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An Interpretation of Schröter's Valley and Other Lunar Sinuous Rills

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Abstract. Several more or less unsatisfactory theories have been proposed for the origin of lunar sinuous rills such as Schröter's Valley. This paper presents a new explanation of the formation of these rills, namely, that they are valleys eroded by nuées ardentes. Characteristics of the rills, including form and association, are cited in support of this theory. Supporting evidence is found in the similarity of the rills to furrows eroded by nuées ardentes on the earth.

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Pickering [1904] called attention to a rare class of features on the moon, the sinuous rills, which he considered to be distinct from the much larger class of normal rills. The latter number in the thousands, and one of their chief characteristics is linearity. The radius of curvature of any segment is measured in the thousands of kilometers. The sinuous rills, on the other hand, number in the dozens, according to Pickering, and have several distinctive features: (1) they are always wider at one end; (2) at the wide end there is always a pear-shaped craterlet; (3) the wider end with its craterlet is nearly always perceptibly higher than the other; (4) the course is composed almost entirely of curves of very short radius (of the order of a few kilometers), giving them a zigzag, winding appearance.

These characteristics were confirmed by R. E. Eggleton and H. J. Moore of the U. S. Geological Survey for about 25 sinuous rills (communicated by E. Shoemaker). Among the fairly conspicuous ones are Schröter's Valley (Figure 1), located at approximately 52°E, 25°N (astronomical convention), which ends in the Oceanus Procellarum, just northeast of the brightest crater on the moon, Aristarchus; the Hadley rill (Figure 2) at about 0°, 22°N, at the foot of the lunar Apennines; and the Conon rill (Figure 3) in the hinterlands of the Apennines at about 2°W, 16°N. Schröter's Valley, the largest, is about 4 km wide at its widest, over 300 m deep at its deepest, and about 200 km long. Marius rill is longer than Schröter's Valley, but is much narrower. The rest of the 30 or so sinuous rills are only tens of kilometers long, a few hundreds of meters wide, and a few tens of meters deep.

In general, selenologists attempt to explain only the normal rills, ignoring the sinuous rills and valleys or else considering them to be a peculiar variant. Explanations for them in the literature may be summed up under three mechanisms: aqueous erosion, faulting, and subsidence. Among the authors who compare the sinuous rills to river beds, though sometimes with reservations, are *Neison* [1876], *Elger* [1895], who cites Birt's analogy to inverted river beds, *Pickering* [1904], and *Firsoff* [1960], who suggests an underground river. Faulting is favored by *Nasmyth and Carpenter* [1874], *Goodacre* [1931], *Baldwin* [1949], and *Khabakov* [1962]. Advocates of the subsidence mechanism are *Spurr* [1948], *Kuiper* [1959], *Fielder* [1961], and *Arthur* [1962].

Each of these three mechanisms for producing rills encounters difficulties when applied to the sinuous features. That of aqueous erosion is the least tenable, since the relatively high vapor pressure for any reasonable liquid at the temperatures of the surface of the moon would be inconsistent with the near-vacuum conditions there. The available information concerning the temperature of its surface, obtained from many different kinds of observations, makes the possibility that water in quantity would remain in liquid form long enough to produce significant erosion seem very remote. A further difficulty with this hypothesis is that branching, when it does occur, is usually at the lower end of the

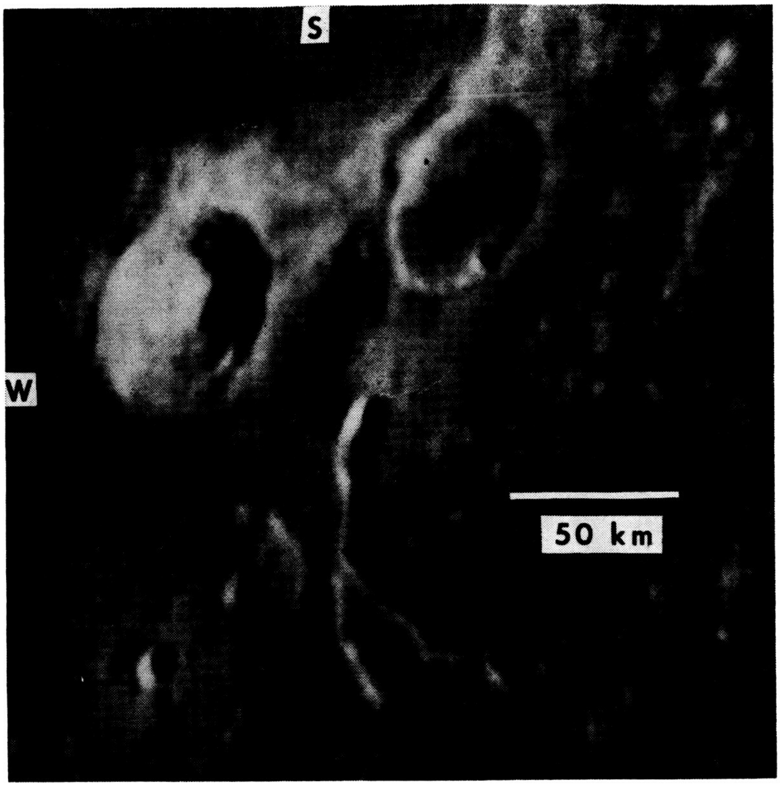

Fig. 1. Schröter's Valley on the moon, a Mount Wilson photograph, reproduced from the Kuiper Atlas (F3c). The two large craters are Herodotus, directly south of the valley, and Aristarchus (39- and 47-km diameter, respectively). Astronomical south is at the top, west is at the left, to correspond to the telescopic appearance.

channel (distributary), according to *Shaler* [1903], rather than at the upper part (contributary), in analogy to terrestrial rivers.

The suggestion that sinuous rills are the result of intersections of planes of faulting contradicts their observable *topological* character. If this were the cause, it would be expected, at least in some instances, that sharp bends, presumably due to intersecting systems of faults, would find observable expression beyond the elbow of the rill itself. We would expect T and X intersections, when in fact we have L's, V's, and U's. We would also expect to see the principal directions of the rill repeated in the pattern of intersecting ridges and valleys in the immediate vicinity. This is not observed. Such patterns can be seen in some localities, such as the Apennines, where they affect the linear rills, but they cannot be seen in the sinuous rills.

Nasmyth and Carpenter's suggestion that a pre-existing chasm had been contorted by strike-slip faulting is counter to the evidence of lack of distortion in contemporary craters and features in the vicinity.

Most hypotheses invoke igneous processes, including subsidence, or intrusion of magma in fault planes. These are subject to the same objections given for faulting. The channel is not likely to have been formed by a lava flow, since this produces a raised feature in the landscape, not a furrow (J. F. Schairer, private communication).

The most significant feature of the sinuous rills is the crater at one end. As nearly as can be determined without hypsometric data the associated crater is at the higher end in every case, which strongly suggests a genetic relation between the two features. Schröter's Valley originates in the pear-shaped crater aptly called the Cobra Head, whose elevation above the neighboring plain is about 1000 m, according to *Guillemin* [1948] (see Figure 1). The Hadley

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Fig. 2. The Hadley rill from a Lick photograph (taken with the 120-inch Coudé focus). It is located at the foot of the lunar Apennines that border Mare Imbrium. The small crater it passes around, Hadley c crater, is about 5 km in diameter. Astronomical north is at the bottom, east is at the right, to correspond to the telescopic appearance.

rill starts in an unnamed craterlet in the Apennines which can easily be seen in Figure 2. The Conon rill also commences in a craterlet in the mountains. The craterlet is masked by shadow in Figure 3. Other examples that can be clearly seen on appropriate maps and photographs are two rills near the crater Bode (near the center of the moon) and two short ones near the crater Marius in Oceanus Procellarum. The beds of these rills look like channels cut by some sort of fluid. We have rejected as improbable the idea that water was the fluid. The association of crater and rill suggests volcanism. The result of volcanic action might be in the form of lava flows or nuées ardentes (ash flows). We have rejected lava flows because they form raised features; hence we are left with the consideration of nuées ardentes. A description of nuées ardentes may be helpful to those readers who are not familiar with this type of volcanism.

A nuée ardente is a fluidized mixture of gas and dust or ash at very high temperature and relatively high density which issues from a volcano with explosive force, often horizontally directed. This mixture rushes down the mountainside with great velocity (of the order of 100 km/hr) with action similar to that of a marine turbidity current excavating a submarine canyon. The irregularities in the terrain provide the explanation for the sinuosity just as they do for the courses of rivers and avalanches. Frequently the nuée ardente possesses great erosive power, probably mostly by abrasion, which comes from the transportation of blocks with diameters of the order of meters to tens of meters. As long as there is a great deal of gas in the mixture, the large blocks are buoyed up and suspended by the upward motion of the gas, and the avalanche is almost noiseless [*Perret,* 1937]. The deposit is smooth because of the great amount

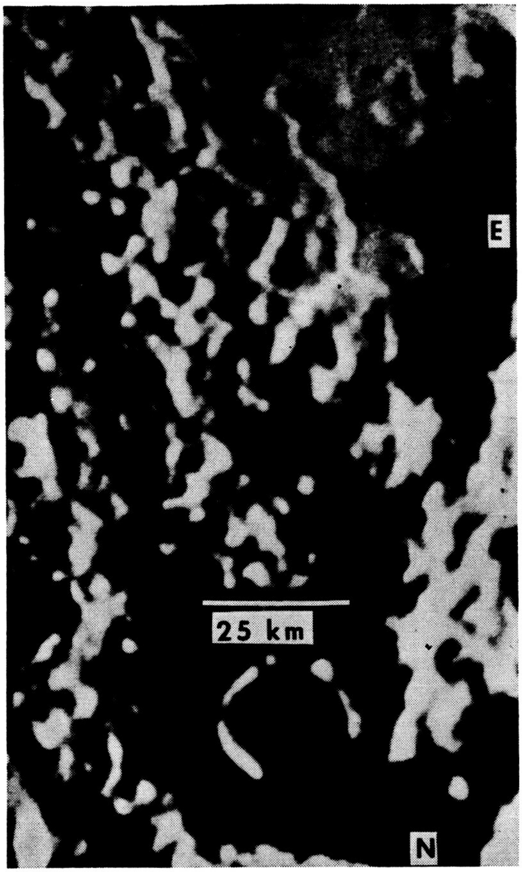

Fig. 3. The Conon rill from a Lick photograph (taken with the 36-inch refractor). The diameter of the crater Conon in the Apennines, below the rill, is 24 km. Astronomical north is at the bottom, east is at the right, to correspond to the telescopic appearance.

of ash that usually buries the boulders. Further in the flow the blocks may slide and roll along at the bottom; at that time they have significant erosive power, and the floor may appear rough from the deposition of boulders. According to theoretical studies by *Lobeck* [1939], a fluid stream has a carrying power proportional to the sixth power of its velocity. Nuées ardentes, with their tremendous velocities, illustrate this extraordinary power by transporting huge blocks to great distances. *Perret* [1937] describes the channels which many of the nuées ardentes from Mont Pelée have made. He said, 'The greater velocity in the center of the avalanche activated the emission of gas and the deposition of material, so strongly displayed by earlier clouds, while on either side the track had been trenched by less buoyant masses, giving it a cross-section shaped like a double U.'

Two surprising features of nuées ardentes are their self-cohesive power and their ability to flow great distances even on slopes with grades of less than 1 per cent. The cloud does not spread out and dissipate readily, but maintains its narrow contours for a surprisingly long time. There are great electrical effects, and Perret suggests that part of the cohesive power is due to electric charge attraction. (Cohesion is also a property of marine turbidity currents and avalanches. In Lake Mead, turbidity currents having a velocity of at least 1 km/hr flow to distances of 125 km. Turbidity currents from great rivers have been observed to maintain their identity for great distances out into the ocean.) In the nuées ardentes on earth, indrafting of air at the edges may also play a part in confining the cloud. *Ross and Smith* [1961] discuss ash flows in detail.

Aramaki [1956] describes the trench carved by the Kambara nuée ardente during the 1783 eruption of Asama volcano, Japan. This trench is the largest terrestrial one known to me. In the Kambara event blocks and fluidized ash and gas dug a ditch from 1.1 to 2 km wide and at least 40 m deep. Scarps 40 m high are still visible in the channel. The interposition of the Agatsuma River altered the course of the nuée ardente so that we cannot know what the uninterrupted flow might have produced. Blocks 15 m in diameter were found as far as 25 km down the river, and destruction from flooding occurred as far as 90 km away. The Kambara ditch is shown in Aramaki's map (Figure 4). The ditch dug by the nuée ardente is sinuous and has a widening near the head. It is known as the Amphitheater and is shown in Figure 5, which is Aramaki's photograph of the Kambara ditch. The area immediately surrounding the volcano is shown, showing the course of the ditch near the source and Amphitheater. In the photograph, the dark material is the andesite lava flow that came immediately after the Kambara nuée ardente and followed its channel, filling and almost obliterating the ditch in places. Aramaki estimates the volume of the Kambara nuée ardente to be about 0.02 km^3. I estimate that the volume, under terrestrial conditions, required to produce Schröter's Valley

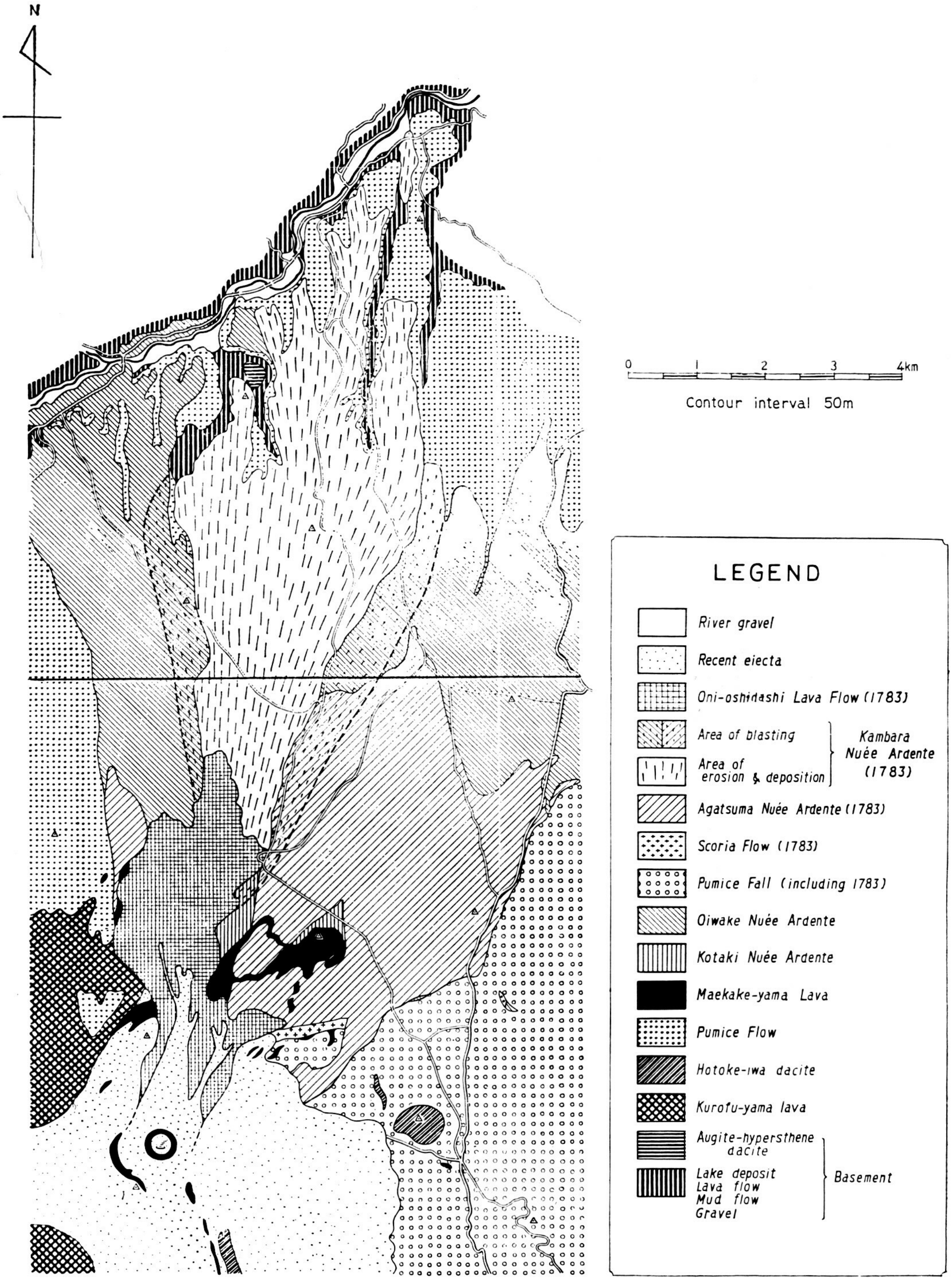

Fig. 4. S. Aramaki's geologic map (by permission) of the 1783 deposits of Asama volcano, including the Kambara ditch outlined partly by a dotted line. The area below the horizontal line in the middle of the map is the approximate area shown in Figure 5.

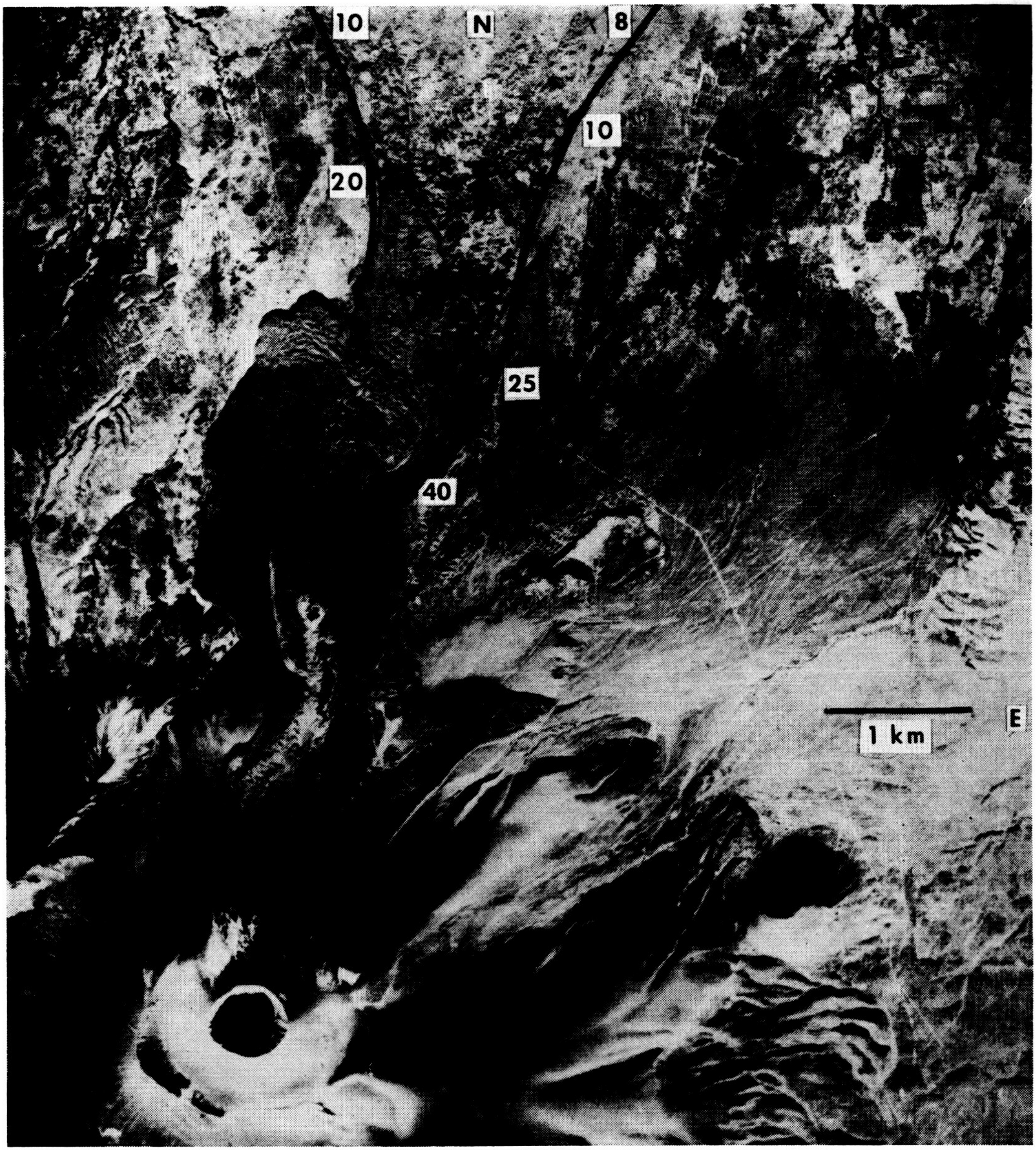

Fig. 5. Aerial photograph of Asama volcano (by permission of S. Aramaki) showing the upper part of the Kambara ditch and the subsequent Oni-Oshidashi lava flow (appearing darker). The 'Amphitheater' is at the left center. The scarps are indicated by black lines and the numbers give the heights of the scarps in meters. The diameter of the central crater is 0.5 km. North is at the top and east is at the right, corresponding to Figure 4.

would be about 100 km^3, greater by a factor of more than a thousand than the volume of the Kambara nuée ardente but less than the volumes of many terrestrial ash flow fields and valleys, which often exceed 1000 km^3. The volume and depth of the Kambara ditch are more comparable to the volume and depth of the majority of the other lunar sinuous rills. Its width, however, is much greater and is comparable to that of Schröter's Valley. The observable length is about 15 km; the true length is undetermined because of the interference of the river and the unknown influence of the erosive power in the river bed.

The bottom of the Kambara ditch (where not covered by the lava flow) is strewn with large boulders, the largest being 160 m long and 5 m high, deposited about 10 km from the volcano. The floor looks rough in the first part of the flow. *Fielder* [1961] has observed that when the lunar rills cut through the mountains, the bottoms always appear to be very roughly sculptured and strewn with innumerable rock blocks. Those crossing mare material usually appear smooth. It is possible that the ridge in the Cobra Head, observed by some, was produced by a mechanism similar to that observed by Perret in the action of many of the nuées ardentes of Mont Pelée which formed medial moraines and in some instances even left a ridge instead of a furrow.

The observed characteristics of the erosional products of terrestrial nuées ardentes are strikingly similar to those of the lunar sinuous rills that fit Pickering's criteria. The proposition submitted here is that Schröter's Valley and the other sinuous rills owe their origin to the erosive agency of lunar nuées ardentes. The momentum for the flow would be provided by the elevated crater of origin. There may be some observational evidence in the literature to support this hypothesis of volcanism. Several lunar observers, notably *Neison* [1876], *Elger* [1895], *Pickering* [1904], *Klein* [1955], *Gruithuisen* [1955], *Firsoff* [1960], and *Thornton* [1960], have noted indistinctness and changes of hue in the vicinity of Schröter's Valley. In one of his drawings Firsoff shows a white spot labeled 'star-like point.' The valley is very bright under a high sun. It is situated in the area known as Wood's Spot [*Wood,* 1910], a region that photographs black in the ultraviolet and is attributed by some to a deposit of sulfur—a product of volcanic activity.

When this paper was submitted for publication, I suggested that if the area of Schröter's Valley were monitored with a spectrograph, like *Kozyrev*'s [1962] watch on Alphonsus, the results might be similarly rewarding. Recently several observations, both spectroscopic [*Kozyrev,* 1963] and visual [*Greenacre,* 1963; *Anonymous,* 1964], of emanations in the Aristarchus region, including the Cobra Head, have been reported.

The interpretation of the sinuous rills as valleys eroded by nuées ardentes implies a number of things about the selenology of the moon. It indicates that the moon has experienced a not inconsiderable amount of volcanism, much of it acidic, which in turn implies a differentiated moon. Further support is found in the accumulating evidence that tektites come from the moon. This evidence comes from investigations by *Chapman* [1960], *Chao et al.* [1961], *Adams and Huffaker* [1963], and *O'Keefe* [1963]. The possibility of acidic volcanism on the moon has been studied by *O'Keefe and Cameron* [1962], *Walter* [1962], and *Lowman* [1963]. The ash flow is a phenomenon that may be expected to occur if the moon is differentiated through igneous processes.

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