TOPOGRAPHY OF SINUOUS RILLES IN THE HARBINGER MOUNTAINS REGION OF THE MOON

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Abstract. Five sinuous rilles occur in mare basalts in the Harbinger Mountains region of the Moon. Complete and accurate topographic data, now available for the first time, make possible a detailed topographic study of these rilles. Rille length ranges from 12 to 79 km and width from 0.8 to 4.8 km. Depth varies from 100 to 300 m and the rilles appear to become shallower to the north. The southern ends of the rilles are characterized by circular to elongate depressions that occur on a 30 km in diameter dome of probable volcanic origin. Longitudinal profiles show that the rille floors have a northward slope of less than one degree. This slope is consistent with the general slope of the surrounding mare surface. Structural studies indicate that slope rather than the regional structural pattern is the dominant factor controlling rille direction. Topographic data lend support to the theory that the rilles were formed as lava channels or tubes.

1. Introduction

Sinuous rilles have long puzzled lunar investigators. Cameron (1964) suggested that the rilles were formed by erosion by nuées ardentes. Urey (1967), Gilvarry (1968), and Lingenfelter *et al.* (1968) proposed that water was the erosive agent. However, considerations of morphology and Apollo mission data that demonstrated the absence of water on the Moon have refuted these theories (Head, 1976). Structural theories of rille formation include tensional fracturing (Quaide, 1965) and fluidization of the regolith by gases emitted from fractures (Schumm, 1970). Another possibility, that has gained wide acceptance, is that the rilles are lava channels or tubes (Oberbeck *et al.*, 1969; Greeley, 1971a, b; and Howard *et al.*, 1972). As an extension of this idea, Carr (1974) described a process of lava erosion by thermal incision within a lava channel. Hulme (1973) argued that thermal erosion may have been caused by turbulent lava flow.

These theories are based on photogeologic interpretations made without the benefit of the detailed and accurate topographic data that have recently become available. This paper summarizes the results of a study of selected rilles using the new data to see if more light can be shed on the problem of rille origin.

The five sinuous rilles studied in detail lie in the Harbinger Mountains region of the Moon. This region is in eastern Oceanus Procellarum within the area covered by LAC 39 (Aristarchus). The rilles were studied using Lunar Orbiter and Apollo Hasselblad, metric, and panoramic photographs as well as maps and profile data. The following maps were used: (1) the NASA Lunar Topographic Orthophotomap (LTO) of the Prinz Province (39A3) at 1 : 250000 scale; and (2) the NASA Lunar Topo-photomap of Rima Prinz at 1 : 50000 scale. Profile data along and across the rilles were supplied by the Defense Mapping Agency/Topographic Center on specially produced 1 : 50000 scale photomaps with ±3 m vertical accuracy.

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RIMA TELEMANN
RIMA HANDEL
E
C
RIMA BEETHOVEN
RIMA PRINZ
PRINZ

On the aforementioned maps, the rilles are given provisional names, i.e., names that have not been formally adopted by the International Astronomical Union (IAU). These names (Figure 1) will be used here for convenience; Rima Prinz and Rima Beethoven replace the former designations of Rima Prinz I and II respectively.

2. General Setting

The Harbinger Mountains region of the Moon (Figure 1) lies east of the Aristarchus Plateau along the main ring of the Imbrium basin (Wilhelms and McCauley, 1971). The five rilles under study are north and northeast of the crater Prinz, a large Imbrian age crater flooded by Imbrian mare materials (Moore, 1965). Its rim appears smooth and subdued and may be mantled by volcanic material (Moore, 1965).

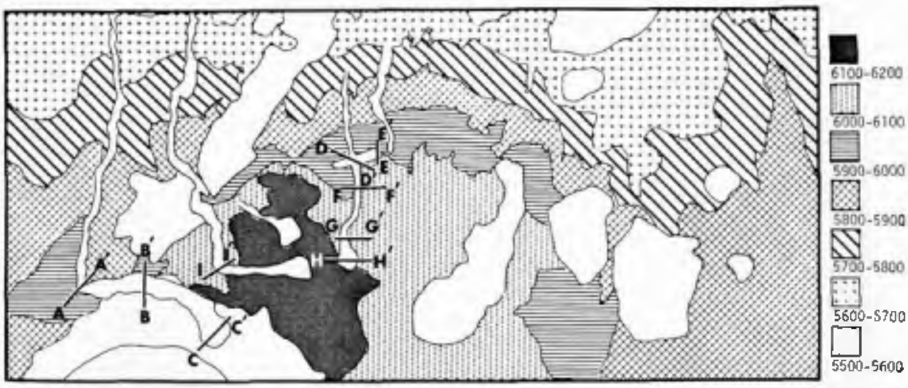

Fig. 2. Sketch showing topographic variation of the maria in the Prinz province summarized from the 1 : 250000 scale LTO. Elevations are in meters above an arbitrary datum of 1730000 m. Note the presence of a dome northeast of the crater Prinz. The rilles appear to originate on this dome. Lettered lines mark the traces of profiles across the rilles as shown in Figure 5.

Rugged terra massif units of the Harbinger Mountains are scattered throughout the area. The largest is 2100 m high. The inferred trace of the main ring of the Imbrium basin falls near the massifs. Massif scarps are oriented tangent and radial to that ring and are probably remnants of it (Wilhelms and McCauley, 1971). A less rugged hilly unit east of the crater Prinz displays a smooth and rounded texture (A in Figure 1). This unit may represent a mantled part of the Imbrium ring massifs. However, a rounded hummocky texture, domelike features with summit craters, and proximity to other volcanic features suggest that these hills may have formed as a complex of domes and other volcanic materials. A third possibility is that the unit represents a combination of the two alternatives.

The rilles lie on the flanks of a dome which is approximately 30 km in diameter and rises more than 200 m above the mare surface (Figure 2). Two smaller domes

←Fig. 1. Apollo 15 metric photograph (2081) of the Harbinger Mountains region of the Moon. Rille names are provisional pending IAU approval. 'A' is a hilly unit east of the crater Prinz that may be a mantled part of a highland massif or a complex of volcanic constructional features or both. 'B' is a roughly-textured mare unit exhibiting sculpture possibly due to secondary impacts of Prinz. Note rugged (C) and smooth (D) domes northeast of the crater Prinz. 'E' marks the unnamed rille east of Rima Beethoven.

rest on top of this dome (Figure 1). One is flat, smooth, and roughly 13 km in diameter and 100 m high (D in Figure 1). The other is steeper, displays a rugged texture, and is 4 km in diameter and 200 m high (C in Figure 1). These domes exhibit morphological features similar to the low and steep-sided volcanic domes of the Marius Hills region described by McCauley (1967). McCauley proposed that the different dome types originated as a result of compositional differences in the magma or changes in mode of eruption of the volcanic materials.

The mare unit that contains the rilles was determined to be of Imbrian age using the method of crater analysis of Soderblom and Lebofsky (1972). Our results are similar to those of Boyce which indicate an average age of about 3.4–3.6 billion years (Boyce *et al.*, 1974). With the exception of portions of Rima Prinz, the rilles occur within a small red region on the color difference photographs of Whitaker (1972). A sixth rille, east of the crater Prinz, lies directly on the eastern boundary of this region. Segments of Rima Prinz border the region's western edge. The red unit is part of a fan-shaped complex of other red units extending from the Aristarchus Plateau region (Figure 3). This complex is characterized by numerous

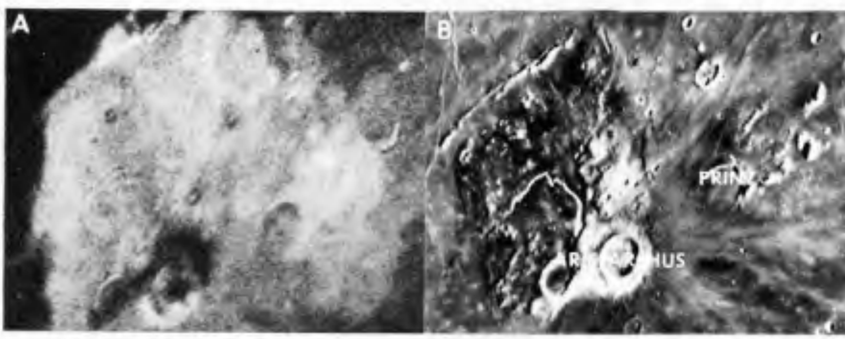

Fig. 3. (A) Color difference photograph of the Aristarchus plateau region showing a fan-shaped area of red mare (light-colored area) surrounded by darker blue mare (dark area). Note the bright red region north of Prinz which contains the rilles. Courtesy of E. A. Whitaker. (B) Earth-based photograph of the same area shown in Figure 3a (Kuiper *et al.*, 1967, photo C21).

sinuous rilles which appear to be lacking in the surrounding bluer units. Mare ridges and arches common in the bluer units are lacking in the red.

The smooth mare unit in which the rilles occur exhibits sharp contacts with an older, roughly-textured, Imbrian age unit (B in Figure 1). Its average age is about 3.5–3.7 billion years (Boyce *et al.*, 1974) and it displays a pattern of V-shaped depressions and elongate craters. These features resemble sculpture caused by secondary crater impacts (Oberbeck and Morrison, 1973). The orientation of these features radial to the crater Prinz suggests that the texture may be the result of Prinz secondary impacts.

3. Rille Characteristics

The rilles range in length from 12 to 79 km. Depth based on available transverse profiles ranges from roughly 100 to 300 m and width from 0.8 to 4.8 km. Highest values of depth and width are found where Rima Prinz lies in Prinz crater rim materials. Both depth and width tend to decrease to the north. With the exception of Rima Telemann the rilles are characterized by large circular or elongate depressions at their southern ends. These depressions are concentrated on the dome northeast of the crater Prinz. (Rima Telemann is the only rille that does not lie on the dome. The southern half of its floor is steeper and shallower than elsewhere. These differences may indicate that the original rille morphology has been obscured by collapse of walls or by later volcanic fill or both.)

Longitudinal and transverse profiles of the rilles were made using the topographic data supplied by the Defense Mapping Agency. Longitudinal profiles (Figure 4)

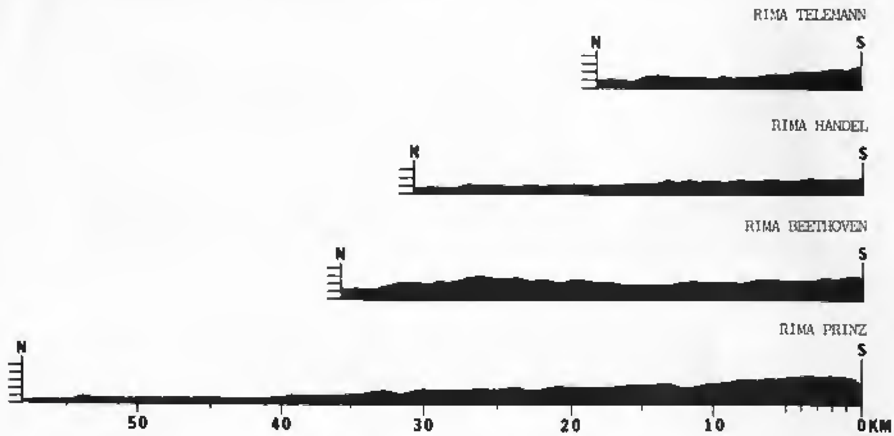

Fig. 4. Longitudinal profiles along four rilles in the Harbinger Mountains region. Vertical exaggeration is 5X. Vertical scale is marked at 100 m intervals. Profiles of Rima Prinz and Rima Beethoven extend to the upper edge of the map in Figure 2.

were constructed from points taken at roughly 600 m intervals along the rille floors. Transverse profiles (Figure 5) were measured every 300 m on the average. Estimates were occasionally made on the transverse profiles at obvious changes in slope.

Transverse profiles show that the rilles are generally flatbottomed, but may approach a V-shape. Rille wall slopes range from roughly 8 to 28 degrees. In some cases, small talus terraces are evident. Levees are not apparent and the rilles appear to be in level terrain, not on small topographic highs as is the case for many terrestrial tubes and some lunar rilles (Greeley, 1971b). As mentioned above, these profiles indicate a depth range of roughly 100 to 300 m. Greeley (1971a) stressed that depths of this magnitude argue against formation by water erosion because a loosely consolidated and easily erodable regolith of this thickness does not exist. This argument was also applied to regolith fluidization models of Schumm (1970) by Cruikshank and Wood (1972).

The longitudinal profiles of the rille floors (Figure 4) indicate a consistent northward slope of less than one degree. This suggests that the rilles are following the slope of the mare unit which also slopes less than one degree to the north. Slope, therefore, appears to be an important factor in rille orientation. The observed rille gradient is comparable to that of terrestrial lava tubes which ranges from roughly 0.4° to 6.5° (Greeley, 1971b). The only deviation from the downhill slope of the rilles

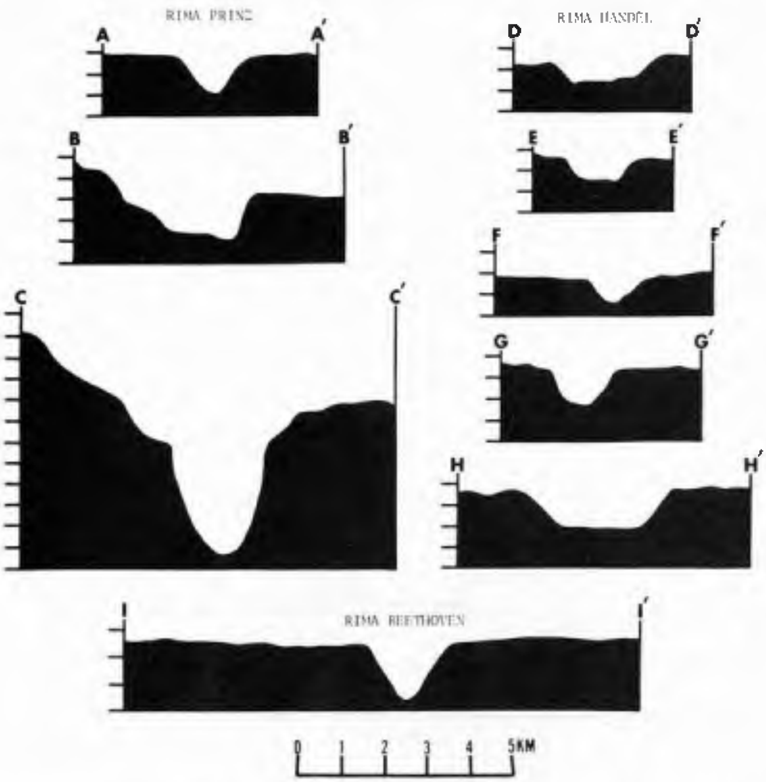

Fig. 5. Transverse profiles of three rilles. Profile traces are depicted in Figure 2. Vertical exaggeration is 5X. Vertical scale is marked at 100 m intervals. A–A' through C–C' cross Rima Prinz. D–D' through H–H' cross Rima Handel. I–I' crosses Rima Beethoven.

occurs in Rima Beethoven whose floor exhibits a 45 m rise where the rille intersects the Harbinger Mountains (Figure 1). The elevation of the rille floor, however, never exceeds the original height at the dome. The rise does not, therefore, represent an obstacle to a fluid flow. Rim profiles show that Rima Beethoven's rim does not rise where the floor does. Close examination of the small unnamed rille to the east of Rima Beethoven reveals that it may have originally crossed through the nearby mountain ridge (Figure 1). Rima Beethoven may have intersected the older rille and followed its path through the mountains.

4. Rille Orientation

Structural elements were measured in six maps of the LTO series (1 : 250000 scale) in the vicinity of the Harbinger Mountains. The area covered is between 40° W and 55° W and from roughly 26° N to 31° N. Rose diagrams were made plotting total length and orientation of structural features. Measured elements were linear segments of ridges, rilles, scarps, and elongate depressions. Figure 6 compares the regional trends to the trends of the five rilles alone. The north-south trend of the rilles is so prominent that it suggests that the northward slope of the mare unit rather than the prevalent fracture pattern controlled rille direction. Directly east of the crater Prinz where the mare slopes to the south is the sixth rille, mentioned above. Unlike the five rilles in the northward sloping mare, this rille originates at a depression on its northern end and terminates in the south, emphasizing again the importance of slope control (Figure 6).

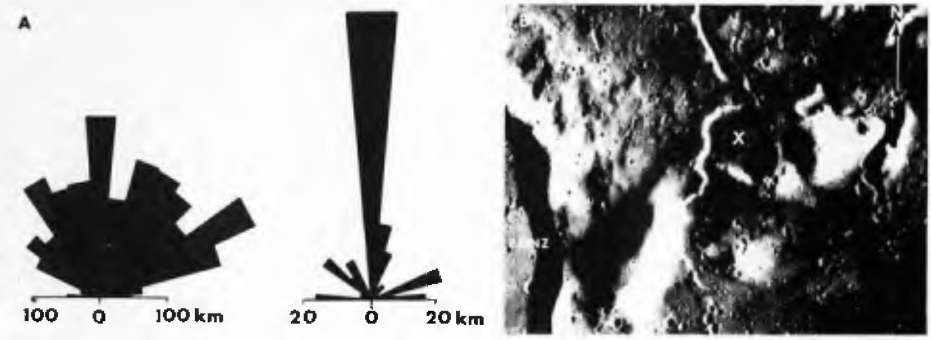

Fig. 6. (A) Rose diagrams indicating total length and direction of structural elements. Diagram to the left shows the regional setting based on measurements in six LTO's, including the Prinz province (LTO 39A3). The area covered was between 40° W and 55° W and from roughly 26° N to 31° N. Diagram to the right gives the orientation of structural segments of the five rilles. (B) Unnamed rille east of Prinz that originates in a circular depression (X) at its northern end and terminates at the southern end (Lunar Orbiter V photograph, 186M).

Both Rima Prinz and Rima Beethoven initially trend roughly east-west and then turn sharply to the north. The initial trend may indicate some structural control. East-west trending scarps and depressions in the immediate vicinity suggest a possible local structural pattern, but the rose diagrams indicate only a weak regional trend. Alternatively, this east-west orientation may be the result of slope, because the rilles lie on the western flank of the dome. In the case of Rima Prinz, direction may also have been influenced by the Prinz crater rim materials which the rille appears to follow (Schumm and Simons, 1969). The 1 : 250000 scale LTO indicates the presence of a patch of higher ground adjacent to Rima Prinz at the point of orientation change (Figure 2). The lava flow that formed the rille may have first followed the westward slope of the dome; when blocked by high ground, it would have followed the northward slope of the mare surface.

A minor northeast trend that corresponds to a similar regional trend was observed in the rilles. The elongate feature crossing Rima Handel is oriented along it and may be a structurally controlled collapse feature.

The break in the mountain ridge through which Rima Beethoven passes is also probably a structural feature. The southwestern part of the ridge is lower in elevation and has a smoother texture than the northeastern segment. These facts suggest that the southwest block was downdropped, and later mantled by volcanic materials, creating a structurally weak zone. The faulting may have facilitated formation of the path through the ridge. Carr (1974) has proposed a model whereby a small channel that initially contains lava at depths of only a few meters is enlarged by erosion (thermal incision) to its present dimensions. In its early stages Rima Beethoven may have existed as a narrow tube or channel in materials that flowed through a gap in the ridge. Lateral erosion may have widened the rille and caused its encroachment on the edges of adjacent massifs.

5. Conclusions

Topographic data recently made available through the NASA lunar mapping program allow detailed studies of sinuous rilles. These data have been used successfully in conjunction with orbital photographs to study the rilles in the Harbinger Mountains region of the Moon.

The sinuous rilles studied follow a path consistent with local slope. In the northward sloping mare, the rilles flow to the north; on the western flank of the dome, they flow westward. Although it is probable that local structural patterns exercise some control on rille orientation, detailed studies indicate that slope is the dominant factor.

The localization on the dome of the depressions from which the rilles emanate suggests that these depressions are source vents for the lava. The dome itself has characteristics indicative of a volcanic origin, displaying smaller domes similar to probable volcanic features elsewhere on the Moon (Smith, 1973).

Detailed topographic profiles show that a rille-forming fluid could have flowed downhill unhindered because rille floors slope consistently downhill. The rise in the floor of Rima Beethoven would not have acted as an obstacle to flow since its height, as well as that of the rim, does not exceed the elevation at the source vent. In addition, lava in terrestrial tubes has been observed to flow over obstacles and thus resembles a closed hydrostatic system (Greeley, 1971b).

Data indicating the downhill trend of rille floors, a slope-controlled orientation, and a relation to volcanic features lend support to the theory that the five rilles formed as lava channels or tubes. This conclusion is applicable to the study of similar rilles elsewhere on the Moon and probably on Mars.

Acknowledgments

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