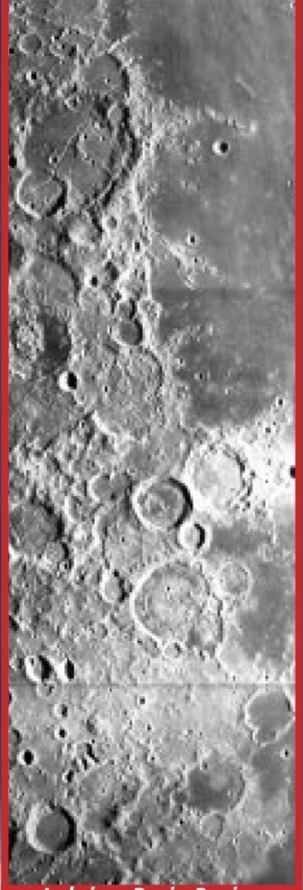
LUNAR ORBITER PHOTOGRAPHIC ATLAS *of the* NEAR SIDE *of the* MOON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CHARLES J. BYRNE

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Cover illustration: Earth-based photograph of the full Moon from the "Consolidated Lunar Atlas" on the Website of the Lunar and Planetary Institute.

British Library Cataloging-in-Publication Data
Byrne, Charles J., 1935–
Lunar Orbiter photographic atlas of the near side of the Moon
1. Lunar Orbiter (Artificial satellite) 2. Moon–Maps 3. Moon–Photographs from space
I. Title
523.3 0223
ISBN 1852338865

Library of Congress Cataloging-in-Publication Data
Byrne, Charles J., 1935–
Lunar Orbiter photographic atlas of the near side of the Moon : with 619 figures /
Charles J. Byrne.
p. cm.
Includes bibliographical references and index.
ISBN 1-85233-886-5 (acid-free paper)
1. Moon–Maps. 2. Moon–Photographs from space. 3. Moon–Remote-sensing images.
4. Lunar Orbiter (Artificial satellite) I. Title.
G1000.3.B9 2005
523.3 022 3–dc22 2004045006

ISBN 1-85233-886-5 Printed on acid-free paper.

Printed in Singapore. (EXP/EVB)

9 8 7 6 5 4 3 2 1 SPIN 10978726

Springer Science+Business Media
springeronline.com

Preface

The Moon is Earth's nearest neighbor. Since the dawn of intelligence, our eyes have seen the Moon, puzzling over its shady figures, its phases, its motions in the sky, and its relation to tides. Even the smallest telescopes resolve the shadows into a heavily cratered surface, stimulating the imagination. Each advance of the astronomer's art has revealed new insights into the nature of the lunar surface, until curiosity and competition led the American and Russian space programs to send orbital cameras, robotic landers and rovers, and the Apollo astronaut exploration teams to the Moon.

The Lunar Orbiter program, a series of five photographic spacecraft launched in 1966 and 1967, was motivated by the need to find and certify safe and interesting landing sites for the Apollo spacecraft. When the Lunar Orbiter program was started (1964), no spacecraft had landed on the Moon, but the Apollo program was committed to safely land the Lunar Module, with two astronauts on board. At the time, I was working in the lunar environment group of Bellcomm, Inc. AT&T established Bellcomm at the request of the National Aeronautics and Space Administration (NASA) to support the Apollo project headquarters group. Our responsibility included the challenging assignment of finding a safe landing site for a vehicle about the size of a helicopter, with a half-meter (0.5-m, 20-inch) ground clearance and limited ability to land on a slope. Of course, we had very little information about the lunar surface at such scales. There was some information from lunar photometry and radar scatter measurements, but there were strong uncertainties about what aspects of the surface were being measured; in particular, the soil strength was an unknown. Speculation raised possibilities of dust floated by static electricity or fragile glasslike lava.

The requirements for Lunar Orbiter were established to achieve the best possible resolution within the state of the art and to obtain imagery of that resolution over a significant percentage of the area available for Apollo landings. Targeted Apollo landing sites had to be as smooth as possible over a large enough area to accommodate the down-range and cross-range navigation errors, determined by the tracking, and control uncertainties associated with factors such as the largely unknown gravity anomalies.

NASA's Langley Research Center was chosen to manage the Lunar Orbiter program. I had the pleasure of drafting the specifications and participating in the selection of contractors. The resulting spacecraft and camera designs of Boeing Aircraft and Eastman Kodak (respectively) were capable of enormous data collection capacity, even in today's terms. All together, about 1000 pairs of medium- and high-resolution exposures were made during the five missions. The negatives were developed in orbit, scanned, and transmitted to photographic and magnetic tape recorders in the three stations of the Deep Space Network operated by the Jet Propulsion Laboratory (JPL) in California, Spain, and Australia. Each exposure results in one medium-resolution frame and one long high-resolution frame, usually presented as three subframes.

Although five missions were planned to compensate for possible failures, either of spacecraft or rejection of initial target sites, the survey for early Apollo landing sites was completed in the first three missions. As a result, the fourth mission was used for a comprehensive survey of the near side of the Moon; these are the photographs that are the primary contents of this book. The fifth mission examined many scientific sites at very high resolution, surveyed a few additional landing sites for later Apollo missions, and improved coverage of the far side of the Moon. Since the Lunar Orbiter missions returned their extensive photographic coverage of Earth's Moon, the pictures have been the basic reference for high-resolution topographic information. The most often referenced images are the comprehensive set of about 600 images selected by Bowker (1971) and the near side set of about 450 images selected by Whitaker (1970).

Following the thorough coverage of the Lunar Orbiter program, the Apollo Command and Service Module, in orbit during landing missions, provided additional coverage of the equatorial regions with its mapping and panoramic cameras. The Clementine mission provided a comprehensive survey of altitude, albedo (intrinsic brightness), and multispectral data in 1994. Lunar Prospector provided gamma ray spectroscopy in 1998. The data from these spacecraft has added insight into the mineral composition of nearly all the lunar surface, extending surveys of the equatorial region by Apollo. The interpretation of the remote sensing data has been supported by ground truth from analysis of lunar rocks and soil returned by Apollo and Luna missions. Despite the advances of these later missions, the Lunar Orbiter photographs, taken at a low sun angle, remain the primary source of topographic images and are used extensively in current scientific presentations, papers, and books.

At the time of Lunar Orbiter's design, image scanning technology was much less advanced than it is today. The methods used resulted in artifacts in the images that distract a viewer. Scanning and transmission limitations required the subframes to be reassembled from 20 to 30 framelets of 35-millimeter film. There are fine bright lines running across each subframe between the framelets, and there are brightness variations from the spacecraft's scanner that appear as streaks within the framelets. The artifacts are particularly distracting when the images are printed at high contrast to show subtle topographic features and brightness variations. Lunar scientists have become used to these artifacts, but they detract from their value to students and casual observers.

Since the first photos were received, I have wanted to clean up the scanning artifacts, but at the time it would have been very expensive. The priorities were to examine the photos and start using them, rather than to improve their visual quality. Advances in the art of computation and the capacity of modern computers have enabled processing of the photos to remove nearly all the scanning artifacts, resulting in clear images that are much easier to view. Drawing on an understanding of the nature of the artifacts, I have written programs that measure and compensate for the systematic artifacts and in addition apply filtering techniques similar to those published by Lisa Gaddis of the United States Geological Survey (USGS) (Gaddis, 2001).

Lunar Orbiter photography has been archived as hard copy photographs, each about 60 centimeters (cm) (about 2 feet) wide, at each NASA Regional Planetary Image Facility, including one at the Lunar and Planetary Institute (LPI) in Houston, Texas. LPI has digitized this important archival source and published the images in the Digital Lunar Orbiter Photographic Atlas of the Moon on the LPI web site (www.lpi.usra.edu/research/lunar_orbiter/). Further, the LPI staff has added annotations to the photos, clearly outlining many of the features and labeling them with their internationally recognized names.

A team led by Jeff Gillis carried out this important work; Jeff was supported by Washington University at St. Louis and LPI. He is currently with the University of Hawaii. LPI technical and administrative support was provided by Michael S. O'Dell, Debra Rueb, Mary Ann Hager, and James A. Cowan with assistance from Sandra Cherry, Mary Cloud, Renee Dotson, Kin Leung, Jackie Lyon, Mary Noel, Barbara Parnell, and Heather Scott. The selection of photos on the LPI Digital Archive is that selected for *Lunar Orbiter Photographic Atlas of the Moon* by Bowker and Hughes (see the reference section for details).

The annotated photos in this atlas provide full coverage of the near side, including nearly all the features whose names have been approved by the International Astronomical Union (IAU). All the high- and medium-resolution photos of Lunar Orbiter 4 (except for a few that were found unacceptable for Bowker, 1971) have been cleaned and are in the online material. Most of these, selected for nonredundancy and interest of features, are printed along with the annotated photos. All the photos (before processing by the author) are courtesy of NASA and LPI.

Photos with annotated overlays label the major features within each of the photos, including the landing sites of manned and unmanned spacecraft. These overlays were extracted digitally from those published by LPI. I added additional annotations to provide latitude, longitude, and scale information and also to bring the set of features up to date with the Gazetteer of Planetary Nomenclature, the list maintained for the IAU by the United States Geological Survey (USGS) Astrogeology Program. Notes with each photo point out salient aspects of the features. The combination of cleaned photos, labeled features, and notes are intended to serve as powerful aids to learning the geography and geology of the near side of the Moon as well as valuable reference material.

Throughout the project of cleaning the photos and writing this book, helpful suggestions and comments were made by Jeff Gillis, Mary Ann Hager, Paul Spudis, Lisa Gaddis, Debbie Martin, Michael Martin, Ewen Whitaker, and Brad Jolliff.

My dear wife Mary worked long and patiently as system administrator, picture processor, and reviewer.

Special gratitude goes to Don Wilhelms, USGS Astrogeology (retired), whose books have been major sources and who was kind enough to review this book and set me straight on lunar geology.

Charles J. Byrne

Table of Contents

The original version of this book was revised. The correction is available at
https://doi.org/10.1007/978-1-84628-154-9_13

Chapter 1

Overview of the Atlas

1.1. Content

The atlas presents full coverage of the nearside of the Moon with a series of photos all taken from orbit by Lunar Orbiter 4, with a nearly vertical viewpoint and sunlight at approximately 20 degrees (°) from the horizontal. Extensive computer processing has been used to improve the quality of these photos. Features whose names have been recognized by the International Astronomical Union (IAU) have been identified on an overlay and listed in the index of features. Notes on each page discuss the geologic processes that formed the features and controlled their interactions.

The high-resolution photos of this book typically cover about 200 by 300 kilometers (km). Approximately 350 of these photos cover the nearside of the Moon (with some overlap). The photos are grouped into chapters that each present one of the regions of the Moon. Six of these regions have been selected to focus on basins of the Moon, the largest coherent lunar features. Chapters on the North and South Polar Regions complete the coverage of the nearside. Figure 1.1 identifies these regions against the background of a photograph of the full Moon. Figure 1.2 identifies the regions of the central latitudes against a Mercator projection map, Figure 1.3 shows the North Polar Region, and Figure 1.4 shows the South Polar Region.

An introduction to each chapter surveys the relevant region, using wide coverage photos. An overview of the geology of each region and its features introduces the specialized vocabulary needed to describe lunar processes. Each chapter provides a guide to the high-resolution photos as an aid to relating them to the wide-angle views and to the Moon as a whole. Each high-resolution photo is marked with the latitude and longitude as a further guide to locating features on the maps of Figures 1.2 to 1.4.

The online extra material (extras.springer.com) contains all the cleaned-up photographs of Lunar Orbiter Mission 4, with an index listing all the officially named lunar features shown in this book. These photos, when viewed on a monitor with appropriate magnification, show more detail than can be seen in the printed pictures.

1.2. How to Use This Atlas

A telescopic observer or photographer of the Moon, working at high resolution, views a small area under lighting that varies both with time and with position. The angle of view is nearly vertical at the center of the Moon as we see it, but severely foreshortened near the limb (edge of the visible Moon). One might ask: What features are in the area? How do they relate to the rest of the Moon? How would the feature look relative to others if seen at similar lighting conditions and viewing angles? What is the current understanding of the processes that formed these features?

The following is a summary of how an interested observer might answer these questions, with the aid of this atlas:

1. Relate a feature viewed in a telescope, photo, or electronic image to its position on the full Moon photo of Figure 1.1.
2. Note the region in which it appears; consult the Table of Contents to find the appropriate chapter.
3. Determine the approximate latitude and longitude of the feature from the maps in Figures 1.2 and 1.3. These coordinates can be used with the chart in the beginning of the relevant chapter to narrow the search for the corresponding photo.
4. Once the photo or photos that cover the area of interest are located, annotations will identify the name of the feature (if it has a formal name) and the names of nearby features.
5. The notes on the page or pages describe something of the processes that took place to form the feature or its surroundings.
6. The reference section refers to more detailed descriptions in the literature for many of the photos.

The process described above can be followed in reverse. If an observer is interested in a feature found by browsing the book, the latitude and longitude on the annotated photo can be used to locate the feature relative to larger features on the maps of Figures 1.2 to 1.4. Then an observer can feature-walk a telescopic field of view to the appropriate part of the Moon, just as one star-walks a field of view from one star group to another to bring dim deep-sky objects into sight.

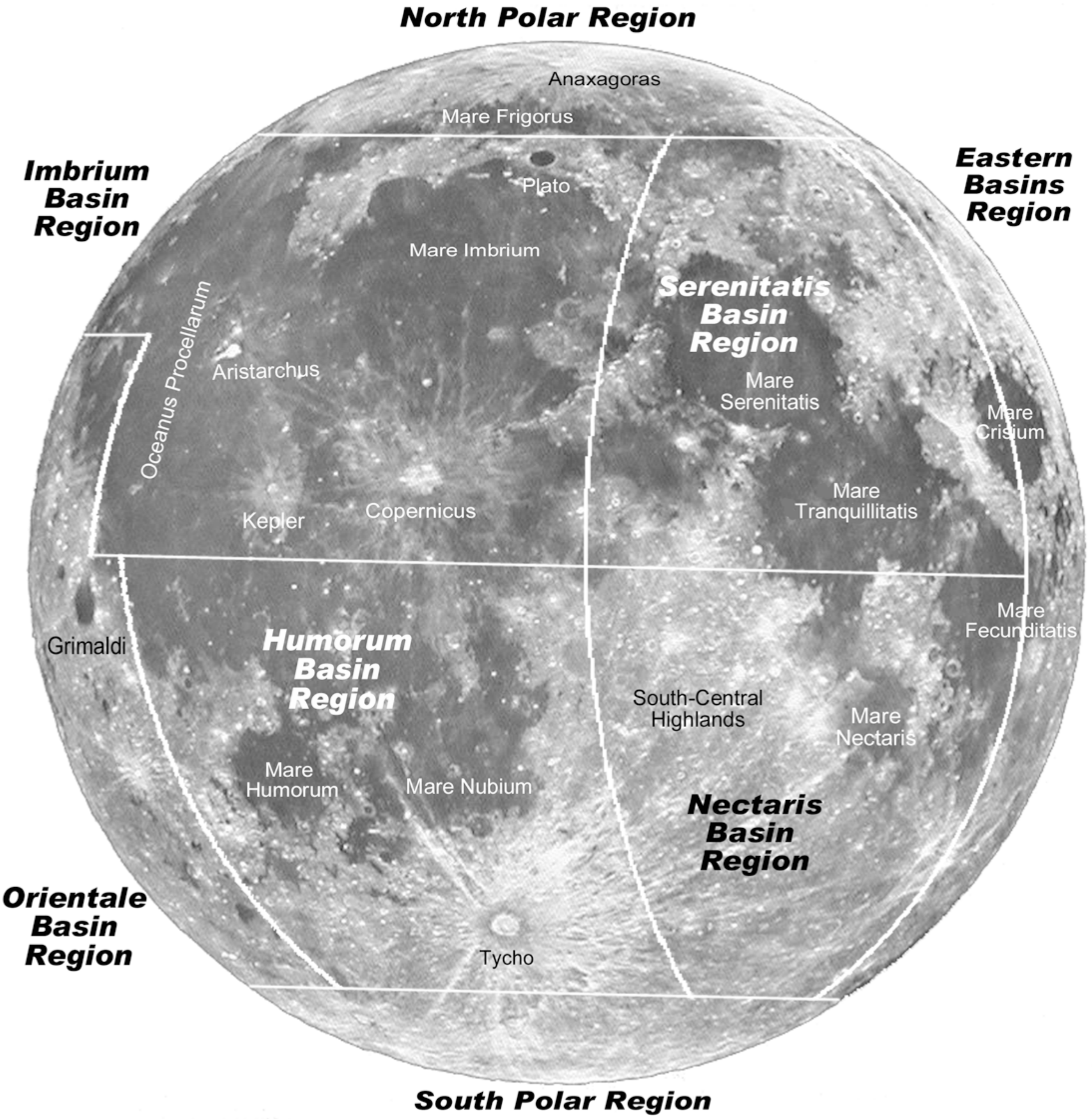


Figure 1.1. These regions of the Moon establish the scope of the corresponding chapters of this atlas. The base photo is from the Consolidated Lunar Atlas (LPI Web site).

Of course, these are only examples of ways this atlas can be useful. The overview chapters and the introductions to the regional chapters can be read as a book summarizing the largest features on the Moon and their relationships. Another way to use the atlas is to browse it. The notes need not be read sequentially. The atlas can also be used as a reference book. The feature index in the online material lists near side features with IAU names and directs the reader to a relevant page. The Source Notes section of the online material often identifies discussion of features in books of comprehensive coverage of the Moon, which refer in turn to additional research publications.

1.3. Large-Scale Maps

Figure 1.1 is the full Moon, photographed from Earth. A few outstanding features are identified as an aid to orientation when looking at the Moon. The dark maria (low-lying areas flooded by lava) form the patterns variously known as the man in the Moon, the rabbit, and so on.

The map in Figure 1.2 is based on data from the Clementine spacecraft. Clementine scanned the Moon from a polar orbit whose plane was aligned with the sun, so that the lunar surface shows its inherent brightness (called albedo),

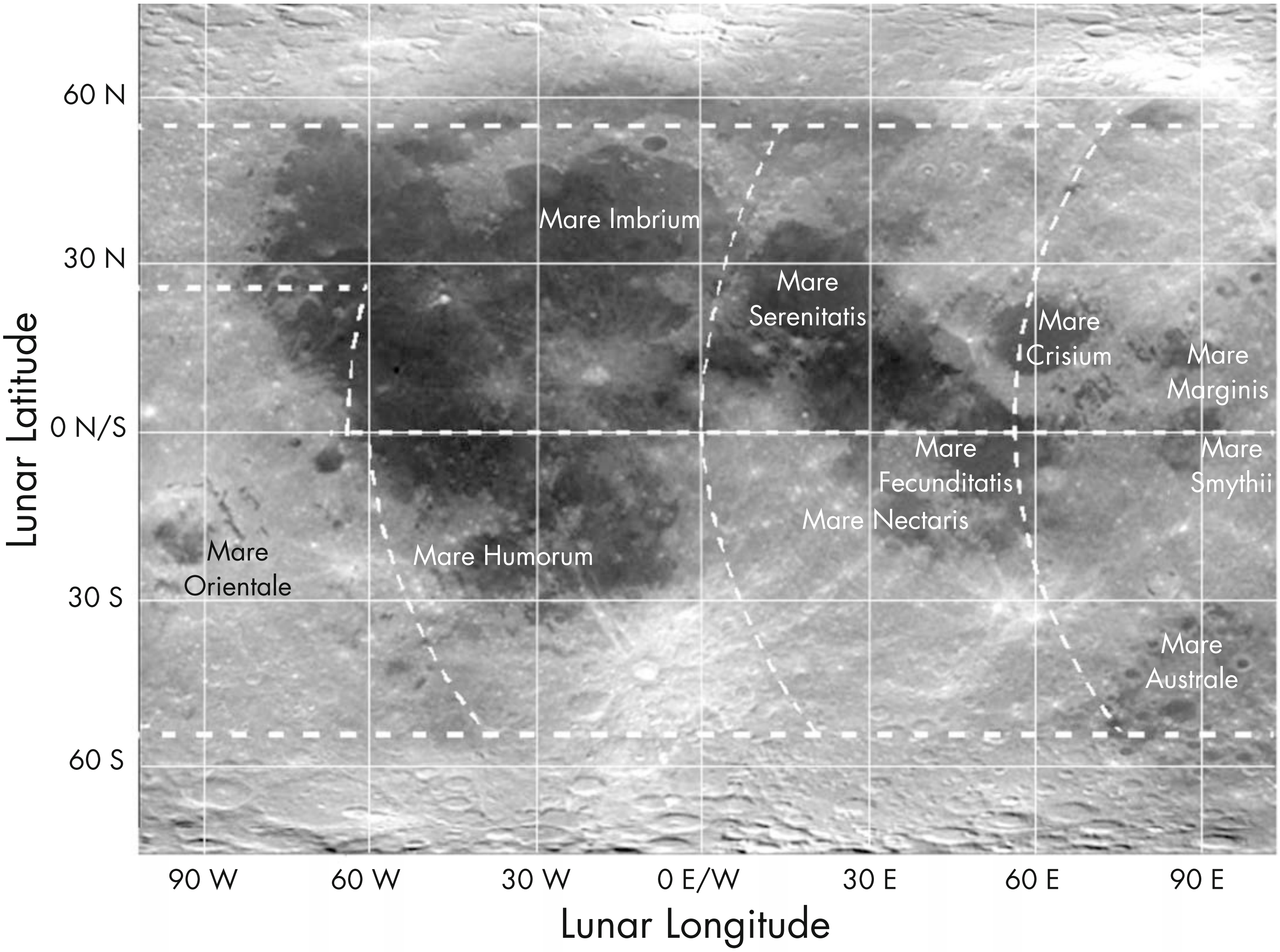


Figure 1.2. Map of the near side of the Moon, based on Clementine brightness data (NRL Web site). Region names are the same as in Figure 1.1; the north-south regional boundaries are curved to follow the Lunar Orbiter 4 photos, planned for uniformity of the sun angle. Mare Orientale and the features on the eastern limb are visible from Earth only at times of favorable libration and then are much foreshortened. Note that features in the polar regions are stretched horizontally in this Mercator projection.

as it appears from Earth when the Moon is full. This map shows features of the eastern and western limbs more clearly than they can be seen from Earth.

Figures 1.3 and 1.4 are polar projections, mosaics of Clementine scans of the polar regions. Clementine's brightness sensor continued to look almost directly down at the surface as the spacecraft passed nearly over the poles, but these maps show the topography of the features rather than the albedo because the sun is always low near the poles. Under such low illumination, crater walls throw shadows.

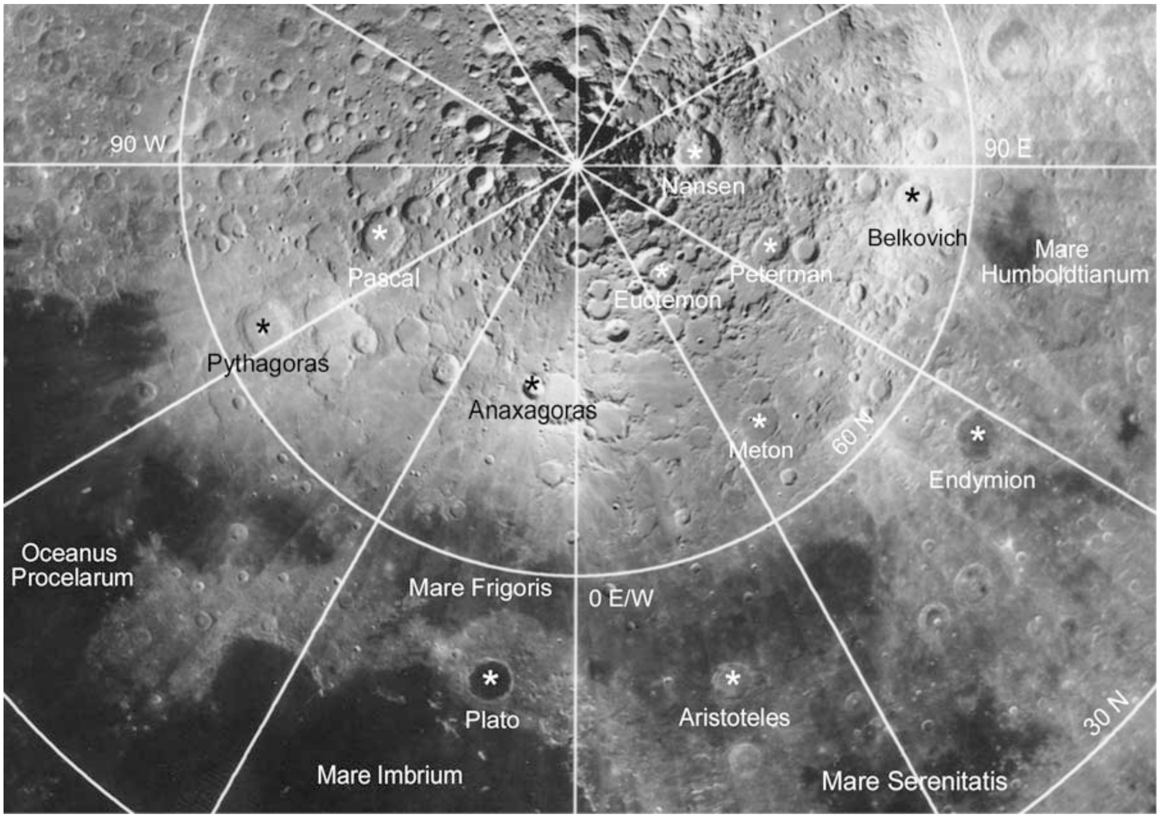


Figure 1.3. North Polar Region; near side is at bottom. This circumpolar projection is based on Clementine brightness data (USGS Web site). The boundary of the North Polar Region (not shown) is at 55° north latitude.

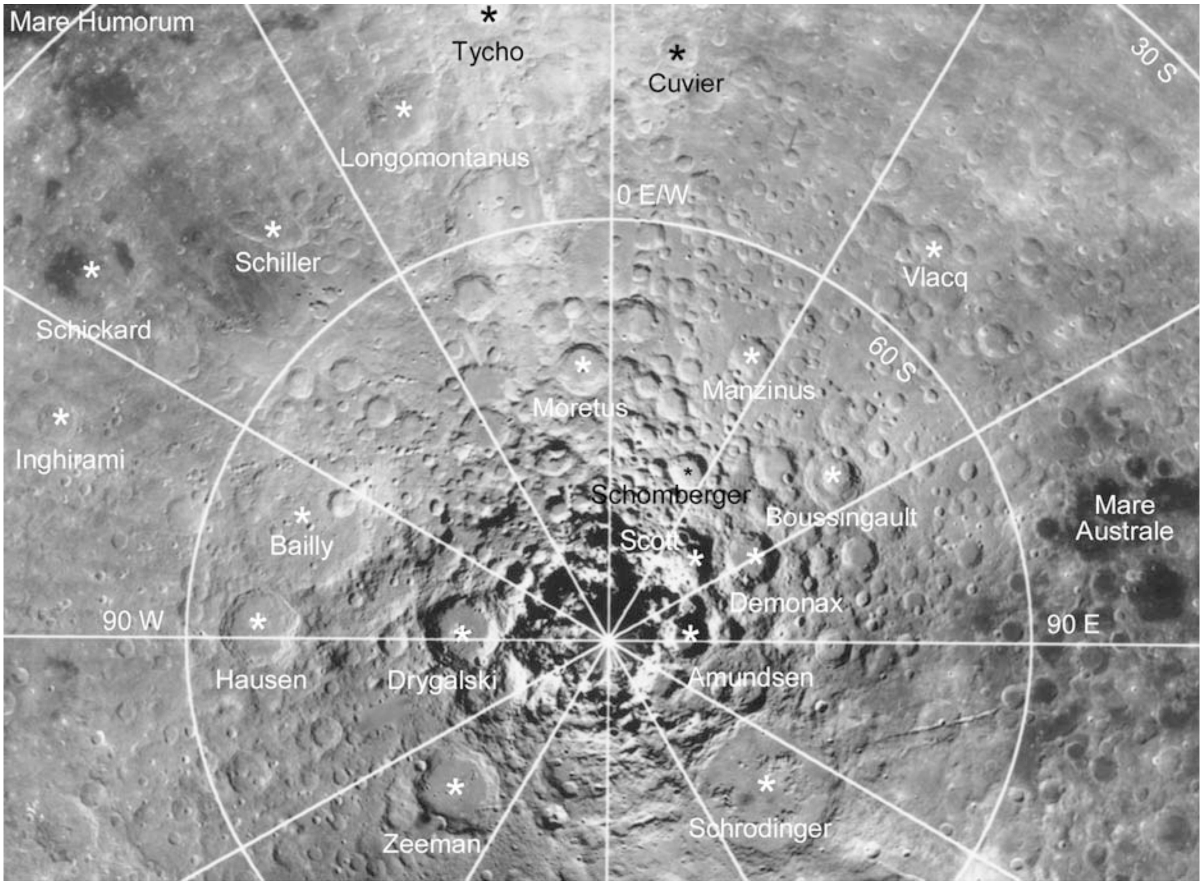


Figure 1.4. South Polar Region; near side is at top. This circumpolar projection is based on Clementine brightness data (USGS Web site). The boundary of the South Polar Region (not shown) is at 55° south latitude.

Chapter 2

Lunar Orbiter Mission 4

2.1. The Mission

Lunar Orbiter Mission 4 produced most of the photos in this book. This scientific mission was planned to systematically cover the nearside of the Moon. Extensive 1-meter (1-m) photography had been taken of the candidate Lunar Orbiter landing sites by missions 1 through 3, and the geologists wanted moderate-resolution photography (about 50 m) of so many large features on the nearside that a systematic survey mission was appropriate.

2.2. Mission Design

The layout of exposures from orbit depends on many aspects of the mission design. The spacecraft was placed in a high-inclination (nearly polar) orbit to provide full coverage of the nearside of the Moon. The orbit was such that the incidence angle of sunlight was about 20° (east to west; morning sun) throughout the photographic mission. While the 2-week photographic mission continued, the Moon revolved under the orbit with approximately uniform sun angle from the east limb to the west limb, presenting a new surface under the spacecraft at each orbital pass. The period of the orbit, the altitude of the spacecraft, and the width of the high-resolution image were coordinated so that high-resolution images taken on successive orbits overlapped by about 10% at the lunar equator, with more overlap at high latitudes. Successive high-resolution photographs taken on the same orbit were timed to overlap between about 10% as well. The overlap of photos avoids gaps in coverage, assists the construction of mosaics, and provides partial stereo coverage.

Most of the photos were taken vertically, except for those near the poles, where this could not be done because of the nature of the chosen orbit. The vertical photography minimizes foreshortening of the features to aid interpretation of the images.

Although all five of the Lunar Orbiters successfully provided extensive new photographic coverage, there were often problems, and Mission 4 was no exception. In this case, the problem involved erratic operation of the thermal door, a lens cap intended to protect the cameras from the cold of deep space when they were not actually making an exposure. Early in the mission, the optics chilled to the dew point of the moisture within the cameras and became fogged. The Boeing operations team and the science team designed a work-around. The thermal door was left open, but the spacecraft was oriented toward the sunlit part of the Moon so that the optics would be kept warm as much as possible.

Many photos of the eastern nearside were lost while the problem was analyzed and resolved, but additional exposures were made at the end of the mission to replace most of the missed coverage. These photos were taken on the "back side" of the orbit, with the spacecraft near apolune. As a consequence they are at lower resolution than the other photos and lighting is reversed, coming from west to east.

A schematic of the layout of the high-resolution images across the nearside of the Moon is shown in Table 2.1.

2.3. The Cameras

The Lunar Orbiter photography system consisted of two cameras, one with a short focal length and wide field of view (called the "medium-resolution camera") and one with a long focal length and a narrower field of view (called the "high-resolution camera"). The high-resolution field of view was centered within the field of view of the medium-resolution camera and was more than three times longer than it was wide.

The image motion compensation was provided by a feedback loop based on a circular scan of part of the high-resolution image. This mechanism, which had failed on Lunar Orbiter Mission 1 but worked flawlessly on all the later missions, moved the film platen in two dimensions to track the image.

Six fiducial marks ("sawteeth") for mapping were provided at the edge of the field of view. These marks have been trimmed from the images in this book.

2.4. The Film

The negative film was a fine-grained low-contrast 70-millimeter (70-mm) black-and-white standard Kodak product. The fine grain assured low graininess at high resolution. The low contrast (about 1 to 1) was selected to tolerate unknown variations in the brightness of the lunar surface at high resolution. A gray scale, resolution charts, and reticule marks (small crosses, barely visible on the images in this

Latitude Range	Photo Number																											
56 N–90 N				190	176		164		152		140	128		116		104		092		080	068				056				
27 N–56 N			189	183	175	170	163	158	151	145	139	134	127	122	115	110	103	098	091	086	079	074	067	062	055		177	165	024
0–27 N		196	168	182	174	169	162	157	150	144	138	133	126	121	114	109	102	097	090	085	078	073	066	061	054	181			018
0–27 S		195	187	181	173	168	161	156	149	143	137	132	125	120	113	108	101	096	089	084	077	072	065	060	053	046	039	027	
27 S–56 S		194	186	180	172	167	160	155	148	142	136	131	124	119	112	107	100	095	088	083	076	071	064	059	052	184, 045	038	178	009
56 S–90 S	193	179		166			154			130		118		106		094		082		070		058		044			005		

Longitude at Equator		95W	89W	82 W	76W	68W	62W	56W	49W	41W	35W	30W	23W	16W	10W	3W	4E	10E	16E	24E	30E	38E	43E	49E	57E	63E	70E	83E	90E

Table 2.1. Layout of the high-resolution photos from Lunar Orbiter Mission 4. Numbers are exposure numbers: the full title of each high-resolution subframe is LO4-XXXH1, -H2, or -H3, where XXX is the Photo Number shown above. See Chapter 4 for an explanation of the subframe suffixes H1, H2, and H3. Photos whose numbers are underlined were taken at the end of the mission, at higher altitude, and with reversed sunlight (from the west). Images shown next to each other in this table, either vertically or horizontally, overlap. All these photos are included in the online material, but some redundant photos have not been printed in this book. A table in each chapter shows the high-resolution photos for that region and indicates which ones are printed.

book) were exposed on the negative to assist in reconstruction and calibration of the images after scanning.

The film was developed in the spacecraft by the Kodak Bimat process. A second 70-mm film, its thick emulsion saturated with developing fluid, was pressed against the exposed negative by rollers. The two-film sandwich was stored in a buffer of rollers until development was complete and then they were separated.

Unfortunately, the Bimat process was susceptible to certain flaws. Small bubbles sometimes interposed between the negative and developer film, leaving various patterns on the negative. Also, rollers sometimes left bars across the film where the film was paused. These defects are easily distinguished from lunar features but unfortunately degrade a minority of the images.

2.5. Scanning and Reconstruction

The developed film was scanned by the available technology of the time; charge-controlled devices (CCDs) were still well in the future. Instead, a cathode ray tube (CRT) was used to provide a single scan line. Of course, this scan line could provide only the equivalent of about 800 pixels because of limitations on the phosphor grain and focus of the electron beam. This short (about 4 mm) scan line was aligned with the long dimension of the film. A mirror directed it across the 70-mm width of the film. A photocell detected variations in brightness as a measure of the density of the developed negative. After the width of the film was scanned, the film was advanced by a little less than the width of the scan line, providing overlap between scans to avoid gaps.

On the ground, the recorded signal was received at a Deep Space Network (DSN) site in California, Spain, or Australia, operated by the Jet Propulsion Laboratory (JPL). A CRT in the Kodak Ground Recording Equipment (GRE) transformed the signal into an image on 35-mm film. A segment of this film (called a framelet) represented a scan of the mirror across the 70-mm film in the spacecraft. There were two GREs, backed up by two Ampex video tape recorders (the original rotating head recorders) at each DSN site.

Once the 35-mm framelets were developed, they were trimmed by automatic machines and assembled on a light table. This was done at JPL (during the mission), Langley Research Center, and the Army Mapping Service. The assembled framelets were limited to about 60 centimeters (cm), 24 inches, in length; this was sufficient to fully reconstruct the medium-resolution frames, but the long high-resolution frames were reconstructed as a set of three subframes. Contact prints were made from these reconstructed frames and subframes; these are the primary records of the photos. Second-generation images at the same scale are stored at NASA Regional Planetary Image Facilities around the world.

The Army Mapping Service often used the tape recorders to adjust the contrast and brightness of the surface. Typical images are at a contrast of about 3 to 1 relative to the brightness variations of the lunar surface. This contrast exaggerates the brightness variation of topography, compressing the variations in the brightest and darkest parts of an image, but also amplifies the inherent brightness variation of rays and ejecta blankets from craters.

2.6. Scanning Artifacts

The complex deconstruction and reconstruction processes, involving multiple electrical, mechanical, optical, photographic, and manual processes, introduced several types of scanning artifacts. Thin bright lines, leaks from the light table between framelets, appear in most reconstructed frames and subframes. Sometimes negative framelets were assembled on the light tables, so these lines are dark on the positive prints. Variations in sensitivity of the phosphors on the two CRTs used in the process (one in the spacecraft and one on the ground) and possibly variations in the sensitivity of the rotating heads of the tape recorder cause systematic brightness variations in the series of framelets. This effect, which is quite distracting, is sometimes called the “venetian blind effect” because it appears as if the image has been projected on a set of venetian blinds.

2.7. Cleaning the Images

A computer program written by the author specifically for this purpose has cleaned the photographs in this book. Appendix A, in the online material, describes this process in detail. As a result, residual scanning artifacts are only occasionally visible in the printed photos. However, artifacts associated with the development process in the spacecraft remain.

Chapter 3

Overview of the Near Side of the Moon

3.1. Origin of the Moon

To understand these photos, one must understand the Moon, its geography, and the factors that have influenced its near side surface. The origin of the Moon was a matter of vigorous debate until about 12 years after the last Apollo mission. In 1984, after many years of analysis of the 300 kilograms (kg), 800 pounds, of rocks and soil returned by Apollo and Luna missions, a consensus was struck that has lasted for the subsequent 20 years. The following narrative retells this consensus origin story, without attempting to review the debate of alternative theories. The curious reader is encouraged to review the references.

As unlikely as it seems, another planet perhaps about the size of Mars and formed in the general orbital vicinity of Mars had its orbit perturbed by some unknown event and struck the early Earth a glancing blow. Just as a small car absorbs much of the energy of an impact with a large truck, the smaller planet, known as Theia, was partly vaporized, partly melted, and largely pulverized and thrown into space. Some of Theia escaped from Earth or fell to Earth, but most of it ended up in an orbit near Earth. Modeling suggests that much of the core of Theia, relatively dense, was pulled into Earth and joined Earth's core.

The pulverized and molten orbital components in near-Earth orbit (perhaps about four Earth radii according to the computer simulations) coalesced. As a result, the resulting body was heated by gravitational energy, supplemented by radioactive energy, and largely melted into a deep magma ocean. Part of Theia had become the Moon.

The strong tidal forces generated by the orbital proximity of these two bodies caused a loss of energy in the total system and a transfer of angular momentum between them. The Moon's rotation relative to its revolution about Earth stopped, so that the near side of the Moon always faces Earth (synchronism). The Moon's orbital radius increased, absorbing some of the angular momentum of the early Earth; that change slowed Earth's rotation to its current 24-hour period.

Most of these events occurred within the first 500 million years after the Earth had itself coalesced and took place in a relatively short interval, perhaps 100 million years (the coalescence of the Moon could have taken place within weeks after the impact). Of course, the chaotic impact would have thrown material into many orbits, some of which may have taken very much longer to impact the Moon. The heavily cratered surface reflects the arrival of many such delayed impactors as well as new arrivals from the solar system after the outer surface had cooled and become solid. The rate of arrival of these later impactors is a matter of intense interest. There is some evidence of a quiet period followed after a time by a brief period of a high rate of arrival, sometimes called the cataclysm to suggest a major chaotic event in the Solar System.

As a result of this history, our Moon is somewhat unusual in the solar system. It contains much the same chemical elements as the other rocky planets, but its crust contains a distinctly different quantitative distribution of those elements. The mineralogy is often familiar to geologists from their terrestrial experience, even to the point of the relevance of an extensive descriptive vocabulary. But the Moon is (to our current knowledge) unique in having experienced two distinct melting phases, one when Theia was formed as a planet and one when the Moon was formed from a part of Theia's debris. Each melting phase resulted in differentiation of the minerals, as heavy material sank and light material rose in two different gravity fields and two different thermal domains. A set of elements called KREEP that is concentrated when massive quantities of material are melted and solidified are unusually abundant in some maria. Erupting magma carried the doubly concentrated material to the surface.

3.2. The Near Side Versus the Far Side

The synchronization of the Moon's rotation with its revolution in the intense early tidal environment established that the near side would always face Earth and be the visible side (visible to humanity before the mid-twentieth century, that is).

Measurements of the Moon's gravitational field have established that the depth of the crust is less on the near side than on the far side. This implies that, for a given size of impactor or strength of internal processes, penetration of the crust is more likely on the near side.

3.3. Mare and Highlands

The Moon exhibits significant differences between the near side and near side. In particular, much more mare material is found on the near side. Mare material is the relatively dark material visible on the face of the Moon, contrasting with the more reflective highlands. It is made of relatively heavy minerals that have risen from the mantle of the Moon, below the crust. How can we explain this paradox of the rise of heavy materials through light materials? The answer lies in the decrease of density that accompanies heating. The material becomes lighter than crust because it is hotter. When it becomes exposed, it quickly cools and is locked in place by the rigidity of a surface exposed to the cold of deep space half the time. The association of most mare material with positive gravity anomalies called mascons (an abbreviation of "mass concentrations") also reveals their high density. Both remote sensing and analysis of lunar rock and soil samples returned to Earth have established that the materials of the maria are heavier than highland materials because of their higher proportion of iron and magnesium.

Historically, the distinction between mare materials and the more pristine highland materials (so called because they are in fact higher than mare, but also resemble terrestrial highlands in their relatively rugged topography) has been very important, because elementary observation distinguishes the dark, flat mare from the relatively bright, rugged, highlands.

3.4. Basins

As understanding grew, it no longer appeared that maria are fundamental to the structure of the lunar surface. Rather, it seems that mare regions are secondary to the formation of large basins by impactors that are large enough to compromise the integrity of the lunar crust. Such basins allow heavy, dark minerals to rise through the fractured crust from the hotter upper mantle below the crust. The basin associated with a mare region can be much larger and has a much more extensive effect on lunar topography. Typically, only the interior of the depression formed by the basin impactor floods (or partly floods) with mare material. However, deposits ejected from the basin can extend for a distance that is a multiple of the crater radius. Such basin ejecta blankets cover or partially cover much more area than the central depression.

Basins that have been flooded with lava to form a mare are named for the mare they contain (the Orientale Basin is named for Mare Orientale). Basins that lack mare fill are named for two craters that happen to be superposed on the basin (the Schiller-Zucchius Basin).

Because basins are more fundamental than their included maria, this introductory section emphasizes basins as landmarks for the geography of the Moon.

3.5. Landmarks for Geography

Strictly speaking, perhaps we should say selenography or lunography (writing about the Moon) instead of geography (writing about the Earth), but the term geography seems to be more evocative of what we mean. Geography is not geology: it refers to landforms and their relation, without emphasis on the mineralogy or the formation process of the landforms. It is difficult to grasp a good mental image of the major features of the Moon in terms of their global distribution and relationships. There is no equivalent of the organization of terrestrial geography in terms of continents and oceans that are so useful in establishing a mental and visual image of Earth.

This section introduces a high-level list of eight regions, centered on interesting, memorable focal points. They are chosen for broad distribution, to ensure roughly uniform coverage of the lunar near side. Each region is sufficiently small to support photographic and other images with reasonable distortion. The proposed regions, and the latitude and longitude of their focal points, are shown in Table 3.1.

Region	Latitude	Longitude
Orientale Basin Region (includes Grimaldi Basin)	19° S	95° W
Humorum Basin Region (includes Nubium Basin)	24° S	39.5° W
Imbrium Basin Region (includes Oceanus Procellarum)	35° N	17° W
Nectaris Basin Region (includes Tranquillitatis and Fecunditatis Basins and nearby highlands)	16° S	34° E
Serenitatis Basin Region (includes the Crisium Basin and nearby highlands)	17.5° N	58.5° E
Eastern Basins Region (the **Smythii Basin**, the Humboldtianum Basin, the Australe Basin, and intervening highlands)	2° S	87° E
North Polar Region (**North Pole**)	90° N	NA
South Polar Region (**South Pole**)	90° S	NA

Table 3.1. Landmarks for the regions of the Moon and their coordinates. Landmarks are in bold print. Note that the center of the Orientale Basin is actually around the western limb; it is included because much of the basin and its ejecta are on the near side.

Basins were chosen as many of the focal points because they are major modifiers of the surface geology, not only through their central rings and maria but also through their ejecta blankets. Specific basins were chosen as much for uniformity of spacing around the lunar globe as for size or interest. In addition to basins, the North and South Polar Regions were included because of the special significance of the shadowed craters in those regions and also because the photographic quality is quite different.

3.6. Descriptions of Landmark Regions

The following sections summarize the characteristics and prominent features of each region. Only enough description is included to differentiate the regions from each other; these descriptions are not intended to be comprehensive or to discuss the geology or stratigraphy of the regions in detail. No attempt is made to establish precise boundaries between the regions: that would be like attempting a precise boundary between the Atlantic and Arctic Oceans. These regions are proposed to serve as a method to organize imagery, an alternative to latitude and longitude, and no representation is made that they are of fundamental geologic or cartographic significance.

Orientale Basin Region

The Orientale Basin, with its central mare and multiple rings, has been called the archetype of basins because it is both large and relatively recent. Consequently, its structure is very clear. The region includes the smaller Grimaldi Basin and craters Schickard and Bailly.

Humorum Basin Region

The Humorum Basin region includes the Nubium Basin and craters Pitatus and Tycho. This region is particularly interesting for understanding the interactions of different types of features such as the manner in which mare floors encounter crater rims and highlands. The Fra Mauro Peninsula is an example of such a feature.

Imbrium Basin Region

The Imbrium Basin and its ejecta blanket dominate much of the near side. The region includes Oceanus Procellarum, and other neighboring maria: Vaporum, Serenitatis, and Frigoris. Craters in this region include Kepler, Copernicus, Archimedes, and Aristoteles. This entire region is rich in maria, ejecta blankets, and rays of craters. It also has a number of features (such as Vallis Schroteri) that are associated with the flooding of the mare floors.

Nectaris Basin Region

The northeastern part of the Nectaris region is rich in maria, including Fecunditatis and Tranquillitatis as well as Mare Nectaris. To the west and south, the region includes extensive highlands. To the west, parts of these highlands are covered with ejecta from the Imbrium Basin.

Serenitatis Basin Region

This region includes the Serenitatis and Tranquillitatis Basins, the northern part of the Fecunditatis Basin, and the western part of the Crisium Basin. The region shows the interplay of overlapping basins.

Eastern Basins Region

From Earth, this region covers the eastern limb (edge, as we see it) of the Moon. It includes the eastern part of the Crisium Basin, the Australe Basin, the Smythii Basin, and Mare Marginis.

North Polar Region

The heavy shadowing in both polar regions obscures both photography and passive spectral measurements, especially for the floors of basins and craters. The near side part of the region and the North Pole itself are largely covered with ejecta from the Imbrium Basin. Craters in this region include Nansen, Shackleton, and Anaxagoras. The region includes the Humboldtianum Basin.

South Polar Region

The South Polar Region is dominated by the rim of the South Pole–Aiken Basin and several smaller basins such as Schrodinger, Planck, and Bailly. Permanently shadowed crater floors in this region (as well as in the North Polar Region) are believed to harbor deposits of hydrogen or water ice. Permanently sunlit crater rims nearby are proposed as sites for solar power.

3.7. The Ages of the Lunar Features

An interesting attribute of a lunar feature is the time it was formed. The ages of different features on the Moon are inferred from several sources.

Estimating Ages

The most precise ages are determined from measurement of isotope ratios in our precious rock samples; association of the samples with specific features establishes their time of formation.

When rock samples are unavailable, geologists resort to less precise measures. For example, sharply defined features are inferred to be recent because meteorite bombardment softens the edges of features by a process called mass-wasting. Also, counts of crater densities can be used to estimate the time a surface has been exposed to bombardment.

Very often, even though absolute time cannot be determined, the sequence of formation can be determined. For example, ejecta from a basin may overlay a crater or lava from a mare may flow into a crater. Such layering and the branch of geology that studies it are called stratigraphy.

Named Age Ranges

Systematic study of stratigraphy, together with other clues, establishes a chain of evidence that leads to relative ages and estimated age ranges of most of the features of the Moon. These age ranges are named for associated archetype features. In order from the oldest to the youngest, the ranges are the Pre-Nectarian, Nectarian, Early Imbrian, Late Imbrian, Eratosthenian, and Copernican Periods or Epochs. Geologists use the term “epoch” as a subdivision of a period. The Early Imbrian and the Late Imbrian Epochs are subdivisions of the Imbrian Period. The boundary between the Pre-Nectarian and Nectarian Periods is the time of the impact that produced the Nectaris Basin. The Nectarian Period ends with the event that produced the Imbrium Basin. The Early Imbrian Epoch spans the time between the Imbrium and Orientale events.

Large basin-forming events are used to divide these time periods because such events spread their deposits so very far, as much as halfway around the Moon. This method allows us to relate many other features to large basin events by analyzing interactions with the widespread deposits. Because Orientale is the last big basin, however, the younger age ranges are based on large craters. The Eratosthenian Period is next, and then the Copernican Period (this interval is open ended; we live in the Copernican Period). These last two periods are not distinguished by bounding events, but on the degree of degradation of craters and their ejecta (especially the fading of rays) as they are exposed to further impacts and to the solar wind.

Chapter 4

Organization of the Photos

4.1. Grouping by Landmark Regions

Each chapter that follows displays images of a particular landmark region. A few medium-resolution frames are shown for each region to provide an overview. Only a few of the medium-resolution photos are presented because they have a high degree of overlap. The high-resolution photos are selected in rectangular blocks so that a reasonable degree of organization is imposed. The relation of the photos and their assignment to regions is shown in a table in each chapter.

4.2. Order: West to East and South to North

The regions are presented from the west limb around the nearside to the east limb; that is because Orientale, the newest and clearest basin and Imbrium, the largest nearside basin, are both toward the west and are should be viewed before the other regions. Keep in mind, however, that the mission and the rising sun move from east to west. To minimize confusion, the photos covering a particular longitude range are presented from south to north (in the order most of the photos were taken, and in order of the numbering convention for those photos). A few of the photos in the Eastern Basin Region were taken in reverse of the usual orbital direction, to compensate at the end of the mission for photos lost at the beginning of the mission.

4.3. Clean and Annotated Images

One page is provided for each high-resolution subframe or frame. The cleaned image is shown on the right side of each page and an overlay with the major features of the image labeled is on the left. A title line shows the photo number, lighting conditions, and spacecraft altitude at the time of the exposure. Latitude and longitude marks and a scale bar are shown in the annotated overlay. The scale bar is derived from the size of prominent surface features, as listed on the USGS Web site. Except for the apostrophe, diacritical marks in feature names have been omitted in both photos and text because they are not supported in the software used to annotate the photos. A list of names with diacritical marks as guides to pronunciation is in the online material.

4.4. High-Resolution Frames and Subframes

In most cases, subframes (designated H1, H2, and H3) are displayed. In some cases, the three subframes are reassembled as a full high-resolution frame (designated H). This is done either to show the relationship of the features across the full exposure or because the features displayed are deemed to be of relatively little interest, usually because of similarity to their surroundings. All subframes are presented at full detail in the online material.

4.5. Discussion Notes

The photo pages contain notes that point out and discuss relevant aspects of the features and their relationships. These notes draw on an extensive lunar literature to include aspects of the stratigraphy, geology, and possible formation and modification processes of the features.

4.6. Online Extra Material

The online extra material contains:

- All high-resolution subframes from Lunar Orbiter Mission 4 (JPEG files)
- All medium-resolution frames from Lunar Orbiter Mission 4 (JPEG files)
- An index of nearside features whose names are recognized by the International Astronomical Union (IAU)
- A description of the process used to clean up scanning artifacts
- Source notes related to individual photos

The feature index includes all the near side features in the master IAU list maintained by the USGS that are larger than 6 km. Several smaller features and some far side features near the eastern limb, the western limb, the North Pole, or the South Pole are also included. Each of the features listed in the index can be found in the annotated photo (and the photo number) on the indicated page.

Chapter 5

Orientale Basin Region

5.1. Overview

Orientale, the Archetype Multi-Ringed Basin

Figure 5.1 shows the spectacular Orientale Basin, the newest large basin on the Moon. It is often called the archetype of basins because it reveals the structure of basins so clearly. Like typical large basins, it is multi-ringed; that is, there are a number of concentric rings both inside and outside of its major raised rim. Mare surfaces have been formed from lava seeping up from below its central floor. Additional lava has seeped up into the low troughs between the external rings.

Although the Orientale Basin has many features in common with all basins, it must be considered that there are significant differences between basins as well. The detailed structure of a basin depends on the nature of the target material. Orientale has formed in an area of thick, somewhat uniform crust. Although there are no major basins in its immediate vicinity, large craters have been identified that influenced its detailed structure.

Orientale Basin and its included Mare Orientale are located on the western edge of the Moon, the edge that rises and sets last. Terrestrial astronomers glimpse its eastern rings as the libration of the Moon turns that edge a bit toward us. Spacecraft Zond 3 photographed it in 1965 at essentially Earth-based resolution. However, the Lunar Orbiter 4 coverage showed the magnificence of its structure at a much higher resolution.

These photos created a major paradigm shift in minds of geologists who had been debating whether volcanism or impacts dominated the lunar surface. This newest basin had a fresh ejecta blanket, revealed in detail by the high-resolution photos. The unavoidable conclusion was that many geologic units whose origins were debated were in fact formed by ejecta, not only from Orientale but also from larger, older basins such as Imbrium. This insight was confirmed and strengthened by the pervasive discovery of impact breccia in the rocks returned by Apollo missions. Such rocks are formed by the hypervelocity shock of impacts welding preexisting rock fragments from diverse sources into larger rocks. They show a diverse set of shock effects, from changes of crystalline structure to partial or complete melting (Wilhelms, 1987).

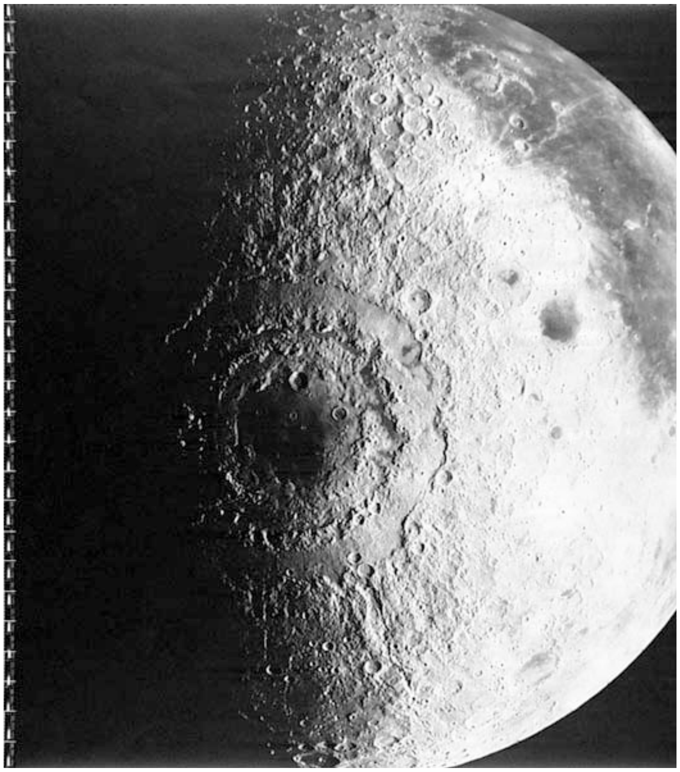


Figure 5.1. LO4-187M. The Orientale Basin is the archetype of multi-ringed basins. The lava flow of Mare Orientale is in the dark center of the concentric rings. The dark mare surface to the upper right is Oceanus Procellarum, the largest deposit of mare on the Moon. The small dark circular feature is a mare deposit on the floor of the 440-km Grimaldi Basin. The bright rays in the upper right corner of the photo radiate from Glushko, a small crater near Oceanus Procellarum, not from Orientale.

A remarkable property of multi-ringed basins is the regularity of the radii of the concentric rings. Such rings are found not only on the Moon (where there is evidence of about 60 multi-ringed basins), but also on Earth, Mercury, Mars, the Jupiter moons Ganymede and Callisto, and the Saturn moons Tethys and Rhea (Spudis, 1993). Measurements of the rings of basins on all these bodies fit a specific relationship; successive rings, both internal and external to the topographic rim (the ring of highest elevation also called the main ring), have radii in the ratio of the square root of 2.

This relationship, equivalent to the doubling of the area of each successive ring, is very regular, but has no consensus theoretical basis at this time.

Crater Morphology as a Function of Size

Small impact craters do not have such concentric rings. The smallest craters have a transient cavity that is nearly hemispherical. The transient cavity is the zone of target material that was melted and pulverized by the hypervelocity impact. Some of this material is ejected, with most of it landing within one radius of the transient cavity from the rim of the transient cavity. This rim is a single topographic ring. Medium-sized craters have a distinctive central peak; the focused sound wave rebounding from the mass of pulverized and compressed material has lifted material nearly vertically, and it forms a mountain in the center of the crater. As the diameters of lunar craters exceed about 300 km (200 miles), the central peak breaks up into one or more internal rings, and external rings form as well. It is these very large craters that we call multi-ringed basins, or basins for short. The bottoms of large craters may penetrate near or through the boundary between the crust and the mantle.

Surroundings of the Orientale Basin

To the north and west, the ejecta blanket from Orientale has been deposited on highlands. To the northeast, the ejecta fell on the surface later covered by the mare material of Oceanus Procellarum. To the east and south lie highlands interrupted by other, smaller basins: Grimaldi and Humorum. The flank of Grimaldi shows fine striations radial to Orientale, so it must have formed earlier. Similarly, the Humorum Basin predates Orientale.

Figure 5.2 shows a mosaic of the eastern sector of the Orientale Basin Region, illustrating the structure of its rings.

5.2. High-Resolution Images

Table 5.1 shows the high-resolution images of the Orientale Basin region in schematic form.

The following pages show the high-resolution subframes from south to north and west to east; that is, they are in the order LO4-194H, LO4-195H1, LO4-195H2, LO4-195H3, LO4-186H1 . . . LO4-161H3. Note that the photos taken on a given orbit are presented in order; both frame and subframe numbers increase in the same order as the pages of this book. However, in moving from west to east to a new orbital sequence, the numbers decrease.

LO4-194H has been assembled as a complete frame. It shows the range of Orientale ejecta from the topographic rim to one radius away from that rim. In addition, it illustrates how subframes are contiguous parts of high-resolution frames. Similarly, LO4-169H and LO4-161H are displayed as full frames.

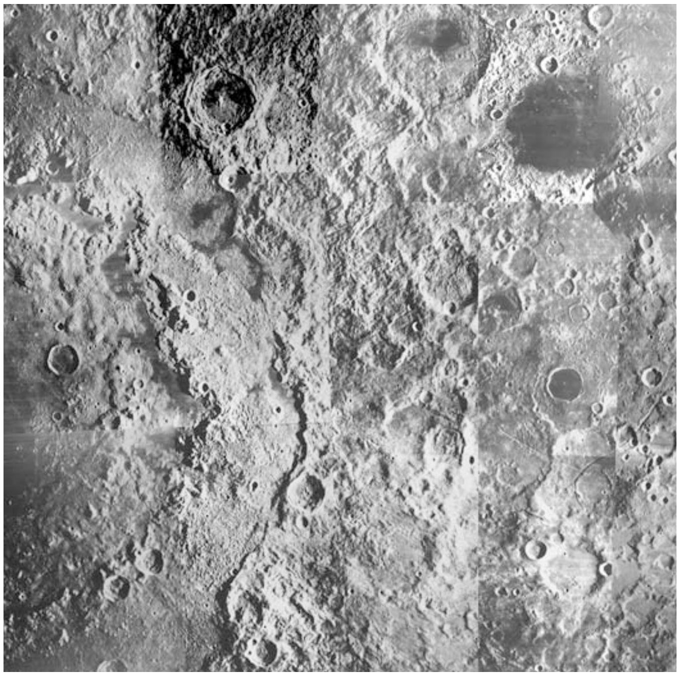


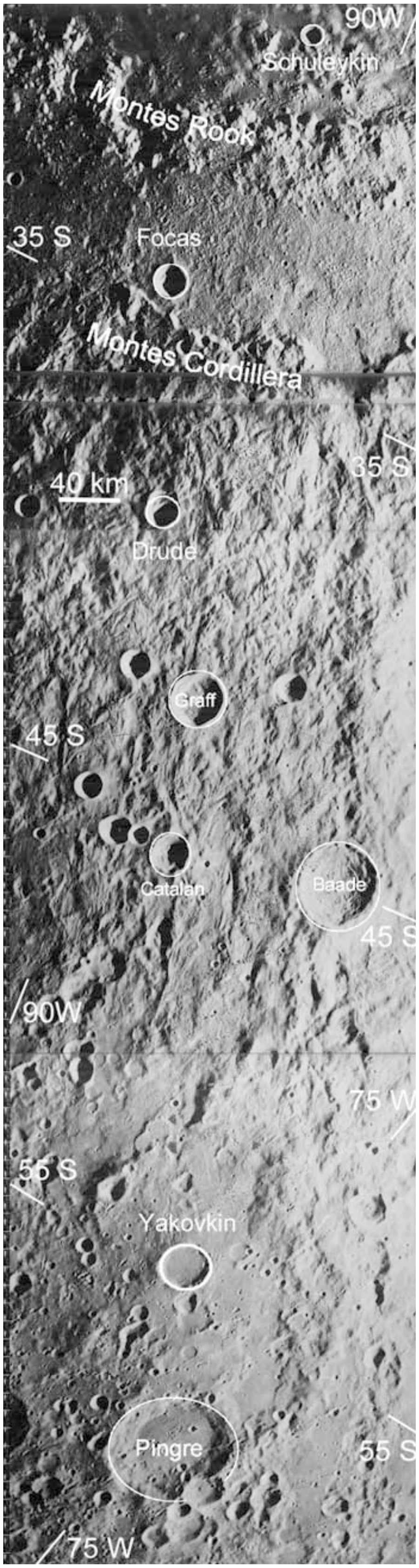
Figure 5.2. Mosaic of Lunar Orbiter 4 high-resolution photos of the Orientale Basin, from the central mare at the left out past the concentric rings to the right. Dark mare material is found not only in the central part of the basin, but also in the troughs between the rings. Note the striations in the ejecta blanket radiating from the central portion of the basin. They have a stronger appearance to the northeast and southeast rather than directly toward the east. Because of the direction of solar illumination, ridges oriented in the east-west direction do not cast shadows. The smaller Grimaldi Basin in the upper right of the mosaic shows both a topographic ring that has contained most of the mare lava and a lower outer ring.

Subframes LO4-180H1 and LO4-167H1 are not printed in this chapter because they are redundant with the subframes to their east and west and show no additional features. The base photos are included in the online material.

Latitude Range	Photo Number							
27 N–56 N			189	183	175	170	163	158
0–27 N			188	182	174	169	162	157
0–27 S		195	187	181	173	168	161	156
27 S–56 S		194	186	180	172	167	160	155
56 S–90 S	179			166			154	

Longitude at Equator		95 W	89 W	82 W	76 W	68 W	62 W	56 W

Table 5.1. The cells shown in white represent the high-resolution photos of the Orientale Basin Region (LO4-XXX H1, -H2, and -H3, where XXX is the Photo Number; LO4 means Lunar Orbiter Mission 4). The Imbrium Basin Region is to the northeast, the Humorum Basin Region is to the east, and the South Polar Region is to the south. The far side is to the west. The next number after LO4 is the exposure number, which increased as the mission progressed from east to west.



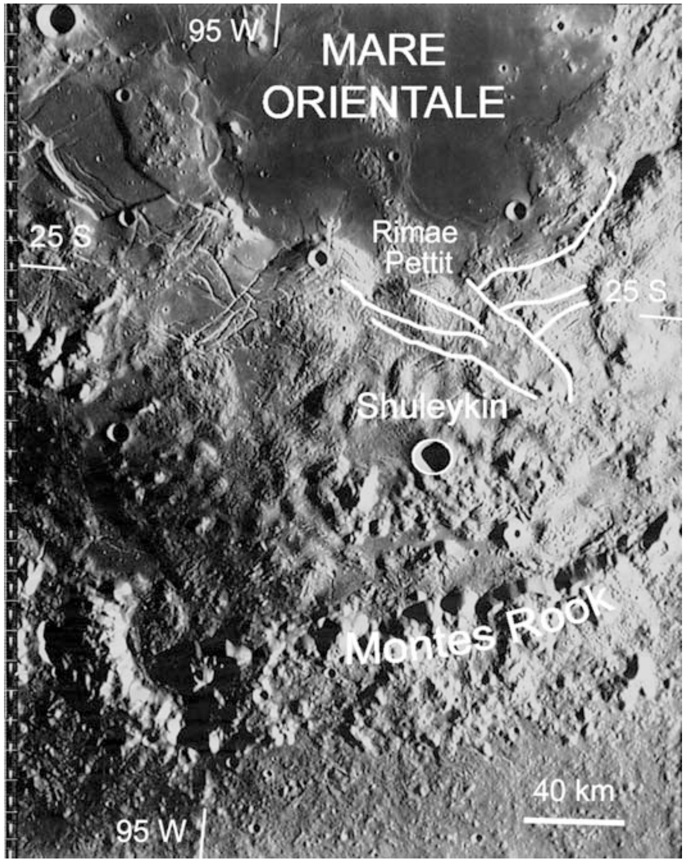
LO4-194H

Sun Elevation: 16.10°
Altitude: 3002.79 km

This full high-resolution frame shows the inner Orientale Basin at the top. Montes Cordillera is the topographic ring. Its scarp bounds the floor of the basin. The arc of Montes Rook shown here is the first inner ring of the Orientale Basin.

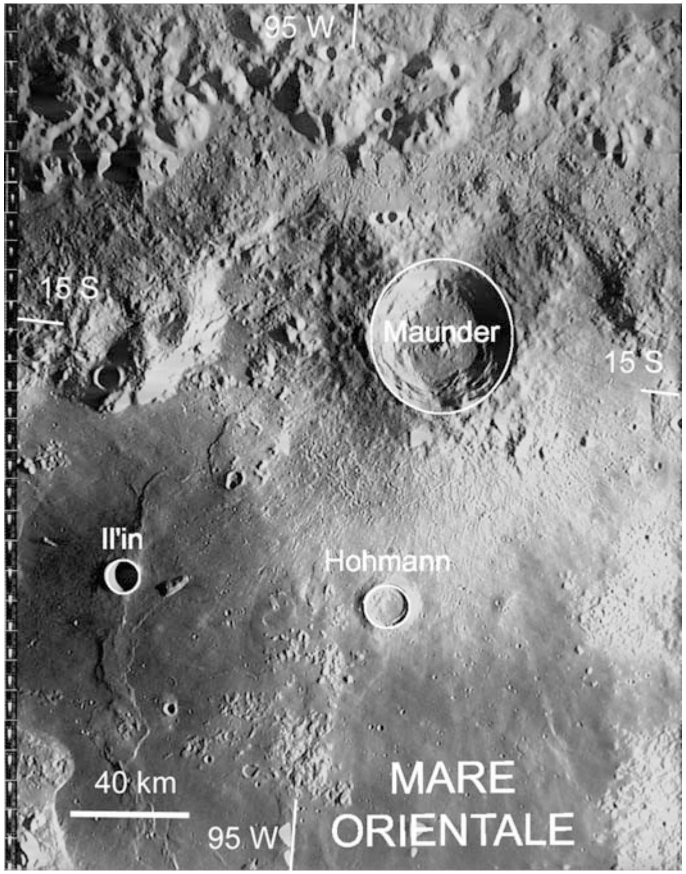
Striations show a heavy deposit of ejecta (the Hevelius Formation) from the inner Orientale Basin to the south. The character of the ejecta changes from the heavy, striated inner Hevelius Formation to the lighter, more uniform outer Hevelius Formation about 440 km away from the rim of the Montes Cordillera ring (930 km in diameter). Graff, Catalan, and Baade have been covered with a heavy deposit while Yakovin has received a lighter deposit. Several other craters in the 10- to 30-km range (probably secondaries from Orientale) left deposits of fine ejecta outside their rims.

The crater Hausen (out of the picture to the southwest) has more recently deposited chains of small secondary craters that can be seen on the floor of crater Pingre and outside its rim. Pingre may lie on the floor of an older basin called the Pingre-Hausen Basin. The large semicircular ridge east and north of Pingre is the boundary of that basin.



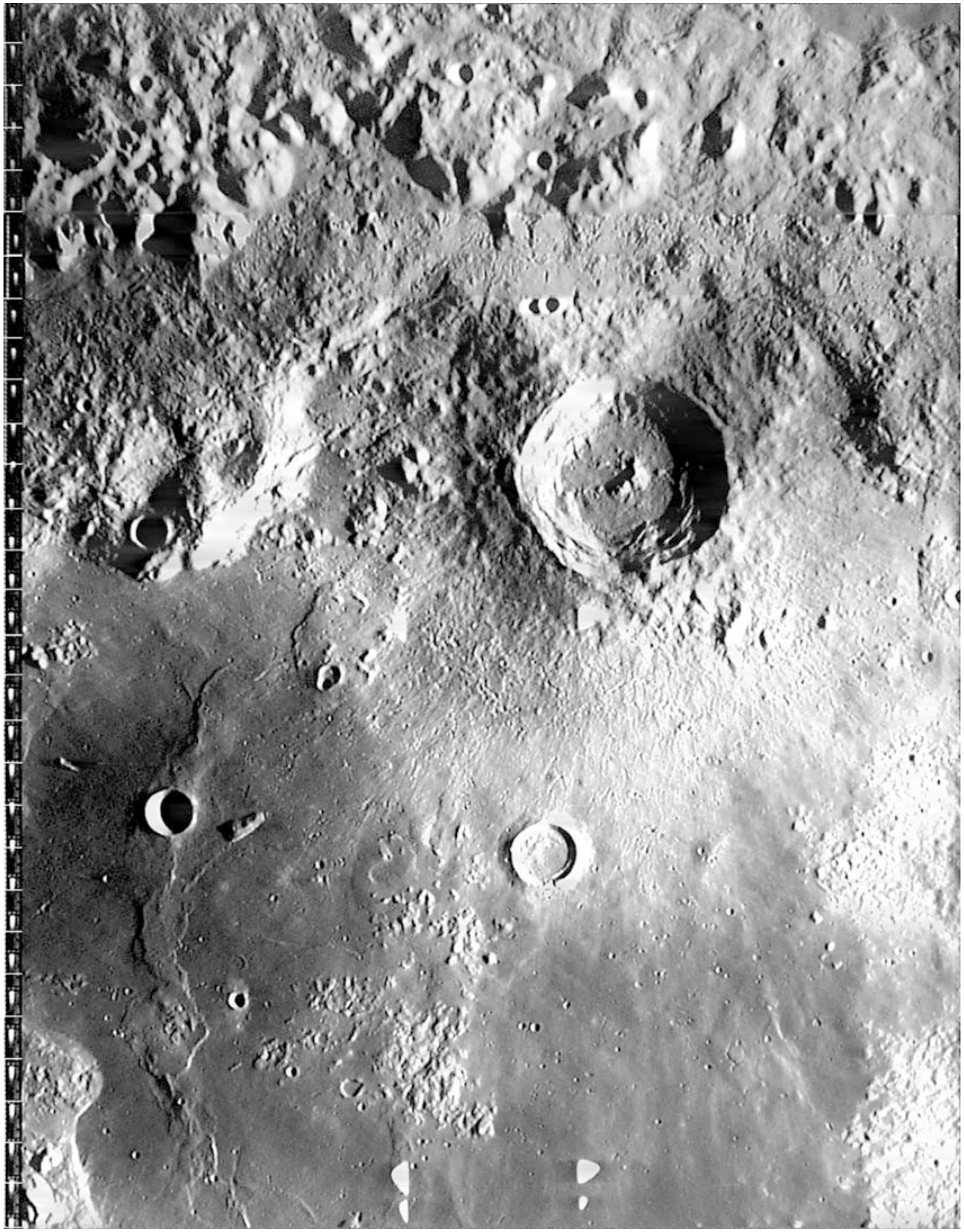
LO4-195H1 Sun Elevation: 14.50° Altitude: 2721.44 km

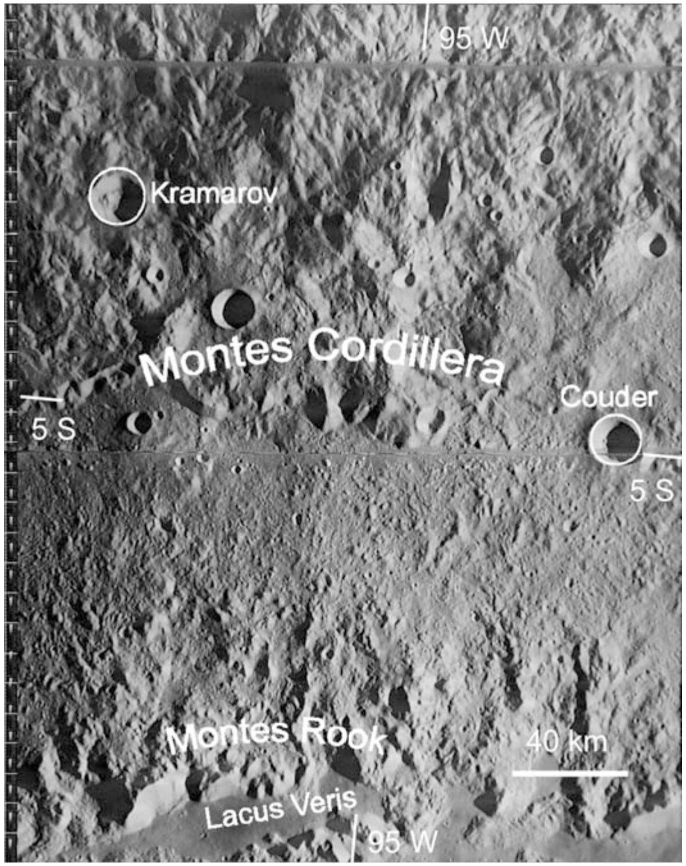
The inner Orientale Basin was flooded long after the impact by mare lava rising from below. Multiple shorelines appear in this photo, suggesting that the lava rose to a certain level and then receded, as is common on earth. A network of radial and circumferential fractures surrounds the border of the lava. The surface between the fractures is often very smooth. This area is called the Maunder Formation, named for the genetically unrelated Maunder crater north of Mare Orientale (see LO4-195H2). The Maunder Formation has been interpreted as the melt sheet of the basin. The fractures relieve stresses that could have been associated with cooling of the melt sheet, settling of underlying pulverized material, or flooding of the mare. Other basins may have had similar melt sheets that were completely hidden by a later covering of mare lava.



LO4-195H2 Sun Elevation: 14.50° Altitude: 2721.44 km

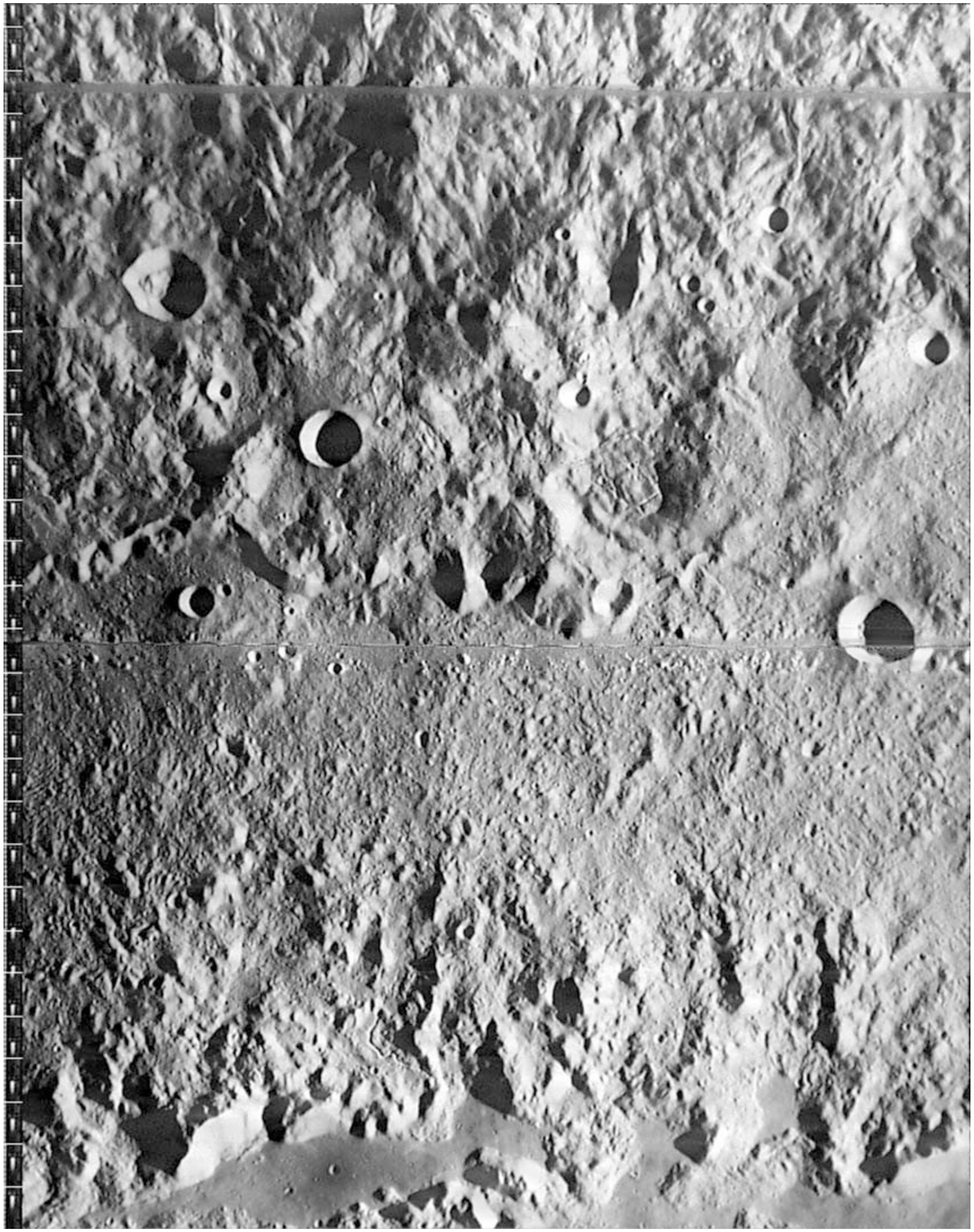
Maunder was obviously formed after the mare floor had solidified. It has a typical profile for a large (55-km) primary crater, with a well-formed central peak, terraced walls, an ejecta blanket with radial furrows, and a field of secondary craters. The melt sheet of the Maunder Formation (named after the crater) appears to have partially collapsed at either side of the Maunder crater, possibly due to the impact shock. The ejecta of some post-mare craters such as Il'in appear to have flow characteristics, as if they impacted while the mare was still semimolten or still hot enough to be melted by the impacts. See the note for Kopff with photo LO4-187H2.

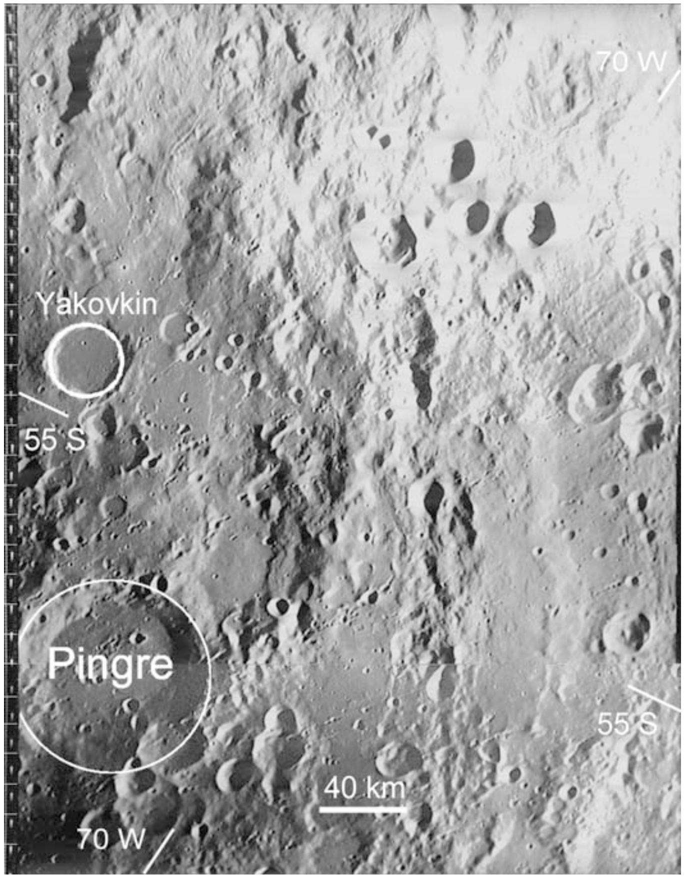




LO4-195H3 Sun Elevation: 14.50° Altitude: 2721.44 km

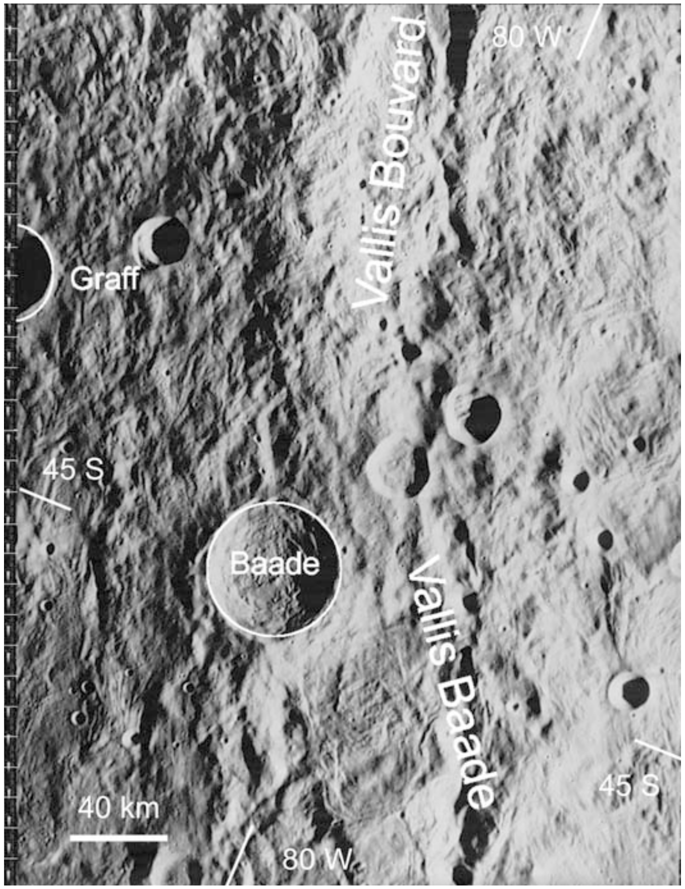
The area in this photo shows many differences in structure and texture. Compare the smooth mare lava of Lacus Veris with the rugged cliffs of the inner ridge of Montes Rook and the knobby, flat Montes Rook Formation between Montes Rook and Montes Cordillera. Note the steep scarp of the rim of Montes Cordillera and the thick, ropy nature of the inner Hevelius Formation of basin ejecta beyond Montes Cordillera. Craters Kramarov and Couder, about the same size and age (judging by rim sharpness), show an interesting contrast in structure. Kramarov, impacting the Hevelius Formation, has thrown more ejecta and part of its wall has collapsed. Couder, impacting the Rook Formation, has a smaller ejecta blanket and smooth wall. Its oval shape indicates a low impact angle.





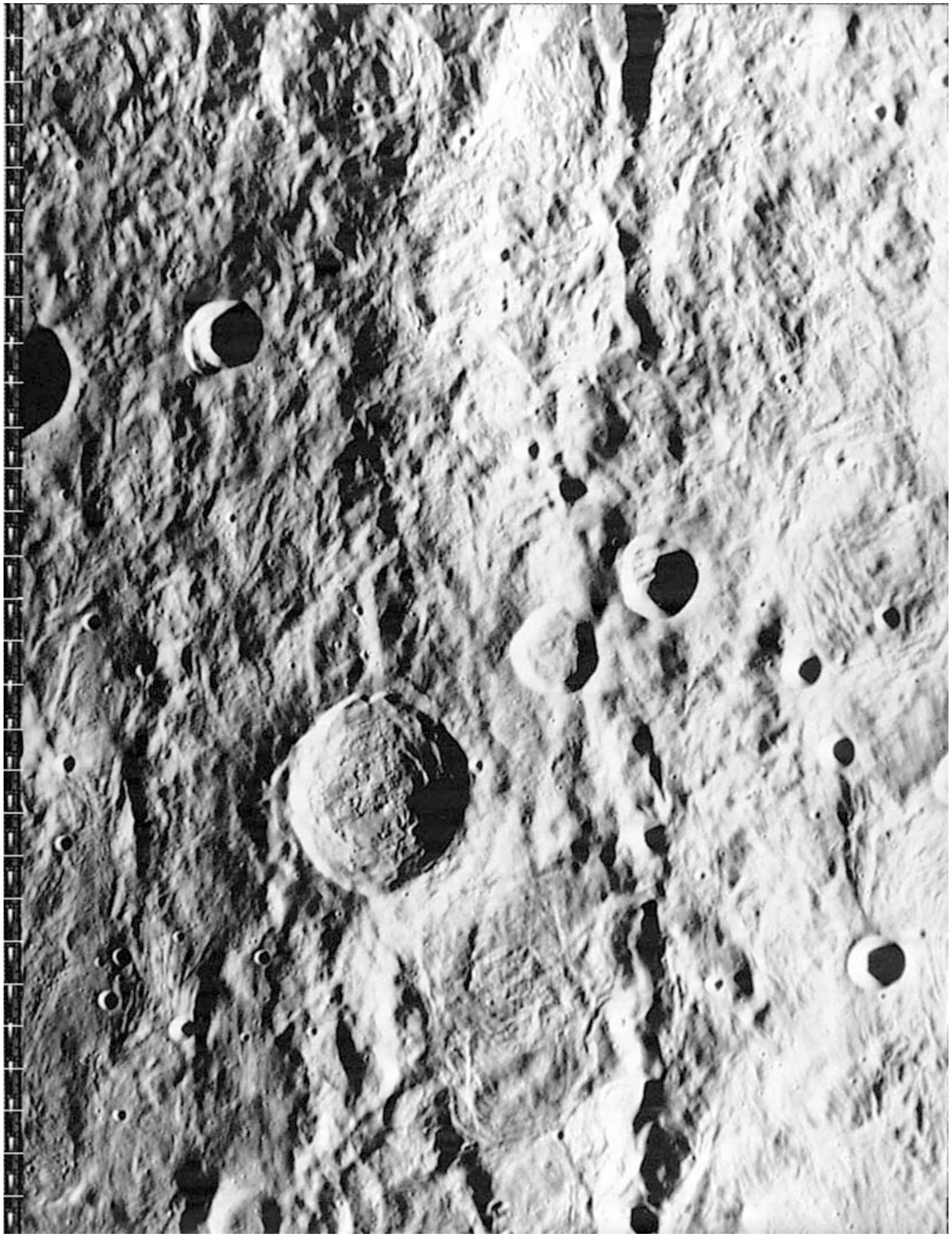
LO4-186H1 Sun Elevation: 15.60° Altitude: 3005.57 km

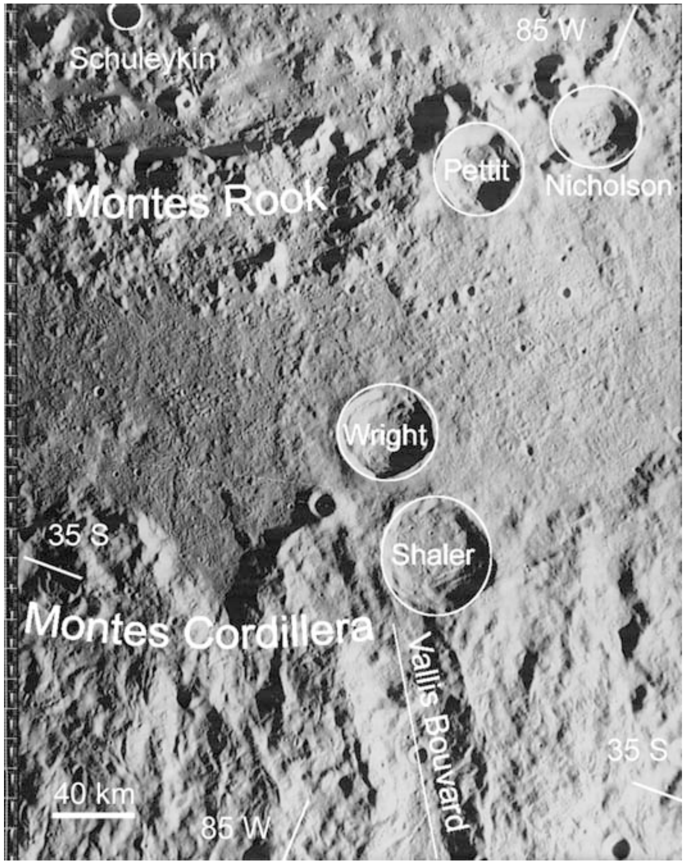
This area has been covered with the outer Hevelius Formation, ejecta from Orientale, as can be seen from the chain of Orientale secondary craters down through the center of the photo. On the right is a series of concentric-walled craters that may have formed as they encountered a firm layer beneath a softer layer of regolith, the ejecta from Orientale and other basins. Simulations suggest that such structures form when the apparent crater diameter is 8 to 10 times the depth of the regolith. Yakovkin appears to have received a relatively light coating of ejecta. It also may have been flooded with lava after the ejecta had been deposited; its surface seems very smooth and free of small craters.



LO4-186H2 Sun Elevation: 15.60° Altitude: 3005.57 km

This area, like much of the Moon, has been repeatedly overlaid with basin ejecta. The largest scale linear features radiate from the Orientale Basin, just to the northwest. However, there are smaller-scale linear features running from southwest to northeast from the older Mendel-Rydberg Basin to the southwest. Baade, formed in a thick ejecta blanket, has a weak central peak. Vallis Bouvard and Vallis Baade are chains of secondary craters and other ejecta from Orientale that plowed these valleys in low-angle impacts. Similar valleys appear around the Imbrium and Nectaris basins.





LO4-186H3 Sun Elevation: 15.60° Altitude: 3005.57 km

Montes Cordillera is the topographic (highest) rim of the Orientale Basin. The outer range of Montes Rook is the next mountainous area toward the center of this multi-ringed basin. Between Montes Cordillera and Montes Rook is the flat knobby plain of the Montes Rook Formation. The bottom of the trough between the two rings of Montes Rook is even lower than the Montes Rook Formation. Craters Pettit, Nicholson, Wright, and Shaler show slumping of their crater walls, suggesting that they may have impacted a low-strength material, a contrast to craters impacting the melt sheet of the Maunder Formation within the Montes Rook rings.