare Nectaris and covering much of the lower half of the southern hemisphere, forms a high plateau densely pitted by craters of all sizes. The areas herein described are representative of these varied landscape types.

It is worth noting that landscape features analogous to terrestrial features of fluid erosion are relatively rare in the younger, linear mountain tracts such as the Lunar Alps, and most common in the older, ragged highlands such as those bordering Oceanus Procellarum. Terrestrial-type valleys, however, appear on the flanks and inner walls of many large craters of all ages.

The conclusions herein reached regarding fluid erosion in the lunar highlands are based on 1) the presence of analogs of terrestrial mountain valleys and 2) the evidence of deep and widespread regional degradation not readily explained by presently known lunar processes. The ideal analog of a fluvial valley would be one with the following characteristics: 1) a V-shape cross-profile, 2) a longitudinal profile descending uniformly downvalley, 3) a curving course, 4) widening of the valley towards its mouth, 5) a feathering out towards the head, 6) asymmetric spurs steeper on the upvalley side, 7) shoulders or terraces, 8) meandering channels in the lower courses of the valleys, 9) tributaries with accordant junctions , and 10) terrestrial-type drainage patterns. The ideal, embodying all the above characteristics, has not been observed on the Moon. Impact cratering, mass movements, and invasion by mare materials since development of the valleys, may have obscured many of the original details. As for regional degradation, neither meteorite impact, mass movements, nor sputtering erosion by the solar wind seem competent to account for the magnitude of the degradation.

Two of the fourteen areas discussed are of particular interest because of the well-known valleys within them, the Aristarchus region with Schröter's Valley, and the Alps with Alpine Valley. Prior to advent of the Lunar Orbiter photography the existence of an inner rille in Alpine Valley was known but few details were available. The presence of an inner rille in Schröter's Valley was a new discovery. These two areas are discussed in detail. The remainder are described only briefly because of the repetitive nature of many of the descriptions.

The geomorphic evidence, although poor in many areas, suggests the possibility of extensive pre-mare fluid erosion.

Locality I. The Aristarchus Region

The Aristarchus Region is herein considered to comprise the Aristarchus Plateau with its isolated mountain masses, and the Harbinger Mountains to the northeast (Fig. 2). The term plateau is used in the geographic sense for a level upland, dissected or undissected, regardless of the nature and attitude of the underlying rocks.

Aristarchus Plateau

The plateau is a broad rectangular island-like mass, convex in profile, rising above the level of Oceanus Procellarum. It is approximately 160 miles northwest-southeast, and about 100 miles northeast-southwest. Because of its angular shape, Moore and Cattermole (1967, p. 119) suggested that the plateau is a horst in the mare surface, partly eroded by substances extruded during formation of the mare depressions. Quaide (1965) had earlier attributed the shape of the plateau to uparching. Both structural interpretations are supported in the present report.

Relief varies in different parts of the plateau (Lunar Aeronautical Charts 38 and 39). The rims of Aristarchus and Herodotus stand some

7900 feet above the adjacent mare surface; their depths are recorded as 8700 and 4700 feet respectively. Outside the area of these giant craters, maximum recorded relief is about 5200 feet, in the area northeast of Schröter's Valley. Elsewhere the relief is less; generally below 3300 feet, in the scattered hills west of Herodotus.

A large part of the plateau appears hummocky in the Lunar Orbiter IV photographs, although most slopes are gentle. Because of the 300-meter (1000 feet) contour interval of the lunar charts, the bulk of the hummocks visible in the photos are not recorded by the contours. The assumption is that most are less than 1000 feet high and many probably considerably less. Many are equidimensional and between 2000 and 5000 feet across. They are fairly densely spaced so that much of the surface appears pimply or cobbly at the scale of the photos. The hummocks occur throughout the plateau except in mare embayments, in inland basins of mare-like material, and in parts of the upland adjacent to Schröter's Valley.

Standing above the hummocky surface of the plateau are scattered hills, ridges, and sprawling masses, largely confined to the southeast quadrant, west of Herodotus, and to the northeast quadrant, northeast of Schröter's Valley (Fig. 2). The ridges and hills west of Herodotus show a preferred northeasterly orientation, but some of the sprawling masses have irregular shapes. Many of the hills are more than 3000 feet high with one peak reaching nearly 4300 feet. The hills in the western half of the group form a semicircular pattern suggestive of a crater rim, but the arrangement may be coincidental. The upland northeast of Schröter's Valley displays some orientation, but much of it consists of broad masses of which only the borders reflect the preferred orientation. The entire northwestern half of Aristarchus Plateau shows only a few scattered hills.

The plateau displays faint tonal and topographic lineations paralleling the rectangular plateau borders and probably indicating fractures. There is no clear evidence, however, of closely spaced fracturing.

Harbinger Mountains

Just east of Aristarchus Plateau and separated from it by about 25 miles of mare, is Prinz Crater with the Harbinger Mountains extending to the northeast (Fig. 2). Prinz Crater, largely submerged by mare material, is about 28 miles across. Harbinger Mountains consist of isolated and rather widely separated hills and ridges of light-toned terra trending to the north and northeast. The higher peaks stand nearly 5000 feet above the adjacent mare surface which surrounds and embays them. The mountains are thus pre-mare in age. Moore (1965) maps them as Imbrium.

Sculpturing of the Aristarchus Region

Examination of the relatively small residual mountains in the Aristarchus Region reveals some valleys similar in appearance to terrestrial valleys. Whether more would be revealed in larger scale photography, is of course problematical.

In Figure 16, note the valley systems in the neighborhood of A and B, and the deep V-shape valleys at C. The smooth mare-like material to the east and west of A and B embays the irregular topography and emphasizes the funnel shapes of some valleys. Note, in contrast, the relatively straight northwest-trending shoreline of Oceanus Procellarum.

The possibility that the hills represent ejecta dumped in ragged heaps is improbable because of 1) the difficulty in accounting for their northeasterly orientation unrelated to any large source crater, 2) the improbability that ejecta would be deposited in scattered piles up to 4000 feet high, and 3) that the ejecta would fall in such fashion as to leave primary valleys, some with possible dendritic patterns. The topography of at least part of the hills, if present on Earth, would be interpreted as the product of fluid erosion.

Although the abundance of craters clearly indicates modification of the topography by meteor impact, few of the craters are more than one mile in diameter and only a few reach 3 miles. The vast majority are small and could only have modified, not created, the deep scuptural details of the hills. Nor is it likely that sputtering erosion by the solar wind created the deep sculpturing. Wehner (1964) has concluded that sputtering erosion probably amounted to only about 17 cm in 4 1/2 billion years and that this was compensated for by dust accumulation. As for mass movements, only debris avalanches seem capable of producing integrated valley systems as at A and B, provided that a linear depression with suitably steep slopes was already available. The valleys we are concerned with, however, differ significantly in appearance from linear mass movement features such as those on the inner and outer slopes of Aristarchus. Figure 17, reveals what appear to be debris avalanche tracks on the northwest wall of Aristarchus at A, B, C, D, and elsewhere. Note that these are 1) long narrow features with uniform widths from source to termination, 2) have narrow confining levees, 3) have only slightly curving paths, 4) have broad U-shaped cross-profiles, 5) display evidence of deposition but not erosion, as along the lower course of A, and 6)terminate on the slopes rather than continuing to the crater floor. Similar features are visible on the outer slope of Aristarchus at the top of the photo. The dark material at E is probably a lava pool; in the original photo, under magnification, its surface appears wrinkled and its margins lobate.

Figure 18 shows other debris flows on the north flank of Aristarchus. Levees and terminal deposits are well displayed. These features, as well as those shown in Figure 17, bear no resemblance to the valley-like features with which we are concerned. The origin of the broad, thin, lobate sheets of dark material with light borders (C and D), is unknown.

Still another type of linear feature is shown in Figure 19 on the southwest flank of Aristarchus. Unlike the debris avalanches, this feature follows a swale that contours the slope and is interpreted as a lava flow.

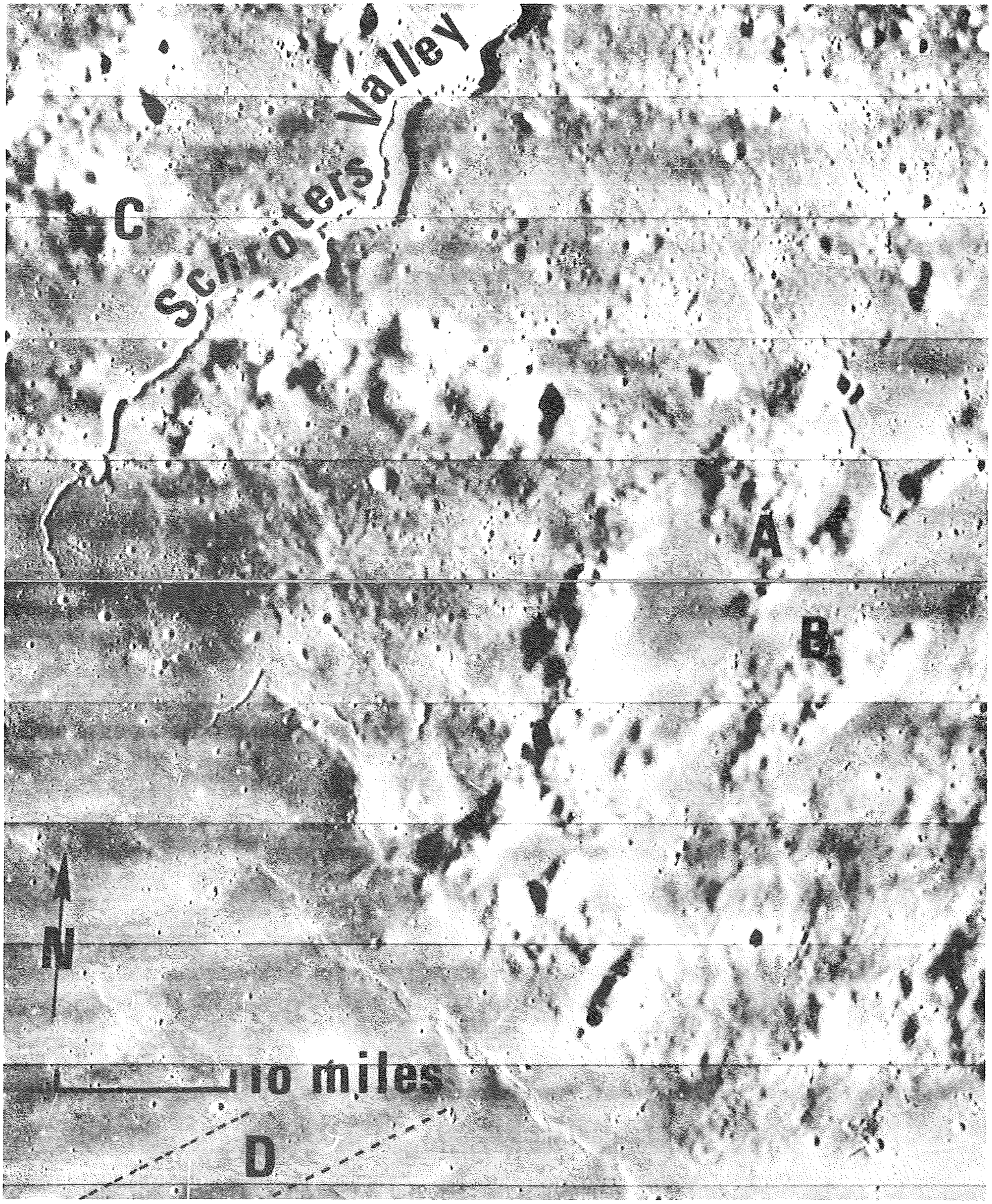

Fig. 16. Mountain groups in Aristarchus Plateau west of crater Herodotus. Oceanus Procellarum in lower left. Note contrast in topography between mare-like material in lowlands in vicinity of A and B, and plateau surface elsewhere. The terra hills have been battered by meteors. Two of the craters are about 3 miles across; most, however, are small and incapable of more than slight modification of the original topography. Neither 1) pelting by meteorites or crater ejecta, 2) modification by mass movements, or 3) mantling by debris from Aristarchus (note rays on mare surface at D), has apparently been able to destroy or conceal the basic topographic forms of these hills. Close examination reveals valley forms and patterns as at A, B, and C.

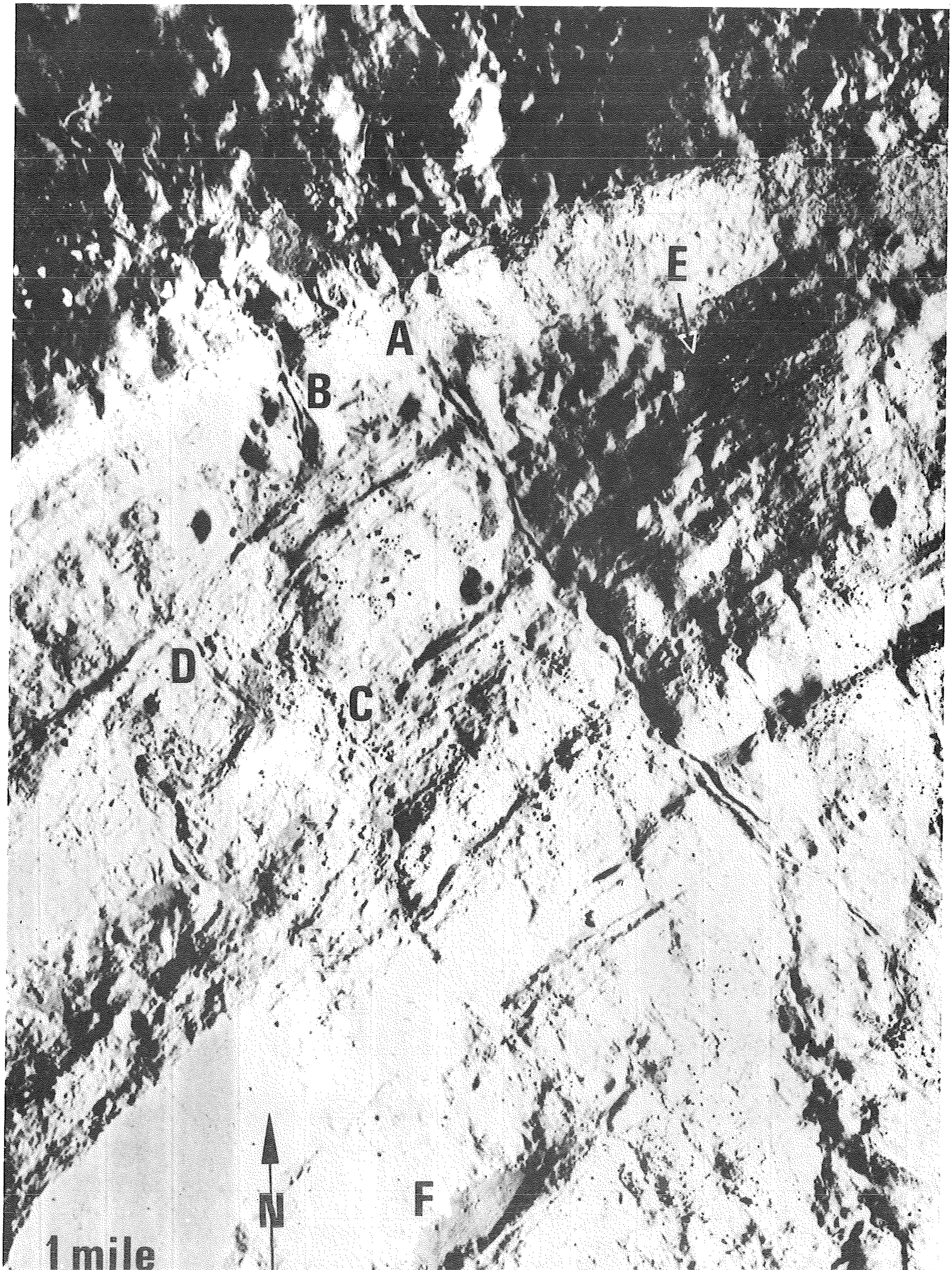

Fig. 17. Debris avalanches with levees on northwest wall Aristarchus (A, B, C, D). Track A is over 6 miles long. Probable lava pools at E, F, and elsewhere at back of slump blocks. Pools display cracking and tumuli or pressure ridges.

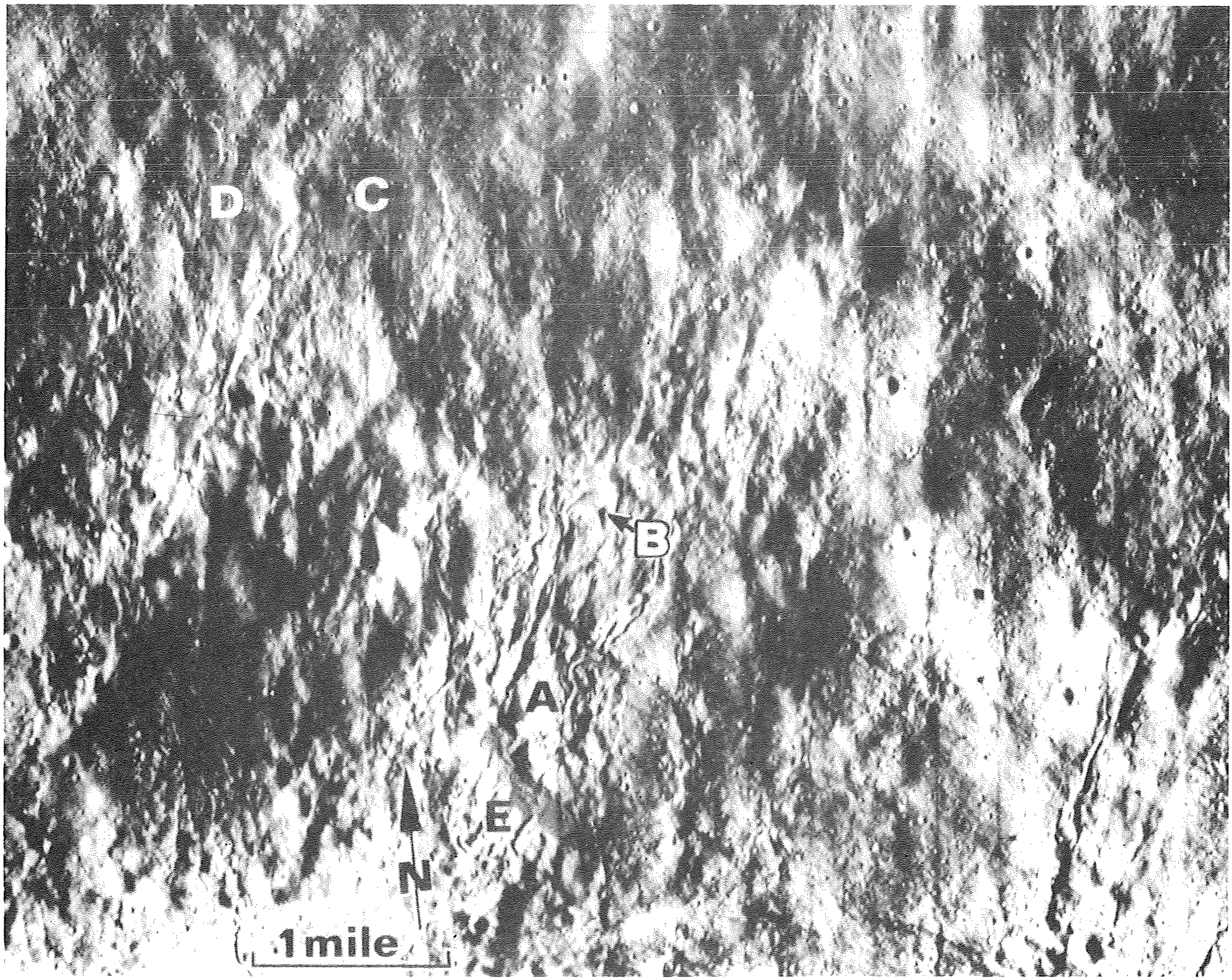

Fig. 18. Debris flows and tabular deposits, north flank of Aristarchus. Multiple flows with levees appear on either side of A and elsewhere. Note the bulbous lobe with crescentic ridges at B. Origin of broad tabular bodies at C and D unknown. Probable lava pool at E.

Fig. 19. Lava flow (?) about 4 miles long on southwest flank of Aristarchus. Most of the following characteristics support lave interpretation: 1) feature follows swale that contours slope, 2) starts in probable lava pool (A), 3) dark tone, 4) intricate braiding in lower course (B), 5) levees in upper course (C), 6) pressure ridges (D), 7) bulbous offshoots (E), and 8) a cross flow (F).

Locality II. The Alpine Region

The Alpine terrain within the area of Figure 9 displays three main topographic elements consisting of 1) the extensive hummocky or hilly terrain, 2) the larger mountain masses which stand above it, and 3) the floor of Alpine Valley and the scattered mare-like pools.

The Alpine Plateau

The hummocky, or intermediate level, will be referred to for convenience as the Alpine Plateau because of its wide expanse and relatively high elevation, but no implication of geologic structure is intended. The rugged plateau consists of a maze of hills most of which appear to fall within a restricted size range with diameters between 1/2 and 1 1/2 miles. Except for the scale, the topography is reminiscent of morainal topography or, on a reduced scale, of a cobble pavement. Judging from scattered slope measurements (Lunar Aeronautical Chart No. 12), largely in the plateau southwest of Alpine Valley, the plateau relief exclusive of isolated mountain masses, is probably 1000 feet or more. Isolated hills and ridges, some of which are comparable in height to the neighboring mountains, are scattered about the plateau. Some of these masses are up to 10 miles or more in length. The plateau surface is pitted with craters the largest of which are Alpes A about 8 miles in diameter, and Trouvelot, about 7 miles across. According to the lunar chart, Alpes A is about 4400 feet deep and Trouvelot, about 3800 feet deep. Most of the craters range from about 3 miles in diameter down to the limits of visibility, with the abundance increasing rapidly with diminishing size.

Very few of the craters display prominent rims. A striking exception is the raised crater, about 1 1/2 miles across, on the south side of Alpine Valley near The Collar. The prominent rim and moderately steep slopes, in contrast with all its neighbors, suggests a cone of internal origin. For convenience, we shall refer to it as The Puck.

The rocks of the lunar Alps have been mapped by Page (1966) as Imbrium in age, representing ejecta from the Imbrium Basin. M'Gonigle and Schleicher (1966), on the other hand, date them as pre-Imbrium or early Imbrium in age, but believe they are mantled by younger material.

The topography of the Alpine Region, including the cobbly plateau, is clearly influenced by intersecting fractures. The fractures are reflected in the topography by elongate hills, aligned hills, low linear ridges and swales, and facetted slopes(Fig. 11). One major fracture set trends NE-SW, parallel to both Alpine Valley and the abrupt mountain border about 40 miles to the northwest. A second major direction is at right angles to this, in a NW-SE direction. It is expressed by aligned high mountains at the Imbrium border, the rough alignment of other mountain masses, and the strike of planar slopes of individual mountain blocks. A third, N-S set is indicated by other planar mountain slopes and by the orientation of the peninsula-like projections into Alpine Valley. A fourth, E-W set is clearly indicated on the plateau surface in the area adjoining Mt. Blanc and in the linear mountain mass just east of The Puck. Many of these fractures have been mapped by Page and by M'Gonigle and Schleicher (op. cit.). The adjacent surfaces of Mare Imbrium and Mare Frigoris, in contrast, are relatively unfractured.

The Alpine Mountains

The Alpine Mountains within the area of Figure 9 have much greater extent north of Alpine Valley than to the south. On the north, they extend more than halfway across the upland toward Mare Frigoris. On the south, except for scattered outliers, they are restricted almost exclusively to the border of Mare Imbrium.

The mountains form ragged groups separated by areas of plateau or embayments of mare-like material. Many individual mountain masses are elongate in a N-S direction, but consist of facets determined by intersecting fractures. Many are asymmetric, resembling tilt blocks. The mountain groups are oriented approximately parallel to the border of Mare Imbrium. They terminate abruptly to the north in a rectilinear front normal to the coastline and parallel to Alpine Valley. This bold front is probably the site of a major fault.

Relief in the Alpine mountains is considerable. Mount Blanc, on the border of Mare Imbrium 25 miles southeast of the mouth of Alpine Valley, stands 4800 feet above the adjacent plateau surface (Lunar Chart No. 25). The high peak midway between Alpes A and Alpine Valley, is 5000 feet high. The highest peak, just outside of the left margin of Figure 9, is 10,000 feet high.

Sculpturing of the Alpine Region

In considering possible origins of the Alpine topography (Fig. 20), the basic question is whether this is 1) a pristine tectonic landscape with each block of terra, from largest to smallest, an original horst or tilt block modified only by scattered large craters and universally smoothed by micrometeorite impacts and mass wasting, 2) an earlier tectonic landscape differentially etched by presently recognized lunar processes, or 3) an earlier tectonic landscape modified by fluid erosion.

An unmodified tectonic landscape seems unlikely. I am unaware of a terrestrial analog where tectonism has produced a comparable array of pristine tectonic blocks in such intimate profusion and with such diversity of scale. The larger blocks may well have been uplifted relative to the plateau surface, but not all of the second order relief of the blocks, and little of the detailed relief of the plateau, can be attributed to original tectonism. Nor do generally accepted lunar processes seem adequate to explain either the magnitude or the selective nature of the degradation. Selective modification of an original fault topography by large meteorites is unlikely because of the relative scarcity of large craters in the area and the widespread preservation of planar slopes. Erosion by basal surges resulting from major meteoric or volcanic

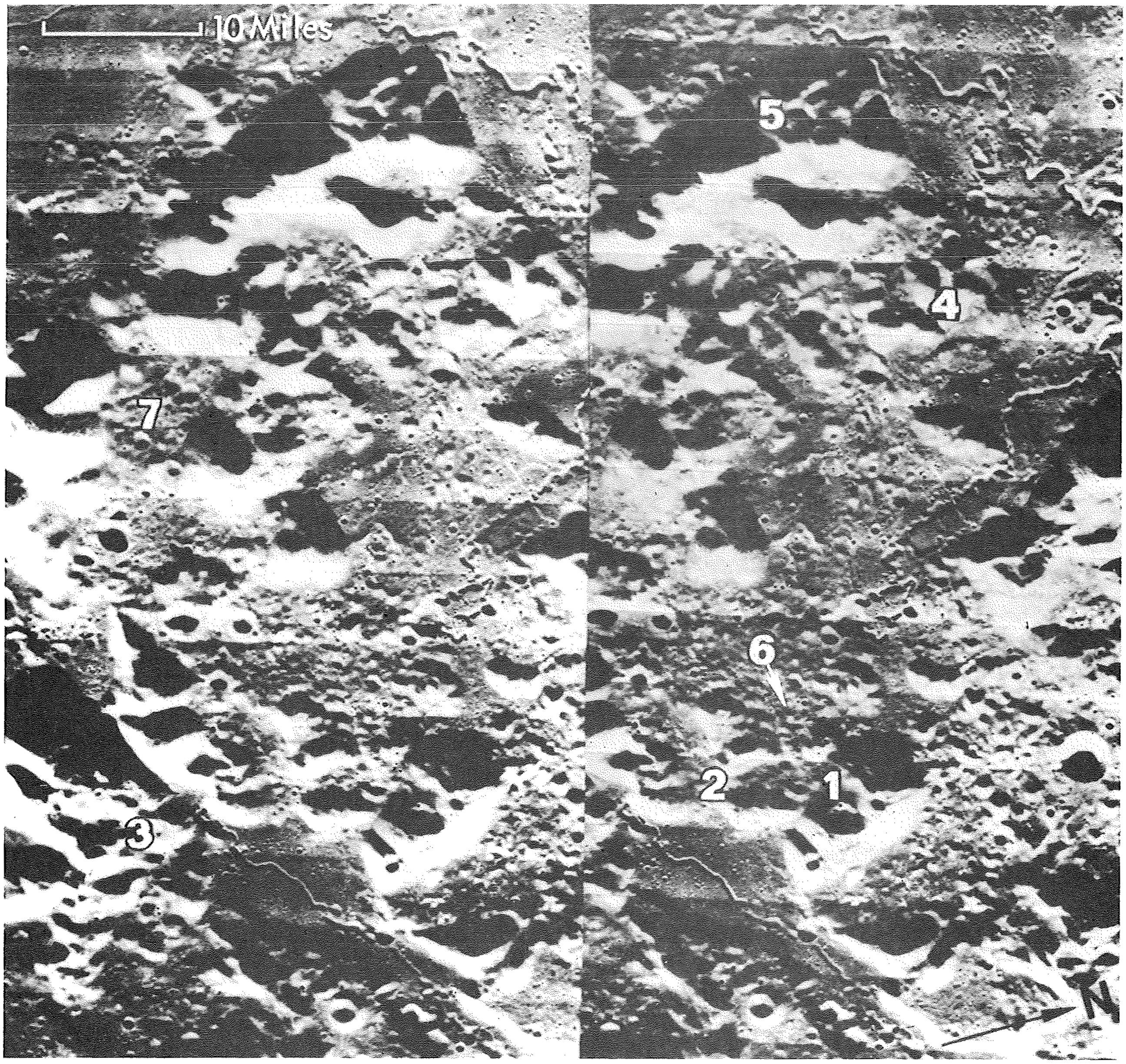

Fig. 20. Stereopair of part of Alpine region. Alpine Rille in lower part of figure. The large sinuous rille is Rima Plato II. Relief amounts to thousands of feet. Fault control indicated by bold, linear, and facetted mountain fronts to west and north of 5; planar faces of hills and ridges as at 1 and 7 (note the multiple, shingle-like facetting of ridge at 1 and its truncation by the linear slope on east); asymmetric ridges and valleys as at 1 and 2; and geometric patterns in the lowlands, as at 6. The valleys at 3, 4, and 5, although fracture-controlled, appear to be integrated. It seems unlikely that this is a pristine fault topography with each unit, from tiniest to largest, an original fault block modified only by recognized lunar processes. A more reasonable explanation based on terrestrial analogs is differential erosion of a complexly fractured area. The displacement of successive horizontal strips is due to the electronic procedures used in photography and transmission.

events outside the immediate area is unlikely because of 1) the lack of evidence that comparable phenomena on Earth, such as nuées ardentes, are effective eroding agents, 2) the magnitude of the differential degradation, and 3) the multiplicity of trends of ridges and valleys in the plateau most of which can not be related to large craters close to the area. Differential degradation resulting from pelting by small meteorites can not explain the relatively deep linear valleys, and erosion by the solar wind is regarded by most investigators as inconsequential.

The inadequacy of known lunar processes to explain satisfactorily the Alpine landscape justifies consideration of the possible role of fluid erosion. Figure 21, of an area in the Black Hills of South Dakota, appears to be a reasonable analog or part of the Alpine Plateau. The area is crisscrossed by fractures in several directions and a number of planar slopes are visible. The topography, however, is due to differential erosion as indicated by the well-developed integrated drainage, parts of which are delineated. The analogy with the Alpine Plateau suggests that the latter too, may have been subject to fluid erosion long enough to have resulted in many hundreds of feet of relief.

M'Gonigle and Schleicher (1966) believe that much of the material of the Alpine region consists of lava and pyroclastic deposits. A sheeting may be observed in this material at many places (Fig. 22). Locally, the trends of ridges conforms to the strike of this sheeting, but over most of the region the topography seems to be independent of it. If the sheeting is actually stratification, its truncation by the plateau surface would constitute additional evidence of considerable erosion. The products of such erosion could conceivably lie buried under the mare-like deposits of the interior basins and under the latest deposits of the neighboring maria.

Locality III. Northwest Border of Mare Serenitatis

Figure 23 is a stereopair of part of the northwestern border of Mare Serenitatis. The topography resembles that of the lunar Alps. The upland joins the Causasus Mountains at the top (west side) of the view with Mare Serenitatis on the left (south). The dark mare-like material on the right (north) is within the irregular crater Alexander.

Fracture control of the topography in at least two directions, northeast-southwest and northwest-southeast, is indicated by 1) the rectangular topographic mosaic in the hummocky plateau between A and B (arrows), 2) the geometric patterns in the higher mountains, as at C, and 3) the orientation of obvious fracture planes at D. The evidence favoring fluid erosion is the same as for the Alpine region although in neither of these two areas may the evidence be regarded as convincing. Earthly analogs of such topography with rugged highlands, intricately engraved lowlands, accordant and rounded lowland hills, and intricately embayed shorelines result from differential erosion of fractured terrain rather than pristine tectonics. Many of the valleys, furthermore, have V-shaped cross profiles as in the vicinity of C and E, and the drainage appears to be integrated at E and F.

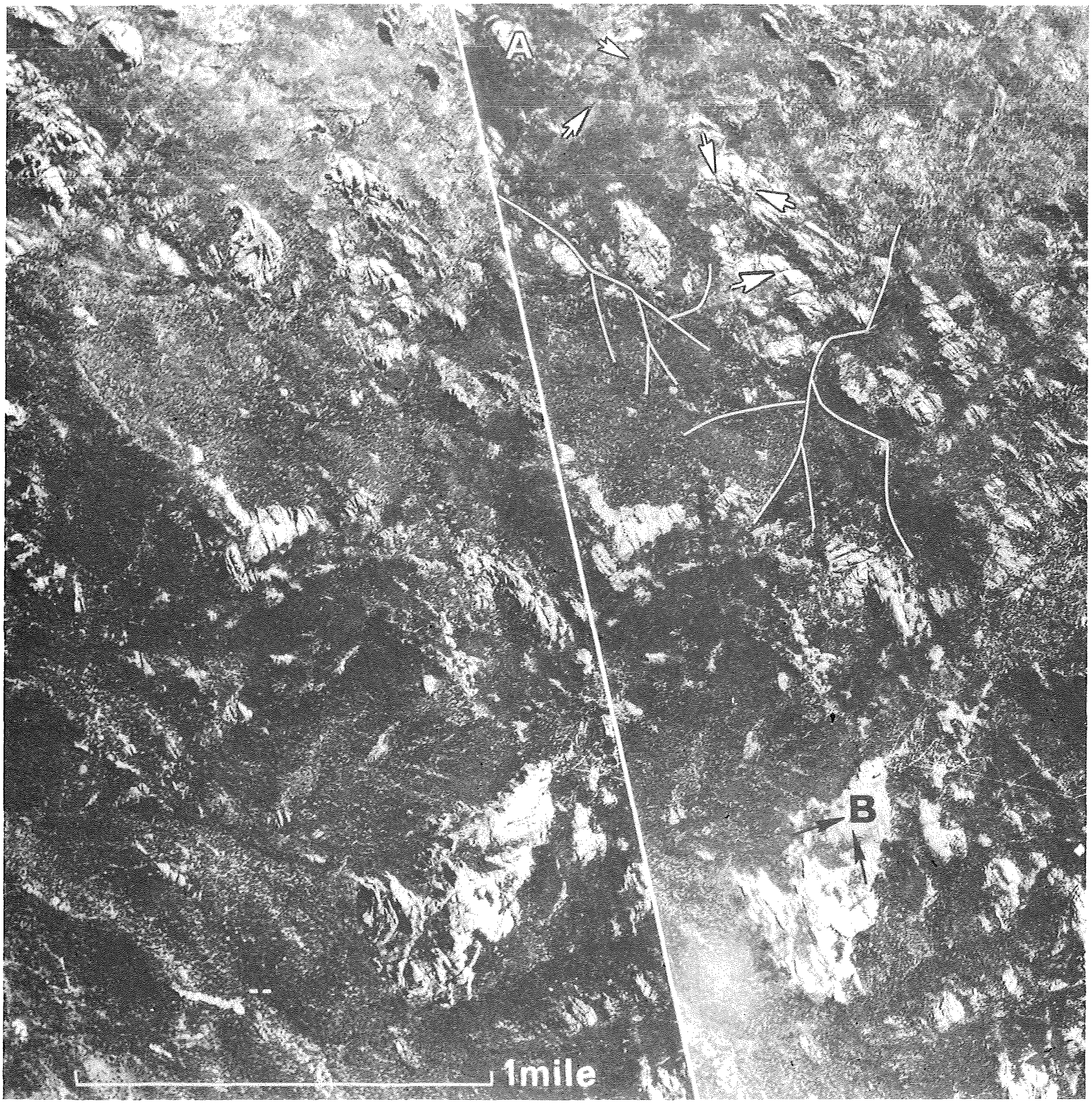

Fig. 21. Fracture-controlled topography in Black Hills, South Dakota. Arrows indicate prominent fracture directions. Planar faces at A and B. Integrated drainage shown locally. Modified from Ray (1960).

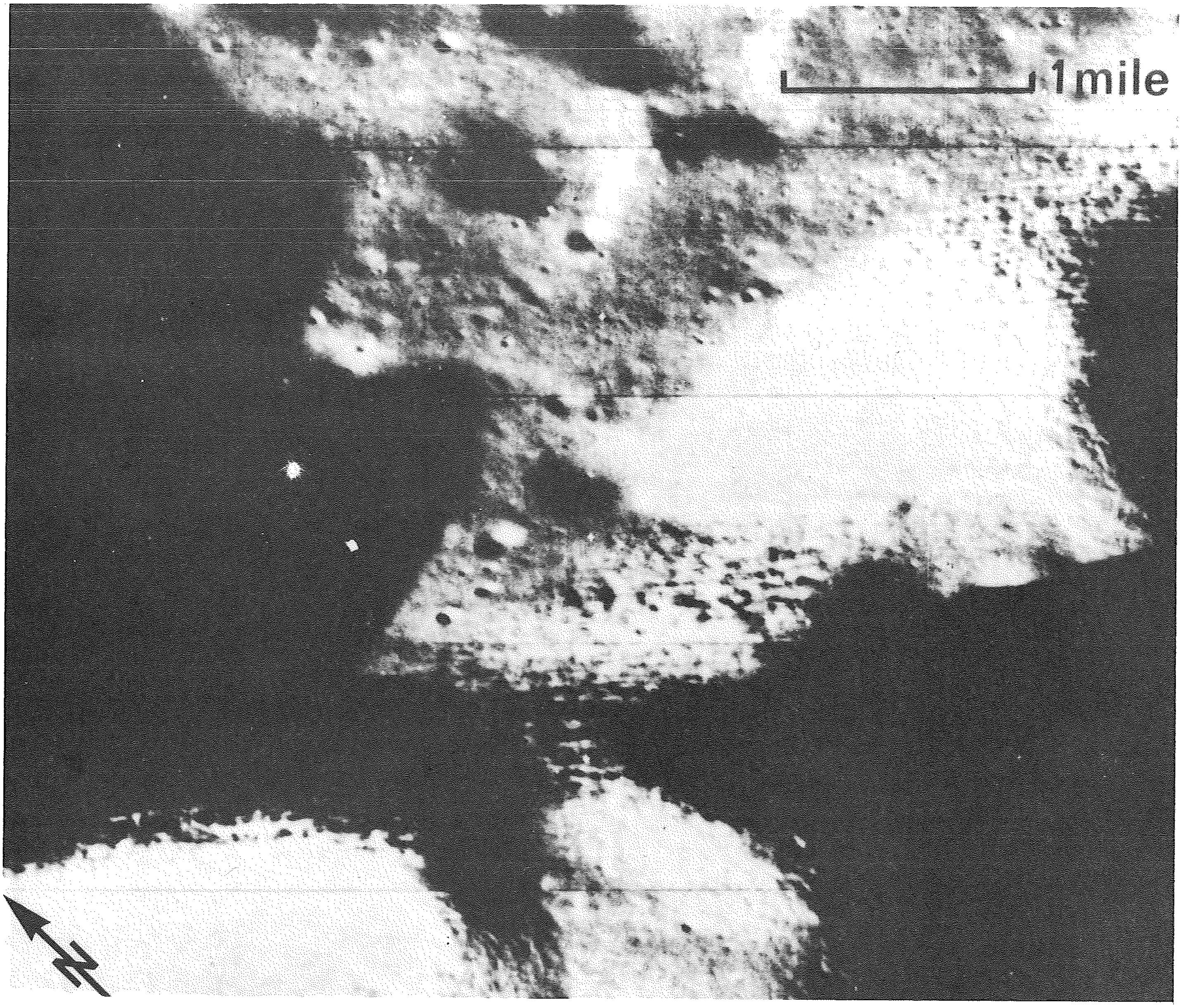

Fig. 22. Sheeting (stratification? shearing?) in terra landscape of the lunar Alps. If the sheeting is stratification, considerable regional degradation is implied. Note the slight divergences in strike in the lower center.

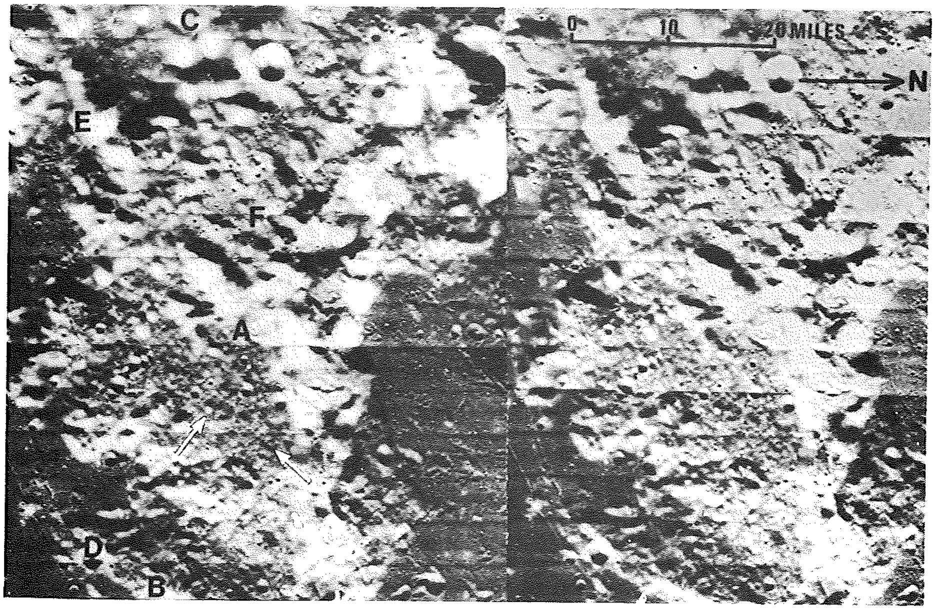

Fig. 23. Stereopair of part of northwest border of Mare Serenitatis. Part of Caucasus Mountains at top (west). For explanation, see text.

If fluid erosion is in fact indicated, it must have occurred at an ancient date to account for the degree of modification of erosional details and for the drowning of valleys by mare materials.

Locality IV. Southern Apennines

Figure 24 shows a segment of the Apennine escarpment overlooking Mare Imbrium, a small portion of which appears at the upper left. Part of Sinus Aestuum is in the lower left. Maximum relief in this area is about 4500 feet. The influence of northeast-southwest and northwest-southeast fractures is revealed by lineaments, particularly in the lowland areas. Fractures in other directions are also present. The rocks of the mountains are older than the mare materials which lap against and invade indentations in the mountain terrain. Large, apparently integrated valleys are indicated in the west, but careful analysis reveals even clearer, but much finer-textured drainage integration in the lowlands in the right center. Fracture control of drainage here is clearly indicated by the northeast-southwest trend of the ridges. The intervening valleys, many V-shape, have been etched out along these fractures by some effective agent of erosion. Except then, for the main scarp, fractures have primarily served as favorable sites for differential erosion.

Locality V. Taurus Mountains

Except for the relatively recent crater Newcomb and the rims of a few smaller craters, the topography shown in Figure 25 is subdued and smooth. This is in keeping with the relatively ancient date (Imbrium and pre-Imbrium) assigned to these materials by Pohn (1965). A subdued NW-SE ridge-and-valley topography disappears under the mare-like filling of old depressions indicating an ancient date for this topography. The depths and V-shape profiles of many of the valleys, their remarkable linearity regardless of the ruggedness of the relief they cross, and the presence of parallel linear scarps in the higher uplands, render it unlikely that these features are in any way related to ancient base surge activity. Fracture control is indicated. A second set of lineaments crosses the first at approximately right angles. In places this has resulted in a segmentation of the NW-SE ridges and commonly a checkerboard topography. The higher, bolder parts of the topography also show an angular blockiness indicative of fracture control. It is interesting to note that Pohn (op. cit.) originally inferred the presence of faulting on the basis of small scale telescopic photos and visual observations.

For reasons presented in the discussion of the Alpine landscape it is unlikely that this topography can be either a pristine fault topography or a fault topography modified only by generally recognized lunar processes. A fluid medium capable of etching out lowland valleys and dissecting steeper slopes seems required. A similar explanation seems required for the sinuous valleys draining the inner slopes of some of the old craters. Where the crater floors are occupied by a mare-like filling, the submerged lower slopes present an embayed shoreline.

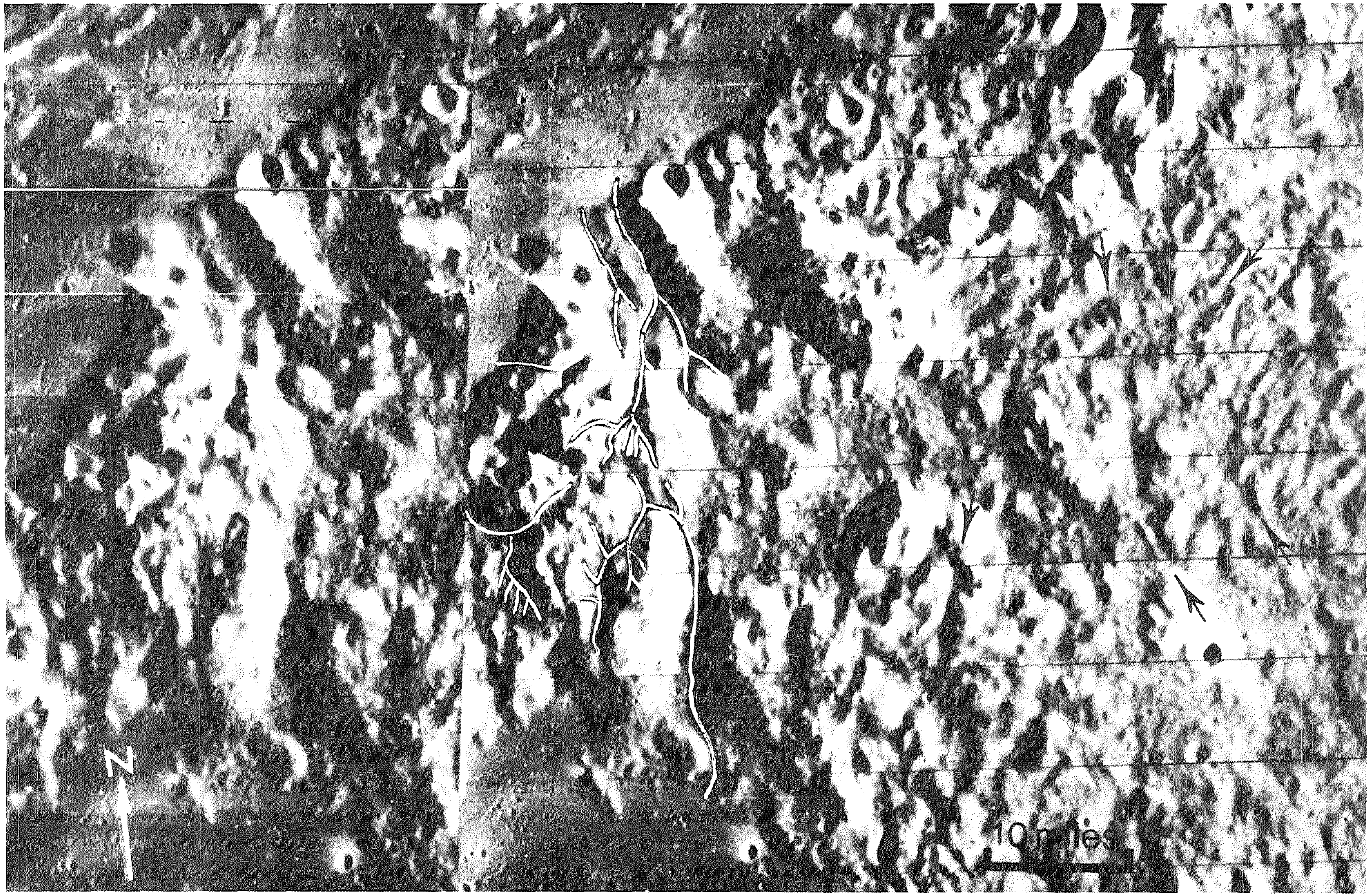

Fig. 24. Southern Apennines. The bold, linear, facetted escarpment overlooking Mare Imbrium in the upper left is clearly a fault scarp comparable to the Alpine escarpment farther north. Fractures, indicated by arrows, are revealed not only by lineaments but by crenulate ridges in the lowlands. Fractures in approximately NW-SE and NW-SW orientations are most common, but lineaments in other directions, two of which are indicated, are also present. Drainage appears to be locally integrated, as in the two areas delineated. Better examples, but on a much smaller scale, are present in the low areas to the right.

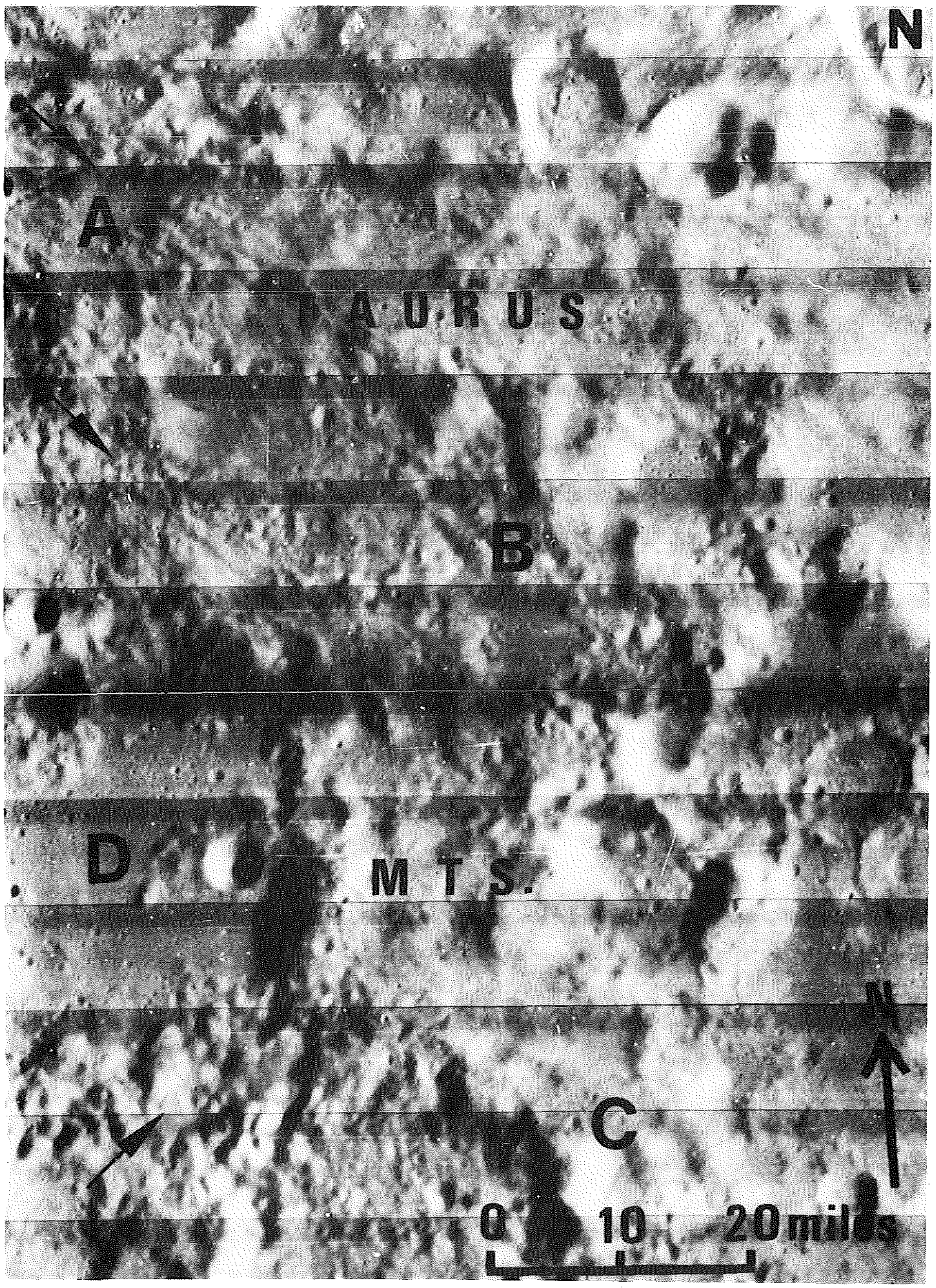

Fig. 25. Taurus Mountains. Except for the rim of the relatively recent crater Newcomb in the upper right (N), and the rims of a few smaller craters, the topography is subdued and smooth. This accords with the ancient date assigned to these materials. In spite of the worn appearance, the influence of NW-SE and NE-SW fractures in controlling differential erosion is obvious. Major fracture directions are indicated by the arrows. In parts of the area, as at A and B, there is a subdued ridge-and-valley topography. This topography crosses areas of considerable relief, as north of B. The higher, bolder parts of the topography, as at C, show an angular blockiness also reflecting fracture control. They include scarps paralleling the indicated fracture directions. The margins of the crater, D, are etched by sinuous valleys which descend toward the crater floor where they are embayed by mare-like material. The intricate details of the topography in this area suggest a prolonged episode of degradation involving a medium capable of eroding lowland valleys and dissecting steeper slopes.

Locality VI. Ukert Region

Ukert is located in the low upland between Sinus Medii and Mare Vaporum. The deposits of the area shown in Figure 26 have been mapped by Wilhelms (1968) as the Fra Mauro formation believed to consist of ejecta from the Imbrium basin to the northwest. These ejecta are beleved to mask an underlying landscape in which older basins, such as Aestuum and Vaporum, as well as their terra borders, already existed. A hummocky member of the Fra Mauro formation is present outside the area of Figure 26 and generally closer to the source of debris. It is believed to consist of clots of ejecta, although parts of the terrain are described as hills of structurally deformed bedrock. The smooth facies of the formation is generally farther from the source of supply and is believed to be thin. Areas of smooth topography closer to the source, are believed to have been levelled by mass movements.

According to Wilhelms, the rugged depressions in the topography are occupied by volcanic materials. Volcanism is presumed to have become increasingly active toward the end of the Imbrium Period with flows of mare material (Procellarum Group) filling old bains. The volcanic flows are believed to have been preceded and followed by pyroclastic deposition. Ukert and some of the fresh-looking smaller crater in Figure 26 are of later origin.

According to Lunar Aeronautical Chart No. 59, in which the topography is expressed by a 300-meter (1000-feet) contour interval, some of the NW-trending valleys are more than 1000 feet deep. The crater Ukert is mapped as 9500 feet deep; its rim stands about 8000 feet above its surroundings.

Possible interpretations of the linear valleys are: 1)they are original depressions between longitudinal ridges of Imbrium ejecta deposited as we now see them, 2) they were eroded in Imbrium deposits, possibly along fractures, after creation of the Imbrium basin but before accumulation of the latest mare materials, 3) they are narrow down-dropped crustal slivers, and 4) they are pre-Imbrium valleys formed in any one of the above ways and subsequently lightly veneered with Imbrium ejecta.

We need concern outselves at this time solely with the question of origin, leaving the problem of age for later. For reasons cited in the discussion of the Alpine region, the down-dropped sliver hypothesis seems untenable. The hypothesis of original depressions between ridges of ejecta also encounters difficulties. The first concerns the ragged pattern of the upland as a whole. It is difficult to conceive of such spotty, primary deposition, and with such high relief, at a distance of more than 185 miles from the Imbrium border. The effectiveness of debris-laden density flows,or basal surges in streamlining topography at this great distance from the Imbrium basin, especially considering the great depths of some of the linear depressions and the presence of steep, linear scarps more than 16 kms long, is doubtful. Fisher and Waters (1969) report that terrestrial density flows of the nuées ardentes type are dispersing and depositing agents, not erosional. They report that the deposits are wave-like with low-amplitude and long axes perpendicular to current direction. These authors suggest that if permafrost exists on the moon, base surges of phreatic as well as impact origin may have occurred. The problem is not solved by assuming that the ejecta form only a thin veneer on an older landscape: it merely moves the problem back one stage in time.

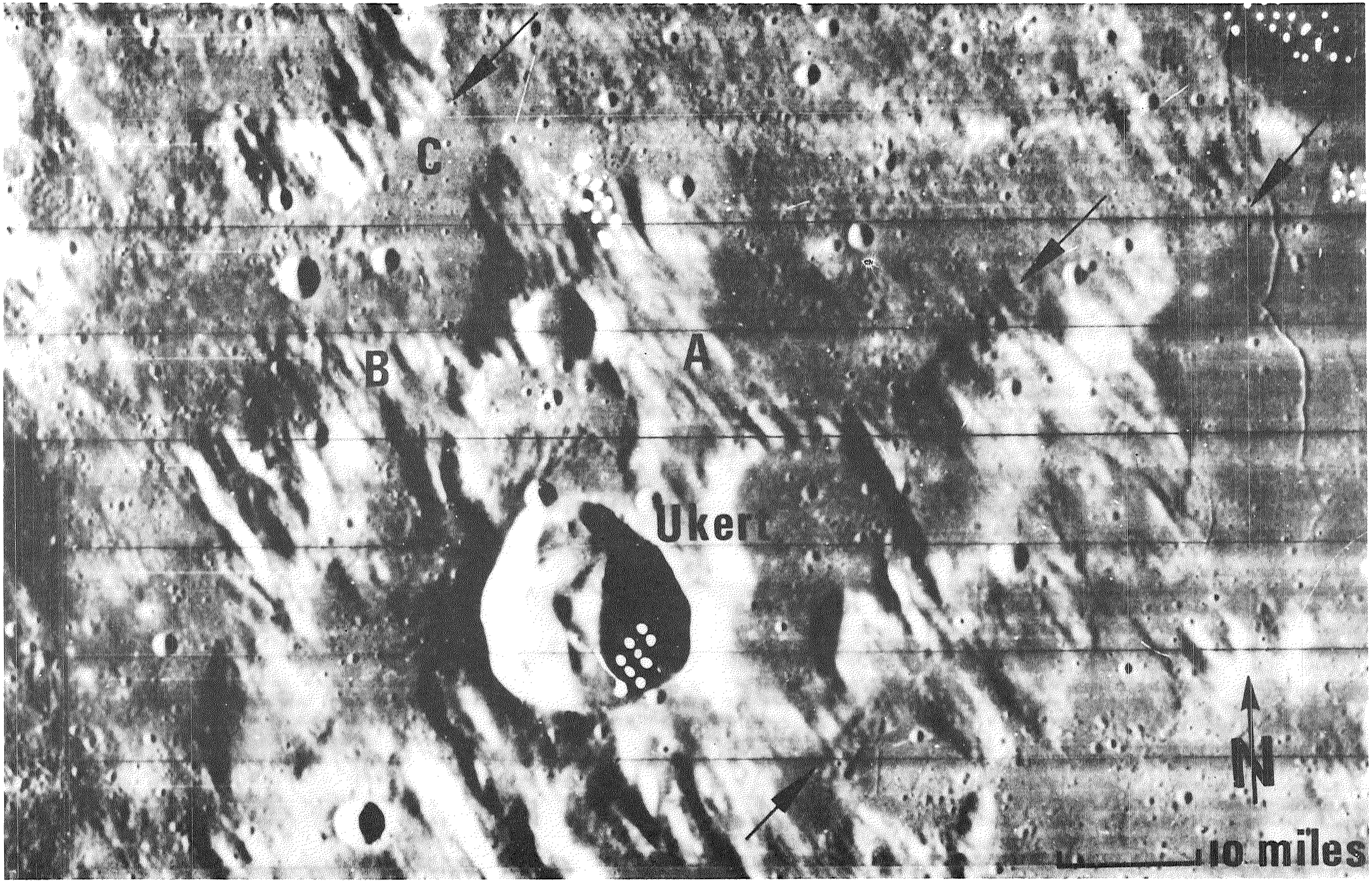

Fig. 26. Ukert region. The northwest-southeast valleys are fracture-controlled. A second fracture direction is indicated by arrows. The landscape is attributed to differential erosion by a fluid (see text). Integrated valleys appear in the upland at A and to the left of B. Embayment of the northwest-southeast valleys by mare material indicates erosion prior to appearance of the latest materials of the maria. At C, the mare material not only banks against a linear scarp, but embays valleys that indent it. This confirms the interpretation that both faulting and erosion preceded flooding by mare material.

That the orientation of the valleys is fracture-controlled is indicated by their rectilinearity and parallelism, by their extension as linear traces across ridge crests, by complete transection of the ridges, and by the asymmetry of some valleys with one side a rectilinear scarp. The evidence fully substantiates the interpretations of Wilhelms (1968) who mapped a closely spaced set of fractures in this direction. A second fracture direction intersects the first at approximate right angles. Major fracture directions are indicated by arrows in the figure. The rectilinear contacts of the mare-like material with the lighter terra along some of these lineaments (as at C, Fig. 26) suggests that the terra was truncated in pre-mare time. Yet the drowning of terra valleys by mare materials indicates that the scarps themselves were eroded prior to appearance of the mare material.

Based on earthly analogs, the terra landscape appear to have been both fractured and dissected prior to appearance of the mare material which invades its borders.

Although stereoscopic coverage is unavailable there does appear to be integration of the faint valleys immediately west of the letter A, extending from the rim of the depression immediately to the right of Ukert, to the edge of the upland some 25 miles to the northwest. Another area of possible integrated drainage is to the left of the letter B.

The deep valleys, some of which are V-shape, the suggestive integrated drainage, and the general arguments used earlier against deep erosion by presently recognized lunar processes, suggests the possibility of fluid erosion, but at some distant date.

Locality VII: Higland border, southwest side Mare Tranquillitatis

The area shown in Figure 27 includes Tranquillity Base, the landing site of Apollo 11. Note that the areas at A, B, and C are 1) intermediate in albedo between the surface materials of Mare Tranquillitatis and the terra highlands, 2) are not as smooth as the mare surface, 3) have a greater number of visible craters, and 4) occupy lowlands in the terra. The western portion of the large circular area (B) is at mare level and is, in fact, embayed by mare materials. The surface of area B rises to the west where it drops off in a steep scarp. West of the scarp, across a deep depression, the terra rises to higher mountainous levels. The general topographic relations suggest that areas A, B, and C are lowland fills younger than the terra highlands but older than the mare surface. They may represent an early mare filling which was tectonically displaced and "eroded" prior to the latest deposits of Mare Tranquillitatis.

The highlands show a variety of topographic forms. Relatively massive areas appear at D and E; an irregular ridge-and valley topography is visible in the lowland at F; and a rectangular topography at G. The highland area south of Moltke resembles a plateau but with shallow ridges and swales. In considering topographic origins, the questions to be answered concern the development of the plateau terra well below

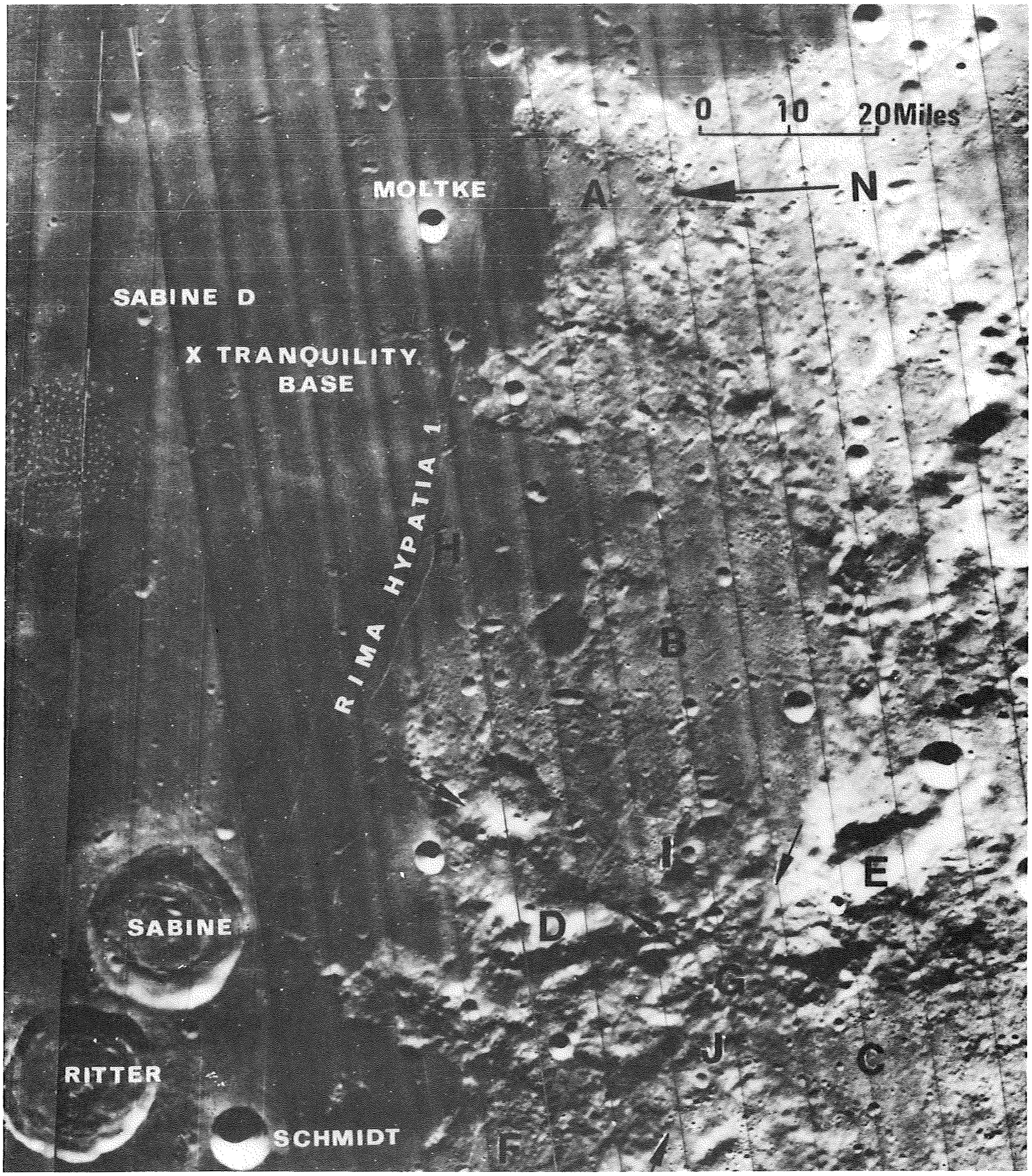

Fig. 27. Highland border, southwest shore Mare Tranquillitatis. A,B,C: lowlands occupied by material younger than mountain rocks but older than latest deposits of Mare Tranquillitatis. D,E: massive terra higlands, F: lowland area of low ridges and valleys, G: rectangular topography, H: Rima Hypatia 1, a graben with oblique offsets, I, J: high rimmed, volcanic (?) cones, X: Tranquillity Base. Mottled area to left, photo defects.

the level of the high peaks and ridges, the origin of the irregular "coastline" invaded by mare material, and the differential erosion of the terra along fracture sets. The two principal fracture directions are indicated by the paired arrows. The orientation is different, however, in the uplands surrounding A. The graben, H, with its oblique offsets, and the lineaments on each side, are obviously post-mare fill in age.

On the basis of earthly analogs, this complex terra topography does not appear to be a pristine tectonic landscape although the influence of fracturing is obvious. Nor, except in the lower part of the figure and around the mountainous border of the large depression, B, are there clear indications of fluvial-type valleys. This, however, may be partly due to the small scale.

There is a far greater concentration of craters of all sizes and degrees of wear than in preceding terra photos. This seems to be typical of the central and southern highlands. As later examples will show, evidence of possible fluid erosion in these regions is restricted to the rims of large craters or to the mare borders. The reasons for this will be explored later. Two high-rimmed cones, I and J, unlike the low-rimmed impact craters, may be of volcanic origin.

The rocks of this area have been interpreted as volcanic, both lava and pyroclastics, by Milton (1968). They are assigned an Imbrium age, next to the oldest rocks recognized on the moon. The rim materials of some of the fresher-appearing craters, such as Moltke, are assigned a younger age.

The rock materials collected on the Apollo Flight at Tranquillity Base have been reported on by the Lunar Sample Preliminary Examination Team (1969, p. 1217-1220). No evidence of erosion by surface water was found, and no secondary hydrated minerals were found in the rocks. Independent evidence of fluid erosion in the form of meandering rilles, however, is found only at a few scattered sites in the lunar maria, hence its absence here does not negate the idea of localized post-mare fluid erosion elsewhere. Nor does the absence of hydrated minerals in the few samples collected negate the former presence of water elsewhere.

Locality VIII. North wall crater Hipparchus.

Figure 28 is a stereopair of part of the north wall of crater Hipparchus. The rocks of this portion of the crater rim are pre-Imbrian in age (Howard and Masursky, 1968), that is, among the oldest recognized lunar rocks. Note the terrestrial-type valleys, with locally good integration, and the embayed lower slopes. The topography resembles drowned fluvial terrain on earth, although modified by craters and probably mass movements.

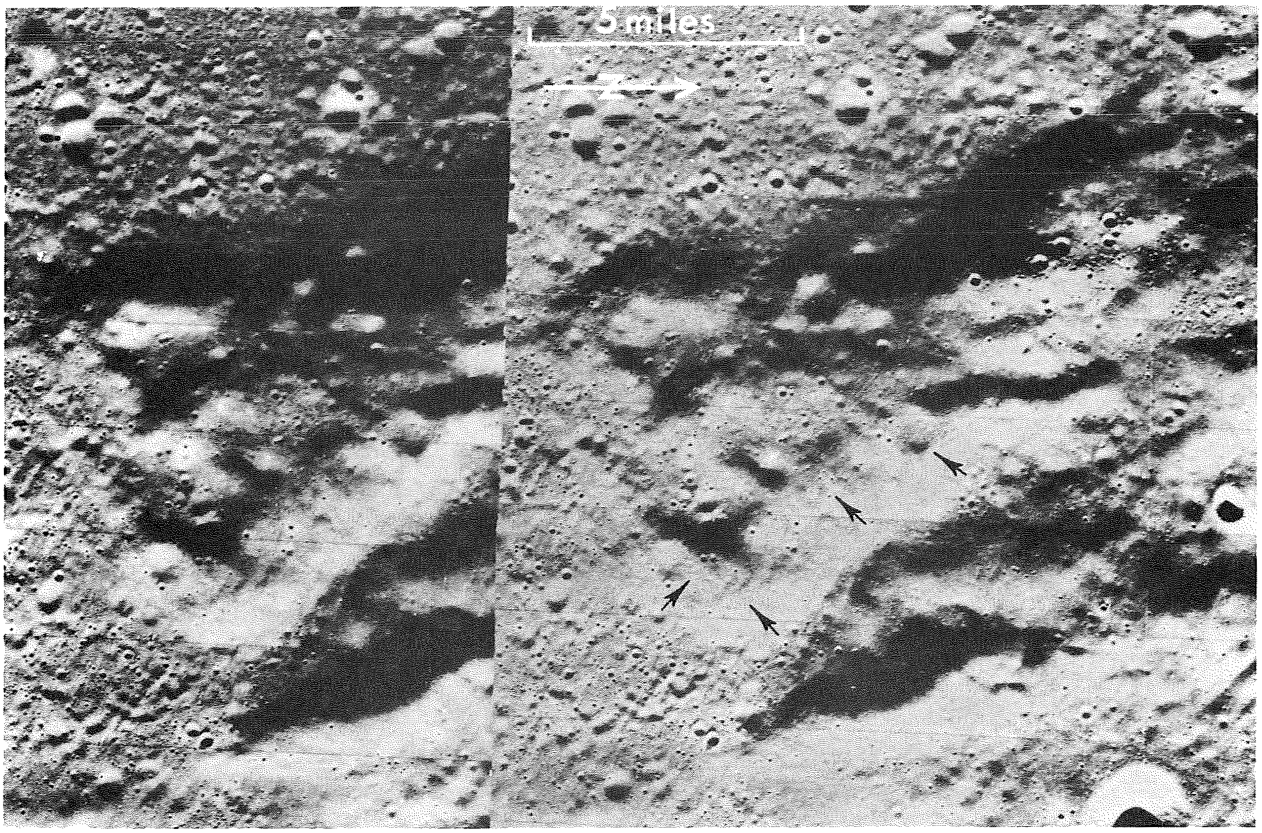

Fig. 28. Stereopair showing spurs descending from north wall of crater Hipparchus. Topography resembles drowned fluvial landscape on Earth. Crater floor material is more densely pitted than terra slopes although not by large craters. Craters possibly of internal (gas vent ?) origin. Arrows indicate fracture directions in terra slopes. Offsetting of parallel strips in stereomodel due to electronic procedures in transmission and recording of images.

Locality IX. Central highlands, Northeast side Mare Nubium

This locality (Fig. 29) is in the central highlands between the crater Ptolemaeus (Ptol.) and Mare Nubium (M). The rugged hills consist of ancient materials, largely pre-Imbrian (pI) in age (Howard and Masursky, 1968). Much of the smooth material which floods the lower areas, including the floors of Ptolemaeus and Alphonsus (Alph.), and which embays the hills, is mapped as Imbrium (I). The dark area in the southwest is youngest of all; the surface materials of Mare Nubium.

The preferred orientation of the linear depressions in the highlands conforms to one of the prominent fracture directions in this part of the moon and these fractures have presumably influenced the differential degradation of the area. Valley-like depressions with tributaries appear to be present in the area west of A and elsewhere.

For reasons presented earlier, the complex network of ridges and depressions is not regarded as a pristine tectonic landscape. An effective discriminatory agent of erosion must have operated prior to the Imbrium floods.

The chain of craters in the left center is clearly fracture-controlled. The parallel sides indicate a graben similar to Hyginus Rille (Fig.14)

Locality X. Rim of Alphonsus, central highlands

Alphonsus, just east of Mare Nubium and immediately south of crater Ptolemaeus, includes some of the oldest known rocks on the moon (Howard and Masurky, 1968). Except on the south, where overlapped by the later (Imbrium) deposits of crater Arzarchel, the deposits are pre-Imbrium in age, that is, older than the mare basins themselves. The topography of the inner and outer slopes (Fig. 30), although locally influenced by fractures, suggests fluid modification. The sculpturing includes curving V-shape valleys, some angular, some rounded. Suggestions of integrated drainage appear at a number of places as at A, in the area below B, and at C. The drainage basin below B presents a trellis arrangement of tributary valleys. In many valleys the downvalley gradients are interrupted. This is not surprising considering that landslides, debris flows, and creep must have been operating for long periods of time. Impact craters may account for other interruptions. The numerous interruptions suggest that the valley-forming processes are no longer operative. In contrast, landslide or other mass movement debris in terrestrial valleys is generally soon removed by stream erosion.

Locality XI. South shore Mare Nubium

In this area (Fig. 31), part of the southern plateau reaches the sea between rugged peninsulas. In terms of earthly analogs, the gross characteristics of the shoreline, that is, the many headlands, embayments, islands, and drowned craters (A, B, C), clearly identify it as a shoreline of submergence. If one concentrates on shoreline details, as at D, E, and south of B, it becomes apparent that many of the small embayments

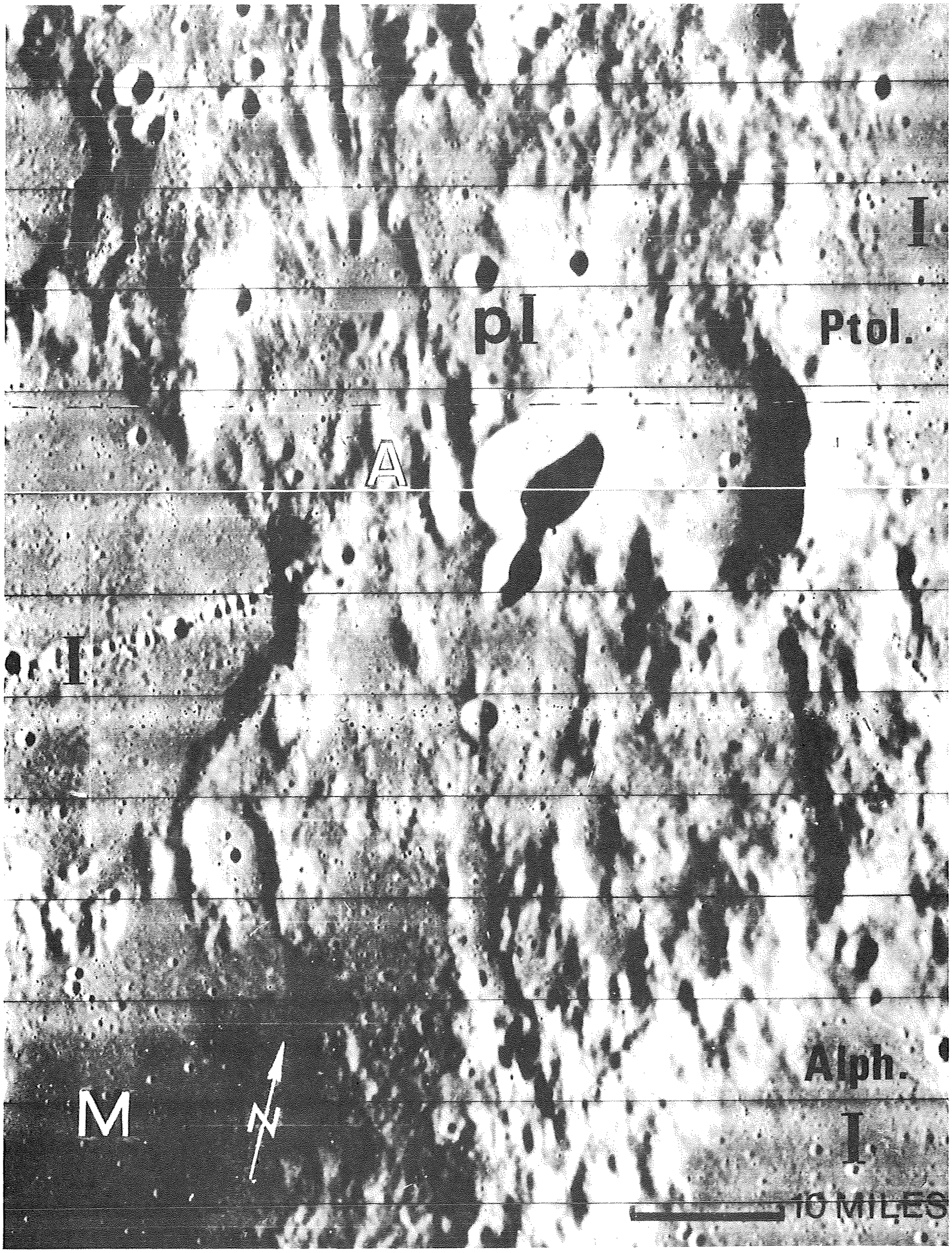

Fig. 29. Dissected upland west of crater Ptolemaeus (Ptol). Part of crater wall of Alphonsus (Alph) in lower right. M: reentrant of Mare Nubium; pI: pre-Imbrium rocks, among oldest on Moon; I: Imbrium deposits. As in Ukert area (Fig. 26), preferred orientation of ridges and valleys conforms to major fracture direction. Crater chain in left center clearly fracture-controlled and similar to Hyginus Rille (Fig. 14).

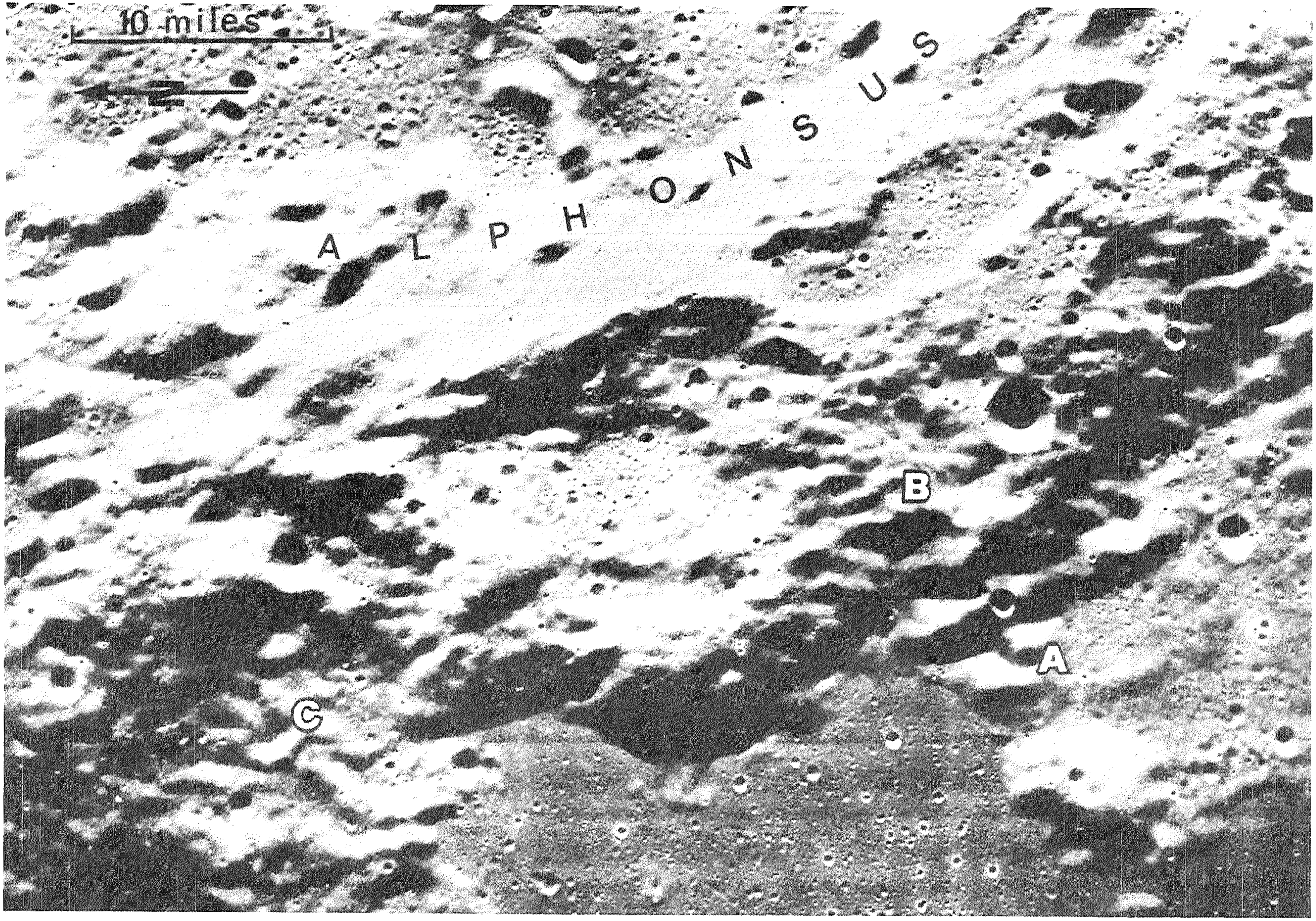

Fig. 30. Western rim of crater Alphonsus. Part of crater floor at top of view. V-shape valleys common. Integrated valleys at A, below B, and at C. Trellis pattern below B fracture-controlled. Dark area in lower part of photo is part of floor of Mare Nubium which inundates valleys in surrounding slopes.

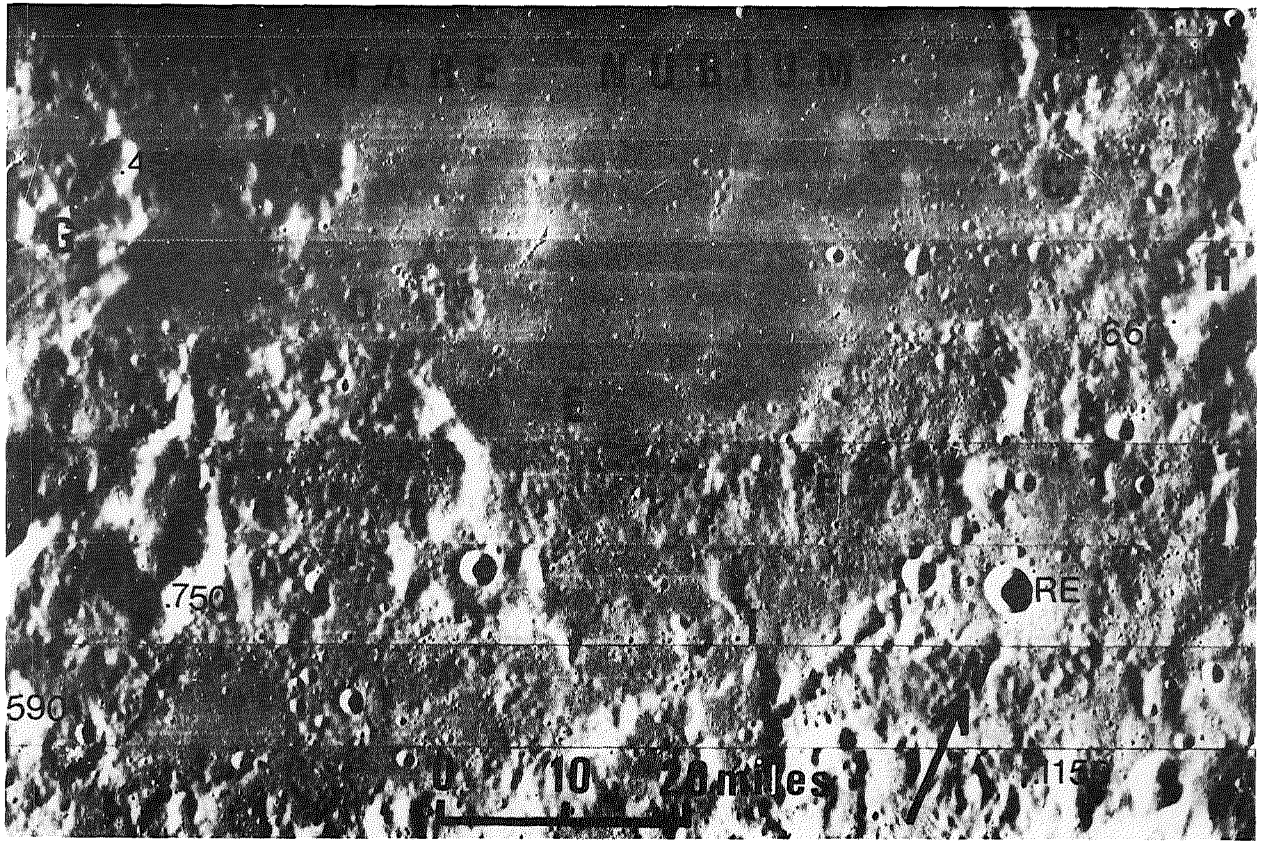

Fig. 31. Southern shore Mare Nubium east of crater Pitatus. A, B, C - drowned craters; B, D, E - embayed funnel-shaped valleys; F - collapse depressions; G, H - fracture-controlled valleys in mountains; I - plateau surface, 1000 feet higher than shoreline; RE - crater Regiomontanus E. The rocks, except for rims of newer craters, are ancient, older than the mare deposits. Numbers refer to heights of slopes on numbered side. The drowned craters, embayed shoreline, and regional slope suggest downwarping of the Nubium basin.

are funnel-shaped and represent the seaward termination of coastal valleys. That the submergence was due at least in part to subsidence of the sea floor rather than to a thickening mare fill is suggested by the progressively greater submergence of craters on the seaward side. Collapse features in the coastal area may support the subsidence theory. Note the string of flat-floored, angular to irregular, rimless depressions a few miles back from the shore (as on either side of F), as well as others inland. Large fracture-controlled valleys are visible in the highlands, as at G and H. Relief in the area is considerable, at least 4500 feet. The scattered elevations shown are heights of prominences in meters above the lowland on that side (Lunar Aeronautical Chart No.95). The depth of crater Regiomontanus E (RE) is recorded at more than 2000 feet. The plateau surface at I, some 15 miles inland, is at least 1000 feet higher than the shoreline near E. Except for local areas of materials of Imbrium age and scattered craters of even younger age, the materials within the area of Figure 31 are mapped as pre-Imbrium, although possibly lightly veneered with Imbrium ejecta (Trask and Titley, 1966; Holt, 1965).

Based on earthly analogs then, the coast is one of submergence probably due, at least in part, to subsidence of the basin. Prior to, and possibly during this subsidence, however, the area had experienced considerable differential erosion as indicated by both the coastal and highland valleys.

Locality XII. Southeastern Central Highlands

The central highlands comprise, for the most part, an extensive plateau pitted by craters of all sizes, including some more than 50 miles across. In some areas, large craters are so densely clustered that little level surface remains; in other areas, as in Figure 32, large craters are widely spaced and considerable level terrain remains. In a preliminary geologic map (Mutch and Saunders, 1968), the greater part of the area, including the large craters such as Pitiscus, Hommel and Vlacq, are mapped as pre-Imbrium in age. The small sharp craters, and the material on the inside slopes of the large craters, is mapped as considerably younger. Crater floor materials are either ancient (Hommel) or quite young (Pitiscus). The plateau surface itself is pre-Imbrium in age.

Because of the small scale, it is impossible to be certain of the presence of fluvial-type valleys. Superficially similar features are present on the inner slopes of the large crater, but details are lacking. The overall view displays no obvious evidence of fluid erosion. If fluid erosion has been absent here in contrast to its possible presence in other terra regions, it could mean either that the fluid sources were not universal or - if they were - the nature of the terrain discouraged surface erosion. Perhaps the essentially level but densely pitted surface, combined with high permeability, explains the lack of valleys.

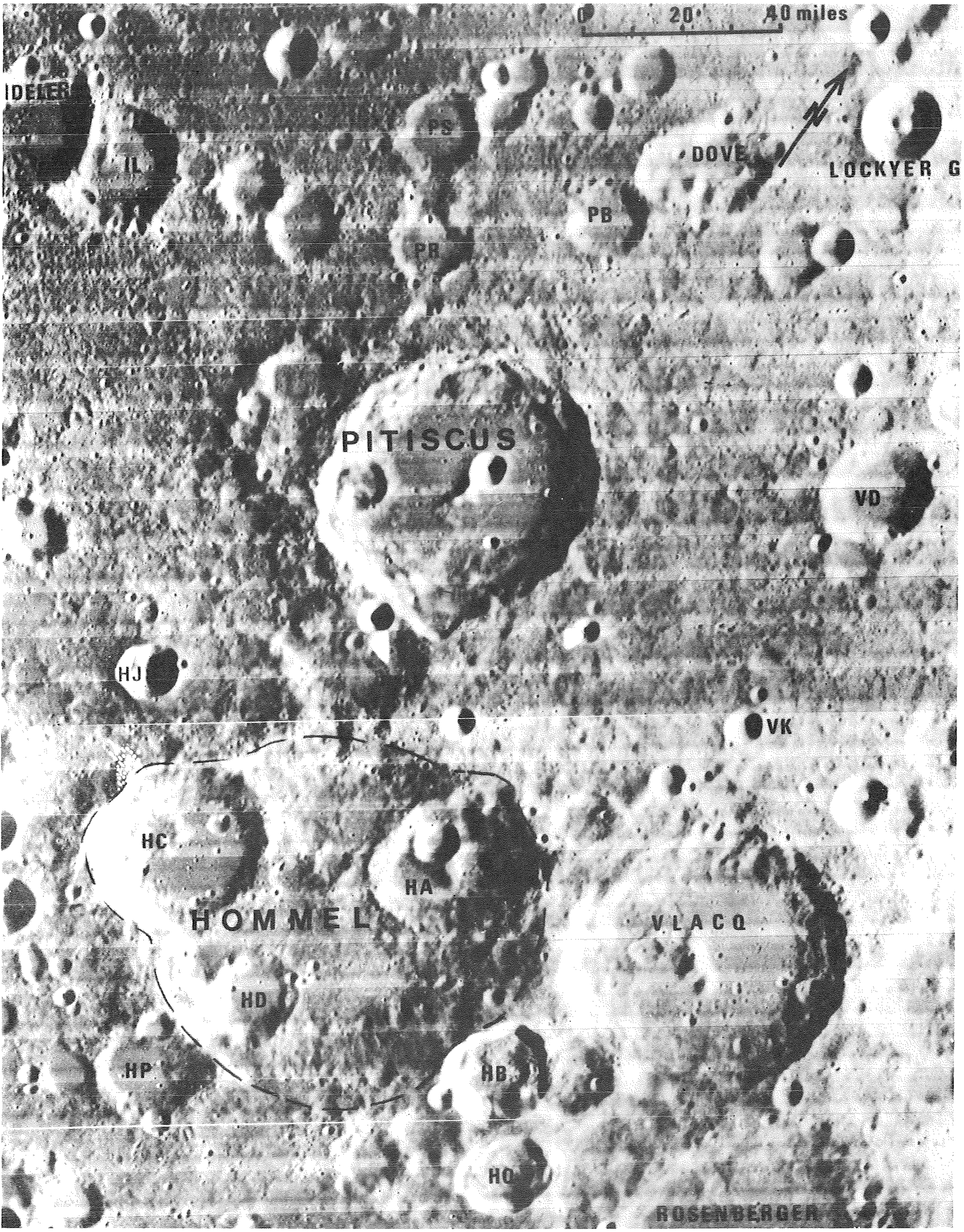

Fig. 32. Central highlands. Secondary craters in vicinity of large craters are lettered: PR - Pitiscus R; HB - Hommel B; etc. In this part of central highlands considerable areas of plateau preserved between large craters. Different degrees of wear indicate wide range of crater ages.

Locality XIII. Southern Oceanus Procellarum

Figure 33 is of an area of nearly submerged highlands in the southern part of Oceanus Procellarum. The center of the area is about 60 miles west of crater Euclides and about 100 miles west of Riphaeus Mountains. The material of this area, and of the Riphaeus Mountains, is mapped as older than the materials of the maria (Marshall, 1963; Eggleton, 1965) a conclusion amply justified by the present photo evidence. Note, for example, that prominent fractures (see arrows, Fig. 33) stop at the mare border and that the mare material embays all the indentations of the hilly landscape. The topography consists of a complex array of hills, ridges, and valleys. Some of the valleys (A, Fig. 33) have fracture-controlled tributaries, also embayed. Marshall (Letronne Quad., 1963) suggests that the material of the hilly terrain consists chiefly of ejecta from the region of Mare Imbrium. Whatever its origin, it was clearly in place long enough to undergo extensive fracturing. It is inconceivable that the material could have been dumped with its present intricate topographic pattern. Nor is it likely that embayed valleys (as at A), or valleys which widen progressively toward their mouths (as at B) could have been fashioned by landslides or related mass movements. The topography, except for the effects of scattered craters, is an excellent lunar analog of many embayed fluvial landscapes on Earth (Fig. 34).

Locality XIV. Flamsteed Ring. Oceanus Procellarum

The rocks of the Flamsteed Ring are mapped as Imbrium (Marshall, 1963). Note in Figure 35 the valley systems draining north from A and B. The well-rounded topography with its many fluvial-like valleys is similar to many terrestrial landscape in areas of fluvial erosion. The linear, V-shape valleys bear no resemblance to mass movement depressions on Earth and can not, in the writer's opinion, be explained by presently recognized lunar processes. Fluid erosion prior to the latest deposits of the mare seems indicated.

The peculiar roll-like terrace at the foot of the hills (as at C, D, and E) is 650 to 1300 feet wide. Trask and Rowan (1967, p. 1531-1532) report such terraces at the foot of steep slopes in other places and the writer has observed them in places along the northwest border of the Aristarchus Plateau. Trask and Rowan suggest that they consist of materials that have come down from the slopes above, a conclusion with which Milton (1967) agrees. Their greater prominence at the foot of the southerly slopes may be due to steeper declivities on that side.

Summary of Observations on Terra Topography and Possible Implications

The following observations and implications have been made or confirmed from study of the terra topography:

1. The older the terra terrain, the more worn and subdued it appears.

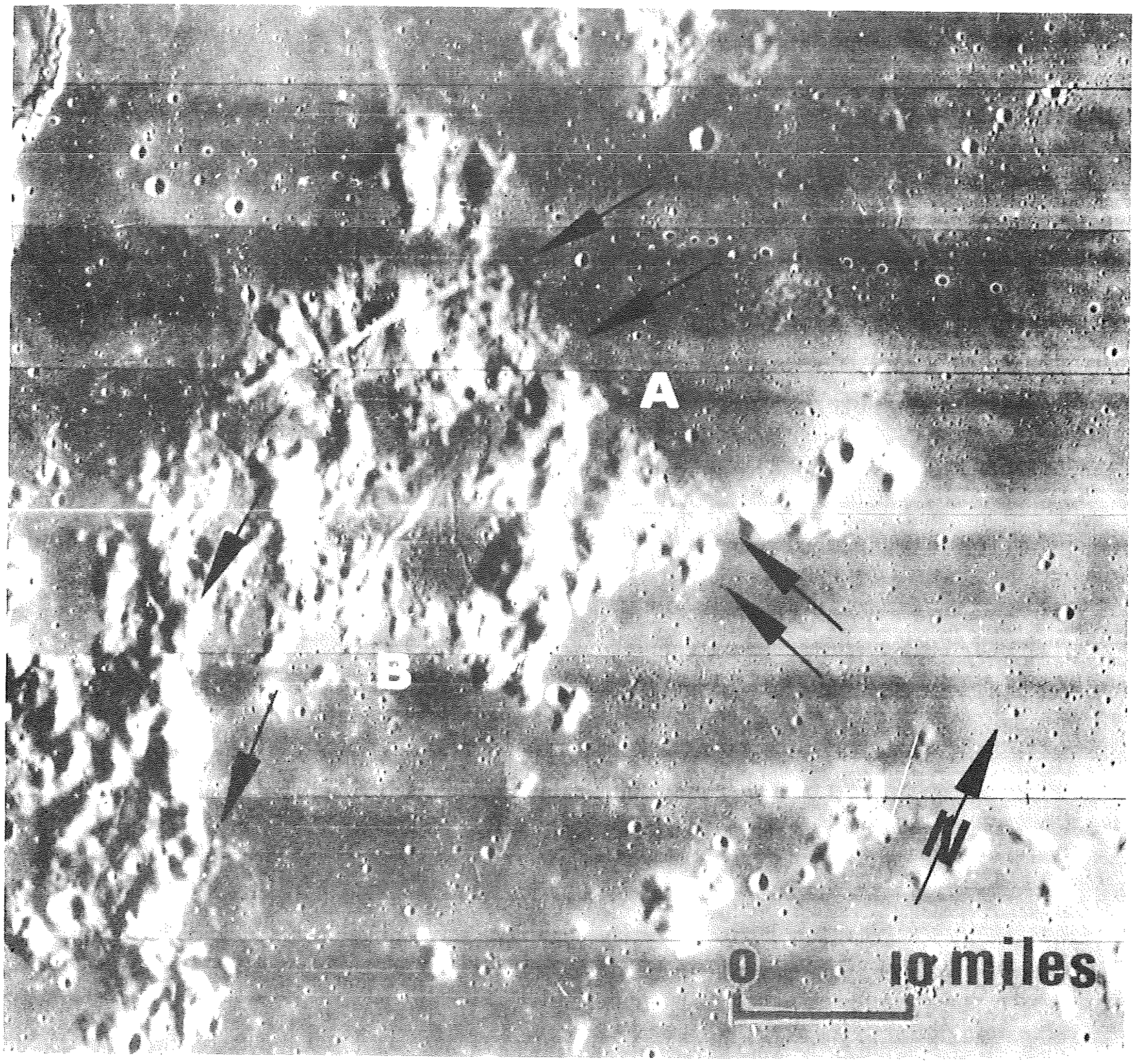

Fig. 33. Ragged hilly upland west of Riphaeus Mountains, southern Oceanus Procellarum. Topography is similar to fluvially-dissected, embayed topography on Earth. Arrows indicate fracture directions. Funnel-shaped valleys with tributaries at A, B, and elsewhere.

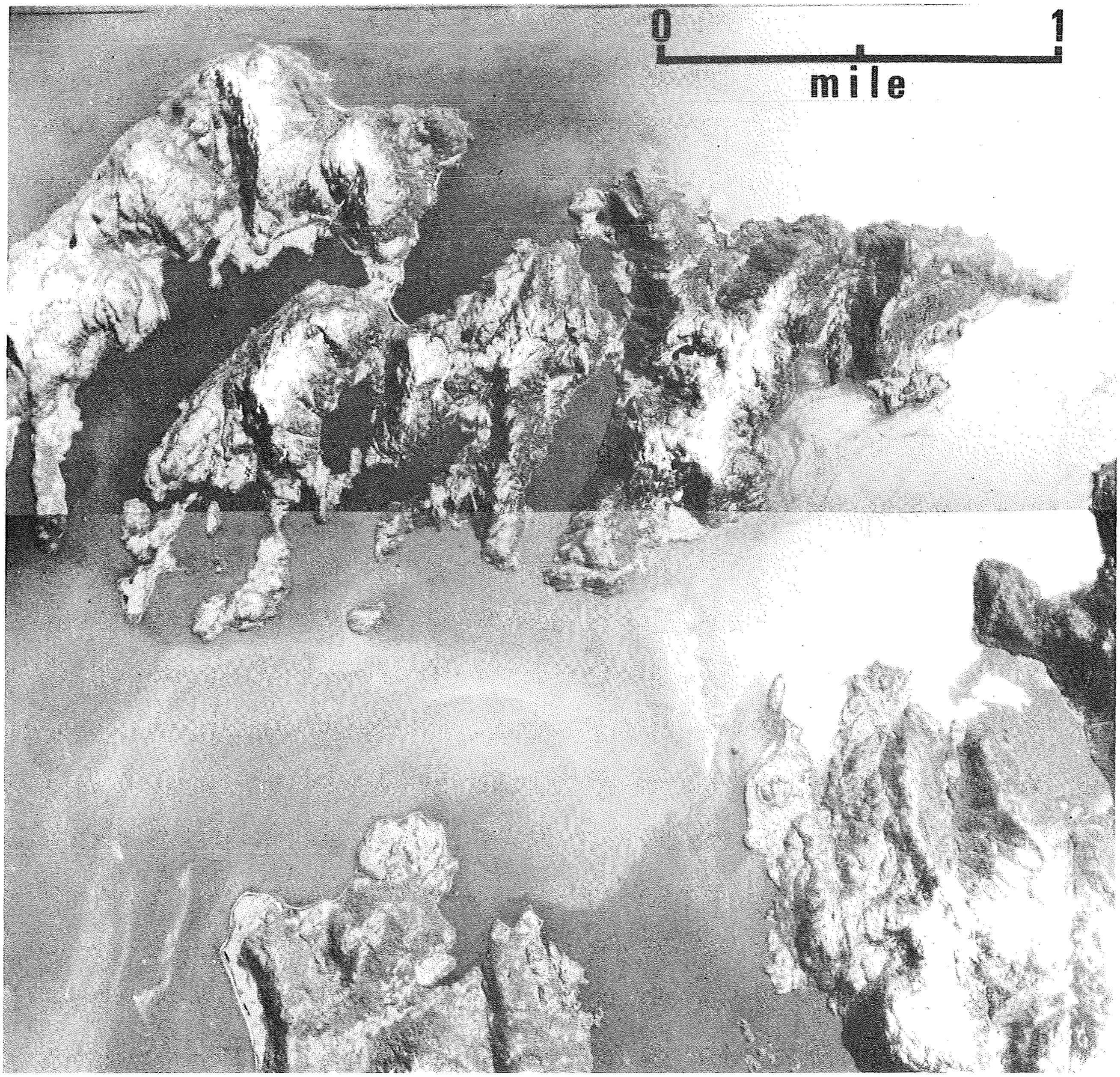

Fig. 34. Embayed coast, Alaska. Fracturing indicated by rectilinear scarps and promontories, and by trends of linear bays. Three fracture directions indicated by arrows in lower part of photo. Note striking similarity of this coast to that shown in Figure 33. Photo by U.S. Air Force.

Fig. 35. Northeast portion of Flamsteed Ring, an almost completely inundated crater rim in Oceanus Procellarum. Center of crater to south. Note valley systems north of A and B and elsewhere. The topography resembles fluvial topography on Earth. The convex basal roll, as at C, D, and E, has been attributed to accumulation of material from the slopes above.

2. All terra landscapes show clear evidence of fracturing generally in two dominant sets, northeast-southwest and northwest-southeast, but with north-south, east-west, and miscellaneous directions also commonly represented.

3. Relatively prominent fault topography, with rectilinear scarps and planar surfaces, is common in the terrain bordering the more recent mare basins such as Imbrium, Humorum, and Orientale. The deposits believed to have been ejected from these basins are grouped as the Imbrium Series on the preliminary geologic map of the moon (Wilhelms, Trask and Keith, 1962).

4. Angular fault topography is rare in the older, pre-Imbrian deposits associated with most of the mare basins.

5. The terra landscapes, particularly the older, appear to have been differentially eroded. Hummocky plateaus dominated by higher massifs suggest differential degradation.

6. Fractures have influenced the erosive processes resulting in rectilinear parallel valleys.

7. Parallel valleys have locally become integrated to provide a drainage pattern reminiscent of the parallel drainage pattern on Earth. Fluid erosion seems probable.

8. Submergence of terra terrain by mare deposits has resulted in analogs of earthly embayed shorelines with bays, promontories, and islands.

9. The pre-Imbrium mare basins have subsided with downward flexing of the marginal regions. This is indicated by partially submerged coastal craters and by almost completely submerged offshore craters.

10. Widespread pre-Imbrium fluid erosion, if such occurred, ceased some time prior to the latest mare deposits which show little evidence of erosion.

11. Widespread fluvial erosion at an early date in lunar history would imply that sediments derived from this erosion should underly at least the latest materials of the mare basins. That the latter are not themselves part of the sedimentary record is suggested by the absence of fans at the mouths of terra valleys and the almost total absence of stream channels on the mare surfaces. In contrast, there are lobate forms analogous to earthly lava flows, and the samples collected by the Apollo 11 crew were volcanic, not sedimentary.

12. If widespread fluid erosion did in fact take place early in lunar history, an early lunar atmosphere may be indicated. In view of the low escape velocity on the moon, this would require that the atmosphere be replenished from internal sources at a rate equal to or exceeding the loss to space. Conditions would of course differ on the hot and cold sides of the moon.

In brief, from the geomorphic point of view, the pre-Imbrium topography of the moon suggests the possibility of widespread fluid erosion early in lunar history. Necessary corollaries would be 1) the presence of an early atmosphere, and 2) the occurrence, at some depth in the mare basins, of sediments derived from this erosion. It is interesting to note that Urey (1967) has suggested the possibility of recurrent atmospheres resulting from comet collisions.

CONCLUSIONS

Localized post-mare fluid erosion is inferred primarily from the characteristics of a number of sinuous rilles although fluvial-type valleys are present on the slopes of some of the larger post-mare craters. Some segments of sinuous rilles not only display a sinuosity comparable to that of earthly meandering streams, but the meander belt maintains uniform width for long distances, a small percentage of the meanders are interlocked, that is, the limbs are pinched at the neck,and - in at least a few places - a cutoff appears to have been imminent. Curves are generally smoothly rounded and the gradient seems to be uniformly downslope in the meandering rilles except where subsequently interrupted by craters or slope debris. These characteristics do not accord with a simple tensional fracture hypothesis for these rilles. A fluid agent seems required, although in some rilles the fluid may merely have modified original ragged fractures.

A variety of explanations for the sinuous rilles have been proposed. These include collapse over lava tunnels or subterranean stream courses, and erosion by lava, nuées ardentes, fluidized debris, or water. The uniform widths and gradients, and meandering habits of many rilles do not accord with a collapse origin. Lava and nuées ardentes are not normally eroding agents nor do they follow tightly meandering courses. Experiments with fluidized debris have not produced rilles of uniform width and gradient, or with meandering patterns. A highly mobile, ground-hugging, erosive fluid seems required and water seems to be the most logical medium.

Water trapped below a layer of permafrost has been suggested as a possible source of fluid for rille erosion. It has been proposed that the water is liberated during creation of impact craters a kilometer or more in diameter. Inasmuch, however, as many rilles do not have craters at their heads, emissions through fractures or by way of endogenetic eruptions may be reasonable alternatives. Volcanic eruptions, with or without permafrost, may explain the terrestrial-type valleys on the inner slopes of some large post-mare craters.

The problem of the retention of surface water in the near vacuum of the Moon has been discussed by several investigators. One proposal is that newly-emerged water immediately freezes over and is able to extend itself by virtue of the protection against evaporation offered by the ice cover. Terrestrial ice-covered streams, however, do not meander. Nor has the proposed mechanism been supported by vacuum chamber experiments in which extruded water boiled explosively and deposited a frothy mass of ice over the ground. The ice evaporated rapidly and no stream channels were formed. The experiments, however, were conducted at constant temperature. It seems likely that frothy ice masses, formed during the lunar night, would undergo more rapid melting than sublimation as the terminator moved across it. Under these circumstances, meltwater streams could develop under the frothy ice cover much as streams develop under terrestrial snow patches. Because such a frothy ice cover would last only a short time, perhaps only a day or two before the surface temperature became extreme, the meltwater streams would be ephemeral. The conditions might be duplicated, however, whenever a similarly suitable combination of circumstances arose. Such activity, although intermittent, might - over long periods of time - result in the erosion of some sinuous rilles. The development of long sinuous rilles, however, would probably require multiple sources of water along the rilles to compensate for loss by evaporation during flow. Perhaps the long sinuous rilles started as ragged fractures.

Pre-mare fluid erosion is suggested not only by differential degradation of broad terra regions on a scale unaccountable by generally recognized lunar processes, but by terrestrial-type valleys around the shores of the older maria and on the inner walls and flanks of the larger of the pre-mare craters. Many of the terrestrial-type valleys are V-shaped, with tributaries that appear to enter at accordant junctions, and locally display integrated drainage patterns.

The widespread distribution of evidence for pre-mare fluid erosion supports the presence of an early lunar atmosphere. The products of the widespread erosion may lie buried under the deposits of the maria.

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