

## No. 121 LUNAR VOLCANIC ERUPTIONS NEAR ARISTARCHUS

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### ABSTRACT

The characteristics of five glowing spots observed near Aristarchus by Greenacre, et. al. (and of similar glows reported by Herschel) are shown to be compatible with moderate-sized eruptions of molten material. Orbiter photographs of the area show that at least three of the sites occur near well-defined lava flows, and either open rifts or cone-like structures. None of the sites contains volcanic structures so anomalous or fresh-looking as to be identified as products of a 1963 eruption. Nevertheless, it appears probable that the 1963 events were volcanic eruptions, probably including "fire fountains."

A report by the Aeronautical Chart and Information Center (ACIC 1964) and an additional paper by Greenacre (1965) describe the 1963 observations, by ACIC observers, of transient red spots near Aristarchus. On October 30, 1963, Greenacre and Barr saw three colored spots in the Aristarchus region, indicated as areas 1, 2 and 3 in our Figure 1. The spots were seen in the 24-inch visual refractor of the Lowell Observatory for about 20 minutes. On November 28, 1963, with the same instrument Greenacre, Barr, Dungan, and (Lowell Observatory Director) Hall observed one or possibly two colored spots, 4 and 5, with the more prominent, 4, confirmed by Boyce at the nearby 69-inch reflector of the Perkins Observatory.

The salient features of the phenomena were: (1) estimated intensity of the spots, varying between 5 and 25 percent fainter than the normal background; (2) colors, described in varying instances and at various times, as "reddish-orange," "light ruby-red," "pinkish," and "pinkish-red," at times "quite brilliant;" (3) a "sparkling" appearance in some cases, with barely resolved "downward flowing motion;" (4) durations, from discovery to disappearance, of

20 and 75 minutes and; (5) "deep violet" or "blue" hazes that formed inside and partially circled Aristarchus persisting for about an hour, obscuring and dimming the floor several hours after each observation of red spots.

In an attempt to confirm his visual observations on November 28, 1963 Greenacre took photographs of the area on Panatomic-X SO 136 emulsion using the Lowell 24-inch refractor, and observed visually with the 12-inch guide instrument. Neither set of observations showed any evidence of the color phenomena. The film used, SO 136 (Greenacre, 1968), is sensitive to longer wavelengths than the eye. We believe that the black-and-white film, by virtue of this *red* sensitivity, probably compensated for the relatively decreased integrated *visual* brightness of the spots, rendering the spots undetectable.

All of these observations appear to be qualitatively consistent with the expected appearance of partially-resolved volcanic eruptions. We have therefore attempted to test this idea by calculating the visibility of an assumed lunar volcanic eruption and by studying the regions of reported events on high-resolution Orbiter photographs.

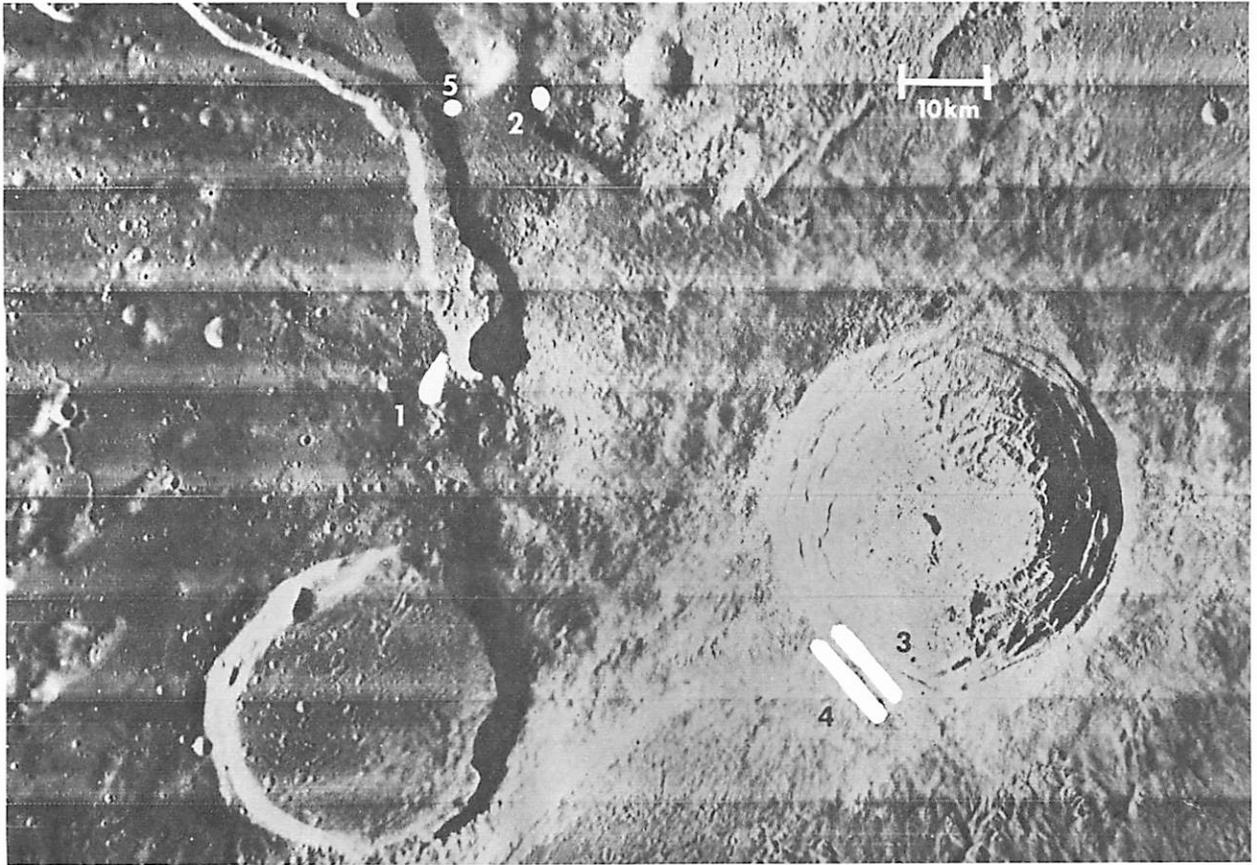


Fig. 1 Aristarchus, Herodotus, and a portion of Schröter's Valley, showing the locations of the five Flagstaff red spots, numbered in order of appearance. Orbiter IV photo, courtesy NASA.

One can test the eruption hypothesis by calculating the area of hot lava required to produce the observed phenomenon. This requires knowledge of the light flux from the observed red spots. In the eruption hypothesis, the flux at the earth from the spots would be due to the "lava," plus reflected sunlight from unresolved adjacent areas. Thus lava eruptions alone can only add to the background intensity, yet Greenacre (1968) reports that the spots were fainter than the normal background. A typical spot was area number 4, on the exterior rim of Aristarchus, where the average of Greenacre's estimates is a deficit of 15% relative to the background. Therefore, we assume that obscuring material was present over the "lava." This is consistent with observations of terrestrial lava eruptions, where eruptions are frequently accompanied by large quantities of obscuring agents ranging in dimension from molecular to cinder-size. The Aristarchus observations give some evidence for the presence of obscuring material. First, there is the violet haze which dimmed and obscured the floor of Aristarchus several hours after

each color phenomenon and second is Greenacre's (ACIC 1964) report of "sparkling" which he later (1965) describes as due to motion of barely resolved white, bright spots, *with the intensity of the adjacent normal surface*, moving downhill inside the colored regions. These could have been areas of normal surface visible through breaks in the obscuring material. The violet haze and bright spots might be used to argue for gas-borne smoke, although such smoke would be brighter than the dark lunar surface and in any case should rapidly dissipate. (Sunlit clouds obscuring eruptions at Halemaumau [WKH-June, July, 1968] strongly scattered blue light, noticeably reddening transmitted light, but were generally brighter than the dark volcanic background.)

Most satisfying as an obscuring agent would be a fountain or enclosing "cloud" of particles. Small particles would be favored on the moon because of the difference between vapor pressure and ambient pressure and because of the violent frothing action of erupted material. The smoke-sized particles produced by condensation would be the most efficient

use of available mass in producing scattering and obscuration. Interparticle shadows among the dark, rapidly cooling particles would contribute to the dark appearance of the red spots. Black-and-white and color plates accompanying *Comm. L.P.L.*, 3, No. 49 (Kuiper 1965) are instructive in this regard. It can be seen that the glowing red fountain of lava and cooling cinders appears no brighter than the background rocks in the black-and-white photographs.

If we assume for purposes of calculation the simplest model, with neutral absorption from particles of albedo similar to the background, and with a low optical depth, then the light from the red spots would be a mixture of twice-absorbed sunlight from the surface and once absorbed blackbody radiation from the "lava." For a transmission of the obscuring "cloud" of 67% (comparable to the terrestrial case), a red spot observed to be 15% fainter than the background (spot 4) would have thermal radiation (from lava over an undetermined fraction of the area) amounting to 61% of the ordinarily reflected sunlight. Using the photometry of Gehrels, Coffeen, and Owings (1964) we find the ordinary background intensity is 4.7 mag/ (arc sec)<sup>2</sup>. Thus the intensity of the unobscured lava is 5.2 stellar magnitudes per arc second square. As will be seen, the conclusions of this paper are not extremely sensitive to the uncertainty of this estimate.

Given the intensity of the "lava" we may calculate the area required to produce that intensity. This calculation may be made by comparing the visual intensities of the sun and the spots. Let,

- $F$  = visual flux at the observer (ergs/cm<sup>2</sup>sec),
- $T$  = temperature of radiating surface (°K),
- $a$  = absorptivity of the radiating surface,
- $f$  = fraction of the flux at all wavelengths visible to the eye,
- $A$  = area of visible radiating surface (cm<sup>2</sup>),
- $m$  = apparent visual magnitude of the entire source,
- $r$  = distance of source (cm),
- $C$  = solar constant (ergs/cm<sup>2</sup>sec),

and let the subscripts  $L$ ,  $\odot$ , and  $\ominus$  refer to "lava," moon, and sun. Then the ratio  $F_L/F_\odot$  given by  $(m_\odot - m_L)$  can be also expressed in terms of  $A_L$  and  $C$ . Solving for  $A_L$  gives

$$A_L = \frac{\pi r^2 \zeta C}{\sigma T^4 a_L \cos \zeta} \frac{f_\odot}{f_L} 10^{0.4(m_\odot - m_L)}. \quad (1)$$

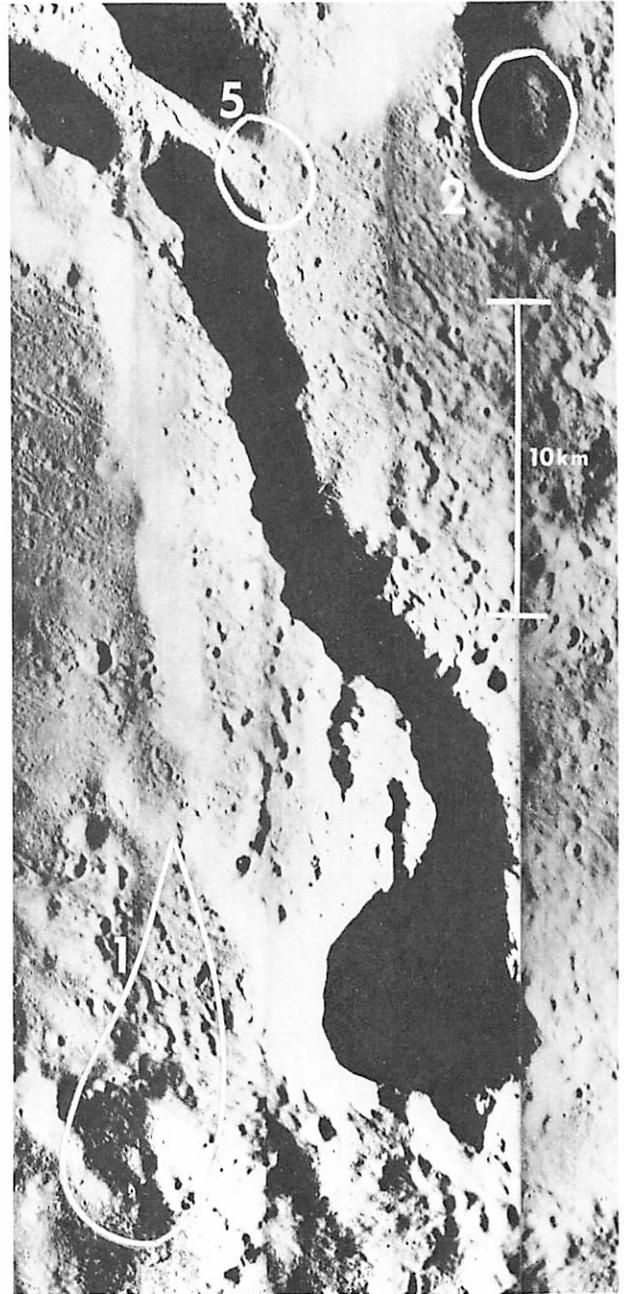


Fig. 2 Head of Schröter's Valley. White lines lie just outside the boundaries of the red-spots as mapped by ACIC (1964). Orbiter V photo, courtesy NASA.

The solar constant, the sun's magnitude, and the moon's distance are well known. Values for the temperatures of erupting terrestrial lavas are in the range 1300–1700°K (Rittmann 1960). For convenience we assume  $T_L = 1580^\circ\text{K}$  (because the bolometric correction is available). We take the absorptivity,  $a_L$ , of the volcanic material to be 0.80. The ratio  $f_\odot/f_L$  is just the ratio of the inverse bolo-

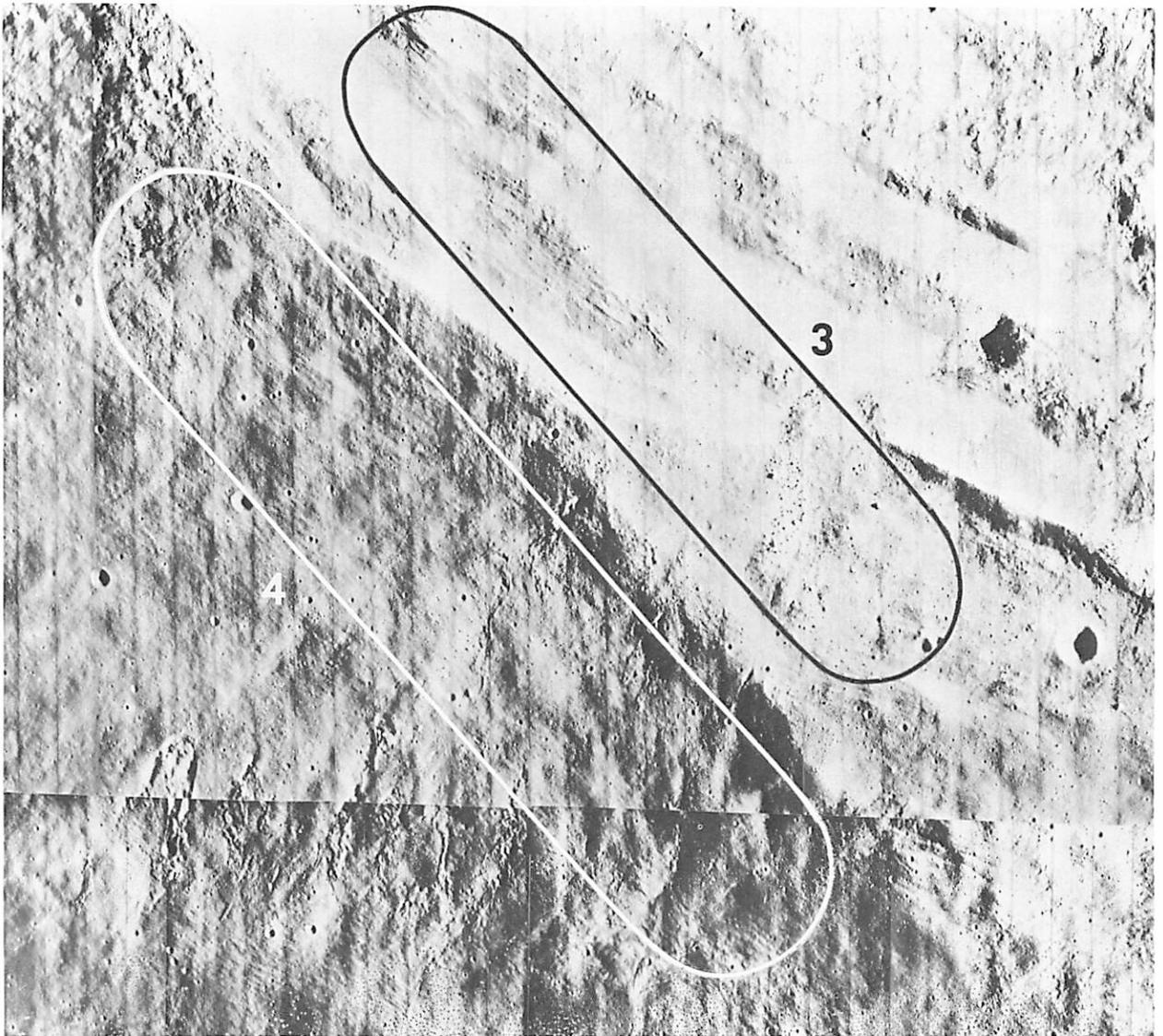


Fig. 3 Southwest rim of Aristarchus. Black and white lines lie just outside the "streak" boundaries by ACIC (1964). Between the two streaks, on the rim, are three fissures. Orbiter V photo, courtesy NASA.

metric corrections at  $5750^{\circ}\text{K}$ , and is here taken to be 450 (Allen 1963). To find the magnitude of the "lava," we integrate the intensity [ $5.2 \text{ mag}/(\text{arc sec})^2$ ] over the area, again taking spot 4 as representative. The area is  $4.1 (\text{arc sec})^2$ , yielding a magnitude,  $m_{\text{r}}$ , of 3.7. The smaller spots were typically two to three times smaller, with a somewhat higher surface brightness.

It is of some interest that this calculation of the magnitude of the source in the Flagstaff observations comes very close to the estimate of "4th magnitude" made by Herschel when he observed what he thought was a volcanic eruption on the unilluminated moon near Aristarchus (Middlehurst 1964).

Substituting the above values into equation (1), we derive an area of about  $8.1 (10^9) \text{ cm}^2$ , comparable to a square 0.9 km on a side of *glowing* material. This constitutes an acceptable fraction of the observed area and is entirely acceptable as a dimension of an eruption. Areas of 19 historic flows in Hawaii tabulated by Stearns (1966) range from  $5 \text{ km}^2$  to  $90 \text{ km}^2$ , and fire fountains there commonly reach kilometer scale in length. Rittmann (1962) notes that the Icelandic fissure eruption of 1783 was 25 km long, at it may be compared with the "streaks" on the Aristarchus rim.

The observed area of spot 4 was about  $18 \text{ km}^2$ . Literally interpreted, our result suggests that a small

fraction (about 4½%) of the colored area was actually covered by glowing material. However, it must be noted that changes in the assumed temperature (within the range 1300 to 1700°K) cause large changes in both the luminosity and the bolometric correction ratio. Such changes, along with the uncertainty in the unobscured brightness, give our area calculation an uncertainty of about a factor of 10. The calculated dimensions could thus cover a range comparable to that observed on earth. We conclude simply that the calculation demonstrates the compatibility of the reported observation with a volcanic eruption on the moon. The other areas as mentioned above were generally smaller and more intense, although spot 3 is comparable in area to spot 4 but less prominent (only 5% below background intensity). All of the observed areas appear to be compatible with lava eruptions.

In view of this conclusion it is important to search the Orbiter photographs of the region for evidence of recent volcanic activity.

Figures 2 and 3 show in greater detail the red spot areas. The spot positions shown have been carefully transferred from the ACIC (1964) map of the events. We believe the positions are accurate to within two kilometers (the marked boundaries in Figures 2 and 3 lie just outside the edges of the reported spots).

Area 2 occurs in a 3km crater-like depression near the rim of a scarp (as shown by Orbiter stereo views). Neither this area nor the doubtful area (5) on the rim of Schröter's valley show any distinctive or diagnostic volcanic structures.

Area 1, on the other hand, contains an unusual and distinctive dome-shaped hill with a summit pit. This structure lies at the apparent source of the "white, bright" spots (see above) which had the "flowing motion." Greenacre and Barr (ACIC 1964; Greenacre 1965) noted the feature's dome-like shape which has been confirmed using Orbiter stereo views. The dome is gently sloped, not as steep as a terrestrial cinder cone, and is part of a larger ridge extending NW-SE. The rim of the summit pit appears to be the highest point on the ridge. To the northeast (the direction of the flowing motion of the "small, bright, white spots") lies a complex of features reminiscent of flows and flow channels. Figure 4 shows the area in detail.

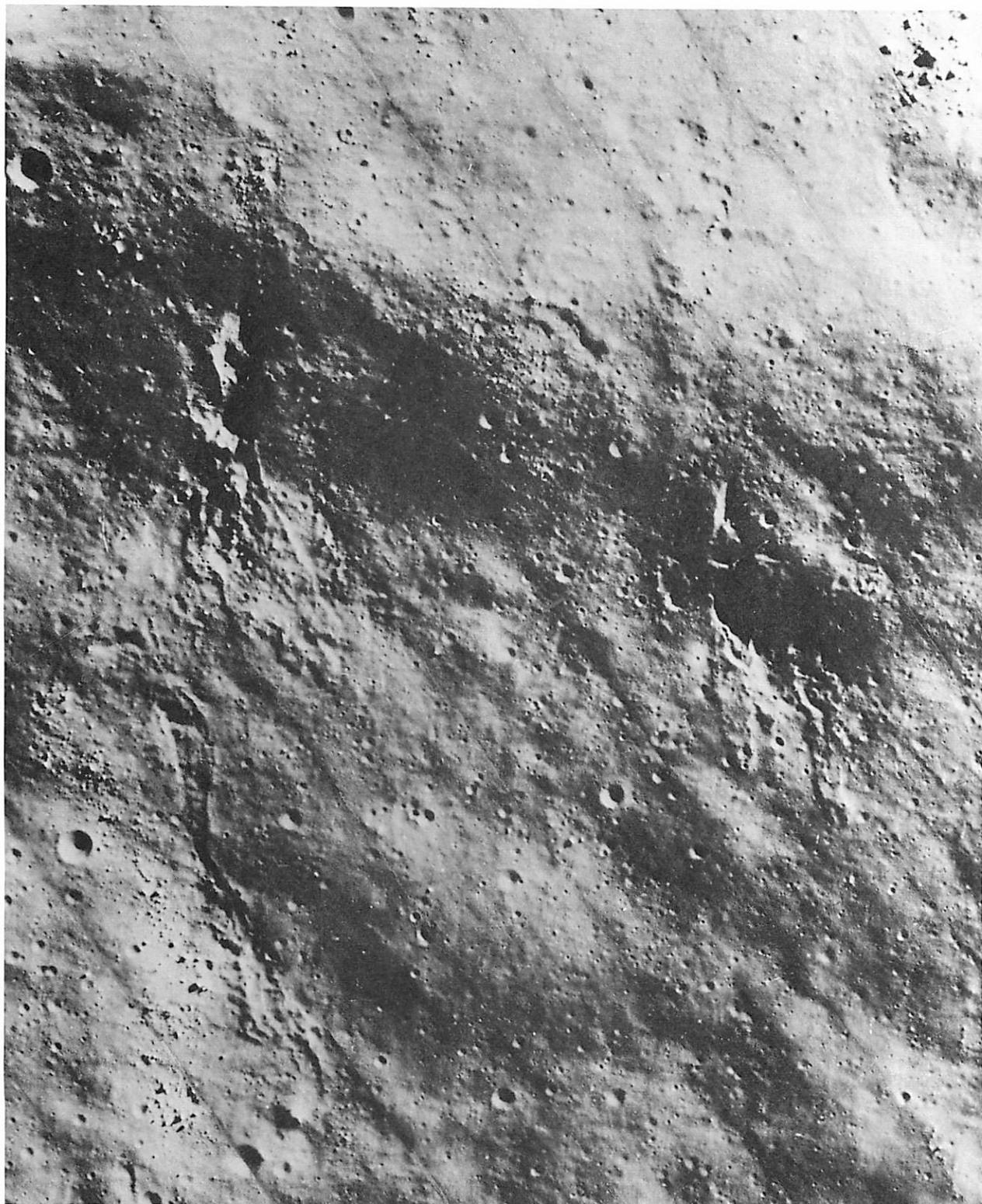
Areas 3 and 4 were described as "streaks" and parallel the crest of the Aristarchus rim on either side. The Orbiter photographs show that this part of the rim is broken by three radial fissures connect-



Fig. 4 Dome and flow structures associated with spot 1. The dome is marked in the margin.

ing unusually clear flows that run down the outer (southwest) wall (see Figure 5). The three open fissures, though perpendicular to the length of the red streaks, lie on a line parallel to the streaks.

Area 3, on the inner rim, did not show the flow-



*Fig. 5* The rim of Aristarchus showing two fissures and associated flow structures. Aristarchus interior is at the top.

ing motion that characterized spots 1 and 2. It consisted rather of individual "pink streaks" paralleling the numerous concentric scarps and stepped faults of the wall's inner slope. In contrast, spot 4 was described as a "pinkish-red streak" with a "more intense reddish-orange" spot "near the southern extremity." A complex of flows lies in the later area (Figure 5).

Of the four well established red spots, then, three appear to be associated with structures of unusual nature. We infer that these structures, a low cone, flows, and fissures, are volcanic. The flow structures are obvious, with well defined boundaries, and appear similar to terrestrial lava flows. It has long been suspected that dome-shaped structures on the moon are volcanic; there is striking similarity to low cones and small shield volcanoes on the earth.

Further interpretation becomes somewhat subjective. It is perhaps surprising that none of the structures appears unusually fresh. We cannot claim detection of any structure that appears only five years old, nor do we find any highly discolored spots (although the area of the cone in area 1 appears somewhat darker than the surroundings). For these reasons we suspect that the 1963 events did not deposit any great volumes of material. Rather, a brief fire-fountain type of pyroclastic eruption might widely disperse cinders and ash (especially on the moon), producing a visible flare without noticeably deforming the surface. The expected small particle size, discussed above, may also contribute to a fresh deposit's anonymity.

We conclude that the Flagstaff observations almost certainly represent volcanic eruptions on the moon, that at least three of the four definite red

spots can be shown to have occurred in areas of demonstrable past volcanic activity, and that the 1963 eruptions were probably genetically associated with these older vents. It should not be inferred that this evidence establishes the volcanic origin of larger associated features, such as Aristarchus. While many local structures, e.g. Schröter's valley, sinuous rilles, and the many domes and flows are undoubtedly endogenous, the rims of larger craters (of whatever origin) would be expected sites of eruptive activity because of known slump faulting, subsurface brecciation, and maximized isotatic instability (especially if the region is already tectonically active).

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