Stratigraphy of Oceanus Procellarum Basalts: Sources and Styles of Emplacement

JAMES L. WHITFORD-STARK AND JAMES W. HEAD III

Department of Geological Sciences, Brown University, Providence, Rhode Island 02912

INTRODUCTION

A major goal in the analysis of lunar maria is to determine the distribution, volume, composition, and eruption sites of lunar lavas as a function of time. By combining photogeologic analysis [Wilhelms, 1970] with remote sensing [Head et al., 1978a, b] and sample return analyses it may eventually be possible to relate the evolution of lunar mare filling with returned samples studies and to provide additional information on the thermal and chemical history of the moon.

Oceanus Procellarum, located on the western nearside of the moon, is irregular in outline and is the largest lunar mare (about 1.7 x 10^6 km² or approximately 25% of the total lunar mare area). Whitford-Stark and Head [1977a] have described the tectonic structure of Procellarum and proposed three distinct areal subdivisions (Figure 1); a shallowly flooded southeastern section, a deeply flooded central section, and a northern section of intermediate depth. A unique aspect of Procellarum is the presence of three large volcanic complexes (Marius Hills, Rümker Hills, and Aristarchus Plateau/Harbinger Mountains), which are the sources for many lavas. The quadrangles covering Procellarum have been mapped by many authors in a U.S. Geological Survey mapping program and combined in the nearside map of the moon by Wilhelms and McCauley [1971].

The purpose of this paper is to outline the surface geologic units visible in Procellarum by using a variety of remote sensing data, to define their stratigraphic relationships, to discuss their sources and styles of emplacement, and to correlate the Procellarum basalts with other lunar mare units. Formal definitions of the mare unit names employed in this paper are presented in an appendix.

UNIT DEFINITION AND CHARACTERIZATION

Remote sensing data are available for definition and characterization of units within Procellarum [Head et al., 1978a]. The most useful information for unit definition is obtained from earth-based and orbital photography and multispectral imagery [McCord et al., 1976]. Photographic information in the visible wavelengths includes (1) superposition relationships evidenced by flow scarps at unit boundaries, (2) structural discontinuities indicated by flooding of preexisting tectonic rilles and ridges by later lavas, (3) crater density variations, and (4) albedo variations [Pohn and Wildy, 1970]. The ultraviolet/infrared color composite photographs by Whiaker [1972] help define regional color variations and the multispectral images by McCord et al. [1976] provide information on spectral variations across each vidicon image. A synthesis of the spectral reflectance data for the lunar nearside maria has been published by Pieters [1978].

Data here employed in the characterization of units include the spectral vidicon imagery of McCord et al. [1976] and Johnson et al. [1977], crater degradation data of Boyce [1976], com-
The third-dimensional properties of the various units have been derived from flow boundary heights, the degree of flooding of preemplacement terrain, topographic variation, and estimates of mare thickness from Marshall [1961], Baldwin [1970], Neukum and Horn [1976], DeHon [1978], and Hörz [1978].

The combined crater degradation/density data of Boyce and Johnson [1978], radar backscatter data of Zisk et al. [1974], orbital geochemical data of Arnold et al. [1977] and Haines et al. [1978], and data derived from analyses of the Apollo 12 lunar samples. The information from each of these techniques is summarized in Table 1.

Fig. 1. Map showing the three subdivisions of Oceanus Procellarum. Highlands are depicted by horizontal ruling. Within the mare the lines represent sinuous rilles; the arrows indicate the direction of flow, and the circles indicate the source craters.
TABLE 1. The Defining and Characterizing Parameters of the Stratigraphic Units Within Oceanus Procellarum

<table>
<thead>
<tr>
<th>Formation</th>
<th>Defining Parameters</th>
<th>Characterizing Parameters</th>
<th>Supporting Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharp Formation</td>
<td>high ultraviolet/visible ratio</td>
<td>strong 1-µm reflectance</td>
<td>well-preserved sinuous rilles</td>
</tr>
<tr>
<td></td>
<td>low albedo</td>
<td>low crater density</td>
<td>timeless pits</td>
</tr>
<tr>
<td></td>
<td>blue color</td>
<td>TiO$_2$ of 3-11 wt %</td>
<td>outlines controlled by topographic highs</td>
</tr>
<tr>
<td></td>
<td>topographic boundaries</td>
<td></td>
<td>Th ~ 9 ppm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$D_r &lt; 199$</td>
</tr>
<tr>
<td>Hermann Formation</td>
<td>average digital vidicon imagery response</td>
<td>average to strong 1-µm reflectance</td>
<td>MgO 6-11.5 wt %</td>
</tr>
<tr>
<td></td>
<td>low albedo</td>
<td>intermediate crater density</td>
<td>FeO 19-22 wt %</td>
</tr>
<tr>
<td></td>
<td>reddish-intermediate-bluish color</td>
<td>TiO$_2$ content of 1-6%</td>
<td>Al$_2$O$_3$ 6-10.5 wt %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CaO 10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SiO$_2$ 42-47 wt %</td>
</tr>
<tr>
<td>Telemann Formation</td>
<td>low ultraviolet/visible ratio</td>
<td>average to strong 1-µm reflectance</td>
<td>low K, Th, U</td>
</tr>
<tr>
<td></td>
<td>red color</td>
<td>high impact crater density</td>
<td>low 3.8-cm radar backscatter</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TiO$_2 &lt; 2$ wt % at mare</td>
<td>$D_r &gt; 250$</td>
</tr>
<tr>
<td></td>
<td>high albedo</td>
<td>topographic highs</td>
<td>flat-floored sinuous rilles</td>
</tr>
<tr>
<td>Repsold Formation</td>
<td>blue color</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>very low albedo</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>high crater density</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

THE UNITS

A formal lithostratigraphic classification of the basaltic fill within Oceanus Procellarum is presented in the accompanying appendix and in part by Pieters et al. [1980] and is used throughout the following text. This classification follows the outlines proposed by the American Commission on Stratigraphic Nomenclature [1961] and includes the definition of unit names, the defining and characterizing parameters of each unit, the location of type areas, the nature of unit boundaries, the geometry of the units, and their estimated ages. Four formations have been defined (Table 1; Figures 2 and 3) and are combined into the Oceanus Procellarum Group. Formations have been subdivided into members where sufficient information exists and subdivision is warranted (Table 2). Parameters employed by Pieters [1978] to define basalt types are also herein partly used to define formation characteristics. In the present work we have combined spectral characteristics with photogeological and age criteria to determine the stratigraphic relationships of the various units. A more detailed description of the spectral characteristics of some of the mare units is presented by Pieters [1978].

The Oceanus Procellarum Group

The Oceanus Procellarum Group covers approximately 1.7 × 10$^6$ km$^2$, which represents 4.5% of the total surface area of the moon. For comparison, the Deccan basalts of northern India have a surface area of 0.26 × 10$^6$ km$^2$ [Macdonald, 1972].

The Sharp Formation

The Sharp Formation covers 7.2 × 10$^5$ km$^2$ (42%) of Oceanus Procellarum occurring in the northeast, a large portion of central Procellarum in isolated patches near the western boundary, and occurs as elongate flows in the southeast (Figure 2). The Sharp Formation, although widespread, is relatively thin and represents only about 2% of the total volume of Oceanus Procellarum basaltic materials (Table 3).

The spectral characteristics of the Sharp Formation [Johnson et al., 1977; Pieters, 1978] suggest that it is composed of medium to high titanium basalts, and crater degradation/density data [Boyle and Johnson, 1978] suggest a young age, in the range of 2.7 ± 0.7 b.y. Materials of the Sharp Formation therefore have characteristics similar to Apollo 11 and 17 basalts but are much younger.

The location and flow directions of basalts of the Sharp Formation are indicated in Figure 4. The maps show the close relationships between the basalts and sinuous rilles, the location of many sources of the Sharp Formation at the mare/highland boundary, and relationships between flow direction and preemplacement topography. The Roris Basalt Member of the Sharp Formation is located in northeast Procellarum (Figure 5). The contact between the Roris Basalt and older units is extremely well defined in the north of the area both on color composite photographs and Lunar orbiter frames. The older units are redder on color composite photography, have a higher albedo than the Roris Basalt, and are heavily cratered by secondaries from the Eratosthenian-aged [Lucchitta, 1978] crater, Pythagoras. Pythagoras secondaries do not occur on the Roris Basalt, but it is covered by secondaries from the Copernican-aged [Wilhelms and McCauley, 1971] crater, Harpalus. This suggests that the Roris Basalt is of late Eratosthenian age, while crater degradation/density data of Boyle and Johnson [1978] suggest that it has an age of 3.2 ± 0.2 b.y. Edges of the Roris Basalt often correspond to the location of higher mare ridges, suggesting that it postdates the formation of those ridges and that the ridges influenced the basalt emplacement. In addition, the Roris Basalt emplacement was restricted by the Rümker Hills volcanic complex, indicating that the complex also predated the Roris Basalt. Materials of the Roris Basalt also flood the lower portions of the Mafran domes which are postulated to be Imbian-aged volcanic domes of nonmare composition [Head and McCord, 1978]. Four large rilles and their source craters have been located within the Roris Basalt (Figure 5). Two of the sources are located near the western end of Mare Frigoris and fed lavas which flowed both eastward into Mare Frigoris and southward into central Procellarum. The third source, located in...
the lower right corner of Figure 5b fed lavas which flowed to the north.

The formally defined (see the appendix) Hansteen Basalt occurs in southern Procellarum (Figure 2). The Hansteen Basalt contains a small sinuous rille with a source located at 52°W, 10.5°S, almost on the rim of Hansteen itself. Passage of the flow which produced the Hansteen Basalt appears to have been blocked to the north by a barrier of highland material (Figure 6). These features combine to suggest that the Hansteen Basalt was a single flow, erupted near the highland/mare boundary.

The Zupus Basalt Member of the Sharp Formation pro-
Fig. 2b. Location map for features referred to in the text. Capitalized names indicate formally defined units, and solid lines demarcate the boundaries of those units. Dotted lines demarcate boundaries of undefined units.

vides an example of basaltic material which occurs in the highlands located to the south of Procellarum (Figure 2). Basalts are interpreted to have been erupted within the crater Zupus (Figure 7), and they continued to thicken until the crater wall was breached in the northeast. Lava then partially drained from Zupus and flooded the low-lying highlands to the north, its further progress being halted by a barrier of highland material.

The Damoiseau Basalt Member of the Sharp Formation provides another example of material erupted near the highland/mare boundary (Figure 2). Although the source(s) of the Damoiseau Basalt cannot be identified and there are no rilles
to indicate its flow direction (Figure 8), the limited areal extent of the basalt indicates that it must have been erupted near the mare/highland boundary. Like the Roris Basalt, the boundaries of the Damoiseau Basalt appear to have been controlled by preexisting mare ridges. These features combine to suggest that the Damoiseau Basalt is a thin unit, possibly the product of a single eruption which buried its own source vent.

The Flamsteed Basalt Member of the Sharp Formation [Pieters et al., 1980] originated from near the southeast of the Marius Hills volcanic complex and flowed in a southeasterly direction, terminating within Flamsteed P (Figure 2). There appear to be at least two flows, each of which has an associated sinuous rille. The westernmost of these flows has been guided between parallel mare ridges apparently composed of material belonging to an older formation. Crater degradation data [Boyce, 1975] suggest that the Flamsteed Basalt has an age of 2.5 ± 0.5 b.y.

The Humorum Basalt Member of the Sharp Formation, defined by Pieters et al. [1980], is located in southern Procellarum (Figure 2) and is associated with a number of sinuous rilles. These sinuous rilles had vents located on or close to mare ridges and the lavas from those vents proceeded southward into Mare Humorum, where they overlie older Mare Humorum basalts. One of the rilles (designated RH1 by Greeley and Spudis [1978]) appears to cross a spectral boundary in contradiction to most sinuous rilles (Figure 9). Several possibilities exist for explaining this relationship:

1. A rille developed by an earlier flow becomes the routeway for a younger flow of different composition issued from the same vent. In this case the spectral characteristics of the younger flow do not appear near the vent region but only where the younger flow escapes the confines of the rille.

2. The lava from a single rille-producing eruption changed in composition with time. This would result in the spectral characteristics changing gradually with distance from the vent, the material erupted last being deposited closest to the vent.

3. The incorporation of underlying material into the flow unit. This could occur by the erosion and incorporation of underlying material by the flow or by regolith mixing resulting from impacts. Greeley and Spudis [1978] argue that the youngest basalts erupted from the Herigonius rilles were of intermediate composition (equivalent to the Hermann Formation) and that they were confined in their upper courses by rilles developed in older high titanium (i.e., Sharp Formation) basalts (examples 1 and 2 above). Pieters et al. [1975], on the other hand, argue that the intermediate spectrum results from vertical mixing between a young titanium-rich unit and an older titanium-poor unit (example 3 above). Crater degradation studies do not uniquely define the relative ages of the units. Boyce [1975] gives D, values (see the appendix) of 215 ± 15 for the area of the intermediate unit and 230 ± 20 for the area of the high titanium unit, where a lower value denotes younger age. Thus on the basis of the Greeley and Spudis [1978] model and assuming the difference in D, values is significant, the Hermann Formation is locally younger than the Sharp Formation. Alternatively, if the Pieters et al. [1975] model is correct and the difference in D, values is insignificant, then, as is most frequently the case in Procellarum, the Sharp Formation postdates the Hermann Formation. However, unlike most of the previously described members of the Sharp Formation, the Humorum Basalt contains rather than is bounded by mare ridges. This would suggest that the Humorum Basalt is older than other members of the Sharp Formation and that in this area of Procellarum the Sharp and Hermann formations are penecontemporaneous.

The major portion of the Sharp Formation occurs within central Procellarum around the crater Schiaparelli and between the Aristarchus Plateau and the Marius Hills. To the east, flows of the Sharp Formation continue into Mare Imbrium (Figure 2) [Schaber, 1973; Saito, 1977]. Although the sources of the lavas within this unit are not as readily identifiable as those of the Roris Basalt, sinuous rilles indicate the flow directions and approximate position of the vents. There is a distinct separation of westward and eastward trending sinuous rilles separated by a 'divide' running parallel to about the 43°W line of longitude (Figure 4). Sources for the westward trending flows include Rima Marius, a sharply defined rille located to the northeast of the Marius Hills (48.5°W, 14.5°N), a more degraded rille, in part parallel to Rima...
TABLE 2. Lithostratigraphic Units of Oceanus Procellarum

<table>
<thead>
<tr>
<th>Member</th>
<th>Defined Spectra</th>
<th>Age, 10^9 years</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sharp Formation</strong> (2.7 ± 0.7)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roris Basalt*</td>
<td>hDSA</td>
<td>3.2 ± 0.2</td>
</tr>
<tr>
<td>Damoiseau Basalt*</td>
<td>mottled</td>
<td>3.2 ± 0.2</td>
</tr>
<tr>
<td>Hansteen Basalt*</td>
<td>mottled</td>
<td>3.2 ± 0.2</td>
</tr>
<tr>
<td>Zupus Basalt*</td>
<td></td>
<td>2.7 ± 0.7</td>
</tr>
<tr>
<td>Flamsteed Basalt†</td>
<td>hDSA, hDSA</td>
<td>2.5 ± 0.5</td>
</tr>
<tr>
<td>Humorom Basalt†</td>
<td>hDSP</td>
<td>3.2 ± 0.2</td>
</tr>
<tr>
<td>Kunowsky Basalt†</td>
<td></td>
<td>2.5 ± 0.5</td>
</tr>
<tr>
<td>Schiaparelli basalts‡</td>
<td>hDSA, HD_</td>
<td>2.5 ± 0.5</td>
</tr>
<tr>
<td>Ulugh Beigh basalts‡</td>
<td></td>
<td>3.2 ± 0.2</td>
</tr>
<tr>
<td>East Nubium basalts‡</td>
<td>HD_and mottled</td>
<td>2.7 ± 0.7</td>
</tr>
<tr>
<td><strong>Hermann Formation</strong> (3.3 ± 0.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delisle Basalt*</td>
<td>LBS</td>
<td>3.2 ± 0.2</td>
</tr>
<tr>
<td>Marius Basalt*</td>
<td>mISP</td>
<td>3.3 ± 0.3</td>
</tr>
<tr>
<td>Cognitum Basalt*</td>
<td>mIG</td>
<td>3.3 ± 0.3</td>
</tr>
<tr>
<td>Lavoisier basalts‡</td>
<td>mISP</td>
<td>3.5 ± 0.1</td>
</tr>
<tr>
<td>Nubium basalts‡</td>
<td>mIG</td>
<td>3.5 ± 0.1</td>
</tr>
<tr>
<td><strong>Telemann Formation</strong> (3.6 ± 0.2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dechen Basalt*</td>
<td>LBG</td>
<td>3.6 ± 0.2</td>
</tr>
<tr>
<td>Aristarchus Basalt*</td>
<td>LBG</td>
<td>3.65 ± 0.05</td>
</tr>
<tr>
<td>Dark mantle materials‡</td>
<td></td>
<td></td>
</tr>
<tr>
<td>South Procellarum basalts‡</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Repsoled Formation</strong> (3.75 ± 0.05)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gerard Basalt*</td>
<td>hDW</td>
<td>3.75 ± 0.05</td>
</tr>
<tr>
<td>Dark mantle materials‡</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The ages in parentheses and in the right-hand column are based on the work by Boyce and Johnson [1978]; the spectra are from Pieters [1978]. The first letter of the spectra designations represents the UV/visible ratio (H, very high; h, high; m, medium; L, low), the second letter designates the albedo (B, bright; D, dark, I, intermediate), and the fourth letter denotes the presence (P) or absence (A) of a 2-/m band. Members are not in relative stratigraphic positions.

*Defined in this paper
†Defined by Pieters et al. [1980].
‡Undefined.

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TABLE 3. Morphometric Properties of the Lithostratigraphic Units Within Oceanus Procellarum

<table>
<thead>
<tr>
<th>Surface Area, km^2</th>
<th>Percentage Area</th>
<th>Maximum Original Surface Area, km^2</th>
<th>Estimated Average Thickness, m</th>
<th>Volume, km^3</th>
<th>Percentage Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharp Formation</td>
<td>720,000</td>
<td>42.55</td>
<td>720,000</td>
<td>25</td>
<td>1.8 x 10^4</td>
</tr>
<tr>
<td>Hermann Formation</td>
<td>770,000</td>
<td>45.51</td>
<td>1,490,000</td>
<td>150</td>
<td>2.2 x 10^3</td>
</tr>
<tr>
<td>Telemann Formation</td>
<td>180,000</td>
<td>10.64</td>
<td>1,670,000</td>
<td>250</td>
<td>4.2 x 10^3</td>
</tr>
<tr>
<td>Repsoled Formation</td>
<td>22,000</td>
<td>1.3</td>
<td>1,692,000</td>
<td>125</td>
<td>2.1 x 10^2</td>
</tr>
<tr>
<td>Total</td>
<td>1,692,000</td>
<td>100</td>
<td>1,692,000</td>
<td>550</td>
<td>8.7 x 10^3</td>
</tr>
</tbody>
</table>

See text and the appendix for discussion of the average thickness values.
bedo, similarity on the Whitaker photograph, and apparently young age the eastern Nubium area is tentatively correlated with the Sharp Formation. No sinuous rilles have been identified within this unit; however, a very low albedo, cinder cone-like structure is located (11°W, 15°S) on a mare ridge within this area. In addition, this part of the Sharp Formation is cut by the southern end of the Rupes Recta fault scarp, suggesting that subsidence of the mare basin continued after the emplacement of these young basalts.

**The Hermann Formation**

The Hermann Formation occupies the largest part of the surface area of Procellarum, about 45% (Figure 2, Table 3). Flow fronts, crater density, and crater degradation data in-
dicate that in large part the Hermann Formation predates the Sharp Formation. The original surface area of the Hermann Formation therefore must include part of the area now buried by the Sharp Formation. The basinal nature of Procellarum and the steep slope of the highlands at the mare/highland boundary suggest that the Hermann Formation might underlie almost all of the Sharp Formation and therefore originally occupied about 85% of the surface area of Procellarum. Also, any surface units which predate the Hermann Formation must have existed as topographic highs during the period of Hermann Formation emplacement. In this analysis much of the present northern Procellarum surface is dated as pre-Hermann Formation, suggesting that sources for the Hermann Formation were not located in this area and that it was topo-

Fig. 4b. Estimated flow directions of pre-Sharp Formation basalt units based on the sinuous rille distribution. The dotted pattern denotes the lunar highlands and volcanic complexes.
graphically high relative to the central area during emplacement of the Hermann Formation. In central Procellarum, pre-
Hermann Formation units are confined to the topographic high around the Aristarchus Plateau. The absence of pre-
Hermann units along the western border of central Procellarum suggests that the Hermann Formation exhibits an onlap relationship with the lunar highlands. In southeast Procellarum, pre-Hermann units are preserved at topographic highs, particularly at the highland/mare boundary, suggesting that the Hermann Formation exhibits offlap relationships.

Spectral characteristics of the Hermann Formation [Johnson et al., 1977; Pieters, 1978] indicate it to be a low-titanium basalt, and crater degradation/density studies suggest an age of $3.3 \pm 0.3$ b.y. Basalts from the Apollo 12 site, included within the Hermann Formation, have $K/Ar$ ages ranging from $3.11 \pm 0.05$ to $3.27 \pm 0.05$ b.y. [Turner, 1977] and $Rb/Sr$ ages ranging from $2.92 \pm 0.18$ to $3.58 \pm 0.3$ b.y. [Nyquist, 1977]. The greater age of the Hermann Formation relative to the Sharp Formation plus the burial of the Hermann Formation by the latter inevitably mean that the emplacement sequence and flow boundaries of the Hermann Formation are less readily definable. Some of these relationships can be ascertained, however, by analysis of specific areas.

The Delisle Basalt Member of the Hermann Formation occurs to the east of the Harbinger Mountains (Figure 2) in an area mapped as Imbrian in age by Wilhelms and McCauley [1971]. Two sinuous rilles occur within the Delisle Basalt, and these can be traced to source craters at $35.5^\circ W, 28.5^\circ N$ and $33^\circ W, 30.5^\circ N$. These sinuous rilles indicate that the Delisle Basalt proceeded eastward into Mare Imbrium, where it has been flooded in its lower reaches by younger lavas of Mare Imbrium. The 180 and 50 km [Saito, 1977] lengths of these rilles therefore represent minimum lengths for the Delisle Basalt flows.

The Marius Hills volcanic complex appears to have been a major source for much of the Hermann Formation emplaced in southwestern Procellarum. About 20 sinuous rilles and over 300 volcanic constructs within the Marius Hills [Whitford-Stark and Head, 1977b] testify to the multiplicity of sources of mare materials and the complexity of the basalt stratigraphy.
The presently exposed Hermann Formation in this area appears to have been derived from sources located on the western side of the Marius Hills. One of the youngest flows is associated with a rille with a source located at 57°W, 11.5°N. This sharply defined rille is continuous for its entire length of 210 km except for a few kilometers in its upper reaches where it has been blanketed by younger materials (Figure 12). The rille skirts the edge of the plateau and cuts through one of the Marius domes, demonstrating that the lava which produced this rille postdated both the formation of the plateau and some domes. However, flows on the western and southern sides of the Marius Hills are more densely cratered than the plateau itself, implying that activity continued on the plateau after deposition of the presently exposed surface basalts of the Hermann Formation. Other rilles on the western and southern edges of the plateau are less well defined than that previously described and have been subjected to varying degrees of flooding or blanketing by younger materials. The present restriction of the Hermann Formation to the south and west of the Marius Hills results from burial by the younger Sharp Formation to the east and north. This is evidenced by the unflooded upper portions of sinuous rilles on the eastern side of the Marius Hills such as that developed on the rim of the crater Marius (51°W, 12°N) and the presence of Hermann Formation at the mare ridge crests which remained unflooded by the Sharp Formation [Pieters et al., 1980].

Along the western border of Procellarum, stratigraphic relationships indicate that the Hermann Formation may have been emplaced in two distinct episodes. Ejecta from the crater Cardanus (74°W, 10°N) partly overlies the Hermann Formation and is partly buried by a younger part of the Hermann Formation (Figure 13). In addition, tectonic rilles developed on the older part of the Hermann Formation were partly buried by flows of the younger part of the unit. These relationships indicate that the gross subsidence of the mare basin which resulted in tectonic rille production [Solomon and Head, 1979] terminated during the deposition of the Hermann Formation and that a significant time span separates the oldest and youngest members of the formation. This interpretation is consistent with the range of crater degradation/
density ages [Boyce and Johnson, 1978] for this unit and the assignment of both Eratosthenian and Imbrian ages [Wilhelms and McCauley, 1971]. For example, some of the Hermann Formation underlies ejecta of the Eratosthenian-aged Cavalarius crater (42°W, 5°N) but overlies the ejecta blanket of the Imbrian-aged Seleucus crater. However, the Hermann Formation also overlies the ejecta blanket of the Eratosthenian-aged [Wilhelms and McCauley, 1971] crater, Reiner. The sources for the Hermann Formation in western Procellarum have not been identified; however, two small sinuous rilles suggest that flows traveled northward, perhaps from the Marius Hills.

In northern Procellarum the Hermann Formation is developed around the Rümker Hills volcanic complex (Figure 2) but the relationships between the complex and the surrounding basalts are unclear. Wilhelms and McCauley [1971] dated the domes of the complex as Eratosthenian in age and surrounding basalts as Imbrian, whereas Guest [1971] suggested that Rümker materials predated the surrounding basalts. Guest's arguments included the observations that some faults within the hills do not extend onto the basalts and fine lineaments developed on the plateau do not continue, or continue only weakly, in adjacent mare basalts. Guest also postulated that the younger units of the plateau may interdigitate with the surrounding mare basalts. At the central southern extremity of the plateau is a pit-shaped crater with a small linear depression leading away from it. This is interpreted as a remnant sinuous rille and its source crater, both of which have been almost completely flooded by younger basalts. These observations support the suggestion that at least the outer edges of the Rümker Hills are in some places older than the surrounding mare basalts. In addition, the flooded sinuous rille suggests that the complex supplied some of the basalt fill. The age of the domes remains unclear, although secondary craters developed on predome materials in the north of the plateau may be from the middle-Imbrian Iridium impact.

The Hermann Formation of the Flamsteed region is described in detail by Pieters et al. [1980], where, in brief, the western part of the Hermann Formation is characterized by Marius Basalts with a strong 1-μm band and the eastern part by Cognitum Basalts with an average 1-μm band [Pieters, 1978]. Though the absence of lengthy sinuous rilles precludes definition of the flow directions of the Hermann Formation in this region, two sources of mare materials may be identified.
Fig. 6b. Diagram showing location of features on Figure 6a. Note the sinuous rille source crater near the rim of Hansteen and the boundary of highland material which apparently formed a barrier to northward flow of the Hansteen Basalt.

with conelike features associated with fractures located at 43°W, 5°S and 31°W, 6°N. The dimensions of these cones are, however, below the resolution limits of the vidicon imagery; it is therefore impossible to state with certainty that they have Hermann Formation characteristics.

Farther east in Procellarum, the basalts occupying the surface of Mare Cognitum are part of the Hermann Formation. A great deal of information about the Hermann Formation is available in this area, since it is near the Apollo 12 landing site. An excellent synthesis of the petrological and geochemical properties of the Apollo 12 basalts by Rhodes et al. [1977] identified four compositional groups: olivine, pigeonite, ilmenite, and felspathic basalts. Of these groups, two (olivine and pigeonite) were believed to be comagmatic. In a study of the degradation state of the lunar surface in the region of the Apollo 12 site, Soderblom and Lebofsky [1972] identified two units, an older unit present at the Apollo 12 site and a probably 0.5 b.y. young unit a few kilometers away from the landing site. This younger unit was identified by Pieters and McCord [1976] as being richer in TiO₂ than the surface basalt at the Apollo 12 site. Thus, although there is general agreement that the TiO₂-rich basalt is the younger of the two, there is a difference of opinion as to whether it overlies or is adjacent to the other basalt. The sources for the basalts have not yet been found, although four very low-profile domes approximately 4 km in diameter have been tentatively identified near the landing site [Whitford-Stark, 1975].

In Mare Nubium the spectral and age relationships are complicated by the ejecta from the Eratosthenian-aged [Wilhelms and McCauley, 1971] crater Bullialdus and by secondaries from the Copernican-aged crater, Tycho. This extensive postemplacement modification of the mare surface in Nubium might account for the apparently older age (3.5 ± 0.1 b.y.) of this surface determined by crater degradation/density techniques [Boyce and Johnson, 1978]. One small sinuous rille with its source located at 19°W, 22.6°S, near the northern rim of the crater Wolf T, was responsible for the emplacement of part of the Hermann Formation in this region. The modification by Bullialdus ejecta precludes determining whether it was the only source.

In the south Imbrium basin [Hawke and Head, 1977] the Hermann Formation appears to have been derived from a number of sinuous rilles with sources located along one of the basin rings, and 'hus the volcanism appears to have been tec-
Fig. 7a. Lunar orbiter IV photograph 156H2 of the crater Zupus in the highlands to the south of Procellarum. Zupus (diameter 38 km) is an old, intensely degraded crater. The basalt floor covering significantly postdates the formation of the enclosing crater. The direction of basalt flow was toward Procellarum, located approximately 100 km to the north, off the top edge of the photograph.

tonically controlled. The flows proceeded northward into the arc-shaped basin (Figure 4) where they are overlain by extensive deposits from the crater Copernicus.

The Telemann Formation

The Telemann Formation occupies only a small part (~10%) of the present surface area of Procellarum, largely in the north (Figure 2). However, the fact that it predates the overlying Hermann and Sharp formations and its present topographically elevated position strongly indicate that it exists underneath at least a portion of the younger units. The onlap relationships of the overlying Hermann Formation in central Procellarum indicate that the Telemann Formation does not underlie the entirety of the two younger formations. The steepness of the highlands at the mare/highland boundary, however, indicates that the degree of overlap is not extensive. Moreover, the onlap relationship of the Hermann Formation to the Telemann Formation in northern and southeastern Procellarum implies that in these latter areas the Hermann Formation was not as extensively developed as the Telemann Formation. It is therefore estimated that the original surface area of the Telemann Formation was close to that represented by its present surface area plus the areas of the two younger formations, that is, from 80 to 98% of the present surface area of Procellarum basalts.

Spectral characteristics of the Telemann Formation [John-

son et al., 1977; Pieters, 1978] indicate it to be a low-titanium basalt. Pieters [1978] suggests that spectral characteristics of materials with the properties of the Telemann Formation are similar to those of the very low titanium (VLT) basalts returned from Apollo landing sites. The age of the Telemann Formation, based on crater degradation/density studies [Boyle and Johnson, 1978], is of the order of 3.60 ± 0.2 b.y., and it falls within the Imbrian System [Wilhelms and McCauley, 1971].

The limited surface exposure of the Telemann Formation
makes it difficult to reconstruct a detailed palaeogeography for this unit. The most informative details can be obtained at the Aristarchus Plateau, where the Aristarchus Basalt Member of the Telemann Formation has been defined (see the appendix). The stratigraphy of the Aristarchus Plateau has recently been described in detail by Zisk et al. [1977]. Figure 14 compares their stratigraphic column with the stratigraphic sequence developed within this paper. The Aristarchus Basalt corresponds most closely in area (Figure 15) with the Im$_2$ unit defined by Zisk et al. [1977], although the Aristarchus Basalt also includes parts of other subdivisions of the Zisk et al. classification scheme. Zisk et al. [1977] define their Im$_2$ unit as having relatively strong radar echoes, a reddish color, a low albedo, and an age of 3.3 to 3.4 b.y., which is slightly older than the Apollo 12 basalts. However, the dating of the mare surface in this area by crater analysis is made difficult by the abundance of secondary craters from both Aristarchus and Kreiger.

The majority of the 36 sinuous rilles of the Aristarchus Plateau/ Harbinger Mountains are developed within the Aristarchus Basalt. Zisk et al. [1977] define an older red mare unit (Im$_1$) which is herein also part of the Aristarchus Basalt. It is in this apparently older unit that the source craters of the sinuous rilles are developed. Almost all the Aristarchus Basalt rilles have been flooded in their lower reaches by basalts of the Hermann and Sharp formations. Some of the rilles have further rilles developed within them, suggesting that they have been the route for more than one flow.

Another feature of the Aristarchus Plateau is the dark mantle material, which is described as reddish brown in color difference photographs [Zisk et al., 1977]. This dark mantle has been interpreted by Zisk et al. [1977], on the basis of its spectral and radar characteristics, to be pyroclastic ejecta with the physical properties of glass containing excess Fe and/or Ti and an age corresponding to that of the Im$_1$ and Im$_2$ lavas. With respect to its color the Aristarchus dark mantling material is similar to other dark mantle developed to the south of Mare Humorum and in western Serenitatis. It differs from the blue mantling material of Mare Vaporum, Sinus Aestuum, and the Taurus Littrow Apollo 17 landing site [Head, 1974],
which have, additionally, been shown [Pieters et al., 1975] to have different spectral characteristics to the Humorum dark mantle. Of the 24 soil samples collected from the Apollo 17 site, 2–18% of the 90–150 μm size fraction composed orange and black spheres [Heiken et al., 1974]. These spheres were found to be chemically homogeneous, have a similar age to the basalts, have a mean grain size of 40 μm, were high in Ti, Fe, Mg, and low in Si, Al, Na, K, and differed only in that the black spheres apparently represent the partially crystalline equivalents of the orange glass [Heiken et al., 1974]. Zisk et al. [1977] model the difference between the blue and red dark mantling materials in terms of the relative proportions of red and black glass (Aristarchus 1:2 parts and Apollo 17 1:6 parts, respectively). However, the association of red mantle with low-titanium basalts at the Aristarchus Plateau, in southern Humorum [Pieters et al., 1975], and in western Mare Serenitatis [Howard et al., 1973] and the blue mantle with the high-titanium Apollo 17 basalts suggests that the red mantle may be Ti-poor. The dark mantle of the Aristarchus Plateau is therefore believed to be a pyroclastic facies of the Telemann Formation on the basis of its age, color, spectral characteristics, and association with sinuous rille source craters of the Telemann Formation.

To the northwest of the Aristarchus Plateau the Dechen Basalt Member of the Telemann Formation occurs in the relatively shallowly flooded northern section of Procellarum (Figure 2). The Dechen Basalt is clearly covered by secondaries from the Eratosthenian-aged Pythagoras crater and overlain by the Roris Basalt to the east. No sinuous rilles or possible source craters have been identified within the Dechen Basalt. However, the crater degradation/density values [Boyce and Johnson, 1978] suggest that the Dechen Basalt and Aristarchus Basalt are of similar age (3.6 ± 0.2 b.y.), and have the same spectral characteristics [Pieters, 1978]. These features plus the vast volumes of materials deemed necessary for the production of the many large sinuous rilles developed at the Aristarchus Plateau and their flow directions combine to suggest, but not substantiate, the possibility that the Dechen Basalt was derived from the Aristarchus Plateau. However, there is also the possibility that (1) the Dechen Basalt was derived
Fig. 8b. Diagram showing the boundaries of the Damoiseau Basalt. The source(s) of this unit have not been identified, though a location near the mare/highland boundary is suggested. Note also that the higher mare ridges appear to have acted as flow barriers. The emplacement of the Damoiseau Basalt therefore postdated the major deformation in Procellarum, which resulted in ridge and tectonic rille production.

from the Rumker Hills but has been flooded to the extent that it can no longer be traced to the hills, or (2) that the flows of the Dechen Basalt were locally derived and buried their own sources.

Although, apart from the Aristarchus topographic high, the Telemann Formation is largely absent from central Procellarum, a patch of the mare surface with the spectral characteristics of the Telemann Formation is located around the craters Bessarion (37°W, 15°N), Bessarion A, and Bessarion B. The boundary between this patch and surrounding Sharp Formation basalts is difficult to discern. Although this region is heavily cratered, the craters appear very fresh and are probably secondaries. The spectral characteristics of this unit differ from those of the Aristarchus Basalt in that it shows a much stronger 1-μm reflectance band [Pieterson, 1980]. The strength of this 1-μm band is a function of both the pyroxene content and agglutinate content of the soil [McCord et al., 1976]. Fresh lunar material rich in pyroxene is strongly absorbent at 0.95 μm due to the electronic transition band of pyroxene, whereas mature soils, rich in agglutinates, are strongly absorbent at shorter wavelengths due to charge transfer absorptions [McCord et al., 1976]. The abundance of secondary craters, the ejecta blankets of the three Bessarion craters, indistinct unit boundaries, and a spectrum which could be that of a young soil combine to suggest that this patch results from the excavation of the Telemann Formation from beneath a shallow covering of younger materials.

In southeast Procellarum the Telemann Formation occurs at a myriad of isolated locations, many below the resolution limits of Figure 2. See Pieterson et al. [1980] for a detailed description of the Telemann Formation in the Flamsteed region. The patches of Telemann Formation have the common characteristic of being located at topographic highs; these are located close to flooded crater rims, at the mare/highland boundary, or at mare ridge crests. Radar sounding data in Mare Serenitatis [Peeples et al., 1976] indicate that subsurface basalts are uparched beneath mare ridges; thus the location of the Telemann Formation at mare ridge crests is interpreted to result from the deformation of that unit into ridges which were subsequently flooded and surrounded by younger lavas. The preservation of Telemann Formation basalts at flooded crater rims and mare/highland boundaries reflects the wide-
spread nature of the unit relative to younger formations. Structural deformation of the Telemann Formation is also seen in the area to the northwest of the crater Lassell (8°W, 15.5°S), where prominent graben (linear rilles) have been flooded at their lowest points by materials of the younger Sharp Formation. These mare ridges and linear rilles indicate that extensive deformation of the mare surface in Procellarum postdated the emplacement of the Telemann Formation.

The Repsold Formation

The Repsold Formation is presently exposed only in a small area (~1%) in northwestern Procellarum. It is interpreted to be composed of medium to high-titanium basaltic materials and to be the earliest recognizable mare basalt unit within Procellarum (see the appendix). The exact age of the Repsold Formation is uncertain. It lies at the boundary of the Boyce and Johnson [1978] age map, where it appears that the mare surface is becoming older toward the north. Extrapolation of the data of those authors would suggest an age of the order of 3.75 ± 0.05 b.y. for the Repsold Formation. Additionally, the Repsold Formation is definitely older than the spectrally similar Roris Basalts of the Sharp Formation to the east, since the secondaries from the Eratosthenian-aged crater Pythagoras cross the former but are flooded by the latter. Furthermore,
the development of tectonic rilles within part of the Repsold Formation indicates its emplacement prior to the major subsidence of the mare, previously shown to occur along western Procellarum during the emplacement of the Hermann Formation. Tectonic rille production has been demonstrated [Lucchita and Watkins, 1978] to have terminated at 3.6 ± 0.2 b.y. The Repsold Formation must therefore at least predate this age. To the east of the main outcrops of the Repsold Formation in northwestern Procellarum the ejecta blanket of the crater Markov E (60°W, 50.5°N) has the spectral characteristics of the Repsold Formation and is interpreted to represent the excavation of materials of the Repsold Formation from beneath the overlying Telemann Formation (Figure 16). No source vents have been identified within the Gerald Basalt Member of the Repsold Formation in northwestern Procellarum.

Several lines of reasoning suggest that the Repsold Formation was considerably more extensive than its present surface exposure. To the southeast of Copernicus (Sinus Aestuum), dark mantle deposits cover an area of 40,000 km². Pieters et al. [1973] have established a spectral connection between Sinus Aestuum, dark mantle material, and the Apollo 17 regolith, while Head [1974] suggested a connection between the dark mantle and an early Ti-rich basalt phase. Ti-rich, dark red glasses were also found [Reid et al., 1972] to compose about 5% of the glasses in the Apollo 12 soil, in marked chemical contrast to the surface lavas at that site. The lack of a date for these glasses means that they could represent either locally reworked Repsold Formation or horizontally transported material of the younger Sharp Formation. The distances to the nearest surface exposure of the latter formation, however, favor the local reworking mechanism.

Further evidence for the widespread distribution of the Repsold Formation may be provided by the material forming the floor of the crater Aristarchus. According to Zisk et al. [1977] the crater Aristarchus has an age of 0.45 b.y. and has a blue, pulverized, high-Ti basalt floor covering. This crater age postdates that of any known mare basalts. Examination of the Zisk et al. [1977] map reveals the crater to lie partly on the Aristarchus Plateau and partly on their reddish Im₉ unit or, in the present classification, on the Telemann Formation composed of low-titanium basalts. On the basis of its young age and different composition to that of local surface materials it is hypothesized that the titanium-rich material forming the floor of Aristarchus crater is an impact melt containing the Repsold Formation underlying the Aristarchus Basalt. This is supported by the crater depth being in excess of 3 km and its floor being below the level of the adjacent mare surface (Figure 15).

These examples serve to illustrate that the Repsold Formation originally occupied a substantially larger surface area of Procellarum than is presently exposed. Its maximum original extent may have been that of the present exposure plus that of the three younger formations. However, its surface absence except in the shallowly flooded northern Procellarum and the onlap relationships of younger formations indicates that its original extent fell short of the maximum surface area of exposed mare materials. The large surface area of Mare Tranquillitatis presently occupied by early titanium-rich basalts [Boyce and Johnson, 1978; Pieters, 1978] would, by analogy, argue for extensive coverage of Procellarum by the early Repsold Formation. The Repsold Formation is therefore estimated to form approximately 24% of the total fill of Oceanus Procellarum (Table 3).

**Pre-Imbrium Basin Mare Basalts**

Two lines of evidence indicate that the earliest basalt units recognized in Procellarum were not the oldest mare basalts erupted on the moon; one is basaltic fragments in breccias believed to have been produced by the large basin-forming impacts [Ryder and Taylor, 1976], and the other is dark halo craters of impact origin on basin ejecta [Schultz et al., 1979].

Mare basalt clasts have been found to be most common in breccias recovered from the Apollo 14 site but were also found in Apollo 16 and 17 samples [Ryder and Taylor, 1976]. Breccias containing basaltic fragments have radiometric or inferred ages in excess of 3.9 b.y., while the basaltic fragments exhibit a variety of compositions; TiO₂ contents similar to low-titanium basalts and values of 7.0 wt % TiO₂ have been reported [Ryder and Taylor, 1976].

Impact-produced, dark halo craters are widespread over the lunar surface but are particularly common on units mapped as Imbrian Plains material considered to be basin ejecta [Wilhelms and Mccauley, 1971]. Schultz et al. [1979] argue that these craters have excavated prebasin mare basalts from beneath the basin ejecta. Clusters of such craters were found south of Mare Humorum, north and east of Mare Marginis, around Mare Crisium, and in Mare Australe. The excavated low albedo unit south of Humorum was found to clearly predate the Orientale impact event [Schultz et al., 1979], while other low-albedo materials near Orientale were interpreted [Schultz and Spudis, 1978] to represent the infill of pre-Orientale, multiring basins.

To summarize, although the large basin-forming impacts extensively modified the lunar surface by excavation and deposition of ejecta, thus obscuring the products of earlier periods, there is significant evidence that eruption of mare basalts did not commence subsequent to the terminal bombardment. Instead, mare basalts were erupted prior to 3.9 b.y. ago, and mare basin eruption and basin formation overlapped in time. These pre-Imbrian mare basalts appear to have been erupted over wide areas of the moon and had compositional variations perhaps as diverse as the younger basalts observed to infill the basins.

**Other Infilling Materials**

Beneath or intermixed with early Procellarum lavas must be ejecta produced during the excavation of the larger circular mare basins such as Imbrium, Humorum, and Orientale. It has not been possible to identify categorically any of this ejecta as covering Procellarum basalts. At the Aristarchus Plateau the Orientale ejecta is interpreted as older than the Im₉ (i.e., Telemann Formation) lavas [Zisk et al., 1977], while the fact that the dark mantle material of the Repsold Formation developed southeast of Copernicus is not covered by Imbrian ejecta demonstrates that the Imbrium basin-producing event predated at least part of the earlier titanium-rich volcanic sequence. Head [1977] has described the relationship of Imbrium ejecta and ejecta from smaller craters to the basaltic sequence at the Apollo 12 site where 1 km of basalt is interpreted as overlying up to 25 km of deposits associated with large craters.

In addition to the crater ejecta there exists the possibility of nonmare basalts underlying and interfingering with the mare basalts. Several spectrally anomalous structures, called red spots, have been identified within the Procellarum area and proposed as representing volcanism of KREEP composition [Malin, 1974]. In northern Procellarum these spectral anoma-
lies are morphologically distinct structures called the Gruithuisen (40°W, 36°N) and Mairan domes (48°W, 41 to 42°N). They are interpreted to be extrusive nonmare volcanic constructs formed most likely between 3.3 and 3.6 b.y. ago [Head and McCord, 1978] and are thus younger than the early mare basalt fill of Procellarum. Hansteed a (50°W, 12.5°S) is morphologically similar to the Gruithuisen domes and, on the basis of crater counts [Malin, 1974], is slightly younger than nearby highland materials but older than the nearby mare surface. The other spectrally distinctive regions within southeast Procellarum (Figure 2) take the form of plains units and hummocky uplands. It has been suggested [Wood and Head, 1975] that these materials may have been excavated by the Cognitum basin event or represent local volcanic deposits incorporated into an ejecta deposit. On the basis of the data accumulated from the Apollo 15 KREEP basalt and Apollo 14 KREEP-rich breccia, Hawke and Head [1978] proposed that KREEP basalts were emplaced as extrusive materials over a time range extending from prior to 4.1 b.y. ago to the period of extrusion of the basin-filling mare basalts. Thus there is evidence for nonmare dome and plains volcanism over much of the Procellarum region. The volumetric significance of this material is unknown at the present time.

Both Wilshire [1973] and McCauley [1973] suggest that materials of possible volcanic origin located in the highlands to the southwest of Procellarum postdate the formation of the Imbrium basin but preceded the formation of the Orientale Basin. Further surficial deposits of possible volcanic origin were believed by those authors to predate the formation of the Orientale Basin. These materials have spectral characteristics and morphologies different from mare basalts, having higher albedos and a plainslike or a hilly and furrowed appearance. The return of breccias from the Apollo 16 site where similar morphologies are developed means that morphology alone is
SHARP FORMATION
OTHER BASALTS
HIGHLANDS

Fig. 10b. Diagram showing the approximate boundaries of the Sharp Formation in the Ulugh Beigh area. The source(s) of this unit have not been located but are suggested to lie close to the mare/highland border. Also, the areal separation of parts of the unit indicates the presence of several vents. For example, the basalts within Ulugh Beigh A are physically separate from those within Procellarum.

not a unique indicator of plains origin. Compositional information derived from remote sensing would help to resolve the question of origin.

SOURCES AND STYLES OF ERUPTION

Identification of sources for progressively older mare basalts becomes increasingly uncertain because of the combined effects of erosion and vent burial by younger materials. In addition, vents of flood basalts are often difficult to identify because they are buried by their own flows [Greeley, 1976]. There is considerable experimental [e.g., Weil et al., 1970] and theoretical evidence [Hulme, 1974; Schaber, 1973] that some lunar basalts were emplaced as extremely fluid flows with viscosities of the order of 1.0 Pa s; there is also evidence for high eruption rates [Hulme, 1973; Wilson and Head, 1980]. Lunar basalts have been emplaced as flood and plains basalts eruptions [Greeley, 1976] similar in style to terrestrial plateau lavas. The results of this study show that there are variations in morphologic features between stratigraphic units and between each of the Procellarum volcanic complexes. These are interpreted to represent variations in the sources and styles of volcanism during the filling of Procellarum.

The youngest formation of the Oceanus Procellarum Group, the Sharp Formation, does not appear to have the sources located on any of the three complexes. However, sinuous rille source craters are found near the eastern edge of the Marius Hills complex (Figure 1) and three low profile domes up to 10 km in diameter and with summit depressions are located within the Sharp Formation near, but not on, the Aristarchus Plateau [Whitford-Stark and Head, 1977b]. More commonly, vents of the Sharp Formation occur at the mare/highland boundary (Figure 1). In the case of the Roris, Hansteen, and the Kunowsky basalts these vents are sinuous rille
source craters. Others, such as the Damoiseau Basalt, do not have identifiable vents, but their limited areal extent indicates eruption from near the mare/highland boundary. In the circular mare basins, location of younger vents along the margin of the basins is consistent with the stress distribution associated with a load consisting of earlier lavas concentrated in the basin center [Solomon and Head, 1979].

Several lines of evidence combine to suggest that the Sharp Formation is relatively thin. The fact that mare ridges formed barriers to flow of the basalts indicates that the formation is less than 100 m thick almost everywhere except where it has flooded preeruption craters. The heights of flow fronts [Gifford and El-Baz, 1978] indicate that individual flow units are of the order of 10 m thick, while Schultz and Greeley [1976] argue that ring-moat structures developed within the formation are associated with surficial flows approximately 10 m in depth. Except in northern and central Procellarum the Sharp Formation basalts could have been derived as single-eruption sequences. In the two exceptions several sinuous rilles indicate multiple flow units and therefore a thickness in excess of 10 m. Neukum and Horn [1976] have argued that irregularities in cumulative crater frequency/crater diameter curves result from flooding of preexisting craters up to a particular crater diameter dependent on the thickness of the lava. This crater truncation...
tion diameter ($D_r$) they relate to the expression $T_c = 0.048D_r^{0.95}$ derived from Pike [1967]. Data obtained from the Flamsteed P region [Greeley and Gault, 1970] indicate a break in curve at approximately a crater diameter of 630 m; this would represent a flow unit of 20 m thickness. In view of the effects of ponding and the possibility of several flow units it is estimated that the Sharp Formation averages 25 m in thickness. The total volume of the Sharp Formation is therefore estimated at $1.8 \times 10^6$ km$^3$, which represents about 2% of the total volume of Procellarum basalts. In addition, the several sources of the Sharp Formation, located at large distances from each other (Figure 4), require either an areally extensive zone of partial melting of the lunar interior or a number of isolated magma pockets which experienced similar evolutionary histories. The similarity in age and defining characteristics of these separate units renders the second alternative unlikely.

The Marius Hills region (35,000 km$^2$) was a major source for the Hermann Formation, while the smaller Rümker Hills (5000 km$^2$) may have been a less important source. The Hermann Formation does not appear to have been derived from the Aristarchus Plateau. The Marius and Rümker hills were not the sources for the entirety of the Hermann Formation but may have been the most important sources for Hermann Formation basalts developed within central Procellarum. In the Flamsteed region the presence of cones along fissures, some steep domes, and poorly preserved sinuous rilles suggest the
local derivation of the Hermann Formation from minor vents [Pieters et al., 1980]. In the south Imbrium basin the Hermann Formation rille source craters are located at the basin ring. Few vents have been identified within the Hermann Formation of Mare Cognitum and Mare Nubium; those identified include the four low-profile domes tentatively identified near the Apollo 12 site [Whitford-Stark, 1975] and the sinuous rille near Wolf T in Mare Nubium. This may reflect a different eruption style, such as vent-burying fissure eruptions, in these areas.

Rhodes et al. [1977] deduce that the stratigraphy at the Apollo 12 site, as indicated by the cooling relationships suggested by the sample texture and excavation depths of local craters, consists of a 40 m thick ilmenite basalt overlying an earlier olivine-pigeonite basalt of similar thickness. Walker et al. [1976] derive a similar thickness (30 m) for the olivine basalt. In central Procellarum the Hermann Formation basalts completely flood all earlier units except at the anomalously high Aristarchus Plateau. This, together with its great areal extent, multiplicity of sources (e.g., Marius Hills), and extensive deformation (Figure 13), combines to indicate that the Hermann Formation is substantially thicker than the Sharp Formation. Baldwin [1970] calculates the lava thickness in western Procellarum as 1100 to 2000 m, as does DeHon [1978]. Hörz [1978] presents somewhat lower thickness values, less than 875 m. Assuming it not to be underlain by earlier units, these must represent upper limits for the Hermann Formation thickness. Since flows of the older Telemann and Repsold formations do predate the Hermann Formation, the latter can only be a fraction of these maximum thicknesses.

Many mare ridges are surficially composed entirely of material of the Hermann Formation. These ridges rise some 200 m above adjacent mare. In the Flamsteed region some of the ridges are composed of yet older materials [Pieters et al., 1980] which must underlie the Hermann Formation. In certain areas therefore the Hermann Formation has a relative altitude of 200 m with respect to younger flows, whereas in other areas it was incapable of surmounting preexisting ridges. It is therefore concluded that an average thickness of the Hermann Formation is of the order of 150 m, taking into account variations resulting from its thinning to zero meters at the mare/highland boundary to thickening in pre-Hermann craters.
The Aristarchus Plateau is the only area that can be categorically identified as a source for the Telemann Formation. This is not to imply that the Aristarchus Plateau was the only source for the Formation. Burial by younger materials at the Marius and Rümker hills may have occurred, while distance considerations make it extremely doubtful that outcrops in southeast Procellarum could have been derived from the plateau. The Aristarchus Plateau may, however, have been the source for the Dechen Basalt Member of the Telemann Formation developed in northern Procellarum, since the two areas are separated by younger flows.

Comparison of the volcanic structures developed within the Telemann Formation of the Aristarchus Plateau and the Hermann Formation of the Marius and Rümker hills demonstrated that the eruption conditions differed [Whitford-Stark and Head, 1977b]. The Telemann Formation rilles are wider, and their source craters have significantly larger diameters (up to 5 km) than those of the Hermann Formation rilles (<1 km). A significantly greater eruption rate and volume of material for the Telemann Formation rilles was hypothesized to account for this size difference [Whitford-Stark and Head, 1977b]. In addition, the identification of hundreds of domes and cones in the Hermann Formation was interpreted to reflect a greater variability in eruption conditions than for the one dome in the Telemann Formation [Whitford-Stark and Head, 1977b]. Rilles of the younger Sharp Formation are generally small and similar to those of the Marius Hills. However, one of the Sharp Formation rilles, Rima Sharp itself, is similar in width (1 km) to the Telemann Formation rilles.

The widespread though patchy distribution plus the large size of the sinuous rille source craters of the Aristarchus Plateau combine to indicate an extensive thickness for the
Telemann Formation. Head and Wilson [1979, 1980] derive an eruption rate range required to produce the source craters of $10^7$ to $10^{10}$ kg/s. Employing the maximum possible eruption rate value, a basalt density of $3 \times 10^3$ kg/m$^3$, and an eruption period of 1 year, sufficient basalt would be erupted from the 36 rilles at the Aristarchus Plateau to flood the entirety of Procellarum to a depth of 200 m. In the region of Lassell in eastern Procellarum ($8^\circ$W, $15^\circ$S) and at the Aristarchus Plateau the Telemann Formation rises several hundred meters above the adjacent younger mare surface. It is therefore estimated that the Telemann Formation ranges in thickness between zero and 500 m with an average thickness of possibly 250 m.

In northern Procellarum the Repsold Formation surrounds isolated highland outcrops. This suggests shallow flooding in this region. Mare ridges suggest local thicknesses of at least 200 m, while estimates of the thickness of dark mantle materials range from about 3 to 50 m [see Schonfeld and Bielefeld, 1978]. It is therefore estimated that the Repsold Formation has an average depth of 125 m. No sources have been identified for the Repsold Formation; this is probably a function of both its age and limited surface exposure.

**Comparison of Procellarum With Other Maria**

The filling sequence that has been outlined for Procellarum is similar to that developed in Mare Crisium (Table 4), although they are widely separated in space and differ in surface geometry. The two maria differ significantly in the proportion of the different units exposed at the surface. For example, the Ti-poor basalts occupy nearly 50% of the surface of Crisium but only about 1% of Procellarum. The two maria

Fig. 13a. Lunar orbiter IV photograph 169H, of western central Procellarum illustrating the relationships between secondary craters, tectonic rilles, and mare flooding. Immediately to the right of Cardanus (diameter 49 km) the mare surface has been covered by ejecta and cut by tectonic rilles, whereas to the right of Krafft (diameter 51 km) the mare surface is smooth and unfractured.
also differ greatly in the volume of material erupted in each. Maxwell and Phillips [1978] model the early Crisium titanium basalts as being 1000 to 2000 m thick, the Ti-poor units as 1000 m thick, and the intermediate unit as 400 m thick. In Procellarum the estimated values for the average thicknesses of similar units are only 125, 250, and 150 m, respectively.

In Mare Serenitatis the three most readily defined units are an early titanium-rich basalt in the southeast, an intermediate basalt occupying the majority of the center of the mare, and a high-titanium basalt unit in the west.

The basaltic sequence of Mare Humorum is essentially that of Procellarum, though Humorum lacks surface exposures of the early titanium-rich basalt [Pieters et al., 1975]. The oldest recognized unit in Humorum is a low-titanium basalt, and like the Aristarchus Plateau, it is accompanied by red dark mantle material of similar age developed in the highlands immediately to the southwest of the mare [Pieters et al., 1975]. The young, high-titanium basalts in Humorum may have been derived entirely from Procellarum [Pieters et al., 1975].

A study of the basaltic sequence of Mare Australe [Whitford-Stark, 1979] also shows the presence of at least four distinct eruption phases from lower Imbrian to Eratosthenian in age. The lack of spectral imagery, however, does not allow correlation with the sequences in the previously described maria.

To summarize, the basalts forming the lunar maria exhibit
nonmare basalts were emplaced both prior to basin formation and at the same time as mare basalts.

Deformation of the mare surface and adjacent highlands has accompanied the emplacement of the basalts. This deformation takes the form of tectonic rilles near the borders and mare ridges within the mare. Tectonic rille formation was apparently most extensive up to the deposition of the Hermann Formation (3.6 ± 0.2 b.y.) and has been insignificant since. Mare ridges are found within the youngest Sharp Formation, but the period of major development of mare ridges appears to predate deposition of the Sharp Formation. The tectonic regime produced by subsidence of the early mare lavas appears to have strongly influenced the location of vents of the youngest Sharp Formation, these vents being located at the highland/mare border.

The major part of the basaltic fill of central Procellarum appears to have been derived from the three large volcanic

some similarities in terms of their evolution despite their wide geographic separation. It would appear, however, that basalts of different composition were being erupted in different volumes across the moon at approximately the same time. Examination of the lunar spectral map [Pieters, 1978] indicates that some units present at the surface in one mare are missing from another. Further detailed geological and spectral mapping of the lunar maria is required to determine whether there was a unique evolutionary sequence in eruptive composition peculiar to each basin or to the moon as a whole.

SUMMARY AND IMPLICATIONS

The basaltic fill of Oceanus Procellarum has been formally subdivided into four lithostratigraphic formations: the Repsold Formation, the Telemann Formation, the Hermann Formation, and the Sharp Formation. The Repsold Formation is composed of high-titanium basalts and pyroclastic deposits with an estimated age of 3.75 ± 0.05 b.y. and an estimated volume of about $2.1 \times 10^6$ km$^3$. This is overlain by the Telemann Formation composed of very low-titanium basalts and pyroclastic deposits with an estimated age of 3.6 ± 0.2 b.y. and a volume of $4.2 \times 10^6$ km$^3$. The Hermann Formation composed of intermediate basalts with an estimated age of 3.3 ± 0.3 b.y. represents the next youngest unit with an estimated volume of $2.2 \times 10^5$ km$^3$. The youngest materials in Procellarum are the medium- to high-titanium basalts comprising the Sharp Formation with an estimated age of 2.7 ± 0.7 b.y. and a volume of $1.8 \times 10^5$ km$^3$. The emplacement of these formations postdates the excavation of the major lunar circular mare basins. These basalts, however, were not the earliest erupted on the moon. Basaltic fragments in returned impact breccias and dark halo craters on basin ejecta indicate prebasinal mare basalt emplacement. Furthermore KREEP and

Fig. 14. Comparative stratigraphies for the Aristarchus Plateau and Oceanus Procellarum and the approximate stratigraphic relationships of returned lunar basalts.
TABLE 4. Stratigraphies of Four Maria

<table>
<thead>
<tr>
<th>Procellarum*</th>
<th>Humorum‡</th>
<th>Crisium‡</th>
<th>Serenitatis§</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharp Formation (R)</td>
<td>H (R)</td>
<td>group III (I)</td>
<td>type IV (I)</td>
</tr>
<tr>
<td>Hermann Formation (I)</td>
<td>L₂ (I)</td>
<td>group IIA (VL)</td>
<td>type III (R)</td>
</tr>
<tr>
<td>Telemann Formation (VL?)</td>
<td>SP (L?)</td>
<td>group IIB (VL)</td>
<td>type II (R)</td>
</tr>
<tr>
<td>Repsold Formation (R)</td>
<td>group I (R)</td>
<td>type I (R)</td>
<td>type I (R)</td>
</tr>
</tbody>
</table>

Apart from Procellarum and Humorum, the stratigraphic sequences are not correlated. Letters in parentheses indicate the suggested titanium contents: R is rich, I is intermediate, L is low, and VL is very low. The table serves to show that the sequences exposed at the surface differ from mare to mare. For example, in Serenitatis, an intermediate unit follows three titanium-rich units, while in Crisium an intermediate unit follows two very low titanium units as defined by Papike and Vaniman [1978]. It is possible that some basalt types are missing from specific maria or they may be totally buried. For example, types I through III in Serenitatis may correlate with the Repsold Formation and type IV with the Hermann Formation, an equivalent of the Telemann Formation being missing or buried.

*This paper.
‡Based on the work by Pieters et al. [1975].
§Based on the work by Head et al. [1978b].
ôBased on the works by Howard et al. [1973] and Thompson et al. [1973].

... complexes; the Telemann Formation can be specifically related to the Aristarchus Plateau and the Hermann Formation to the Marius and Rümker hills. The younger Sharp Formation was erupted from vents located near but not on the Aristarchus Plateau and Marius Hills. The Hermann Formation does not appear to have been erupted at the Aristarchus Plateau, and it is not possible to determine whether the earlier Telemann and Repsold formations were erupted from the Marius and Rümker hills.

Extensive pyroclastic deposits appear to be associated with the emplacement of the Repsold and Telemann formations but not, apparently, with the younger Hermann and Sharp formations. The large size of the sinuous rille source craters within the Telemann Formation suggests that these early basalts were erupted at greater rates and volumes than the later Hermann and Sharp formations, which contain smaller sinuous rille sources and a variety of other volcanic constructs including low-profile domes, steep domes, and cones [Head and Wilson, 1980].

The present analysis of the basaltic fill of Oceanus Procellarum has established the following observations which can be employed in the generation of models describing basalt petrogenesis: (1) an age range of the basalts from 3.75 ± 0.05 to 2.7 ± 0.7 b.y., (2) a multiplicity and widespread location of vents, (3) a variation in composition from early Ti-rich, through Ti-poor, intermediate, and, finally, medium to Ti-rich basalts, each with different volumes, (4) a possible overlap in time of eruption of units with different compositions, (5) an estimated total volume of 8.7 × 10⁵ km³ of basalts, (6) an apparent change in composition of magma erupted at the large volcanic complexes within central Procellarum, and (7) there are three large volcanic complexes in central Procellarum which are unique on the moon.

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