Mare volcanism in the Herigonius region of the moon

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Abstract—The region near the crater Herigonius has been studied in detail to derive a volcanic history for the emplacement of mare basalts using photogeologic methods integrated with earth-based reflectance spectroscopic data. The region is one of the few well-documented mare vent areas on the moon, and appears to have supplied lavas both northward to Oceanus Procellarum and southward to the Humorum basin. The sequence of mare volcanism involved four stages: 1) eruption of low titanium basalt from two primary vent regions, one northwest, the other southwest of Herigonius; these lavas were emplaced partly by flow through lava tubes and channels; 2) eruption of high titanium basalts to produce flood lavas; initially, the flows were restricted in the northern part of the area studied; 3) continued eruption of the high titanium lavas filled the topographically low areas with “ponded” lavas perhaps more than a hundred meters thick, until the topographically high area of the third ring of the Humorum basin was breached, permitting flow southward into the basin; the ponded flows were partly drained by flow through lava tubes and channels (sinuous rilles), leaving high lava benches on some mare-highland contacts; and 4) eruption of late-stage intermediate titanium lavas that reactivated some of the former lava channels to be emplaced primarily between the second and third rings of the Humorum basin.

INTRODUCTION

The geological history of mare emplacement on the moon is much more complex than was generally considered prior to the Apollo missions. The lunar maria are heterogeneous in age, composition, and surface morphology. Differences in age are demonstrated both by radiometric dating of returned samples and small crater statistics for the various mare regions. Differences in composition are shown by samples, orbital geochemical data, and earth-based reflectance spectroscopy. The differences in surface morphology observed photogeologically are considered to reflect differences in the styles of volcanic eruption and lava flow emplacement. A study is currently in progress (Greeley, 1976) for selected mare regions to assess these differences in terms of volcanic histories and to devise models for the emplacement of lunar mare basalts. This report considers the area in the vicinity of the crater Herigonius (Fig. 1).

The Herigonius region is in the southern part of Oceanus Procellarum on the northeastern rim of the Humorum basin. The geology of the region has been mapped by Marshall (1963), Titley (1967), and Wilhelms and McCauley (1971). Regional volcanism in Oceanus Procellarum is currently being studied by Whitford-Stark and Head (1978).
Fig. 1. Medium resolution view of the Humorum basin showing location of the area mapped. Crater Gassendi (98 km) is shown at A. Portion of LO IV-143M.

The area selected for detailed analysis is shown in Fig. 2. This area contains numerous sinuous rilles, craters with irregular planimetric form, possible pyroclastic cones, and other features of probable volcanic origin, and appears to be the vent region that supplied lavas both northward to Oceanus Procellarum and southward to the Humorum basin. Thus, the area is of particular interest because it is one of the relatively few identified mare vent regions on the moon and may provide insight into the mechanisms involved for the flooding of two physiographic provinces by lavas from a single source area.

The approach used in this study involved photogeologic interpretation of surface features and mapping of mare units to derive a regional stratigraphic sequence.
Photographs used in the study involve Apollo metric, panoramic, and Hasselblad images. Near-terminator photography was especially useful for fine-scale surface detail. The southern half of the area studied (Fig. 2), however, is not covered by Apollo mapping photography, and Lunar Orbiter IV images were used, supplemented by oblique Apollo Hasselblad frames. Earth-based reflectance spectroscopy data of Pieters et al. (1975) and color difference data from Whitaker (pers. comm.) were used for interpretation of the compositions of the mare units. A sequence was then derived for the volcanic history and interpretations made for the styles of volcanism involved in the emplacement of the lava flows.

**GENERAL GEOLOGY**

Figure 3 is a geological sketch map of the Herigonius region; for convenience, sinuous rilles are designated by number. The area includes mare regions of Oceanus Procellarum and Mare Humorum, and pre-mare highland structures dominated by the Humorum basin rings and ejecta of the ~98 km crater Gassendi. Structural imprints of the “South Procellarum” basin as mapped by Wilhelms and McCauley (1971) may also be present. Prominent Imbrium structural patterns are not seen but Orientale radial lineations are found in the highlands west of the mapped area. Although the map shows primarily mare units, a pre-mare light plains unit is also shown in two outcrop areas in the southeast part of the area studied. The northern outcrop of this unit is one of the red spots of Malin (1974) and may be a remnant of pre-mare volcanism in the Herigonius region.

**EARLY LOW-TITANIUM LAVAS**

The earliest unit of clearly volcanic origin is a moderately high albedo mare basalt that embays several highland areas and crops out south of Herigonius. This unit appears spectrally red and is interpreted as a low titanium mare basalt (Pieters et al., 1975). Some parts of the unit contain remnants of graben in the form of linear rilles, reflecting early tectonic deformation.

Sinuous rilles are present in several parts of this unit. Several rilles (Fig. 4) appear to originate in a highland area on the third ring of the Humorum basin, southwest of Herigonius. RH2 originates in an irregular crater and trends south; RH3 originates in the vicinity and can be traced northward where it is covered by ejecta from Herigonius EA. The rille is very subdued, possibly indicating a greater age than the more prominent rilles in the area, and has been partly buried by mass wasted debris in the highland areas to the south. The presence of these rilles suggests that the area southwest of Herigonius was one vent region for the low titanium lavas.

Rille RH7 originates in a pit crater and trends northwest. It is very subdued and has been truncated by a mare ridge formed in the younger high titanium basalt unit (Fig. 5). RH3, RH7, and other rilles preserved in the low titanium lavas are considered to represent “Hawaiian” style basaltic eruptions involving lower rates of effusion than flood eruptions (Greeley, 1976).
One area in the northwest contains large (4 km) "dimple" shaped craters (Figs. 3, 6). The craters may be: 1) degraded and/or mantled or buried impact craters; 2) endogenic, representing collapse of material into subsurface cavities; or 3) endogenic, perhaps representing pit craters developed in the mare lavas; pit craters typically indicate volcanic vents, suggesting that this area may have been a source region for some of the old, low-titanium lavas.

The low titanium lavas in the southeast part of the area studied are dominated by a prominent set of north-south trending mare ridges. The ridges form a topographically high area that evidently prevented the low-titanium lavas from being buried by subsequent flows.
Fig. 3. Geologic sketch map of the Herigonius region. Distinction of mare basalt types based on work of Pieters et al. (1975) but contacts mapped photogeologically. Basin ring locations taken from Wilhelms and McCauley (1971).
An elongate zone (mapped L on Fig. 3) some 35 km by 50 km is the main vent for the prominent rilles (such as RH1) and has been mapped by Pieters et al. (1975) as low titanium basalt. Examination of the color-difference images of Whitaker (pers. comm.) shows that this unit is slightly redder than the other four titanium units in this area which suggests a slightly different composition.

HIGH TITANIUM MARE BASALTS

High titanium lavas form the most extensive unit mapped (Fig. 3). They are
characterized by low albedo, dominant “blue” spectral characteristics and relatively featureless surface morphologies on a fine scale. When viewed on high resolution, low sun angle panoramic frames, this unit lacks hummocky surface textures, ring moat structures, and other small features; their absence may signal flood-type lavas that are thick and which were perhaps ponded in topographically low areas.

Numerous mare ridges occur in the high titanium lavas. The location of some ridges appears to be partly controlled by underlying topography such as buried crater rims and regional trends associated with old basin structures. Post-mare craters transected by ridges show that at least some ridges and ridge elements are...
Fig. 6. Unusual "dimple" craters (arrows) in the older low-Ti basalts. These structures may be endogenic collapse craters or they may reflect pre-flow topography buried by lavas. Picture is 12 by 20 km; portion of panoramic frame AS16-5480.

structural in origin, as proposed by many investigators (Bryan, 1973; Howard and Muehlberger, 1973; Lucchitta, 1976; and others). Some ridge elements however, appear to be volcanic, as proposed by investigators for other areas (Fielder, 1965; Strom, 1972; Hodges, 1973; and others). Figure 7 shows a section of a mare ridge in the northwest part of the area mapped, in which a small flow lobe extends from the crest of the ridge. The truncation and superposition of rille RH7 by this same ridge suggests that the rille was partly buried by flows extruded from the ridge. These relations suggest: 1) the lavas had developed crusts of sufficient thickness to preserve superposed impact craters; 2) the crusts were subjected to structural deformation, perhaps related to pre-flow tectonic patterns; and 3) lavas beneath
Fig. 7. Possible extrusive flow lobe(s) (arrow) on the crest of a mare ridge that is part of an extensive ridge system (see Fig. 2 for location). Picture is 10 by 15 km; portion of panoramic frame AS16-5472.

Fig. 8. Topographic bench (arrow) along mare-highland contact interpreted as a high lava mark, or terrace. Lavas may have been locally drained in this region by the sinuous rille, lowering the surface. Oblique view southward; near field width approximately 30 km; portion of frame AS16-19140.
the crust were fluid enough to be extruded from the ridges. This, in turn, implies rather thick (more than a couple hundred meters) flows of the type expected from flood eruptions.

"Benches" occur along the mare-highland contact in many of the areas mapped (Fig. 8) and are common in the high titanium lavas in the north. Benches occur in many areas of the moon and have been described as volcanic (high lava marks; Holcomb, 1971; Schultz, 1976) or as mass wasted materials derived from the highlands (Young, 1976). In the Herigonius area, if the benches resulted from mass wasting, then they should occur at the bases of all highland slopes and their sizes should be proportional to their source area and relative morphologic age; the benches, however, occur only in some areas and are remarkably uniform in size. Moreover, their albedo is more closely akin to the mare with which they are associated than the adjacent highland blocks. Thus, the preferred interpretation is that the benches here are high lava marks. In addition, several small hillocks located within the mare unit and adjacent to some of the benches are rather dark—much like the mare—and may have been draped by mare lavas. They are about the same height as the benches and would have been flooded when the mare lavas stood at a higher level.

**Intermediate Titanium Mare Basalts**

The youngest mare lavas in the Herigonius region are intermediate titanium lavas, mapped between the second and third ring of the Humorum basin. These lavas appear to be related to rilles RH1 and RH2. Pieters et al. (1975) interpret the composition of this unit, which has properties intermediate between the H and L lavas, to be the result of vertical mixing of a surface H-lava with an underlying L unit by impact processes. Crater degradation studies have shown that the I unit in this region is age-equivalent to the Apollo 12 basalts (Boyce, 1976) and hence, their regolith median thicknesses will be similar. A model has been developed (Quaide and Oberbeck, 1975) which permits an estimate of the percent of total regolith debris derived from an original depth greater than the youngest unit thickness. This relationship may be scaled for Apollo 12-age mare using the model of Hörz (1977). Results indicate that for a 50-50 mix of H and L lavas (to produce a soil with I composition), the average flow thickness must be less than approximately 2 meters over the entire lateral extent of the I unit (roughly 30 by 100 km). It is unlikely that a flow this thin would cover such a large area. For these reasons, it is considered that the I unit represents a late stage eruptive phase of chemically distinct lavas. These lavas were erupted from the vents at the head of RH1 and RH2 and flowed down and were confined to previously established lava channels until the unit was emplaced in the topographic low between the second and third basin rings. Because it was restricted to the vent and channel outside the third ring, this unit does not show in spectral data near the vent regions due to insufficient spatial resolution.
Fig. 9. Sequence to show some of the stages in the development of a tube-fed compound lava flow. Stage 1 is a single flow unit emplaced by a shallow lava channel; stage 2 involves a second flow unit, in which lavas flowed down the previous channel and formed a roof. Stage 3 includes a third flow unit that was turbulent and formed a large channel; continued eruption of the same flow resulted in the formation of a roof, with downward erosion by melting and physical removal of some of the previous flow and preflow rocks. Continued eruption of this third flow unit in stage 4 produces a roof over the channel and continues thermal and mechanical downcutting. In stage 5 a fourth flow unit was erupted at a high rate; it initially used the previous tube as the feeding conduit, but because the volume of lava was large, the previous tube was destroyed and an open-flow channel developed, segments of which may have become roofed; overflow from the channel formed distributory lava tubes and small channels. Stage 6 marks the end of eruption with collapse of roofed segments by bank collapse.

Although this sequence is hypothetical, elements of each stage are based on observations of active lava tubes and channels and studies of cooled structures (from Greeley, 1977).

GEOLLOGIC AND VOLCANIC HISTORY

Information on morphologic and stratigraphic relations determined by photogeologic methods as well as chemical data obtained by earth-based remote sensing
techniques have been integrated to provide a detailed geologic and volcanic history of the Herigonius region. This history depends in part on interpretation of geologic process through the use of small scale surface morphologic indicators.

Sinuous rilles in the Herigonius region are all considered to be lava channels and collapsed lava tubes that developed in the basaltic flows. Through considerations of their mode(s) of formation and from terrestrial analogs, lunar sinuous rilles can be used as indicators of flow source and flow direction, and to interpret styles of basaltic eruptions (Greeley, 1976).
Lava tubes and channels are flow conduits that develop within the flows that they emplace; thus, they are primarily constructional features. Tubes and channels, however, typically develop in flows which erupt at lower rates of effusion than in flood lavas and which involve sporadic, but prolonged activity. With continued flow down the same tube or channel, both thermal and mechanical erosion can occur and the conduit may “entrench” (Fig. 9). Furthermore, once conduits are established, they frequently serve as conduits for subsequent flows erupted from the same vent, or flows erupted from another vent, which then intersect older channels or tubes. These relationships have been derived from observations of active flows (e.g., Greeley, 1971, 1972; Peterson and Swanson, 1974) and studies of prehistoric features. Because lunar sinuous rilles are analogous to lava tubes in origin, the processes and relationships of the tubes and channels to the associated flow should be similar in many respects to their terrestrial counterparts.

From the mapping and considerations discussed above, a generalized geologic history can be derived for the major volcanic events in the Herigonius area (Fig. 10).

Stage 1

The earliest recognizable mare volcanism produced low titanium basalts, mapped as “L” on Fig. 3. Vestiges of sinuous rilles suggest lower rates of effusion than
later stage high titanium lavas and prolonged, but sporadic eruption. Two primary source vent regions (Fig. 11) appear to be: 1) an area about 50 km NW of Herigonius (mapped as “L”) which initially fed lavas northward (indicated by rille RH7), and 2) an area centered on the third ring of the Humorum Basin, and about 20 km SSW of crater Herigonius EA which fed lavas both north (rilles RH3, 5 and 7) and south (rille RH2). Both of these source areas appear to be associated with regional basin structures. A third possible vent region involves the unusual “dimple” craters in the northwest part of the area mapped. Graben preserved in the low titanium unit, but covered by later high titanium basalt flows suggest structural deformation occurred in intervals between the emplacement of the two units, probably due to subsidence (downwarping) of the emplaced lavas as seen elsewhere on the moon (Howard et al., 1973).

Stage 2

Superposition and cross cutting relations show that the next oldest volcanic unit is the high titanium (“H” on Fig. 3) mare basalt. This is the most extensive mare unit in the area. Its characteristics most closely resemble flood lavas and it is interpreted to have been erupted at very high rates of effusion to emplace widespread flows. Although few of the vents are clearly indentified for this unit (flood lavas are erupted through fissures that typically are buried by their own products), it appears likely that some of the sinuous rilles developed in the prior flows were reactivated.

Stage 3

Early flows of this stage filled topographically low areas in southern Oceanus Procellarum; with time and progressive filling, the topographically high area of the third ring of the Humorum Basin was breached, spilling lavas southward through gaps into Humorum. The focusing of flow through valleys in the highlands enhanced the reactivation and extension of the lava channels that were originally formed in the older flows. Some of the lavas that had been ponded in southern Oceanus Procellarum then drained into Humorum, leaving high lava marks (Fig. 8) and permitting entrenchment of the channels into the highland massifs (Fig. 12) in the breached zone. The lowering of the partly crusted surface of the high titanium lavas may have resulted in the structural deformation of the crust to form some of the mare ridges; fracturing of the crust along the ridges permitted large scale “squeeze ups” and “flow outs” of molten lava in some areas (Fig. 7). Eruption of lavas down the lava channels concurrent with structural deformation of the crusted lavas could explain the geometry of the mare ridge-sinuous rille relationships (Fig. 13).

Stage 4

The youngest mare lavas are the intermediate titanium basalts (“I” on Fig. 3.) situated primarily between the second and third rings of the Humorum Basin.
These lavas are interpreted to represent an evolution of magma to an "intermediate" form in the waning stages of volcanic activity in the area. They may have been erupted primarily from vent regions NW of Herigonius to flow down rille RH1 and be emplaced between the second and third Humorum Basin rings. RH1 truncates RH6, and changes its character at the contact between the high titanium and intermediate titanium lavas (Fig. 2). The interpretation is that the "I" lavas were confined mostly to the entrenched rilles, RH1, to the point where the basin ring was breached. From this point southward, the intermediate titanium lavas spread out from the rille to be emplaced.
CONCLUSIONS

The volcanic history of the Herigonius region is complex, involving multi-stage eruptions of basaltic lavas of a variety of compositions. Although the sequence of events and the interpretations of the processes presented here are speculative, they are consistent both with geologic relations observed on the photographs and in the remote sensing data and with the understanding of processes of basaltic volcanism. These sequences provide insight into the complex emplacement of lunar lavas and the general volcanic history of the moon.

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