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The Procellarum volcanic complexes: Contrasting styles of volcanism

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Abstract—Three major volcanic complexes have long been recognized in the Oceanus Procellarum region of the moon. Detailed study shows that although the complexes share some characteristics they also display major differences which provide clues to eruption style. The *Rumker Hills* occupy 5000 km^2 in northern Procellarum and are apparently Imbrian-Eratosthenian in age; they are dominated by domes, suggesting relatively low effusion rates. The *Aristarchus Plateau-Prinz/Harbinger region* occupies 40,000 km^2 in central Procellarum and is predominantly Imbrian in age; it is dominated by large sinuous rilles and associated dark mantling deposits of probable pyroclastic origin, suggesting relatively high eruption rates. The *Marius Hills* occupy 35,000 km^2 in south-central Procellarum and appear to be predominantly Eratosthenian in age; they are dominated by low domes, steep domes, cones, and sinuous rilles, suggesting variable eruption rates and possible different volatile contents associated with eruption conditions that produced each type of feature. Viscosity differences appear to play a minor role in the variation in style of the three complexes. The volcanic complexes, particularly Aristarchus and Marius, appear to be the sources for much of the central Procellarum mare fill.

I. INTRODUCTION

ON EARTH, a concentration of volcanic features such as domes, cones, and shield volcanoes generally marks the location of a major volcanic source area. In addition, the morphology and relative numbers of specific features, and their density, can provide clues to styles and rates of eruption. These factors are significant in interpreting the characteristics of the lava source regions. On the moon, three of the largest lunar volcanic complexes occur in the western nearside mare.

Descriptions of parts or all of the igneous complexes within Oceanus Procellarum have been previously presented by McCauley (1967, 1968), Karlstrom *et al.* (1968), Moore (1967), Guest (1971), Scott and Eggleton (1973), Smith (1974), Zisk *et al.* (1977), and Strain and El Baz (1977). Data for this study included Lunar Orbiter and Apollo images, Lunar Topographic Orthophotomaps, infrared/ultraviolet composite images (Whitaker, 1972), and vidicon images (McCord *et al.*, 1976). From north to south, these complexes are the Rumker Hills (5000 km^2), the Aristarchus Plateau-Prinz/Harbinger region (40,000 km^2), and the Marius Hills (35,000 km^2), each of which is characterized by a large number of volcanic structures occurring within well-defined boundaries (Fig. 1). The purpose of this study is to compare and contrast the characteristics of these complexes and to document the styles of volcanism indicated by these characteristics.

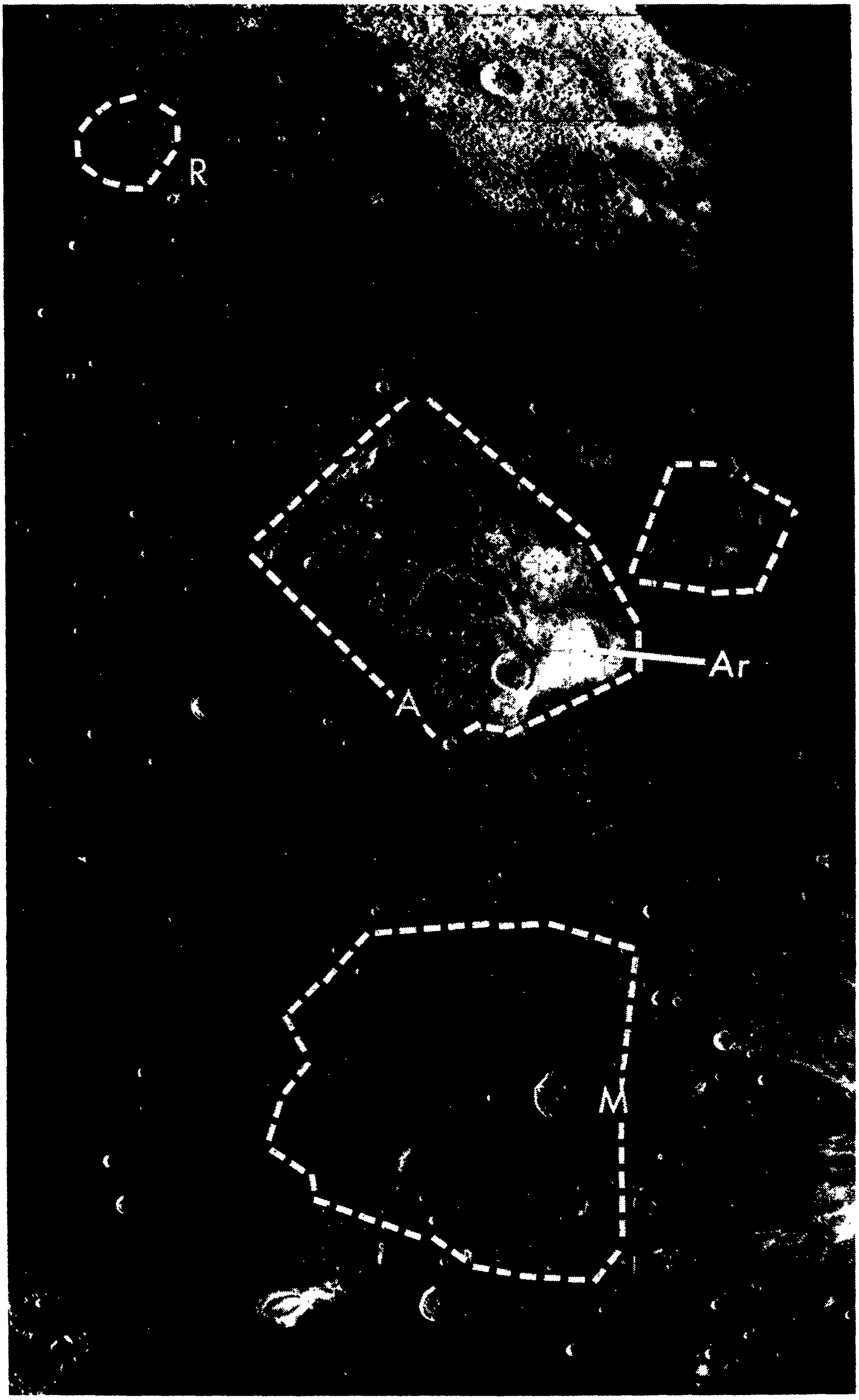

Fig. 1. Part of Lunar Orbiter IV 162 M photograph showing the distribution of the three igneous complexes in the center of Oceanus Procellarum. Rumker is at the top left, Aristarchus-Prinz/Harbinger Mountains in the center, and Marius in the center south. The crater Aristarchus (Ar) is 40 km in diameter.

II. Brief Descriptions of the Complexes

Rumker Hills

All volcanic edifices of the Rumker Hills are domes (Figs. 2a,b). These have been divided by Smith (1974) into three types: (1) eumorphic; irregular to convex upward and less than 2 km in diameter, (2) subcircular; irregular, flat-topped to convex upward with sharp outer edges and diameters of 6–9 km, and (3) low subcircular; irregular, flat-topped with indistinct outer contacts and diameters of 1.7–7.8 km. The plateau appears to contain pre-mare materials of the Fra Mauro Formation (Scott and Eggleton, 1973) but the volcanics have been assigned an Eratosthenian age (Scott and Eggleton, 1973). Guest (1971) concluded that at least one unit of the complex was older than the adjacent mare surface lavas but that the other units were synchronous with or postdated the mare lavas. The area is intermediate to red in color on combined UV-IR prints (Whitaker, 1972) and its albedo is not significantly different from adjacent lavas. Mare ridges cross the Rumker Hills (Fig. 2).

The Aristarchus Plateau-Prinz/Harbinger Mountains

This plateau is bounded by NW and NE trending scarps (Figs. 3a, b). The main part of the complex is separated from Montes Agricola (the linear outlier to the NW) by red lavas (Whitaker, 1972) filling what is apparently a fault trough. The sources of sinuous rilles are located mainly on the northern and southern edges of the complex; however, the largest and most distinctive rille (Schröter's Valley/Cobra Head) is centrally located. Rille widths are indicated in Fig. 4. Some of the sinuous rilles appear to have been the flow route for more than one phase of lava extrusion (Strain and El Baz, 1977). Dark mantling material covers much of the region but predates Aristarchus. Three low domes up to 10 km in diameter with summit depressions are located near the plateau; two on mare lavas adjacent to the plateau and one within the Prinz/Harbinger area (Head and Gifford, 1977). The plateau surface has a local gamma-ray anomaly (Metzger *et al.*, 1973) and a high alpha-particle anomaly near the crater Aristarchus (Gorenstein *et al.*, 1977). The surface materials (dark mantle) of the plateau were first dated as Copernican in age (Moore, 1967) but have more recently been dated as Imbrian, overlying Imbrium ejecta (Zisk *et al.*, 1977). The Prinz/Harbinger area is separated from the Aristarchus plateau by mare lavas but, like the plateau, contains sinuous rille source craters and has a similar surface morphology. This area is described in greater detail by Strain and El Baz (1977).

The Marius Hills

The Marius Hills (Figs. 5a,b) contain the most numerous and diversified volcanic structures of the three areas (Table 1). Low domes in the Marius Hills are up to 25 km in diameter and 50–200 m high. Less than 10% of these domes

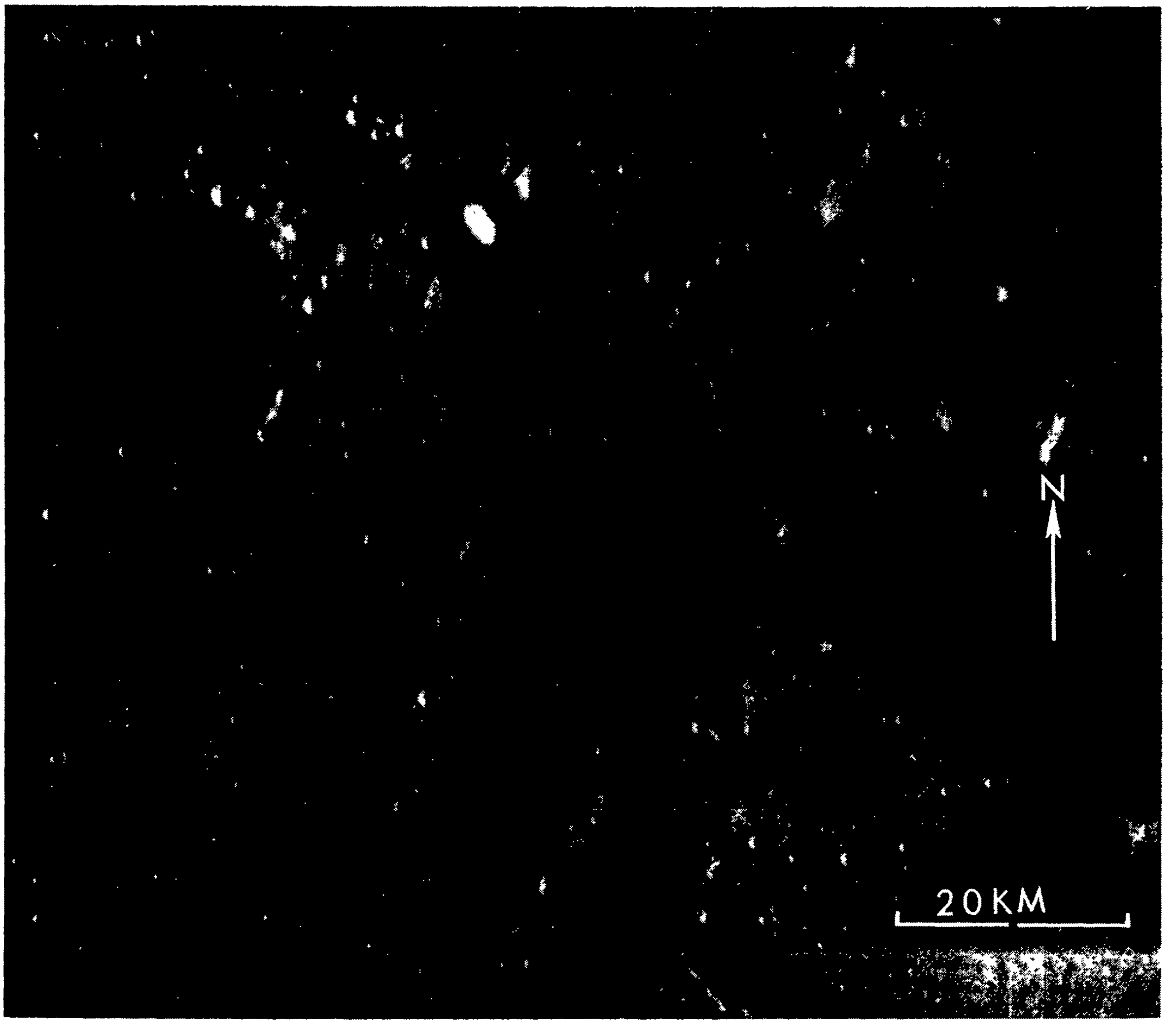

Fig. 2. (a) Part of Lunar Orbiter IV 163 H_2 frame showing the Rumker Hills.

have summit craters; those craters on low domes on the east side of the complex appear to be collapse pits since they lack raised rims. The domes are most numerous in the center of the complex. Marius steep domes are 2–15 km in diameter, 200–500 m in height, and many are located on low domes. Cones are up to about 3 km in length, have heights of up to 300 m, and are located on ridges, domes, and on plains materials between other edifices. Greeley (1971) has shown that at least one of the Marius rilles has a cone at its source. The sinuous rilles are located predominantly on the western edge of the complex and their widths are shown diagrammatically in Fig. 4. The surface materials are intermediate in color according to the red-intermediate-blue classification scheme of Whitaker (1972). The albedo is not significantly different from adjacent mare lavas. The surface materials of the complex have been assigned an Eratosthenian age (McCauley, 1967).

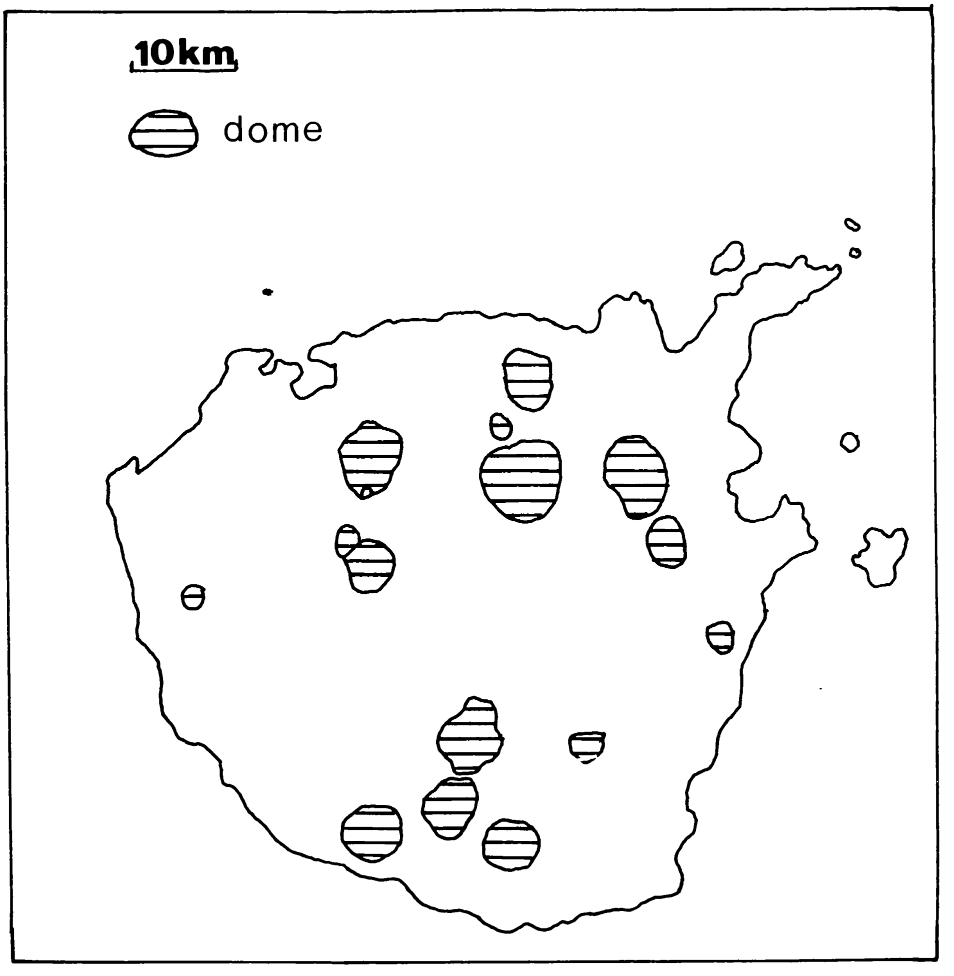

Fig. 2. (b) Map of the Rumker Hills showing the distribution of domes. Only the most prominent of the domes mapped by Smith (1974) are shown here.

III. Inter-complex Comparisons and Contrasts

The three complexes have a number of common features but also show distinct differences. All are located on or near the central ridge system of Oceanus Procellarum and are the most conspicuous areas of lunar volcanism with sharply defined boundaries. The Aristarchus Plateau differs from Marius and Rumker in that the mare ridges pass around it rather than through it. The centers of each complex are approximately 400 km apart yet the size of each complex is different (Rumker, 5000 km^2; Aristarchus, 40,000 km^2; Marius, 35,000 km^2). Aristarchus and Rumker differ from Marius in that pre-mare materials are exposed in the former but not in the latter.

The three complexes differ in the morphological expression of volcanism (Table 1; Fig. 6). The Rumker Hills are characterized by domes, the Aristarchus region is distinguished by a large number of sinuous rilles and few domes, while the Marius Hills exhibit a large number of domes and rilles plus steep domes and cones, neither of which has been identified on the other two complexes (Table1).

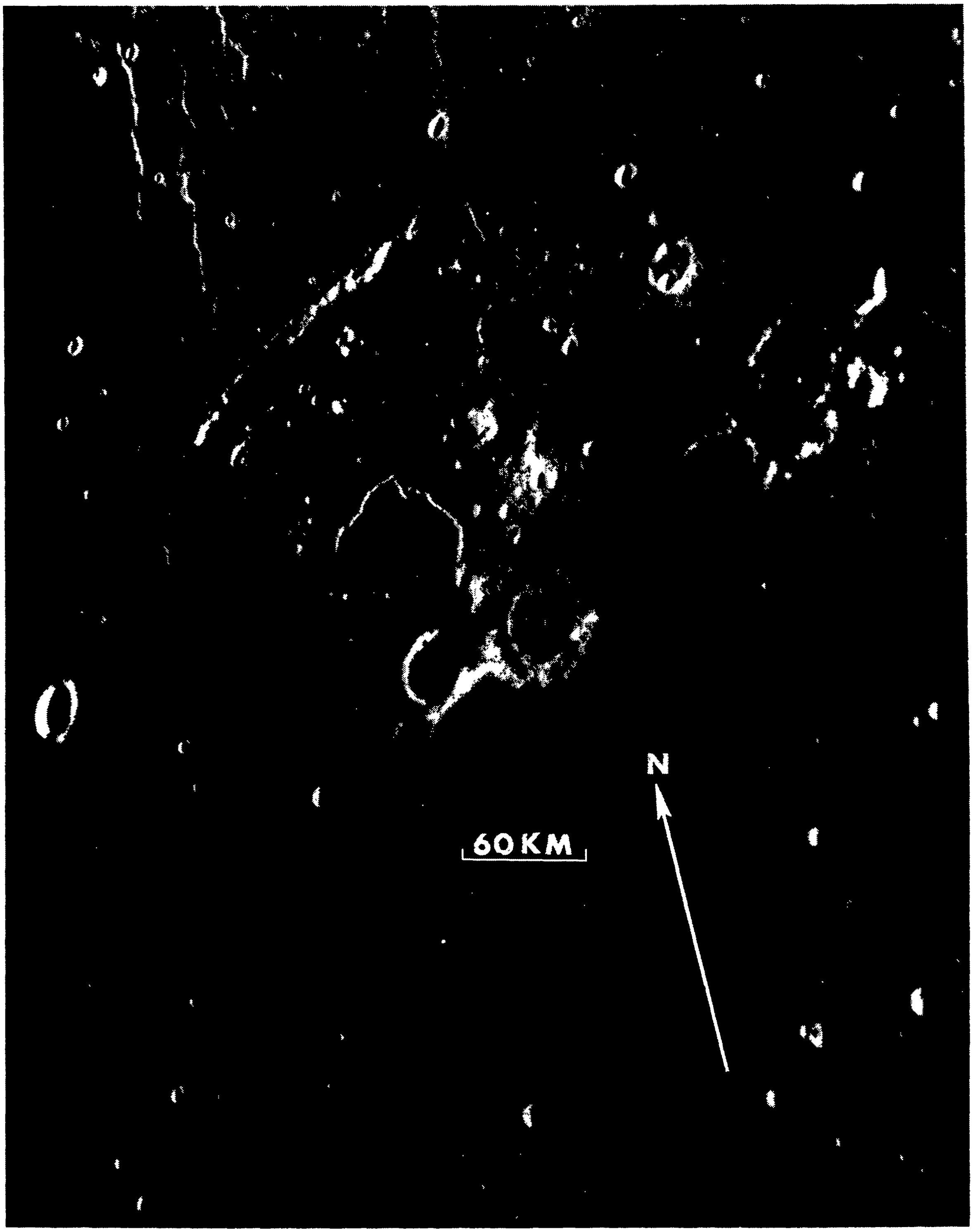

Fig. 3. (a) Earth-based photograph of the Aristarchus Plateau-Prinz/Harbinger Mountains area. Consolidated Lunar Atlas LPL (1967).

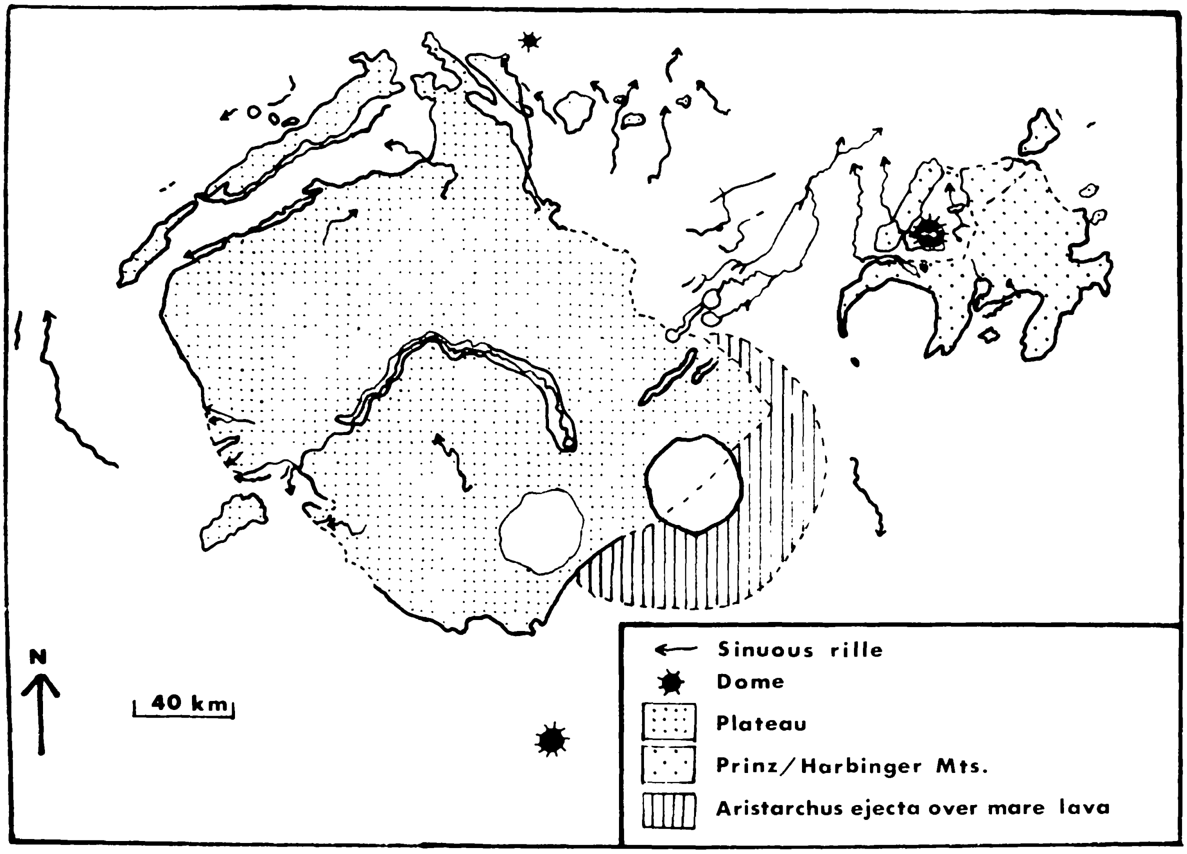

Fig. 3. (b) Map showing the distribution of domes and sinuous rilles in the Aristarchus region.

On Rumker the domes are mostly low, circular and smooth, often with a summit pit crater (Classes 1 to 3 of Head and Gifford, 1977), whereas on Marius many of the domes are very irregular, lack summit craters, and have a rough surface texture (Class 7, Head and Gifford, 1977). The rilles of the Aristarchus Plateau generally have parallel sides and flat floors for a larger part of their discernible length than those of Marius, which decrease rapidly in width with distance from their sources.

Concentration of volcanic features (domes, cones, sinuous rilles) per unit area show differences between the areas; at Marius there is approximately one feature per 103 km^2, at Rumker one per 170 km^2, and at Aristarchus one per 1525 km^2. These are lower limits since they omit both structures which cannot be categorically assigned a volcanic origin, and the effects of large post-volcanic impact craters (such as Aristarchus) that obscure the volcanic terrain. Cinder cone concentrations in terrestrial volcanic fields are variable and, in the areas analyzed, higher than the concentrations of volcanic features on the Procellarum complexes. The cone concentration in the San Francisco Field is one per 11.5 km^2, that of the Paricutin Field, one per 20.4 km^2, and that of Nunivak Island, Alaska, one per 41.4 km^2 (McGetchin and Settle, 1975). The reasons for these density variations have not been explained though varied rates of magma supply and different degrees of crustal fracturing may be important. An inter-

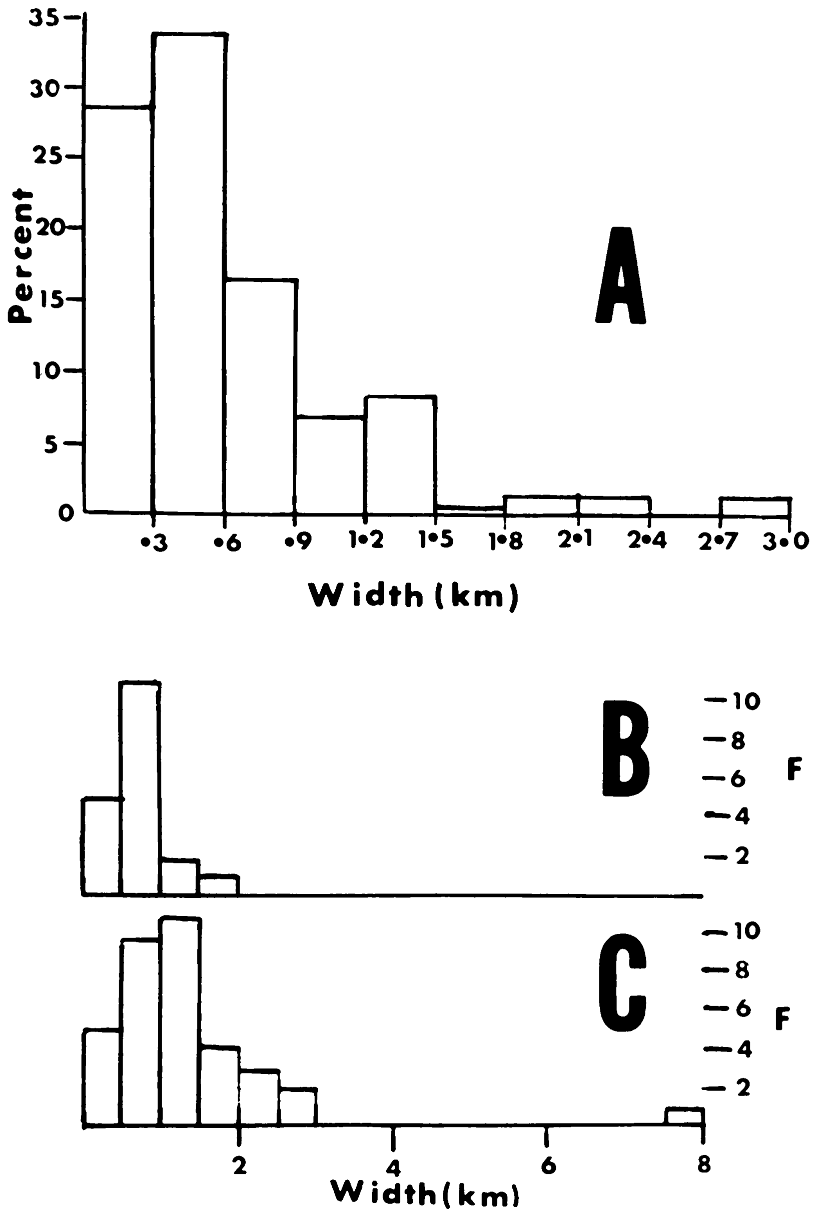

Fig. 4. Width/percent diagram for sinuous rilles obtained by Schubert *et al.* (1970) (A), and width/frequency diagrams for the Marius Hills (B), and the Aristarchus region (C).

mittent supply rate would result in the closure of specific fractures as lava crystallized in occupied vents, and the production of new channels to the surface with each new batch of magma. Thus many separate features would be produced. Alternatively a highly fractured crust would provide many separate pathways for magma whereas an unfractured crust would not. The differences in concentrations of volcanic features on the lunar complexes may therefore be explicable in terms of varying magma supply rates or degree of crustal fracturing.

It is not clear whether there are any structural controls on the location of the features within each complex. The Rumker domes appear randomly distributed

(Fig. 2b), but there is a slight indication that the Aristarchus rille sources could be aligned along WNW and ENE trending fractures (Fig. 3b). At Marius the dome distribution appears to be random. However, there is a higher concentration of cones in the north of the Marius complex relative to the south.

IV. Determinants of Volcanic Feature Morphology

Studies of active terrestrial volcanism have indicated that factors governing the morphological development of volcanic edifices are complex and interrelated (Macdonald, 1972). Such factors include the viscosity of the erupted material, its temperature, its composition, the volatile content, the duration of the eruption, the number of repeated eruptions from the same vent, and the eruption rate. The viscosity of the magma depends on its temperature, volatile content, and composition—the presence of gas bubbles and crystalline material will both increase the viscosity of the magma, and the amount of crystalline material will depend upon how fast it is transported from its reservoir to the surface and the crystallization temperature of its component phases (Macdonald, 1972). Degassing of the magma at eruption will also change the viscosity of the lava because gas loss inhibits crystallization. However, at least under terrestrial conditions, this effect is less important than lower temperature in governing lava fluidity (Swanson, 1973). Walker (1973) has argued that the factors cited above are not of equal importance and that eruption rate is the major determinant of lava flow morphology. The Procellarum complexes are examined in terms of their morphological variation and possible relation to eruption conditions.

Sinuous rilles

Eighty-three percent of the lunar sinuous rilles measured by Schubert *et al.* (1970) have widths less than 1 km and the median width is 400 m. Median rille widths in Marius Hills and the Aristarchus Plateau are larger, and Aristarchus Plateau rilles are significantly wider than those of the Marius Hills (Fig. 4). The morphologies of lunar sinuous rilles can mostly be explained in terms of either lava tube collapse (Greeley, 1971) or lava erosion (Hulme, 1973; Carr, 1974). In either case, the outline of the rille indicates the path of the lava flow and the source crater for the rille indicates the location of the vent. Hulme (1973) argues convincingly that lunar lavas were able to flow in a turbulent manner since their low viscosities enable them to behave more like Newtonian liquids (terrestrial lavas have higher viscosities and flow in a laminar manner). As a result, the lunar lavas may have eroded their bedrock and thus produced sinuous rilles.

Examination of returned lunar basalts has indicated that the phenocrysts within these rocks could have formed after the emplacement of the magma on the lunar surface (Lofgren, 1974); however, this has been disputed because of preferred orientation of phenocrysts but not matrix crystals (Greenwood *et al.*, 1972). If no phenocrysts were present, the viscosity of the magma at eruption would be largely determined by its chemical composition. Figure 7 indicates that

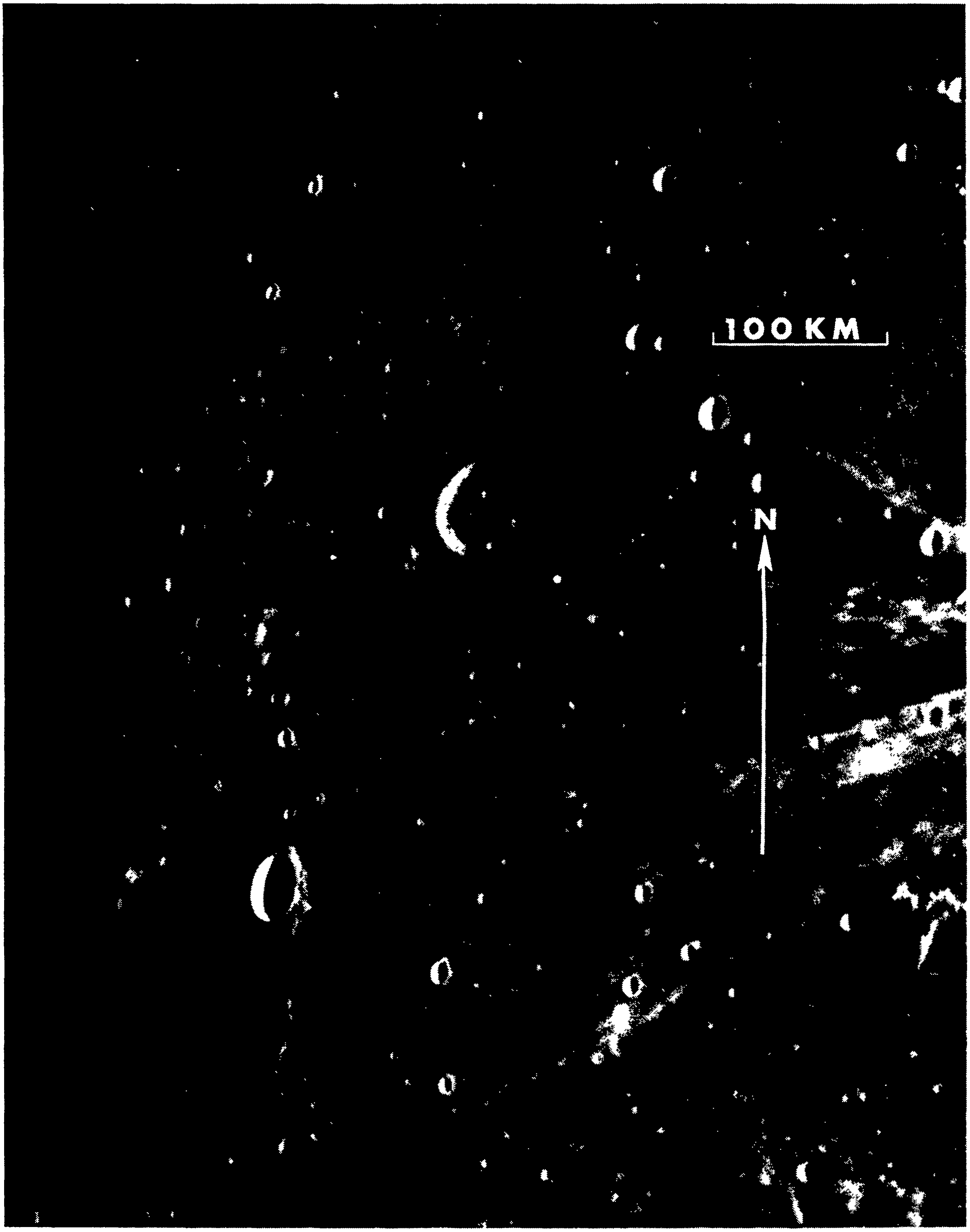

Fig. 5. (a) Earth-based photograph of the Marius Hills. Consolidated Lunar Atlas LPL (1967).

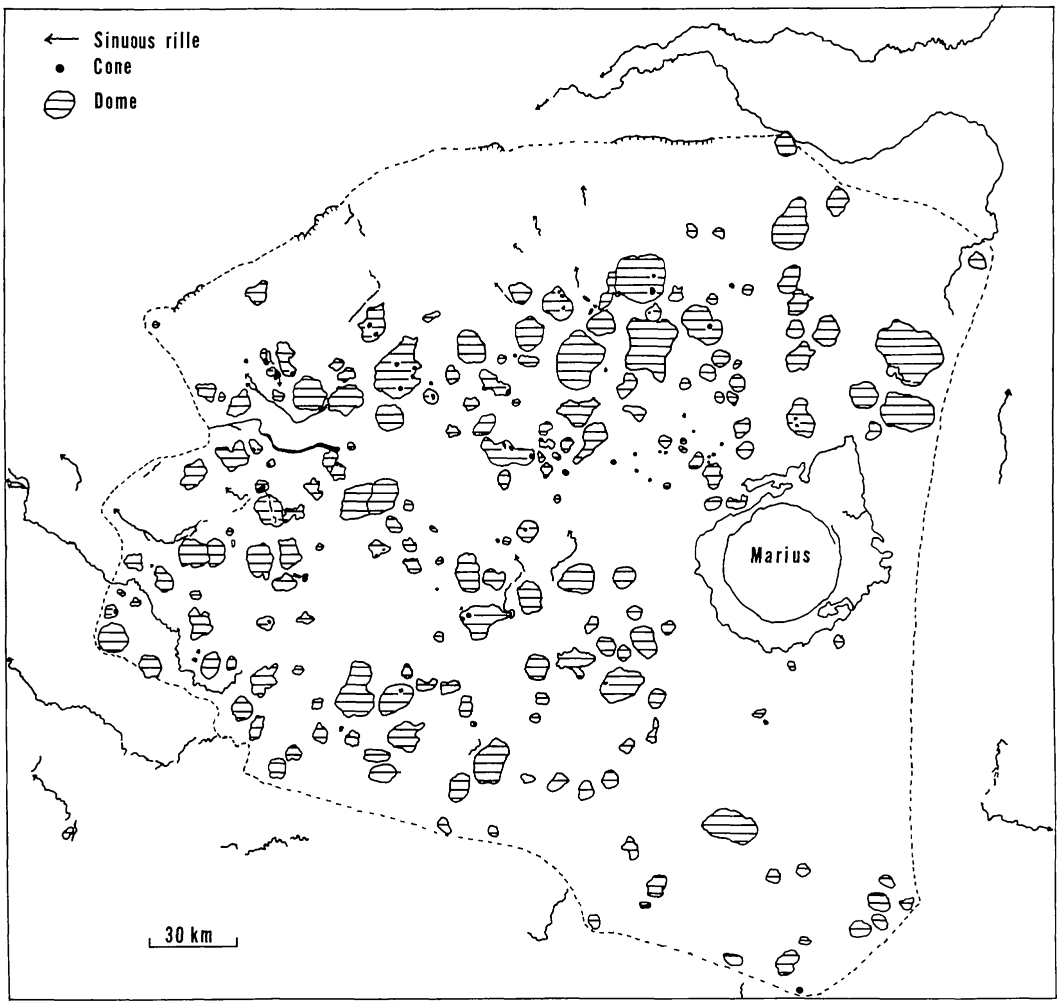

Fig. 5. (b) Map showing the distribution of domes, cones, and sinuous rilles within and around the Marius Hills.

the supraliquidus viscosities of the returned lunar lavas show as much variation at a single site as between sites of different basaltic composition. Therefore, differences in lava morphologies resulting solely from viscosity variations caused by chemical differences are unlikely. In addition, since sinuous rilles occur within lavas of different composition as indicated by spectral reflectivity measurements (i.e., Rima Brayley, blue, and Rima Hadley, red), a composition-viscosity relationship is unlikely as the major determinant for rille variation, although temperature-induced viscosity variations are possible. In the areas under investigation, the Aristarchus rilles are in red lavas whereas those of the Marius Hills are in intermediate color lavas. Also, the size variations of the rilles from the two complexes (Fig. 4) suggest either different temperatures, different degrees of structural control, or varying eruption rates. Higher temperatures would result in lower viscosity lavas which would erode the bedrock more effectively and produce larger rilles. However, if the lavas were erupted at supraliquidus temperatures the viscosity change would be small compared to the

Table 1. Volcanic features of Procellarum complexes.

	Sinuous rilles	Low domes	Steep domes	Cones	Color
Marius Hills	20	135	127	59	Intermediate to red
Aristarchus and Harbinger Mts.	36	3	—	—	Red
Rumker Hills	—	30[1]	—	—	Intermediate to red

[1]After Smith (1974).

temperature difference since the lavas have very low supraliquidus viscosities. It is doubtful whether temperature-induced viscosity differences could produce the gross morphological differences between the rilles. Fracture zones may provide more readily erodible bedrock and result in the formation of larger rilles. Finally, the differences could result from varying eruption rates; the larger rilles formed by lavas erupted at greater rates for longer periods. Assuming Hulme's and

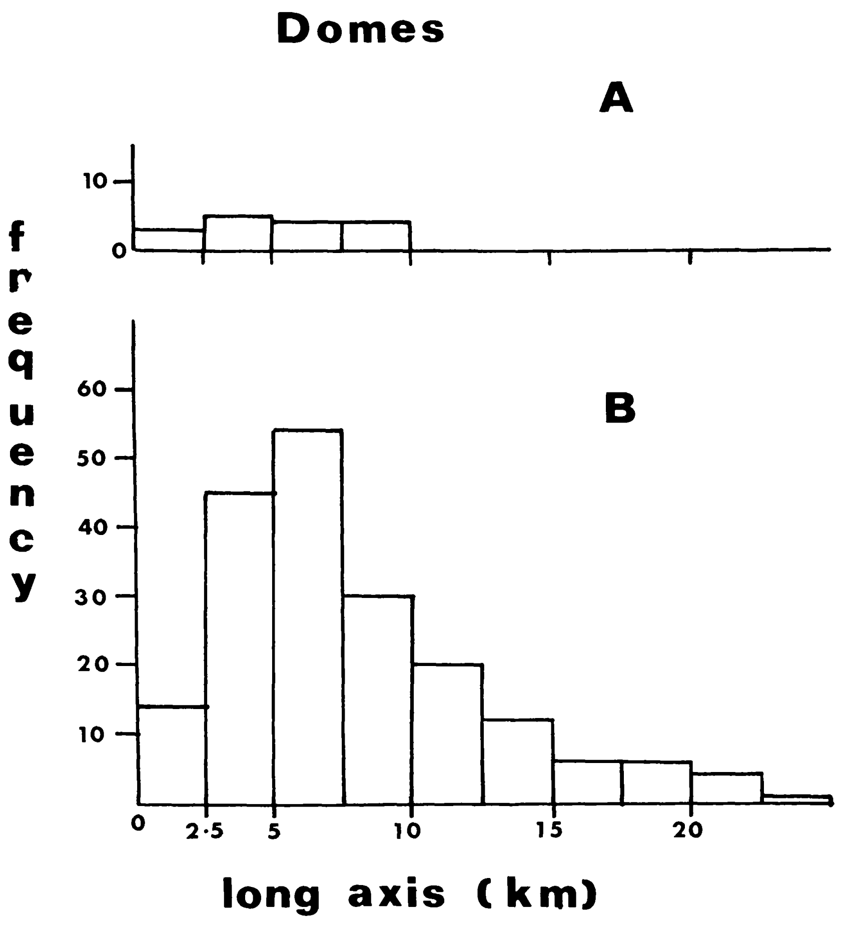

Fig. 6. Frequency/length of long axis plot for domes in the Rumker Hills (A) and the Marius Hills (B).

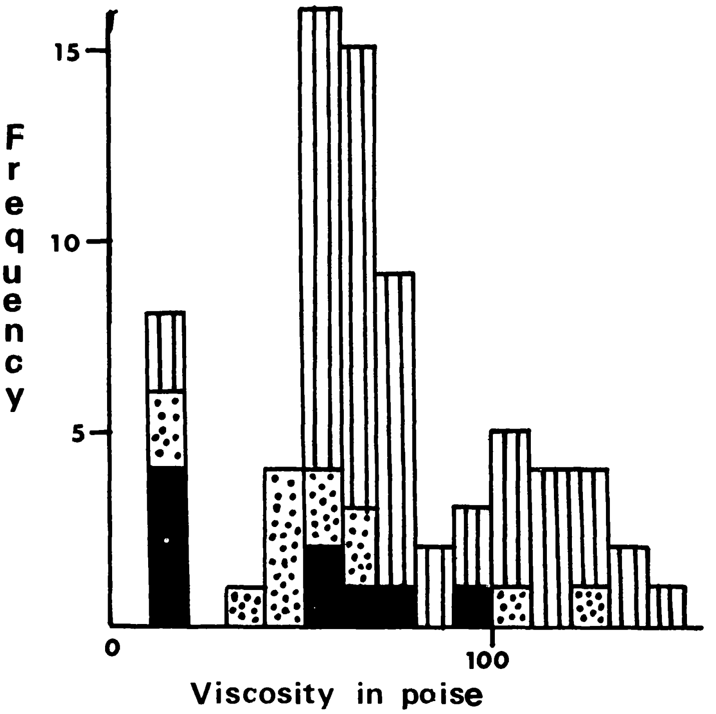

Fig. 7. Calculated viscosities for lunar basalts at 1300°C after the method of Bottinga and Weill (1972). Apollo 11 (black), Apollo 12 (dotted) and Apollo 15 (ruled). The graph shows that any variations in lava morphologies at these sites do not result from viscosity differences since the viscosities are essentially similar at each site. The viscosities obtained by this method depend solely on the composition of the rocks. The compositions employed were the averages of published analyses for specific mare basalts (Whitford-Stark, 1975).

Carr's models to be correct, lava turbulence and thus erosion takes place at a critical Reynolds number; the Reynolds number based on flow depth is given by

$$\mathrm{Re}_d = p\frac{Q}{n}$$

where p = density, Q = volume rate of flow per unit width of channel, and n = viscosity (Hulme, 1973). So, if lunar lava viscosities are approximately similar, the change in Reynolds number of the lavas will be largely a function of the volume rate of flow. Under these constraints, sinuous rille production is determined to a large extent by eruption rate. Hulme (1973) has estimated an eruption rate of 4×10^4 m^3/sec for one of the Marius Hills rilles (see Fig. 4)—this compares with values of 4 to 300 m^3/sec (mean about 60 m^3/sec) for the Hawaiian flows (Walker, 1973) and 1.16×10^4 m^3/sec per kilometer length of fissure for the Roza member of Yakima Basalt flows of the Columbia River Plateau (Swanson *et al.*, 1975).

Domes

Two major types of domes occur in the complexes. Smooth mare domes commonly with central pit craters are seen in the Rumker Plateau and are typical of mare domes common elsewhere on the moon (Class 1–3 domes of Head and Gifford, 1977). At the Marius Hills, numerous low domes occur, but most are capped with irregular steep-sided domical structures (Class 7 domes of Head and Gifford, 1977). Although the domes of the complexes are not comparable with the Hawaiian shield volcanoes in size (Fig. 6), they do have sizes and morphologies similar to some of the Icelandic domes (Whitford-Stark, 1975). In particular the Marius steep domes resemble the Icelandic "eldborg" type of feature while the low domes resemble Icelandic "dyngja." The eldborgs have a circular outer wall and have been produced by a combination of lava fountaining and the eruption of thin sheets of lava (Thorarinsson, 1960). Variations between eldborgs and dyngja are ascribed to changes in temperature and explosivity of the magma (Thorarinsson, 1960).

In the Hawaiian Islands the magma changes in composition with time; the younger lavas are more alkalic, gas enriched and contain more phenocrysts. This change is ascribed to lowering of the temperature of the magma chamber (Macdonald and Abbott, 1970) and results in a change in morphology of resulting landforms. In the Marius Hills the steep domes are often superimposed on the low domes and are therefore contemporaneous or of younger age. Terrestrial observations suggest that these morphologic variations may be due to compositional changes or to changes in magma temperature and explosivity. Thus, the Marius sequence of low domes–steep domes–cones, may represent either decreasing temperature, increasing gas content, or increase in silica content of the magma. McCauley (1968) has suggested that the earliest domes may be mafic whereas the steep-sided later features may be intermediate to felsic. Because flow length is proportional to eruption rate in terrestrial lavas (Walker, 1973), steeper edifices could also be produced by decreasing eruption rates.

Cones

The simultaneous eruption of lava and pyroclastic material from the same edifice is a well-known phenomenon of terrestrial volcanic activity (e.g., Heimaey) (Self *et al.*, 1974). The reason this happens is not well understood. Films of Hawaiian eruptions show quite clearly the doming of the magma surface in the vent prior to its explosive disruption. It is probable that this phenomenon represents the explosion of a (or many) gas bubble(s). Hence the variation between domes and cones might be partly due to differing volatile concentrations or the gas diffusion rate relative to the eruption rate of the lava. If the quantity of the gas is small, it will not be able to achieve concentrations capable of disrupting the magma. Alternatively, if the eruption of lava is extremely rapid, then even if the volatile content is high, the volatiles might not have time to concentrate sufficiently to produce explosive eruptions. The fact that lunar volatiles will commence nucleation at six times the depth of terrestrial volatiles and that the volatile component was probably not water (Whitford-Stark, 1973) suggests that the rarity of lunar pyroclastic edifices is a function of low volatile content rather than insufficient time for bubble nucleation. Cones in the Marius Hills might indicate a relatively high volatile content for the lavas erupted therefrom.

In an earlier paper McGetchin and Head (1973) argued that terrestrial cinder cones erupted under lunar conditions would form pyroclastic rings with very low slopes because of low gravity and lack of atmosphere. However, a variety of pyroclastic features has been observed on the moon, ranging from low pyroclastic rings (some dark halo craters) to various features resembling terrestrial cinder cones (Head, 1975). This led to the proposal that edifices on the moon shaped like terrestrial cinder cones may be spatter cones rather than cinder. However, the size of particles erupted under lunar conditions may be larger than those erupted on earth because of lower gravity, possibly resulting in steeper rim deposits than those proposed by McGetchin and Head. The shape of the cone might also be a function of the time interval between explosions. If the explosions are more or less continuous (Plinian-like) small tephra particles may be produced and a low cone will result. On the other hand, a time interval between eruptions may allow a more viscous magma to occupy the vent which is then broken into a variety of sizes by the explosions (Strombolian) and a steeper cone is produced because of the larger particles concentrated near the vent.

Numerous areas on the moon, including the Aristarchus Plateau, exhibit dark mantling deposits that appear similar to the material of dark halo craters, but are much more extensive. These are interpreted to be of pyroclastic origin (Head, 1974; Lucchitta, 1973; Lucchitta and Schmitt, 1974). Although the deposits are more extensive, evidence has not been found for abundant, widespread vents that might have been the sources of the mantle. Instead, only a few large sources have been identified, leading to the hypothesis that extremely active pyroclastic activity, perhaps fire fountaining, at these major vents produced the widespread mantling deposits. Two factors may have been significant in producing these deposits, high volatile content of the magma (Head, 1975) and/or extremely high eruption rates causing lava fountaining. The size and abundance of sinuous rilles at the Aristarchus Plateau suggests that its extensive dark mantle may be related to high eruption rates and associated fountaining at the sources.

V. Age Relationships

The length of activity at each complex and the age relationship at each complex are unknown. By analogy with similar terrestrial structures, each of the various edifice types could form within a time period of a few months or less, but all the edifices within any one complex were not simultaneously active. Greeley (1971) has shown that the floor of one sinuous rille in the Marius Hills maintains a constant elevation where it crosses a mare ridge, whereas an adjacent rille floor appears to be raised at the ridge crossing point. This observation implies that the rilles were separated in time by at least the period of ridge formation. In Aristarchus the superposition of one sinuous rille source crater part-way along the length of another sinuous rille and the presence of a meandering rille within the floor of Schröter's Valley (Murray, 1971) implies at least two phases of eruption at the Aristarchus Plateau. Smith (1974) considered that the three types of domes of the Rumker Hills were representative of three distinct periods of eruption.

Geologic maps compiled primarily from earth-based telescopic observations indicate ages of volcanic surface materials of Imbrian-Eratosthenian at Rumker (Scott and Eggleton, 1973), Imbrian-Eratosthenian in the Prinz-Harbinger region (Moore, 1967), Eratosthenian-Copernican in the Aristarchus Plateau (Moore, 1967), and Eratosthenian in the Marius Hills (McCauley, 1967). Subsequent examination of higher resolution Lunar Orbiter and Apollo imagery has provided some additional age information and some revisions to the earlier age assignments.

Rumker Hills

Recent crater degradation ages (Boyce, 1976), although not of sufficient resolution to date the plateau itself, suggest an age of 2.7–3.3 b.y. for the surrounding lavas. Although these dates are subject to the inaccuracies introduced during the crater measuring method and the calibration of the absolute ages with relative ages, the technique employed by Boyce suggests that the area surrounding Rumker Hills is relatively young in terms of lunar mare history. Secondary craters and associated lineations which may be from the middle Imbrian crater Iridum are observed on the northwest edge of the plateau. These features appear to form in mare-like units and have been embayed by subsequent volcanic activity on and around the plateau.

Aristarchus Plateau/Prinz-Harbinger region

Compositional and age relationships derived from spectral data (Whitaker, 1972) and near-terminator photography suggested that the Aristarchus Plateau rilles, mantling material, and related lavas were Imbrian in age, rather than Eratosthenian-Copernican (Head, 1974). More recent detailed study (Zisk *et al.*, 1977) indicates a complex history for the Aristarchus–Harbinger area during the Imbrian period. There appears to be little evidence for extensive Eratosthenian-age activity centered in these complexes.

Marius Hills

On the basis of crater degradation ages (Boyce, 1976) the Marius Hills contain some of the youngest deposits (Eratosthenian) seen in the three complexes. Detailed examination, however, suggests that the region has had a long and complex history. Ejecta from the Imbrian crater Marius appears to have been deposited on several constructs, while numerous volcanic deposits and rilles are superposed on its rim and ejecta. The Eratosthenian crater Reiner has Marius Hills-associated lava flows superimposed on its ejecta.

On the basis of the above observations, the Aristarchus Plateau appears to be the oldest complex (primarily Imbrian), while activity at Rumker appears to have started in the Imbrian and may have continued into the Eratosthenian. Although activity at the Marius Hills may have begun in the Imbrian, it is the only complex where there appears to be substantial evidence for major activity in the Eratosthenian.

VI. Summary and Conclusions

Though located at similar positions with respect to the Oceanus Procellarum ridge system, the morphologies and the relative abundances of the volcanic features of the complexes are significantly different. In terms of the analogs and models discussed here, these morphological differences may be largely explained by varying eruption rates and to a lesser extent, different volatile contents and viscosities of the erupted materials. The topographic data required for the calculation of the eruption rates of lavas that produced the Marius Hills rilles and some rilles of the Aristarchus Plateau are not available. Even if the data were available, it would still be necessary to assume values for the densities, temperatures, compositions, and viscosities of the lavas. On the basis of an eruption rate of 4×10^4 m^3/sec determined for a 50 km long, 500 m wide Marius rille (Hulme, 1973), eruption rates of the order of several hundred m^3/sec appear necessary for the production of sinuous rilles.

The low viscosities of lunar lavas suggest that low domes were produced by lavas erupted at rates less than those which produced terrestrial shield volcanoes ($\lesssim 10$ m^3/sec) and lunar steep domes at yet smaller rates (< 0.1 m^3/sec?).

Terrestrial plinian eruption velocities are of the order of 300 to 600 m/sec (Fudali and Melson, 1972; Nairn, 1976) and strombolian velocities in the range of 15 to 200 m/sec (Blackburn *et al.*, 1976). The lack of a lunar atmosphere would lower the velocities required to produce similar tephra deposits. McGetchin and Ullrich (1973) indicate that a velocity increase of about 200 m/sec is required for terrestrial eruptions to produce the same effect as that exerted on lunar particles of the same size in the range from 1 to 1000 cm.

From this we deduce that high eruption rates resulted in the production of the large Aristarchus sinuous rilles, some of which contain rilles which were produced by lavas erupted at lesser rates. These were apparently not followed by materials erupted at the lower rates required for dome production. The Marius Hills also experienced high eruption rates like those at Aristarchus but the rates for individual eruptions declined with time, resulting in the production of features characteristic of lower eruption rates (domes, cones). The Rumker Hills had low eruption rates which led to the production of domes. Causes of these eruption rate variations are unknown but might include such parameters as different localized stress fields in the lunar interior, variations in radioactive element distribution, or a chemically inhomogenous lunar mantle. No completely satisfactory explanation has been proposed for the concentration of these complexes in Procellarum. A possible reason for the location of the complexes on the central Procellarum ridge system might be that this ridge system represents a ring fault of the Pre-Imbrian Gargantuan Basin (Cadogan, 1974) (Whitaker, pers. comm. 1977). However, this suggestion does not account for their spacing along the ridge system or their variation in age. Crustal thickness models for the Procellarum region (Bills and Ferrari, 1977) show no obvious local or regional variations related to the complexes. Analysis of associated volcanic and tectonic features in Procellarum (Whitford-Stark and Head, 1977) shows the mare region to have undergone a history analogous, in terms of compositional changes and structural deformation, to the circular mare basins and reveals no specific reasons for volcanic complex location. Mare lava sources are believed to have been at 100–400 km depth (presumably the thickness of the lithosphere at the time). The spacing of the complexes (300–400 km) may possibly be related to spacing of major fractures whose dimensions are comparable to lithospheric thickness, as postulated for earth (Vogt, 1974). Alternatively, the location and spacing may reflect the radius of magma source areas.

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