TERRACED DEPRESSIONS IN LUNAR MARIA

by

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ABSTRACT

Some shallow, irregularly shaped mare depressions are bordered by terraces. Morphologic study suggests that some of these depressions are drained lava lakes. If so, mare materials in which they occur originated as lava. Some associated sinuous rilles and craters may have had volcanic origins. The terraced depressions may yield clues to the development of the large multi-ring basins.

CHAPTER 1

INTRODUCTION

Described here is a new class of lunar surface features discovered through study of Lunar Orbiter photographs. These features are here termed *terraced mare depressions*. An example is described in detail, and an origin is proposed for it. The locations of similar depressions are noted and morphologic variations are summarized. The significance of these features is then discussed.

CHAPTER 2

TERRACED DEPRESSION NEAR LUBINIEZKY

A good example of a *terraced mare depression* is located near the crater Lubiniezky. It was chosen for detailed study because it is well revealed on Lunar Orbiter photographs, is in a region well mapped geologically, and has an associated group of features amenable to coherent geologic interpretation. It was hoped that detailed study of this depression would determine its origin with a fair degree of confidence and that a similar interpretation could then be extended to other, somewhat different though generally similar, lunar surface features.

Description

Near the western rim of the crater Lubiniezky lies a roughly crescent-shaped depression floored by mare material (Figure 1). It is about 40 km long and locally more than 20 km wide. The depression is bordered by two terraces (A and B in Figure 1). Each terrace appears to be level, and the outer one is higher than the inner one. Low hills in the depression (C in Figure 1) appear to have flat tops and may be accordant with or slightly lower than the lower terrace. Terrace scarps facing away from the sun appear to slope at about the elevation angle of the sun (Figure 1). The slope suggests a relief of about 20 to 60 meters on each scarp. If the total relief is about 100 meters, the volume of the depression below the brink of the upper terrace is about 50 km³.

Fig. 1. Lubiniezky area as seen in Lunar Orbiter 4 photograph H125.

Terrace brinks are shown by lines where observed and by dots where inferred. Locations of enlarged insets are shown by rectangles. At points F are terraces not discussed in the text.

The stratigraphy of the area is summarized in Figure 2, which is simplified from a geologic map made prior to the Lunar Orbiter flights (Trask and Titley, 1966). On telescopic photographs of the full moon, the mare west of Lubiniezky is darker than most maria in the region; therefore it is probably younger (Wilhelms, 1966, p. 277). A similar dark mare occupies an area south of Lubiniezky (D in Figures 1 and 2). Relative youthfulness of this mare is supported by the narrow northwestern rim pattern of the crater Bullialdus (Figure 3). One interpretation of this narrow rim pattern is that the dark mare material overlies the Bullialdus rim materials, whereas the rim materials overlie the lighter mare. As shown in the geologic map, the southern patch of dark mare plain is separated from the dark mare west of Lubiniezky by a narrow band where dark mare material appears to veneer upland topography (E in Figures 1 and 2). The albedo differences between map units are not readily discernible in Figure 1 because of the large phase angle (71.4°) when the photograph was made.

The two patches of dark mare plain (Figure 2) are connected by a sinuous rille (Figure 4). The rille has its head in an elongate craterlet (F in Figure 4) at the south end of the terraced depression and crosses the narrow band of dark upland (E in Figures 1, 2, and 4). The floor of the depression has been mapped as higher in elevation than the mare plain to the south (U.S. Air Force, 1964; map accuracy discussed in Carder, 1961). Thus the sinuous rille probably descends as it crosses the upland band and fades out across the dark mare plain (D in Figures 1, 2, and 4).

Fig. 2. Geologic map of the Lubiniezky area.

The map is generalized from a geologic map of the Pilatus region by Trask and Titley (1966).

Fig. 3. Reduced view of the Bullialdus region.

The terraced mare depression is at X. The northwestern Bullialdus rim pattern is narrow and ends abruptly against the mare at Y; elsewhere the rim pattern is wide and fades gradually outward on comparative light mare.

Fig. 4. Enlarged view of the sinuous rille southwest of Lubintzky.

Interpretation

Many processes might be invoked to explain the origin of the terraced depression, and several were evaluated morphologically. They include various types of faulting, subsidence, mass movement, fluvial and marine planation, and extrusion of volcanic material. The hypotheses evaluated morphologically are:

1. Differential erosion of horizontal strata (structural terraces).
2. Changes in base level of fluvial erosion (alluvial terraces).
3. Shoreline erosion (wave-cut terraces).
4. Shoreline deposition (deltas).
5. Expansion of ice on a freezing lake (ice-pushed ridges).
6. Slump (terraces, tobeva blocks).
7. Creep (solifluction terraces, etc.).
8. Talus accumulation (protalus ramparts, etc.).
9. Flow of debris lubricated by fluid (debris flows).
10. Flow of igneous extrusives (laterally coalescing lava flows).
11. Simple normal faulting (fault scarps).
12. Faulting and scarp retreat (fault scarps or fault-line scarps).
13. Melting and drainage of permafrost (thaw sinks).
14. Drainage of a lava lake or ponded lava flow (lava terraces, stony rises).
15. Melting and drainage of ash-flow deposits.
16. Underground solution and drainage of soluble rock (karst).
17. Differential compaction of ash-flow deposits.
18. Differential compaction of regolith.

For each hypothesis predictions about the terrace morphology were made and tested by measuring appropriate features of the terraces and searching for predicted subtle features. Among the features evaluated were terrace heights and widths; terrace distribution; strikes of terrace scarps; albedos of materials above, on, and below the terraces; and other morphologic aspects of the surroundings.

Several observations are considered most critical for the interpretation. The terrace material appears similar to mare material flooring the depression and different from surrounding upland materials. The terraced depression is connected to a similarly young but lower mare by a sinuous rille that dwindles as it descends. Twin terraces are seen, or can reasonably be inferred, at almost all points near the edge of the depression but nowhere else in the area. The terraces appear to have nearly constant heights but varying widths. Flat-topped hills within the depression appear to be roughly accordant with the lower terrace. Terrace scarps do not appear to parallel the trends of inferred structures in the area. Drainage channels do not appear to lead into the depression from the surrounding upland.

Though the evaluation was generally morphologic, some other considerations are also pertinent. Of these, three are thought most important. First, abundant liquid water probably does not exist on the lunar surface. Second, heat generated within a surficial ash-flow deposit probably could not melt the deposit. Third, vesicular rock samples returned from other maria are similar to terrestrial basalts (Lunar Sample Examination Preliminary Team, 1969, 1970).

The hypothesis that seems most consistent with these observations is the drainage of a lava lake. This phenomenon, commonly associated with basaltic volcanism on the earth, also appears to have been widespread on the Moon (Mutch, 1970, chap. 8). If the lava-lake hypothesis is correct, events may have occurred as follows:

Lava flowed into the depression west of Lubiniezky, forming a lava lake. After partial cooling, some of the still-molten lava drained away, leaving a chilled rim to form the upper terrace. A second cooling and drainage episode then formed the lower terrace. Some of the lava drained laterally, partly flooding an older mare south of Lubiniezky and forming the deposit indicated by D in Figures 1 and 2. The small sinuous rille (Figure 4) was the channel for a part of the drainage. If one stage of filling and two of drainage occurred, the volume drained from the terraced depression was roughly 50 km^3 . Alternatively, two episodes of both flooding and drainage may have occurred, with a total drainage volume of about 70 km^3 . For comparison, the designed storage volume of Lake Mead behind Hoover Dam is about 36 km^3 .

Terrestrial Analogues

Lava-lake activity is common at Kilauea Volcano in Hawaii. Activity in Halemaumau pit crater in 1917 produced twin terraces very similar in form to those near Lubinezky, though at a smaller scale (Figure 5). The 1959-1960 eruption (Eaton and Murata, 1960) is a more recent example. For at least two years the volcano summit swelled as magma rose into near-surface reservoirs. Finally, lava erupted and began to fill the crater Kilauea Iki, forming a lava lake. The surface level

Fig. 5. Lava lake in Halemau mau, 1917.

These pictures are reproduced from Jaggar (1947, plate 24) through courtesy of the Geological Society of America. A high outer bench is A, and a lower bench at the edge of the lava lake is at B. A lower bench within the lake is at C. The crater diameter is 350 meters.

fluctuated as lava periodically poured into the lake and then drained back into the vent. Lava terraces formed during the drainage episodes. In two months a total of about 0.10 km^3 was erupted, of which about 0.06 km^3 drained back into the vent. Meanwhile, the summit area continued to swell until suddenly lava issued from a rift on the flank of the volcano. Within five weeks 0.12 km^3 of lava drained through this rift and flowed to the sea. The volcano deflated rapidly, and the eruption ceased.

The amount of lava inferred to have drained from the terraced depression west of Lubiniezky is about 500 times greater than the volume of the 1960 flank eruption at Kilauea. However, much larger eruptions have occurred at Kilauea. Moreover, in the view of Jaggar (1947, p. 103) a lava lake is simply a ponded or confined lava flow, and flows elsewhere are even more voluminous. The flow that constitutes the Pomona Basalt on the Columbia Plateau is estimated to have a volume of about 540 km^3 (Schmincke, 1967).

CHAPTER 3

OTHER TERRACED MARE DEPRESSIONS

Other terraced mare depressions may have origins similar to the one near Lubiniezky. For example, six depressions in the eastern floor of Zupus (A to F in Figure 6) are connected in series by restricted passageways. At the north end of the series a small sinuous rille (G in Figure 6) appears to connect the floor of Zupus to a lower mare-floored depression to the north. Here again, lava can be inferred to have drained laterally on or near the surface. However, the depressions in Zupus have only one terrace level.

Other terraced depressions show little evidence of lateral surface drainage. For example, an irregular flat-floored depression in Mare Autumni (Figure 7) is similar to those in Zupus, but here a drainage deposit cannot be inferred. If this depression represents a partially drained lava lake, the lava presumably drained into the subsurface, perhaps down the eruptive vents.

Some terraced depressions may be associated genetically with craters. Three depressions occur in an U-shaped patch of mare material that partly surrounds Crüger F (A to C in Figure 8). They are similar to the one in Mare Autumni and may represent a partly drained lava lake. Associated with these terraced depressions is the peculiar egg-shaped crater Rocca G. Its floor is occupied by many small bulbous hills that appear to be arranged in rings concentric with the crater wall. The

Fig. 6. Zupus area as seen in Lunar Orbiter 4 photograph H149.

Location of enlarged inset is shown by smaller rectangle.

Fig. 7. Terraced depression in the northern part of Mare Autumni as seen in Lunar Orbiter 4 photograph H181.

Fig. 8. Crüger F area as seen in Lunar Orbiter 4 photograph H161.

southern wall is breached in two places. Mare material containing a small rille (D in Figure 8) extends through the eastern breach, and this material appears to be continuous with the mare containing the terraced depressions. These associations and other features suggest that Rocca G may have a volcanic origin or may have been extensively modified by volcanic activity.

Other terraced depressions differ even more from the one near Lubiniezky, and they probably are not drained lava lakes. For example, some depressions in southwestern Mare Orientale are bounded by linear scarps parallel to apparent nearby faults, and these depressions probably have structural origins.

The distribution of known terraced mare depressions is shown in Figure 9. Most of these features are in the southwestern quadrant of the earth-facing hemisphere. They are especially concentrated around the basins of the Mare Orientale and Mare Humorum. Most occur in small patches of mare material surrounded by upland. Many are far removed from the principal maria.

Fig. 9. Equal-area projection of the earth-facing lunar hemisphere, showing the distribution of known terraced mare depressions and similar features.

Numbered open circles indicate inferred lava lakes. Unnumbered solid circles indicate morphologically similar features. The area shown in Figures 1 and 2 is enclosed by the rectangle northeast of Mare Humorum. Areas numbered are (1) west of Lubiniezky; (2) floor of Lubiniezky A; (3) southwest of Fourier; (4) eastern floor of Zupus; (5) southeast of Puiseux; (6) area surrounding Crüger F; (7) south end of Mare Aestatis; (8) Mare Autumni; (9) southeast of Mare Veris; (10) floor of Riccioli; (11) floor of Hedin; (12) west of Sharp B; (13) northern part of Mare Australe.

CHAPTER 4

SIGNIFICANCE OF THE TERRACED MARE DEPRESSIONS

The origin of terraced mare depressions is relevant to some current problems in lunar research, including the origin of mare surfaces. Several modes of mare formation have been proposed (Gilbert, 1893; Gold, 1962; Gilvarry, 1968; Mackin, 1969), and maria in different areas may have different origins. If the terraced mare depressions are drained lava lakes, the particular mare materials in which they occur were emplaced as lava, not as sediments or ash flows.

A second problem concerns the origin of sinuous rilles. Genetic hypotheses include fluidization troughs, lava and ash-flow channels, and special types of fluvial erosion (Cameron, 1964; Kuiper et al., 1966; Lingenfelter et al., 1968; Schumm, 1970). Sinuous rilles near Lubiniezky and Zupus are associated with terraced depressions in ways that suggest they are lava channels or collapsed lava tubes.

A third problem concerns the origin of lunar craters. Many seem to be impact craters, but others may have different origins. Some craters, such as Rocca G, are associated with terraced mare depressions in ways that suggest these craters may have volcanic origins.

A fourth problem concerns the development of the large multi-ring lunar basins, of which the Orientale basin is an example (Hartmann and Kuiper, 1962). Terraced mare depressions occur near this basin, and they could yield clues to its evolution. For example, if the

terraced depressions are drained lava lakes, surfaces defined by the terraces should have been nearly level when formed. If those surfaces are not now level, they could be used to measure post-terrace tilting around the multi-ring basin. The terraces thus might serve as natural tiltmeters for evaluating processes of basin development.

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