Exercises Two and Fifteen are suggested as introductory exercises.

■ ★ 3.0 hours

Photogeologic Mapping of the Moon

Instructor Notes

Suggested Correlation of Topics

Geologic time, geometric relations, geomorphology, maps, remote sensing, satellite observations, stratigraphy

Purpose

The objective of this exercise is to become familiar with the techniques of constructing geologic maps of planetary surfaces, as applied to the Moon. Upon completion of this exercise the student should understand the concept of superposition and be able to make interpretations about the geologic history of part of the Moon.

Materials

Suggested: clear acetate or overhead transparency, tape, overhead projector markers

Substitutions: tracing paper, colored pencils

Background

Planetary photogeologic mapping differs from geologic mapping on Earth because field work generally is not possible. Photogeologic mapping depends on photo interpretation, supplemented with other remotely sensed data. Despite the lack of "ground truth," photogeologic maps are important for deriving the geologic histories of planetary surfaces. It is assumed that students are familiar with geologic processes and landforms, as investigated in earlier exercises.

All the necessary information for completing this exercise is contained in the student's introduction. This can be a difficult exercise, and student maps will vary. Students should have some familiarity with the general geology of the Moon, and have completed Exercise 15. Encourage students to record their unit descriptions before beginning to draw the contacts, as this will help maintain consistency within each map. Contact placement will vary with different unit choices and descriptions. The map included in the answer key should be used as a general guide in assessing student maps.

Science Standards

- ■ Physical Science
  - • Motions and forces
- ■ Earth and Space Science
  - • Origin and evolution of the universe

Answer Key

Part A

1. Contacts are sharp; transition from plains to mountains is abrupt; hills appear as islands in smooth plains; relief of hills is variable; sinuous rilles appear to be controlled by hill topography (hills predate rilles); there are more craters on plains than on hills.
2. Smooth plains appear to be more heavily cratered than hills; explained as function of : 1) areal exposure of plains emphasizes number of craters; 2) hard to preserve craters on steep slopes of hills; 3) craters difficult to see in shadows and bright hill slopes.
3. Mountainous terrain pre-dates (is older than) smooth plains.
4. A smooth, gently undulating surface; contains numerous sinuous rilles. One rille lies on a topographic crest and is therefore unlikely to be an erosional channel. The unit is probably volcanic in origin, emplaced in part by the sinuous rilles (lava tubes/channels).
5. The hills are part of the system that surrounds Mare Imbrium and are probably related to one or more of the highly degraded and flooded multi-ring basins. Hence, they are analogous to crater deposits around smaller structures.
6. Presence of possible flow scarp. Numerous channels (rilles), some with leveed sides (Note: channel network does not interconnect and is therefore unlikely to be a fluvial "drainage" system, analogous to terrestrial watersheds—the rilles are probably lava channels).
7. Clusters of irregular, overlapping craters—herringbone pattern points to south-southeast. All are younger than smooth plains.
8. Secondary crater clusters from a large primary outside the field of view (somewhere to the south-southeast).
9. Hummocky, irregular topography associated with inner facies; radial and concentric texture in outer facies.
10. The topography is a result of ejecta from the Euler impact event. The inner facies represents continuous deposits, modified by post-impact slumping; the outer facies is a result of secondary cratering processes.
11. NW 33 km; NE 64 km; SE 31 km; SW 23 km. Note: distances may vary somewhat, depending upon where contact is drawn.
12. Presence of numerous sinuous rilles around regions of the west and south show that some Euler ejecta deposits have been covered by emplacement of late-stage mare lava.
13. Parts of the smooth unit post-date Euler, other parts seem to have faint texture associated with outer ejecta facies of Euler and are pre-Euler.
14. Crater clusters post-date Euler (are superposed on Euler ejecta), clusters post-date all mare deposits.
15. The clusters are probably secondary craters from some primary crater located to the south-southeast.

Answer Key, continued

Part B

Unit Name	Observation	Interpretation
ce1 (continuous ejecta; pre-mare craters)	inner facies (crater rim materials) of pre-mare craters; arranged concentrically to crater depression	pre-mare crater material; of early Eratosthenian age
ce2 (continous eject; post-mare craters)	rough hummocky inner facies of post-mare craters; arranged concentrically to crater depression	crater materials; of Eratosthenian age
de (discontinuous crater ejecta)	radial and sub-radial texture at distal end of rim materials - herringbone structure; at Euler, gradational with secondaries - not related to irregular crater clusters	crater materials; of Eratosthenian age
cc (crater cluster)	groups of large, irregular craters; v-shape pointing SSE; occur predominantly in SE corner - one group superposed on Euler ce2	secondary craters from a large primary located to the SSW; of Copernican age
mt (mountainous terrain)	large isolated massif structures in W and SW of map area; not continuous - appear to proturde through mare (smooth plains)	basin and large crater ejecta fromed in pre-mare times; of Imbrium age
m1 (old mare)	rough textured mare underlying Euler ejecta; pre-Euler mare with most primary structure degraded or destroyed	pre-Euler mare flows; of Eratosthenian age
m2 (young mare)	smooth mare plains overlying Euler ejecta; contains large number of channel-like structures (sinuous rilles)	flows emplaced primarily by sinuous rilles (volcanic origin); of Eratosthenian age

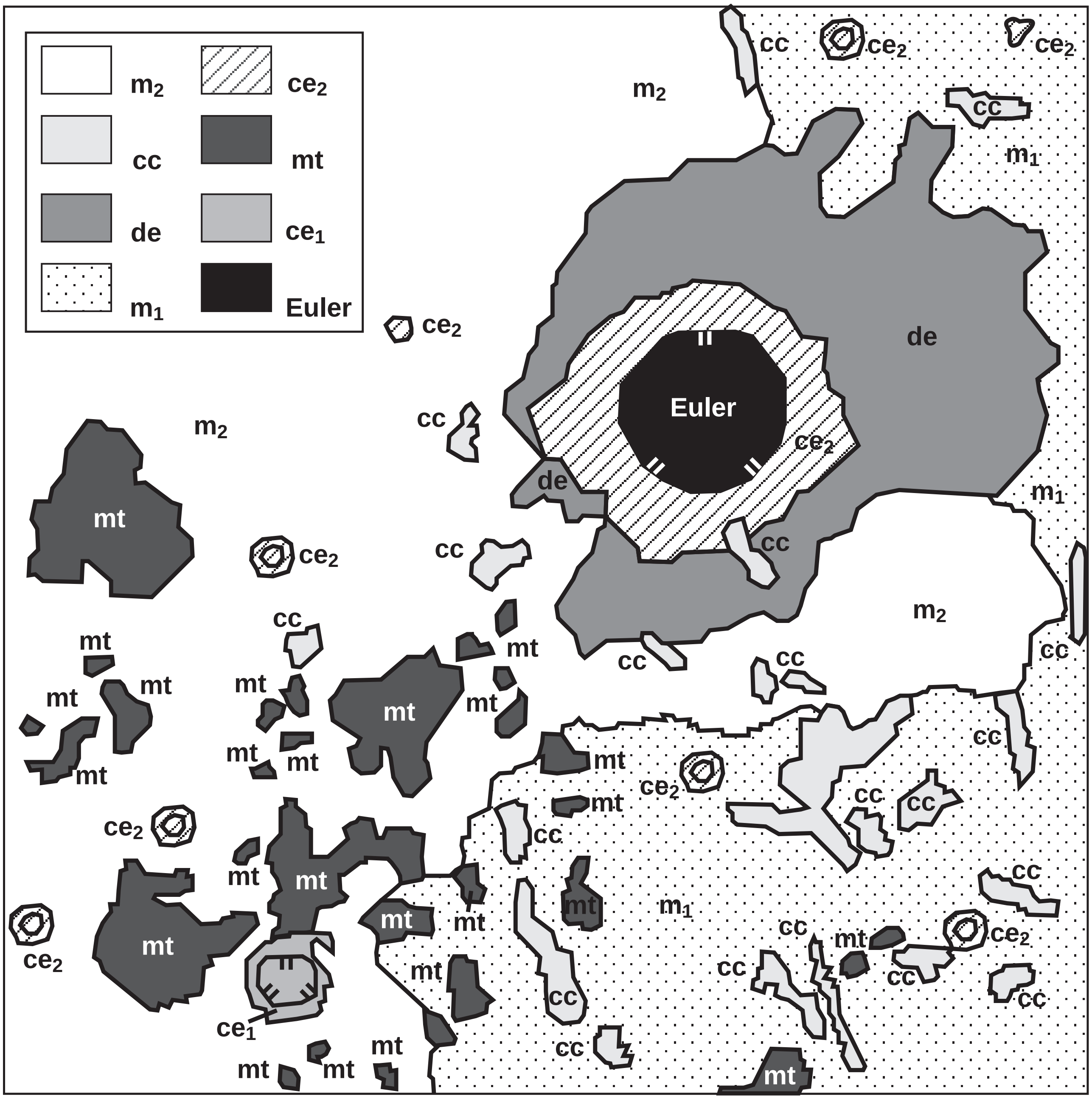
Answer Key, continued

	Geologic Unit	Structural Event	Age
Youngest	cc		Copernican
	ce2,de	Channels	Eratosthenian
	m2		
	m1	Euler impact	
	ce1		Eratosthenian
Oldest	mt		Imbrian

Geologic History

Unit mt is rim and ejecta material formed by a massive impact, or series of impacts related to the formation of the Imbrium Basin and is the oldest unit in this region. Cratering continued with the formation of the ce1 craters. The smooth plains (m1) were emplaced by volcanic activity prior to the impact and formation of Euler crater. After Euler was formed, volcanic activity continued with the formation of the m2 flows. Cratering continued with the formation of the ce2 craters. The youngest craters in the area are the cc secondary craters from a large impact outside the map area.

Answer Key, continued



Name ______________________________

Photogeologic Mapping of the Moon

Purpose

Through observation and analysis of photographs of the Moon you will become familiar with the techniques of constructing geologic maps of planetary surfaces.

Materials

Tape, clear acetate or overhead transparency, overhead projector markers (or tracing paper and colored pencils)

Introduction

A **geologic map** is a graphic portrayal of the distribution and age of rock types, structural features such as folds and faults, and other geologic information. Such a map allows geologists to link observations made at different localities into a unified form and to represent those observations in a form that can be easily understood by others. One of the first tasks in preparing a geologic map is the identification of units. By definition, a **unit** is a three-dimensional body of rock of essentially uniform composition formed during a specified interval of time and that is large enough to be shown on a conventional map. Thus, the making of geologic maps involves subdividing surface and near-surface rocks into different units according to their type and age. On Earth, this involves a combination of field work, laboratory studies, and analyses of aerial photographs. In planetary geology, geologic mapping must be done primarily by remote sensing methods, commonly the interpretation of photographs. Units are identified on photographs by their surface appearance (**morphology**—smooth, rugged, hilly, etc.), their **albedo** (how they reflect sunlight—light to dark), their state of surface preservation (degree of erosion), and other properties. In some cases remote sensing of chemical compositions permits refinements of photogeologic units.

Three decades of planetary exploration have shown that the solid-surface planets and satellites have been subjected to the same basic geologic processes: **volcanism, tectonism, gradation,** and **impact cratering.** The relative importance of each process in shaping the surface differs from body to body, depending on the local environment (presence of an atmosphere, running water, etc.). All four of these processes have worked to shape the surface of the Moon and have produced landforms and rock units that can be recognized and mapped. An important part of preparing a geologic map, once the units are identified, is interpreting the geologic process(es) responsible for the formation of each map unit. When preparing a planetary photogeologic map, unit descriptions are divided into two parts: the observation (what you see) and the interpretation (how you believe it formed).

After identifying the units and interpreting their mode of formation, the next task in preparing a photogeologic map is to determine the stratigraphic (age) relation among all the units. Stratigraphic relations are determined using: (a) the **Principle of Superposition, (**b) the law of cross-cutting relations, (c) embayment, and (d) impact crater distributions. The Principle of Superposition states that rock units are laid down one on top of the other, with the oldest (first formed) on the bottom and the youngest on the top. The law of cross-cutting relations states that for a rock unit to be modified (impacted, faulted, eroded, etc.) it must first exist as a unit. In other words, for a rock unit that is faulted, the rock is older than the faulting event. Embayment states that a unit “flooding into” (embaying) another unit must be younger. On planetary surfaces, impact crater frequency is also used in determining stratigraphic relations. In general, older units show more craters, larger craters, and more degraded (eroded) craters than younger units.

Once the stratigraphic relations have been determined, the units are listed on the map in order from oldest (at the bottom) to youngest (at the top). This is called the **stratigraphic column.** The final task, and the primary objective in preparing the photogeologic map, is to derive a general geologic history of the region being mapped. The geologic history synthesizes, in written format, the events that formed the surface seen in the photo—including interpretation of the processes in the formation of rock units and events that have modified the units—and is presented in chronological order from oldest to youngest.

Figure 16.1 shows a sample geologic map, including its unit descriptions and stratigraphic column. The relative ages were determined in the following manner: The cratered terrain has more (and larger) craters than the smooth plains unit—indicating that the cratered terrain unit is older. In addition, fault 1 cuts across the cratered terrain, but does not continue across the smooth plains. Faulting occurred after the formation of the cratered terrain and prior to the formation of the smooth plains—indicating that the smooth plains unit is younger than the cratered terrain and fault 1. The crater and its ejecta unit occurs on top of the smooth plains unit, and thus is younger. Finally, fault 2 cuts across all the units, including the crater and its ejecta unit, and is thus the youngest event in the region. The geologic history that could be derived from this map would be similar to the following:

"This region was cratered and then faulted by tectonic activity. After the tectonic activity, a plains unit was emplaced. Cratering continued after the emplacement of the smooth plains unit, as seen by the craters superposed on the smooth plains and the large, young crater mapped as its own unit. Finally, there has been a continuation (or reactivation) of tectonic activity, indicated by the major fault which postdates the young crater. "

The geologic mapping principles listed above have been applied to the Moon as a whole and a generalized geologic time scale has been derived (Figure 16.2). Two important units on the Moon are the Fra Mauro Formation and the Janssen Formation, ejecta deposits from the Imbrium and Nectaris impact basins, respectively. These are widespread units that were formed in the hours following the gigantic impacts that excavated the basins, and hence are excellent **datum planes.** Rock samples returned from several localities on the Moon enable radiometric dates to be placed on the generalized time scale.

Geologic mapping of impact crater-related deposits requires some knowledge of the impact process. When one planetary object such as meteoroid, strikes another there is a transfer of energy that causes the crater to form by having material excavated from the "target" surface. Most of the incoming object is destroyed by fragmentation, melting, and vaporization. Figure 16.3 is a diagram showing typical impact crater deposits. Extending about one crater diameter outward from the rim is a zone of **continuous ejecta deposits** consisting of material thrown out from the crater (called ejecta) and local material churned up by the ejecta. Extending farther outward is a zone of **discontinuous ejecta deposits;** unlike the zone of continuous ejecta deposits, these are surfaces that have been affected only locally by the impact. Bright, wispy rays extend beyond the zone of discontinuous ejecta deposits. Distinctive **secondary craters** formed by blocks of ejecta occur in singlets, doublets, triplets, chains and clusters. They often form a "herringbone" ridge pattern, the apex of which points toward the primary, or parent crater.

On the Moon and Mercury, geologic mapping involves distinguishing various deposits related to impact craters. In addition, most of the terrestrial planets have experienced volcanism that produced vast basaltic lava flows. Samples returned by the Apollo astronauts show that the dark, smooth areas of the Moon, named **maria,** are basalt flows. Some of these basalt flows were generated as enormous "floods" of lava, similar to the Columbia River Plateau of the northwest United States; others were produced as thin sheets that were fed by rivers of lava, visible today as **sinuous rilles** (Figure 16.4).

Procedure and Questions

The area you will be mapping is the Euler (pronounced 'oiler') crater region on the Moon. Euler is an impact crater, 28 km in diameter, located at 23°20'N, 29°10'W, placing it on the rim of the Imbrium basin on the near side of the Moon(see Figure 16.5). It is about 450 km northwest of the 93 km-diameter Copernicus impact crater. The photograph (Figure 16.6) was obtained with a mapping camera on board the Apollo 17 service module from an altitude of about 117 km. The photograph is 180 km on a side; the sun elevation angle at its center is about 6.5°.

To establish age relations and interpret the mode of formation of the rock units in the area it is best to examine the area in detail. Enlargements of Figure 16.6 will be used for this purpose.

Part A

1. Study Figure 16.7 (an enlargement of the southwest quadrant of Figure 16.6) in detail and list observations and evidence which might establish the relative age of the rugged clusters of hills and the intervening smooth regions.

2. List possible reasons why craters are more readily apparent on the smooth regions (vs. the hills).

3. Indicate your conclusion about the relative age of the two terrains (which is older).

4. List the characteristics of the smooth unit which might bear on its mode of formation; suggest a possible origin(s) for this unit.

5. List the characteristics of the rugged hills and suggest possible origins. Interpretations should be preliminary pending examination of the other quadrant enlargements (see also Figure 16.5).

6. Study Figure 16.8 (an enlargement of the northwest quadrant of Figure 16.6). List any additional characteristics associated with the smooth region which might bear on its mode of origin.

7. Briefly describe the several clusters of craters visible in Figure 16.8. What is their age in relation to the smooth region?

8. Propose a tentative mode of origin for these crater clusters, including any possible directional information.

9. Study Figure 16.9 (an enlargement of the northeast quadrant of Figure 16.6). Briefly describe the various characteristics of the topography surrounding and associated with the crater Euler.

10. Propose an origin for the topography of the material at crater Euler.

11. Study the outer boundary of the unit which includes Euler and its associated crater materials (recall Figure 16.3). Using Figures 16.6, 16.7, 16.8, 16.9, 16.10 measure and record the distance from the rim crest of Euler to the outer boundary of the crater materials in a NW, NE, SE, and SW direction.

Asymmetry in deposits surrounding a crater can result from several factors including: (1) oblique impact of projectile, (2) fractures in bedrock causing asymmetric ejection of material, (3) strong prevailing winds (on Earth and Mars), (4) later events modifying parts of the deposits, (5) topographic effects on flow of material from craters (on Venus), (6) a combination of the above.

12. Study the stratigraphic relations around the Euler deposit and list evidence to account for the observed deposit asymmetry.

13. Study Figure 16.10 (an enlargement of the southeast quadrant of Figure 16.6) and Figures 16.7, 16.8, and 16.9. What is the age relation of the deposit surrounding Euler and the smooth unit. Present evidence for your conclusions.

14. Describe the large crater clusters in Figure 16.9 (craters larger than about 500 meters). What is their age in relation to Euler? What is their age in relation to the mare deposits (smooth unit)?

15. Describe the mode of origin of these clusters and include any directional information concerning their source.

Part B

Examine Figure 16.6 in detail (as well as the enlargements of the four quadrants) and classify the terrain into geologic units based on surface morphology, albedo, crater frequency, and other characteristics. There are at least 3 major geologic units in the region. Tape the acetate or tracing paper over the photo (Figure 16.6). If you are using tracing paper, tape it at the top only so that the paper can be flipped up to see the photograph. Make reference marks in the four corners, in case the acetate or paper shifts while you are working on it , and also to help in overlaying with other maps for comparison. Draw preliminary contacts around the units—DO NOT WRITE ON THE PHOTO. Label the units by writing the name, or letters symbolizing the name, within each unit. Areas of a unit need not be laterally continuous on the surface, but may exist as isolated patches. Use symbols for features such as faults, grabens, fractures, and crater rims (see symbols sheet, Figure 16.13). Tabulate the units on Figure 16.11 and describe their main characteristics. Names are of your choice, such as “mountain unit,” “smooth plains.” Names should be based on observations, not interpretations of possible mode of origin (“smooth plains” rather than “volcanic plains”). If you are using tracing paper, color the map, using a different color for each unit.

Using the stratigraphic relations and interpretations developed in part A compile a stratigraphic column and geologic history for the Euler region. Based on your observations, determine the stratigraphy of the units (the relative order of units from youngest to oldest). List the units in the column “Geologic Unit” in Figure 16.12 in order from youngest at the top to oldest at the bottom. Place any structural information in the column “Structural Events”. Use the lunar time scale to determine the age (e.g., Eratosthenian) in which the units formed and note this information on your stratigraphic column and in the geologic history.

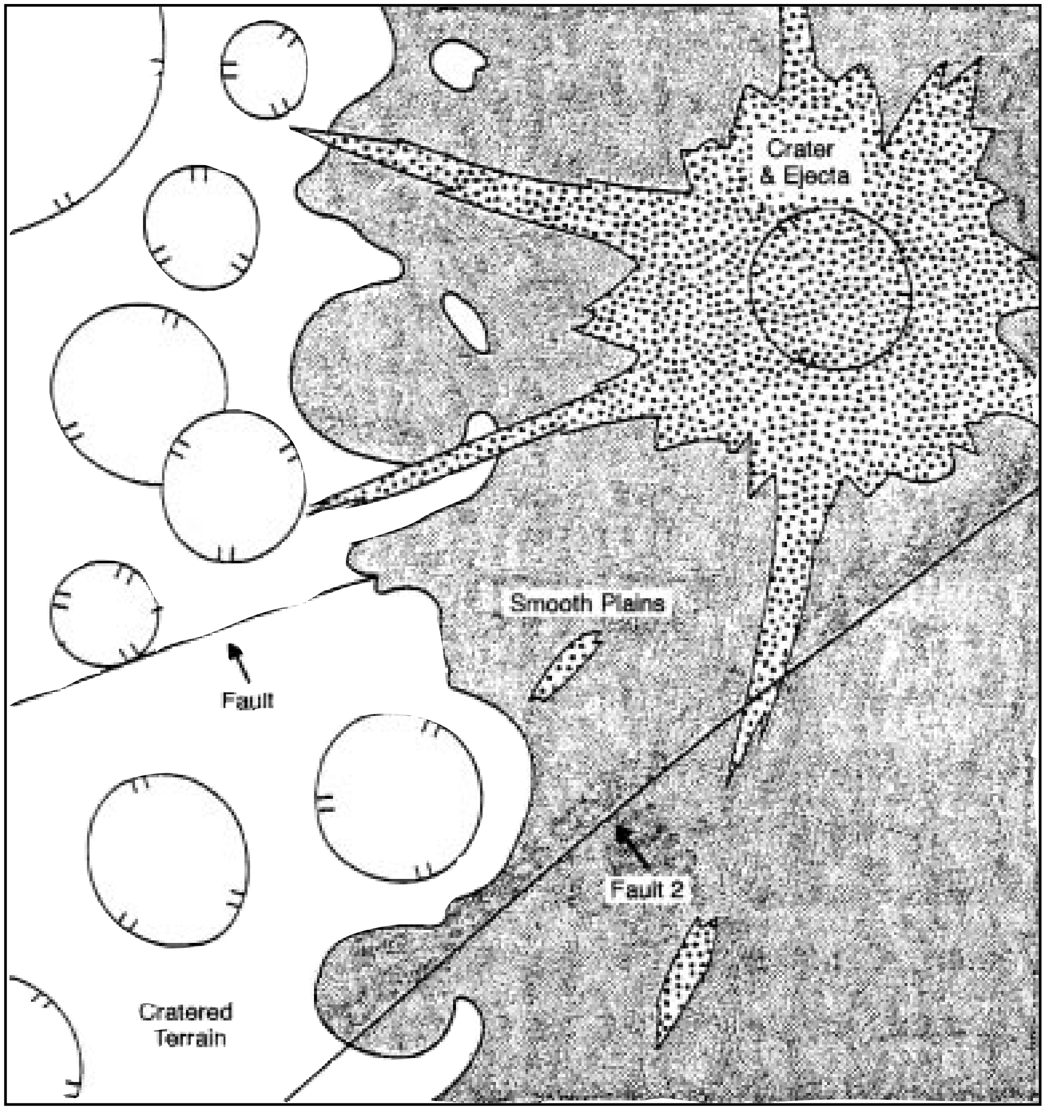


Figure 16.1. *Sample geologic map and derived stratigraphic column.*

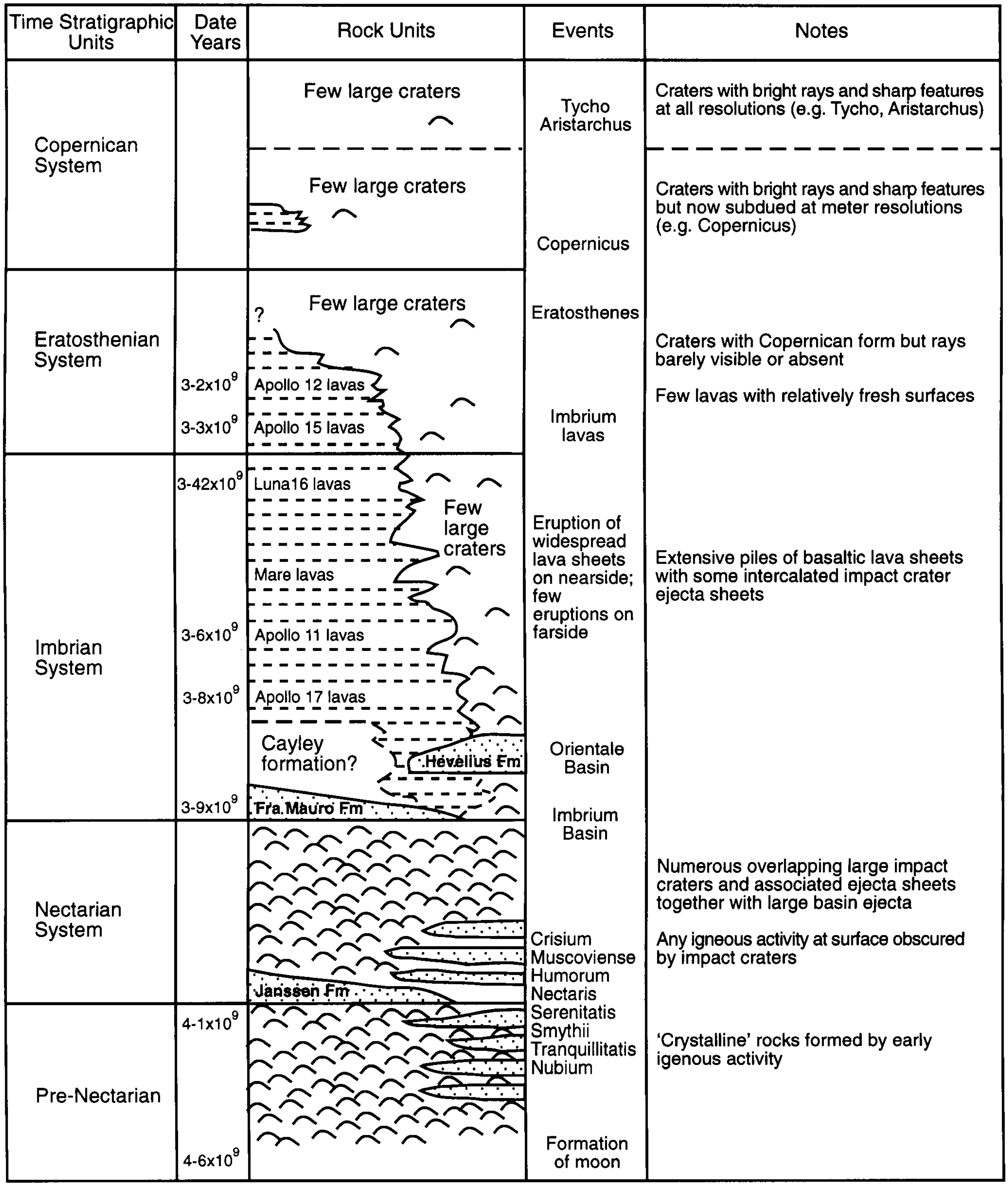
Stratographic Column

	Geologic Unit	Structural Event
Youngest		Fault 2
↑	Crater and Ejecta	
	Smooth Plains	
		Fault 1
Oldest	Crater Terrain	

Unit Descriptions

Unit Name	Observation	Interpretation
Crater and Ejecta	rough, blocky surface, high albedo, surrounds and includes crater	crater and ejecta formed by impact
Smooth Plains	smooth plains, few craters, low albedo, lobate (rounded) margins	volcanic flow
Crater Terrain	rugged, heavily cratered plains, high albedo	old unit, possibly of volcanic origin, has had extensive cratering

Lunar Geologic Time Scale



(after Guest and Greely, 1977)

Figure 16.2.

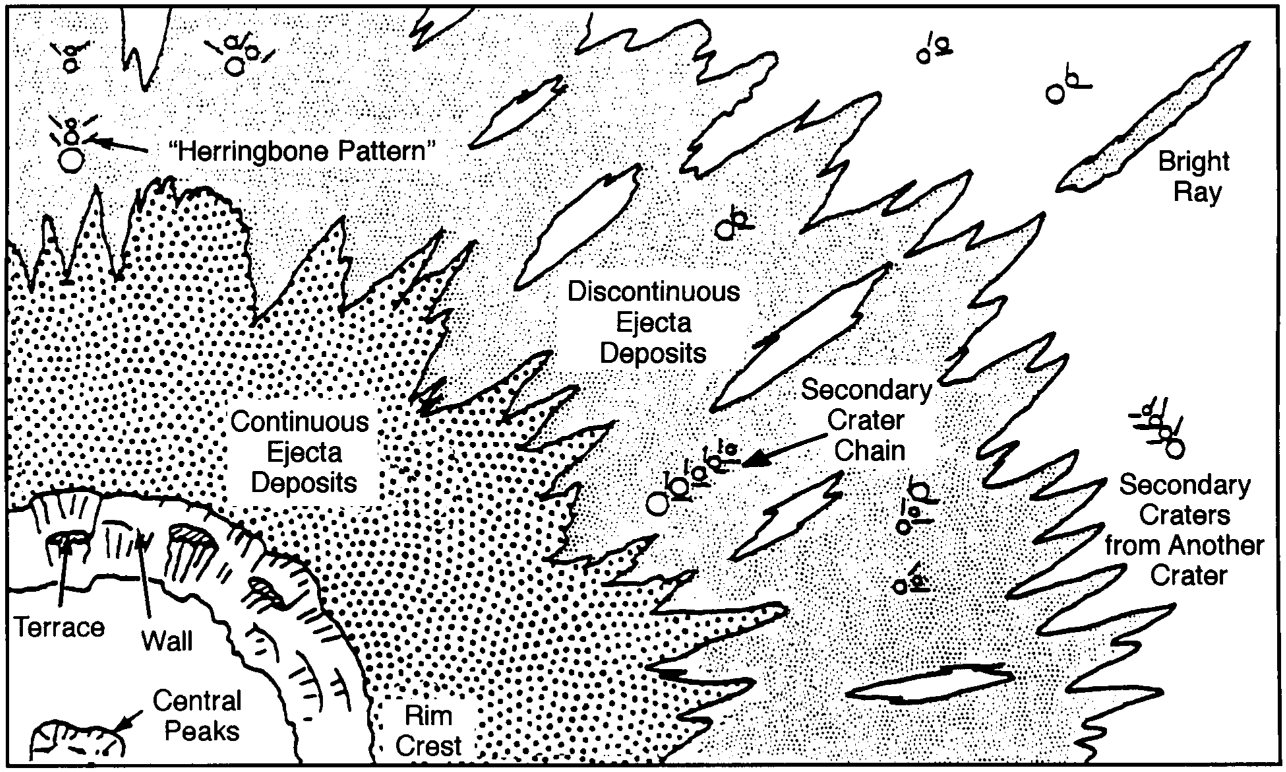


Figure 16.3. *Diagram of typical impact crater deposits.*

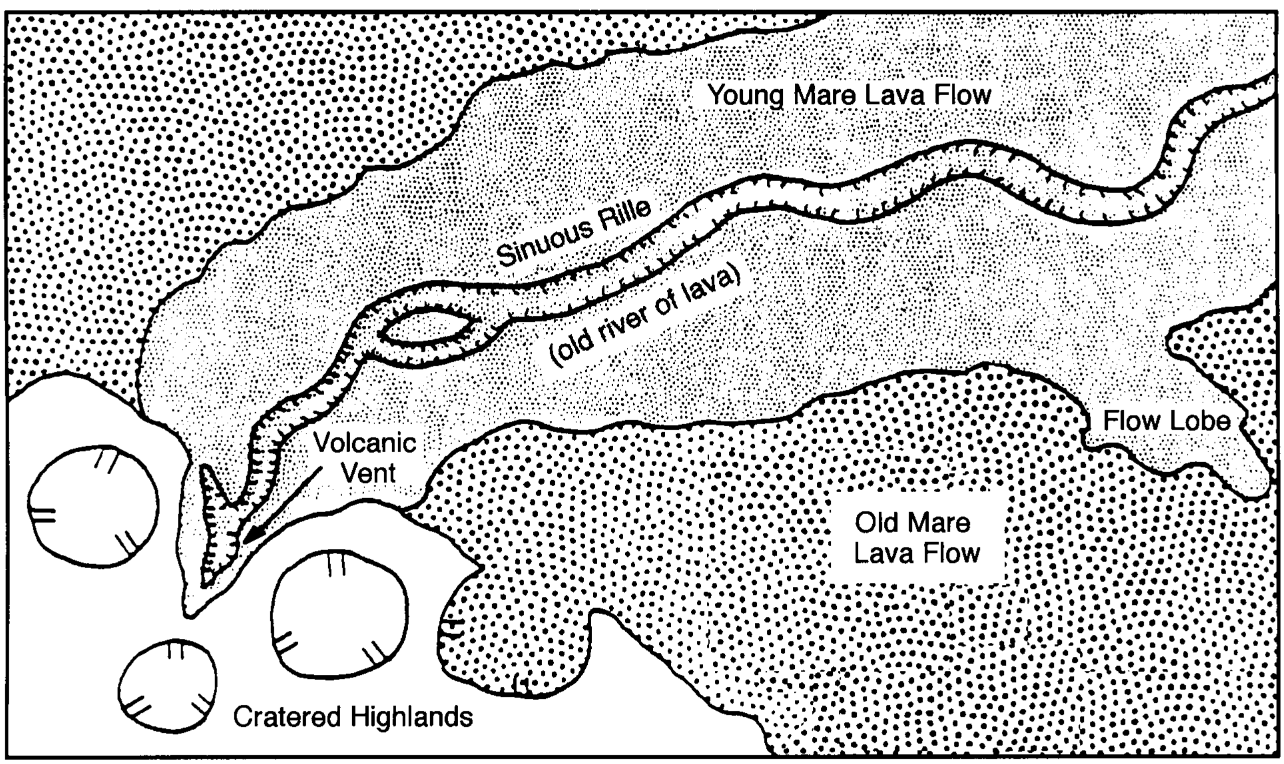


Figure 16.4. *Diagram of a typical sinuous rille.*

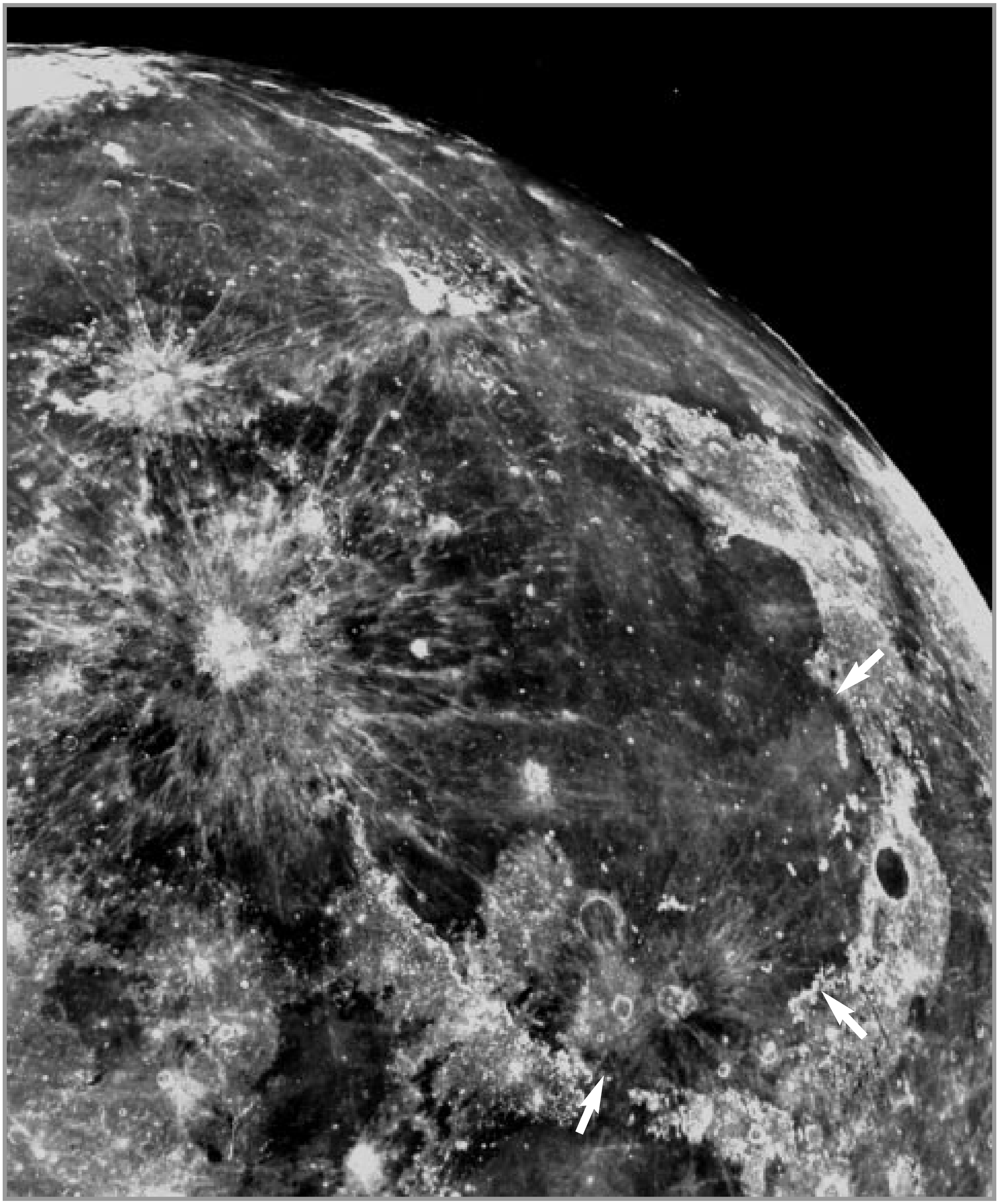


Figure 16.5. *Photograph of the near side of the moon, showing the Imbrium Basin (indicated by arrows). North is to the top. (courtesy of Ewen A. Whitaker, Univ. of Arizona)*

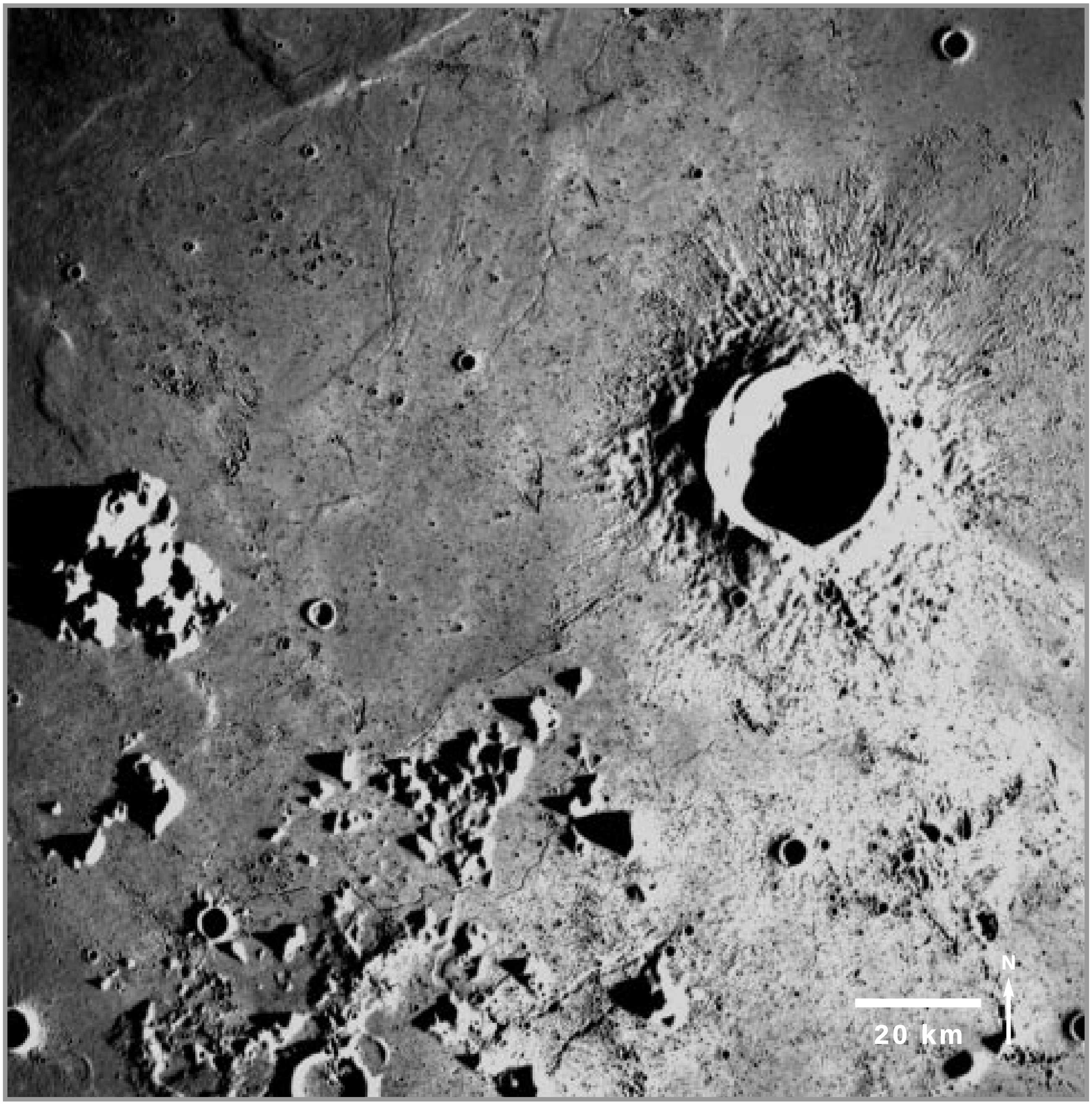


Figure 16.6. *Photograph of the Euler crater region on the near side of the moon. North is to the top. Euler crater (the large one) is 27 kilometers in diameter. Apollo 17 metric photo AS17 2730.*

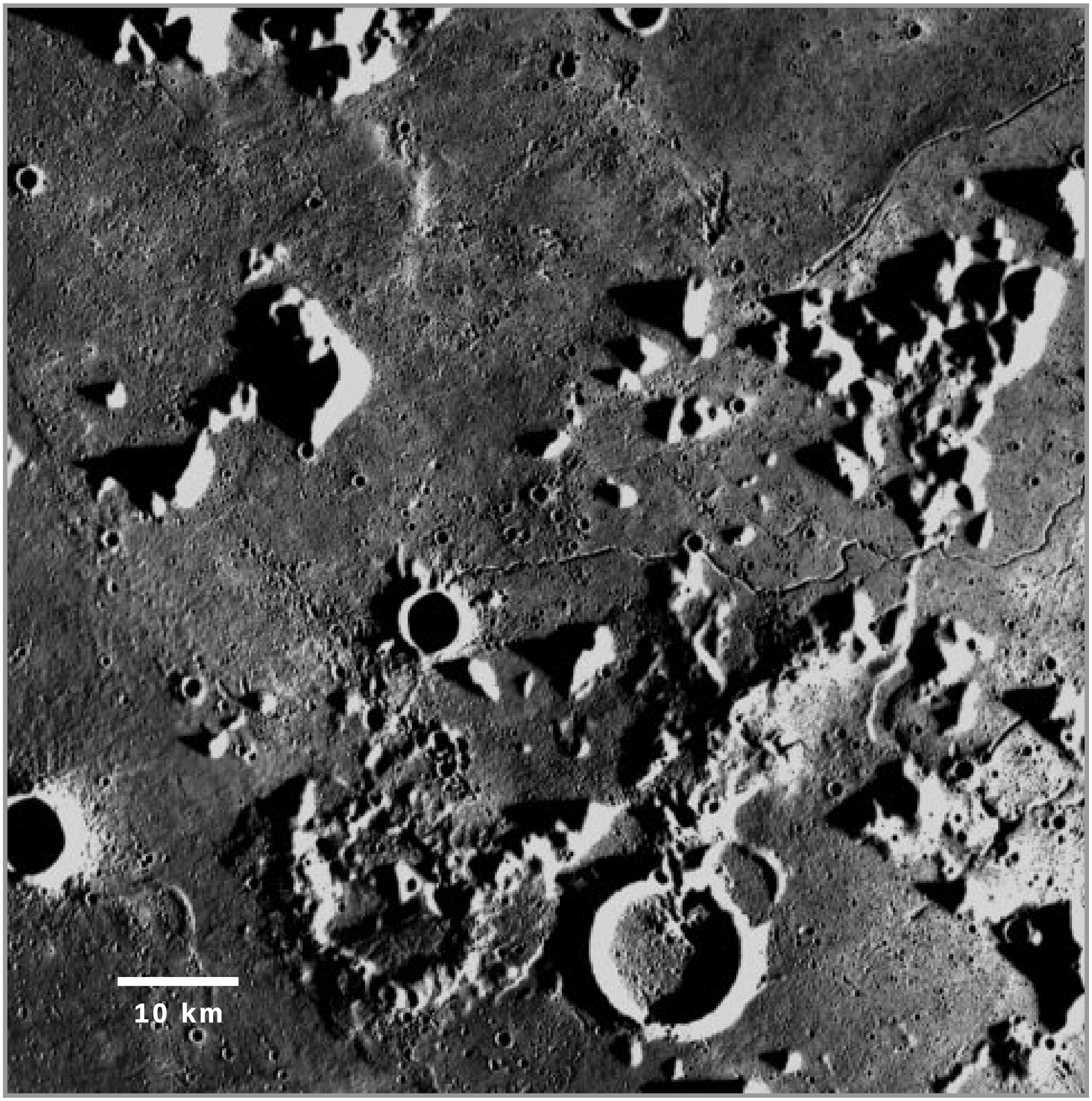


Figure 16.7. *Southwest quadrant of Euler region photo. North is to the top. Apollo 17 metric photo AS17 2730.*

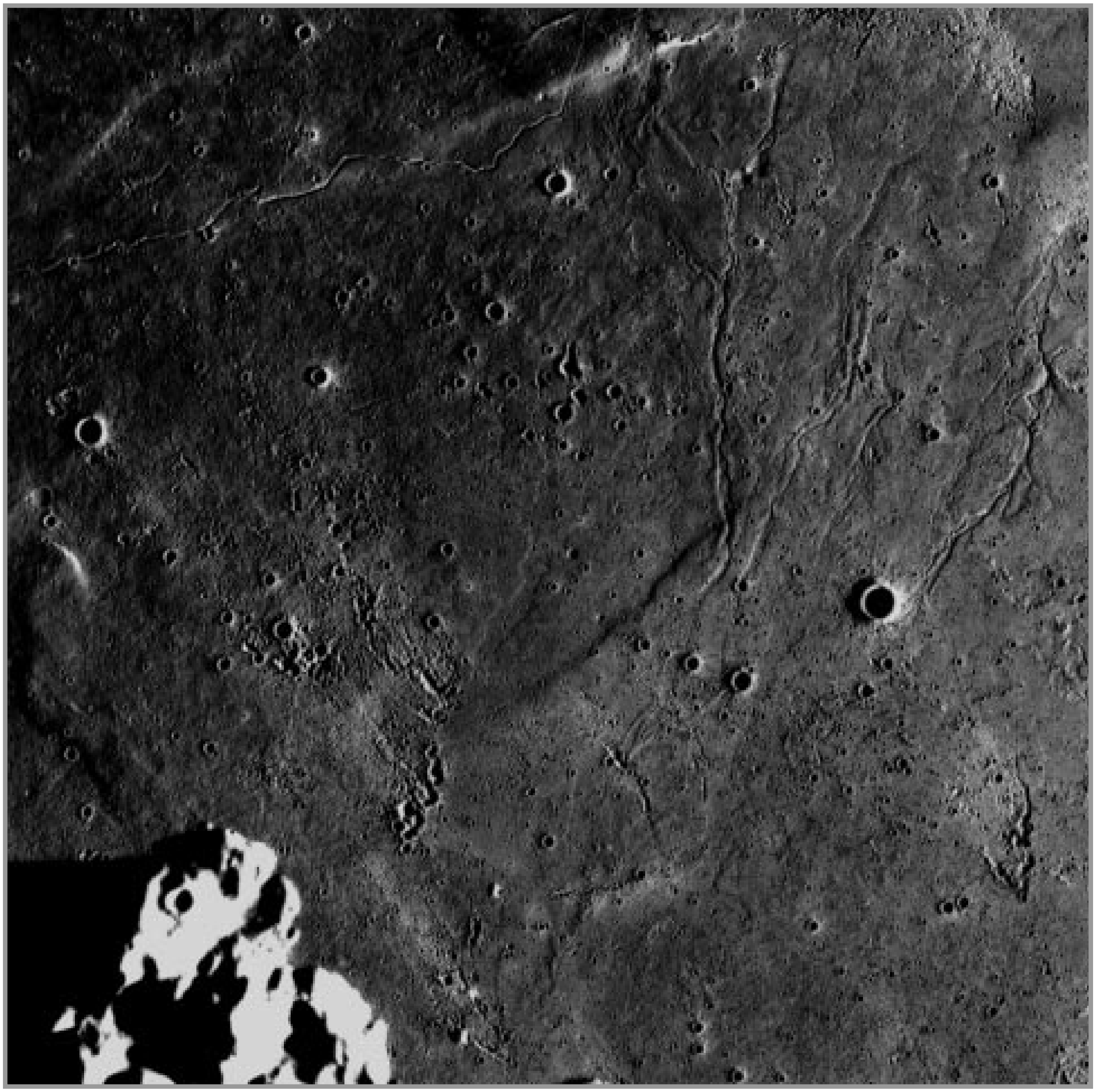


Figure 16.8. *Northwest quadrant of Euler region photo. North is to the top. Scale is the same as for Figure 16.7. Apollo 17 metric photo AS17 2730.*

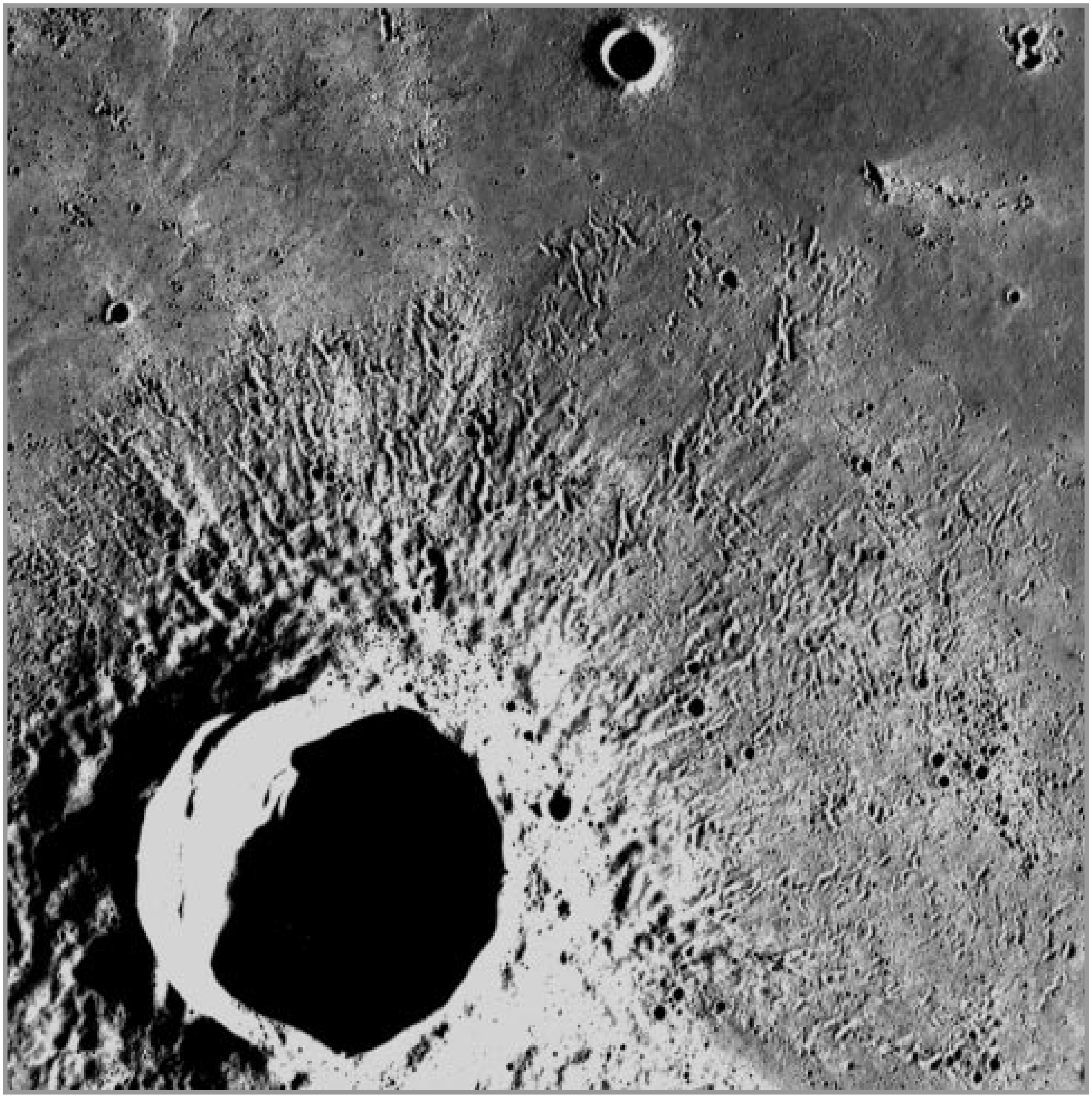


Figure 16.9. *Northeast quadrant of Euler region photo. North is to the top. Scale is the same as for Figure 16.7. Apollo 17 metric photo AS17 2730.*

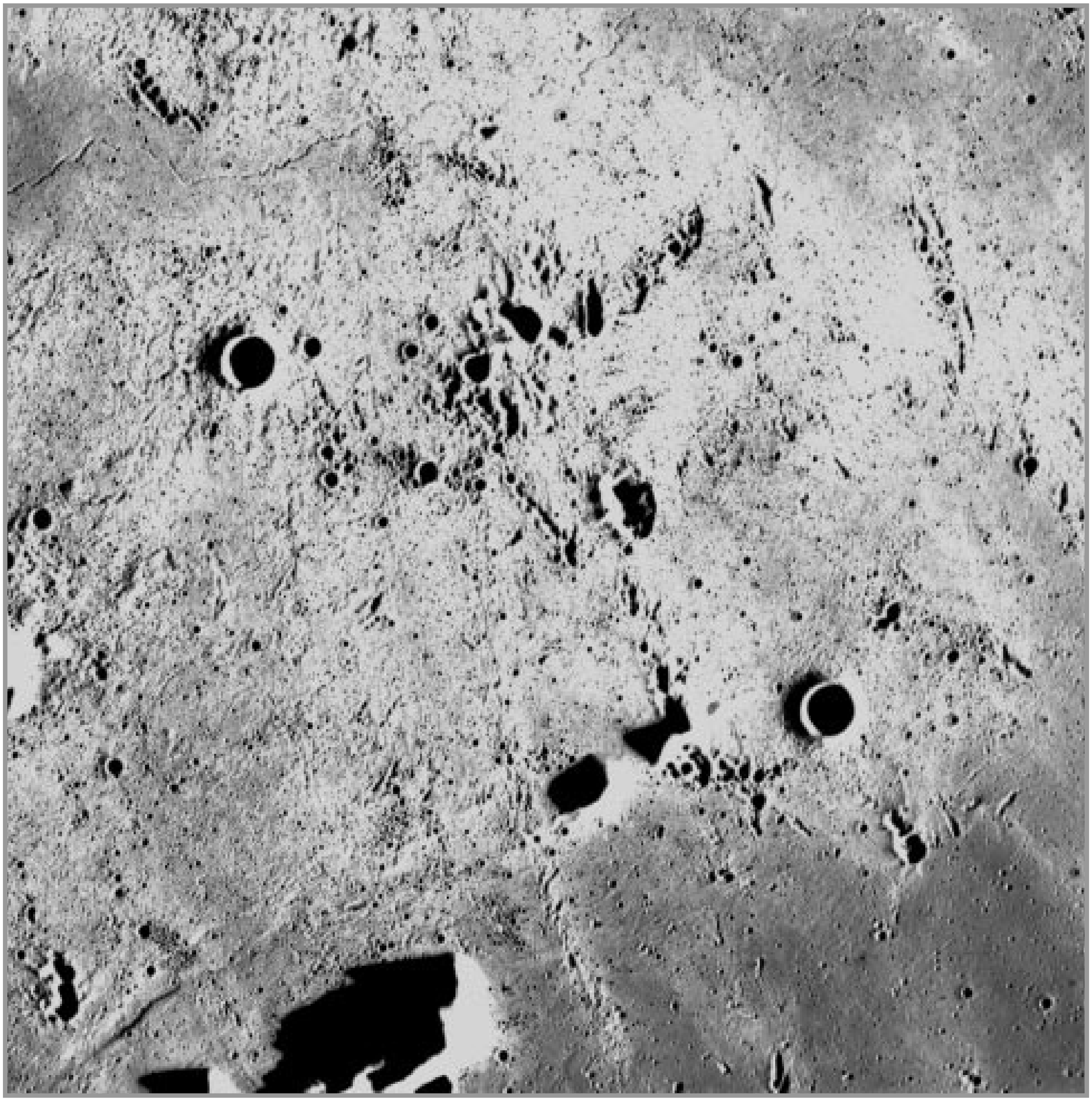


Figure 16.10. *Southeast quadrant of Euler region photo. North is to the top. Scale is the same as for Figure 16.7. Apollo 17 metric photo AS17 2730.*

Unit Name	Observation	Interpretation

Figure 16.11. *Unit descriptions.*

	Geologic Unit	Structural Event	Age
Youngest			
Oldest			

Figure 16.12. *Stratigraphic column.*

Geologic History: