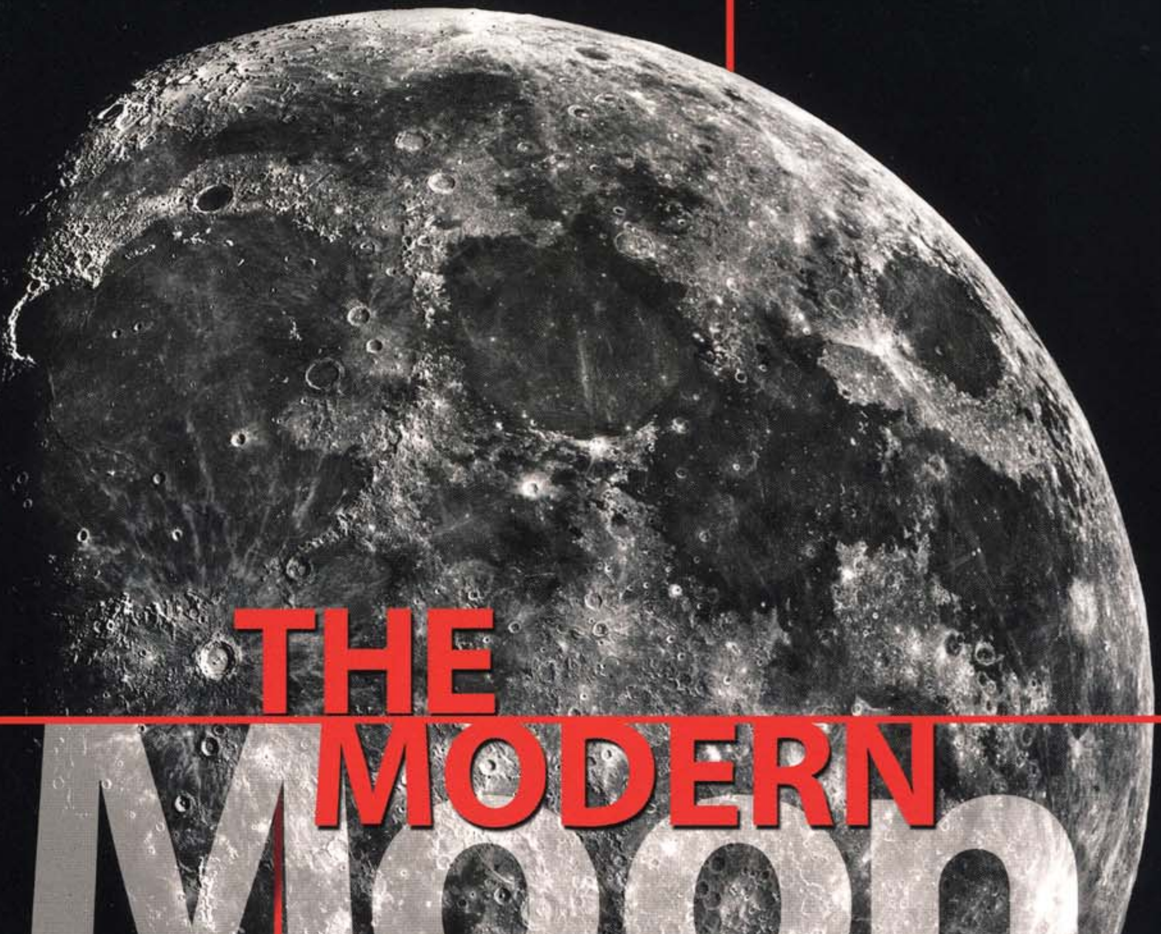
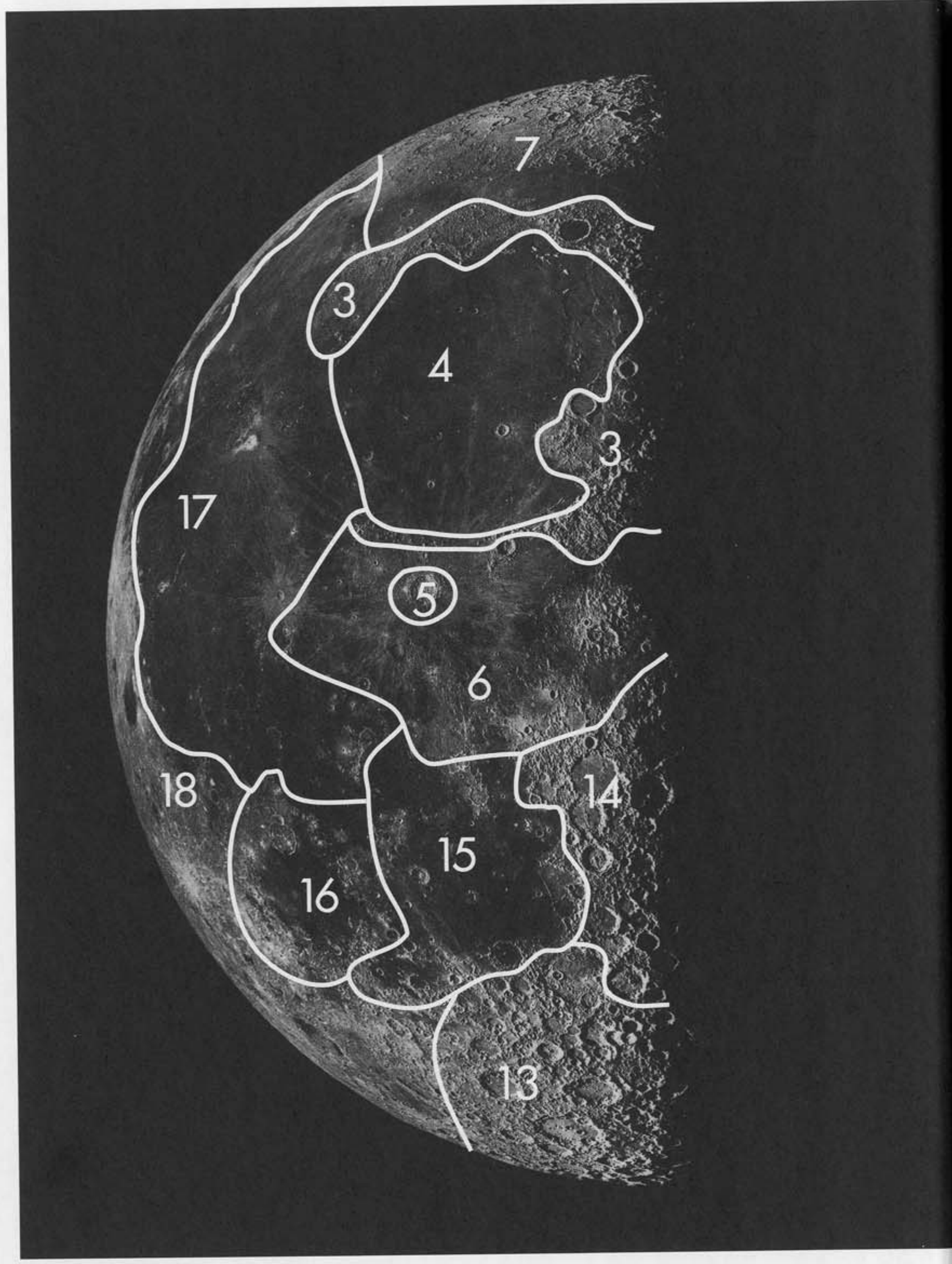


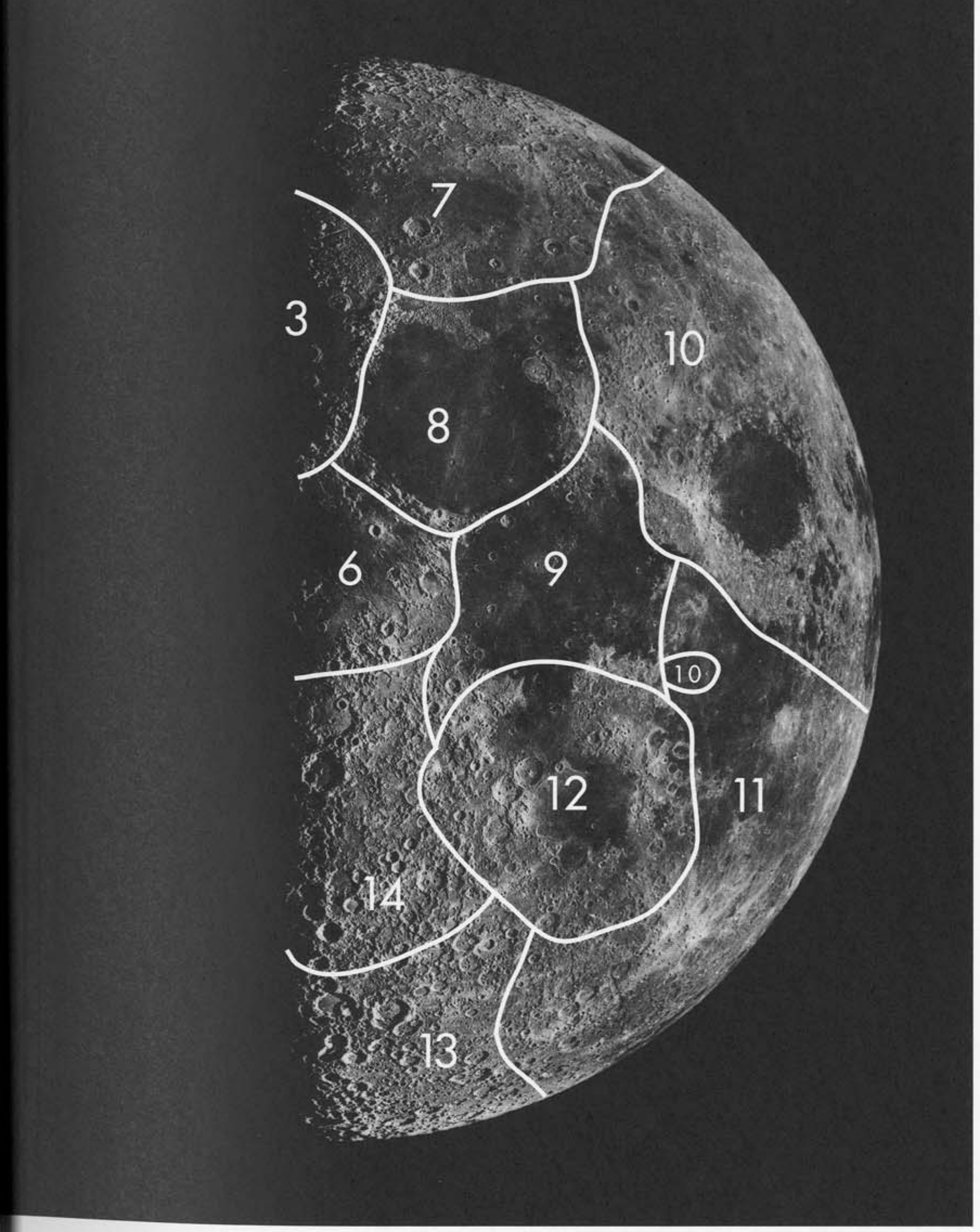
THE MODERN Moon

A PERSONAL VIEW

Charles A. Wood

CHAPTER KEY



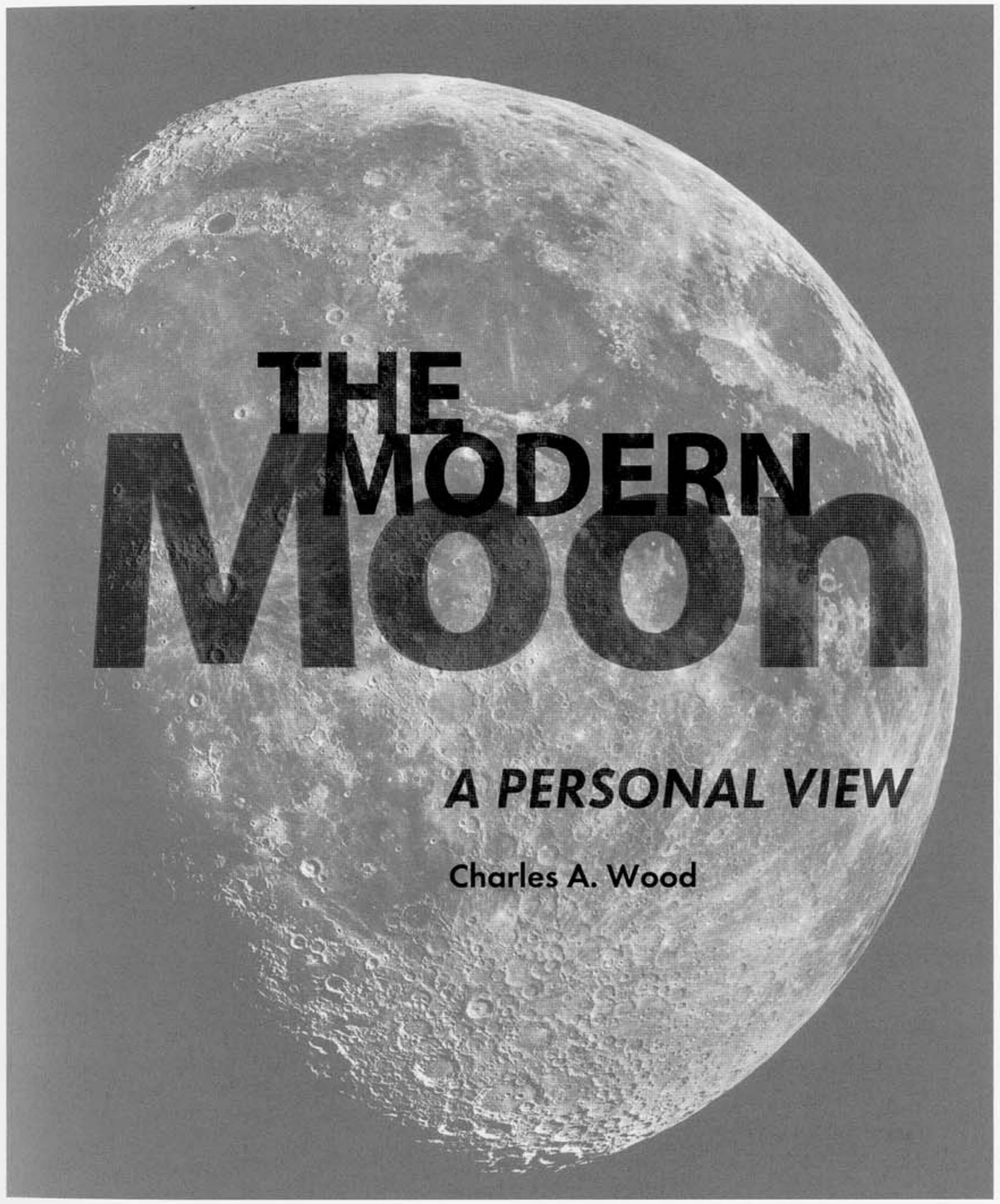


Published by Sky Publishing Corporation
49 Bay State Road
Cambridge, MA 02138-1200, USA
SkyandTelescope.com/

Library of Congress Cataloging-in-Publication Data

Wood, Charles A.
The modern moon: a personal view/Charles A. Wood.
p. cm.
Includes bibliographical references and index.
ISBN 0-933346-99-9 (alk. paper)
1. Moon. I. Title.
QB581.W76 2003
523.3—dc22

2003016080



THE MODERN Moon

A PERSONAL VIEW

Charles A. Wood

Sky Publishing Corp. / Cambridge, Massachusetts 2003

Contents

Preface

In December 1972 Apollo 17 astronauts Eugene Cernan and Harrison Schmitt blasted off toward Earth from their Taurus Mountains lunar-landing site, and astronauts have neglected the Moon ever since. In the ensuing years Mars, Mercury, Venus, and distant Jupiter, Saturn, Uranus, and Neptune were all explored by robotic spacecraft. Meanwhile, the Moon, a mere three-day journey away, waits for humans to return. These days space advocates perceive the Moon as a barren diversion on the way to Mars. But the Moon is too accessible and too convenient a proving ground not to be a near-term goal if human space flights beyond Earth orbit are ever renewed. And the Moon is too fascinating to ignore any longer.

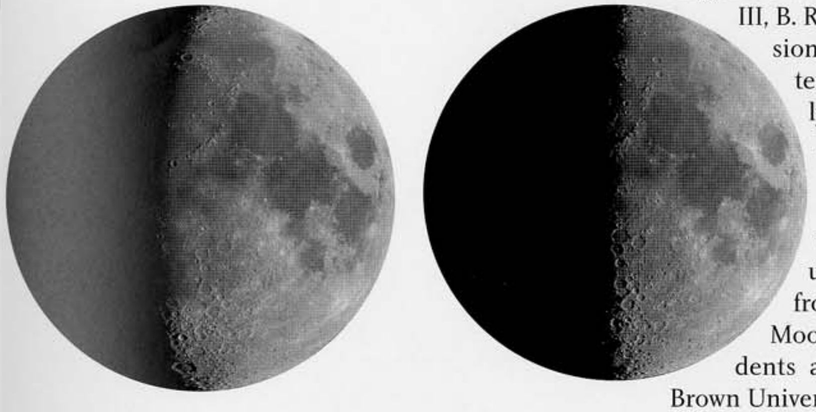
Perhaps one reason that the public seems so uninterested in the Moon is that they don't know much about it. Unfortunately, existing books don't help much. Many published before the Apollo program were simply titled *The Moon* and were written by devoted amateur astronomers who systematically described every lunar landform in painstaking detail, craterlet by craterlet. Such a gazetteer approach quickly becomes boring. These books were seldom more than telescope references for amateur astronomers and were usually accompanied by Moon maps that divided the lunar surface into sections (traditionally, 25) defined by an arbitrary grid. This technique effectively obscured the large-scale features and relationships that define the various regions of the Moon. Consequently, the most important geologic features — impact basins — were not recognized because they were invariably split up between two to four map sections and several chapters.

By contrast, post-Apollo lunar books have generally been written by Apollo-era scientists who never studied the Moon with telescopes. These volumes are imbued with the desire to understand the physical, chemical, and geological processes that formed and modified the Moon. This is modern science, which provides a significant understanding of how nature actually works but is often divorced from nature itself. In these books the Moon is not a place but a source of rock samples and remote measurements less real than the computer printouts that mathematically model its various aspects. Such books are arranged by process topics, with chapters on impact-cratering mechanics, rocks and minerals, regolith geochemistry, and interior structure. The Moon itself hardly makes an appearance in a recognizable form. As Thoreau said, "What sort of science is that which enriches the understanding but robs the imagination?"

The ideal book (which of course this strives to be) integrates the strong sense of place and awe that traditional telescopic observers felt for the Moon, with a knowledge and understanding of how the Moon formed and evolved. To fulfill that ambition this book is geographically organized into scientifically meaningful regions of various sizes and shapes. Many of the observable features within regions are used to explain what Apollo and other modern studies of the Moon have taught us about how moons and planets work. This book is neither a comprehensive catalog of lunar features nor an exhaustive treatment of every scientific discovery but an amalgam for the nonspecialist reader who ideally has a small telescope in the backyard. It is also personal, reflecting my interests and involvement in studying the Moon over four decades, both as a backyard observer and as a bit player in spacecraft explorations.

So, for whom is the book meant? Publishers always want to know. So do reviewers and potential readers. It should be sufficient to point out that an informed citizenry is vital for any debate about returning to the Moon or moving on to Mars. But that's not why I wrote this book, nor why you might want to read it. The Moon is the most conspicuous and fascinating object in the night sky. It looks different every time you view it — constantly changing as the Sun rises and sets over its stark terrain of craters and mountains. It was the goal of the most audacious journey in human history, and it is the most accessible part of the cosmos, being visible even from pollution-shrouded cities. The Moon is an enchantment, made more — not less — remarkable by our modern understanding of it. If you are susceptible to the wonders of the Moon, then this book is for you.

Dedication and Acknowledgments



The Moon is a harsh mistress, claimed Robert A. Heinlein in the title of his classic 1966 science-fiction novel. But she is also a seductive one — alluring Moon-struck scientists to observe her features and explore her checkered past. This book is dedicated to all observers — ancient and modern — who have been captivated by her thin crescent in the evening twilight or her bold brightness two weeks later. I am especially thankful to Galileo Galilei, Johann H. Schröeter, Wilhelm G. Lohrmann, Johann H. Mädler, Johann Friedrich Julius Schmidt, Grove Karl Gilbert, Thomas Gwyn Elger, Walter Goodacre, Ralph B. Baldwin, Eugene Shoemaker, Don E. Wilhelms, James W. Head III, B. Ray Hawke, and Paul Spudis, whose obsessions with the Moon helped all of us to better understand her history. And I especially thank B. Ray Hawke, Ewen Whitaker, Don Wilhelms, Thomas A. Dobbins, and the late Peter Francis for suggesting improvements and corrections to various versions of this manuscript. My ideas and understanding of the Moon have resulted from exciting years of investigating the Moon with colleagues, professors, and students at the Lunar and Planetary Laboratory, Brown University, and NASA's Johnson Space Center.

Transforming a manuscript into a book requires multiple talents and skills beyond mere writing. I have been blessed with the enthusiastic assistance of the Sky Publishing team — a group made up of people who actually are interested in the Moon! In particular, I thank Gary Seronik, who deftly led Sky's efforts.

Images are critical to telling the story of the Moon, and I thank the Lunar and Planetary Laboratory at the University of Arizona for use of plates from the Consolidated Lunar Atlas, Lick Observatory for the classic series of lunar images taken in the 1930s and 1940s, and Peter Neivert of Brown University, who gave new life to Lunar Orbiter images from the 1960s.

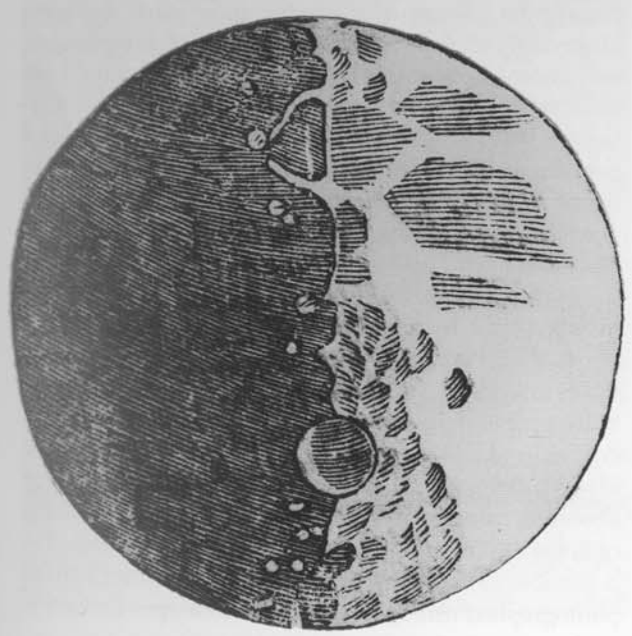
Writing a book is also a harsh task — especially if it takes a decade or so, as this one has. My children, Lilia and Morgan, have lived with "the book" for substantial portions of their lives. I thank them and my wife, Vera, for their patience and long continued support.

Two Moon images by two Galileos. The one at right was drawn by Italian astronomer Galileo Galilei and published in his Sidereus Nuncius (Starry Messenger) in 1610. The above image was assembled from multispectral images transmitted by the spacecraft Galileo as it swung by Earth and the Moon in 1992 on its way to Jupiter.

Introduction: Learning About the Moon

In 1609 Galileo Galilei in Italy and Thomas Harriot in England both pointed crude spyglasses at the Moon. Harriot's drawings of the Moon were more accurate, but Galileo began the scientific tradition of investigating the Moon, which continues today. Over time, telescopic observers discovered that the Moon has neither an atmosphere nor water, that life there is impossible, and that the lunar topography and geology are quite unlike that of Earth.

Hundreds of years after Galileo, Soviet and American robotic spacecraft obtained detailed orbital images of the Moon's Earthward hemisphere and invisible far side, captured dramatic panoramic views from the lunar surface, and made the first chemical analysis of lunar rocks. But almost all of our scientific understanding of the Moon has come from the Apollo explorations. Without the samples carefully selected by Apollo astronauts, lunar science would hardly exist. Studies of these Moon rocks revealed the age of the Moon, details of its violent birth and evolution, its chemical composition, and the nature of the geological processes that shaped it. Understanding the Moon has also permitted astronomers and geologists to interpret spacecraft images of other planets and moons and to provide insight into the early history of Earth.



After a two-decade interruption, robotic lunar exploration half-heartedly resumed when the Galileo spacecraft flew past Earth and the Moon twice in the early 1990s, grabbing gravitational boosts enroute to its ultimate destination, Jupiter. During these flybys, modern remote-sensing instruments were used to image the Moon for the first time. Although the resolution of the images was relatively poor (only about 1 kilometer), observations in different spectral bands provided new clues about the chemical composition of the lunar surface.

But the most comprehensive photographic survey of the Moon occurred almost as a sideshow. The hundreds of billions of dollars spent on the Strategic Defense Initiative (the Star Wars that lacked Luke Skywalker and R2D2) were suddenly focused on a test project to see if tiny sensors would actually work. In 1994 a small Department of Defense spacecraft named Clementine was placed in orbit around the Moon. Clementine was not the ideal lunar probe, for its sensors weren't adequately calibrated for the work at hand, but the resulting high-resolution images in a multitude of spectral wavelengths, combined with a half million laser measurements of lunar topography, provided an immense windfall of data that gave a new generation of scientists a chance to experience the thrill of lunar discovery.

In 1998 NASA launched its first probe to the Moon in a quarter century. The Lunar Prospector spacecraft was sent to the Moon to complete basic mapping. The mission was the result of two coinciding factors. First, a lone scientist, Alan Binder, obsessively worked nonstop for a decade to find someone — anyone — to pay for the small polar-orbiting satellite. Second, NASA invented the concept of "faster, better, cheaper" to do something despite declining budgets. Lunar Prospector was the cheapest mission anyone proposed, and it was selected largely for that reason. Such a mission was a far cry from what NASA used to fly, but it was better than nothing. As Binder expected, Lunar Prospector made breakthrough discoveries that altered our understanding of the Moon and made a future human presence there much more likely.

But the United States has no plans to return humans to the Moon, or to do much else beyond Earth orbit that requires daring. There have been many, many studies of future Moon missions that have gone nowhere. One of the reasons I quit NASA was that I wanted to do things — not just study the possibility of doing them. Now NASA spends its big bucks on the International Space Station and hopes that tiny, cheap space probes can keep planetary science alive. But there are plans for someone else to explore the Moon and perhaps ultimately return to engage in mineral exploitation or even tourism. The Japanese Space Agency quietly flew the Muses-A probe past the Moon in 1990, just to see if they could do it. And Japan's Lunar and Planetary Society has proposed a $26 billion, 30-year plan that utilizes increasingly complex lunar probes leading to eventual human-piloted lunar missions. Just as adventurers and traders from Great Britain built a vast overseas empire in the 19th century, perhaps another small island nation will establish the first space empire of the 21st century. Sadly, the U.S. will probably continue searching for a grand vision for space exploration while sending ever-smaller microprobes to planets instead of our sons and daughters.

Despite the U.S. government's lack of interest in going back to the Moon, there is continuing interest from the public — especially from children. The future pioneers who will design, build, and fly spaceships back to the Moon are alive today. I hope this book will excite them about the Moon and encourage them to dream of one day living there.

LUNAR REGIONS

Lacking oceans, continents, nations, or climatic zones, the Moon may appear to be without identifiable regions, making the arbitrary divisions used in older Moon books seem reasonable. But modern studies of the lunar surface have shown that the fundamental natural unit of the Moon is the impact basin — the largest variety of impact crater. Therefore, the natural geographic regions of the Moon are the basins and their surroundings. Indeed, virtually every kind of lunar feature, except randomly distributed impact craters, is associated with impact basins:

- Large mountains like those glimpsed in the lunar south polar regions are the rims of giant basins, as are the Apennine Mountains that partly encircle Mare Imbrium.
- Lava flows (the Moon's dark spots and maria) fill the basins excavated by huge impacts.
- Ridges and many channel-like rilles are concentric to basin rims and are associated with subsidence due to lava filling the basins.
- Domes, concentric craters, flooded craters, and floor-fractured craters are all basin-edge features.
- Peculiar, peakless craters are secondary impacts made by material ejected during basin formation.
- Scouring and lineations superposed on older terrain are due to ejecta from impact basins.

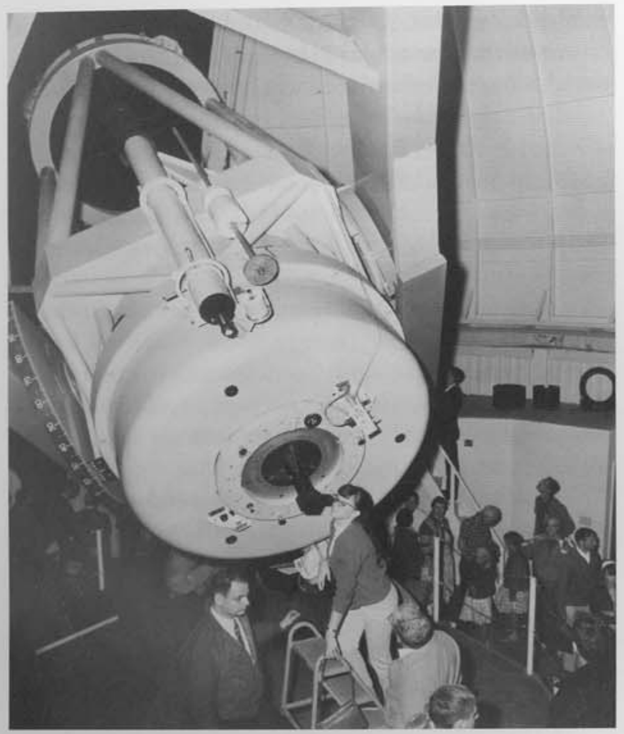
Not surprisingly, the major regions described in this book are keyed to the basins of the lunar near side. Some areas distant from basins have less certain boundaries, but, in fact, each heavily cratered region of the Moon has distinctive characteristics. Although these boundaries are somewhat subjective, most lunar observers will probably agree with the divisions used here. Some regions associated with one or more basins (for example, Mare Frigoris) are sufficiently distinct to merit individual descriptions. In spite of this basin-centered approach, in a few cases arbitrary boundaries still sneak in.

Finally, this book, which is aimed at telescopic observers, does not describe the lunar far side. It is an interesting and very little explored realm, but it is not available for personal exploration.

ILLUSTRATIONS

During my career I have made memorable observations of the Moon with many different optical instruments, ranging from binoculars and my first 3-inch reflector to a succession of 12-, 16-, 36-, 61-, and 84-inch telescopes. But most of my familiarity with the Moon has come from poring over photographs made by large observatory telescopes, Lunar Orbiter spacecraft images, and photographs taken by the Apollo astronauts. I am not the only one to be inspired by photographs — during the 1940s Ralph Baldwin and Josiah Spurr, both pioneers in the field of lunar geology, initiated major investigations of the Moon after becoming captivated by marvelous Moon photographs taken with the 100-inch Hooker reflector on Mount Wilson in California.

Many of the pictures in this book were made back in the 1960s by staff of the University of Arizona's Lunar and Planetary Laboratory using the Catalina Observatory's 61-inch telescope near Tucson, Arizona. Most people have never seen these pictures, but they continue to have great value because they show the Moon's features as they can be seen by diligent observers using backyard telescopes. One of the ironies of lunar observing is that a homemade 6-inch reflector is capable of revealing much of the detail that can be photographed through the largest telescopes on Earth.



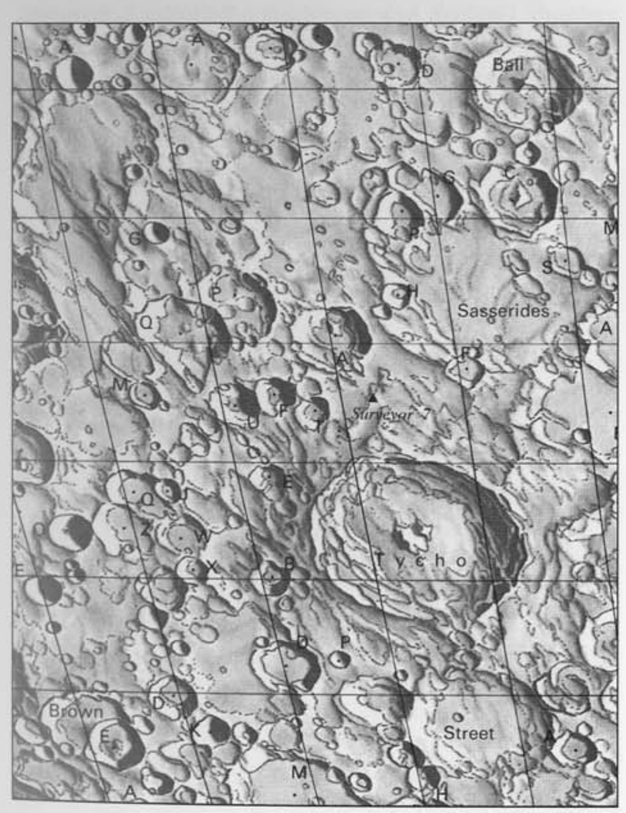
Many of the Moon photos in this book were taken with the Lunar and Planetary Laboratory's Catalina Observatory 61-inch telescope. Here the telescope is pressed into service for a night of public Moongazing.

The reason for this is that our planet's atmosphere is constantly in motion, distorting parts of the image that forms on your eye's retina or on photographic film. Astronomers refer to the steadiness of the atmosphere as the *seeing*. Your brain can discard the periods of fuzzy seeing and concentrate on the fleeting moments of sharp viewing, but photographic film integrates the variability of the seeing conditions during an entire exposure and averages together the crisply defined and blurred views. However, improved technology has led to amazing advances in lunar imaging. Charge-coupled-device (CCD) electronic cameras (essentially high-quality digital cameras) allow such short exposures that atmospheric distortion becomes minimized.

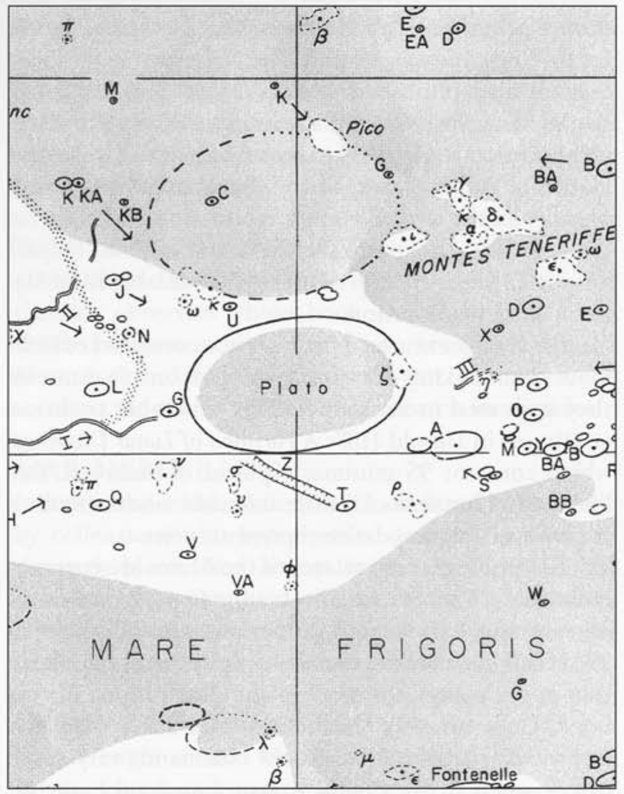
But the real reason for using Earth-based photographs is that they show many of the things we know about the Moon after hundreds of years and billions of dollars of exploration. It's satisfying that so much of what we understand about the geology of our nearest celestial neighbor can be seen on these photographs and visually through amateur instruments.

TO OBSERVE OR NOT TO OBSERVE?

You can enjoy this book without ever observing the Moon, but why would you? The Moon is conveniently



A portion of chart number 64 from Antonín Rükl's Atlas of the Moon.



Plato and its environs as depicted in this portion of the Lunar Quadrant Maps. These charts are presented with south up, to match the view in an inverting telescope.

available — visible nearly every night. You can follow its phases and identify the dark mare patches with your naked eye, and binoculars will reveal the major craters. Even a modest telescope costing only a few hundred dollars will provide amazing views that are far more vivid and exciting than anything on TV. If you decide to buy a telescope, ignore the typical department-store wonders that are covered with chromed plastic and promises of high magnification. These are junk scopes, and higher quality is available even without spending more money. A far better choice is a basic 4.5- or 6-inch reflecting telescope from one of the companies that advertise in *Sky & Telescope* magazine. For more detailed information on telescopes and how they work, visit the SkyandTelescope.com Web site and read through some of the excellent online articles presented there.

MAPS, BOOKS, AND OTHER REFERENCES

These days it can be difficult to find adequate maps of the Moon. NASA and the U.S. Geological Survey published an extensive series of maps during the 1960s and early 1970s, but as the Moon was relegated to the back burner of planetary exploration, the remaining maps were literally thrown away. Fortunately, Czech engineer and artist Antonín Rükl has produced a number of excellent lunar atlases and maps. I frequently consult his wonderful *Atlas of the Moon*, but he also drew a poster entitled *The Moon* that is a useful guide for finding your way around. The National Geographic Society also published a convenient wall map, *The Earth's Moon*, in 1969, and a revised version is still available. A more workmanlike depiction is the Lunar and Planetary Laboratory's *Lunar Quadrant Maps*, which identify all the named craters, mountains, and rilles on the near side. I am partial to this map because I helped draw it 35 years ago! All of these are available from Sky Publishing Corporation.

For three centuries lunar science consisted of little more than making drawings of the Moon's features as they appeared in telescopes. This venerable tradition continues in Harold Hill's *A Portfolio of Lunar Drawings*, which contains 95 minimasterpieces of lunar art. But like the old lunar books, little scientific understanding is conveyed, just evocative representations.

Few photographic atlases of the Moon are currently available. The absolute best is the *Consolidated Lunar Atlas* compiled by Gerard Kuiper and his colleagues in 1967. This is a massive blue box of photographic prints that is the source for most of the illustrations in this book. Unfortunately the *Consolidated Lunar Atlas* was not widely distributed and now commands very steep prices when it does make a rare appearance on the used-book market. A version of it, however, is available online at the Lunar and Planetary Institute Web site, www.lpi.usra.edu/research/cla/menu.html.

The *Lunar Atlas* compiled by Dinsmore Alter and reissued by Dover Publications in 1964 can sometimes be found in second-hand bookshops and the Internet. It provides a nice collection of pictures made with the Yerkes, Lick, and Mount Wilson observatory telescopes from the 1920s through the 1960s.

One of the few photographic atlases currently for sale is the *Atlas–Guide Photographique de la Lune* by the French amateur Georges Viscardy, which costs about $120. Many of Viscardy's photographs record very delicate details, but they cover areas that are too small to provide a regional understanding of lunar geology.

Springer-Verlag has recently reissued the *Hatfield Photographic Lunar Atlas*, which consists of 88 photographs of the Moon taken by British amateur Henry Hatfield through a 12-inch reflector during the 1960s. While these 40-year-old images are of lower quality than the professional photographs of the massive *Consolidated Lunar Atlas*, the convenience of the Hatfield atlas makes up for this.

I also routinely refer to three of the classic books from the days when the Moon was almost the exclusive province of amateur visual observers. All are by British authors, but they draw on the tradition of the great 19th-century German selenographers Wilhelm Lohrmann, Wilhelm Beer, Johann Mädler, and Julius Schmidt. Thomas Gwyn Elger (1895), Walter Goodacre (1931), and Hugh Percival Wilkins and Patrick Moore (1955) all published books titled *The Moon*. Each includes maps that are progressively more crowded with detail and less artistically depicted. But I like these books mainly because they are the ones I grew up reading.

If you find Thomas Mutch's *Geology of the Moon* at a used-book store, buy it. Mutch's book provides an excellent review of pre-Apollo lunar science. Most of the other books about the Moon at your local library are probably oblivious to everything we've learned about the Moon during the last 25 years. They might be fun, but they are almost certainly wrong or naïve about the science.

The largest and best-illustrated professional book on the Moon is generally available only in university libraries. *The Geologic History of the Moon* is the summary of a lifetime of devoted study of the Moon by Don Wilhelms, a U.S. Geological Survey pioneer of the Apollo program. It was published in 1987 as *USGS Professional Paper 1348*. A totally different approach to summarizing modern knowledge of the Moon is represented by the *Lunar Sourcebook*, compiled by Grant Heiken, David Vaniman, and Bevan French. This is a technical anthology by 28 lunar scientists that lacks a story line but is a great reference. Another good professional summary of lunar and planetary science is *Planetary Science: A Lunar Perspective* by Stuart Ross Taylor. A more popular but still authoritative book is Peter Cadogan's *The Moon — Our Sister Planet*. All these books are at least a decade old, and though new understandings are developing (especially based on Clementine and Prospector data), the basic information in these post-Apollo books is still relatively current. *The Once and Future Moon* by Paul Spudis is the most up-to-date and easily understood scientific explanation of the Moon. Spudis devotes about a quarter of his pages to the politics of returning to the Moon, which he dearly would love to do.

Wilhelms has recently published his memories of the scientific side of the Apollo program. I call it *The Double Helix of the Moon*, but he titled the book *To a Rocky Moon*. Andrew Chaikin's *A Man on the Moon* is an excellent retelling of the adventure of the Apollo program from the astronauts' perspective. My favorite Apollo astronaut book is Mike Collins's *Liftoff*, even though he considers the Moon "this monotonous rock pile, this withered, Sun-seared peach pit out my window."

Finally, three recent books provide historical perspective on lunar studies. Ewen Whitaker summarized his passion for old lunar maps in the definitive *Mapping and Naming the Moon*, and William Sheehan and Thomas Dobbins have written the first comprehensive history, *Epic Moon: A History of Lunar Exploration in the Age of the Telescope*. But the most intriguing perspective comes from Scott Montgomery, whose *Moon and the Western Imagination* traces how artists, philosophers, and scientists invest the Moon with the issues of their day.

Gerard P. Kuiper (left) and Ewen A. Whitaker, two of the big names in lunar science, stand inside the dome of the Catalina Observatory 61-inch reflector.

CAST OF CHARACTERS

Like a good Agatha Christie mystery novel, the cast of characters in this book is large enough to require a convenient reference. Here are the major players in this tale, with capsule descriptions. The list includes scientists who have been significant in lunar science over the last 400 years, including many whom I have known and with whom I have worked. I admire the contributions to lunar science made by most of these people, but in addition to being scientists, they're also very human — in some cases their personalities influenced and sometimes even dominated their science!

DINSMORE ALTER (1888–1968)
Director of the Griffith Observatory during the 1950s and 1960s; compiled lunar atlases; believed that many craters were of volcanic origin.

DAVID WILLIAM GLYN (DAI) ARTHUR (b. 1917)
Irascible, self-taught Welsh-American; measured accurate positions of lunar craters and coordinated compilation of catalogs of lunar craters; my boss in the 1960s.

RALPH B. BALDWIN (b. 1912)
Businessman/astronomer; early proponent of impact origin of lunar craters; right on almost everything he wrote about the Moon; hero to many on this list.

WILHELM BEER (1797–1850) and
JOHANN H. MÄDLER (1794–1874)
German observers whose book, *Der Mond* (1837), was the first modern study of the Moon; recognized that the Moon is a dead world — no air or water. Their book was so respected that it stifled lunar research for decades.

ALAN BINDER (b. 1939)
Independent-minded scientist (i.e., believed to be wrong by colleagues) who hypothesized complete melting of the early Moon. Now almost universally accepted, but Binder is seldom credited with seeing the evidence first. His reputation improved in 1995 when NASA selected his Lunar Prospector spacecraft to study the Moon.

THOMAS GWYN ELGER (1838–1897)
British engineer and Moon mapper who published a succinct book and map in 1895.

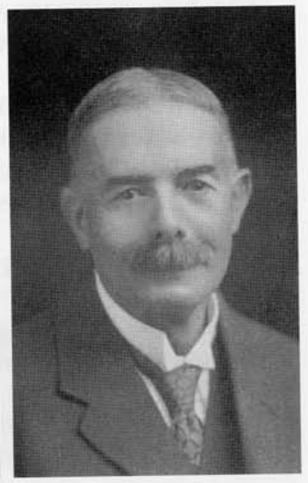
PHILIPP FAUTH (1867–1941)
Intensely nationalistic German lunar observer; believed that the Moon was encased in a shell of ice. The long-delayed posthumous publication of his huge lunar map in 1964 guaranteed that it influenced no one.

GALILEO GALILEI (1564–1642)
First telescopic observer of the Moon; discoverer of lunar craters, mountains, and the flatness of the mare.

GROVE CARL GILBERT (1843–1918)
First Geologist of U.S. Geological Survey; discoverer of Imbrium radial system; proposed impact origin for lunar craters but with supreme irony argued incorrectly that Arizona's Meteor Crater was volcanic.

WALTER GOODACRE (1856–1938)
British businessman and amateur astronomer, he privately published *The Moon* in 1931, the last lunar book bearing that title unencumbered by useless details.


Alan Binder


Walter Goodacre

FRANZ VON GRUITHUISEN (1774-1852)
Bavarian astronomer who first advanced in 1824 an impact theory for the origin of lunar craters. Unfortunately, his spurious "discoveries" of a lunar city and temple diminished his reputation.

WILLIAM K. HARTMANN (b. 1939)
Former graduate student of Gerard Kuiper and the discoverer of impact basins; recognized the great falloff in lunar cratering rate and gave birth to modern theory of lunar origin; prolific writer and talented space artist.

B. RAY HAWKE (b. 1946)
Caffeine-powered devotee of the Moon; detailed geologic and spectral studies of craters and other features.

JAMES W. HEAD III (b. 1941)
Driven lunar scientist who trained Apollo astronauts and legitimized photo-geologic studies by linking them to sample sites and geologic processes.

GERARD P. KUIPER (1905–1973)
Autocratic superscientist; rescued the Moon from obscurity and organized major photographic investigations of the Moon.

JOHANN H. MÄDLER (*see* WILHELM BEER)

H. JAY MELOSH (b. 1947)
Physicist-turned-planetologist; dominates impact-cratering theory with forceful personality and daunting mathematics.

PATRICK MOORE (b. 1923)
Chatty British popularizer of astronomy and prolific author who was once a very active observer of the Moon. Minimized U.S. space successes while reveling in Soviet accomplishments. Even today he is not yet fully weaned from the volcanic theory of crater origin.

CARLÉ PIETERS (b. 1943)
The only woman in the bunch; made career of mapping subtle colors (and hence compositions) of the Moon's surface.

GIOVANNI RICCIOLI (1598–1671)
Published (1651) lunar map based on observations of his graduate student Francesco Grimaldi — a practice that is still common; initiated modern system for naming lunar features.

ANTONÍN RÜKL (b. 1932)
Director of Prague Planetarium and the preeminent lunar cartographer today.

GRAHAM RYDER (1949–2002)
A pugnacious expatriate British petrologist; on a "first number" basis with every lunar sample.

JOHANN FRIEDRICH JULIUS SCHMIDT (1825–1884)
The great "Schmidt of Athens," drew a detailed 72-inch-diameter Moon map; announced the supposed disappearance of the crater Linné.

HARRISON SCHMITT (b. 1935)
Only geologist to go to the Moon; temporarily U.S. Senator.

JOHANN HIERONYMUS SCHRÖETER (1745–1816)
German magistrate addicted to observing the Moon; published massive two-volume work *Selenotopographische Fragmente* in 1791 and 1802.

PETER H. SCHULTZ (b. 1944)
Napoleon-sized lunar scientist with a large impact; crater-making experimentalist and Moon morphologist extraordinaire.


Peter Schultz


John Wood

EUGENE SHOEMAKER (1928–1997)
Father of the U.S. Geological Survey lunar group; first to understand the physics of impact cratering and lunar stratigraphy but frustrated in his desire to become an astronaut. He died tragically in an automobile accident in the Australian outback while studying impact craters there.

PAUL D. SPUDIS (b. 1952)
A Don Wilhelms for the 1990s; Clementine scientist addicted to the Moon; published an excellent book on lunar science in 1996.

JOSIAH SPURR (1870–1950)
American economic geologist who privately published four dense tomes in the 1940s that claimed that all lunar features are volcanic or tectonic in origin; widely ignored.

HAROLD UREY (1893–1981)
Nobel Prize–winning chemist; wrong about virtually everything he said about the Moon but managed to convince NASA to undertake the Apollo program.

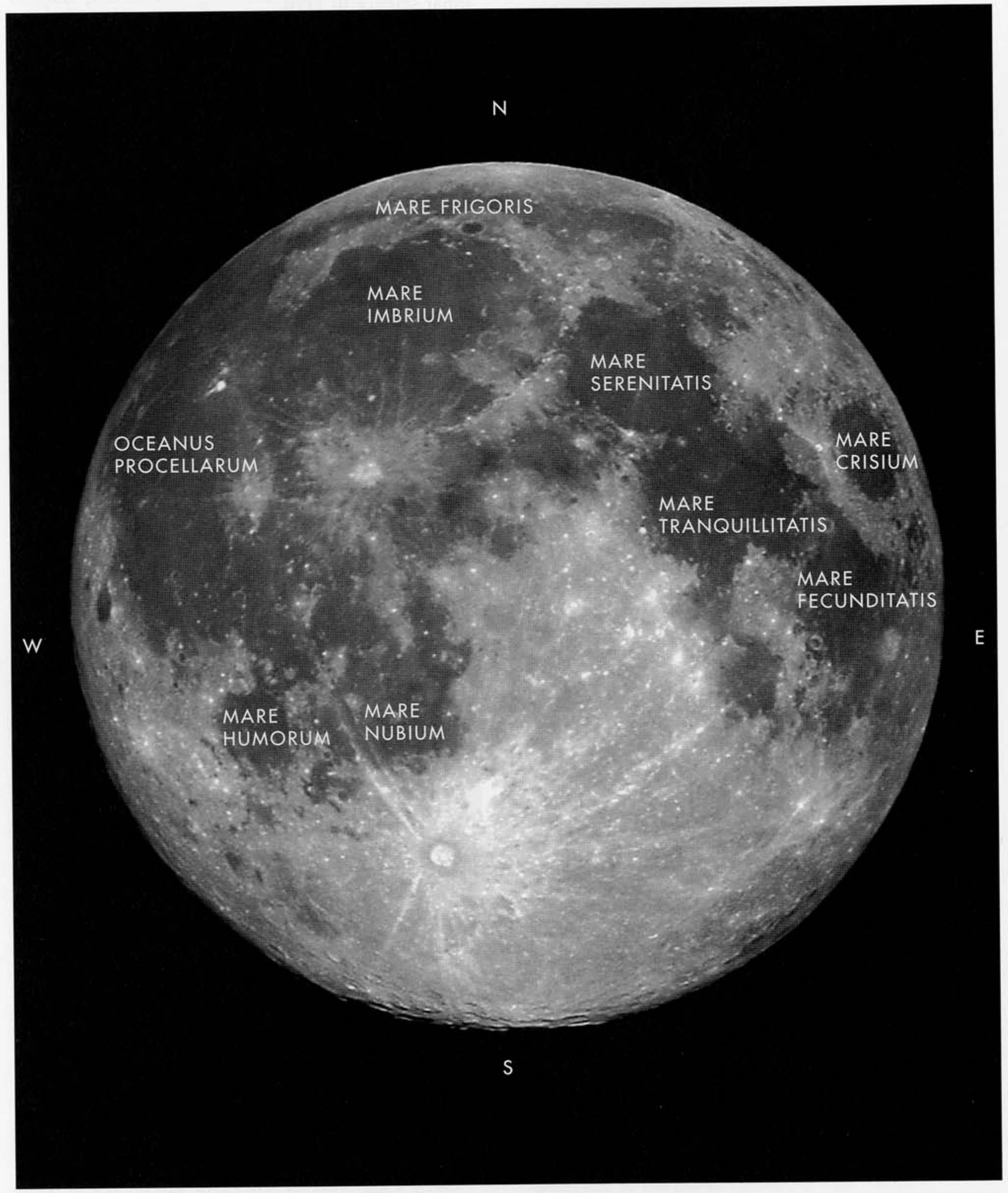
EWEN WHITAKER (b. 1922)
Pixieish, self-taught British-American lunar scientist who knows the history of lunar studies and the geography of the lunar surface better than anyone else.

DON WILHELMS (b. 1930)
Previously chief USGS Moon mapper; published magnum opus on lunar stratigraphy and engaging insiders view of Apollo site selection.

HUGH PERCY WILKINS (1896–1960)
Last of the British school of amateur Moon mappers; a poor scientist and an even worse cartographer.

CHARLES A. WOOD (b. 1942)
A bit player (but this is my book!) involved in cataloging lunar craters and studying impact basins since 1961; attracted to bizarre theories, some of which turn out to be correct.

JOHN WOOD (b. 1932)
Petrologist-laureate of Moon; first recognized nature of the lunar highlands crust and magma ocean.



The full Moon is bright, but the main features are easy to distinguish. The dark patches are lava plains and the light areas are highlands made up of many impact craters. Except where noted, north is up in this and all other Moon photographs appearing in this book.

1

Observing the Moon

You can see the Moon on about half of the clear nights, and it's there as frequently during the day but often escapes notice. Perhaps you haven't looked at it carefully in years. When you were a child the dappled patterns that make up the Man in the Moon or the Woman in the Moon or the Rabbit in the Moon were probably pointed out to you. Seeing those light and dark patches is the single most important visual observation that can be made about the Moon — they demonstrate that the lunar surface is made of at least two different kinds of materials.

When Galileo first pointed his small, crude telescope at the Moon, he saw that the dark regions were smooth and the brighter regions were rough and heavily pockmarked. Some early scientists concluded that the dark areas were oceans. If so, the watery expanses should brilliantly reflect sunlight near the time of full Moon, but few observers seemed to notice that such bright specular reflections were never seen from the purported lunar seas. Although faulty, such analogies influenced opinions as late as the 1960s when lunar sinuous channels were proposed to have been cut by running water.

Galileo specifically compared the dark, smooth regions and the bright, rough regions of the Moon to terrestrial seas and continents, respectively. His choice of the Latin words *maria* (singular: *mare*) and *terra* to represent these features are still used, though later designations such as *lunabase* and *lunarite* have thankfully been forgotten. A few other Latin terms applied to odd bits of mare material have a long history and are still employed. These are *palus* (marsh), *sinus* (bay), and *lacus* (lake). During an early phase of multiculturalism in the 1960s, the International Astronomical Union latinized other names used to describe landforms on the Moon. I personally don't know any readers of Latin, and since this book is intended for an English-speaking audience, I will not burden you with *dorsum* when "ridge" is perfectly understandable.

Following Galileo's first sketches of the Moon, a host of astronomers drew additional maps that depicted many craters and mountains. Eventually it became necessary to assign names to the maria and major craters. In 1645 Langrenus, a member of the court of King Philip IV of Spain, curried favor by naming lunar features after kings, nobles, patrons, and scientists, but his sycophantic scheme of nomenclature was quickly rejected in favor of a contemporary's system, that of Giovanni Riccioli. In 1651 Riccioli used the names of scientists and philosophers, living and dead, to designate lunar craters. He distributed the names in a logical pattern with the most ancient savants near the lunar north polar region and more recent ones toward the south pole. He also placed teachers and their students near each other. This has been the accepted system of lunar nomenclature for more than 350 years now, and the names of Plato, Tycho, Ptolemy, and hundreds of other scientific luminaries are enjoying a second life as craters.

Riccioli named the lunar maria after weather conditions and states of mind. Mare Imbrium, the largest round patch of dark material on the Moon, was called the Sea of Rains, and Apollo 11 landed in Mare Tranquillitatis, the Sea of Tranquillity. Mare patches more recently noticed have been named for people (maria Humboldtianum and Smythii) or are scientifically boastful, like Mare Cognitum (Known Sea),

Giovanni Riccioli.

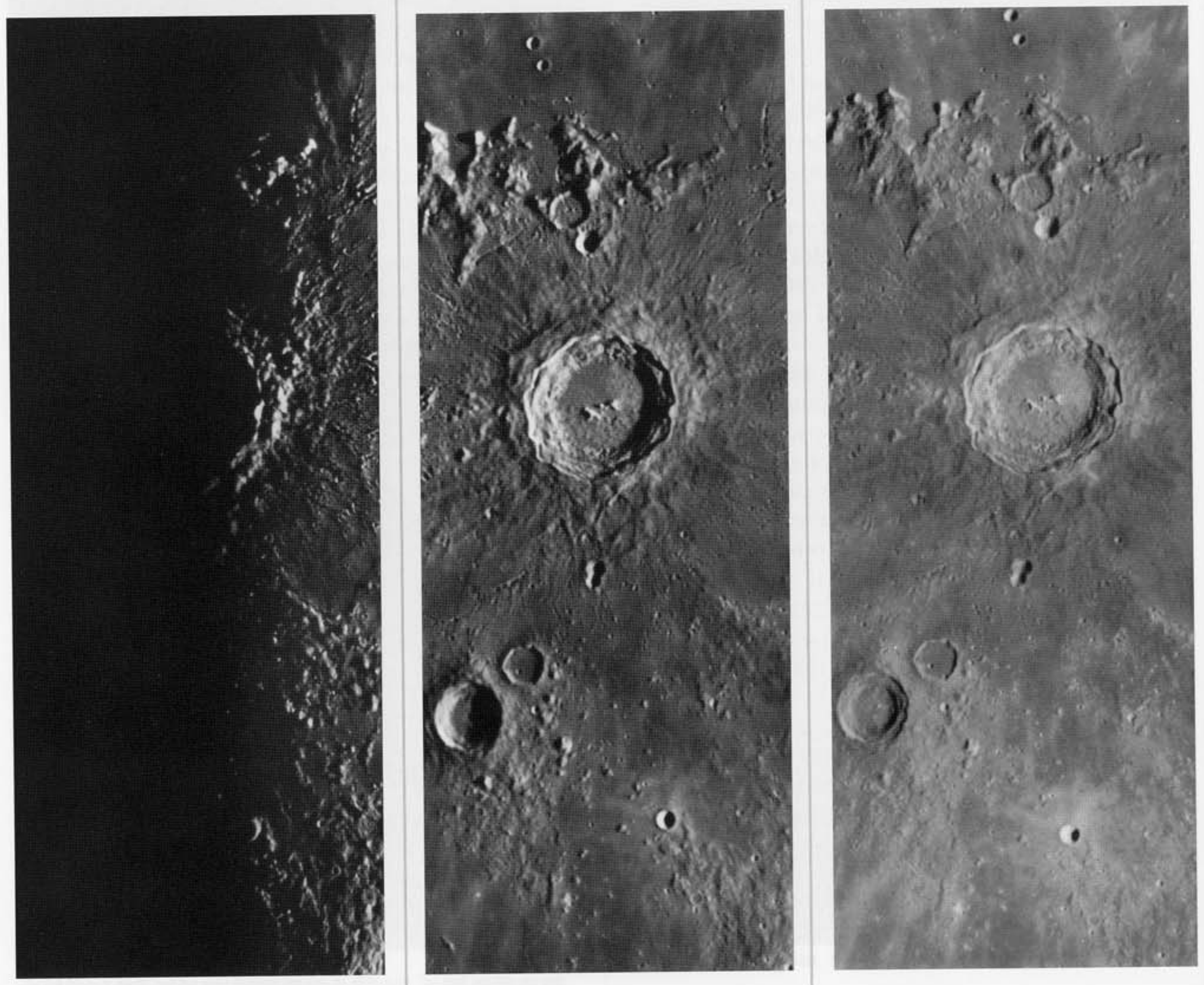
where the first successful Ranger probe impacted. It is not clear if Mare Moscoviense (Sea of Moscow), discovered by the first Soviet space probe to fly over the lunar far side, is intended to describe a state of mind or is simply boastful.

As a Jesuit priest, Riccioli faithfully rejected the newfangled heliocentric theory of a Sun-centered solar system and placed the leading advocates of that controversial notion — Aristarchus, Copernicus, and Kepler — in the seething Oceanus Procellarum (Ocean of Storms). He also took pains to honor fellow Jesuits such as Clavius and Grimaldi with prominent craters. As one last nomenclatural aside, the mathematician and philosopher René Descartes suggested that the spirits of the dead lived in the craters bearing their names. But in fact, Riccioli stated at the top of his map, "People do not inhabit the Moon, neither do spirits migrate there."

VIEW THE MOON

One goal of this book is to entice you to explore the Moon. The main maria can be identified with the naked eye, while ordinary binoculars will bring into view a few bright craters, such as Copernicus, Tycho, and Aristarchus. Even more revealing views come with small telescopes. I assume the reader will have opportunities to observe the Moon with his or her own telescope or at a public observatory or astronomy club star party.

If you watch the Moon intermittently for even a few hours, you will notice that the *terminator* (the abrupt boundary between the sunlit and dark sides of the Moon) advances perceptibly. The Moon's 29-day orbit around the Earth causes the terminator to advance or retreat at the rate of 12° of lunar longitude each terrestrial day, thus creating the lunar phases. As the Sun rises over a large crater, the crater is at first filled with darkness, and its walls cast long shadows. Two or three hours later the floor is revealed. It takes about three days for sunrise to occur over the entire expanse of a large feature like Mare Imbrium.


Sunrise at Copernicus was captured in these photos taken at 24-hour intervals.

From the observer's point of view the always-changing Sun angle makes the Moon appear to undergo dramatic transformations as shadows lengthen or shorten. But in fact this is a trick of lighting. For as the provocatively titled 1942 *Popular Astronomy* magazine article "Does Anything Ever Happen on the Moon?" implied, very little actually *does* happen on the Moon today. Except for the infrequent formation of new impact craters, the Moon is largely dead and has been so for most of the last 2 to 3 billion years. So why have scientists spent so much time and billions of dollars studying it? And why should you read any further in this book? Well, our dead Moon is an immaculately preserved museum displaying the first billion or so years of the solar system's history. On Earth, records from these early times are almost completely absent because of our planet's continuous geologic activity. Volcanic eruptions, earthquakes, and especially the slow but relentless movement of tectonic plates have buried and consumed nearly all rocks more than 3 billion years old. Yet the violence of early cataclysmic collisions and the vast outpourings of lava flows that are so well preserved on the Moon must have had counterparts on the primordial Earth. Without that fantastic museum we call the Moon, we never could have imagined our own world's dramatic history.

Our Moon is a cosmic Rosetta stone that allows us to interpret the other planets and moons in the solar system with greater confidence. We are fortunate to be living right next door to the solar system's version of the Smithsonian Institution. A Martian scientist would have a much harder time understanding the local cosmos with his relatively uninformative and tiny branch museums, Phobos and Deimos.

FINDING YOUR WAY AROUND THE MOON

The Moon is 3,476 kilometers in diameter, about the same distance as from Los Angeles to Pittsburgh. As an American, I think in terms of miles, but the metric system is the unit of measurement that prevails once you leave the U.S. and the Earth. So all distances and sizes given in this book are in meters or kilometers. Personally, I don't have trouble using different units for the Moon — it's part of the other-worldly experience of planetary exploration. But if you don't think metric yet, a kilometer is about six-tenths of a mile. The smallest features that can be seen when looking at the Moon through a telescope measure 1 or 2 km across. However, many craters are immense. The bright crater Copernicus is about 93 km wide — a large city could fit comfortably on the floor of Copernicus, and hopefully someday one will.

It's easy to be overwhelmed by the vast numbers of craters and other features on the Moon, but it is easy to find your way around by first learning to recognize the dark mare patches and a handful of the most conspicuous craters. These can then serve as landmarks for finding any place on the Moon. The map facing page 1 schematically outlines features you can easily learn. The map is oriented as you see the Moon with your naked eye or binoculars. Thus, the north polar region of the Moon is located at the top of the map near Mare Frigoris (Sea of Cold, as expected for a polar zone). Modern lunar maps like this one reflect conventions established during the Apollo program and show the Moon with north at the top, because that's the way an astronaut would see it. But for many telescope users — stuck between a lover's glance at the romantic Moon and an astronaut's close encounter — the Moon and everything else in the universe is inverted. This is why older, pre-Apollo Moon maps have south at the top. South up matches the view in Newtonian reflectors as well as in refractors, Schmidt-Cassegrain telescopes, and Maksutovs used without star diagonals. However, if used with star diagonals, these same telescopes show the Moon with north up but east and west reversed.


The relative sizes of the Earth and Moon.

To make things even more confusing, the astronautic convention of lunar directions also switches east and west from an Earthbound perspective. Traditionally, the lunar region nearest the eastern horizon of the Earth (as seen from our planet's Northern Hemisphere) was said to be the eastern limb of the Moon. Thus, a dark patch on that limb was named Mare Orientale, the Eastern Sea. However, on modern astronautic maps, Mare Orientale is now confusingly located on the western limb of the Moon. So unless otherwise noted, the charts and photographs reproduced in this book will have north at the top and south at the bottom, which will place lunar west to the left and lunar east to the right. Got that?

A large part of the western hemisphere of the Moon consists of interconnected dark maria. Oceanus Procellarum is the largest and least well defined mare region on the Moon, merging southward with Mare Humorum and Mare Nubium, and north into Mare Imbrium. Mare Frigoris, the only mare patch that's not even roughly circular, connects Procellarum to the eastern maria: Serenitatis, Tranquillitatis, Nectaris, and Fecunditatis. Mare Crisium is easy to spot as an isolated circular mare near the eastern limb.

After getting your bearings, it's fun to use a telescope to identify other craters and basins as they come into view over the course of a month. As a lunation progresses, the Moon gradually becomes fully illuminated as the morning terminator sweeps across its surface. When the Moon grows from a thin sliver to first quarter and then to full, it is said to be *waxing*. After full Moon, the evening terminator appears on the eastern limb and moves progressively westward; then the Moon is *waning*. It takes about 29.5 days for the Moon to pass from one new Moon to the next, and it is customary to designate lunar phases by the number of Earth days that have passed since new Moon. First quarter occurs at about 7 days, full Moon at 15 days, and third quarter at 22 days.

When the Moon is young and appears as a thin crescent in the western sky at sunset, Mare Crisium is the most conspicuous feature, with the large, flat-floored crater Cleomedes (126 km)* nearly touching it to the north. Southward, the principal landmarks are two large, fresh craters with central peaks: Langrenus (132 km) and Petavius (177 km). Two or three days later the Moon is nearly at first quarter, and the terminator passes through western Mare Serenitatis. To the north are the shadow-filled craters Aristoteles (87 km) and Eudoxus (67 km), while Posidonius (95 km) appears as a fine object on Serenitatis's eastern shore. Probably the most dramatic crater at this phase is the 100-km-wide Theophilus on the edge of Mare Nectaris.

By the time the Moon is gibbous (more than half illuminated), about 10 days after new Moon, a variety of spectacular craters appear. The 225-km-wide crater Clavius is visible near the lunar south pole, and nearby is Tycho (85 km), probably the youngest large crater on the Moon — only 109 million years old! Near the center of the Moon, three craters in a row, Ptolemaeus (153 km), Alphonsus (119 km), and Arzachel (97 km), are a fascinating case study of variations in impact-crater morphology. But the king of all craters is Copernicus. Compared to Tycho, Copernicus is not only larger but better placed for a more powerful impression of grandeur on terrestrial observers. Nearby is the lesser crater Eratosthenes (58 km) on the southern rim of the Imbrium basin. Skipping other less-conspicuous craters, we come to two similar dark-floored craters, Archimedes (83 km) and Plato (101 km).

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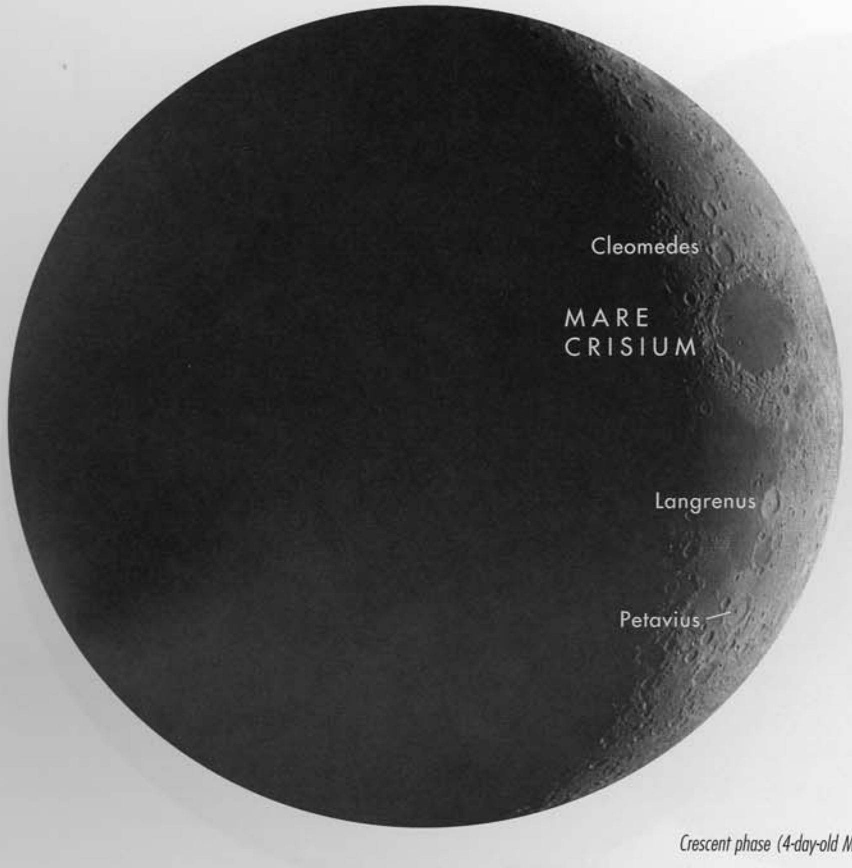
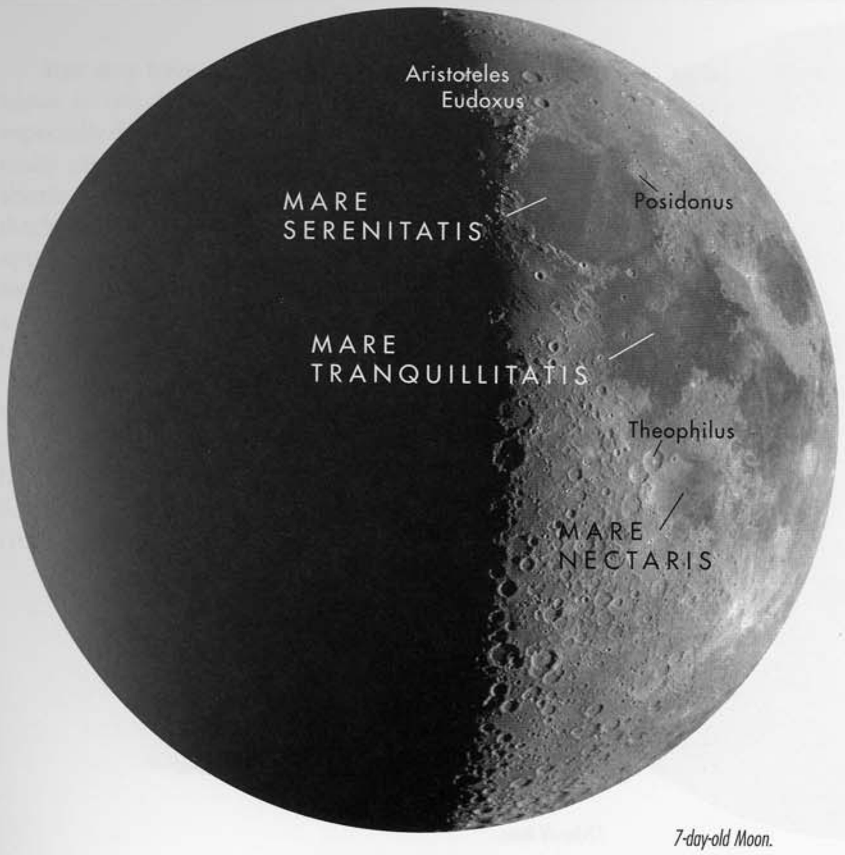
* *Throughout this book crater diameters are given in parentheses immediately following the crater's name.*

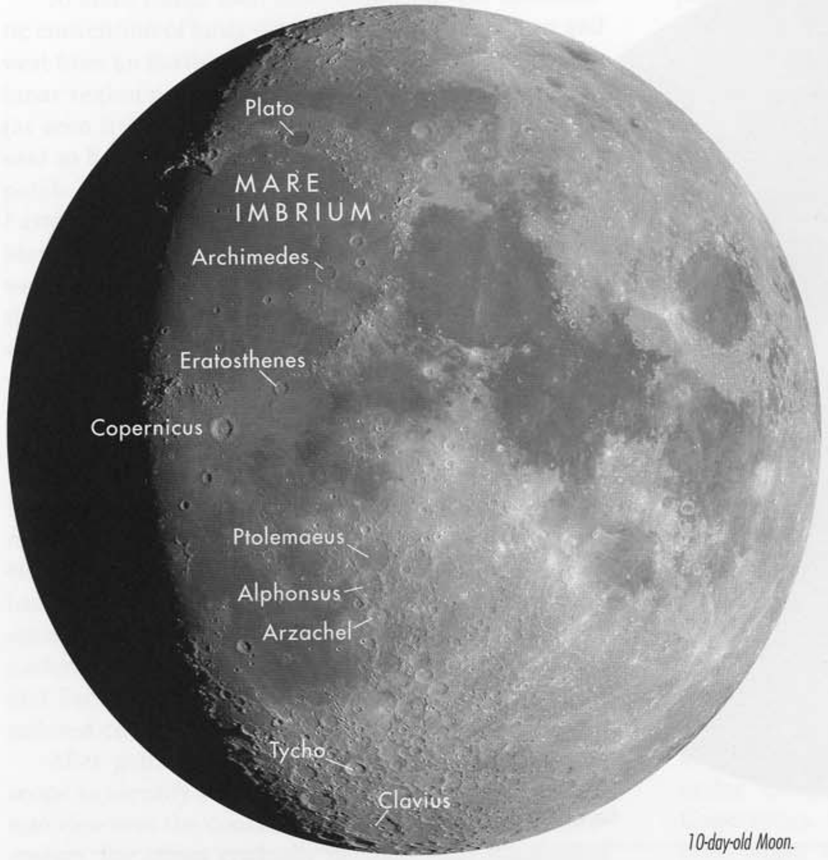
Three views showing different orientations.



Crescent phase (4-day-old Moon).



7-day-old Moon.



10-day-old Moon.

12-day-old Moon.

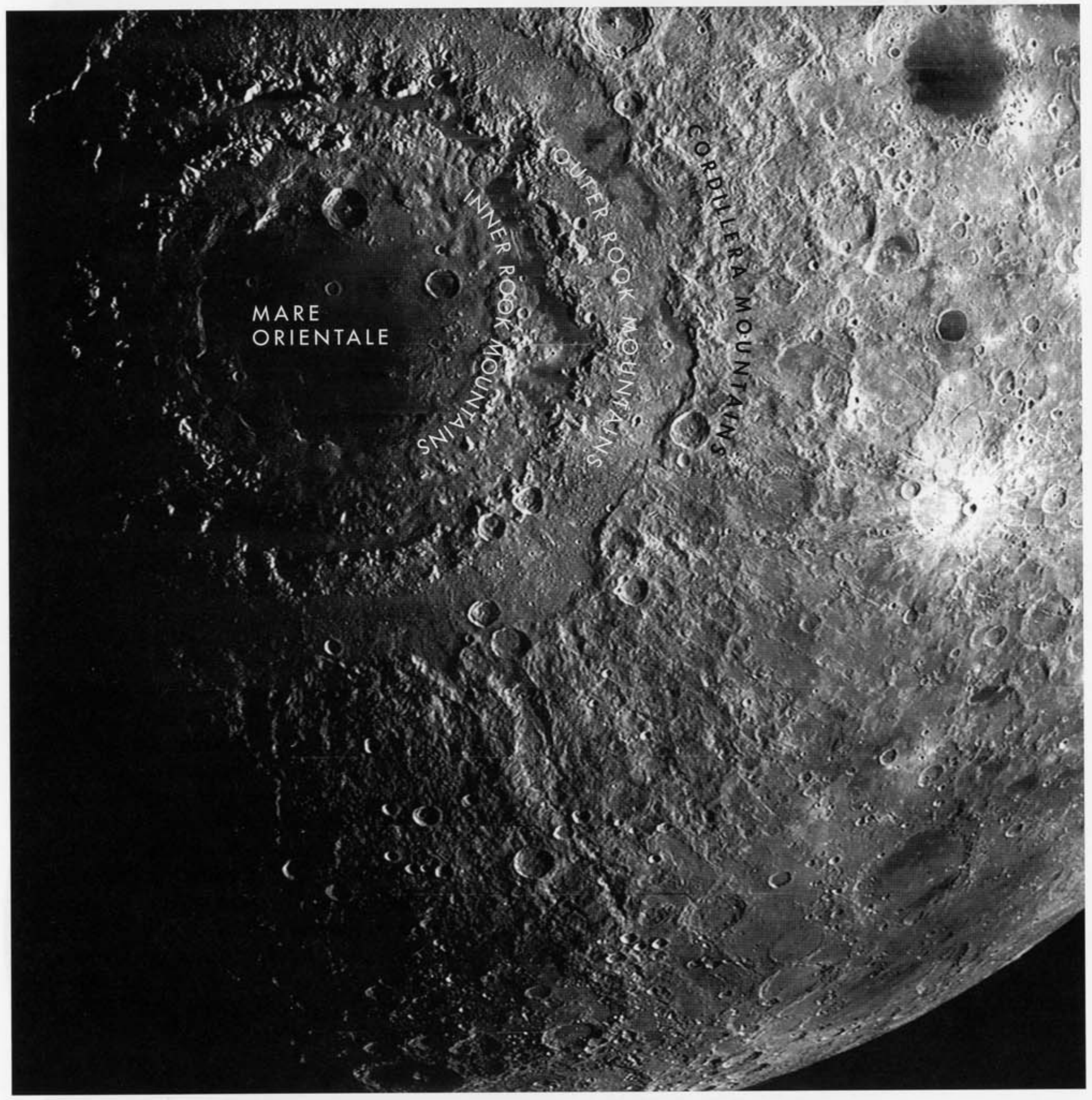
14-day-old Moon.

You may have noticed that the outline of Copernicus is roughly circular but that Archimedes and especially Plato appear elliptical. Lunar craters are generally circular, but the ones near the limb are foreshortened by the viewing geometry. Use a felt-tipped marker to draw a circle on a balloon and watch how it appears to change its shape as you rotate the balloon away from you. Craters right on the limb of the Moon are foreshortened to almost nothing and are seen only in profile.

By the time the Moon is 12 days old the advancing terminator reveals additional craters. In the south polar region there is one of the largest craters on the Earth-facing side of the Moon, 227-km-diameter Schickard. Cutting into the northern rim of the Humorum basin is Gassendi (110 km), with broad troughs crisscrossing its floor. West of Copernicus is Kepler (32 km), a similarly shaped but pint-sized bright crater. And near the terminator is the brightest large crater on the Moon, Aristarchus (40 km). Finally, on the north shore of Mare Imbrium is a lava-flooded crater so huge it is generally not called a crater at all but is given the poetic mare-type designation Sinus Iridum (260 km), the Bay of Rainbows.

Just before full Moon, one new crater or small basin becomes conspicuous, dark-floored Grimaldi (410 km). But surely the star of the show is Tycho. This glistening white crater surrounded by a dark collar is the source of the most conspicuous system of bright rays girdling the Moon.

Now that the Moon has been properly introduced, let's start learning something about it.



Orientale basin.

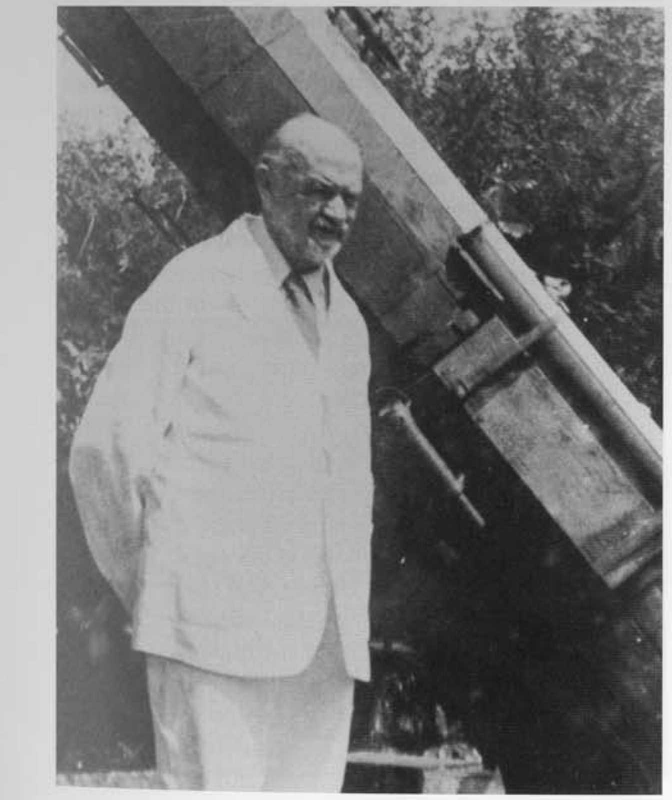
2

Impact Craters and Lava Flows

The Moon is a crater junkyard. With even a small telescope, thousands of craters are visible. For generations people who study the Moon, or selenographers (derived from Selena, the Roman goddess of the Moon), struggled to understand the origin of lunar craters. This was the central question of lunar science. Until the latter half of the 20th century, most observers believed that lunar craters were volcanoes. They were wrong.

IMPACT OR VOLCANIC CRATERS?

There were long and heated debates about the origins of lunar craters, but few of the early arguments were valid. By and large, the lack of progress stemmed from two factors. First, geological and physical understanding of the mechanisms of impact and volcanic crater formation on Earth were at a rudimentary stage. Prior to 1906, when Meteor Crater in Arizona was identified as having been formed by the impact of an iron meteorite, such features were not even believed to exist on Earth. Furthermore, until field mapping, nuclear bomb tests, and laboratory experiments took place in the late 1950s and early 1960s, the actual physics governing the way impact craters form remained uncertain.



William Henry Pickering.

The early ignorance of the impact process misled even experienced observers such as William Henry Pickering, an astronomer at Harvard College Observatory. Pickering made many excellent telescopic observations of the Moon and compared them with volcanic features in Hawaii. Some of his analogues are still accepted. For example, lunar domes are small lava shield volcanoes like their counterparts in Idaho and Iceland. But Pickering could not accept the impact theory for craters, which as he said in 1920, had "recently been revived from obscurity," because there was little evidence to support it. Pickering listed several objections to the impact hypothesis:

1. *If the Moon's myriad craters are due to impact, why are there not more of them on Earth?* Currently, we know of about 200 impact craters and their remains on Earth and that a great many more must have been erased by erosion and plate tectonics, a process that was unknown in Pickering's time.
2. *The only known terrestrial meteorite crater [in 1920] is Meteor Crater, Arizona, which — unlike lunar craters — has no central peak.* The mistake here was in failing to notice that small lunar craters the size of Meteor Crater (a mere 1 km wide) also lack such peaks! As we will see, central peaks only become common in lunar craters larger than about 15 km.
3. *Lunar craters are nearly circular, but projectiles should come from all directions, so impact craters should be elliptical.* If impact craters were formed simply by the gouging action of a falling projectile, this argument would be valid. However, mathematical analyses by isolated scientists in Estonia and New Zealand demonstrated that the great speeds of impacting meteorites, which would instantaneously release a tremendous amount of energy in a violent

point-source explosion, would produce round craters. In the 1960s these theoretical arguments were dramatically proved in a series of experiments at NASA's Ames Research Center. Don Gault and his colleagues at NASA fired small projectiles at hypervelocity (speeds of kilometers per second) into targets, thus documenting for the first time the effects of very high energy impacts. These experiments were critical to understanding secondary craters, oblique impacts, and impact-crater stratigraphy.

Pickering made a number of other objections concerning the details of crater morphology, in particular the reported occurrence of crater pits on the summits of central peaks. It would, indeed, be very difficult to explain these pits as chance meteorite impacts, but such pits would be expected if the peaks were volcanic cones like Vesuvius in Italy. This argument was endlessly repeated through the 1960s until high-resolution photography from the Lunar Orbiter spacecraft showed that the pits didn't exist. They were among the many illusions created by poor telescopic resolution.

Pickering's arguments were all cogent, and his rejection of the impact origin of lunar craters was consistent with the knowledge generally available at the time. In this respect he was a competent scientist, but the science of his day was simply not good enough to provide the correct answer.

Pickering also seemed unaware of a paper published in 1893 by Grove Karl Gilbert, chief geologist of the United States Geological Survey (USGS). Gilbert was probably the first scientist to theorize about the origin of lunar craters who had actually studied both terrestrial volcanoes and impact craters (Meteor Crater in Arizona). Moreover, he had observed the Moon through the powerful 26-inch refractor at the Naval Observatory in Washington, D.C., and even made his own experimental craters. His geologic and telescopic experience prepared him to write the most prescient paper in lunar science, which, unfortunately, was also the most overlooked. Gilbert rejected the various volcanic theories for lunar craters because their detailed features did not match terrestrial volcanoes. He observed that lunar craters have floors that are lower than the surrounding plains, their central peaks are lower than their rims, and their diameters are much larger than any of Earth's volcanoes.

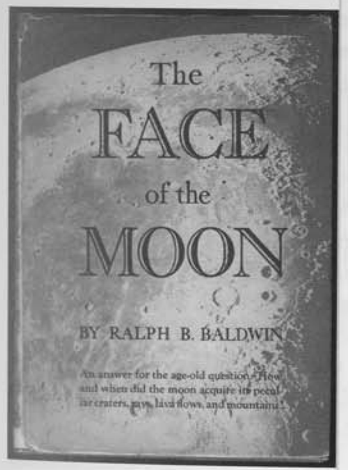
Grove Karl Gilbert.

Gilbert's simple experiments in impact-crater formation produced craters that matched the rims, peaks, and rays of lunar craters. He eventually came to the startling realization that impact craters had no size limits — larger or faster-moving projectiles would excavate larger craters. Gilbert proposed that virtually all lunar depressions from small pits to mare basins were created by impacts. He was essentially correct in nearly everything he said, but nobody seemed to notice. Perhaps the reason his great work was overlooked for more than 50 years was that it appeared in the *Bulletin of the Philosophical Society of Washington*, a prestigious journal no doubt but one not commonly read by geologists and astronomers. Another reason was pointed out by USGS scientist Eugene Shoemaker, who noted that Gilbert's ideas were immediately and roundly attacked by European geologists, including Eduard Suess, the most famous geologist of the era. Gilbert's outrageous hypothesis, though based on observations, experiments, and physical theory, could not surmount the authority of a prominent scientist — even one who knew virtually nothing about the Moon!

The second factor that stalled progress in understanding the origins of lunar craters was the general quality of the observations and the arguments. Although many of the participants in the lunar crater debates were scientists, they often overlooked obvious facts that would be fatal to their pet theories. Or as Phillip Fauth, an opinionated and somewhat crazed lunar observer, perceptively wrote of other lunar theorists, "The less they know of practical observation of the Moon in detail, the more they seem prepared to solve the riddle [of the origin of the craters]." Perhaps the most frequent errors involved the neglect of scale and morphology. Rarely did the proponents of volcanic theories notice that terrestrial volcanic craters are much smaller than lunar craters and that terrestrial volcanic craters commonly occur atop broad and massive mountains, which is certainly not the case for lunar craters. In addition, the volcanists were not deterred by the observation that lunar craters are rarely associated with definite volcanic landforms such as lava flows or conical, crater-capped mountains. Many of the proposed volcanic mechanisms were for processes that had never been observed or even hinted at on Earth, like the bursting of 100-km-wide magma blisters. Finally, many of the arguments about crater origins were simply puerile and not constrained by known physics or geology.

Much of the 20th century's debate about lunar craters was waged by dedicated amateur astronomers who had little or no formal training in geology, astronomy, or any other science. Professional astronomers had all but abandoned the Moon for astrophysics, and most geologists never seemed to look at the Moon. So it was amateurs who earnestly asserted their opinions in periodicals like the *Journal of the British Astronomical Association*, and almost no one else cared.

The correct interpretation of the origin of lunar craters came from careful quantitative analysis of the shapes and sizes of both experimental and natural craters. The hero of this story is Ralph Baldwin, who was trained as an astronomer but spent most of his life running the family machinery business. Baldwin became interested in the Moon while lecturing at Chicago's Adler Planetarium in 1941. He told me that while waiting for his class to begin he became fascinated by the details visible in the large photographs of the Moon adorning the planetarium's walls. His first paper describing his observations and theory, "The Meteoritic Origin of Lunar Craters," was rejected by three astronomical journals. Baldwin was so incensed by these rejections that he vowed to continue his lunar studies.



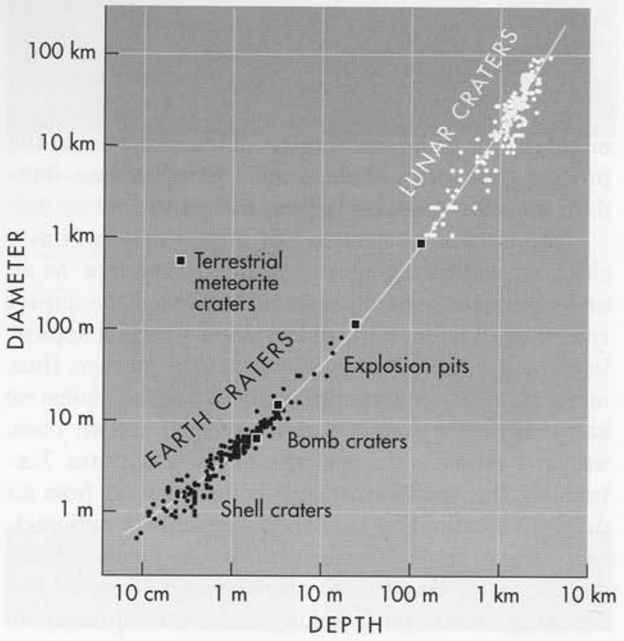
The book that convinced most scientists that lunar craters formed by impacts of asteroids and comets.

Ralph Baldwin.

During World War II, Baldwin noticed that the Allied bombing produced craters in Germany that were very similar to lunar craters. After the war he made small explosive craters in the beaches of Lake Michigan. Careful measurements showed that the depth-to-diameter ratios of his beach, bomb, terrestrial impact, and lunar craters were very similar. In his classic 1949 book, *The Face of the Moon*, Baldwin published the depth-to-diameter ratio graph for these craters and concluded:

> *There is thus a very smooth curve which represents equally well the largest Class 1 [freshest] lunar crater and smallest terrestrial explosion pit. These two groups, tied together perfectly by [terrestrial] craters of known meteoritic origin, form a relationship which is too startling, too positive, to be fortuitous. . . . The only reasonable interpretation of this curve is that the craters of the moon, vast and small, form a continuous sequence of explosion pits, each having been dug by a single blast. No available source of sufficient energy is known other than that carried by meteorites.*

Baldwin's crisp, persuasive writing style, experimental data, and quantitative approach brought his book to the attention of Gerard Kuiper, Harold Urey, and other leading students of the Moon, who were convinced by his arguments. But some scientists and many lunar observers clung tenaciously to volcanic theories. Many of these holdouts were geologists, notably Jack Green and G. J. H. McCall. Interestingly, there was



This graph of crater depth versus diameter is based on Baldwin's work.

also a strong national bias in accepting the impact theory. In general, many American scientists embraced impact, but many Europeans (especially Soviets) defended volcanism. At last count, only two or three scientists still believe that lunar craters are volcanoes.

In my mind the clinching evidence for impact cratering was not found in Baldwin's graph but through space exploration. Lunar rocks brought back to Earth by the Apollo astronauts were predominantly *breccias*, rocks fragmented by impact. The minerals within the breccias were strongly shocked by high pressures and temperatures that are known to occur only in high-speed impacts, and some minerals melted completely. While some holdouts continued to claim these effects were due to volcanism, it is very unlikely that exactly the same style of volcanism would have affected meteorites, which are also shocked, nonvolcanic breccias but from elsewhere in the solar system.

Another conclusive observation is that nearly every rocky or icy planet and moon visited by spacecraft shows the same kind of cratering that we see on our Moon. This multiplanet evidence demonstrates overwhelmingly that nearly all craters in the solar system (including the Moon's) were formed by high-speed collisions caused by impacting asteroids and comets. Volcanism did occur on the Moon as vast lava flows that formed the maria, but almost all lunar craters are, without a shred of doubt, impact scars.

IMPACT CRATERS AS TOOLS

Impact craters are as common in the solar system as sand grains in Florida. As spacecraft have explored deeper into space, impact craters have been discovered on virtually every world with a solid surface. There must be billions of impact craters of microscopic size and larger in the solar system. They result from cosmic collisions repeated ad infinitum or, as some might say, ad nauseam. Because of the sameness of the process that forms them, craters have become standard tools for investigating a planet's history.

The most important use of impact craters is as a clock for estimating ages of planetary surfaces. As an undergraduate research assistant I counted the impact craters on different parts of the Moon. As a first approximation, the more craters, the older the surface; thus, maria are clearly younger than highlands. But unless we know how many craters were formed per million years, we can't estimate the real age of these features. Fortunately, the Apollo astronauts collected rocks from six different locations on the Moon. Subsequent radiometric dating of the Apollo samples transformed the lunar surface-crater counts into absolute ages. Now, by just counting craters (and making some assumptions) we can estimate the age of any part of the lunar surface, and with more assumptions, the ages of all the terrestrial planets. Thus, Mars has surface regions that range in age from a few hundred million to 4 billion years old, while the entire landscape of Venus seems to be less than 500 million years old.

The details of a crater's shape or morphology depend somewhat on the strength of the target rock it forms in, so impact craters can also provide information on the physical properties of near-surface rocks without actually having to retrieve samples of them. But one of the most exciting uses of craters is as marker fossils, whose battered or fresh appearance is a clue to geologic processes, such as erosion, sedimentation, or lava flooding, that can modify a planetary surface. Because a newly formed impact crater has a characteristic shape, deviations are probably due to later alterations. On Mars, for example, windblown dust has shallowed many impact craters, and many crater walls on the Moon have been obliterated by lava flooding or repeated abrasive "gardening" by countless tiny impacts.

THE CRATER MAIN SEQUENCE

Most early selenographers thought the variety of crater morphologies represented fundamentally different types of structures. Not really understanding how craters formed, early Moon mappers demonstrated their scientific mettle by classifying craters into types with a plethora of different names: walled plains, mountain rings, ringed plains, crater plains, craters, craterlets, crater cones, crater pits, obscure rings, and depressions. While these various designations generally reflect differences in crater details (often due to later modification), they also obscure the underlying progression in crater morphology, which is simply a function of increasing diameter. Each lunar impact crater is unique, just as each human is, but there are only a few standard types of craters. From smallest to largest, impact craters have either simple, complex, or basin morphologies. This progression has been termed the main sequence of impact craters by lunar geologists at the USGS.

SIMPLE CRATERS: LALANDE A

Most lunar craters are of the simple variety in main-sequence terminology. A good example is Lalande A, a 13-km-wide, 2.6-km-deep, fresh-looking impact crater near the center of the Earth-facing hemisphere of the Moon. Lalande A is so small that even in a telescope at high power it appears only as a circle with a curved black shadow running from the arcuate rim through the middle of the crater. There are thousands of similar simple craters on the Moon, all small and with interiors that are difficult to see.

Apollo images reveal Lalande A to be a flat-floored bowl with a low, circular rim rising only a few tens of meters above the surrounding plain. The narrow streaks of bright material on the crater wall are tracks of boulders that tumbled down the relatively steep slope, contributing to the small, flat floor. Some simple craters do not have flat floors, apparently because debris did not roll down their rims. With careful use of a telescope an observer can determine whether a simple crater has a flat or rounded floor by examining shadows, which, when they fall in the exact center of the crater, are either rounded (parabola-shaped floor) or truncated (flat floor).

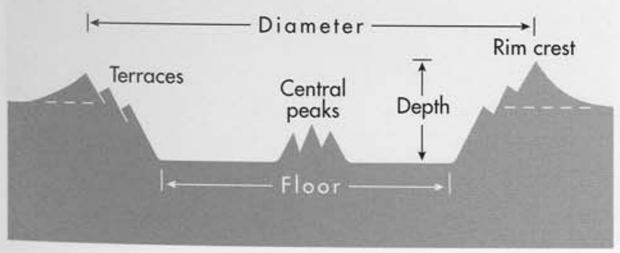
Despite their name, the formation of simple craters is an extraordinarily complex process that few lunar scientists clearly understand. But a fundamental explanation of this important and dramatic solar-system process is easy — just stick with me. The following is based on the ideas presented by Jay Melosh of the University of Arizona in his definitive book *Impact Cratering*.

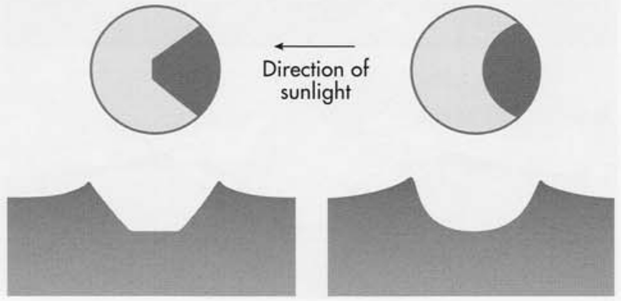
One reason the impact origin of craters was not accepted for many years is that the very high energy levels involved are beyond human experience. For example, the 1-km-diameter Meteor Crater in Arizona was probably formed by the impact of a 30-meter-diameter nickel-iron meteorite traveling through space with a velocity of about 20 km per second. That crater-forming impact was equivalent to a head-on collision with a mile-long freight train speeding along at 43,000 miles per hour!

Although the formation of a simple crater is a violent event that takes only a few minutes, there are three phases. First, naturally enough, is the compression phase, the contact of the projectile with the target rocks. The incoming meteorite is traveling so fast that it pushes the solid target material down and sideward, out of its way, virtually instantaneously. Shock waves (which are just highly energetic versions of pressure waves such as sound) travel through both the target rocks and the meteorite, creating intense pressures that fragment, melt, and vaporize portions of both.

Simple crater Lalande A as seen from lunar orbit (top) and from Earth.

THE PARTS OF AN IMPACT CRATER





Simple craters with flat floors have angular shadows (left); curved floors produce rounded shadows (right).

The previously inert patch of target rock has now absorbed the unbelievable kinetic energy of the impact and is aquiver from the effects of the intense pressures, temperatures, and velocities. At this point only about $^{1}/_{100}$ second has elapsed.

In the second phase, which immediately follows the compression phase, an expanding hemispherical shock wave passes deep into the target but is finally rarefacted — bounced back toward the surface and decompressed — ejecting material away from the impact point in curtains of debris that rain down onto the quaking surface. The force of the explosion also overturns a flap of rock, forming a rim, with deeper rocks on top of near-surface ones. Thus a hole in the ground (a transient cavity) is opened up by explosive excavation. This excavation phase takes a few minutes and produces a hole tens of times larger than the errant projectile that started everything.

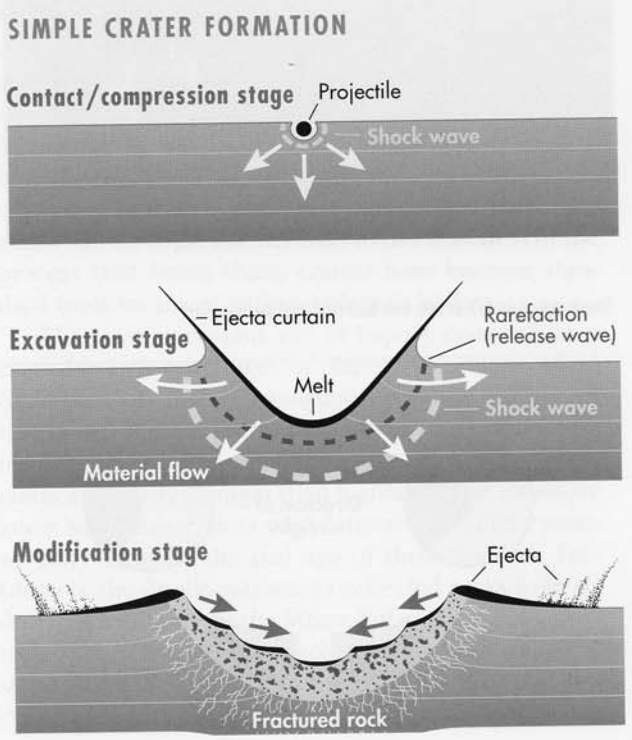
Once the target rocks have unburdened themselves of the intense pressures from impact, modification of the resulting crater begins, marking the third phase. Originally a deep, bowl-shaped transient cavity, the walls now readjust to form a broader but shallower depression, essentially the simple crater we see today. Small-scale changes continue as debris slides down the steep inner rim and ponds onto the crater floor. For simple craters, life's one great fling is pretty much over. The future, such as it is, will bring only slow degradation or maybe even destruction or burial by later impacts or lava flows.

This understanding of impact cratering stems from field studies, nuclear-weapon tests, and laboratory experiments that duplicate lunar crater shapes and sizes. Indeed, research into cratering continued as part of the Strategic Defense Initiative. It's nice to know that some of the billions of dollars spent on Star Wars is providing something useful and uplifting.

COMPLEX CRATERS: TRIESNECKER

Lunar craters with diameters larger than 15 to 20 km have a completely different appearance than simple craters. Triesnecker is a classic example — a 26-km-diameter crater with a somewhat irregular outline, bright upper wall, and wreath of rim material that apparently slumped onto its floor. The crater's west rim appears to have a bite taken out of it; this "scallop" was created by a large landslide that widened the rim on the west and dumped massive heaps of wall rubble that spread halfway across the floor. Besides the slumps, Triesnecker's floor has a small central peak complex and a patch of smooth, marelike material.

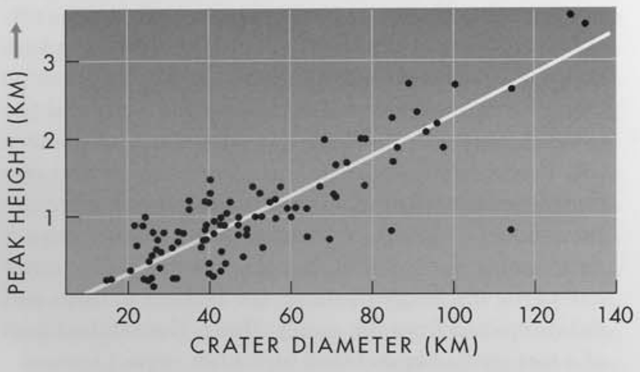
About 80 Triesnecker-type craters are found on the Earthward hemisphere of the Moon, with diameters that range from 15 to 50 km. While a simple crater will typically have a depth $^{1}/_{5}$ its diameter, the large-scale slumping of material from the walls of complex craters makes them shallower, with depths measuring only $^{1}/_{10}$ to $^{1}/_{40}$ their diameters. Furthermore, the floor itself is commonly veneered by totally melted target rocks.




Triesnecker.

Complex craters like Triesnecker owe their characteristic shape, or morphology, to the interplay of the strength of the lunar crust and the gravitational pull of the Moon. At the end of the excavation phase of crater formation, the rocks that make up the inner walls of simple craters are sufficiently strong to withstand collapse as they suddenly face the cavity of the newly formed crater pit. In other words, the rocks are strong enough to withstand the gravitational force trying to pull them into the newly formed hole. But for complex craters, the greater depth of the transient cavity and the larger expanse of the inner walls overwhelm the strength of the wall rocks, so they collapse in a jumble onto the crater floor.

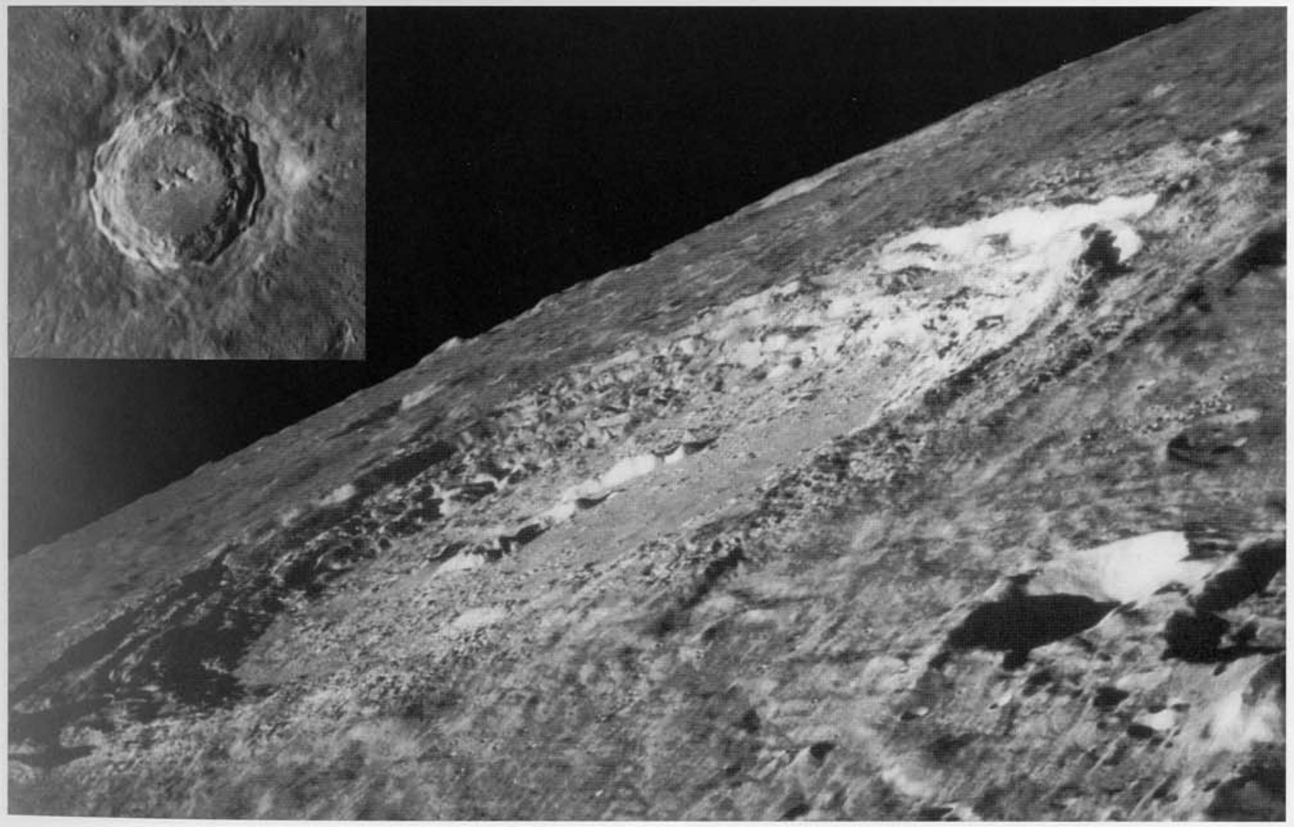
At the same time the walls are collapsing, intense compression at the center of the transient cavity imparted by the downward pressure of the impact leads to a concentrated rebound that uplifts subsurface rocks into a central mountain. Studies of central peaks of terrestrial impact craters demonstrate that the amount of uplift depends on the energy of impact and hence the diameter of the crater. For the 10-km-wide Deep Bay Crater in Saskatchewan, Canada, the uplift was only about 1 km. But at the 22-km-wide Gosses Bluff impact crater in Australia, 3 km of uplift occurred. Measurements show a similar proportional increase in the height of central peaks with increasing crater diameter for lunar craters, providing additional strong evidence of their impact origin.



The relationship between central-peak height and crater diameter is illustrated in this graph based on my research.

LARGER COMPLEX CRATERS: COPERNICUS

Copernicus is one of the grandest craters in the entire solar system. Compared to Triesnecker, Copernicus is not only much larger but also has "benches" on its


This oblique Apollo 17 photo of Copernicus shows the crater's steplike terraces, central peaks, and flat floor. Inset: The familiar telescopic view.

walls and a much broader, relatively flat floor with conspicuous central mountains. The shallowness of Copernicus was graphically illustrated by Dinsmore Alter, former director of Griffith Observatory near Los Angeles and a leading lunar scientist of the 1950s and early 1960s, who pointed out that if Copernicus were compared to a 9-inch-diameter pie pan, its depth would be only ⅓ inch. It was a startling revelation to me in graduate school when a friend pointed out that a large lunar impact crater resembles a saucer far more than the tea cup that sits on it.

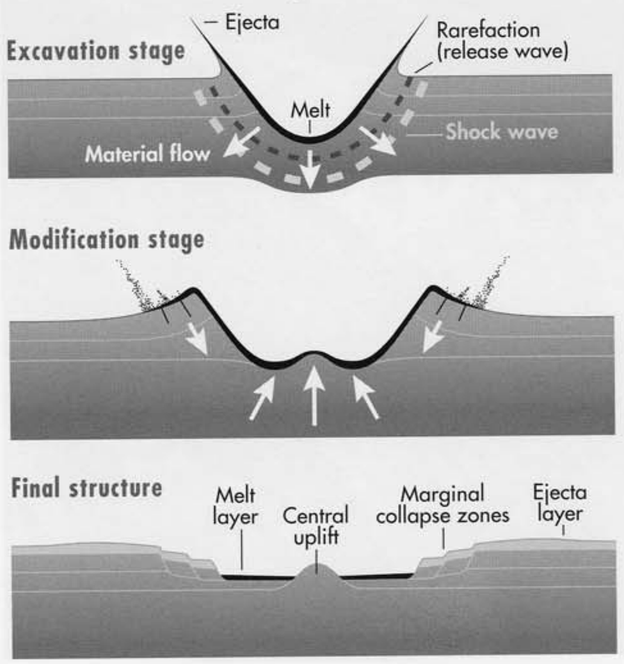
For craters larger than about 35 km in diameter, complex-crater morphology begins to change from the Triesnecker style to the Tycho style. For such large craters the collapse of the walls no longer yields incoherent slump masses but rather large concentric terraces bounded by relatively steep scarps. All of the large craters on the Moon are of this type — Tycho and Copernicus are the best-known examples, but approximately 45 more can be found on the near side of the Moon.

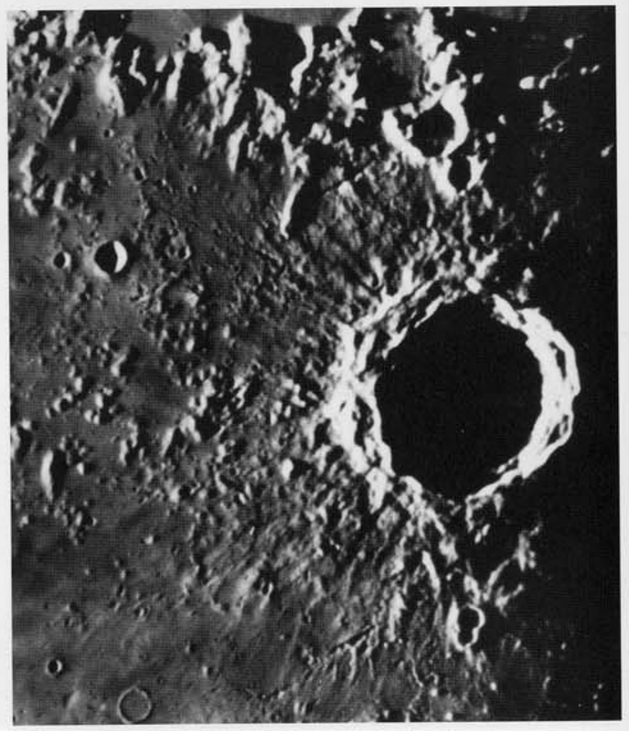
The formation of large complex craters like Copernicus simply results from greater impact energy. Melosh believes that the only way the observed terraces of complex craters can be explained is if lunar rocks temporarily behaved as if they were a viscous fluid. He proposes that rock debris (crushed in the compression stage of impact) beneath a crater moves like a fluid when strong impact pressure waves pass through it. This fluidized region allows transient cavity walls to flow or collapse inward toward the center of the cavity. The moving material converges in the middle and pushes up the rocks that become the central peak. All of this monumental readjustment takes place within a few minutes — impact cratering is the fastest geologic process known!

CRATER EJECTA

When the Sun's elevation is low you can see that the rim of Copernicus rises suddenly from the surrounding maria so that the crater appears to be built upon a circular platform. A hundred years ago selenographers called this external wreath a *glacis*, the word for a slope that provides a buffer between a castle's walls and the ground. Although the term has passed out of modern use, it accurately describes this often-ignored part of a crater's anatomy. The glacis is partially formed when the tremendous horizontal compression of the impact shock uplifts rocks under and near the crater. The other half of the rim height is simply the fallback of rocks and debris ejected from the crater. This is the thickest part of a vast ejecta blanket that surrounds impact craters.

Another feature that makes Copernicus a favorite of observers is its system of bright streamers, or *rays*, that radiate for hundreds of kilometers. The rays are virtually invisible at low Sun angles, but near full Moon Copernicus's rays are second only to those of Tycho in extent and visibility. The rays are actually lines of small secondary impact craters formed from debris ejected from Copernicus during its impact formation. What makes the rays of Copernicus so conspicuous is that they contain bits of bright highland rocks, excavated from beneath Copernicus, that are much brighter than the maria they landed on.


COMPLEX CRATER FORMATION


This sunset view of Copernicus highlights the crater's glacis.

ORIENTALE BASIN: ONE YOU CAN'T SEE

Basins are the largest class of impact craters, but they differ greatly from their much smaller brethren. Basins are considerably larger, measuring 300 to 2,500 km in diameter. They also feature strongly developed multiple rings, radial features, and massive ejecta blankets. All the large impact basins on the Earth-facing side of the Moon have been flooded by lava flows. Thus, while their circular shapes are apparent, details of their interior structures are hidden. It was only with the discovery of the nearly pristine Orientale basin, just beyond the western limb of the Moon, that the actual structure of impact basins could be clearly recognized. Although the best photographs of Orientale are from the Lunar Orbiter 4 spacecraft that flew directly over it in 1967 (see pages 8 and 19), the basin was discovered six years earlier as part of a systematic study of the limb regions of the Moon.

Gerard Kuiper, an imposing Dutch-American astronomer, convinced the U.S. Air Force to fund a series of detailed photographic surveys of the Moon. The resulting *Photographic Lunar Atlas*, *Orthographic Lunar Atlas*, *Rectified Lunar Atlas*, and *Consolidated Lunar Atlas* provided a wealth of high-quality images that became the standard data sources for astronomers, geologists, and Moon mission planners. The Orientale basin was discovered in 1961 by Kuiper's graduate student Bill Hartmann while he was working on the *Rectified Lunar Atlas*. This impressive work showed all regions of the Moon as seen from directly overhead, a perspective achieved by projecting Earth-based telescopic images of the Moon onto a 3-foot-diameter white hemisphere and then rephotographing them.

This process stretched out the foreshortened craters near the Moon's limb, transforming them from narrow ellipses into circles. I was an undergraduate assistant in Kuiper's Lunar and Planetary Laboratory at the time and vividly recall the excitement and awe of looking at the undistorted limb of the Moon in the darkened projection tunnel.

Orientale is a 930-km-wide multiring impact basin with only a small amount of mare basalt covering its interior. Because it is the youngest large basin on the Moon (only about 3.84 billion years old), it has not been battered by debris from subsequent basin-forming events. Thus, the entire structure of Orientale, from its exterior ejecta blankets to its inner rings, can be clearly seen.

Unlike complex craters, basins do not have central peaks. However, as the Lunar Orbiter photograph on page 8 shows, Orientale does have three relatively distinct rings. The outermost ring (named the Cordillera Mountains) has a conspicuous inward-facing scarp with radiating furrows of ejecta extending outward from it. The outer Rook Mountains define an intermediate, scarp-faced ring, and the inner Rooks form a broken circle of mounds and massifs. Only a small mare deposit occupies part of the basin interior, but other patches of volcanic material appear to have leaked out along the inner scarps of the Cordillera and outer Rook mountains.

Compared to complex craters, the vastly greater energy involved in basin formation somehow trans-

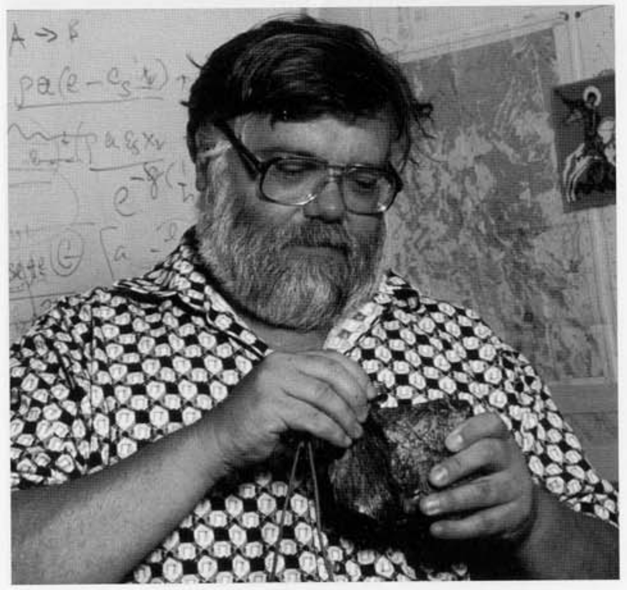

Copernicus's ejecta rays.


Bill Hartmann photographing telescopic images of the Moon projected onto a large white hemisphere.

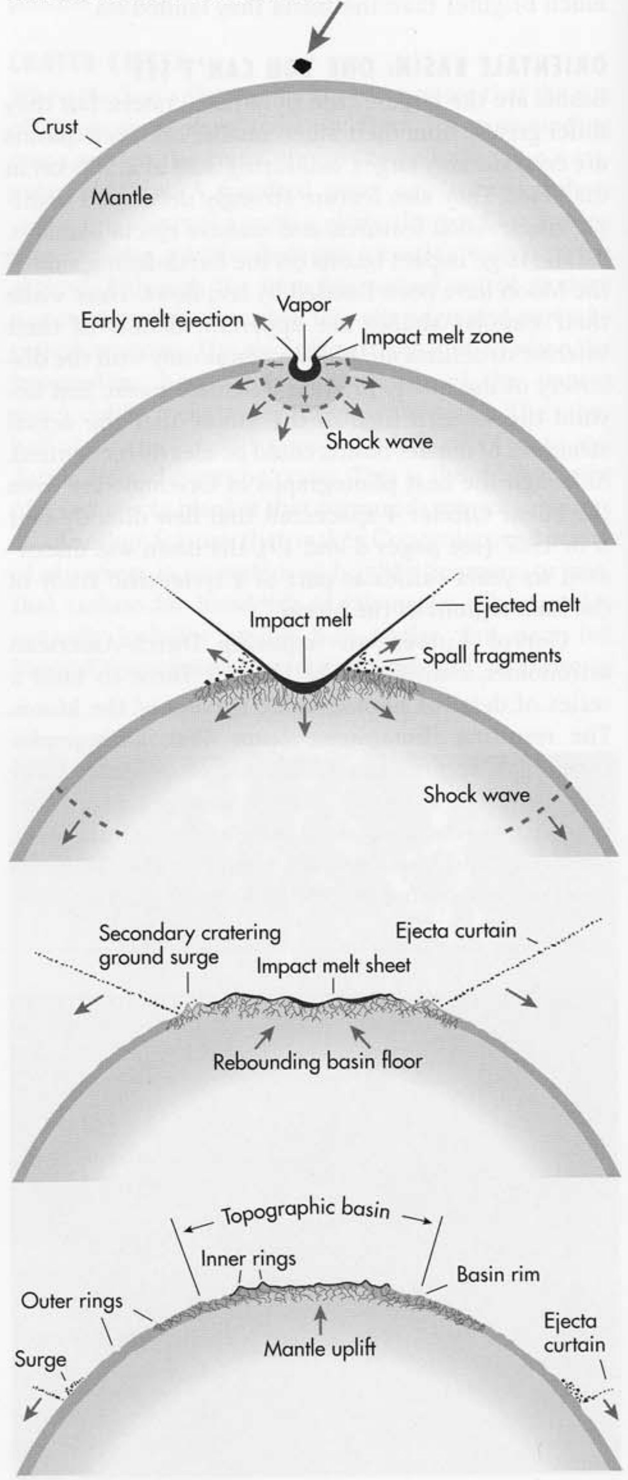
mogrifies central peaks into one or more inner rings. "Transmogrifies" is a good word for this process because it implies a fundamental change that is somewhat mysterious. There are various theories to explain the development of multiple rings, but we still don't understand the process clearly. An entertaining explanation emerges when the Moon's surface is compared to a pond into which a stone has been dropped — the Moon responds to the impact like a liquid, its surface making a series of ripples that freeze in place.

This analogy may not be as far-fetched as it seems. Melosh has conducted the most comprehensive analysis of impact cratering and offers a ring-tectonic theory for multiring basins. He posits that the actual strength of rock layers decreases with depth into the Moon. This is certainly true on Earth, where strong rocks overlie warmer, more plastic rocks farther down. Melosh reasons that the extraordinarily high pressures induced during basin formation would cause the lunar interior near the impact site to act like a liquid. If so, the movement of the fluid layers toward the center of the basin would drag the more rigid surface layer toward the basin's center as well, creating one or more fracture scarps or rings where the surface breaks apart. In this model the innermost basin ring (the inner Rook Mountains, in the case of Orientale) is the same size as the actual impact crater. The larger, usually better developed, outer rings are simple collapse scarps that greatly enlarge the apparent size of the actual impact crater.

The great beauty of Melosh's work is that by simply changing the diameter of the initial impact crater and the thickness of a planet's near-surface layer, his model predicts the morphology of complex craters, multiring basins, and weird basins with tens of rings like those discovered on the icy satellites of Jupiter.


Jay Melosh.

IMPACT BASIN FORMATION

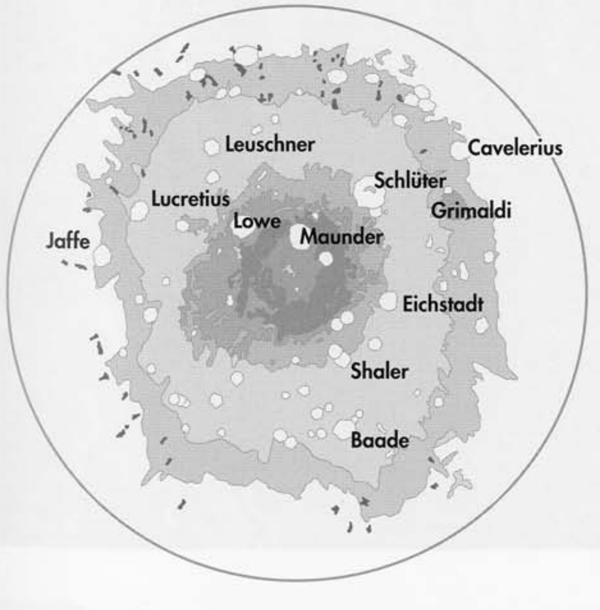


Nonetheless, many lunar scientists don't like Melosh's model because the inner rings of basins are often the least conspicuous. Perhaps, they hope, the model ignores some obscure but critical factor, and in reality the outer, usually well-defined ring represents the real crater diameter. But for now Melosh's overwhelming mathematical analysis has quieted most of his critics, who await a similar quantitative genius to elegantly "prove" their theories.

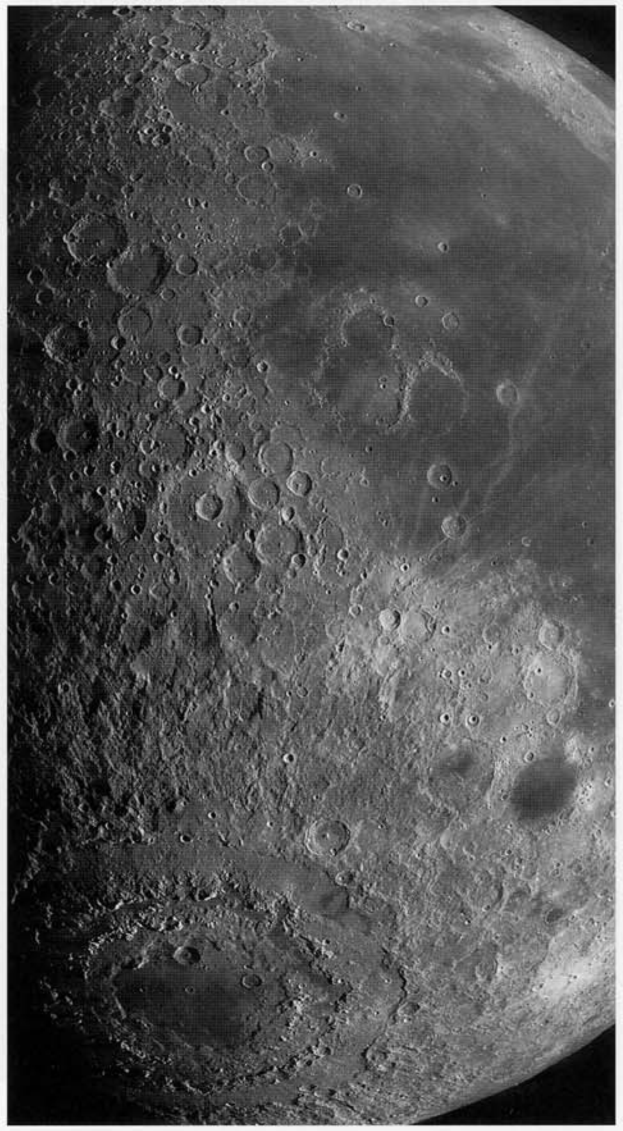
Basin rings have provided a lot of controversy and opportunity for planetary scientists to argue over the rings' number and size. I've played the basin-ring games myself. But basins are not just holes in the ground with interesting internal structures. They are also sources of rock flour, boulders, and mountains explosively excavated and ejected during the basin's formation.

As crater diameters increase, the area of surrounding terrain that is obliterated, buried, and subdued by ejecta increases exponentially. Thus, the separate linear rays of a Copernicus-type impact crater give way to the massive hemispherical blanketing that radiates from basins like Orientale. The vast area of the Moon affected by the formation of a single basin is well illustrated by the map of ejecta and secondary craters that ring the Orientale basin. If the bull's-eye of Orientale were centered on the side of the Moon facing the Earth, basins would have been discovered by Galileo, and the important role played by catastrophic impacts in solar-system history would surely have been gleaned much sooner.

As the terrain surrounding the Orientale basin illustrates, basin ejecta are terribly destructive, causing instant "aging" within minutes of the impact event. The erosive effects decrease with distance so that identical, preexisting impact craters can immediately develop radically different appearances depending on their distance from ground zero. The photograph below shows variations in a series of impact craters at increasing distances from Orientale. Close to the basin rim, preexisting craters are buried by thick deposits of flowlike ejecta and are hardly recognizable. Farther away, craters are shallowed by infill from ejecta and their rims are battered. At even greater distances the main effect is bombardment by large, relatively slow moving ejecta, which create secondary impact craters. These don't resemble main-sequence craters and until now had long worried geologists, who couldn't explain them.



This schematic geodic map from the USGS shows that various ejecta and mare deposits from the Orientale basin cover nearly an entire hemisphere of the Moon.


This Lunar Orbiter picture shows the battered lunar terrain surrounding the Orientale basin.

CRATER SHAPES REFLECT AGE TOO

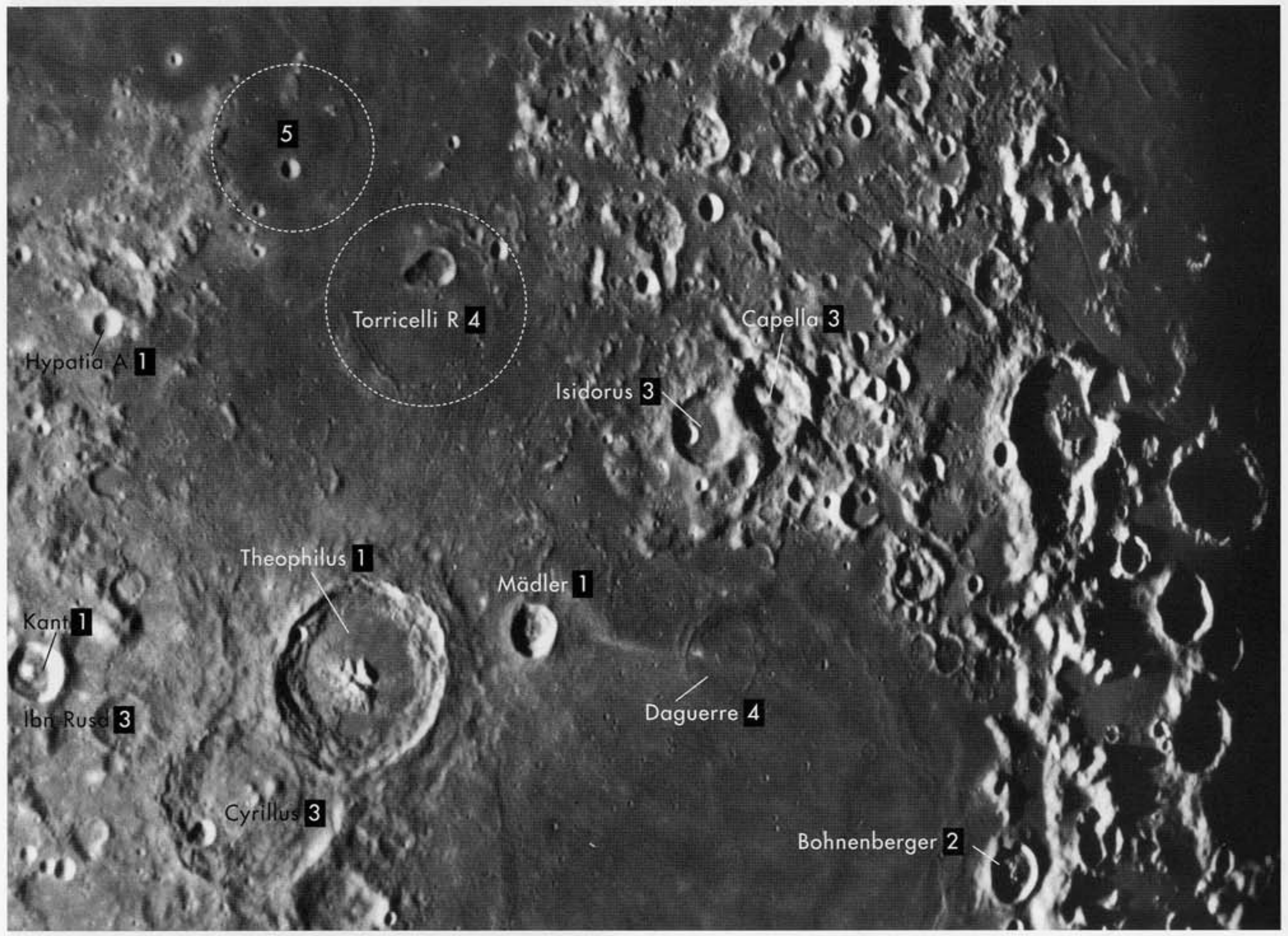
Prior to the 1960s many students of the Moon failed to appreciate that lunar craters were not all of the same age. Clearly some craters are directly superposed on earlier ones, while others are degraded, with broken walls or buried central peaks. Craters range from fresh to severely degraded. In an attempt to categorize a crater's erosional state, Baldwin introduced a crater classification scale. David "Dai" Arthur, an opinionated and clever Welshman who led a crater cataloging project that I participated in while at the University of Arizona some 30 years ago, later modified Baldwin's scheme.

The Arthur scale runs from Class 1 to Class 5. Fresh, Class 1 craters appear bright at full Moon and have complete, sharply defined rims with halos of bright material or even bright rays streaking away from them. Over time, fresh craters pass through a progressive sequence of morphological softening of their rims and central peaks. The most degraded craters we can recognize (Class 5) are fragmentary ruins that may possess only battered portions of the original circular rim. Of course, many previously existing craters must have been degraded beyond recognition.

There are too few craters accurately dated by Apollo samples for precise calibration, but a rough correlation between a crater's classification and its absolute age is:

ARTHUR CLASS	AGE (BILLIONS OF YEARS)
1	0 to 2.9
2	3.0 to 3.4
3	3.5 to 3.7
4	3.8 to 4.0
5	4.1 to 4.5

As an example of the pitfalls that stem from the failure to recognize that craters are of different ages, consider the case of Alter. Though a leading lunar scientist in the 1950s and early 1960s, he accepted that rayed craters like Copernicus must have been formed by impacts — the only mechanism sufficiently powerful to generate the tremendous energy necessary to throw out distant bright rays. However, he thought that craters like Eratosthenes formed from less powerful explosions because they had no far-flung bright rays. For Alter, Eratosthenes resulted from a weaker volcanic explosion that created an immense caldera. Instead of viewing the morphologies of Copernicus and Eratosthenes as essentially identical, he instead fixated on the latter crater's lack of bright rays and secondary craters. He didn't see the faint rays that radiate from Eratosthenes and didn't know that rays weather and disappear with age. Like so many selenographers before Baldwin, Alter attributed all crater morphologies to their formation and failed to recognize the profound role played by subsequent modification.



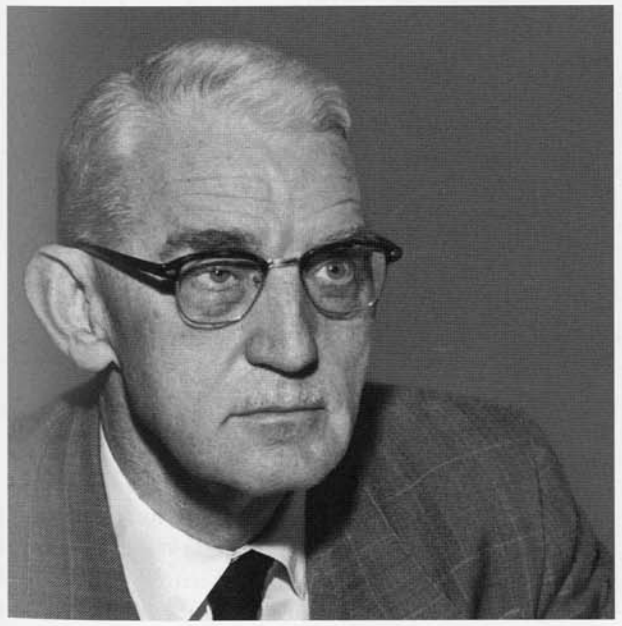
A region of the Moon near Theophilus with Arthur scale numbers indicated.

LUNAR VOLCANISM: HOW MUCH?

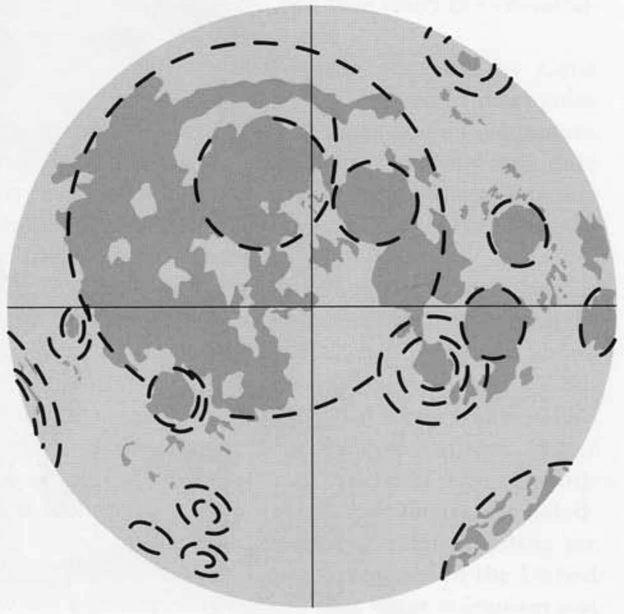
Most of the Moon is covered by craters — that's why descriptions of them dominate this chapter. But about 30 percent of the Earthward hemisphere of the Moon is covered by dark mare deposits. Samples of these deposits brought back to Earth by Apollo astronauts show them to be lava flows. In fact, virtually every solid planet or moon in the solar system is dominated by just two geologic processes: impact cratering and volcanism. The Earth is the leading exception to this generalization. Volcanism is certainly here — 75 percent of our planet is covered by lava flows — but most of the volcanic activity happens to be hidden beneath the oceans. The vast majority of the impact craters, however, have been destroyed by plate tectonics and other geologic processes. And our planet's active erosion cycles produce large quantities of reworked and redistributed sediments that fill in and obscure craters.

On Earth we tend to think of volcanic activity in terms of majestic mountains like Mount Fuji in Japan, whose eruptions form summit craters, build tall cones, and spread localized lava flows and ash deposits. Conspicuous conical volcanoes such as these do not exist on the Moon; only small volcanic hills or domes have been found there. Lunar volcanism has much less variety than volcanism on Earth. On the Moon volcanic activity was largely restricted to massive flows of basalt that filled the depressions of the giant impact basins. This large-scale, sheetlike volcanism is similar to vast deposits of lavas such as the Columbia River basalts of Washington, the Ethiopian and Siberian Traps, and the Parana Basalts of Brazil. Most, but not all, of these terrestrial plateau basalts formed in association with the plate-tectonic breakup of continental crust, where magma could rapidly rise from the mantle through crustal fractures to the surface. Plate tectonics never occurred on the Moon. Instead, deep fractures created by the formation of impact basins provided pathways for lunar magmas to rise up and erupt onto the surface as mare lavas.

Jim Head of Brown University has added up all of the mare material. He estimates that it makes up only 17 percent of the entire surface area of the Moon (there is very little on the far side) and that its combined volume is only about a trifling 1 percent of the total volume of the lunar crust. On Earth, only 10 to



Dinsmore Alter.



The dark maria make up most of the volcanism on the Moon. This schematic chart shows that the volcanic lavas filled the giant basins (dashed circles).

20 percent of the magma that is melted in the mantle reaches our planet's surface. The rest cools and solidifies within the crust. Even if we accept similar ratios for the Moon, apparently only a few percent of the lunar mantle melted — much less than for Earth. Perhaps the Moon contained much lower amounts of radioactive elements and did not heat up as much as Earth.

Only rarely can individual lava flows or their source areas be recognized on the maria. The best spot on the Moon to see the edges of lava flows is in southwestern Mare Imbrium. Individual lava flows are difficult to recognize, in part because they are many hundreds of kilometers long. Lunar lava flows could only have traveled such vast distances if they were extremely fluid. In fact, chemical analysis of lunar mare samples indicates that their viscosity was more like hot maple syrup than the thicker lavas common on Earth. Because lunar lavas were so fluid, they didn't solidify into very thick sheets. Measurements of the most conspicuous flows show that they are only 10 to 30 meters high. The margins of these thin sheets of lava were easily worn away by the continuous rain of tiny meteorites.

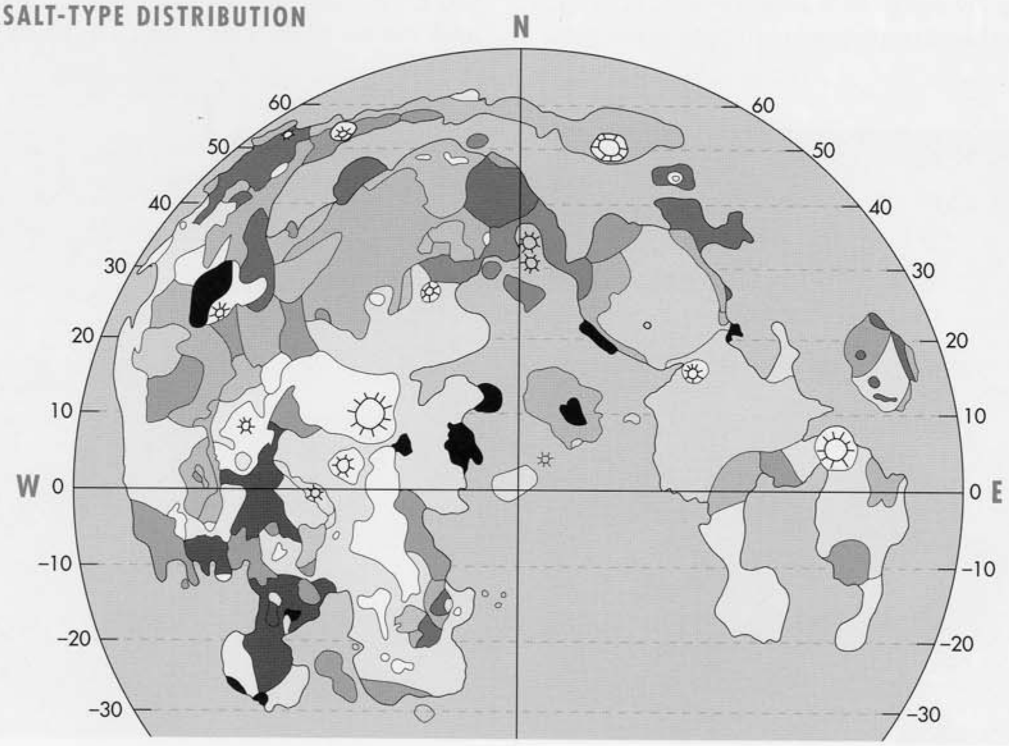
VOLCANIC ROCK COMPOSITIONS

The lavas making up the lunar maria are chemically very much like terrestrial basalts, the most common rocks on Earth. Basalts are about 50 percent silica but contain calcium, iron, magnesium and aluminum, as well as a smattering of other elements. Basaltic lavas from the Moon have more iron, magnesium, and titanium than most of the basalts found on Earth.

However, the most obvious difference between terrestrial and lunar basalts is that lunar basalts lack any trace of water. All terrestrial rocks contain some water (about 0.1 percent for basalts) in their constituent minerals. Scientists now believe that the Moon lost all its water because it completely melted during its formation.

The study of the chemical and isotopic compositions of terrestrial rocks has been a growth industry in geology over the last 70 years. Although only a handful of universities have academic units studying volcanism, and fewer still study impact cratering, every geology department on the planet has one or more petrologists. (*Petro* is Greek for rock, and just as Peter was the rock on which Christianity was built, petrology is the foundation of modern geology.) The very tools that petrologists employ — optical and electron microscopes and electron microprobes — determine their world view by permitting the examination of ever smaller details of rock and mineral compositions. Remarkable advances in understanding have followed from these studies, but petrologists are fascinated by small details and are more inclined to look for differences between rocks than for similarities. Thus, some volcanic rock types (for example, Kivuiites) are found at only one location on Earth.

MAJOR BASALT-TYPE DISTRIBUTION



In this schematic of the Moon's visible surface, each shade of gray represents lava flow of a different composition, as determined by Carlé Pieters. Note the diversity of types.

Lunar petrologists are like their terrestrial counterparts in defining many different compositions of lunar volcanic rocks — 21 thus far. They enjoy doing this, but most of us can lead full lives knowing only the three major families of mare basalts: high titanium, low titanium, and very low titanium. The element titanium (Ti) is not very important in classifying Earth's rocks, but its large variation in Moon rocks has led lunar petrologists to emphasize it when classifying basalts. Of course, there are other elements that need to be considered for detailed classifications. The table below is the work of Clive Neal and Larry Taylor of the University of Tennessee and shows how each of the three titanium basalt groups are further divided according to their abundances of aluminum and still further subdivided by differing concentrations of potassium.

CLASSIFICATION OF LUNAR BASALTS

TITANIUM	ALUMINUM	POTASSIUM	SAMPLE SOURCES	AGE (BILLIONS OF YEARS)
very low	low	low	Ap17, L24	3.6 – 3.7, 3.2 – 3.4
		high		
	high	low		
		high		
low	low	low	Ap12, Ap15	3.2 – 3.4
		high		
	high	low	Ap14, L16	4.0 – 4.3, 3.2 – 3.4
		high	Ap14	3.8 – 4.0
high	low	low	Ap11, Ap17	3.6 – 3.9
		high	Ap11	3.6
	high	low		
		high		

Modified from Neal and Taylor (1992) *Ap = Apollo, L = Luna*

Neal and Taylor's classification scheme defines 12 possible basalt compositional types, but only six of these have been sampled so far — the remainder likely await our return to the Moon. Neal and Taylor also note that the low-titanium, high-aluminum suite of rocks erupted over a period of nearly 1 billion years and are the most ubiquitous of the basalt types. Also notice that usually more than one rock type was recovered from each Apollo landing site. This is because each mare is complex and not simply filled with basalt of the same type and age. Finally, this table shows that basalts were produced by the lunar mantle from 4.3 billion to at least 3.2 billion years ago. Thus, it is unlikely that the basin-forming impacts (more than about 3.8 billion years old) generated the maria. These must have formed in response to heat left over from the formation of the Moon and from the decay of radioactive elements.

High-titanium basalts appear to be very common on the Moon, being widespread in Tranquillitatis, Procellarum, Imbrium, and Humorum. Low-titanium basalts seem to be concentrated within the northern part of Mare Imbrium, in Mare Frigoris, and in other nearby patches of mare material. The eastern maria Serenitatis and Crisium seem to be the home of the very-low-titanium basalts.

You may be asking yourself how Humorum, Procellarum, and other maria can have their rocks chemically classified if Apollo astronauts never went near them. The answer is extrapolation, the creative leap that distinguishes science from accounting. Not only were the Apollo samples chemically analyzed in laboratories, but their reflectivity in different parts of the spectrum was also measured. Although no one-to-one correlation exists, in general, samples that appear bright in the blue end of the spectrum tend to be high-titanium types. Low-titanium samples are brighter in the red end, and low-titanium, high-aluminum types are intermediate. Thus, spectral measurements or photographs taken through red and blue filters can chemically map out the main rock types.

More detailed, post-Apollo mapping by Carlé Pieters of Brown University has defined 13 mare color units, most of which were not sampled by astronauts. Perhaps this type of "remote prospecting" will have practical value in the future, for the mineral ilmenite in the high-titanium basalts may be a source of oxygen to use as fuel for lunar exploration.

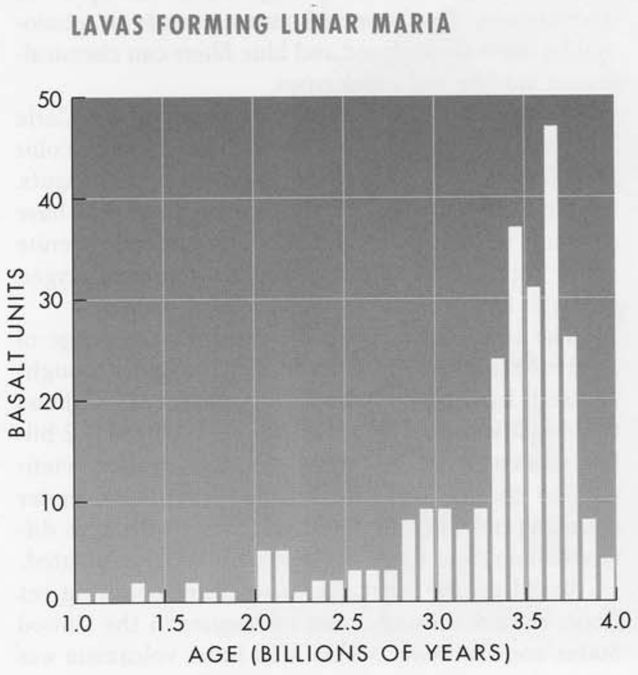
The table on this page summarizes the range of ages for radiometrically dated lunar samples brought to Earth by the Apollo and Luna programs. It shows that basaltic magmas erupted between 4.3 and 3.2 billion years ago. But just as spectral studies allow scientists to indirectly define rock compositions, crater counting has identified volcanic rocks with ages different than from those we have radiometrically dated.

Based on the most extensive crater counting yet done, Harald Hiesinger and colleagues in the United States and Germany believe that lunar volcanism was most intense from about 3.7 to 3.3 billion years ago, but that small amounts of volcanic activity continued to about 1.1 billion years ago. Combining both Apollo and crater-counting data, we see that volcanism spanned at least 3.2 billion years of lunar history — longer than previously thought.

Detailed crater counting also indicates variations in the duration of volcanism within different basins. In most cases it appears that volcanism began about 100 million years after basin formation, and in some basins volcanism lasted only 500 million years, while in others it continued for 1.5 billion years. The youngest mare material dated by Hiesinger and colleagues occurs in Serenitatis, Imbrium, and Procellarum. I note that these young basalts all occur within a hypothesized ancient and large impact basin called Gargantuan. Perhaps this putative giant basin remained warm longer than most places on the Moon, making it easier for rising magmas to reach the surface. In Chapter 17 we will see that most geologists who study the Moon doubt that Gargantuan exists, yet, as speculated here, it does offer explanations for a multitude of otherwise strange observations.

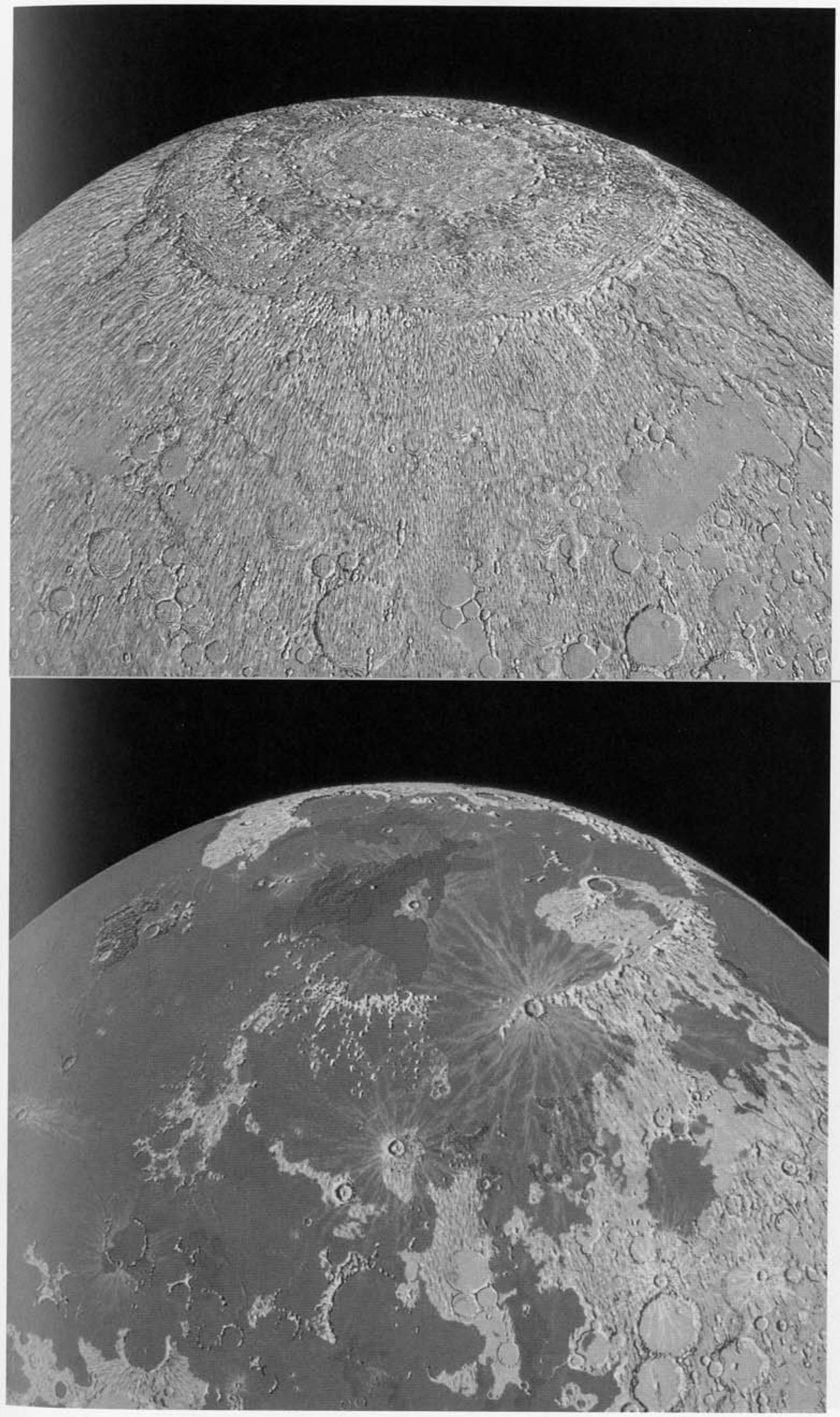
This discussion has focused on lunar basalts, but studies of Earth's volcanism reveal that our planet has many types of volcanic rocks besides basalts. What's the story for the Moon? For geologists, one of the joys of the Moon is that it is relatively simple compared to the Earth. Because the Moon lacks plate tectonics and water, surface rocks aren't pulled back down beneath the crust, melted, mixed with other rocks, and spewed back up onto the surface as completely different types of volcanic rock. The Moon doesn't have significant amounts of rhyolites, granites, andesites, and other silica-rich volcanic rocks that the Earth regurgitates with plate tectonics. This absence of familiar terrestrial volcanic rocks is consistent with the Moon's lack of composite volcanoes and large ash-flow calderas. Thus, the observation of large-scale surface landforms allows inferences about the very small scale composition of lunar rocks. My colleague Peter Francis and I used such landform-composition associations to similarly argue that Mars — which, like the Moon, lacks composite volcanoes — has no silica-rich rocks and none of the plate tectonics that generate them on Earth.

But the Moon does have some igneous rocks other than basalts. In fact, virtually all lunar rocks are igneous, in that they formed by the solidification of previously melted material. The lunar crust is dominated by a low-density, aluminum-rich rock called anorthosite that was once the frothy scum floating atop a Moonwide magma ocean. A variety of other unusual nonbasaltic rocks apparently also formed during the earliest period of lunar evolution. And a few strange varieties of basalt — most famously the so-called KREEP basalts — further enliven debates among petrologists. Most of these rocks can be safely ignored, but KREEP and anorthosites will figure prominently in later chapters.

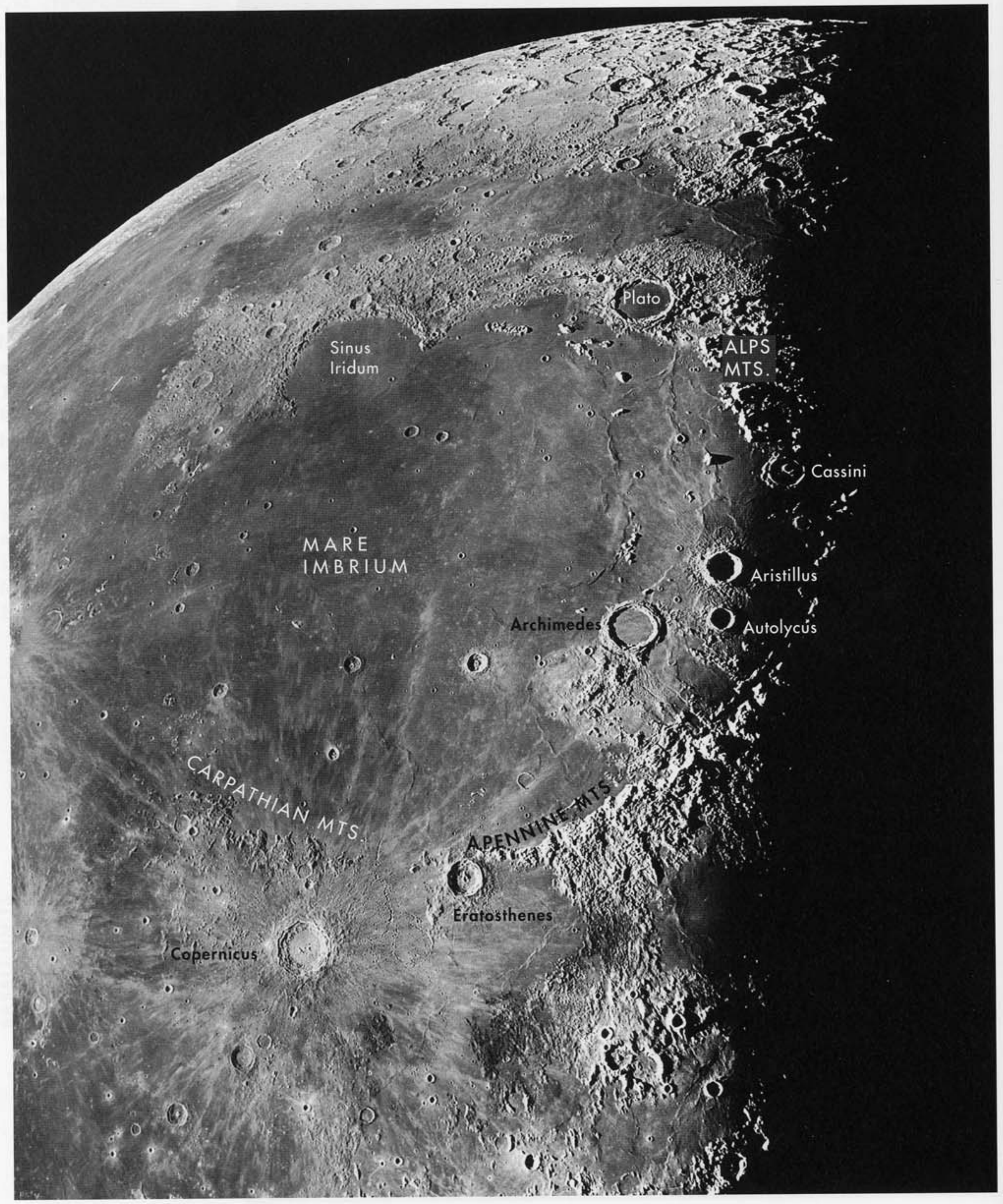


As this graph shows, the lavas forming most lunar maria erupted between 3.3 and 3.7 billion years ago.

Apollo 17 astronaut Harrison Schmitt collects rock samples beside a large boulder near the Taurus-Littrow valley.



These illustrations show the lunar surface just after formation of the Imbrium basin (top), before lavas flooded a significant portion of the lunar surface, and (left) shortly before the Copernicus impact, which marked the end of the Eratosthenian period, the final phase of mare formation.

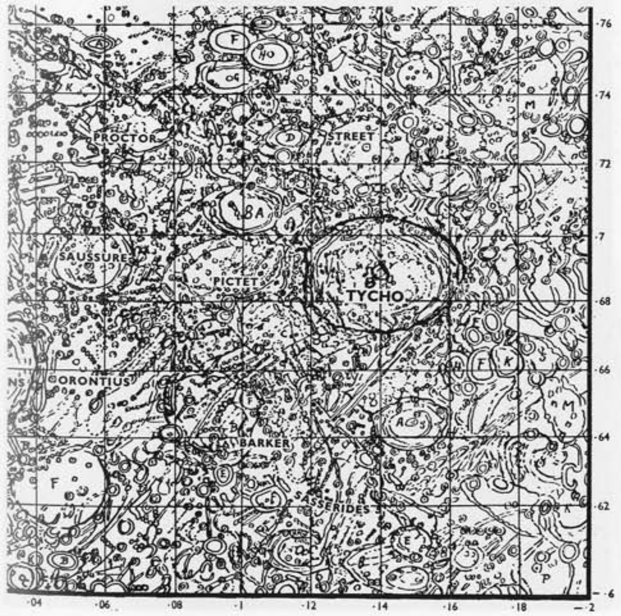


The Imbrium basin.

3

The Imbrium Basin

The main sequence of impact-crater morphology described in Chapter 2 culminates in impact basins — megacraters that are the largest features on the Moon. On the lunar near side, the youngest and biggest is the Imbrium basin. Ironically, the unity of this large region was not recognized clearly until the mid-1960s. Until then, except for the studies of Baldwin and Gilbert, there was little awareness of the underlying depression that contained the mare lavas. Hartmann discovered a common pattern among multiring lunar basins such as Imbrium and gave them that name while still a graduate student at the University of Arizona. He speculates that basins were overlooked for hundreds of years because the goal of lunar observing had been to map ever smaller features. As a result, the context and interrelations of large lunar landforms went unnoticed, while maps became densely filled with small and often dubious detail. The culmination of this tradition was the 300-inch-diameter Moon map drawn by Hugh Percy Wilkins, a British amateur astronomer whose draftsmanship was woefully inadequate to depict clearly the complexity of the tens of thousands of small details visible through his telescopes. There were simply too many angels dancing on the lunar pinhead.



This portion of Section XXIII of H. Percy Wilkins's lunar map shows the crater Tycho.

FIRST LOOK

The 1,200-km-wide Imbrium basin dominates the lunar near side. The eye is immediately drawn to its well-defined rim segments and smooth, circular mare deposits. Within its embrace are some of the most informative and fascinating craters on the Moon, including Archimedes, Cassini, and Plato, as well as the gaping partial crater, Sinus Iridum. Once pointed out, Imbrium's effects can be traced over more than half of the Moon's visible hemisphere.

Imbrium is bounded by high, spectacular mountains, low rough zones, and imaginary lines that complete the circle. The Apennine mountain range is the most conspicuous on the near side of the Moon. Clearly arcuate about the center of Imbrium, it is in fact part of the rim of the largely buried Imbrium impact basin. The Apennines rise up steeply 5 km above Imbrium, then taper away radially. Urey once proposed that such mountain ranges were dropped into place as ejecta from the basin-forming impact, but that idea seems incompatible with the continuity of the Apennines. The southern rim of the Imbrium basin is marked by the subdued Carpathian Mountains, but to the eye these hills are overwhelmed by the bright rays and secondary craters of Copernicus.

To the north of the Apennines, the Caucasus Mountains mark an ambiguous boundary between Imbrium to the west and the Serenitatis basin to the east. The Caucasus Mountains are more nearly concentric to Serenitatis than to Imbrium, but structurally they seem to have some association with both basins. The lunar Alps — a short line of massifs backed by a jumble of small peaks — delineate the northeast shore of Imbrium. The basin's northern shore is a lowland, pockmarked by small craters, which leads to the large half-crater Sinus Iridum, the Bay of Rainbows. Iridum is one of the few craters on the Moon whose rim, or partial rim in this case, has its own name, the Jura Mountains. The western shore of the Imbrium basin is defined by only a few isolated hills and the belief in the circularity of basin rims. The lava flows of Imbrium and Oceanus Procellarum co-mingle in this area.

IMBRIUM AND BASIN ORIGINS

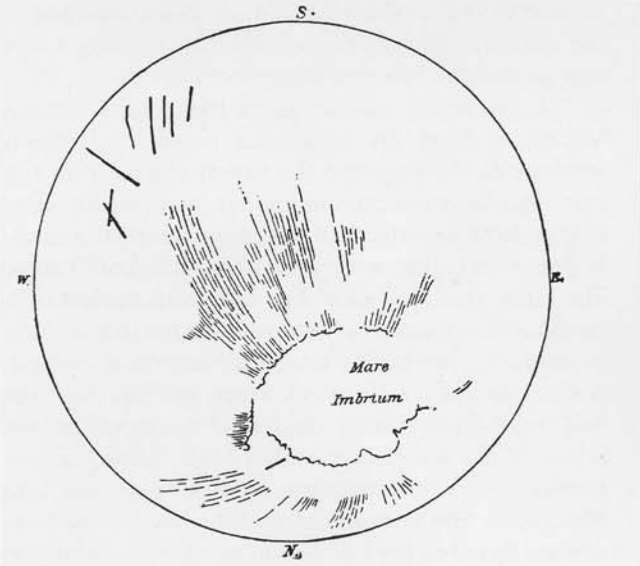
Imbrium has long been at the center of the debate about the origin of lunar maria. In 1893 the great pioneer geologist G. K. Gilbert, one of the founders of the USGS, published a prescient paper noting that many crater walls, chains of craters, "great furrows," and apparent gouges formed a "lunar sculpture" aligned radially to Mare Imbrium. He concluded that "a collision of exceptional importance occurred in the Mare Imbrium, and that one of the results was the violent dispersion in all directions of a deluge of material — solid, pasty, and liquid." Imbrium was just the biggest crater on the Moon. As explained in Chapter 2, little attention was paid to what Gilbert said. But also the Moon was not an important subject for astronomers during the first 60 years of the 20th century, partially because of the rapid development of astrophysics. For the first time astronomers could determine the distances, compositions, and life histories of stars and galaxies. Compared to the euphoria of understanding the cosmos, astronomers disparaged the Moon as a bright provincial nuisance that made it impossible to photograph the rest of the universe for half of each month.

After being left to amateur astronomers for two generations, the Moon finally resumed its place as the subject of professional interest when a host of scientists prepared for the Apollo program. Aerospace engineers and scientists turned to libraries as sources of the current understanding of the Moon but found books written only by amateur observers. The most comprehensive of these was the 1955 tome *The Moon* by Wilkins and Patrick Moore. These British amateurs continued the long-standing tradition of emphasizing tiny details and held firmly to the belief that lunar craters must be volcanic in origin because impact craters tens and even hundreds of kilometers across were unknown on Earth. They failed to note, however, that volcanic craters hundreds of kilometers across weren't found on Earth either.

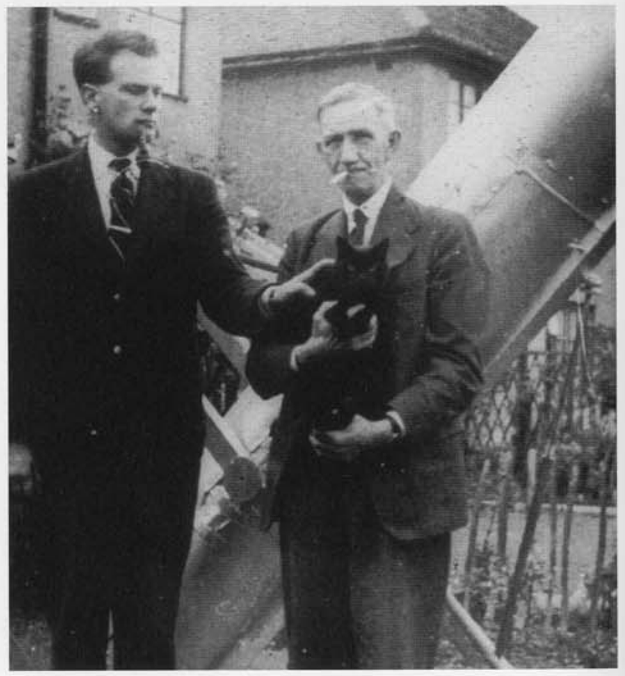
It was the most original and unlikely of all lunar scientists, a Michigan factory owner and astronomer, Baldwin, who marshaled convincing scientific evidence for the impact origin of normal craters and impact basins. Baldwin's solution to controversy over the origin of lunar craters was detailed in the previous chapter, but his *Face of the Moon* also explained the basins. Baldwin concluded that "Every type of structure on the moon . . . can be easily explained as direct or indirect results of these collisions and explosions." With remarkably keen insight, he explicitly recognized that basins were simply large craters, mare surfaces were formed by lava flows, impact craters provided a mechanism for determining ages on the Moon, and impact craters must also exist on other planets. The only other book I can think of that contains as many groundbreaking and correct ideas is Charles Darwin's *Origin of Species*.

Baldwin's book was published by the University of Chicago Press and strongly influenced two major planetary scientists who taught at the university: Urey and Kuiper. Urey had won a Nobel Prize in chemistry when he was only 41 years old and remained famous for the rest of his long life. According to one story, while attending a cocktail party, Urey happened to see a copy of Baldwin's *The Face of the Moon* on a coffee table and proceeded to sit down and read the entire book! Urey's own 1952 book *The Planets* restored respectability to the study of the solar system and inaugurated the modern period of planetary science. Baldwin's impact arguments were endorsed without reservation by Urey in *The Planets*. Kuiper, on the other hand, was a great observer. The director of the Yerkes Observatory in Wisconsin and the McDonald Observatory in Texas, he brought to the study of the Moon and planets important new observational data and the application of the rigorous methods of physics. Like Urey, Kuiper also quickly embraced the impact theory.

When Urey and Kuiper became involved in planning NASA's exploration of the Moon during the 1960s, they brought with them a common belief in the impact hypothesis, bringing the reign of Wilkins and Moore to an abrupt end. Baldwin's second book, *The Measure of the Moon*, published in 1963, became the standard companion for Apollo mission planners. His impact theory had emerged as the new consensus.



G. K. Gilbert's "lunar sculpture."



Patrick Moore (left) and H. Percy Wilkins.

Harold Urey.

Gerard P. Kuiper.

THE APENNINES

The most prominent topography of the Imbrium region is the arcuate Apennine Mountains. Stretching about 600 km from the crater Eratosthenes to beyond Mount Hadley, near the Apollo 15 landing site, the Apennines are fronted by relatively steep bright scarps rising nearly 5 km above the mare surface. Look closely and you will see that the scarps are not continuous but are broken into a series of roughly parallel, but sometimes slightly offset, massifs that are typically 25 to 50 km long. These massifs are immense blocks that tower 1 to 2 km above the less rugged and less bright back-side slopes of the Apennines. Jim Head suggested that the Apennine massifs were blocks of flat-lying crust at the edge of the giant Imbrium crater and had been warped upward in response to the impact. Great amounts of material excavated from the Imbrium crater must also have been deposited along the massifs at the basin rim.

A visit to one of these massifs near the northern end of the Apennines was a major reason for selecting the Apollo 15 landing site near Mount Hadley. If the massifs were elevated from great depths and coated by ejecta from even greater depths, they would provide the best opportunity for astronauts to collect samples from deep within the Moon.

Scientists were divided about what the Apollo 15 samples would show. The "deep excavators" thought that basins should have the same 1:5 depth-to-diameter ratio as small, simple impact craters. If true, the Imbrium impact might have excavated rocks from depths of 200 to 300 km — well within the Moon's mantle! The "shallow excavators" thought that large, complex impact craters had different depth-to-diameter ratios than smaller, simpler craters and that they would have been excavated much less deeply. They believed that the Apennine samples would come from depths of only 30 to 60 km. It turns out that they were probably right. The returned samples don't show the dense, mineralogically distinct features expected from lunar mantle rocks. But I don't recall ever hearing any admissions of error from the other side.

Beyond the Apennine massifs are lesser hills (known technically as *hummocks*) that gradually diminish in size with distance from Imbrium. There are also thick wedges of material that taper to the southeast, away from Imbrium. These wedges are probably a combination of boulders that fell out of the ejecta cloud and massive flows of ground-hugging material, both created by the tremendous impact. Similar but even more dramatic flowlike deposits occur around the Orientale basin on the western limb of the Moon.

The hilly terrain of the Apennine back slope is cut by lineations that, like everything else, radiate from Imbrium. A remarkable example extends about 300 km. Starting as the Archimedes rille, it marks the abrupt termination of a massif at the Apennine front, continues as a groove through the back-slope rubble, and ends as a series of linear ridges in the Haemus Mountains bordering Mare Serenitatis. This is one example of Gilbert's "lunar sculpture."

In other places the back slopes of the Apennines are embayed with smooth, dark mare deposits. One region includes a small sinuous channel, the 45-km-long Conon Rille, named after the nearby impact crater. Conon the crater (not to be confused with Conan the Barbarian) is a bright-rimmed, 22-km-wide, 2.3-km-deep impact crater that is clearly superposed on the Imbrium ejecta. But if you examine Conon when the Sun is high over it, you'll see a partially smooth, dark floor with no central peak. There are mounds of slump debris on part of the floor, but Conon is not the complex-type crater that it should be, given its diameter. Perhaps Conon is actually a secondary crater formed by the impact of a large chunk of Imbrium ejecta.

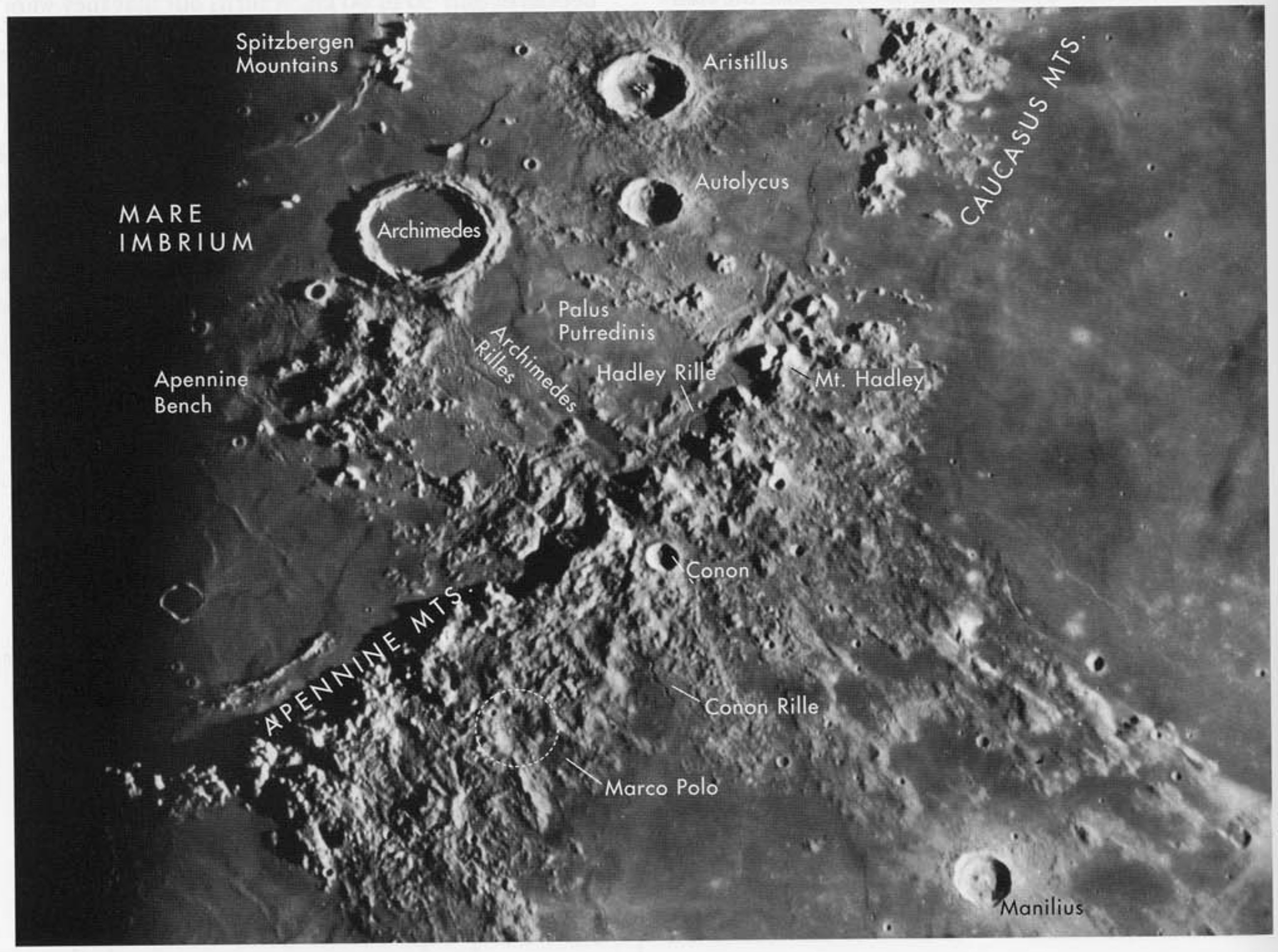
The Apennine hinterlands also include a number of roughly circular patches surrounded by arcuate ridges. These are thought to be remnants of early impact craters that were scoured and blasted by Imbrium ejecta. Most of these features probably are, but others may require more creative interpretations. One such ruin (about 25 km across) carries the name Marco Polo but is so poorly defined that really it is undeserving of any designation. The value of these structures lies in the recognition that nearly all landforms on the Moon, even obscure ones, are likely to be bits and pieces of craters. Geology on the Moon is largely a study of impact craters of all sizes and states of preservation.

THE APENNINE BENCH

One of the key geologic relations on the Moon was first understood when astronomers studied the anomalous region of light-hued and hilly terrain between the Apennine Mountains and the crater Archimedes. In *The Face of the Moon*, Baldwin proposed that this area was part of the original floor of the Imbrium basin. He also realized that Archimedes, whose outer rim is partially covered by Mare Imbrium lavas, must have formed on the basin's original floor. Thus, Baldwin discovered that lava flows (in Mare Imbrium) must have erupted after a delay that was long enough for Archimedes to form.

About a dozen years later, Gene Shoemaker and Robert J. Hackman (USGS) suggested that the light-colored terrain — which they named the Apennine Bench Formation — was not the floor of the Imbrium impact basin but rather ejecta and/or impact melt from the basin's formation.

Orbital measurements made during the Apollo program revealed that the Apennine Bench region is richer in the radioactive element thorium than nearby mare lavas. Additionally, some rock fragments collected at the Apollo 15 landing site near the Apennine Bench are rich in potassium (K), rare-earth elements (REE), and phosphorus (P) as well as thorium and uranium. The shorthand designation for this unusual composition is KREEP, showing that at least some lunar scientists have a sense of humor.



The Apennine Mountains are the best-preserved portion of the rim of the Imbrium basin.

Based on the Apollo rock analyses, the Apennine Bench materials are neither the original Imbrium basin floor of Baldwin nor the impact-created melt and ejecta of Shoemaker and Hackman. The Apennine Bench–area KREEP is probably igneous rock that erupted onto the lunar surface about 3.84 billion years ago, soon after the formation of the Imbrium basin. Isolated mountains in Mare Imbrium, such as nearby Spitzbergen, are also KREEP-rich. Such hills were probably uplifted during the Imbrium impact, so KREEP volcanism must also have occurred before the basin's formation.

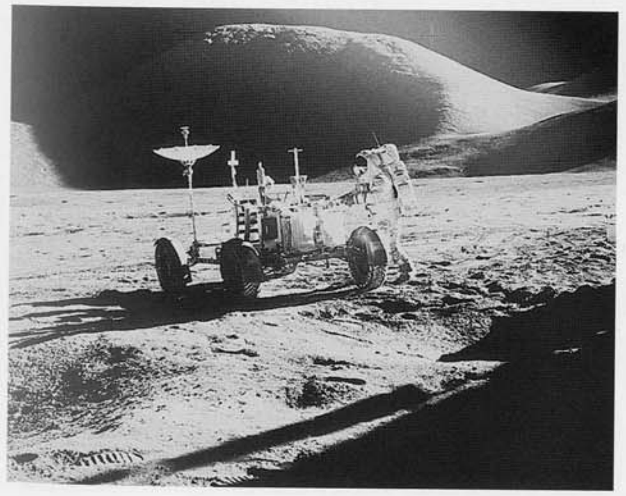
The Apennine Bench is the only part of the floor of the Imbrium basin to have escaped flooding by the later mare lava flows. Why did this occur? A careful look at the front of the Apennine Mountains near the crater Conon shows a large mass that must have collapsed as giant landslide blocks when the Apennines were uplifted. Additionally, a thin rocky crest protrudes from the surrounding mare lavas about 25 km in front of both the northern and southern parts of the Apennine scarp. These narrow, nameless ridges are probably the top edges of mostly inundated slump terraces similar to those seen inside Copernicus and other craters. All these blocks slid from the highest part of the Imbrium basin rim, lifting up a local plateau that was embayed but not flooded by the subsequent mare basalts. Similar rough regions occur widely inside the Orientale basin beyond the west limb of the Moon but are easier to see because Orientale suffered very little subsequent flooding by mare basalts.

APOLLO 15 AND HADLEY RILLE

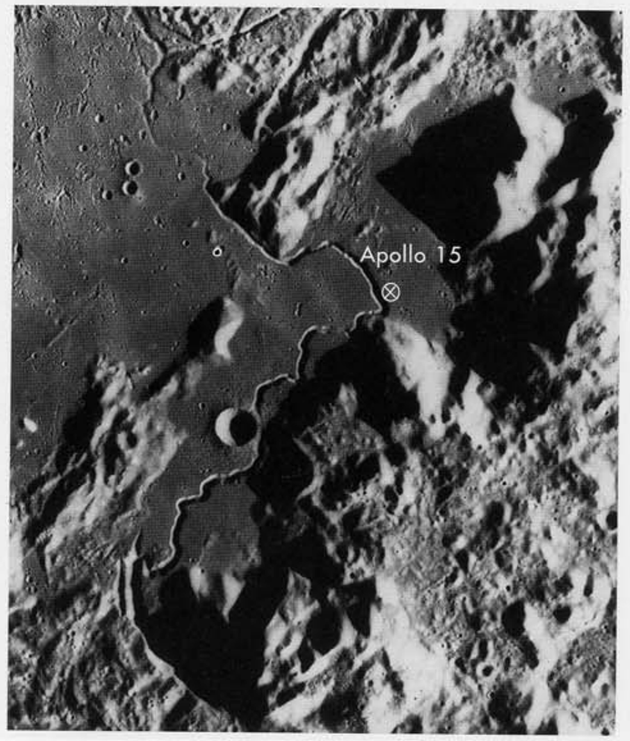
Apollo 15 was the first visit to the Moon in which astronauts used a lunar rover — a four-wheel-drive electric car. As a result, astronauts James Irwin and David Scott were able to travel farther than previous Moonwalkers and visit a variety of interesting targets.

The site selected for the landing was on the lava flows of Palus Putredinis, the patch of mare material southeast of Archimedes near the base of the Apennine Mountain range, which marks the southeastern rim of the Imbrium impact basin. Scientists were anxious to examine Apennine rocks so they could determine how deeply the basin had been excavated by the impact that formed it. They also hoped that sampling the impact-shocked rocks and lava flows would enable them to date the formation of the Imbrium basin and the mare lavas as well. Another major goal for the Apollo 15 mission was to investigate Hadley Rille, both to examine the exposed vertical cross section of the mare and to decipher how sinuous rilles formed.

The Moon buggy allowed Scott and Irwin to range over 28 km of the lunar landscape alongside the Apennine Mountains and to skirt the edge of Hadley Rille — if they'd brought a lunch along, it could have been considered a picnic. All this driving allowed them



Apollo 15 astronaut James Irwin with the lunar rover near Hadley Rille.



The Apollo 15 landing site as seen from orbit.

to see and sample more than any of the previous Apollo astronauts had done. The main scientific result was that the melted rocks from the Apennines were dated at 3.86 billion years, an age equated with the Imbrium impact event. Apollo 15 samples also showed that the Imbrium lavas were as much as 600 million years younger. This finally put to rest Urey's idea that heat from the basin-forming impact had melted the mare, and it vindicated Shoemaker and Baldwin, who argued that radioactive heating in the lunar mantle had generated the lavas that flooded the basin long after its formation.

Another discovery consistent with previous Earth-based observations was that Hadley Rille was not carved by running water but is a typical (albeit huge) lava channel like those found in Hawaii. I've watched such channels form on the flank of Kilauea volcano. The flowing lava builds its own levees as molten material splashes over the flow edges and cools. Gradually the overflowing material builds levees so high that flowing lava becomes trapped within its own channel. Sometimes the flowing lava thermally erodes downward into the rock already there. The layers of lava that the Apollo 15 astronauts observed on the walls of Hadley Rille are probably preexisting lava flows exposed by such down-cutting.

You can see the landing area for Apollo 15 and glimpse the delicate Hadley Rille by looking between the crater Archimedes and the nearby arc of the Apennine range. The rille is only a little more than 1 km wide, but it can be made out in a 5-inch telescope in the patch of mare just in front of the Apennines. The actual landing site is at the northern end of the rille where it turns away from the mountains.

ARCHIMEDES, AUTOLYCUS, ARISTILLUS, AND TIME

The largest crater within Mare Imbrium is Archimedes. It is 83 km wide, 1.6 km deep, and has two distinctive neighbors: Autolycus and Aristillus. These nearby craters are typical members of the impact-crater main sequence, with Autolycus (39 km wide, 3.4 km deep) being a Triesnecker-style complex crater, characterized by slumped walls and a debris-strewn floor. Aristillus (55 km wide, 3.6 km deep) is a good example of the Copernicus end of the complex-crater sequence, having terraced walls, a smooth, dark floor, and a massive clump of central peaks. Archimedes, however, does not fit within the main sequence; its large size dictates that it should have a central-peak complex, but there is only a broad, flat floor.

It was recognized early on that Archimedes (like Plato to the north) must be partially flooded with mare lavas. Measurements of the lengths of shadows cast by its rim onto the surrounding mare surfaces demonstrate that Archimedes' floor is at about the same level as the surrounding Mare Imbrium. There are no breaches in the crater walls, so Archimedes must have been flooded by lava that rose up through fractures in the basin and crater floor. If Archimedes were a typical, Copernicus-like complex crater, it would be 4 km deep and have a 2-km-high central peak. But the crater is only about 1.6 km deep, so it must be filled by 2.4 km of lava (4 – 1.6 = 2.4), which means that its 2-km-high central peaks are completely buried!

Look at the mare surface near Aristillus under a low Sun and you'll notice the radiating ridges and tiny secondary craters that are part of the crater's ejecta system. Nearby Autolycus has similar but weaker ridges to its south. Aristillus has a strong ray system, well seen near full Moon, and Autolycus has a weaker system whose rays are clearly detectable only where they cross Archimedes and Palus Putredinis. Clearly both craters are relatively young, having formed on top of the Imbrium lavas. Based on the dating of samples brought back from the nearby Apollo 15 site, those lavas are approximately 3.25 billion years old. The astronauts did not go anywhere near the craters but an observant lunar scientist noticed that some unique Apollo 15 KREEP-rich samples were collected from an area covered by a ray from either Aristillus or Autolycus. This material was dated at 2.1 billion years. Graham Ryder (Lunar and Planetary Institute) and his colleagues at NASA's Johnson Space Center in Houston argue that this KREEP is shocked ray material excavated from the Apennine Bench by Autolycus. Another impact-heated Apollo sample, dated at 1.29 billion years, is proposed to date to the time of the Aristillus impact event. Since there are two events identified in the Apollo samples and two nearby young craters, it is reasonable to link the older sample with the morphologically older crater and the younger sample with the younger-looking crater.

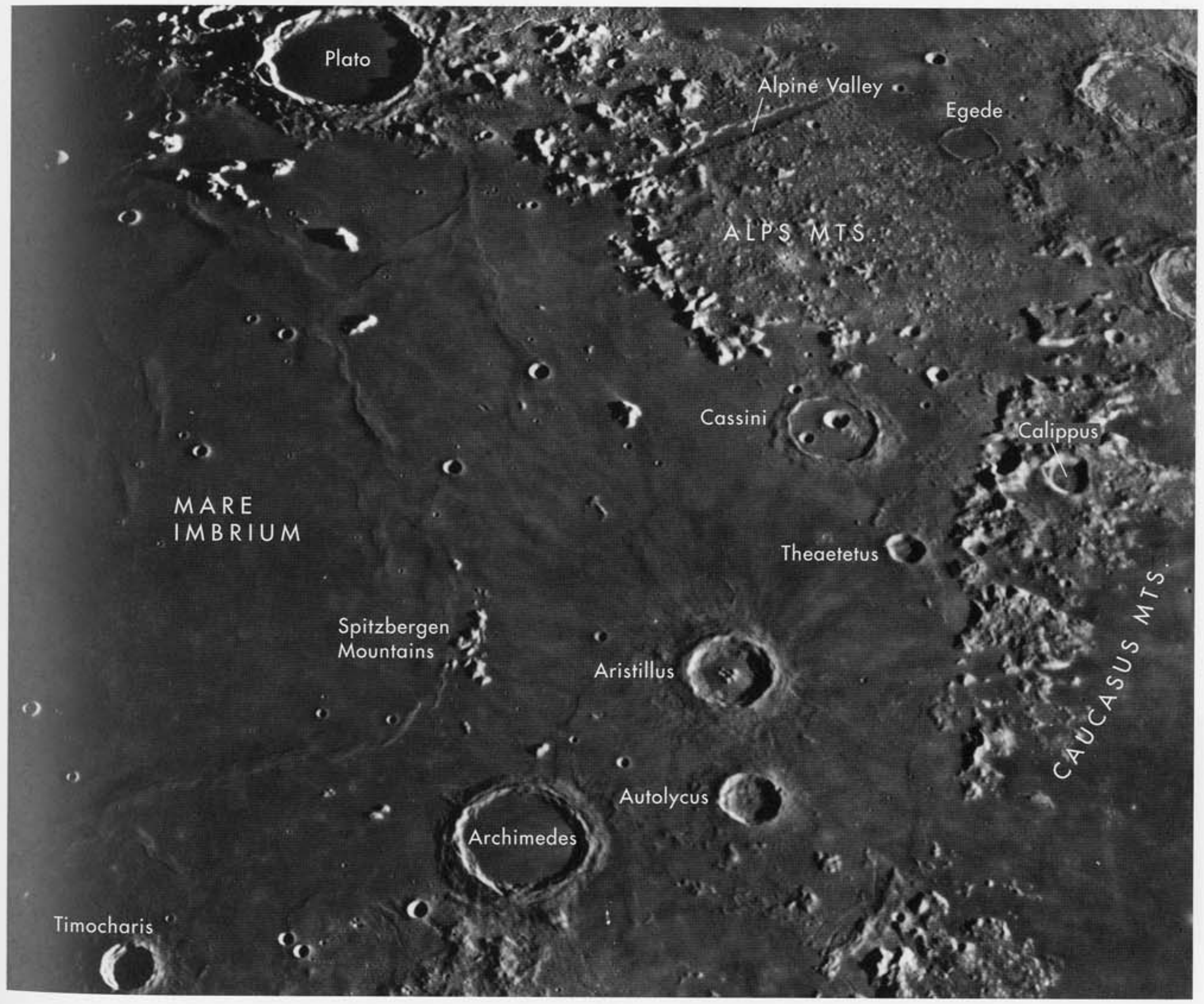
With the data collected, a detailed chronology of events can be inferred for this area of the Moon. Approximately 3.84 billion years ago the Imbrium basin formed, creating the Apennine Mountains. A half billion years later, Imbrium basalts flooded the area. Therefore, at some point between these two events, the Archimedes impact occurred. Thanks to the Apollo 15 samples, we can assume that more than a billion years later — 2.1 billion years ago — a projectile excavated Autolycus out of the Apennine Bench, and that nearly another billion years later Aristillus was formed. In 1958 the Soviet Lunik 2 became the first probe from Earth to reach the Moon, crashing somewhere between Archimedes and Autolycus. And in 1971 Apollo 15 astronauts visiting the nearby Hadley Rille brought the first automobile to another planet. This area of the Moon seems destined to be a historic site, for both human exploration and scientific understanding of the Moon.

There are few places on the Moon where sequences of events are known in such detail. However, a word of caution is in order: these age assignments are little more than informed speculations, even if they do fit the sparse data. One is reminded of Mark Twain's wry comment: "There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact."

THE CAUCASUS TO PLATO

North from the Apennines is a 50-km-wide gap in the mountains bordering Imbrium where lavas from Imbrium and Serenitatis merge. Just to the north of this lie the Caucasus Mountains, an old, battered range of massifs rising 3 to 4 km above the mare plain. These mountains were mapped by USGS geologists as Imbrium ejecta, just like the Apennines. But the Caucasus are much more broken and seem different to me. The Caucasus are not arcuate toward either the center of Imbrium or Serenitatis, suggesting that something strange has happened.

Calippus is a lumpy-floored, 33-km-wide, 2.7-km-deep crater superposed on the Caucasus Mountains. It is similar to the nearby Theaetetus (25 km wide, 2.9 km deep) — both have roughly polygonal outlines and unbroken inner walls. They are probably Triesnecker-like members of the complex-crater sequence, but they could be Imbrium basin secondary craters. Stratigraphically inclined readers may question the possibility that Theaetetus could be an Imbrium secondary crater because it apparently formed atop Imbrium mare



Northeastern Imbrium.

lavas. Fair enough. But look at Theaetetus under a low Sun angle and you'll see that it sits on a broad, linear ridge that is covered with many small hills and is generally not as smooth as the mare. This low ridge is of uncertain origin but may be another surviving piece of old material, like the Apennine Bench. So Theaetetus could be an Archimedes-like crater, perched on the basin floor and surrounded by a thin veneer of mare lava.

Cassini (57 km wide) is a wonderful crater with a wreathlike outer rim partially covered by Imbrium lavas. It is another Archimedes-style crater, formed in the interval between the creation of the Imbrium basin and the flood of later mare lavas. Lavas also welled up to nearly fill Cassini, which has only a narrow inner wall that rises a mere 1.2 km above the floor at the high west rim. Two prominent craters (9 and 15 km in diameter) reside on Cassini's floor, along with a striated mound under the larger crater and extending east. The three tiny hills just barely visible between the two craters may be the tops of lava-covered central peaks, but if this were true, the peaks would be unusually tall. Cassini sits in a broad, mare-covered embayment of the hilly terrain behind the Alps and Caucasus mountains. Why does this embayment exist?

Moving northward, the Imbrium rim is marked by the Alps Mountains, which continue the progressive diminution seen from the Apennine to the Caucasus mountains. The Alps are a short (about 250 km long), relatively low (elevations of 1.8 to 3.5 km), remarkably straight line of peaks. Behind the peaks is a broad field of small hills that are essentially huge boulders of ejecta from the Imbrium impact. What makes the Alps famous is the sharp-sided gash known as the Alpine Valley that cuts through the hilly rubble. The Alpine Valley measures about 190 km long and 10 km wide. Although its sidewalls appear steep and bright, its floor is covered with dark mare lavas. Just visible snaking down the middle of the valley floor is a narrow channel or rille — a challenging test object for a 6- or 8-inch telescope.

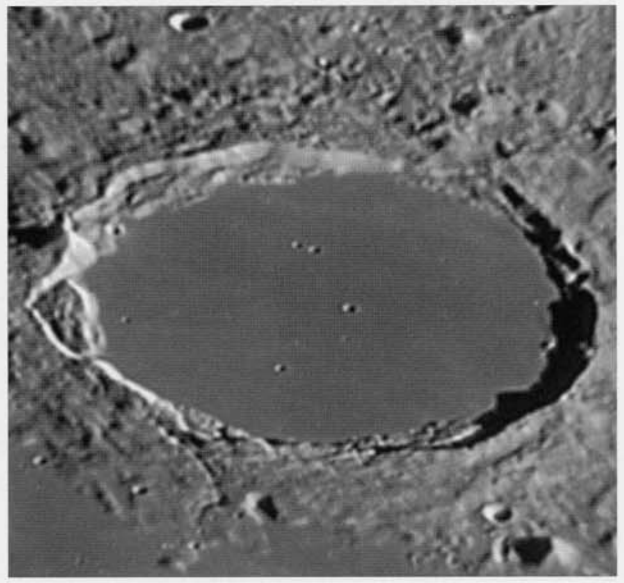
The Alpine Valley has been the subject of many flowery adjectives and not a few wild suggestions as to its origin. Gilbert, in his 1893 paper, pointed out that the valley is one of the most prominent features of the radial Imbrium sculpture and was probably formed by the "forceful movement of a hard body" thrown out from the Imbrium collision. The long, tapering feature would thus be a gouge. Urey and Baldwin accepted this conclusion, but careful observers long ago noticed that two mountains at the Imbrium end of the valley virtually squeeze it into a thin cleft, rendering the gouge theory untenable. Geologists such as Nathaniel Shaler in 1903 and Josiah Spurr in 1945 recognized the Alpine Valley as a *graben*, a down-faulted block of crust. They are almost certainly correct. The feature must have formed as a local adjustment to the stresses built up during the Imbrium impact event.

PLATO

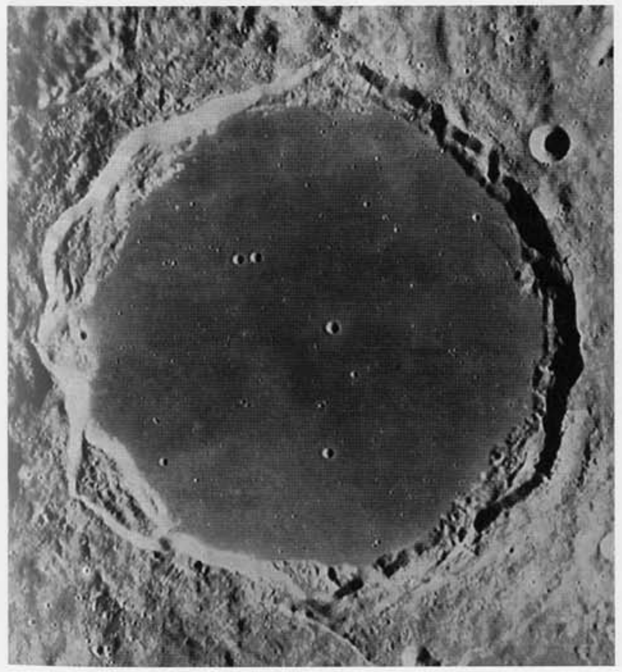
Plato is one of the superstars for observers of the Moon. It's big, conspicuous, and features a dark floor ringed by a bright rim. It has also long been the subject of detailed scrutiny, speculation, and controversy. The 101-km-wide crater was named *Lacus Panciroli* by Langrenus in 1645, *Lacus Niger Major* (Great Black Lake) by Hevelius in 1647, and was finally christened Plato by Riccioli in 1651. Like Archimedes, Plato was formed after the Imbrium impact but before the lava flooding that formed Mare Imbrium. Fractures and fragmented rock under the crater provided a conduit for rising mare lavas to leak out onto Plato's floor. Following the pattern at Archimedes, the lavas just managed to bury Plato's central peaks (which theory suggests should rise 2.2 km above its floor) and reduced the crater's original depth from a predicted 4.6 to 2.4 km.

Surprisingly, the lava that filled Plato is considered to be somewhat younger than the lava in the nearby Mare Imbrium. USGS researchers deduced the younger age from the observation that there are fewer small impact craters on Plato's floor than would be expected if it were exactly the same age as the mare.

The view through a telescope is especially intriguing because of the irregularity of Plato's rim, as shown dramatically by variations in the lengths of shadows cast onto its floor. According to measurements reported in Thomas Gwyn Elger's 1895 book, *The Moon*, three peaks on the eastern rim rise 1.5, 1.8, and 2.1 km above the floor, with other parts of the rim being only about 1 km high. On the western rim an obvious, large triangular massif is partially disconnected from the crater rim. This prominent block, and another one farther north, resulted from giant landslides, where 15-km-long segments of the rim slid slightly inward, creating a scallop — or bite — out of the circular rim. Variations in rim height and width may thus be due to slumping. However, the height differences on Plato's east rim must be of other unknown origins, for there are no scallops there.


Plato as imaged by Ohio amateur Stephen Keene.

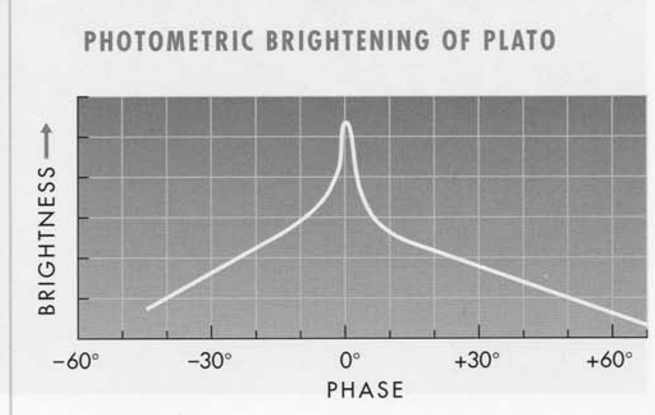
For over one hundred years Plato's floor has provided countless hours of quasi-scientific debate. Three types of observations caused controversy: detection of small craters on Plato's floor, variation in floor darkness with changing Sun angles, and obscurations of the floor itself. Because the floor possesses a few small impact craters near the detectability limits with small telescopes, there have been unacknowledged contests to detect the largest number of craters. Harvard astronomy professor W. H. Pickering apparently won in 1892 by announcing his mapping of 71 spots on Plato's floor. Comparison of these old maps of floor details with very high resolution photographs obtained by the Orbiter IV spacecraft in 1967 demonstrates that the observers did detect the largest four craters and some of the others, but that their estimates of sizes, locations, and numbers were often seriously in error. Because many 19th-century observers believed that changes occurred frequently on the Moon, the inevitable differences between depictions of Plato's floor by experienced observers were often attributed to real physical variations rather than to the difficulties of interpreting features at the threshold of visibility. Pickering claimed that the floor of Plato was "one of the most continuously active volcanic regions on the moon." He was also convinced that other changes on the Moon were caused by the growth and decay of tracts of vegetation. I wonder how many equally preposterous ideas we currently accept as fact.


This Lunar Orbiter 4 view of Plato shows more detail than Earthbound observers can see in their telescopes.

In *The Moon*, Elger states that "The gradual darkening of the floor of Plato as the sun's altitude increases from 20° till after full moon may be regarded as an established fact, though no feasible hypothesis has been advanced to account for it." Actually, just the opposite is true, according to measurements of the floor's brightness by sensitive photometers mounted on large telescopes. Like the rest of the Moon, Plato's floor brightens until near full, when it rapidly gets much brighter, and then darkens after full Moon.

These measurements document what you may have already noticed — the full Moon is much brighter than a nearly full or gibbous Moon. The explanation for this phenomenon lies in the fact that lunar soils are full of tiny cracks and hollows that cast microshadows, until the Sun is shining directly over the observer's head (that is, at full Moon), when the Moon exhibits a sudden surge in brightness.

The third of the controversies about Plato concerns reports that the dark floor is occasionally obscured by mists or clouds. Most of the observations were made during the 19th century; Walter Goodacre's 1931 book, also called *The Moon*, mentions that there are "a number of well authenticated cases." Descriptions include a fog that cleared as the Sun rose, a "curious luminous milky kind of light," and a lack of detail. Another 19th-century observer found that the floor was covered by a myriad of points of light, "as if reflected from flocculent clouds lying near the surface."



Telescopic measurements reveal that the floor of Plato brightens rapidly at full Moon.

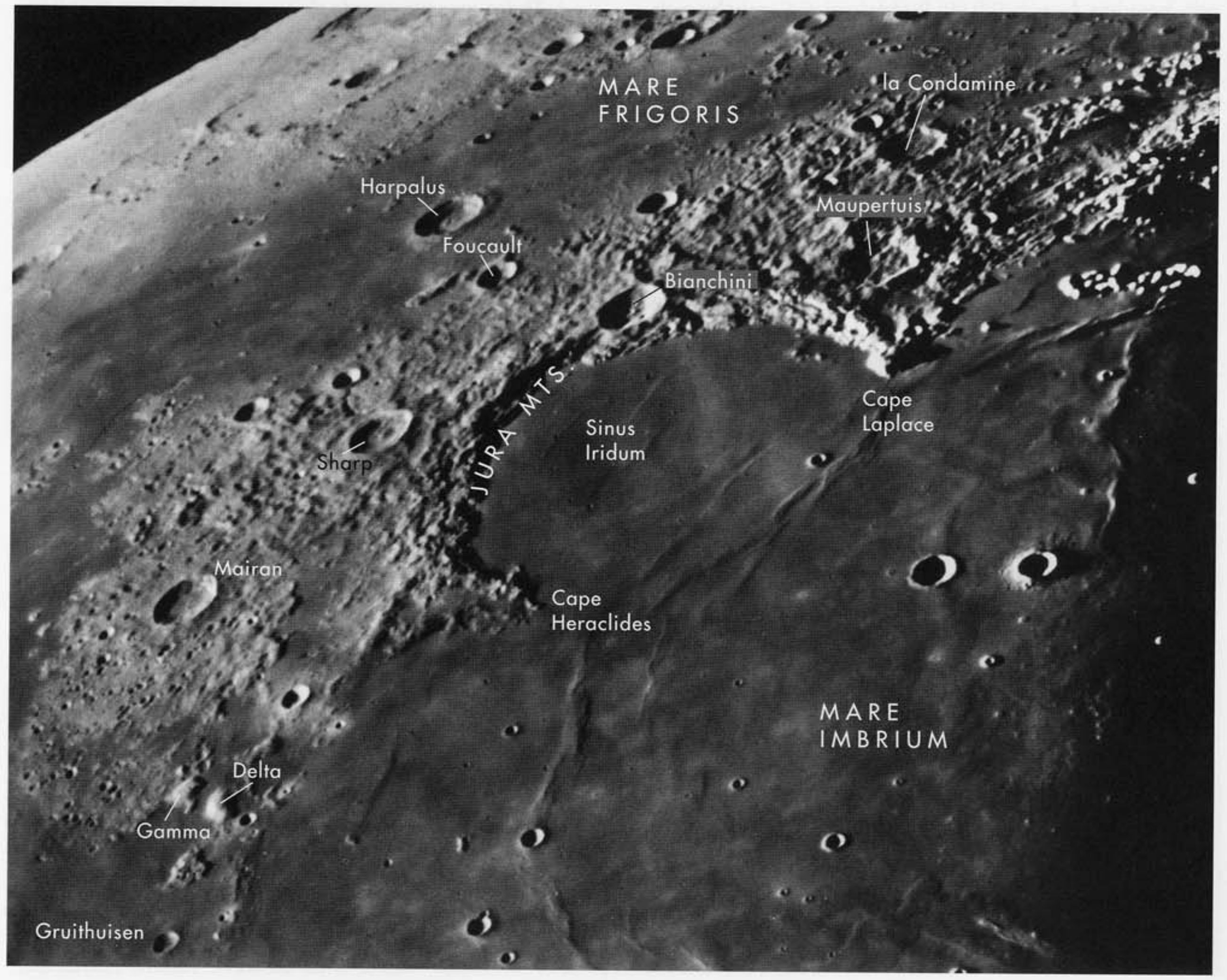
Modern lunar scientists politely ignored such reports until the 1960s, when a statistical study suggested a correlation between reports of obscurations at Plato and at a handful of other locations on the Moon and the times when the tidal forces exerted by the Earth on the Moon were maximum. These Lunar Transient Phenomena or LTPs (also known as Transient Lunar Phenomena or TLPs) provided the first clues that the Moon might occasionally release small amounts of gas, not from volcanic activity but perhaps from radioactive decay of uranium and thorium. But on none of the many photographs taken by space probes or by large telescopes has there been obscurations of Plato's floor. Perhaps, like UFOs, only believers see them.

Just to the east of Plato there are two thin, sinuous channels or rilles, only one of which is easily seen. Such features are thought to be formed by flowing lava. An unusual aspect of these rilles is that they cut through the rubbly Imbrium ejecta. In radar images of the region, a large, smooth area four to five times as wide as Plato itself is seen. One possible explanation is that the source of the rilles erupted explosively, flinging dark ash deposits over a wide area. Although the dark halo is subtle, it can be noticed visually when the Moon is full.

IRIDUM AND ITS HINTERLAND

From Plato westward the arc of the Imbrium boundary is an undistinguished, rubbly lowland of ejecta created by the impact that formed Sinus Iridum. Although generally regarded as simply a bay in Mare Imbrium lavas, Sinus Iridum is a 260-km-wide crater with an abundance of names. Its rim is called the Jura Mountains, and capes Heraclides and Laplace mark the termination points on the northwestern shores of Mare Imbrium.

Urey believed that the projectile that excavated Imbrium came in from the northwest and "plowed out" Sinus Iridum before continuing to make the huge Imbrium crater defined by an inner ring of mare ridges. He recognized that this collision scattered material widely over the center of the Moon, producing a great fan-shaped pattern of ridges and grooves, as was long ago discovered by Gilbert. Detailed mapping showed that ridges and grooves of Imbrium ejecta traveled widely in all directions, including over the lunar north pole to the far side of the Moon. Sinus Iridum, like Plato and Archimedes, is a crater that formed after the Imbrium basin but before the subsequent mare flooding. Urey's idea of Iridum as Imbrium ground zero has been discarded.



Sinus Iridum.

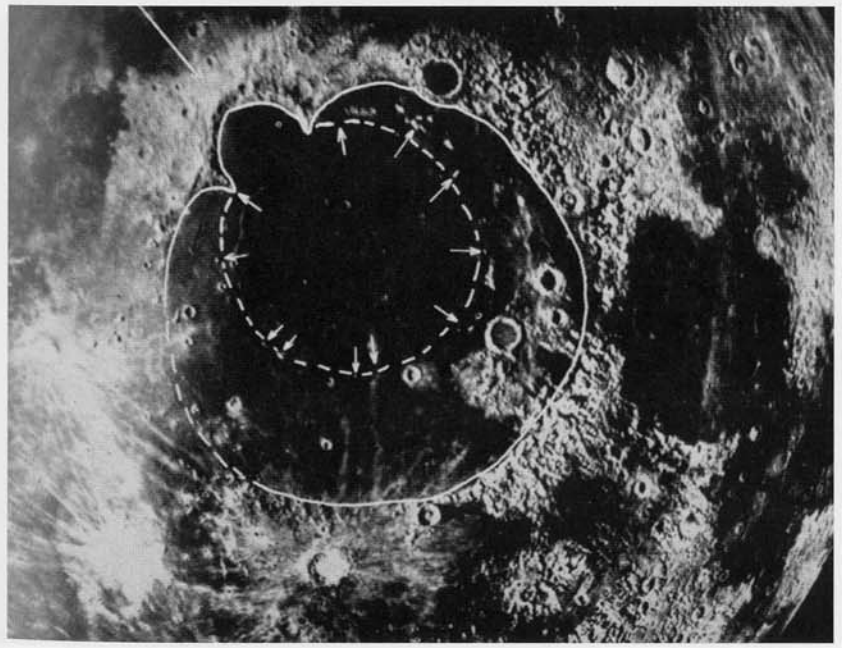
The southern rim of Sinus Iridum is missing. Where did it go? The most likely explanation is that the Sinus Iridum projectile impacted on the sloping floor of the Imbrium basin and that the southern rim is buried under mare lava. But this doesn't quite explain all the observations. Look at Sinus Iridum when the Sun is low and you'll see that, though the western segment of the rim does appear to become lower toward Cape Heraclides, the northeastern rim maintains its height until it reaches Cape Laplace, a large massif that casts impressive shadows. Perhaps the rim of Iridum was dropped by a giant fault. Is there a large, Apennine scarp–like feature buried under Imbrium lavas that truncates the rim of Sinus Iridum? There is little evidence one way or the other.

There is a sameness in the large craters that litter the back side of Sinus Iridum: la Condamine (37 km), Bianchini (38 km), Harpalus (39 km), Mairan (40 km), and Sharp (40 km). The last four are superposed on Sinus Iridum ejecta and thus are clearly younger. All are small complex craters with scalloped walls and small central peaks.

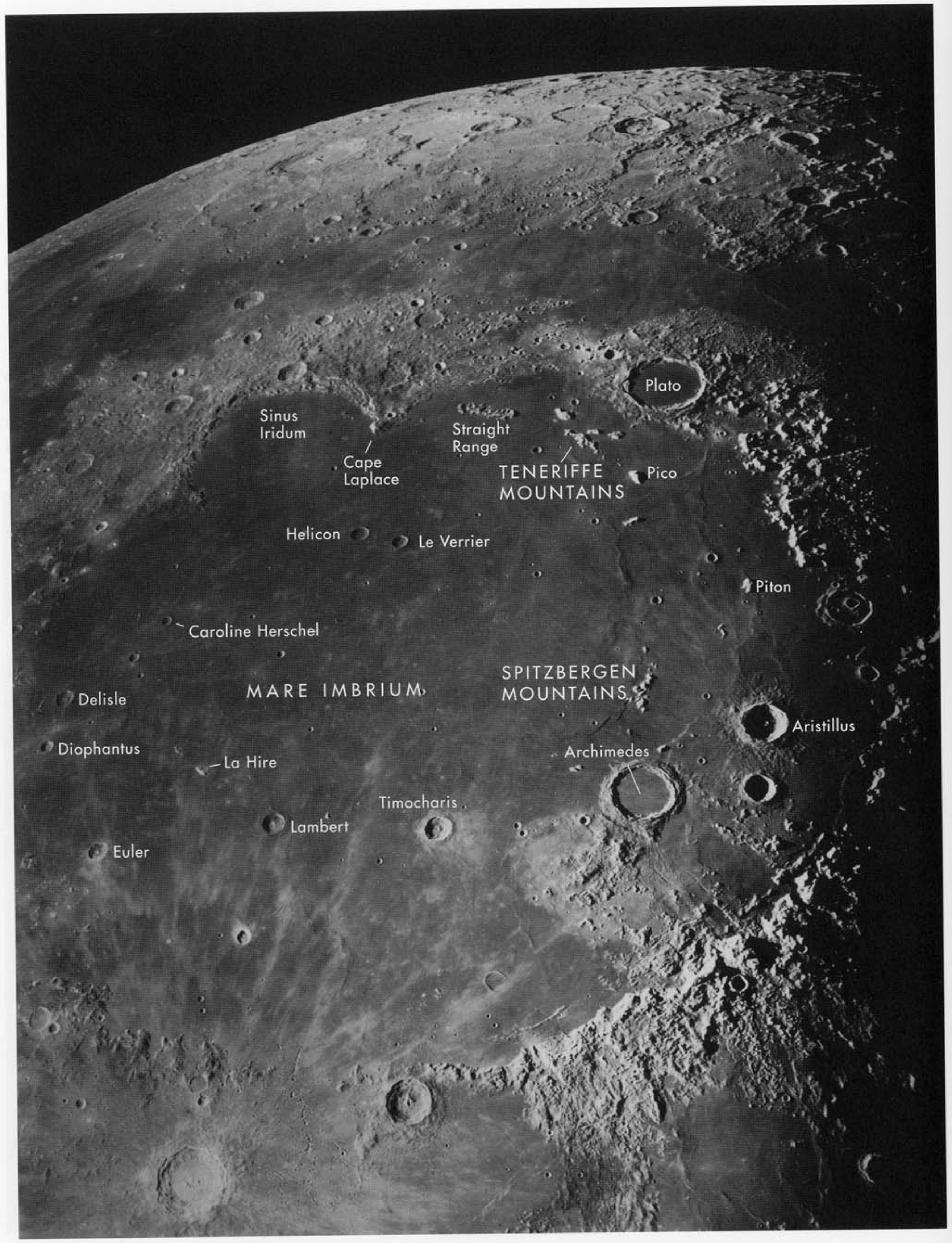
La Condamine, on the other hand, appears to have been battered by Iridum's ejecta and is therefore older than that large crater. Telescopic views show that la Condamine lacks a conspicuous central peak, but spacecraft images show that its floor has an inner ring of hills and fractures, making it a member of a unique class of volcanically modified, floor-fractured impact craters (FFCs). The remaining named crater north of Sinus Iridum is Maupertuis (46 km). Like la Condamine, Maupertuis is older than Iridum, but, being closer, it was more heavily battered. The most notable signs of this are the large, ropelike ridges of Iridum ejecta draped across the crater, burying the central peak.

Southwest of Cape Heraclides, where the nearly continuous semicircle of Imbrium ejecta ends, are two possibly volcanic landforms that are perhaps unique on the Moon. Named after Gruithuisen, the mare-cutting crater to the south, the Gruithuisen domes are bright, rounded mounds sitting at the edge of Imbrium mare lavas. Lunar Orbiter images clearly show what is only hinted at in the best telescopic photographs — Gruithuisen Gamma, the westernmost dome, has a small summit crater. This, plus the bulbous shape of the domes, has convinced some lunar geologists that the Gruithuisen domes are extrusive piles of silicic volcanic rocks like similarly shaped features on Earth.

This is really important because the vast majority of volcanic samples brought back from the Moon by astronauts are basaltic. Basalts form by partial melting of olivine and pyroxene-rich materials like those found in meteorites and rocks from within Earth's mantle. The existence of basalts on the Moon's surface implies that similar olivine and pyroxene source rocks exist in the lunar mantle. The chemical structure of basalts makes for a fluid lava that would not typically build rounded features like the Gruithuisen domes. But more silica-rich materials, as suggested for the Gruithuisen domes, require lava types that are quite rare in the lunar samples. It's frustrating that the composition of these little domes and the origin of their unusual lavas remain a mystery. Someday geologists will bang on the domes with their rock hammers, collecting samples for later analysis at a lunar lab.



According to Harold Urey, a projectile coming from the direction of the arrow (upper left) gouged out Sinus Iridum and ultimately exploded within the inner, arrowed circle.



Mare Imbrium.

4 Mare Imbrium: The Great Lava Plain

To the naked eye the dark plain of Mare Imbrium is one of the most easily recognized features on the Moon. Although Imbrium is the largest (about 1,300 km across) circular patch of mare material on the Moon, it is pockmarked by only a few large impact craters. Imbrium is also one of the most expansive piles of lava in the solar system. But until Apollo astronauts returned with samples from the Moon, the nature of the material making up the dark plains was contested. Geologist Spurr wrote that "Lava flows, indeed, have apparently been exceedingly sparse on the moon." But most serious lunar scientists — and there weren't more than a handful before the Apollo program — agreed with Baldwin that the maria were made of volcanic rocks. Other scientists proposed a variety of other compositions. For example, because the mare basins are deep depressions, analogy with the Earth suggested that they might be ocean basins filled with sediment from evaporated seas. Therefore, the craters naturally were really coral atolls! This old-ocean idea was resurrected by Urey and others just as the Apollo 11 astronauts brought back the proof of its error.

Thomas Gold.

LAVA FLOWS IN THE MIND

The most ardently advanced wrong theory was that the maria are vast piles of dust. This peculiar idea was proposed by the brilliant physicist and astronomer Thomas Gold. Gold claimed that dust eroded from the higher cratered terrains migrated electrostatically to the lowlands of the mare basins. There was never any significant evidence for great thicknesses of "Gold dust," but the mathematical theory was elegant and strongly asserted. Gold warned that the Apollo program might end disastrously with a lunar module sinking out of sight into an abyss of dust. NASA managers breathed a collective sigh of relief when the first Surveyor spacecraft landed safely, and stayed, on the surface of the Moon. This demonstration of the strength of the lunar surface should have led Gold to admit that perhaps there was a flaw in his theory. But it didn't. Gold continued to assert that the maria were deep dust piles even after the last Apollo missions brought back hundreds of kilograms of basaltic rocks and soils. Old theories don't die, they just get ignored.

It is remarkable that so many originators of completely discredited ideas can't admit their mistakes. We will see the pattern repeated later with another interesting, but ultimately wrong, idea — the notion that tektites (a peculiar type of meteorite-like stone) come from explosive lunar volcanoes. Few people, scientists included, seem to realize that most scientific explanations are wrong. Whenever new observations or phenomena come to our attention, there are almost always a variety of proposed explanations. Most are later shown to be at best partially correct or, often, completely wrong. But this is the way the scientific method works. It is also why it was once called the method of multiple working hypotheses. Trial explanations are devised to explain sparse facts and to make predictions. As new information becomes available, the original ideas are accepted, modified, or rejected, and our actual understanding of the universe increases incrementally. But many scientists can't let go of their creations and continue to twist and massage their lovely but inadequate theories — trumpeting the data that fit and ignoring everything that doesn't. There is perhaps nothing else that so well illustrates that the image of the scientist as an unemotional seeker of the truth is an ideal that most of us, as complex humans, fail to live up to.

After that philosophical diversion, you may not remember what Mare Imbrium and other lunar maria are made of. Many mare samples have been brought from the Moon and studied in terrestrial laboratories, and we now know with complete certainty that they are basaltic lavas. In fact, if you go to the Smithsonian Air and Space Museum in Washington, D.C., you can even touch a basaltic rock from the Moon.

But Baldwin and others didn't have samples, so how did they arrive at the correct conclusion? In *The Face of the Moon*, Baldwin stated: "It is beyond question that the seas were once liquid, for they have overflowed thousands of craters and left only occasional high spots to mark their existence." He also noted that measurements of variations in the Moon's brightness, polarization, and temperature implied a rough and broken surface, like that made up of volcanic ash. Finally, because the maria are level surfaces in depressions, a fluidlike emplacement seemed likely. However, Baldwin's evidence did not only support the idea of lava flows — the maria could also have been entirely volcanic ash, as was later suggested in the 1960s.

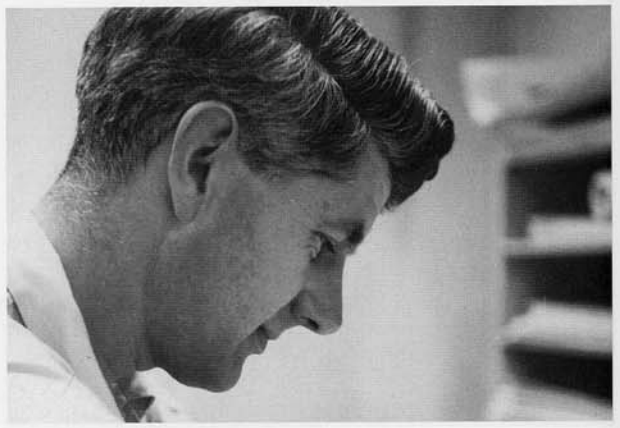
Kuiper's approach to understanding the origin of mare materials was very practical. In 1953 he wrote that "an independent study, based not on published records but on new visual observations with a large telescope, might resolve some of the ambiguities. Accordingly, a systematic study was begun with the 82-inch telescope." As director of the Yerkes (Wisconsin) and McDonald (Texas) observatories, Kuiper had ready access to the McDonald 82-inch telescope — then the third largest in the world. Thus he continued the classical tradition of visually observing the Moon. But Kuiper didn't make the mistake of focusing attention on unimportant tiny craters. He made detailed observations of features such as ridges, rilles, and central peaks that might yield clues to the origins of craters and maria. And he also realized the value of a photographic record that could be analyzed by various researchers, even on cloudy nights. He convinced the U.S. Air Force to fund a program of lunar photography using large telescopes to compile the most detailed and comprehensive photographic atlases of the Moon. These atlases became the basis for many geologic and statistical studies of the lunar surface, as well as many of the photographs in this book.

Kuiper's observations of the Moon convinced him that the maria were made of lava flows. This conclusion was based on a number of facts, but what seemed to impress him the most were the actual observations of lava flow margins and the discovery by Ewen Whitaker (now retired from the Lunar and Planetary Lab in Tucson, Arizona) of subtle color differences in the maria, often right at the lava-flow margins. Kuiper used these observations to blast the Gold dust theory: "These color contrasts indicate . . . *that the lunar maria are not covered with even one millimeter of cosmic dust,* which would have obliterated color differences." Kuiper included the italics to indicate that this was of fundamental importance.

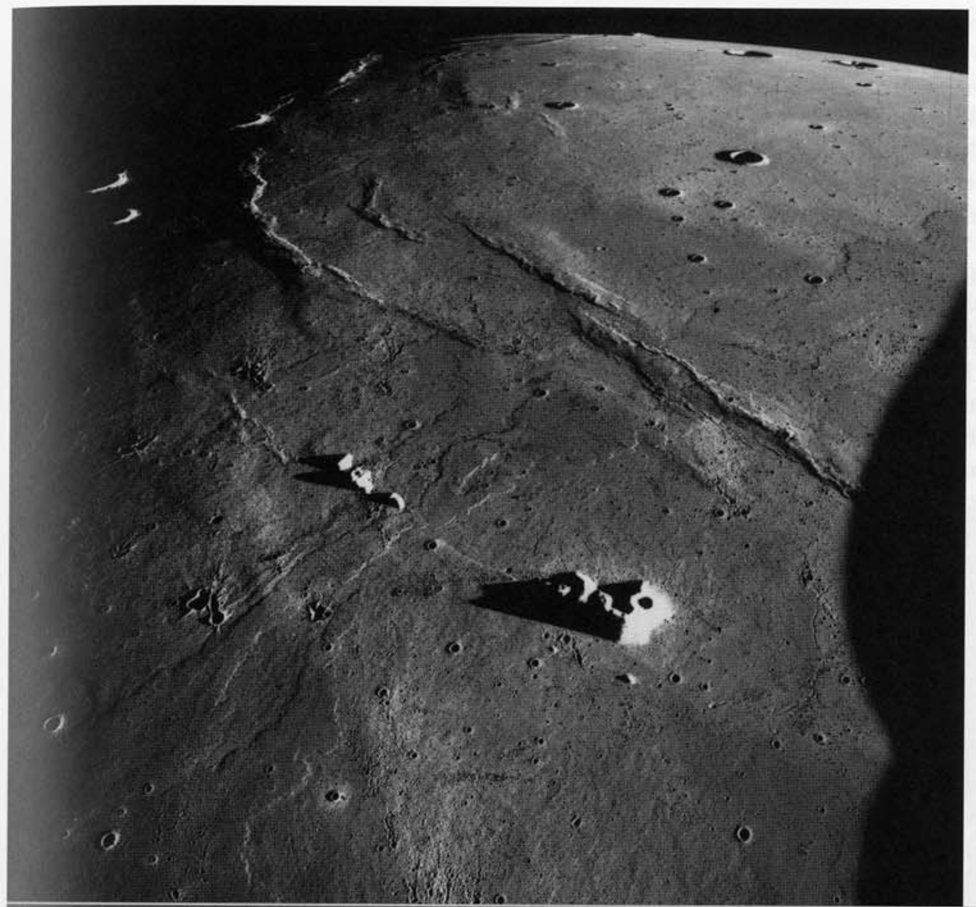
Baldwin, Kuiper, and even Urey (though he flirted with an ocean interpretation) all argued that maria were made of lava flows. Not only did their views carry the day, but they have proved to be right. Urey, however, had a somewhat different slant. Because he clung to the belief that the Moon had never been hot, it obviously could never have melted to produce lava flows. Consequently, Urey believed that mare lavas were produced instantly by melting during basin-forming impacts, and he disparaged Baldwin's and Shoemaker's evidence that maria formed significantly later than basins. Urey also suggested at various times that maria might consist of "dust, sand, and gravel" produced by basin-forming impacts. He knew nothing about geology and always talked in terms of what seemed "reasonable" to him as a chemist, emphasizing the degree of uncertainty there must be in all interpretations. He disagreed with the geological interpretations of Shoemaker, Hartmann, Kuiper, and Baldwin. Urey was a prime example of a gray eminence in one field who arrogantly assumes that his ideas are superior to those of specialists in other disciplines.

LAVA FLOWS ON THE MOON

As Kuiper's observations showed, actual lava-flow fronts — the leading edges and sides of streams of lava — can be detected with a telescope. When the terminator is just past the center of Imbrium, look for



Ewen Whitaker.



This Apollo 15 photograph beautifully shows the young Imbrium lava flows. The view is to the northeast. The large peak in the foreground is la Hire, and the pair of craters near the horizon are Helicon (left) and le Verrier.

This composite photograph of the Mare Imbrium region shows lava flows of differing compositions. Dark-hued flows are titanium rich, whereas the bright ones are titanium poor.

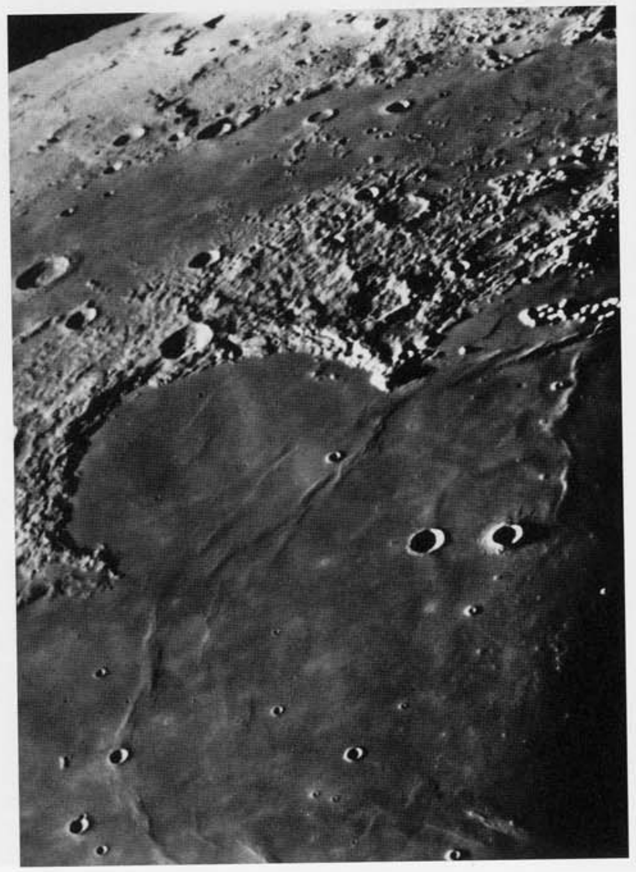
the very subtle edges of a flow about 60 km southeast of the crater le Verrier (20 km wide). Apollo photographs show that the flow originates near the crater Euler and can be traced back to near the peak la Hire. This single lava flow, extending almost 600 km from the edge of the Imbrium basin to its center, is only about 35 meters thick and has washed down an almost nonexistent slope of 0.01°! The lava must have been very fluid, more like water than terrestrial lava, and it must have roared across the Moon's surface at speeds of many kilometers per hour.

This particular flow is the second of three large, young lava flows that ran into Mare Imbrium. Gerry Schaber at the USGS Astrogeology Branch in Flagstaff, Arizona, mapped the flows using high-resolution, low-Sun-angle photographs taken during the Apollo missions. Actually, the flows were known earlier from telescopic photographs (like the ones reproduced here) and from "trick" photography. Whitaker took pairs of photographs of the Moon, one through an infrared filter and the other through an ultraviolet filter. He then combined infrared positives with ultraviolet negatives so that brightness differences all but disappeared, but the subtle differences in the color of the lunar surface were greatly accentuated.

Whitaker's composite photograph reveals obvious color differences on the surface of Imbrium. Areas that are dark on the image are bluer than average mare material, and light areas are redder. We talk of red and blue flows, but in fact they are all monotonous shades of gray, and only Whitaker's clever composite photography shows the subtle differences. Comparison with the Apollo photographs allowed Schaber to put together a nice story. The older of the three main flows (not easily visible through a telescope) is blue and, according to some inferences, about 3 billion years old. The youngest flow visible through a telescope is red and perhaps only 2.5 billion years old. These flows are apparently the most recent events in the lava flooding of the Imbrium basin.

One peculiar observation that wasn't explained, or apparently even commented on, was that the oldest and longest of Schaber's three lava flows extends from near the south rim of Imbrium, downhill to the deepest part of the Imbrium basin, and then *uphill* past le Verrier and Helicon onward to Sinus Iridum! How did these lava flows move hundreds of kilometers uphill? Were they so fluid and moving so fast that they sloshed across the bottom of the giant basin and slopped uphill, like milk poured carelessly into a cereal bowl? Or has the low point of the Imbrium basin changed over the last 3 billion years? Is it possible that at the time of the first eruption the center of Mare Imbrium was much shallower but has since subsided a few kilometers? Neither of these suggestions is very believable. Maybe Imbrium is flatter than it appears.

No matter how the flows traveled so far across Imbrium, they are there and visible in backyard telescopes. But how can you see a lava flow that is only 35 meters thick? The surfaces of lunar maria are typically so flat that you have to look closely to see any relief. But because the Moon lacks any significant atmosphere to dim and diffuse the Sun's rays, every small crater rim and hillock casts a long black shadow when the Sun is low. This "shadow magnification" permits viewing many fine details that provide information unavailable from studies of mare surfaces under higher illuminations. Although the smallest features that can be resolved with a 6-inch telescope measure about 1,000 meters across, with "shadow magnification" you can see vertical features only 25 to 50 meters high, because they cast shadows thousands of meters long! Cruise the terminator with high magnification, and, if the seeing is steady, you will be rewarded with details unknown to scientists who study only Lunar Orbiter photographs that are compromised by their relatively high Sun angles.

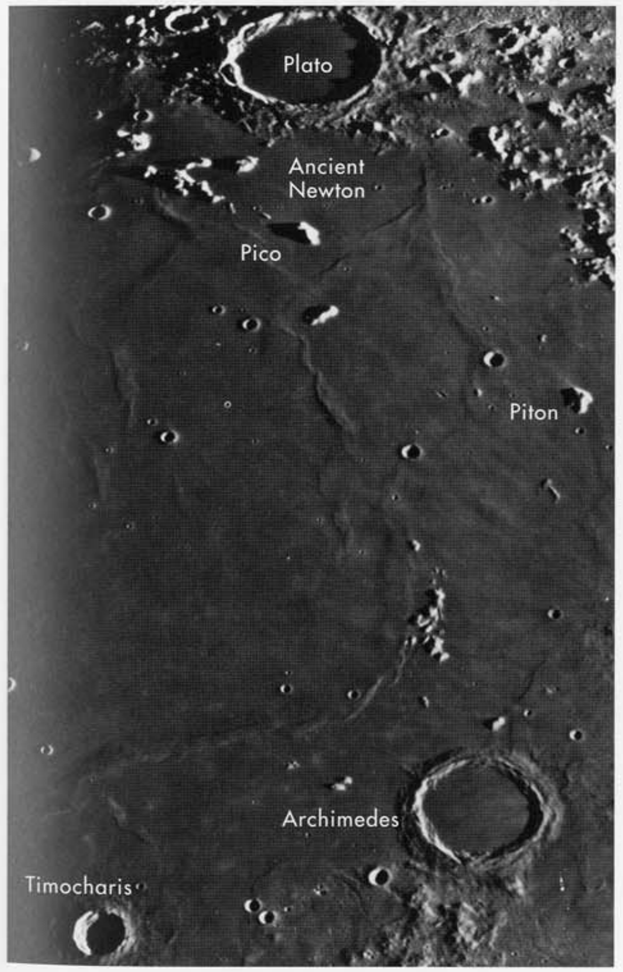


Lava flows near Sinus Iridum.

WRINKLE AND OTHER RIDGES

The most conspicuous subtle features on the surface of Mare Imbrium are low ridges. These are of two types: buried crater rims and basin structures. An easy-to-view example of the former is the 30-km-wide ring just north of Aristillus. Radial ejecta and part of the mountainous rim of Aristillus are draped over the relict rim.

A much more ambiguous ridge ring is a sharply defined but very low enclosure immediately south of the crater Lambert. Although this indistinct 55-km-wide ring had been noticed a hundred years ago, it appears on none of the classical lunar maps. It was named Lambert R during the early 1960s when the first modern catalog of lunar craters was compiled at the University of Arizona by a half dozen students (including me) under the direction of David Arthur. During the Apollo era some scientists proposed that portions of the ring had been formed by volcanic eruptions. Perhaps so, but a more likely explanation is that the ring is simply an impact crater that was later completely buried by lava flows.

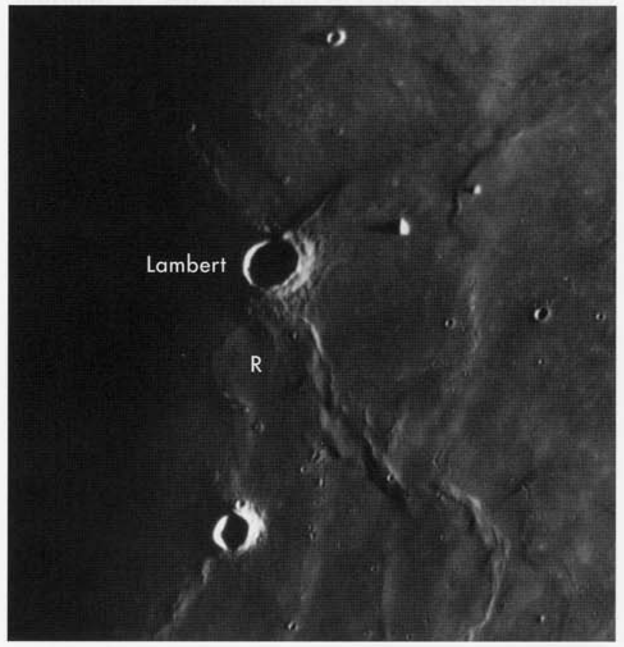


The prominent wrinkle ridges of eastern Imbrium, south of Plato.

Another ring of even less certain origin is Ancient Newton (so named by Johann Schröter nearly 200 years ago) — an elliptical grouping of ridges and isolated mountains just south of Plato. Ancient Newton is slightly larger than Plato and appears to have a smoother and slightly lower surface than the surrounding parts of Mare Imbrium. In fact, there is no real evidence that this is a buried crater, so perhaps this is no relic but just a trick of the eye and the mind. After too many hours of looking at the Moon, crater-like shapes could probably be seen in the texture of a blank piece of paper!

Subtle ridges of the second type are much more important than buried craters, for they offer insight

David Arthur.



Ghost crater Lambert R.

into the structure of impact basins and their lava fills. These ridges have long been called *wrinkle ridges* because they appear as if a pasty lava surface had been compressed from the sides, creating folds or wrinkles. During the "scientification" of the Moon when it passed from amateur to professional scientists, the more dignified term *mare ridge* was invented. In an early outbreak of political correctness in the 1970s, the features were renamed with the sharklike term *dorsa*, a term that only pedants use.

Wrinkle ridges are miniature mountain chains that occur in all maria. They are very low bulbous features best seen near the terminator, and they completely disappear when the Sun is high. In *The Moon*, Elger noted that under low illumination, ridges "are strikingly beautiful in a good telescope, reminding one of the ripple-marks left by the tide on a soft sandy beach."

Look closely at almost any wrinkle ridge and you will see that it is actually composed of two components — a broad, bulbous swelling and a narrow ridge crest that commonly occurs along one side of the broad swell. Although not very high (100 to 300 meters), ridge crests are often sufficiently steep that they cast shadows, and their sunward-facing slopes are brighter than those with gentler arches. Ridge crests are usually sinuous and sometimes migrate from one side of the swell to the middle or even the other side. Good examples of wrinkle ridges arc around the eastern side of Imbrium from near Archimedes toward Plato.

Although short, isolated ridges do exist, nearly all wrinkle ridges are part of interconnected systems that typically parallel the curved edges of maria; less frequently they are radial to the mare edge. In Imbrium, wrinkle ridges define a 650-km-wide circle. Starting near Lambert the ridges pass north of Timocharis; bend northwest of Archimedes; pass just inside of the Spitzbergen Mountains, Mount Pico, and the Teneriffe Mountains south of Plato; curve up past Sinus Iridum; through the small crater Caroline Herschel; and on around back toward Lambert. Look at any part of this wrinkle-ridge ring and you will see that it is not a continuous structure but is made up of numerous short segments, often offset from each other, yet continuing the same trend. What is the origin of this wrinkle-ridge circle? Before we solve this riddle, let's look at some other features that are part of the answer.

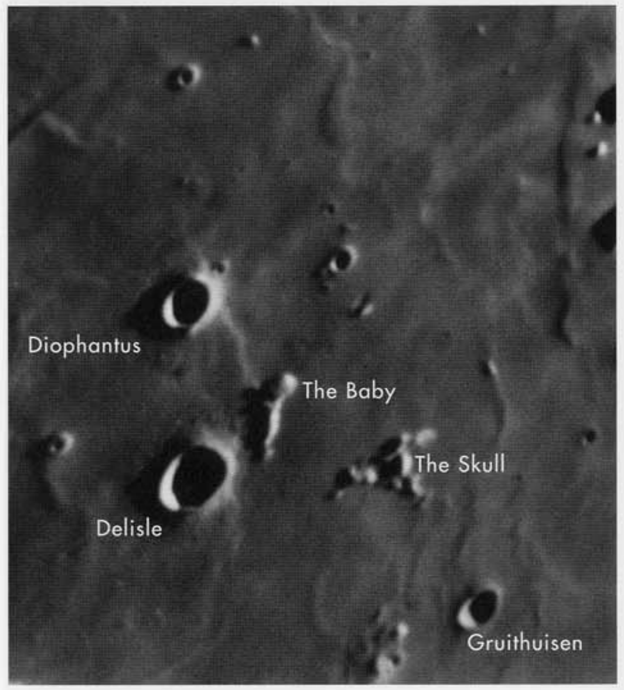
ISOLATED MOUNTAINS AND BASIN RINGS

Glistening bright mountains rising abruptly out of the gray maria make wonderful sights as the Sun rises or sets over them. All the classical selenographers remarked upon the beauty of isolated mountains such as Pico and Piton in northeastern Imbrium. Pico is the tallest of the peaks, rising about 2.4 km above the mare south of Plato, and Piton is only slightly lower at 2.3 km. Although their dramatic shadows stretching 50 to 100 km toward the terminator give the strong impression that Pico and Piton are steep, jagged peaks, in reality they are just gentle hills. Their modest heights combined with the curvature of the lunar surface render Pico and Piton invisible from the lunar surface at a distance of only 100 km; they would be below the horizon.

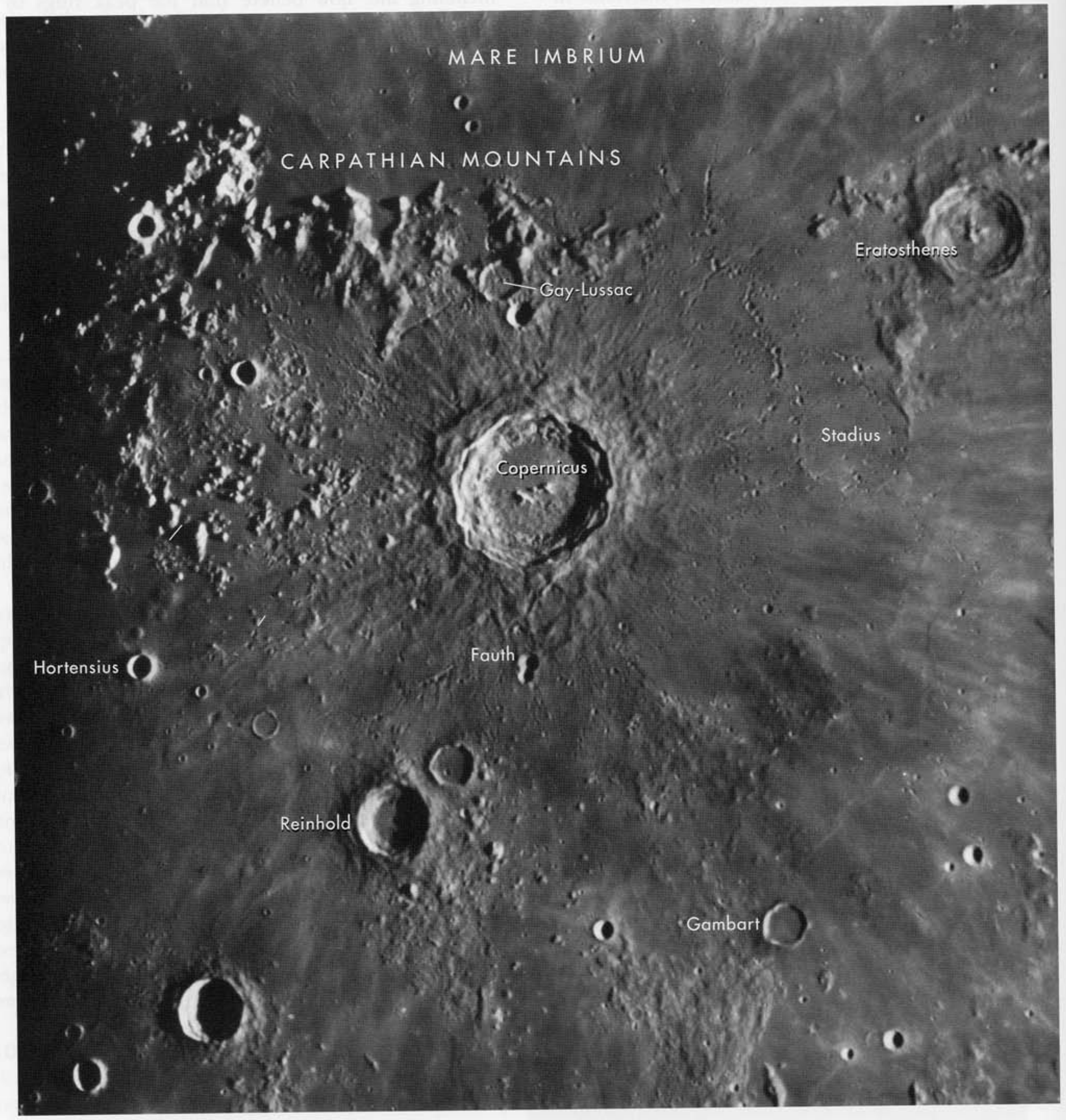
Other smaller peaks and mountain chains crop out along the periphery of Mare Imbrium. West of Pico are the Teneriffe Mountains and the Straight Range, stretching along the northern edge of the mare. Cape Laplace is along the same curvilinear line as these mountain ranges. Only a few tiny peaks are visible on Imbrium's western side, including two unnamed hills lying to the west of the 13-km-wide crater Caroline Herschel. Another peculiar small mountain mass just west of the crater Delisle (25 km) is called Mount Delisle but was christened "the Baby" by Kuiper. The southern, bulbous part of the mountain is the Baby's head; two arms stretch forward, and the Baby's body drags along behind as it crawls toward the nearby crater Diophantus (18 km). Whitaker suggests that the Baby is scurrying away because it is being hungrily eyed by the scary animal skull (replete with a saliva drip) just to its west! A few isolated peaks are found along Imbrium's southern shore. West of Lambert is la Hire and a smaller peak, and east of Lambert are two more small unnamed peaks. Completing this ring of peaks is another unnamed hill just west of Archimedes and the Spitzbergen Mountains, a 60-km-long, 1.5-km-high range.

Why are these peaks located there, and why aren't there others even closer to the center of Imbrium? In the early 1950s, Kuiper proposed that the peaks were solid crustal blocks thrown out by the impact that formed the Imbrium basin. But he didn't notice, as Baldwin did, that the isolated peaks and short mountain ranges defined a ring concentric with Mare Imbrium. In 1971 Hartmann and I noted that the peak ring has a diameter of about 670 km, just half the diameter of the impact basin defined by the arc of the Apennine Mountains. We had also found that other, less deeply flooded basins on the Moon have this ratio of 1 to 2 between the diameters of inner and main rings, so we suggested that Imbrium's ring of isolated peaks was the top of an otherwise buried inner basin ring. We saw that the concentric pattern of wrinkle ridges in Imbrium occurred near the peaks and had a similar diameter, so we proposed that both the wrinkle ridges and the peak ring were due to volcanism along circular ring faults caused by sagging and fracturing of the basin's original floor.

This was a great early effort on basins (he says modestly), but it was wrong. Sigh. Most lunar scientists, including me, now believe that the peak rings in Imbrium and elsewhere are structural rather than volcanic in origin. The most compelling evidence is the lack of volcanism associated with the inner rings of the few multiring basins identified and studied on the Earth. As impact craters transition in size to basins, there is a poorly understood transformation from a central peak to a ring of rebounded peaks. Wrinkle-ridge rings are simply indicators of submerged ring structures — they appear to be later lavas draped over preexisting basin rings. And in some cases the mare surface on the inner side of the ridge is lower than the surface on the basin shore side. In these cases the ridge also marks a fault where the center of the underlying basin floor abruptly dropped downward.



South is up in this photograph of the features Kuiper dubbed "the Baby" and "the Skull."



Copernicus.

5

Copernicus

Copernicus is a spellbinding crater. In Goodacre's *The Moon* the description of Copernicus includes the phrases "solitary grandeur," "most imposing object," "noble proportions," and "superb spectacle." Copernicus is a magnificent large and bright crater well placed for study from the Earth. It beautifully illustrates many characteristics of impact cratering, including terraced walls, secondary craters, bright rays, and central peaks. Copernicus is also a lasting reminder of the monumental contributions of the remarkable Gene Shoemaker. Late in the pre-Apollo period of modern lunar studies, he used Copernicus and its environs to understand two fundamental aspects of the Moon — the mechanics of impact cratering and lunar stratigraphy (relative layering).

IMPACT-CRATER MECHANICS

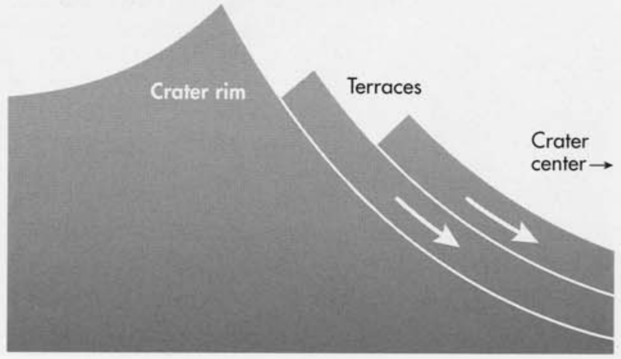
I remember coming home from college one holiday and mentioning to my father that I was studying mechanics. He was pleased that at long last I was learning something useful. To my father and many other people, the word "mechanics" called to mind overall-clad grease monkeys who repair cars. But in science, mechanics is the physics of how objects respond when forces are applied to them. In the late 1600s Isaac Newton invented orbital mechanics to describe how the planets, moons, comets, and all other bodies in the sky move in response to the force of gravity. Impact-crater mechanics is a much younger discipline that studies how rocks respond when violently struck by immense, incredibly fast-moving projectiles. Because events such as these are beyond everyday experience (if they weren't, life wouldn't exist!), understanding them requires imaginative extrapolation based in part on lessons learned from nuclear explosions and small-scale laboratory impacts, as well as studies of lunar and terrestrial impact craters.

CRATER RIMS AND WALLS

The basic impact-cratering process was described in Chapter 2; here we tie the theory to features visible in and around Copernicus, where the individual components of a large crater are well seen. First is the rim that rises 1 km above the surrounding mare. As the photograph shows, the rim of Copernicus is a rough area that forms a wreath (or glacis, to use the term favored by 19th-century selenographers) around the inner parts of the crater. Based on comparisons with terrestrial impact craters, probably a quarter to a half of the 1-km height of the rim is due to uplifting or arching of the local lunar surface resulting from the explosion of the projectile after it penetrated the ground. The remainder of the rim is made by the fallback of material ejected from the crater. Extrapolation from Shoemaker's mapping of Meteor Crater in Arizona suggests that the uppermost layers of the fallback deposits at Copernicus are from the deepest part of the excavated crater. When future lunar geologists visit Copernicus, they'll find this upside-down layering invaluable for sampling rocks from deep below the surface.

The crest of Copernicus's rim is not circular but is instead made up of eight or more relatively straight segments, each measuring up to 30 km in length. Like Meteor Crater's rather squared-off outline, these segments probably formed in response to stresses in the surface of the Moon that influenced the collapse of the inner walls. Some of the scientists who used to argue that lunar craters were formed by volcanic activity claimed that impact craters should have perfectly regular, round rims, but they neglected the complexities introduced by real rocks with preexisting zones of weakness. And apparently they never looked at an aerial photograph of Meteor Crater.

CROSS SECTION OF CRATER RIM FAULTS



The inner wall of Copernicus is about 20 km wide, with an apparently steep rim crest leading down to terraces, and less-coherent mounds near the crater floor. Shoemaker long ago suggested that the diameter of Copernicus had been increased by 25 km (the cumulative width of the terraces) during the modification stage of the crater's formation. High-resolution spacecraft images of Copernicus show that some of the terraces actually tilt away from the crater's center, with small ponds of impact-melted rocks along the low sides, closest to the rim. This tilt demonstrates that the terraces slid down a curved fault surface — the terrace blocks did not simply collapse vertically, like an elevator going straight down.

CENTRAL PEAKS AND IMPACT MELTS

The floor of Copernicus is 55 km wide — large enough for most metropolises to fit into easily. The floor has two distinct areas. Most of it is covered with small hills, or *hummocks,* as geologists call them. A pie-shaped piece on the northwest part of the floor is dark and smooth and is generally thought to be veneered with rocks melted by the energy of the impact that formed this huge crater. The surprising thing about Copernicus is that the melt is not more evenly distributed.

But there's something wrong with the impact-melt idea when applied to Copernicus. Evidence of a problem came from measurements of the shadows cast by the tallest of the central mountains on the crater's floor. Using simple trigonometry, shadow lengths can be directly converted into mountain heights. Twenty years ago I found that for 93 fresh lunar craters, the central-peak heights correlate wonderfully with crater diameters. For a 93-km-wide crater like Copernicus, the peaks should rise 2.0 km above the floor, but Copernicus's highest peak is only 1.0 km high — too short by a full kilometer.

Confirmation that something was wrong came from a comparison of the predicted and actual crater depth of Copernicus. From measurements of the depths of 32 Copernicus-like craters, I found that a 93-km-wide crater should be 4.4 km deep, but Copernicus measures only 3.7 km deep — too shallow by 0.7 km. Copernicus is too shallow by roughly the same amount that its peaks are too low. The best explanation is that the floor has been filled to a depth of 0.7 to 1.0 km by some material, but what?

Ray Hawke, a fellow graduate student at Brown University during the 1970s, suggested from careful measurements and calculations that the pool of impact-melted material at Copernicus should be only about 0.25 km thick, too thin to cause the observed shallowing. So I suggested that Copernicus, long the crowning example of a pristine impact crater, had actually been modified by volcanism. In fact, high-resolution Lunar Orbiter photographs show a hill on the floor of Copernicus that has a pit right at its summit, and looks for all the world — or the Moon — like a cinder-cone volcano. But my measurements and observations don't agree with the conventional wisdom, so lunar scientists ignore the evidence.

A more widely acceptable explanation is that variations in both the heights of central peaks and the depths of craters may be great enough to explain away the inconsistencies at Copernicus. And maybe the pit atop the hill really is just a random impact and not a volcanic crater. The reason lunar scientists accept such unconvincing arguments is that Copernicus is less than 1 billion years old. How would we account for volcanic activity occurring here so long after it apparently died out at most other places on the Moon? The evidence must be wrong — otherwise we may have to reconsider our currently cherished models.

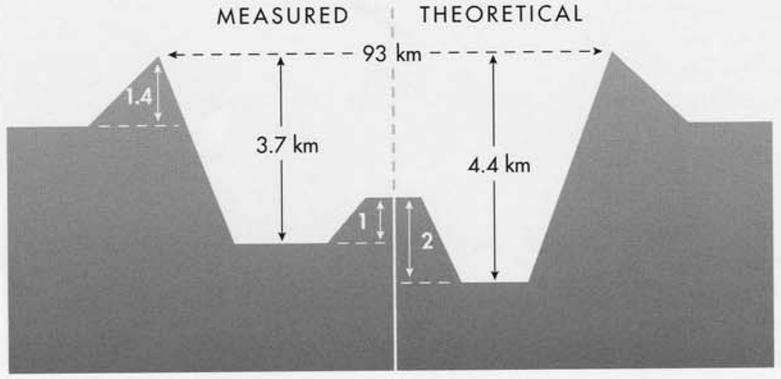
Even though the Copernicus peaks are runts, they are big enough to beautifully confirm the crater mechanic's view of how central peaks form. From measurements of the brightness of the Copernicus peaks at different wavelengths, Carlé Pieters, a researcher at Brown University, measured and was able to infer their mineral compositions. She discovered that the peaks are not made of the mare material the Copernicus impactor plowed into, but are most likely composed of olivine-rich rocks. Abundant olivine is due to the settling of heavy olivine crystals in magma that cools very slowly at depth. So the peaks of Copernicus must be made of deep rock (from 10 km down) that rebounded up to the surface during the crater-forming impact. And this is exactly what we see from geologic mapping of impact craters on Earth. The olivine in Copernicus's central peaks confirms the impact origin of lunar craters!

SECONDARY CRATERS

Copernicus is surrounded by hundreds of small pits — some aligned radially to the crater, others dispersed in loops and clusters. The pits extending in lines away from Copernicus have long been interpreted as having formed from material thrown out of the main crater: volcanic bombs (if Copernicus were a giant volcano) or ejected country rocks (if Copernicus were an impact crater). Even the most diehard impact-crater proponents like Baldwin accepted that the chains of craterlets east of Copernicus were "definitely igneous [volcanic] in origin." But he was wrong.

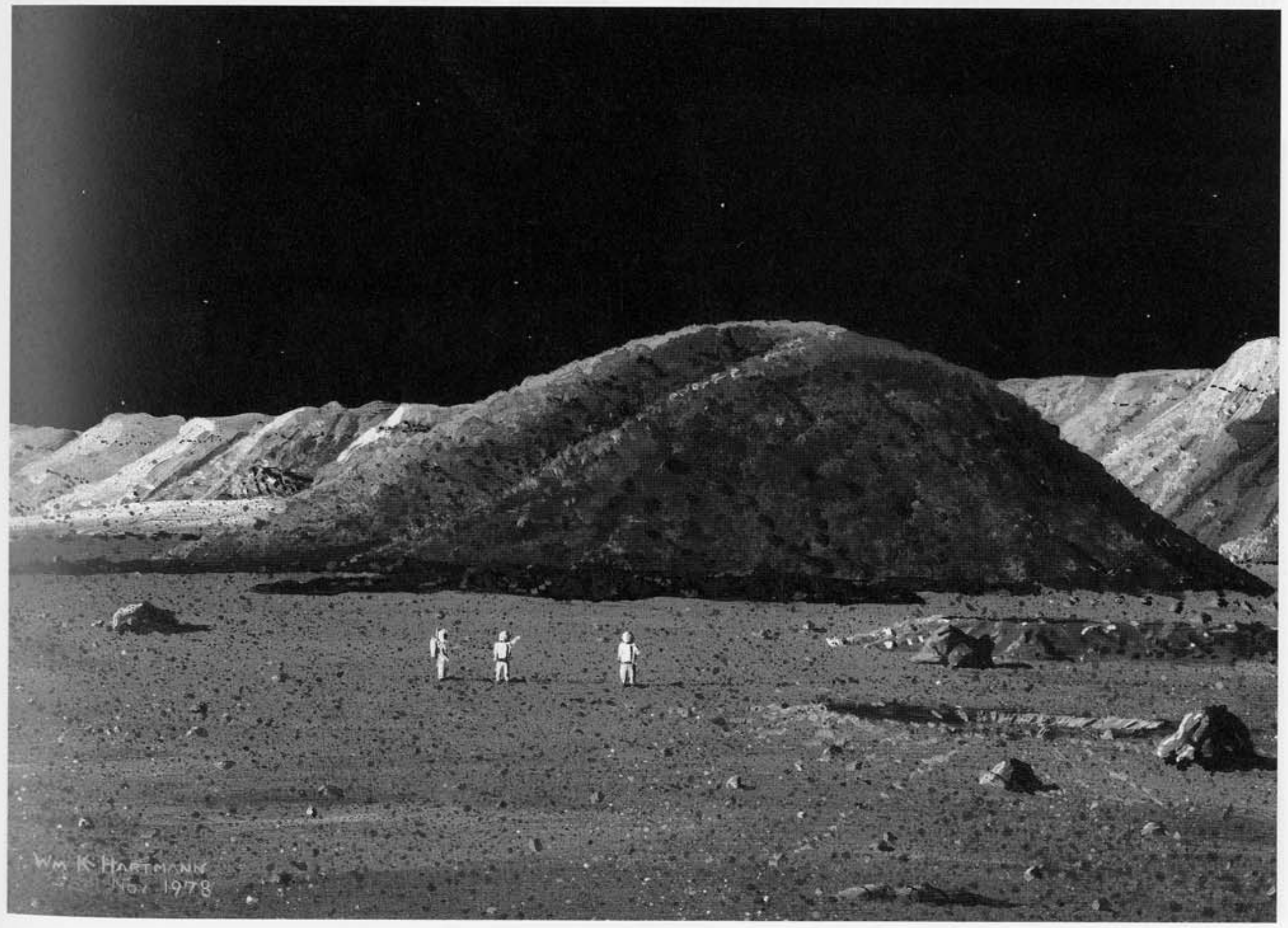
Shoemaker was the first to quantitatively model how the craterlets around Copernicus could have been made by fragments ejected during impact. In 1962 Shoemaker pointed out that such secondary craters have distribution patterns that differ from bomb pits around terrestrial volcanic craters. These

COPERNICUS CROSS SECTION



The central peaks of Copernicus are too low and the crater is too shallow (left) compared to predictions (right).

Carlé Pieters.



As a present when I completed my Ph.D., astronomer, artist, and friend Bill Hartmann painted this depiction of future astronauts exploring a cinder cone on the floor of Copernicus. Bill said I'm the astronaut in the middle.

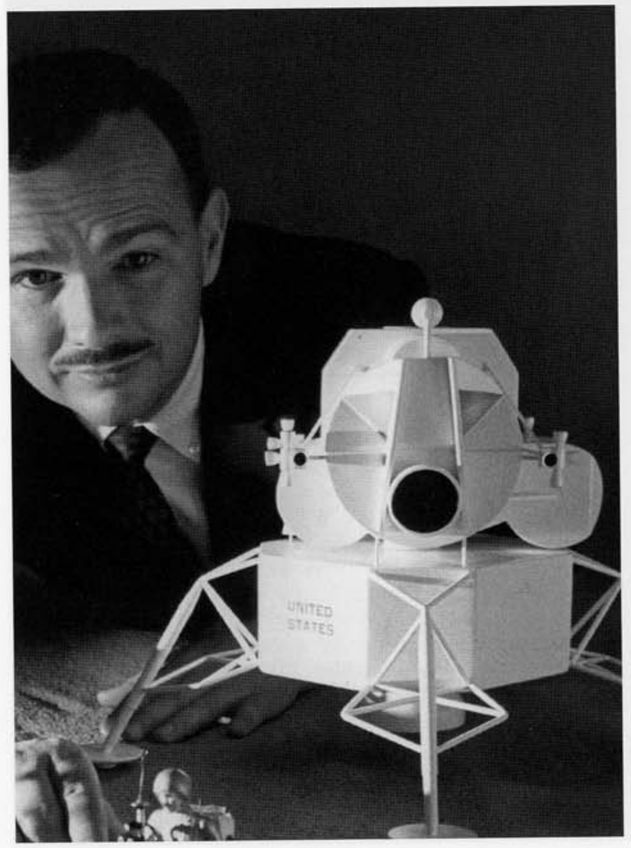
are generally more or less uniformly distributed around a volcano, but Shoemaker noticed that the craters excavated by nuclear explosions (which he had mapped before turning to study the Moon) had ejecta that formed distinct streaks or rays. By mapping these manmade-explosion craters it was established that the streaks were related to the irregular way the ground is fractured by the explosion's shock wave.

From the observed distribution of secondary craters around Copernicus, Shoemaker calculated that the craterlets could have formed by the impacts of hundreds of 0.1- to 0.5-km-wide rock fragments thrown out at a velocity of 0.4 km per second from the impact of an asteroid traveling 17 km per second that formed Copernicus itself. This calculation was an intellectual triumph, for it demonstrated that the understanding of high-energy impacts was sufficient to correctly explain even small features of craters.

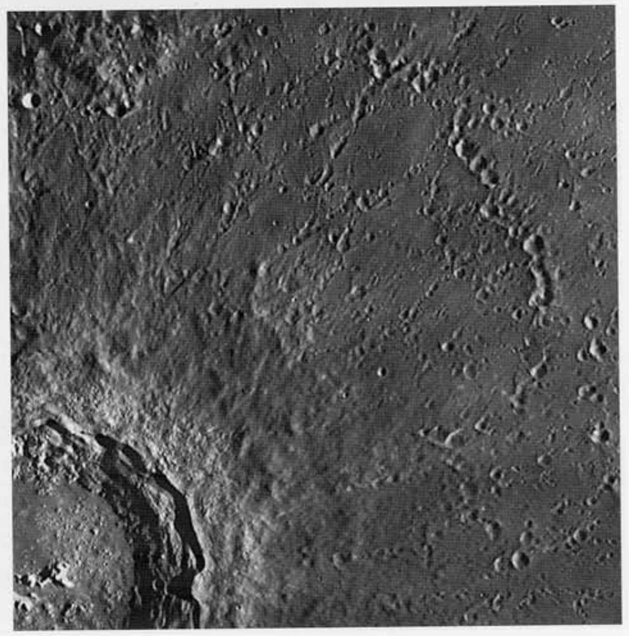
Shoemaker's model was beautifully confirmed by a combination of very high resolution photographs from the Lunar Orbiter spacecraft and laboratory experiments. The Orbiter pictures showed that secondary craters were irregularly shaped pits, usually formed right next to each other. Wrapped around each pit are coarse, herringbone-shaped dunes pointing back toward Copernicus.

Mimicking impact craters in a laboratory is difficult because very high speeds are necessary to simulate the cratering processes that occur in nature. But at NASA's Ames Research Laboratory near San Francisco, a remarkable gun was constructed that could do just this — hurtle small projectiles into targets at 6 to 8 km per second (about 15,000 miles per hour!), just as on the Moon. The experimenters found that if two projectiles hit the target surface at nearly the same time, as with secondary craters, the waves of the two expanding curtains of ejecta interfere, causing the ejecta to fall into herringbone piles around the craters that subsequently form. The match between these experiments and the Orbiter photographs is stunning. Once again, Shoemaker was right.

Under very low lighting angles, these herringbone patterns can just be glimpsed, especially along the secondary chain that lies between Eratosthenes and the eastern end of the Carpathian Mountains, northwest of Copernicus. Given the impressive number of secondary pits around Copernicus, it is surprising that only around 2 percent of the volume of lunar rocks that were excavated to form the main crater made secondaries. The remaining material was either pulverized into pieces too small to produce secondary craters or was ejected at speeds great enough to escape the Moon's gravitational hold. Almost certainly some of Copernicus's ejecta rained down on the Earth a billion or so years ago.



Gene Shoemaker.



Lunar Orbiter IV close-up view of Copernicus and associated secondary craters.

BRIGHT RAYS

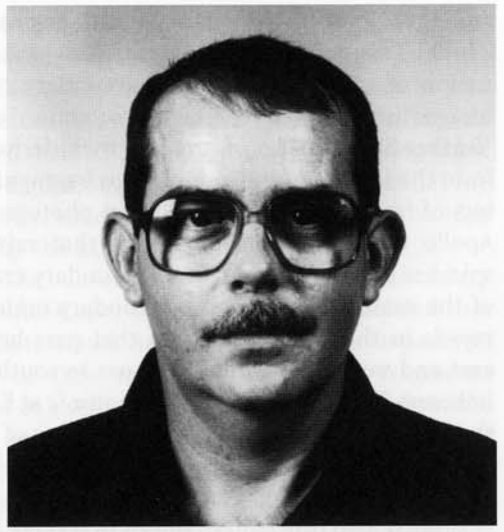
The greatest glory of Copernicus is its far-flung system of bright rays that extend almost 700 km across the surrounding maria. Even the most casual moongazer will notice the numerous milky white rays so conspicuous at full Moon. Classical selenographers widely debated the origin of these rays. Goodacre stated that they were "probably the greatest of all the unsolved enigmas presented by the lunar surface." Yet rays were one of the few lunar features whose origins were approached in a scientific manner by early selenographers. Careful observations demonstrated that rays were centered on and extended from bright craters, had lengths proportional to their source crater's diameters, were discontinuous, crossed over high and low areas without deviation, and often contained tiny bright crater pits. Based on these observations and terrestrial experiences, two interpretations emerged, both arising from a volcanic origin for the source craters. In the first case, huge eruptions flung bright ash vast distances. In the second case, the volcanic action that formed the craters also fractured a brittle lunar crust, allowing volcanic ash, dust, or even salts to escape from small cracks.

But we now know that source craters are not volcanoes, so what are the rays? The reason rays were misinterpreted is that impact cratering was inconceivable, and thus so were the immense distances that rocks could be ejected during an impact. Shoemaker's explanation of an impact origin of secondary craters led him naturally to describe the formation of rays as "feather-like splashes of crushed rock derived chiefly from the impact of individual large fragments or clusters of fragments." High-resolution photographs from Apollo cameras beautifully show that rays are the splashes of ejecta around small secondary craters. One of the easiest places to see secondary craters within rays is in the Copernican rays that pass both to the east and west of the crater Pytheas in southern Mare Imbrium. When the waxing terminator is at Euler, both the brightness of the rays and the dozens of small pits within them can be seen through a 6-inch telescope at moderately high magnification. Take a look.

Hawke and others have shown that there is more to the rays of Copernicus than even Shoemaker realized. The mechanism that Shoemaker proposed is correct, but an additional factor accounts for the brightness of the rays. Apparently, Copernicus excavated below the surface mare rocks into buried highland rocks. These highland materials — thrown out as part of the ray-forming ejecta — are as bright as the lunar highlands. The high albedo of the Copernican rays is actually due to sprinkles of bright highland material.

Copernican rays.

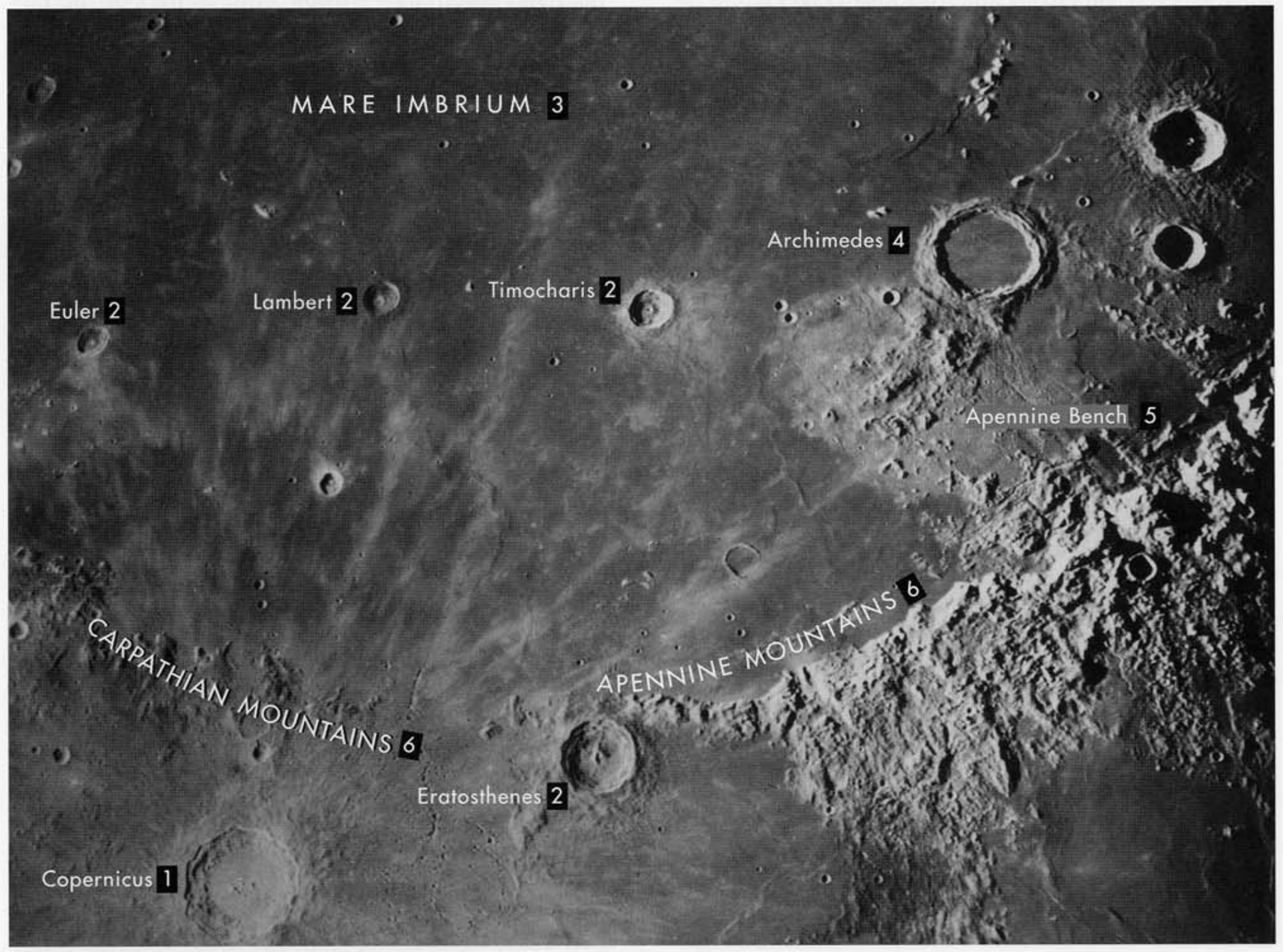
Copernican rays near the crater Pytheas.



B. Ray Hawke.

LUNAR STRATIGRAPHY

In the late 1790s one of the key stages in the development of Earth geology occurred when British engineer William Smith recognized a relatively consistent sequence of rock types throughout southern England. This succession of layered rock or strata provided a framework for determining the relative ages of rocks and fossils, and offered a means for correlating the geology of different parts of England. One of the amazing facts about the Earth is that the rock sequence initially defined from one small island was in fact generally representative of the stratigraphy of the entire planet! Despite all the local geologic convulsions that make one part of the globe different from others, the major events seem to have been planetwide. There is a crude synchronicity in the Earth with periods of mountain building, volcanic eruptions, and the rising and falling of ocean levels, all occurring at about the same time at many widely separated locations. This is probably attributable to the fact that these events are ultimately driven by deep convection currents that bring heat and material to the Earth's surface in coordinated spasms. Stratigraphy is perhaps the most fundamental of the Earth sciences because it organizes all geological events into coherent time sequences.



Sequence of events numbered from youngest (1 = Copernicus formation) to oldest (6 = Apennine Mountains from Imbrium basin formation).

On the Moon we can't identify individual rock sequences that would enable us to construct an Earth-like stratigraphy. Because few geologists studied the Moon, few selenographers seemed to recognize the loss. But in 1962 Shoemaker and Hackman realized that the instantaneous and literally far-reaching nature of impacts make them excellent stratigraphic time markers. By concentrating on the far-flung ejecta of impact craters and basins rather than on the holes themselves, Shoemaker and Hackman were able to distinguish younger (top) from older (lower) deposits and thus sequences of events. This elegantly simple principle of superposition is one of the most powerful of the lunar geologist's tools. In fact, two of the best books about the Moon — Don Wilhelms's *The Geologic History of the Moon* and Thomas A. Mutch's *Geology of the Moon: A Stratigraphic View* — are infused with the principles of stratigraphy.

The area around Copernicus was selected by Shoemaker for his first geologic lunar map based on stratigraphic principles. Copernicus was clearly the youngest major impact deposit because its bright rays and secondary craters drape over the surrounding maria, the Carpathian Mountains, the nearby crater Eratosthenes, and everything else nearby. Eratosthenes itself is clearly older than Copernicus but is still relatively young, as indicated by its small secondary craters, which cover the nearby lavas of Mare Imbrium and Sinus Aestuum, a small patch of mare material southeast of Eratosthenes. You can just see Eratosthenes' secondary craters when the terminator is beginning to reveal Copernicus. A defining characteristic of Erastosthenian craters is that, though they look quite fresh, they lack significant rays.

Shoemaker and Hackman identified the lava surface of Mare Imbrium as the next oldest stratigraphic unit, since it was the material beneath Eratosthenes' secondary craters. As explained in Chapter 3, the rough terrain near Archimedes — the Apennine Bench — is embayed by Imbrium lavas and thus must be older than them. And the next older units are the Apennine, Carpathian, and other Imbrium-surrounding mountains that form the basin's rim. Finally, the oldest terrain recognized was the cratered lunar terrae or highlands that had been battered by the Imbrium basin's secondary craters and scouring ejecta.

Shoemaker and Hackman realized that mare lavas embay and partially bury the flanks of the crater Archimedes. And yet Archimedes is clearly younger than the Imbrium basin because it lies within the basin. They had a flash of inspiration and realized that there must have been a sufficiently long interval between the formation of the Imbrium basin and the deposition of its mare lavas for Archimedes to have formed on the basin floor. Their simple geologic mapping proved that the mare lavas could not have been melted from the heat generated by the basin-forming impact!

As good geologists, Shoemaker and Hackman realized that for their stratigraphic concept to be accepted and extended to other regions of the Moon, they had to invent catchy names for the various time periods represented. They proposed the following nomenclature for lunar stratigraphy and ages, from youngest to oldest:

SYSTEM/PERIOD	GENERAL CHARACTERISTICS
Copernican	Rayed fresh craters
Eratosthenian	Non-rayed fresh craters
Procellarian	Maria
Imbrian	Impact basins
Pre-Imbrian	Terrae

The name *Procellarian* came from the vast expanse of mare lava in nearby Oceanus Procellarum. The Imbrium maria could just as well have been the prototype, but that name was reserved for the basin-forming impact event that created the Imbrian system as then defined. Two points about this stratigraphic scheme should be noted. First, the "ian" endings refer to the stratigraphic "time-rock" system, not the particular feature that gives its name to the system. Second, and far more important, is that the lunar stratigraphic sequence represents deposits formed in greatly unequal durations of time. The formation of the Imbrium basin took place over a period of minutes or days, but the lavas that fill it oozed out over tens to hundreds of millions of years.

The Shoemaker-Hackman concept was immediately applied to other regions of the Moon in an amazingly productive period of geological mapping initiated under Shoemaker's direction at the USGS center in Flagstaff, Arizona. Never before had so many scientists studied the Moon so carefully or in such a coordinated manner. The result was a collection of 44 of the most detailed maps ever made of the entire near side of the Moon. Such stratigraphic mapping has been applied successively to every planet and moon visited by spacecraft during the last 30 years. Another benefit of this effort was the training of a cadre of planetary scientists who have since played key roles in the geologic study of the solar system. In fact, one USGS Moon mapper, geologist Harrison Schmitt, went to the Moon on the last Apollo mission and is still the only scientist to have visited another planetary body.

As the Flagstaff geologists progressively mapped the Moon, they found that the original stratigraphy was remarkably appropriate, but refinements were necessary. The current USGS stratigraphy as presented in Wilhelms's *Geologic History of the Moon* is:

SYSTEM	APPROXIMATE AGE
Copernican	Present – 1.1 b.y.
Eratosthenian	1.1 – 3.2 b.y.
Upper Imbrian	3.2 – 3.75 b.y.
Lower Imbrian	3.75 – 3.85 b.y.
Nectarian	3.85 – 3.92 b.y.
Pre-Nectarian	3.92 – 4.5 b.y.

Currently we are in the *Copernican* period of lunar history. There are no definite mare lava flows as young, but small numbers of superposed impact craters suggest that a few lava deposits in northern Oceanus Procellarum are of Copernican age. The most significant geologic activity on the Moon during the Copernican period has been the continuing (but infrequent) impact cratering. According to Wilhelms of the USGS's Astrogeology Branch, there are 44 Copernican-age craters larger than 30 km in diameter. They are among the most interesting objects for telescopic observers because they are so bright and virtually uneroded.

The *Eratosthenian* period was the longest in lunar history, lasting 2 billion years. During this era late-stage volcanism filled low-lying regions in and around Mare Imbrium and Oceanus Procellarum. Ejecta and secondary craters from some Eratosthenian impact craters are flooded or embayed by mare lavas. Astronauts brought back Eratosthenian-age (3.08-billion-year-old) basalt samples from the Apollo 12 landing site. Interestingly, virtually all of this youthful (for the Moon) volcanism occurred within an immense, ancient, and controversial impact basin called the Gargantuan or the Procellarum basin. We'll talk more about this putative basin later.

The *Upper Imbrian* period was when most of the maria that we presently see on the Moon formed — apparently radioactive heating was intense during this time. Lava flows had undoubtedly erupted earlier, but most were buried by Late Imbrian–age outpourings and by earlier basin ejecta. Large craters that formed near impact basins during this epoch often have lava-flooded floors — Plato and Archimedes are the best-known examples.

Further mapping away from the Copernicus region showed that another large impact basin — Orientale — formed after Imbrium. It too provided geologists with an important time marker. The formation of the Imbrium and Orientale basins provides the most important and widespread stratigraphic boundaries between the ancient, heavily cratered Moon and the more recent Moon dominated by lava flows and a great reduction in impact cratering. The short interval beginning with the Imbrium impact and ending with the Orientale impact is called the *Lower Imbrian* period.

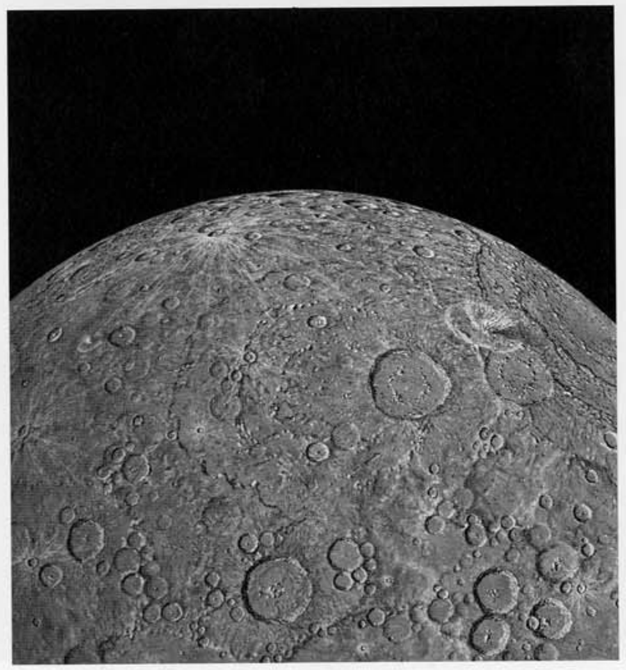
The *Nectarian* period is named for the impact basin that contains the relatively small Mare Nectaris, which is just one of about ten multiring basins that formed in a brief interval. These basins are all heavily degraded by impacts. Wilhelms estimated that during this 200-million-year period more than 1,700 craters larger than 20 km in diameter were formed. This was obviously a period of rapid change and heavy impact erosion.

Before the formation of the Nectaris basin, about 3.9 billion years ago, there was such an intense barrage of impacts that it is difficult to distinguish separate rock units. The *Pre-Nectarian* period started with the intense cratering associated with the accretion of the Moon by mutual collisions of millions of smaller bodies. At some point the bombardment rate slowed down enough that earlier craters were no longer completely destroyed by later impacts. These fragments of ruined craters are the oldest and most difficult to recognize on the Moon. Wilhelms mapped 30 basins from the pre-Nectarian period, along with thousands of craters. Tiny fragments of basalts found in clumps of impact rocks date at 4.2 billion years old, demonstrating that volcanism also occurred during the earliest days of the Moon.

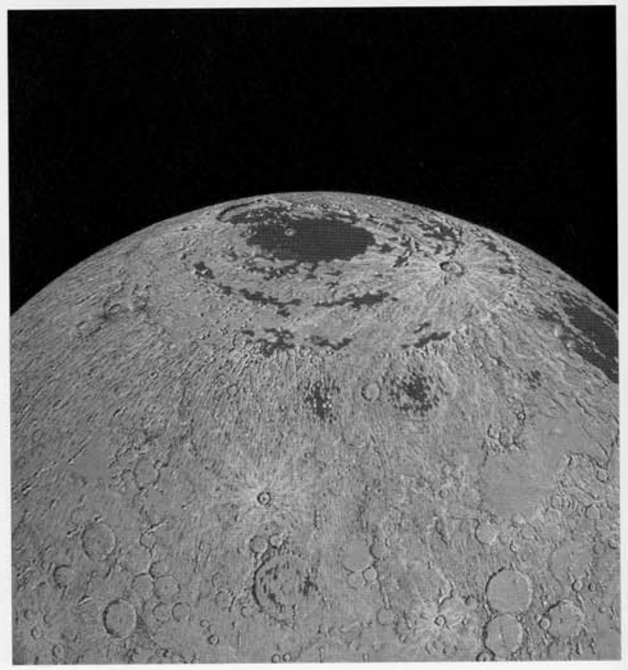
Below is a list of the major craters and basins of each stratigraphic age group. Try to find them all, and as you view them, notice the features that characterize their assigned ages.

STRATIGRAPHIC LIST OF MAJOR CRATERS AND BASINS

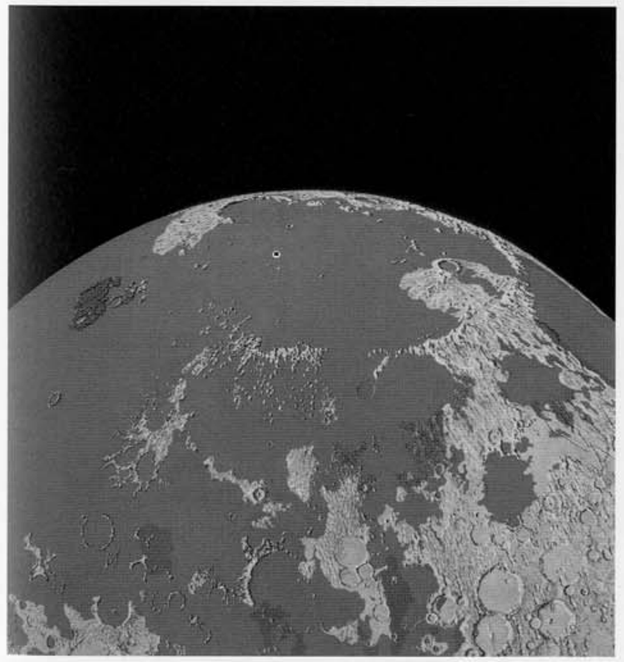
COPERNICAN	ERATOSTHENIAN	UPPER IMBRIAN	LOWER IMBRIAN	NECTARIAN	PRE-NECTARIAN
Copernicus	Eratosthenes	Archimedes	Petavius	Cleomedes	Manzinus
Tycho	Pythagoras	Plato	Arzachel	Clavius	Grimaldi
Aristarchus	Bullialdus	Posidonius	Cassini	Humorum	Ptolemaeus
Kepler	Theophilus	Piccolomini	Macrobius	Crisium	Tranquillitatis
Eudoxus	Langrenus	Sinus Iridum	Vitello	Nectaris	Gargantuan



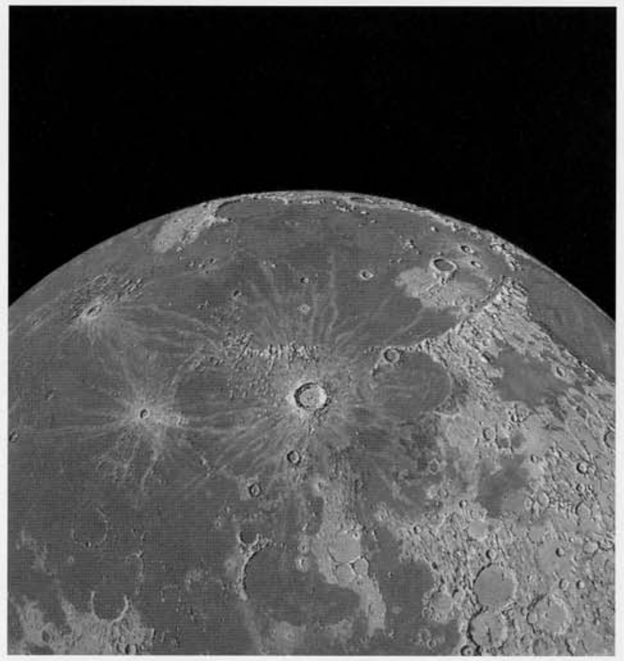
Nectarian-period Moon.



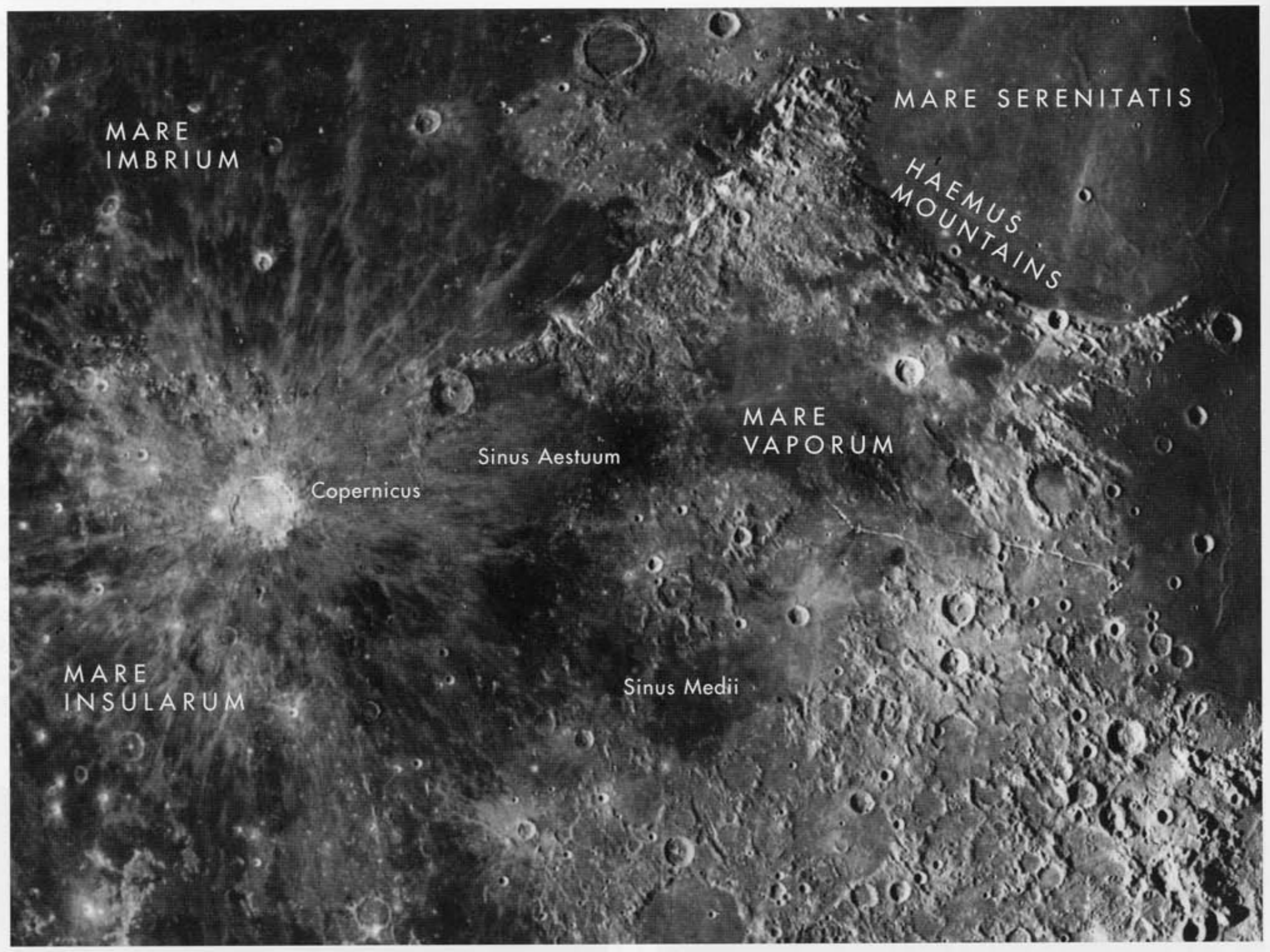
Lower Imbrian.



Upper Imbrian.



Copernican (present day).



Imbrium South.

6

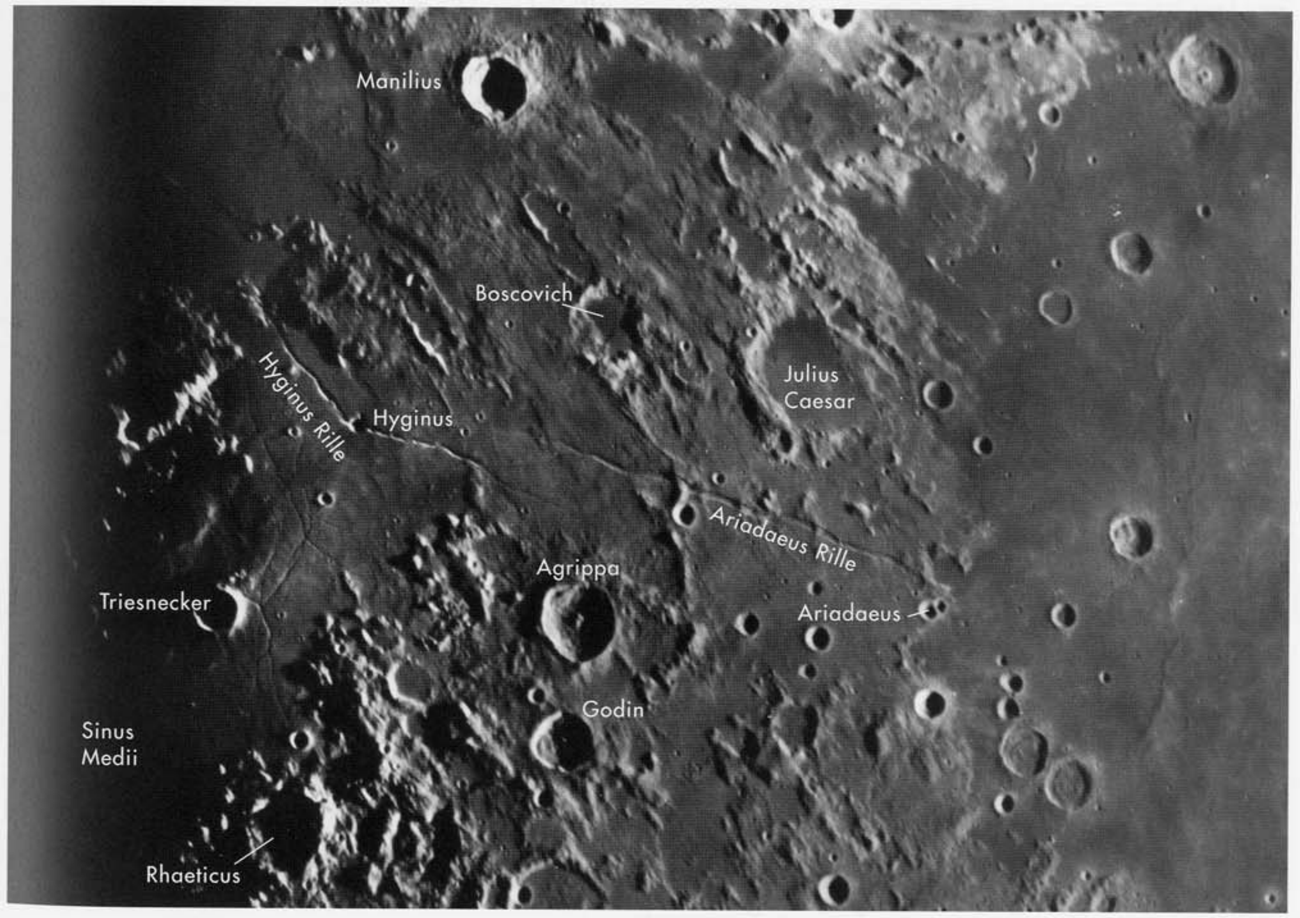
Imbrium South

Immediately south and southeast of Mare Imbrium is a region of circular mare patches and highland remnants that have been scoured by Imbrium basin ejecta. This area defines an arc extending roughly 600 km behind the Apennine and Carpathian rims of the Imbrium basin and includes three small mare patches (Mare Vaporum, Sinus Medii, and Sinus Aestuum) as well as the northern end of Mare Nubium, which was needlessly named Mare Insularum in 1976. Everything in this region is irregular and somewhat ambiguous in morphology.

Compared to the intense discussions of impact cratering, stratigraphy, and basin origins in the preceding pages, this chapter is relatively calm. Most of the excitement comes from (1) the great modification of craters by the overwhelming barrage of Imbrium ejecta; (2) fields of little volcanoes reminiscent of those in Iceland; and (3) dark deposits of volcanic ash that may someday be mined for their mineral resources.

HAEMUS MOUNTAINS SOUTHWARD

The Haemus Mountains are a striated chain of lumpy hills marking the south-southwestern border of the Serenitatis basin. Their present form is entirely due to Imbrium ejecta, which scoured and partially buried the preexisting terrain. Notice all the ridges aligned



Rillelands.

southeast to northwest and the crater rims between the edge of Serenitatis and the Ariadaeus Rille. This unnamed area includes conspicuous examples of the Imbrium sculpture that convinced Gilbert, Baldwin, and later geologists that a tremendous explosion had taken place at Imbrium. All the light-hued material in this region was blasted from the great hole that is the Imbrium basin and deposited as a thick veneer across the area.

The movement of material from Imbrium must have included a near-surface flow of debris — some preexisting craters like Julius Caesar and Boscovich were so heavily pelted that the sides of their rims radial to the center of Imbrium were eroded almost completely flat. Look at the ruined crater almost in contact with the northeast rim of the much younger Manilius. This nameless feature was battered and filled with lineated ejecta. Notice the lava-flooded, elongated walled troughs that radiate from Imbrium as well. These are believed to have formed by overlapping secondary impacts from Imbrium debris. Nomenclatural nabobs of the 1970s who understood little of the catastrophic origins of these features christened them with inappropriate names like *Lacus Felicitatis* (Lake of Happiness), *Sinus Fidei* (Bay of Faith), and *Lacus Gaudii* (Lake of Joy). But there would have been little to be happy about 3.85 billion years ago, when all hell (or Imbrium, to be more exact) broke loose.

The crater Julius Caesar and other elongated troughs and features in this area have long been recognized as unusual. One detailed earlier interpretation was that of Spurr, who believed that the features were *horsts* and *graben* (linear ridges and depressions formed by uplift and subsidence) associated with the supposed volcanic origin of Imbrium. This tectonic idea was accepted even by people who knew that Imbrium was a giant impact basin, until Lunar Orbiter photography demonstrated that the similarly battered terrain around the Orientale basin was due to massive scouring and deposition of ejecta. Once again, without spacecraft images we would never have correctly understood the Moon.

RILLELAND

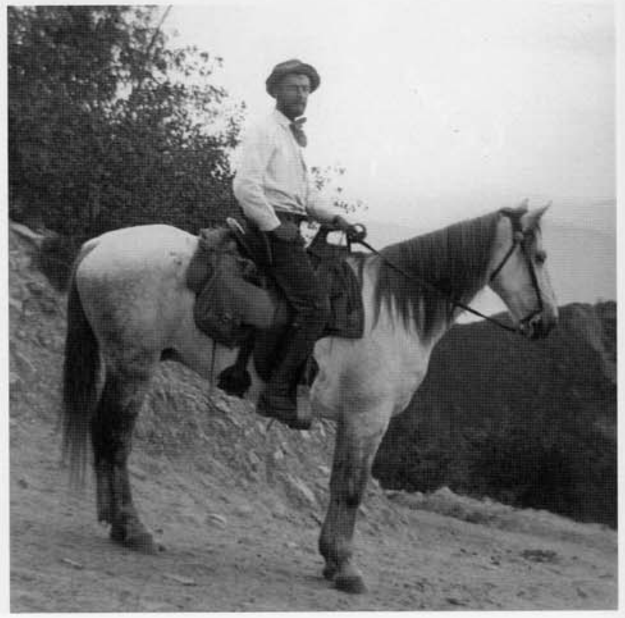
Between Julius Caesar and Sinus Medii is a concentration of rilles that is remarkable for its variety and ease of viewing. In Rilleland we find three systems, each with different characteristics.

The Ariadaeus Rille (named for the small simple crater at its eastern end) is a classic example of the flat-floored, parallel-walled straight rille. It is about 220 km long, 4 to 5 km wide, and roughly 0.8 km deep. The Ariadaeus Rille is an excellent example of a graben, like those found on Earth. Graben form when opposing horizontal forces pull apart with enough strength that parallel faults form, and the terrain between them drops. Where the rille crosses some ruined crater rims we can see that they also drop down a few hundred meters.

Based on the geometry of the graben's sloping walls, the two inward-facing faults of the Ariadaeus Rille meet at a depth of 2 to 3 km, which agrees closely with the estimated thickness of the fractured and crumbled ejecta (called the megaregolith) that overlie the deeper, more coherent lunar rocks. This similarity of depths is probably more than a coincidence since graben faults often start at the boundaries where rock layers of different strengths meet.

Connected to the western end of the Ariadaeus Rille by a narrow diagonal branch is the remarkable Hyginus Rille. It consists of two sections, one paralleling the nearby Ariadaeus Rille and the other aimed toward the center of the Imbrium basin. These two segments join at the 9-km-wide Hyginus crater. What makes the Hyginus Rille unique is that it contains a series of rimless collapse pits that are best visible in the segment northwest of the crater. It is beyond belief for even the most rabid impact-crater advocate that the pits in the rille are chance alignments of impact craters; they must be of internal origin. If so, why not the rimless Hyginus crater too?

Peter Schultz, while still a graduate student at the University of Texas, suggested that Hyginus may in fact be a volcanic caldera or collapse crater. High-resolution Lunar Orbiter photographs show that the crater's flat floor contains small domes that may be volcanic in origin. Schultz also pointed out that Hyginus is in the center of a 100-km-wide saucerlike depression about 1.5 km in depth. Some volcanoes on Earth are similarly centered on broad sags that result when subterranean magma reservoirs empty during volcanic eruptions. But if Hyginus formed by subsidence, where are its eruption products? One possibility is that an irregular dark patch, seen around the crater at full Moon, consists of volcanic ash deposits. Hawke, of the University of Hawaii, confirms (from spectral measurements) that the dark material is likely to be ash, but only amounts to quite a small volume. It's fair to say that despite all our lunar exploration we still don't clearly understand how Hyginus and the rimless pits along its rille really formed.



Josiah Spurr.

The third rille group near the center of the Moon's face is the Triesnecker Rilles. Triesnecker itself is the archetypal complex impact crater featuring a wreath of slump blocks inside its bright and steep rim. It is clearly younger than the nearby rille features, since one of them is apparently interrupted by the crater.

The Triesnecker Rilles are an intertwined system of mostly straight and narrow (0.75 to 1.5 km wide) rilles that generally extend north to south. An intriguing feature is the continuation of a rille southward past the shallow crater Rhaeticus. Train your telescope on it and you'll see that where the rille crosses into rough highland material it seems to be made of coalescing pits — like parts of the Hyginus Rille. This is a delicate feature that is difficult to observe. Understanding how it formed is even more difficult.

Mare Vaporum.

Unlike the Ariadaeus Rille, the narrow Triesnecker Rilles can't be grabens unless the depth to the underlying coherent rock layer is much shallower. Spurr believed that Triesnecker crater was a volcanic caldera and that the rilles were fractures formed by the uplifting of the surrounding plain as the caldera erupted. We are now completely certain that Triesnecker is an impact crater, and it just happens to have formed on the edge of a preexisting rille complex. But no one has yet explained how or why the rilles formed. Notice how it's usually a lot easier for scientists to poke holes in each other's theories than it is to come up with good alternatives.

SINUS MEDII

Southwest of Triesnecker is the approximately 200-km-wide patch of mare material called Sinus Medii, or Central Bay. For Earthbound observers, this area is the center of the Moon, but don't look for a landmark. The exact center is a nondescript point between the small, bright crater Bruce and the decrepit, ruined crater Oppolzer. Sinus Medii isn't very interesting either, having only a few ridges that appear to be draped over submerged craters.

The only claim to fame for Sinus Medii is as a target for two of the American Surveyor spacecraft during the late 1960s. Surveyors were supposed to demonstrate the soft-landing technology to be used on Apollo landers, though Surveyor 4 was destroyed when it crashed into the Moon, which doubtlessly caused more than a little concern among Apollo mission planners. Surveyor 6 was in some ways the most successful of the series — taking 30,000 photographs of the lunar surface. Like its predecessor Surveyor 5, number 6 determined that the chemical composition of the soil was most similar to basalts — a disappointment to those theorists who believed the Moon was made of meteorite-like material, granites, or green cheese.

MARE VAPORUM, SINUS AESTUUM, AND FIRE FOUNTAINS

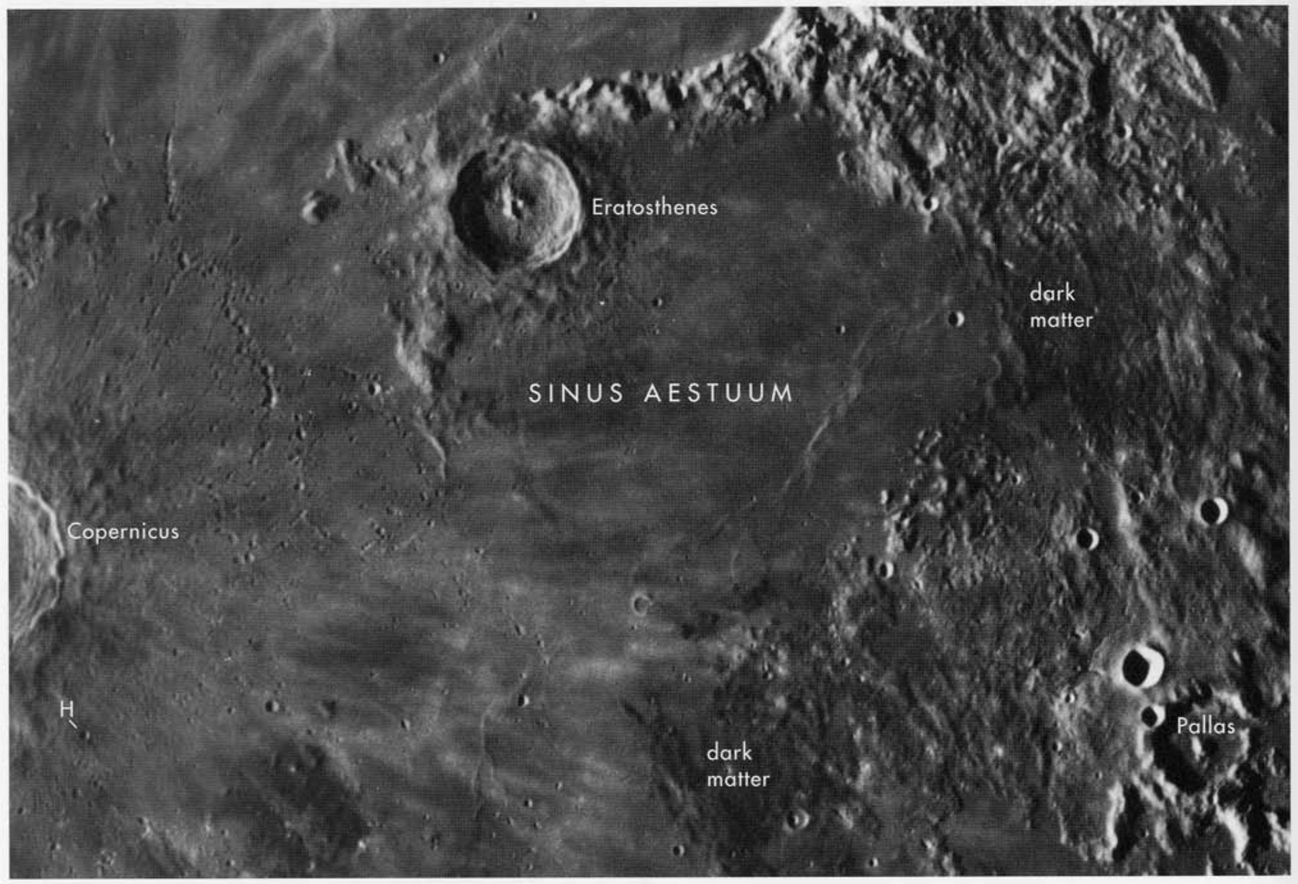
The Sea of Vapors (how did 17th-century Moon mappers think up these names?) is a 200-km-wide circular patch of Eratosthenian-age lava. Its relative youthfulness is obvious by comparing its dearth of impact craters to the mare material that surrounds Triesnecker and Hyginus.

Vaporum lavas embay the back slopes of the Apennine Mountains, which are composed of ejecta from the Imbrium basin. A few small mare ridges in the southwest and a small hill and adjacent lava dome on the northeast side of the mare are the only topographic features of interest. Clearly, Vaporum lavas fill a circular low spot, and on the Moon that implies that they fill an older, undetected crater.

Sinus Aestuum is a similar, 230-km-wide circle of mare material that lies to the south and east of Eratosthenes. Although it means Seething Bay, Aestuum is boring real estate except for a braidlike wrinkle ridge that extends from southwest to northeast. The Aestuum lavas are low-titanium basalts estimated to be 3.2 billion years old.

An instructive aspect of Sinus Aestuum and Mare Vaporum is that the region features some of the most extensive deposits of dark mantle material anywhere on the Moon. Based on work by Head, Hawke, Pieters, and others, such dark coatings are now believed to be fine volcanic ash from explosive eruptions. You can see this unusual lunar volcanic deposit even when the Sun is relatively low. Dark material is visible on both the eastern and western shores of Vaporum. The rough terrain south of the crater Manilius is obviously ejecta from the Imbrium basin, but it has been subsequently coated by a layer of dark ash. On the east side of Vaporum the dark material partly covers the mare but is apparently thicker on the patch of subdued hills that separate Vaporum from Aestuum. Similar ash-coated hills lie south of Aestuum and southeast of Copernicus. Small rilles and domes can be seen in some of these dark deposits. Perhaps these are the volcanic vents that were the sources for the ashes, or maybe the vents are buried under the younger lavas filling Aestuum and Vaporum. Some samples brought back by Apollo astronauts are rich with glassy beads, which seem to be quickly chilled drops of magma from the gas-rich eruptions (similar to the fire fountains in Hawaii) that probably produced the dark mantle deposits.

Look now, preferably under a high Sun, at Copernicus H, a 5-km-wide crater close to the southeast rim of Copernicus. Copernicus H is a normal little impact crater, except that it is surrounded by a halo of dark material. Spectroscopic studies show that the halo (and several others nearby) is made of the same material as the volcanic glassy ash at Aestuum and Vaporum. It seems that the impact event that produced Copernicus H excavated material from beneath the lighter-hued surface lavas and produced an ejecta blanket from the otherwise buried ash layer. The dark mantle material near Aestuum must continue under the mare lavas near Copernicus. It is unclear why so much of this dark mantle material exists in the area south of Imbrium.



Fire fountain deposits on Sinus Aestuum.

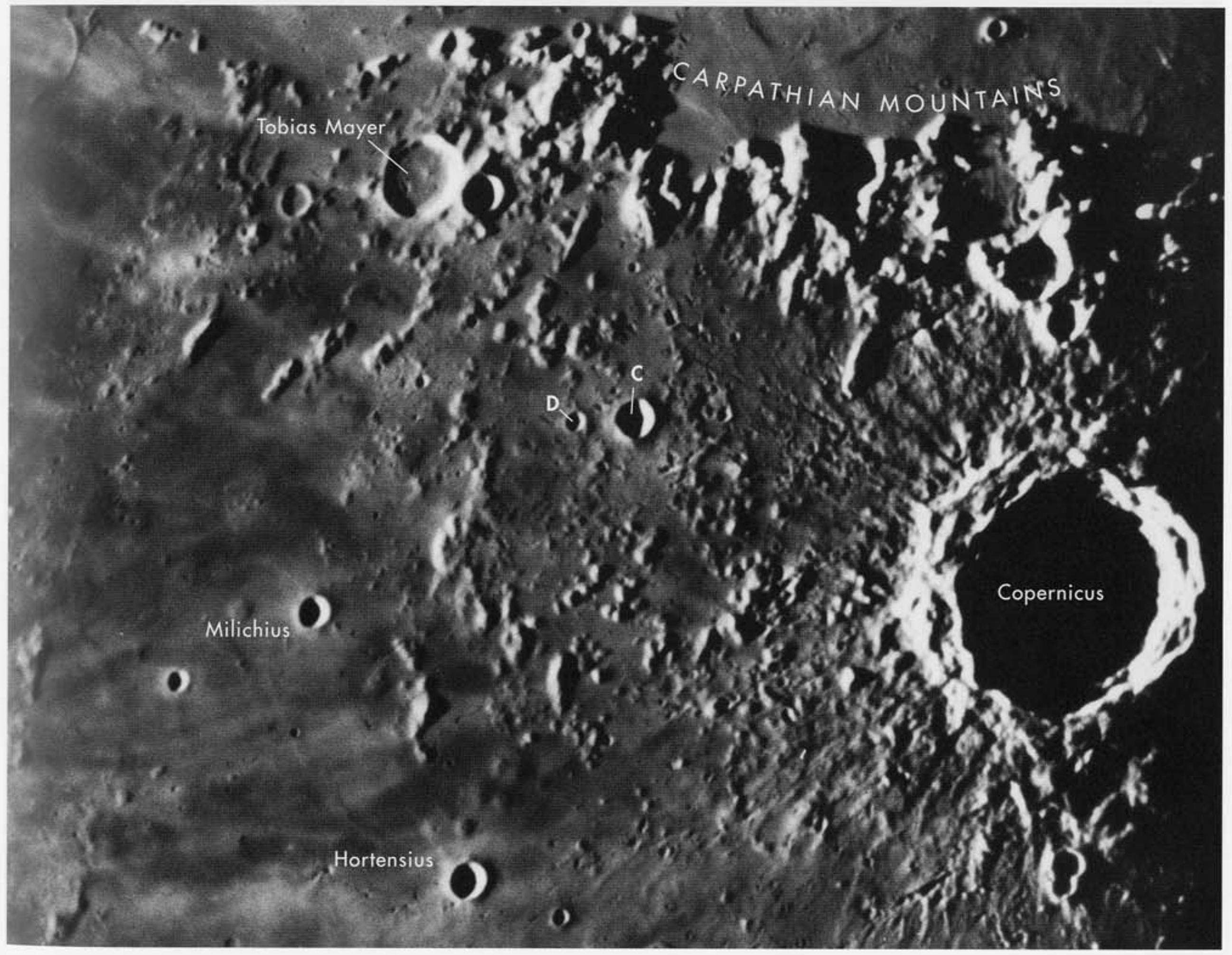
MARE INSULARUM

Mare Nubium (described in Chapter 15) traditionally encompassed all the mare material stretching from the craters Pitatus to Copernicus. In truth, the extent of the mare is poorly delineated; only the southernmost part lies within a definite impact basin (the Nubium basin). In the 1970s a new basin centered near Copernicus was proposed, and the patchy mare region south of the crater was christened Mare Insularum (Sea of Islands). This provided a name for the putative basin (Insularum basin) and commemorated Apollo 12's arrival on the surface of this newly christened piece of Moon. More than three decades since Apollo 12's departure, there remains very little evidence that the proposed basin actually exists, but we're still stuck with the name.

DOMELAND

The area south and west of Copernicus is characterized by clustered and isolated hills, surrounded by relatively thin mare lava flows. Presumably the hills are tops of continuous ejecta from the Imbrium basin that have been buried by later lavas. But the real objects of interest in this area of the Moon are the dozen or so low domes that present an observing challenge even under low Sun conditions.

The easiest domes to find are a cluster of six just north of the 15-km-wide crater Hortensius, located west-southwest of Copernicus. Each dome measures about 6 to 8 km wide and a few hundred meters high, and thus has very gentle slopes. Five of the six Hortensius domes have tiny summit pits, which are a real

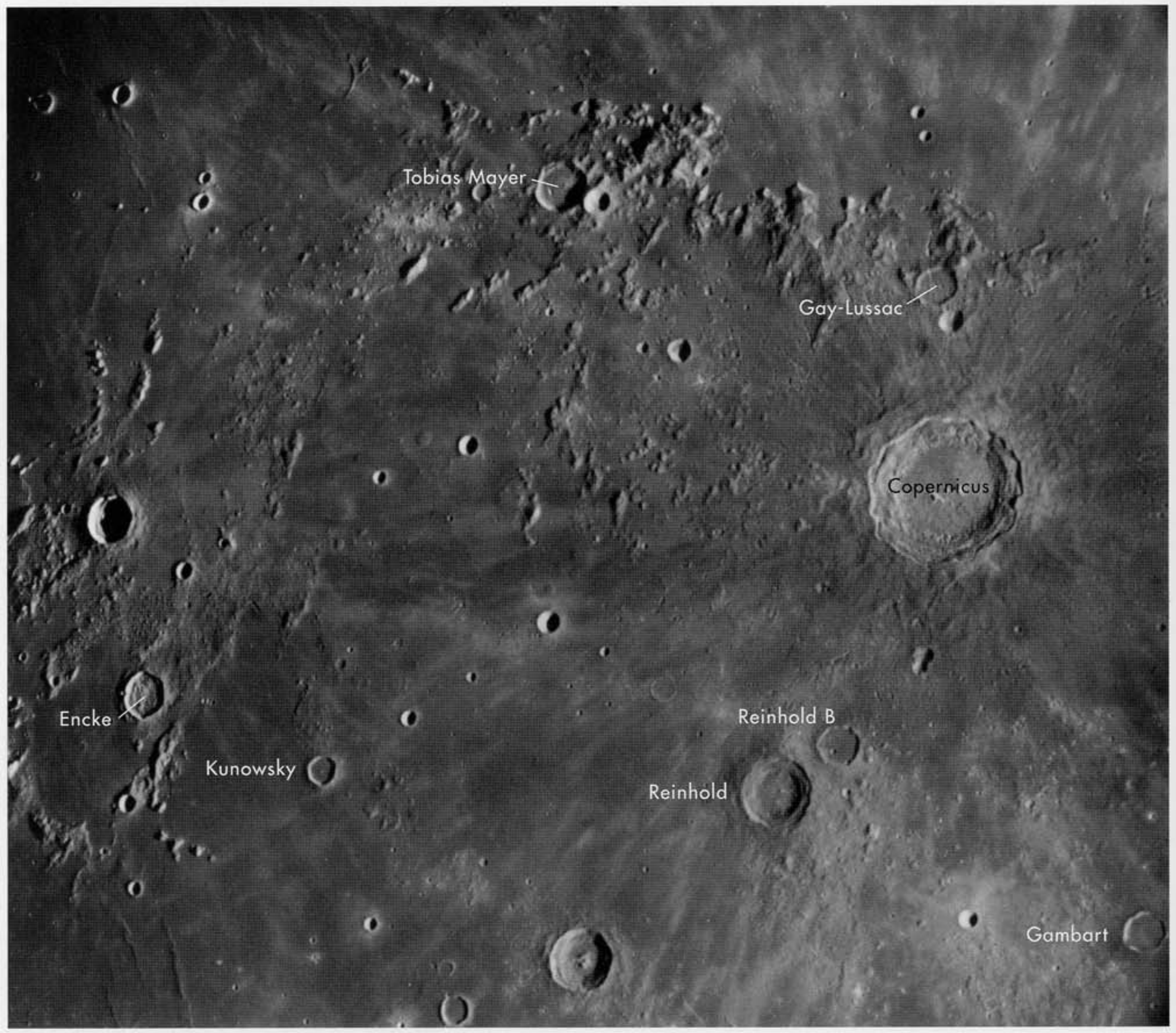


More than 17 subtle domes are visible west of Copernicus.

test of a telescope's optical quality and the atmospheric seeing conditions. They are difficult features for 6- to 10-inch instruments, even on a very steady night.

Another prominent dome is located just west of the small crater Milichius. This dome is about 12 km wide, has a summit crater, and is steeper than average. A broader dome with two summit craters lies northwest of Milichius. If you go prospecting between this double dome and the crater Tobias Mayer at the western end of the Carpathian Mountains, you will find an additional half dozen or so low domes. A final dome in this area is just west of the two small craters Tobias Mayer C and D.

Domes are clearly not impact features. A frequent proposal has been that domes are *laccoliths* — localized swellings of the mare surface as volcanic material intruded into and uplifted overlying layers. Another idea was that of Harvard astronomer W. H. Pickering, who argued in 1908 that domes are true volcanoes — mountains built up by the eruption of lava and/or ash from a central conduit. More recently, Head and his student Ann Gifford at Brown University proposed that lunar domes are small shield volcanoes like those found in Iceland. Shields are volcanoes formed by the quiet eruption of lava flows from a central crater. The Icelandic examples are about the same diameters and heights as lunar domes. They are probably the same types of landforms, even though they formed on two completely different worlds. The question is, why are there so many domes west of Copernicus? And why are there virtually none in Mare Imbrium? Notice that the domelands west of Copernicus are part of the same arc outside the rim of the Imbrium basin that includes the volcanic ash deposits around Sinus Aestuum and Mare Vaporum and perhaps the volcanic material at the Marius hills and the Aristarchus plateau. Apparently, manifestations of volcanism exist around the southern and western rim of the basin, so perhaps the question should be, why aren't volcanic features found on the northern and eastern sides of the basin too? Are they buried beneath thicker lavas?

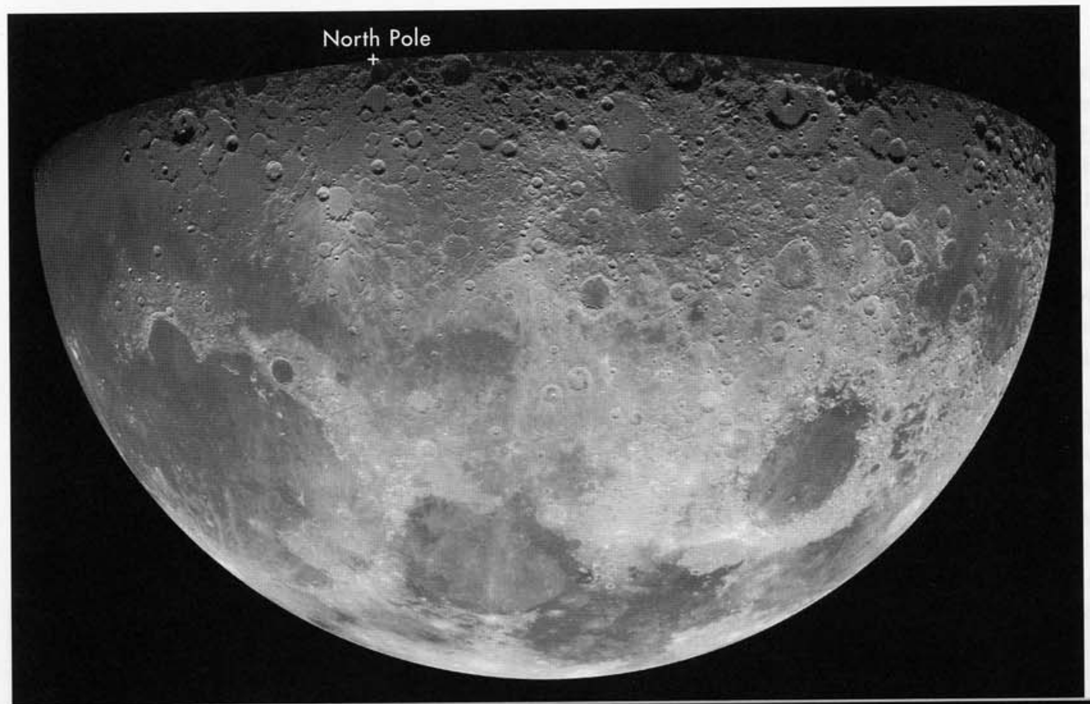


Shallow craters like Gambart are visible near Copernicus.

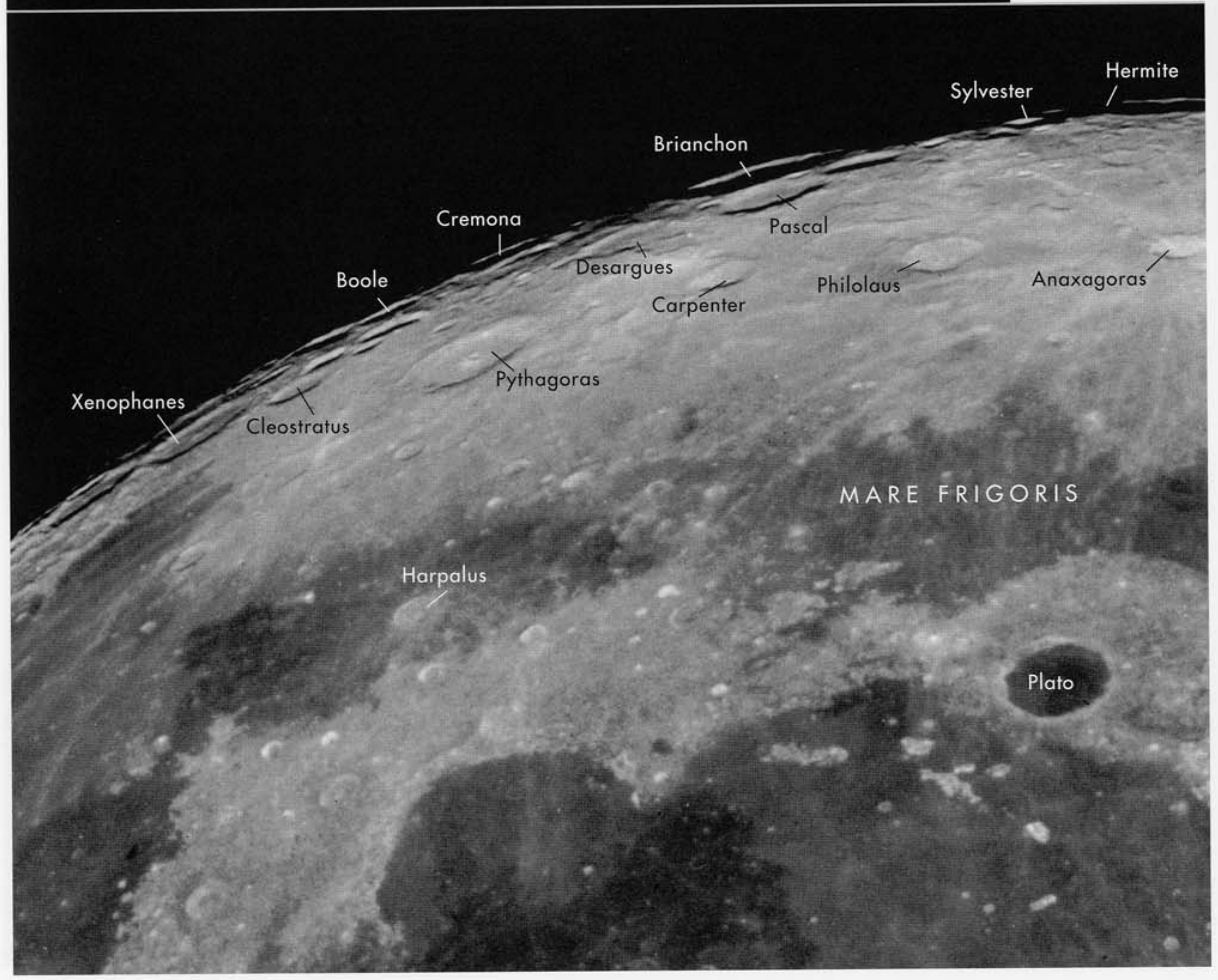
GAMBART-TYPE CRATERS

South-southeast of Copernicus is the unusual 25-km-diameter crater Gambart. Unlike typical impact craters of this size, Gambart has smooth inner and outer rims of equal widths, polygonal sides, and a shallow floor only 1.1 km deep. Gambart has no wreath of slump blocks or central peaks and thus is not a member of the impact-crater morphological main sequence.

Nearby are other Gambart-like craters: Reinhold B (26 km), Kunowsky (18 km), Encke (28 km), Tobias Mayer (33 km), and Gay-Lussac (26 km). Note that all of these craters formed on the preexisting Imbrium ejecta; no Gambart-like crater exists on the thick mare deposits. Also, note that these craters are about the same diameter and are located within 350 to 400 km of Imbrium's rim. Because Gambart-type craters are clearly not like main-sequence impact craters, they were widely interpreted as volcanic calderas in the early 1970s. But there is no reason why calderas should be predominantly of a single size range (20–30 km) and concentrated near but outside Imbrium. The Moonwide distribution of Gambart-like craters supports the idea that they are secondary craters formed by ejecta from giant basin impacts, but it is still uncertain why they have such peculiar shapes.



This unusual view of the Moon's north-pole region was captured by the Galileo spacecraft in 1992 before it left the inner solar system, bound for Jupiter.



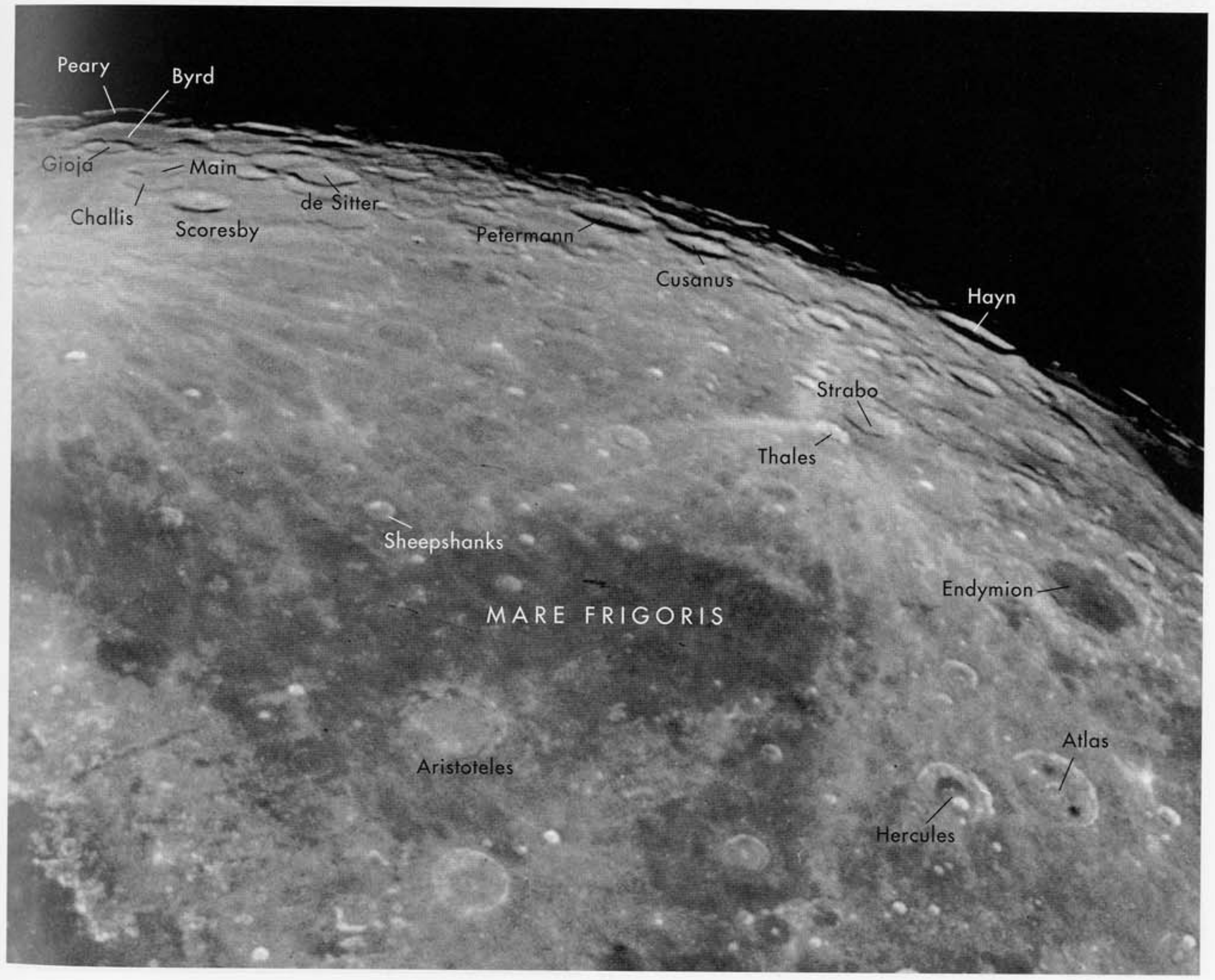
Lunar north under favorable libration.

7

The North Polar Region

The Earth's North Pole has long been an irresistible attraction for nearly crazed explorers who competed to be the first to reach this inaccessible point whose only significance is its geographic uniqueness. The snow and ice, searing whiteness, menacing bears, and sheer remoteness still make travel there a rare and dangerous experience. The Moon's poles lack the snowy whiteness and bears but, like the terrestrial extremes of latitude, are also hard to access. Our satellite's spherical curvature foreshortens and compresses craters and other features near its limb so that they become progressively more difficult to interpret. Perhaps that is why almost no one (except the map makers of the Moon who have an obligation to leave no spaces blank) seems to study the lunar polar regions very much.

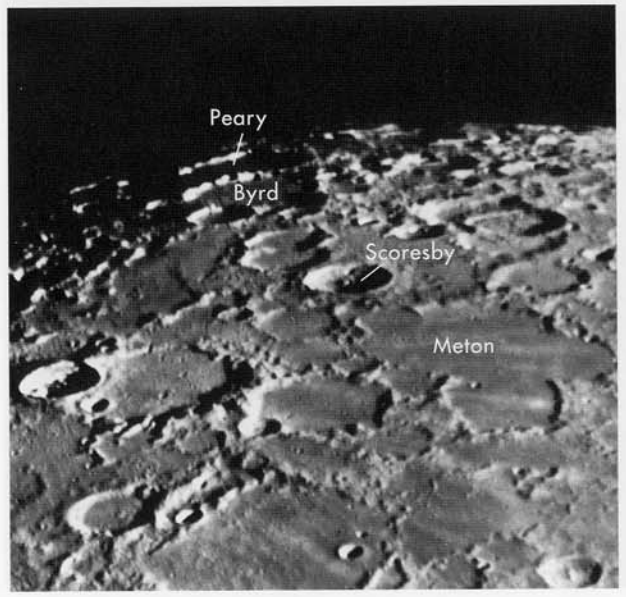
Frankly, the lunar north pole offers nothing as visually interesting as the soaring mountains and multitudinous deep craters of the south pole. But the broad



region of the north pole does contain subtle features that provide more evidence of the Imbrium basin impact, provokes questions on the origin of noncircular maria, and offers unusual views of bright crater rays and a nearly edge-on perspective on an impact basin. Even more important, the recent possible discovery of ice within its permanently shadowed craters makes the north pole a potential target for future exploration.

One of the most challenging aspects of the north pole region is simply finding your way around. Most older maps of the lunar poles are so confused and confusing that even identifying named craters can be very difficult. But finally in 1967 the Lunar Orbiter spacecraft took pictures of the poles from directly above, without foreshortening, and provided clear views of the features found there. The map and photographs in this chapter take advantage of the spacecraft clarifications to unambiguously identify the polar craters but still present them as seen from Earth.

The nomenclature of lunar craters at the north pole reflects our fascination with explorers of the terrestrial poles by sprinkling a few of their names among those of the ubiquitous dead Greeks. The name of Admiral Peary, the first person to reach Earth's North Pole (discounting Santa), is given to a 75-km-wide crater centered at 89° N. Nearby, but not as far north, are craters named for Richard E. Byrd, the American pilot who first flew over the pole, and Fridtjof Nansen, the Norwegian polar explorer who first crossed Greenland. The South Pole explorers have not been forgotten. Roald Amundsen, Robert F. Scott, and Erich D. von Drygalski similarly are honored with craters at the opposite pole of the Moon.



The craters Byrd and Peary.

As you look through this chapter you will notice that in some photographs the craters are squashed up closer to the edge of the Moon than they are in others. This results from a nodding of the Moon called *libration*. Libration isn't as invigorating as liberation or libation, but it does help us study the lunar limb regions. Lunar libration is the combination of several different factors that allows us to see 59 percent of the Moon's surface. The polar nodding (libration in latitude) occurs because the lunar equator is tilted 6.41° to the Moon's plane of revolution around the Earth. So during the Moon's monthly orbit it alternatively tips one polar region and then the other toward Earth. Any time you observe, one of the poles is likely to be better exposed than the other, but if you wait two weeks the situation will reverse. As Czech lunar cartographer Antonin Rükl puts it, librations "create a lunar face that nods its assent." *Sky & Telescope* magazine and various astronomical almanacs publish dates of maximum librations to aid in planning observations of limb regions.

FRIGORIS: AN ELONGATED MARE

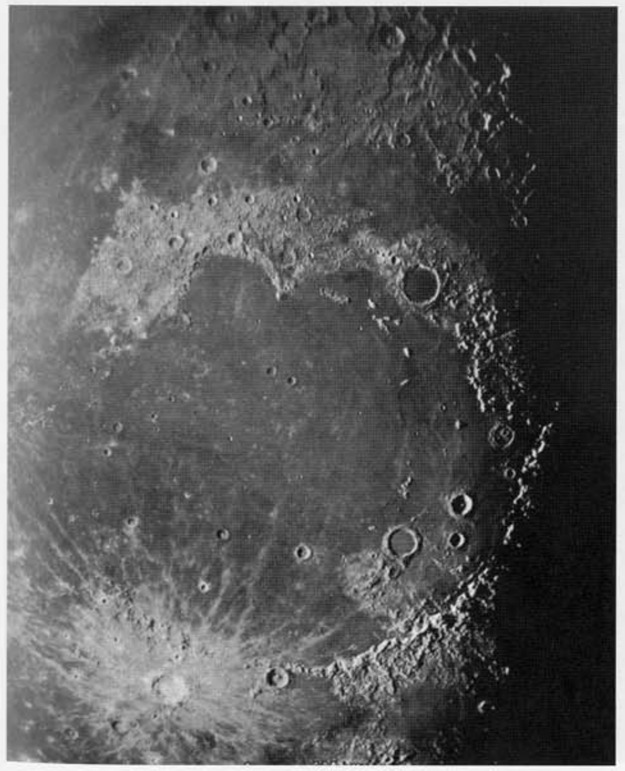
Look at the Moon. Nearly every patch of dark mare material is round — from the floor of Plato to the vast expanse of Mare Imbrium. The mare patches are circular because they fill impact crater or basin depressions, which are themselves round. But Mare Frigoris isn't circular at all. Lying north of Imbrium, Frigoris stretches roughly 1,500 km in an east-west direction, but only about 200 km from north to south. In fact, it may be even more elongated, but that is difficult to ascertain because the eastern and western ends of Mare Frigoris are poorly defined. To the east Frigoris seems to end near the craters Atlas and Hercules, though mare material extends southward into Lacus Mortis. On the west Frigoris merges with Sinus Roris, which opens out into the vast Oceanus Procellarum.

Probably the key to understanding Frigoris is the observation that it seems to mark a low trough that partially surrounds the Imbrium basin. In *The Face of the Moon*, Baldwin noted that Frigoris is part of a concentric, lava-filled depressed zone around Imbrium. Other parts are Mare Vaporum, Sinus Aestuum, Oceanus Procellarum, and Sinus Roris. According to Baldwin, the collision that formed the Imbrium basin was followed by a rebound that raised a 1,200-km-wide dome ringed by a concentric depression. It now seems unlikely that Baldwin's dome ever existed, but the annular depression is certainly there. So how did Frigoris form?

Although it has been suggested that Mare Frigoris opened up by massive sliding of the arc of lunar crust that includes Plato toward the great hole of Imbrium, there is another, preferred explanation. Wilhelms suggested that the main ring of the Imbrium basin doesn't actually arc past Cassini, Plato, and Sinus Iridum, as might be expected since those features lie at the edge of the dark mare lavas, but instead runs along the northern shore of Mare Frigoris. Thus, Frigoris is low and lava-flooded because it is part of the floor of the Imbrium impact basin.

In order to understand Wilhelms's proposal it is necessary to recognize two things. First, the Imbrium basin has a well-defined rim only around the Carpathian and Apennine mountains, so the remainder of the basin rim must be sketched in by presuming circular symmetry. And second, Imbrium is so large that the northern edge is squashed inward by foreshortening, so that we can't just draw a circle to define the rim location. The way around the foreshortening is to look at Imbrium from above its center point, which was done by rephotographing an image projected on a globe (remember the photograph on page 17?). Based on the rim arc from the Carpathians and Apennines, the north rim of a circular Imbrium basin must dip down and run along the northern shore of Frigoris, just as Wilhelms proposes. But this still isn't very satisfying. There is very little evidence of a rim along Imbrium's purported north side, and if there were, what is the highland material that arches from Calippus to Plato to Mairan doing inside the basin rim? Wilhelms considers it an inner ring. While I have great respect for his years of study of the Moon and understand the logic of assuming the circularity of a basin rim, I'm just not convinced that he's right in this case.

Don Wilhelms.



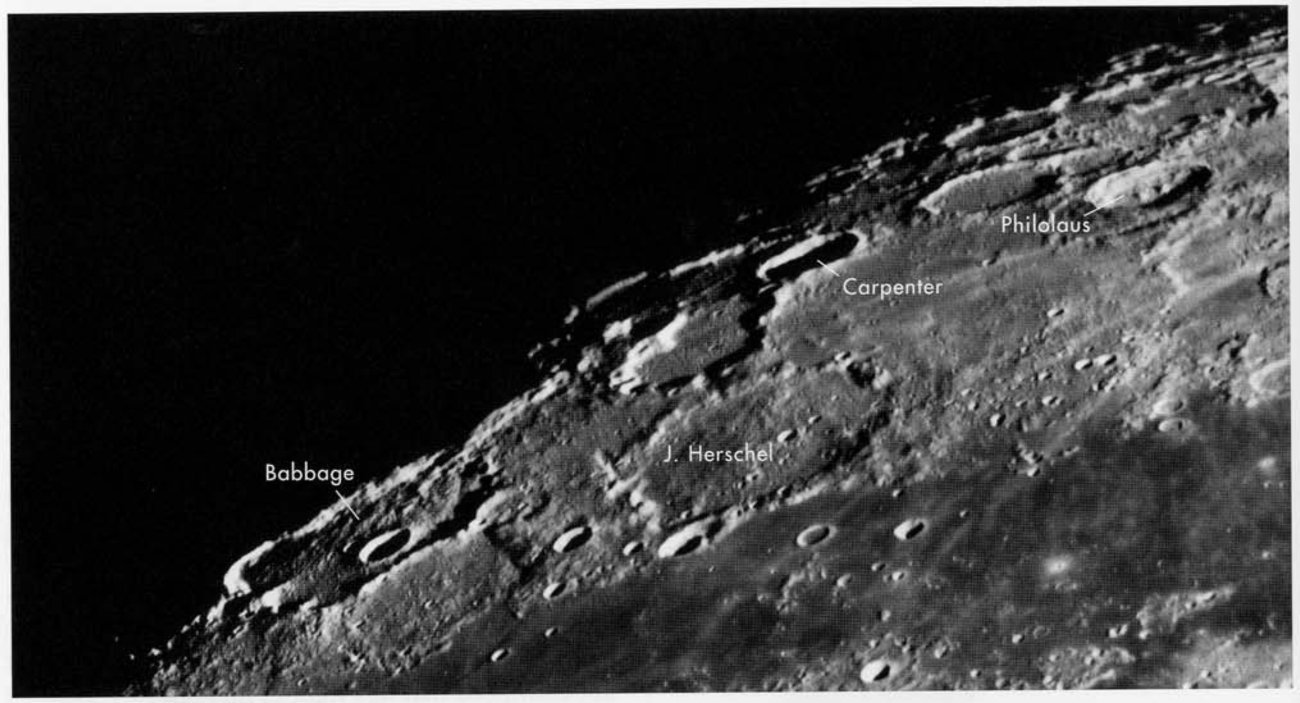
A rectified view of the Imbrium basin and Mare Frigoris.

According to Wilhelms's tyranny of the circle, the arc of bright ground running from the Alps past Plato and beyond Sinus Iridum must have a similar origin to the Apennine Bench near Archimedes. That is, it must be uplifted and fallout material excavated from within the Imbrium basin. It also includes locally excavated ejecta from the Plato and Sinus Iridum craters. Wilhelms draws a second basin ring through this area, and a third, innermost one is marked by the isolated mountains sticking through Imbrium lavas (Piton, Pico, Teneriffe, and the Straight Range). Is Wilhelms correct? I wish I could think of a way to test his idea!

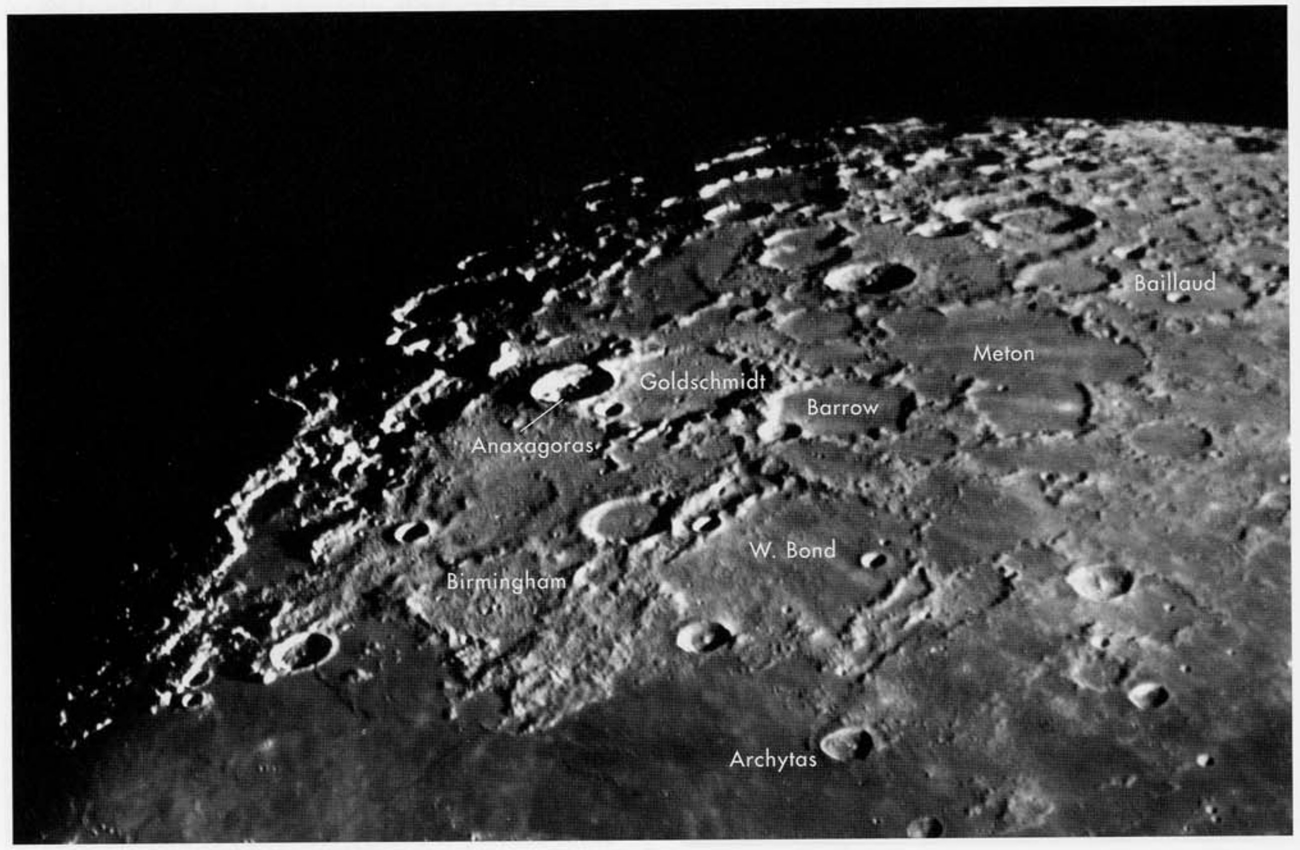
BEYOND FRIGORIS

According to the USGS interpretation, Frigoris is not so much a new kind of elongated mare that needs a unique interpretation as it is a shallow part of Imbrium that is separated by ejecta from the basin's deeper interior. This implies (as does almost any other interpretation) that the cratered land north of Frigoris should be covered with Imbrium ejecta and secondary craters. And it is.

The highlands around the lunar north pole are dominated by degraded, shallow, often interconnected craters. Look at J. Herschel, Birmingham, W. Bond, and Meton — even the names sound old and worn out. These old craters formed before the cataclysm that excavated the Imbrium basin, and so they have been scoured and partially infilled by Imbrium ejecta. Their floors are either rubbly looking from small clots of basin debris (W. Bond, J. Herschel) or they are smooth



J. Herschel and region.



Old craters Meton and W. Bond.

from filling with plains material (Meton, Baillaud, Arnold). Their rims are shaped by the same processes that produced the "Imbrium sculpture" that is so conspicuous on the southern side of Imbrium. But because of the foreshortened view, it is a challenge to recognize the striations and secondary crater chains that are radial to Imbrium. The easiest to spot is an alignment of ill-defined linear depressions and ridges lying between the craters Archytas and W. Bond. Other linear features closer to the limb are harder to see. Look near Thales and Xenophanes, but proceed methodically — even finding these craters takes some hunting. I doubt if one in a thousand of this book's readers will ever see these crater chains!

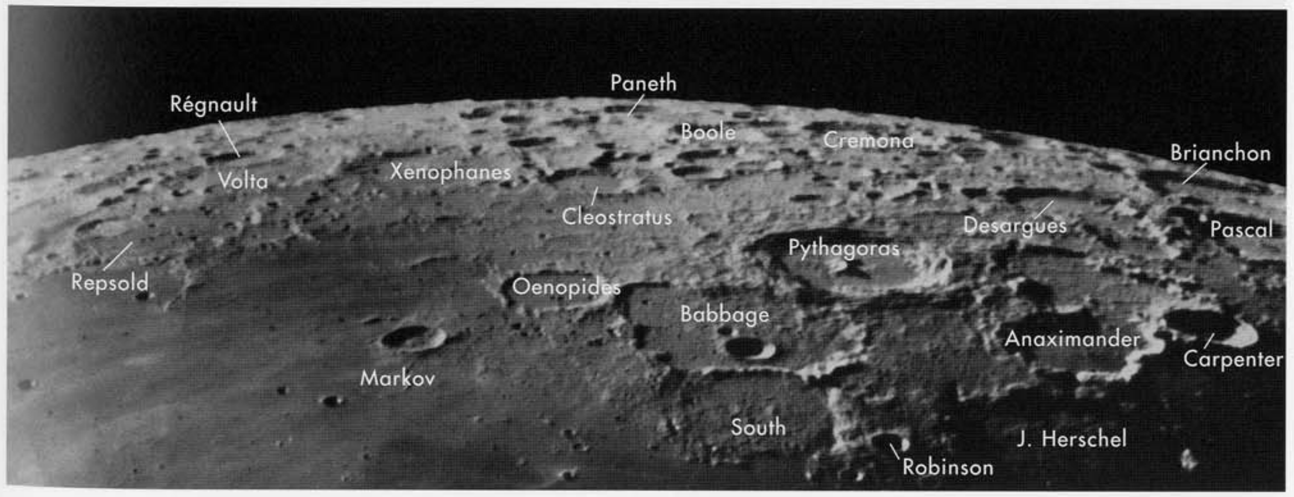
A few craters that formed after the Imbrium impact provide landmarks in this region. Perhaps the most conspicuous is the bright-walled Anaxagoras (50 km in diameter), a Copernican-age rayed crater that is the northern polar region's answer to Tycho. Like a miniature version of that brilliant crater, Anaxagoras has rays that radiate away like meridians of longitude on a globe. Because Anaxagoras is so close to the limb, its floor is virtually invisible; occasionally the bright top of its central peaks can be glimpsed in an otherwise shadow-filled cavity. But when the libration is good and it is near full Moon, the inner wall of the crater can be seen to be crossed by two or more bright stripes of ray material.

West of Anaxagoras are two other less bright Copernican-age craters — Philolaus (70 km across and featuring twin central peaks) and Carpenter (60 km). Still farther west is the somewhat older crater Pythagoras (129 km). The only other bright young crater of appreciable size is Thales (32 km), beyond the eastern end of Mare Frigoris. Thales is only easy to locate near full Moon, when its bright interior and rays pinpoint it. Thales and Anaxagoras represent the last major activity in this part of the Moon, and their rays cross everything else.

A FACTORY AT THE NORTH POLE?

The region described in this chapter is easily overlooked because there are more spectacular and more readily seen craters and basins on other parts of the Moon. But the importance of the north polar area greatly increased in 1998 when the Lunar Prospector spacecraft detected large amounts of the element hydrogen there. Hydrogen can be implanted by the solar wind — a steam of charged particles blowing away from the Sun — and much of the Moon carries solar hydrogen trapped in its soils. But Prospector discovered that both lunar poles had far more hydrogen than was likely to come just from solar wind. The only other way that hydrogen is commonly found in our solar system is in the form of water — H_2O. Water fills Earth's oceans, contributes to the polar caps on Mars, mixes with dust to make comets, forms the crust of Europa and many of the other icy satellites in the outer solar system, and even occurs in tiny amounts in the upper atmosphere of Venus. Water is pervasive.

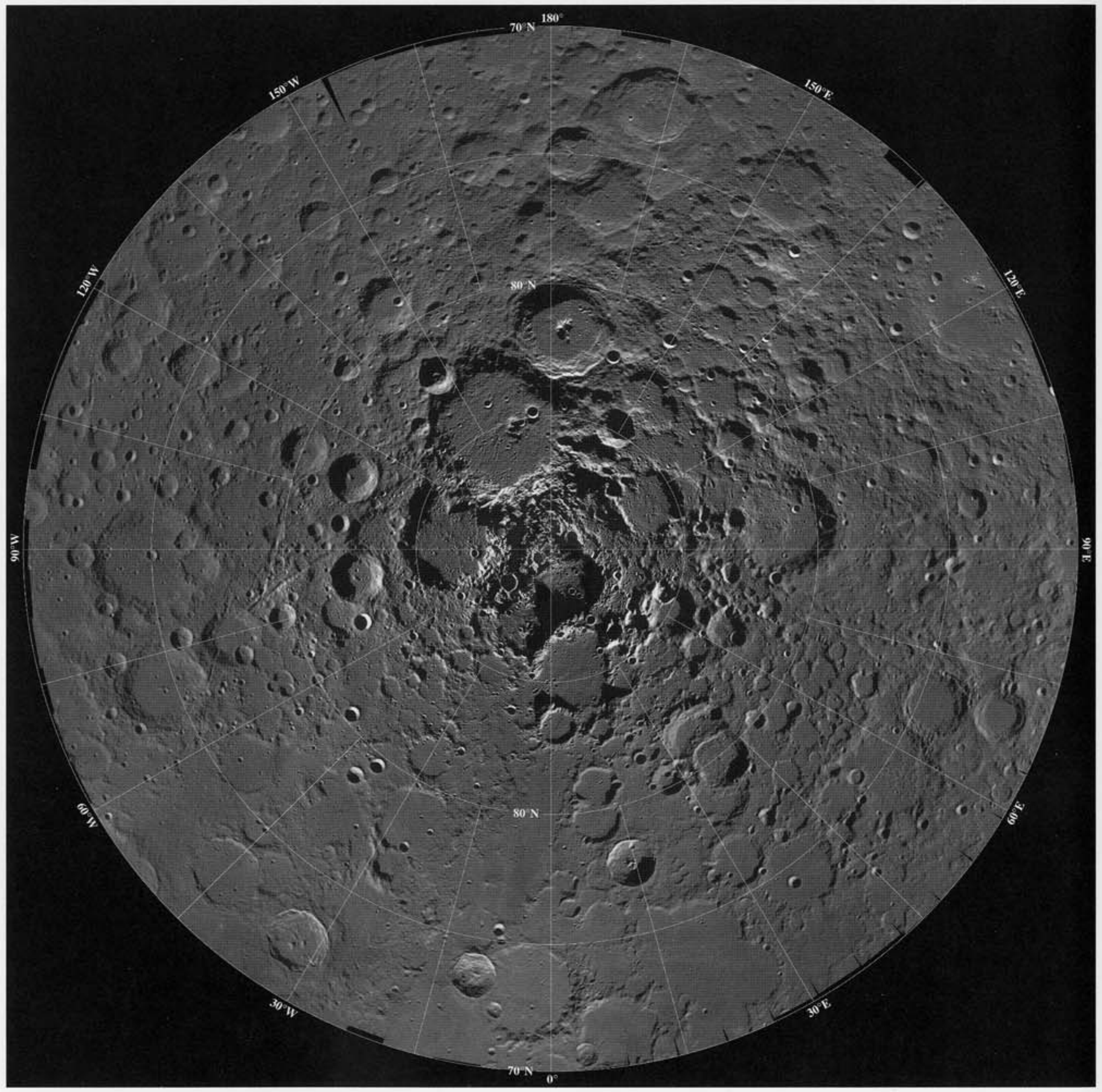
But the lunar samples brought to Earth by the Apollo astronauts showed no evidence of water. So how could water be at the lunar poles? Forty years ago, scientists had speculated that comets that impacted the Moon would make short-lived atmospheres of water vapor. Most of the water vapor would break down to oxygen and hydrogen and quickly escape to space because lunar gravity is too weak to hold on to those elements, especially during the hot lunar days. But there are safe places for water on the Moon. At each pole there are craters whose floors are permanently dark — in the



Northwest limb during a favorable libration. North is to the upper right.

shadows of their own walls. These are truly the places where the Sun never shines! If any of the temporary lunar atmosphere found its way into such shadow-filled craters, it would condense out and freeze. Optimistically, the Lunar Prospector data imply the existence of billions of tons of ice at the lunar poles.

Visionaries have often advocated mining the Moon's solar-wind hydrogen, but the logistical problems are huge. Because the solar hydrogen is in such minute concentrations, many square kilometers of the lunar soil would have to be strip-mined to get enough hydrogen to be useful — the lunar chapter of the Sierra Club wouldn't like that! But if the Prospector team is correct, there is enough ice at the poles that mining operations could be much more localized and therefore more economical. Someday on the floor of the pole-hugging crater Peary there may be a small factory to mine the relatively thick layers of water ice, heat it with nuclear or solar energy, and supply liquid water, hydrogen, and oxygen. These materials would ensure the viability of a lunar civilization and make the first lunar billionaires.



This Clementine mosaic of approximately 1,500 images shows the north polar region of the Moon. Anaxagoras and Goldschmidt are the pair of craters slightly west of 0° longitude and between 70° and 75° latitude at the bottom of the image.

One more thing. The Clementine team named a tall peak near the south pole (see Chapter 13) after their spacecraft to commemorate their ambiguous identification of ice. In fairness, and because I don't suffer from the humility of the Lunar Prospector team, I propose that the small crater on the rim of Peary — and right at the north pole — be christened Prospector.

BETWEEN FREEZING AND SERENITY

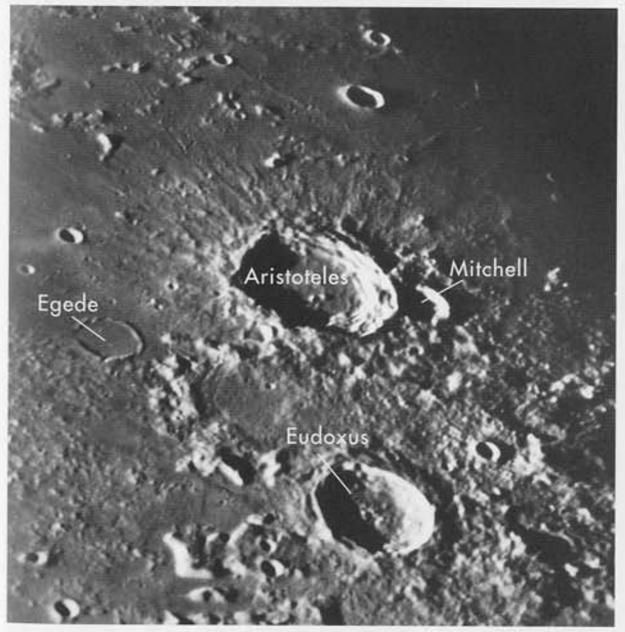
Although it lacks rays (and thus is considered Eratosthenian in age, 1.1 to 3.2 billion years old), the crater Aristoteles is the largest, best-placed young crater in the Mare Frigoris region. With a diameter of 87 km, Aristoteles is a Tycho-type crater, but its interior looks more like a Triesnecker-style crater — instead of a strong central peak it has only a scattering of small hills. The rim of Aristoteles seems to be a combination of slumps and terraces, as if the crater were a transition between the Triesnecker and Tycho types. Interestingly, the nearby crater Eudoxus is also large enough (67 km in diameter) to be considered a standard Tycho-type crater, but it too has unusual peak and rim structures similar to its larger neighbor.

Aristoteles also has two other noteworthy features. First, it has a beautiful array of radial ridges and secondary craters spread across Mare Frigoris. Second, the crater provides an uncommon example of a large crater being superposed on a smaller one — in this case the 30-km-wide crater Mitchell.

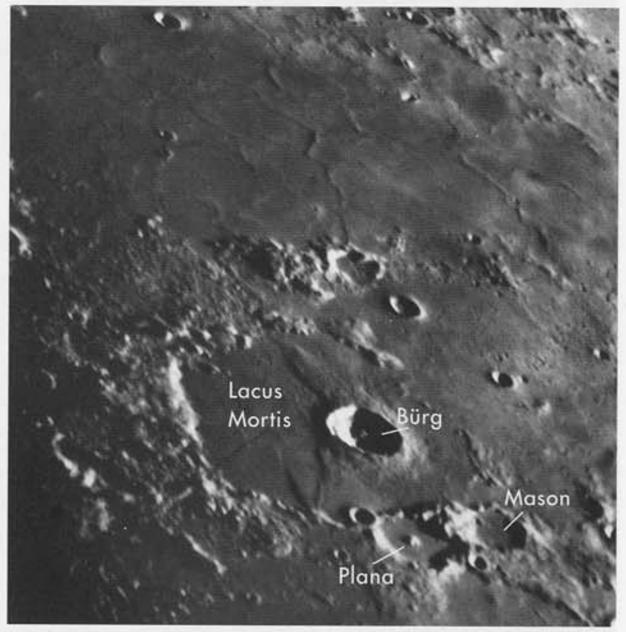
East of Eudoxus is one of the Moon's largest and least-known craters: Lacus Mortis. Like Sinus Iridum, Lacus Mortis (Lake of Death) is usually not considered a crater because its Latin name implies an expanse of mare material. It is that, but the mare patch is contained in a 156-km-wide, hexagon-shaped crater. The western rim of Lacus Mortis is very straight, but the eastern rim seems to be squashed in and is partially missing. Off center is the conspicuous, 40-km-wide crater Bürg, which has a dark floor, a large central peak, and a massive slump that extends from its western wall to its floor.

From the point of view of geology (and amateur telescope sleuthing), the most interesting features are the faults and rilles west of Bürg that cut the floor of Lacus Mortis. Under low Sun, two ridges can be seen running from Bürg to the northern and southern rims of Lacus Mortis. The most intriguing landform, however, is a fault scarp that extends across the southern portion of the Lacus. Look closely and you can see that the eastern side is the high side of the fault but that it turns into a narrow rille! The fault indicates a vertical force, but the rille could form only if there were horizontal extension. This is a very strange transformation that has not been described, much less explained. Also on the floor of Lacus Mortis are four or more other rilles, only one of which is easy to see, striking diagonally into the Lacus from the southwest corner of the large crater. All the classic Moon mappers disagree on the number and location of the other rilles. What do you see?

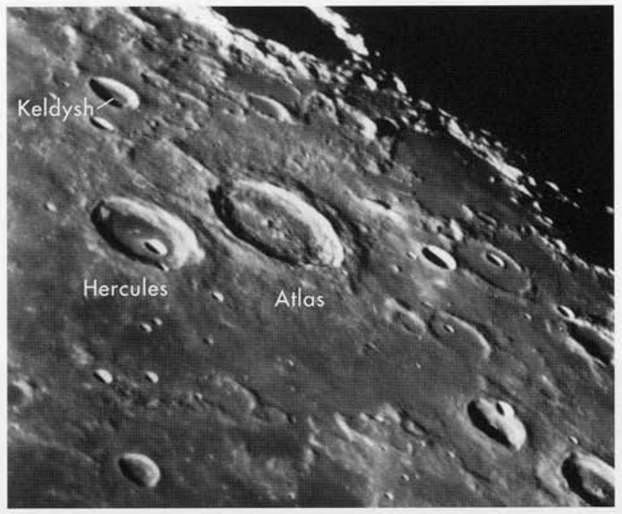
One other nearby feature needs pointing out. On



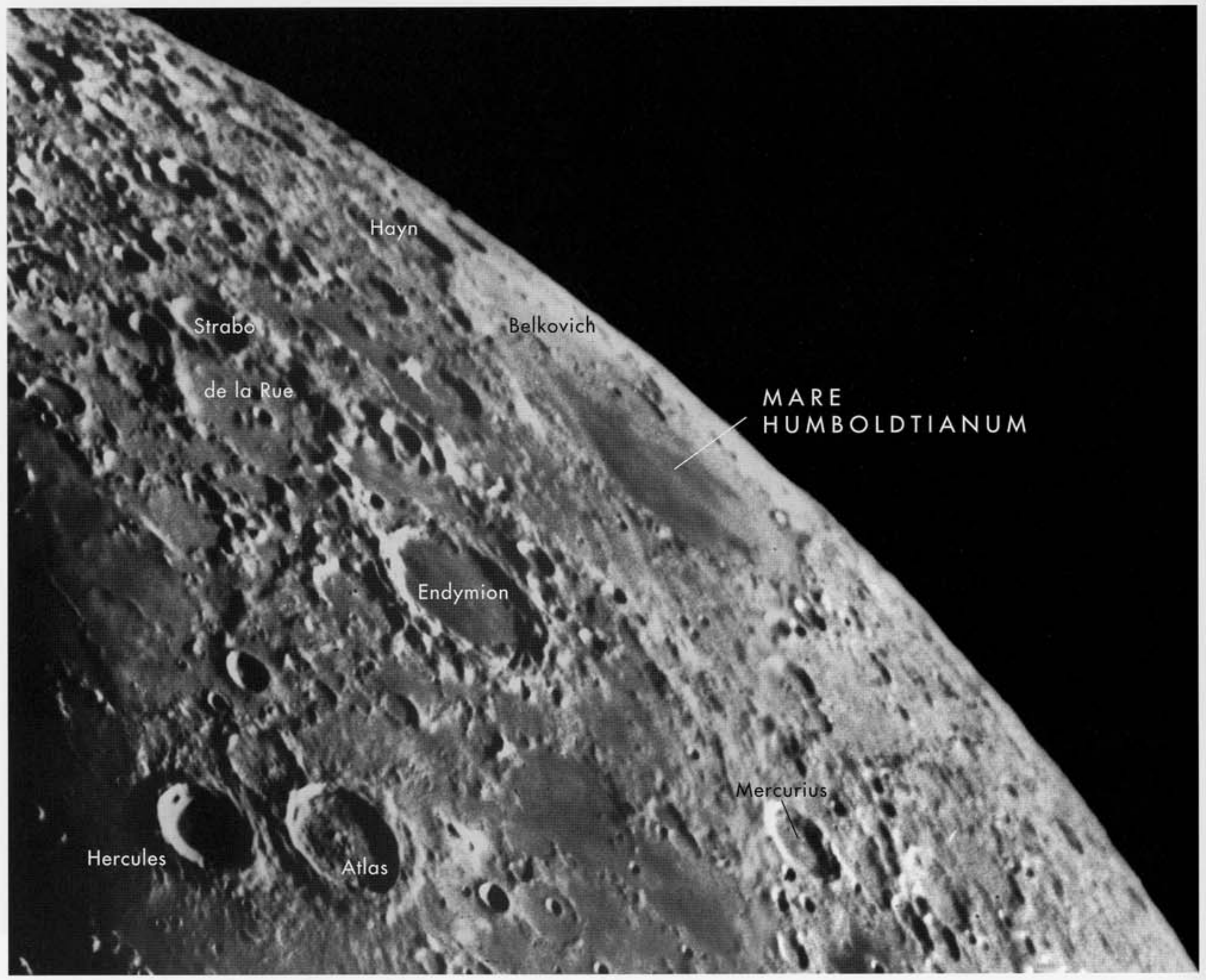
Aristoteles and Eudoxus.



Lacus Mortis and the crater Bürg.



Atlas and Hercules.



The Humboldtianum basin.

the southeast rim of Lacus Mortis are two middle-aged craters, Plana and Mason. A tremendous triangular mountainous mass of material is centered at the intersection of their two rims with that of Lacus Mortis. The mass seems to have spread downward onto the floors of the three craters. What in the world (or the Moon) is the origin of this mass? Is it a volcanic extrusive — a fancy phrase for an erupted lava pile — or maybe an ancient block from some basin rim? This may be another question that will not be answered until people live on the Moon.

ATLAS AND HERCULES

Just east of Lacus Mortis are two favorite craters for observers: Atlas and Hercules. Although these are almost always described together, they are not twins but friends or, according to Spurr, brothers. Goodacre calls Atlas "noble" and Hercules "magnificent," and Elger said they are "a beautiful pair, scarcely surpassed by any other similar objects."

Atlas is 87 km in diameter, while Hercules measures 69 km across. Each has a bold outer rim or glacis, that rises steeply out of a plain that is marelike, but lighter in hue. Both Atlas and Hercules have continuous ejecta deposits that are draped over the surrounding terrain. Their similarities beg the question: were they formed at the same instant? According to USGS mappers, no. Atlas is said to have formed first, in Upper Imbrian time, followed later by Hercules, which formed during the Eratosthenian period. Although Atlas is scarred by some tiny crater chains (apparently secondaries from Hercules), crater statistics hint that Hercules is the older of the two: three superposed impact craters occur in Hercules, whereas Atlas has none of comparable size.

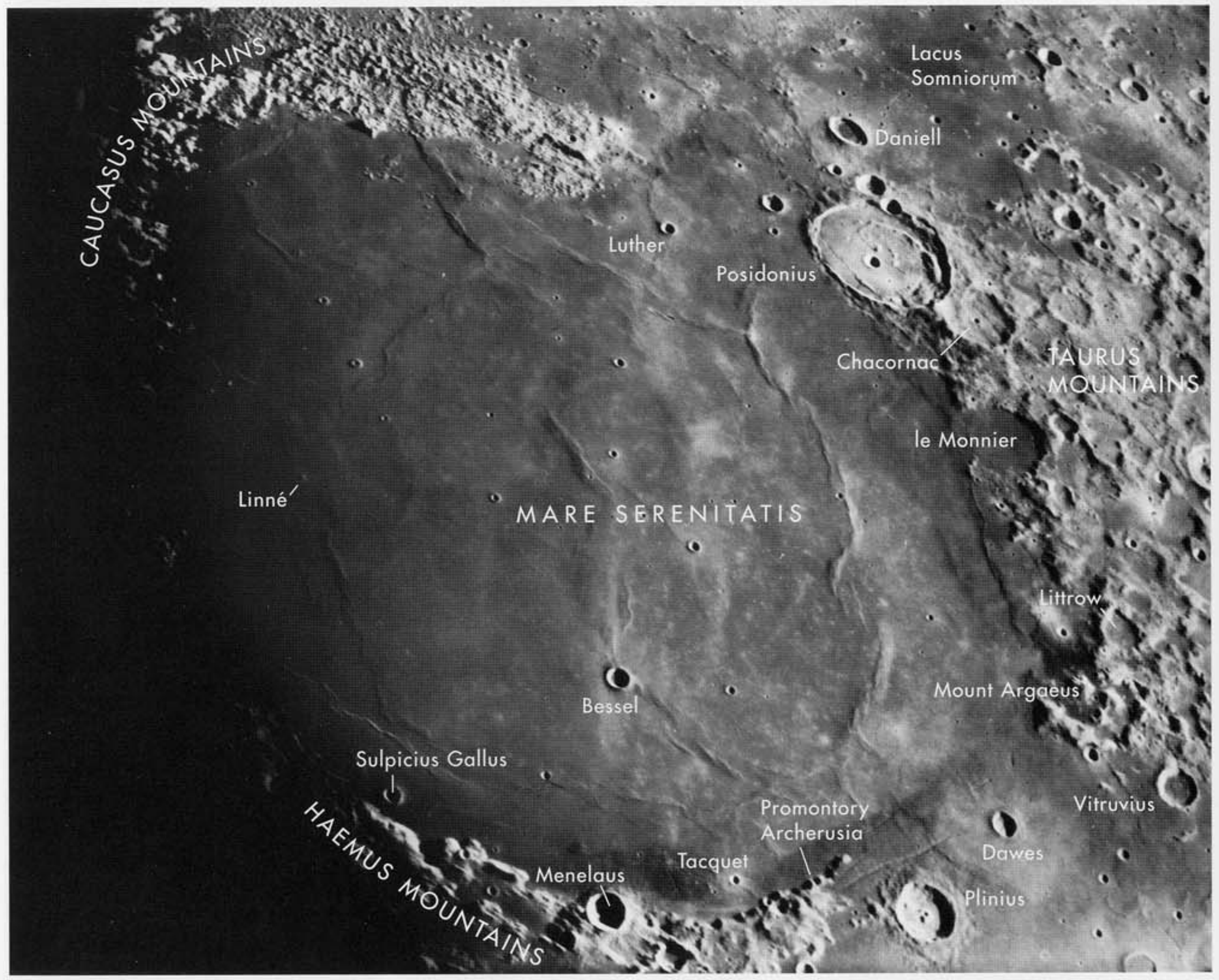
The real differences between these craters are their floors. Hercules has a flat floor, with two bumps that might be the tops of central peaks protruding through dark-hued lava. The floor of Atlas is much more interesting. Atlas is a so-called floor-fractured crater, with central peaks surrounded by a network of rilles. And like Alphonsus, two dark spots centered on tiny pits occur along the rilles. Telescopic spectral data by Hawke and his University of Hawaii colleagues demonstrate that these dark spots result from volcanic eruptions of volcanic glass and lava fragments. Why, I wonder, does Atlas have a volcanic manifestation of rilles and explosion craters, whereas nearby Hercules simply has a lava-covered floor? We see this frequently on the Moon; small-scale volcanic features occur in one place but not in similar nearby areas. The circumstances that gave rise to explosive volcanism on the Moon must have been very special.

AN EDGE-ON BASIN

What do you say about a huge front-side lunar basin that almost no one ever sees? Even the Lunar and Planetary Laboratory in Tucson, Arizona, whose scientists exposed 8,000 photographs of the Moon to compile their *Consolidated Lunar Atlas*, had to settle for a 1938 photograph taken at the Lick Observatory in California to depict this obscure region of the Moon. Hugging the northeast edge of the Moon is the Humboldtianum impact basin, which can be glimpsed only during a favorable libration. More often, Humboldtianum simply makes the northeast limb of the Moon appear flattened.

Mare Humboldtianum is one of only two maria named after a person. The greatest of all classic selenographers, the German Johann Mädler, named it after his friend and countryman Alexander von Humboldt, who explored uncharted regions of the Earth. Humboldtianum is easy to find (if librations make it visible), for it is just limbward of a 125-km-diameter mare-floored crater called Endymion.

The mare material that comprises Mare Humboldtianum is about 160 km wide, and it is contained within a 300-km-wide inner basin rim, which is in turn surrounded by a 600-km outer rim that stretches from near Endymion around the limb to the lunar farside. The structure of Humboldtianum is well preserved; if this feature were nearer the center of the Moon's disk, it would have hastened the recognition of basins.

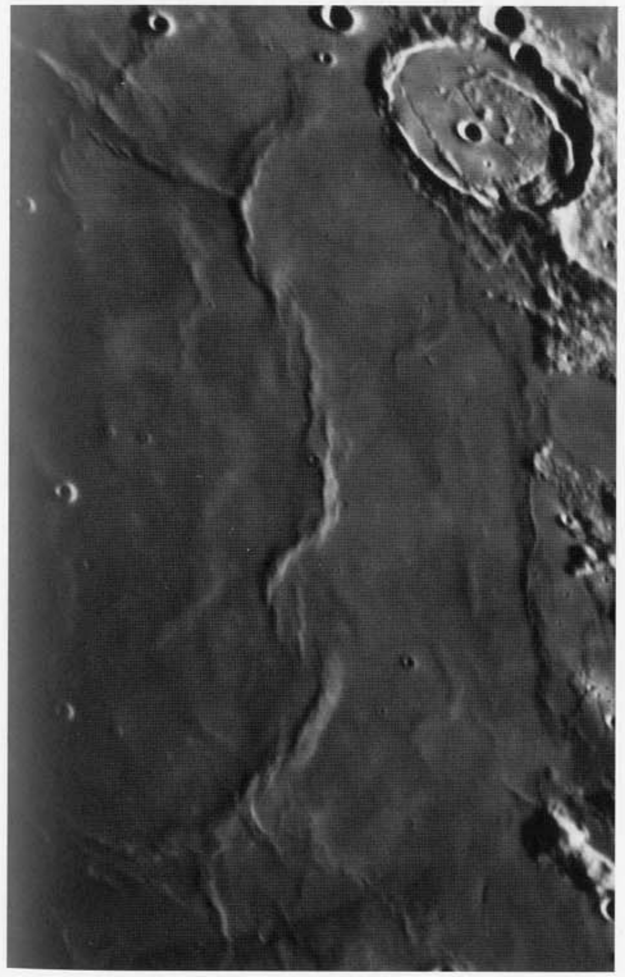


Mare Serenitatis.

8

Serenity

"Houston. Tranquillity Base here. The Eagle has landed." The first words from Earthlings on the Moon were spoken from a nondescript lava plain not far from the lunar equator. And the last expedition to the Moon, just three and a half years later, landed on the edge of the adjacent Mare Serenitatis. Why were these nearby sites selected for the first and last Apollo landings, and what in particular do they tell us about the Moon? These questions, discussed in this chapter and the next, link the two similar-sized, near-circular mare basins bearing restful names.



The Serpentine Ridge and Posidonius.

The Imbrium basin is the youngest and biggest impact basin on the Earth-facing side of the Moon. The recognition of its concentric and radial structures immediately initiated a hunt for similar basin features at other maria. But in the original work on basins by Hartmann and Kuiper, Serenitatis and Tranquillitatis were not even listed because their basin structures are so difficult to see. However, once the progression of pristine-to-degraded basin structures is appreciated, the trained eye can pick out bits and pieces of basin topography. Serenitatis and Tranquillitatis provide a look at progressively older basins with differing degrees of preserved structure and mare-fill effects.

THE SERENITATIS BASIN

Serenitatis is a two- or three-ringed basin with a diameter of about 750 km. The arcuate Haemus Mountains on the southwest edge of the mare are the only conspicuous part of the Serenitatis basin's circular rim. Continuing the basin's rim requires faith in the significance of several isolated features that seem to lie in the right places. It also requires deciding which of two or three proposed ring locations to accept. Though it differs from later USGS maps, I like the original mapping by USGS geologists Wilhelms and his colleague Jack McCauley. Their rim ignores the back sides of the Caucasus that border Imbrium and proceeds as a dashed line through the northwest of Mare Serenitatis, clipping unnamed hills at the north shore of the mare, then cutting through the large craters Posidonius, Chacornac, and le Monnier, before finally completing the circle by arcing through the isolated Mount Argaeus and Promontory Archerusia. This ring pretty well follows the boundary between the mare and various bits of bright highlands, hills, and rubble that circle it. I like a basin ring to be physically marked by something.

Wilhelms and McCauley also drew an outer dashed basin ring around Serenitatis, passing through or near the craters Manilius, Eudoxus, Römer, and Maclear, but you have to be a true believer with the utmost credulity to see it. In my mind the emperor is naked. Far more believable is an inner ring for Serenitatis defined by a 400-km-wide plexus of wrinkle ridges that is beautifully seen whenever the terminator marches across Serenitatis. Wilhelms and McCauley fit the inner ring in eastern Mare Serenitatis to the Serpentine ridge (such a wonderful wrinkle ridge that it earned a name among classical writers), but because they believed in perfect circles, they forced the western arc to miss the conspicuous ridges there that lay outside the imagined circle. This is a good example of how people can be misguided by strong beliefs in their theories of how things ought to be — a perfect imaginary circle is more believable than the off-center, irregular ring that actually exists!

THE APOLLO 17 LANDING SITE

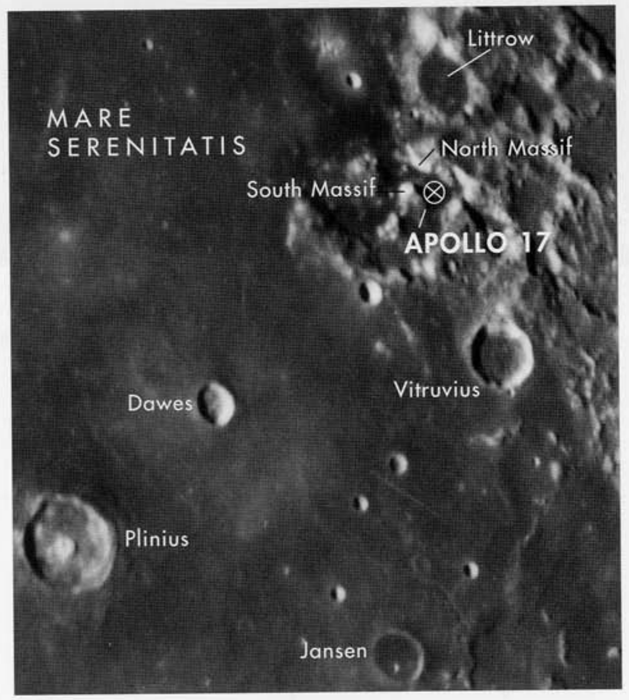
Well, why do we care where these rings really are? The answer goes right back to the first paragraph of this chapter. The United States spent $25 billion to send astronauts to the Moon, and they brought back 380 kilograms of lunar rocks to unravel its secrets. But rocks are of limited use unless we can understand where they come from. Is a particular sample a rock that formed near the lunar surface, or some type of primitive highland crust, or a piece from great depth (plutonic) brought up by a basin impact?

A major justification for the Apollo 17 landing site was based upon an interpretation of basin rings. Apollo 17 set down on the eastern edge of Mare Serenitatis, just south of the crater Littrow in a valley between two large mountains, the North and South Massifs. Using the lunar rover the astronauts drove to the base of each mountain and sampled the rocks. What is the origin of the massifs and hence the rocks? The massifs show no evidence of being giant volcanoes (and the collected samples aren't lavas), but because reconstructed basin rings pass right through them they are thought to be massive piles of ejecta from below the Serenitatis basin. Indeed, photographs taken by astronauts of the massifs reveal their structure to be like a giant breccia, with jumbled light and dark patches. The returned samples reproduce this jumbled texture in miniature, with a mixture of impact-melt breccias and plutonic rocks.

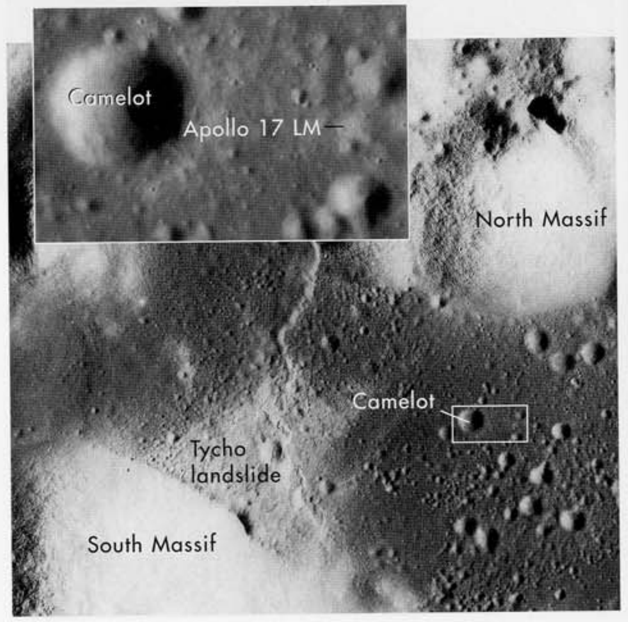
The impact-melt rocks were formed during the giant collision that formed the Serenitatis basin, which is well dated by the melt rocks at about 3.87 billion years — only about 20 million years before the formation of the Imbrium basin. The lava flows have an age of 3.72 billion years, and the impact-excavated plutonic rocks include magnesium-rich varieties known as *norites* that are as old as 4.3 billion years, making these among the oldest known rocks from either the Earth or the Moon.

You can easily find the Apollo 17 landing site, especially when the Sun is a little bit high so that shadows from the mountains don't hide it. South Massif is the largest isolated mountain, and North Massif is the bright, rimlike ridge north of it. The Apollo 17 astronauts daringly flew in over the tall massifs and gently dropped onto the smooth, dark mare between them.

Another just barely visible feature of the Apollo 17 landing site provides a clue about an event that occurred 2,000 km away. With good seeing and high sun illumination, you may notice a small triangle of bright material that extends northward from the base of South Massif onto the mare floor. This whitish material has been interpreted as rocks that avalanched down the slope of South Massif when ejecta from the formation of the crater Tycho hit the mountain. Astronauts collected some of this landslide material, which is 109 million years old, an age that is assumed to date the formation of Tycho! Although there is some uncertainty that the small secondary craters and avalanche deposits visible at the Apollo 17 site really are due to Tycho's formation, I'm a firm believer. The Apollo results support a previous finding by Hartmann and me that the age of Tycho was about 160 million years, based on the number of impact craters superposed on Tycho itself. It is reassuring when two totally different methods agree reasonably well.



Apollo 17 landed on a small patch of mare lavas between towering mountains.



A close-up view of the Apollo 17 landing site as photographed from the command module by astronaut Ron Evens.

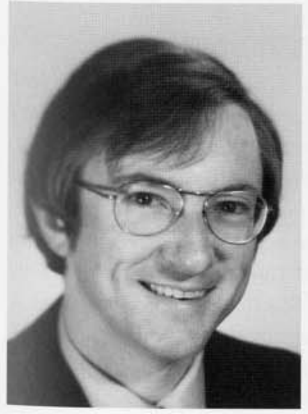
SERENITATIS LAVA FILL

Mare Serenitatis is not a simple pile of lava; it has a more complex history that can be clearly read from the stratigraphy of its lava flows. This was first recognized by USGS scientists, but their complex designations for lavas (EIsw, Isg, EIe, and four more alphabet-stew labels) made the stratigraphy unnecessarily confusing. Fortunately, a simplified nomenclature system was later introduced by Sean Solomon at the Massachusetts Institute of Technology and Jim Head.

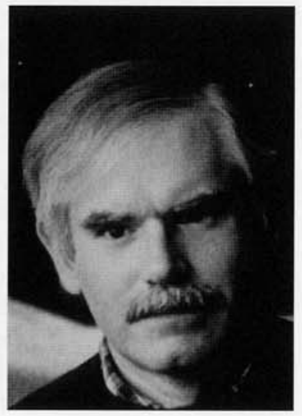
A photograph of the full Moon shows that Serenitatis is a bright-hued mare, edged by darker lavas that are especially conspicuous along its southern and eastern shores. This dark margin is well seen north of the crater Plinius, which reminded Elger of "a great fortress or redoubt erected to command the passage between the Mare Tranquillitatis and the Mare Serenitatis." The dark margin of Serenitatis contains a series of arcuate rilles near Plinius, Menelaus, and to the west by Sulpicius Gallus. On Apollo photographs this dark material can be seen to have many more small impact pits than the nearby lighter mare, so the dark rim must be older lavas. This distinctive old lava margin was called Unit I by Solomon and Head. Unit I includes lavas from the Apollo 17 landing site, which are high-titanium mare basalts and are dated at 3.7 to 3.8 billion years old.

Other areas of darkish lavas occur along the eastern rim of Serenitatis and also extend from the western edge nearly one-third of the way across the mare. Apollo pictures show fewer impact craters here than in Unit I but more than in the central bright zone. These younger lavas, categorized as Unit II, have no arcuate rilles but are crossed by the concentric wrinkle ridges that define Serenitatis's inner ring. The broad, bright inner patch of Serenitatis makes up Unit III and contains the youngest lavas in the basin. Although there are no dated lunar samples from Units II and III, the numbers of superposed impact craters indicate ages of about 3.5 billion years for II and 3.0 to 3.4 billion years for III. Thus, the lava-filling history of this lunar basin lasted 700 to 800 million years, a span of time that is immense by the standards of terrestrial geology.

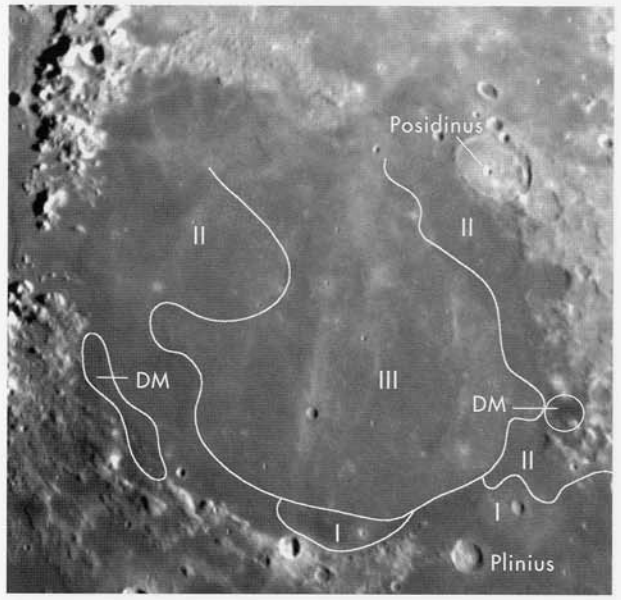
Two additional patches of even darker material occur near the Apollo 17 site close to the crater Littrow, and across Mare Serenitatis on a low ridge of the Haemus Mountains near the crater Sulpicius Gallus. These areas seem to be mantled — material is draped over existing terrain, rather than being lava flows — and are called Unit DM for dark mantle. At the Apollo 17 site, the astronauts found a scattering of



Sean Solomon.



Jim Head.



View of Mare Serenitatis with approximate lava unit boundaries indicated.

dark mantling material that contains spheres of orange and black glass. This volcanic material is believed to have sprayed into the lunar sky from a nearby lava fountain. Some of the microscopic spheres are coated with sulfur and compounds of chlorine and fluorine, gases common in terrestrial eruptions. Thus, Unit DM is interpreted as volcanic fire fountain deposits, similar to gas-rich ash eruptions in Hawaii and deposits at Mare Vaporum. The lower lunar gravity and absence of an atmosphere allowed the lunar pyroclastic material to travel much farther than in similar terrestrial eruptions.

What made the study of Solomon and Head especially significant is that they interpreted the four different units in Mare Serenitatis in terms of the history of subsidence, or slow sinking of the center of the mare basin. The earliest basalts (Unit I and the associated DM deposits) spread over the floor of the newly formed Serenitatis basin and also apparently flowed from nearby Tranquillitatis. Perhaps the weight of the lava caused the basin floor to sag and form concentric cracks (arcuate graben) at the edges of the basin where the bending was greatest. Continued lava flooding (Unit II) buried nearly all of the earlier Unit I lavas, leaving only the dark lavas along the southern shore of Serenitatis exposed. Further down-warping of the basin floor occurred, and new lavas (Unit III) ponded in the central low spots of the basin. Wrinkle ridges formed extensively in Units II and III, apparently due to horizontal compression. As the lava flows sagged, they were forced to occupy smaller areas, and as a result one part was thrust over its neighbor. High-resolution Apollo photographs beautifully illustrate ridges that have moved laterally, in one case partially covering a small crater.

If the history of lava filling in the Serenitatis basin were controlled only by its local subsidence, then concentric rilles should have formed throughout all the time units I, II, and III were forming. In fact, rilles only formed in Unit I. Solomon and Head propose that the local stresses due to the subsidence of the basin itself were modified by global lunar stresses. Moonwide, the formation of *all* arcuate rilles apparently ceased by about 3.5 billion years ago, a time when the Moon had cooled sufficiently that it changed from being mildly expansive (thus promoting the formation of rilles and graben) to being compressive (thus conducive to the formation of thrust ridges on the mare).

SERENITATIS — AN ATTRACTIVE PLACE

The story of the Serenitatis basin and its lava fill isn't finished yet. Precise tracking of the Lunar Orbiter spacecraft that circled the Moon in the mid-1960s revealed that the Orbiters deviated slightly from their predicted orbits as they passed over circular mare basins, including Serenitatis. Apparently, concentrations of denser materials under these basins accelerated the orbital motion of the spacecraft. Nearly 30 years after this discovery, scientists still aren't exactly sure of the origin of these *mascons* (mass concentrations). Long ago Hartmann and I noticed a correlation between the size of the lava flows in the mascon basins and the quantity of mass excess. Based on this, we suggested that the weight of 3- to 6-km-deep piles of mare lavas provided the excess mass. But it is likely that other masses may also contribute to the mascons. For example, Hartmann later suggested that under each basin the lunar mantle was upwarped as a result of the basin-forming impact so that these heavy rocks would be closer to the lunar surface than normal. Probably some combination of these two methods of producing extra near-surface mass are responsible for mascons.

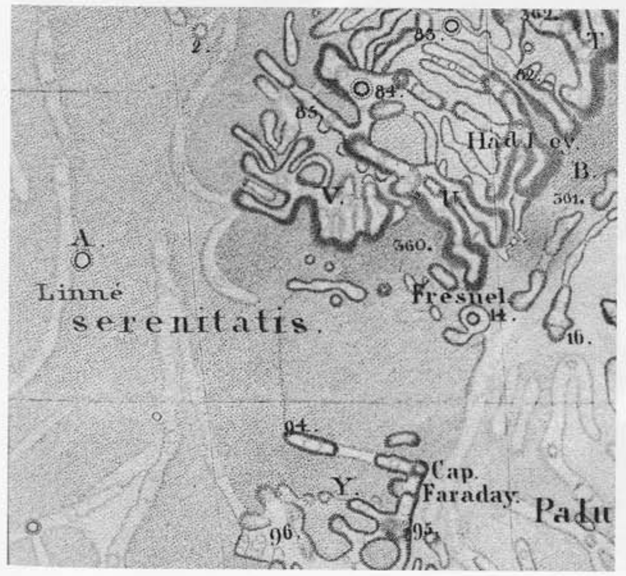
In any case, one of the most remarkable things the mascons tell us is that the lunar crust must be very stiff and strong. On the Earth, piling huge amounts of material in a depression causes it to subside so that there is no long-term gravity excess. The Earth has a very plastic crust and upper mantle that deform, so there is a tendency for every vertical pile of Earth material to have the same mass. This concept is called *isostasy*. Although mass anomalies do exist on Earth, they are usually associated with young structures that have not yet had a chance to achieve isostatic equilibrium. But the lunar mascons are 3.5 billion years old, and if they haven't equilibrated yet, they never will. The lunar crust and mantle must be far more rigid than Earth's. This is an eminently reasonable inference. Since the Earth's upper rock layers are clearly warm, they are easily uplifted and folded into mountain chains by plate tectonic movements. The Moon is like an elderly man — old, stiff, and inflexible — whereas the Earth is like a supple young gymnast — able to bend and flex and twist into unbelievable positions.

LINNÉ: HERE TODAY, GONE TOMORROW

The vast expanse of Mare Serenitatis contains few craters worthy of prolonged note, but one is notorious for a controversy concerning its very existence. In 1866 the renowned astronomer Julius Schmidt made a startling announcement: a conspicuous crater on the Moon had disappeared! The most authoritative lunar map of the time, published by German astronomers Wilhelm Beer and Johann Mädler in 1837, showed a 10-km-wide, 330-meter-deep crater in northwestern Mare Serenitatis called Linné. That map was consistent with an 1824 chart made by an earlier German Moon-mapper, Wilhelm G. Lohrmann. But Schmidt had found that Linné was no more; in its place was a brilliant white patch.

Schmidt's report caused a sensation, and astronomers — who generally thought that the work of Beer and Mädler concluded lunar studies — once again pointed their telescopes toward the Moon. They found that there certainly was no obvious deep crater at Linné's location; in its place was a bright spot that was reported to change in size and visibility. To add to the mystery, a tiny crater pit now lay at the center of the spot. The bright patch is easily visible through even small telescopes, but the pit is far more challenging. Keen-eyed observers may be able to make it out with a 5- or 6-inch instrument.

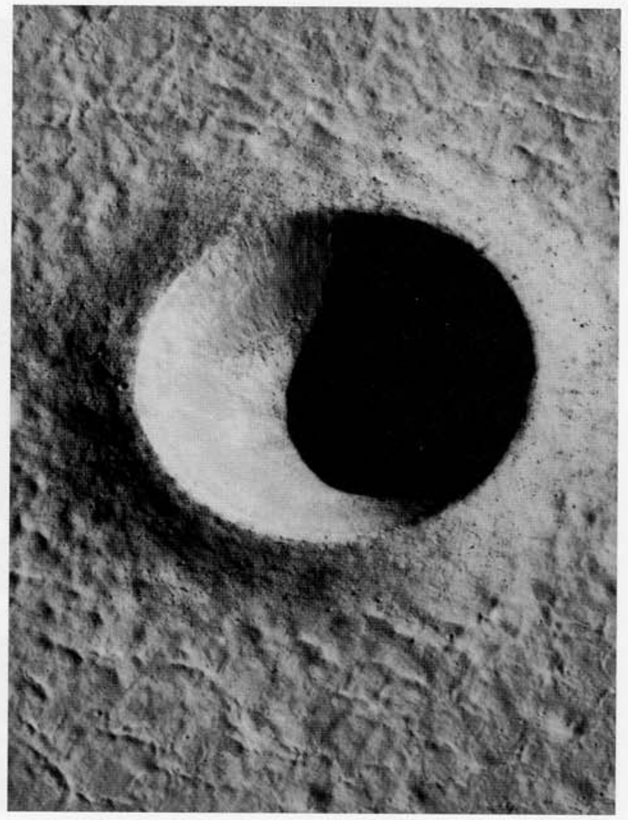
J. F. Julius Schmidt.



Lohrmann's 1824 map showed Linné (labeled A) as an easily seen crater. South is up in this chart.

A variety of speculations were advanced to explain the purported changes of Linné, including crater collapse, filling with viscous lava flows, and impact of a meteorite that destroyed the original Linné and created the tiny replacement. Harvard astronomer William H. Pickering even attributed the changes to the bright spot as being due to hoarfrost!

The real present-day character of Linné was carefully documented by USGS scientist Richard Pike using very high resolution photographs taken during the Apollo missions. Pike's measurements showed that Linné has a diameter of 2.45 km, a depth of 600 meters, and a rim that rises 125 meters above the surrounding mare surface. A series of telescopic photographs illustrated that the nature of Linné and its bright spot does change, but the changes are due sim-



Apollo 15 view of Linné.

ply to the angle of the Sun above the crater — a factor that classical selenographers never seemed to adequately appreciate. The crater is a textbook example of a very fresh impact crater, about twice the diameter of Meteor Crater in Arizona.

And so the resolution of the Linné controversy is best summed up by Pike as due to "the perils of interpreting visual lunar observations near the resolution limit of small Earth-based telescopes." This same view was expressed in 1907 by Fauth:

> *As a student of the moon for the last 20 years, and as probably one of the few living investigators who have kept in practical touch with the results of selenography, he [Fauth] is bound to express his conviction that no eye has ever seen a physical change in the plastic features of the moon's surface.*

THE VALENTINE DOME

Mare Serenitatis has no volcanic features of interest beyond its dark-colored margins and mantle deposits except for an unusual volcanic dome in the northwest sector of the mare, near the mountain gap where Serenitatis lavas apparently flowed into Mare Imbrium. The Valentine Dome (named for its heart shape) is a broad, low (100 meters high) structure popularized by a sketch appearing in the April 1962 issue of *Sky & Telescope* magazine (page 212), drawn by the Hawaiian lunar artist Alika Herring. The 30-km-wide dome is unusual in that it has three conspicuous and six less obvious smaller hills that apparently protrude from it. Under suitable lighting conditions it is a striking formation, visible with small telescopes.

SERENE CRATERS

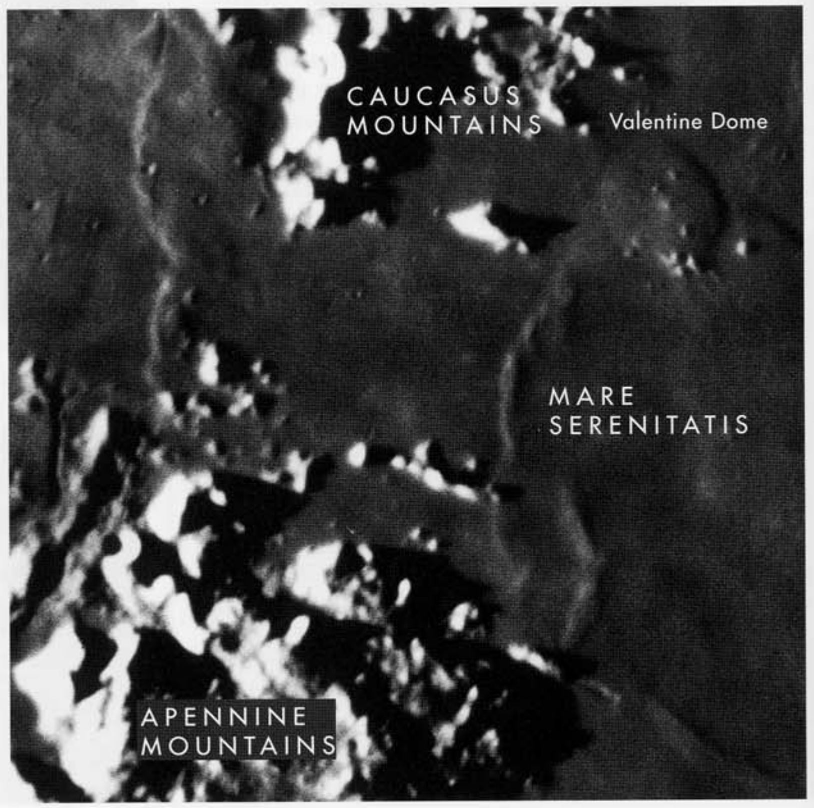
Mare Serenitatis holds fewer interesting craters than any other impact basin on the face of the Moon. The only noteworthy crater on the mare itself is the 16-km-wide Bessel. This simple crater is probably best known for the famous ray that crosses it and seems to continue across Lacus Mortis and on to eastern Mare Frigoris. This ray appears to radiate from the crater Menelaus on Serenitatis's south shore, but its orientation has led to speculation that it originated thousands of kilometers away at Tycho.

The long Bessel ray has been the subject of intense remote-sensing studies by University of Hawaii scientists who found that it includes rock-size fragments, 40 percent of which are ejecta from the highlands. But they can't say if this ejecta originated from the highlands excavated by Tycho or the Haemus Mountains under Menelaus. I would bet that Menelaus is not the source, since it was formed by an oblique impact that ejected rays in a southeasterly arc — not north like the Bessel ray. Perhaps the last words are best left to the uncharitable Fauth: "The crowns of rays spread out over the face of the full moon, and seem to mock at all explanation."

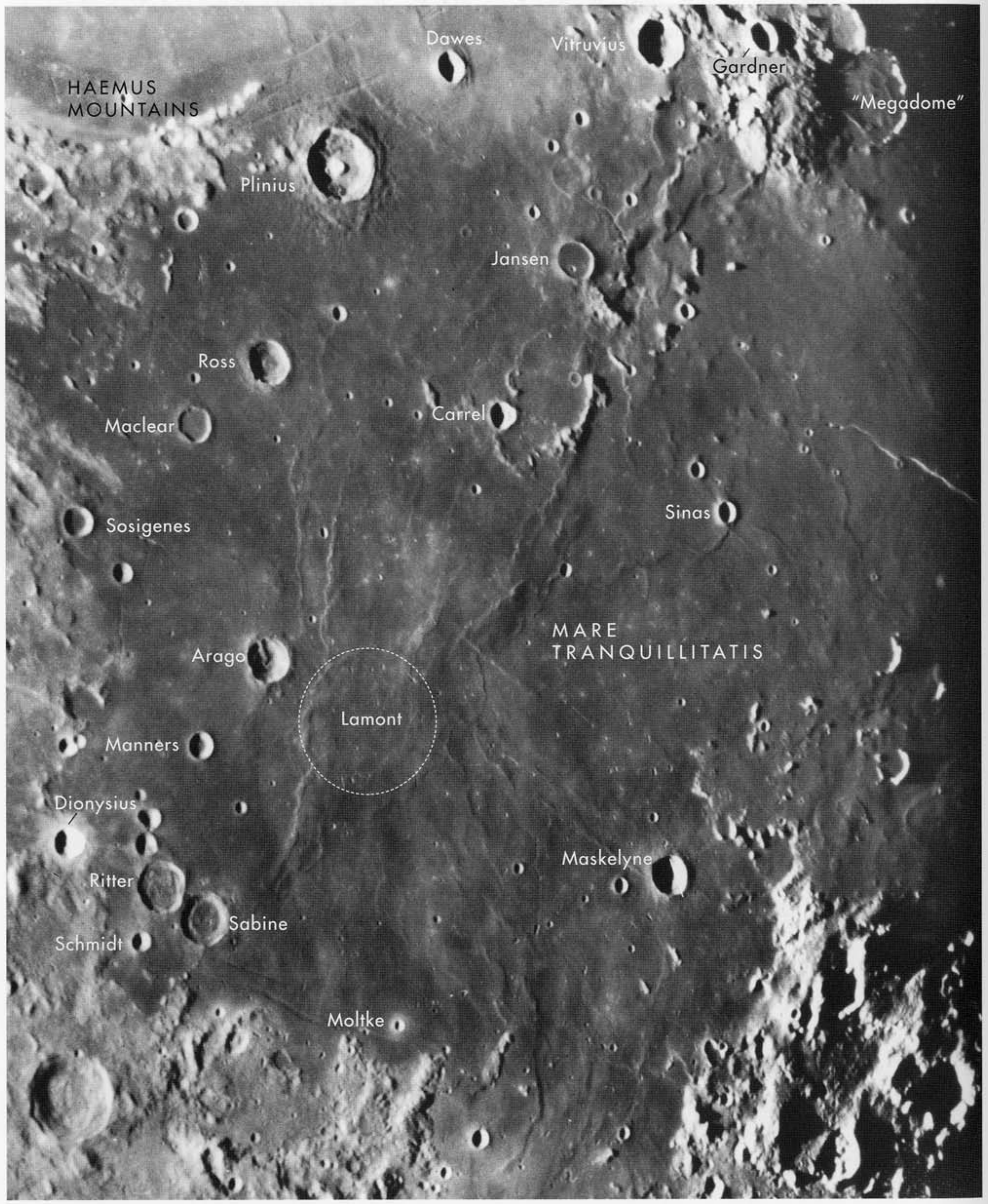
The only craters of significance near Mare Serenitatis are along the basin's subsided and lava-flooded eastern shore. Here is the battered ruined crater near where the Apollo 17 crew landed, and le Monnier (explored by the Soviet Luna 21 Lunakhod rover) and Posidonius — one of the most interesting features on the entire Moon.

All three of these craters along the eastern margin of Serenitatis have had their rims breached or even removed. A low Sun over le Monnier reveals a subtle ridge where its missing rim should be. These craters formed on the lip of Serenitatis, and as the basin subsided under the weight of the early lavas, the mare-ward sides of the craters also sank. It may not have been just a gentle warping either, for as Goodacre noted more than 70 years ago, there is a sudden drop just to the mare side of the subtle ridge. Thus, faulting probably dropped the le Monnier crater rim enough that later lavas were able to cover it. The low but not quite submerged western rim of Posidonius is consistent with its young age — it probably formed after the basin subsidence started. The faults that down-dropped the basin interior apparently allowed magma to rise into Posidonius, flooding its interior, creating its rilles, and arching up its broad inner plateau.

Philipp Fauth.



The Valentine Dome, located at the western edge of Mare Serenitatis.



Mare Tranquillitatis.

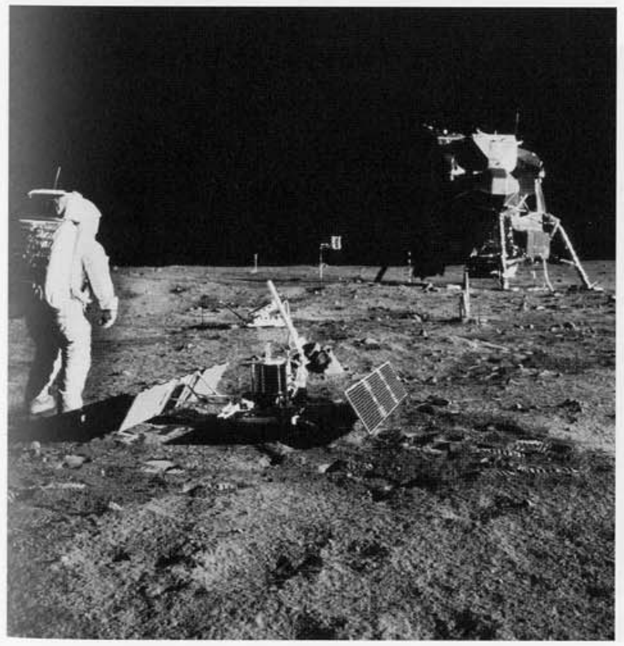
9

Tranquillity

Tranquillitatis is the most interesting mare on the Moon. Note that I said mare, not basin; there is little evidence for the existence of the impact basin that the mare presumably fills. Since all other large and roundish lunar maria are in basins, Mare Tranquillitatis probably is also, though the only suggestion is its roughly circular, 800-km-wide outline. So the mare itself is the only area of interest here. Fortunately, it includes a variety of easily observed and interesting features: volcanically modified impact craters, faults that vertically offset the mare surface, rough-textured domes, a buried miniature basin, and the place where men from Earth first touched the Moon.

APOLLO 11

In his book *A Man on the Moon* Andrew Chaikin recounts the dramatic last few seconds of the Apollo 11 landing, when Neil Armstrong overrode a failing computer to steer the lunar module Eagle to a successful landing. The spot for the first Moon landing had been selected with one primary feature in mind — safety. Yet as Armstrong approached, he saw unexpected boulders and crater rims that could destroy his fragile Eagle. If nothing else, Apollo 11 taught us that blandness as seen through the telescope or on spacecraft photographs does not guarantee smooth, even terrain. It also demonstrated the virtue of piloted spacecraft — a robotic lander would have meticulously executed preprogrammed commands and crashed on the boulders Armstrong so deftly avoided.



Apollo 11 astronaut Buzz Aldrin stands next to the lunar seismometer and looks back toward the lunar lander, Eagle, perched on the surface of Mare Tranquillitatis.

The first Apollo samples brought to Earth demonstrated that lunar materials were remarkably similar to those that make up our world. There were no new elements found, and only a few minor new minerals. The most famous is *armalcolite* (after *Arm*strong, *Al*drin, and *Col*lins), an iron titanium oxide mineral that crystallized in a rapidly cooled hot magma. After its discovery on the Moon, armalcolite was found in Earth rocks as well.

But lunar rocks do differ greatly from terrestrial rocks in a number of ways. We knew the Moon of today lacks water — there is no atmosphere, and the lack of atmospheric pressure means that any water released on the Moon would rapidly escape into space. But the absence of water in ancient lunar rocks demonstrated that the Moon has always been bone dry. This was a surprising discovery, considering that Earth is awash with water. While the lack of water was a perplexing clue to the remarkable origin of the Moon (discussed in Chapter 13), it also means that minerals in lunar rocks have not been altered by chemical interaction with water, so their origin and history are easier to interpret. Given the absence of water, it was not surprising that detailed microscopic examination of lunar samples yielded no evidence that life ever existed on the Moon.

Apollo 11 samples proved that the maria are made of basaltic lava flows rather than thick dust that, as noted in Chapter 4, Gold had categorically stated would swallow the lander. And the existence of basalt, a rock formed by heating within a planetary body, destroyed the cherished hope of Urey, who had long argued that the Moon had been forever a cold and chemically unevolved world. He wanted a cold Moon so that we could study primordial stardust, the material that made the solar system but was long ago altered beyond recognition on Earth by our planet's history of heating geologic activity. The Moon turned out to be more prosaic than Urey's dreams — it formed almost entirely of elements, minerals, and rocks similar to those found on Earth.

The discovery of basalts brought smiles of victory to the faces of the few holdouts who believed lunar craters were formed by volcanic activity rather than by impact. But they were deceiving themselves, just as they had been for years. What they failed to understand was that the mare and craters had two separate origins. In fact, the observation that most lunar samples were mechanical mixtures of fragments of larger rocks or *breccias* was profound evidence for the pervasiveness of impacts on all scales.

Radiometric dating of the Apollo 11 rocks showed that the maria were ancient beyond belief — 3.57 to 3.86 billion years old. This age was an abrupt comeuppance for the two giants of lunar science. Both Shoemaker and Baldwin had made the biggest mistakes of their careers by publishing articles stating that the maria were less than 1 billion years old. Only one scientist, newcomer Hartmann, had correctly estimated the age of the maria.

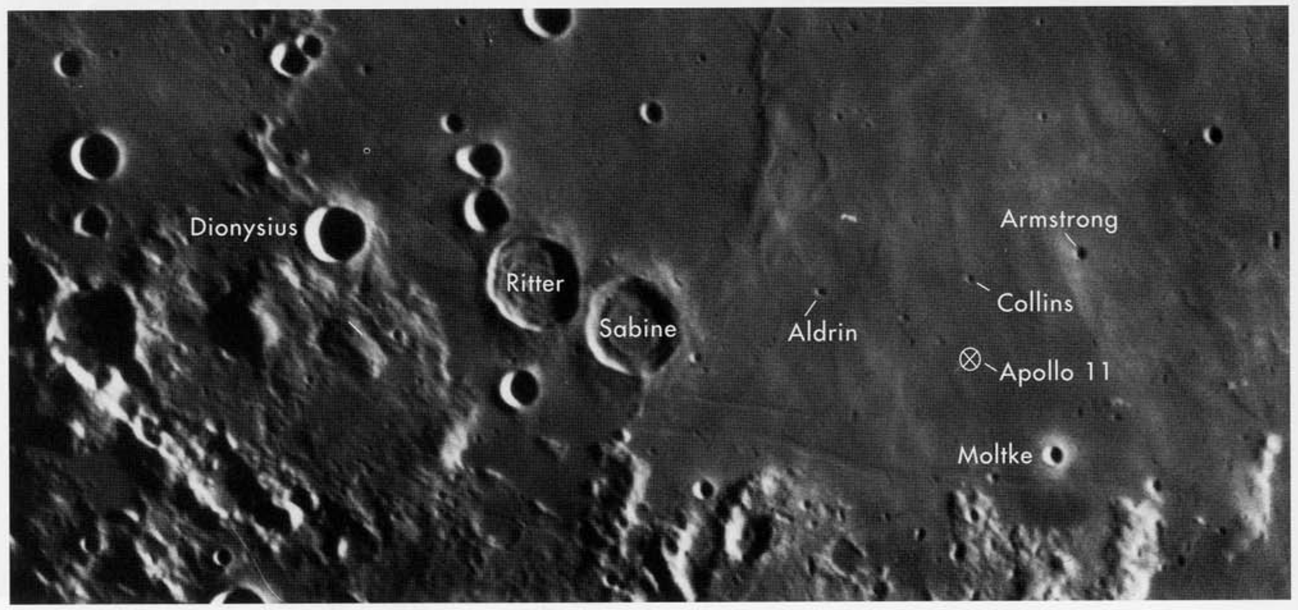
Two different chemical types of basalts were brought back by the Apollo 11 astronauts. Titanium-rich basalts, low in the elements potassium and aluminum, were most common and erupted onto the surface 3.69 to 3.86 billion years ago. The other basalt, similar to the first but high in potassium, is distinctly younger at 3.57 billion years old. Thus, different types of volcanic activity must have occurred in Mare Tranquillitatis over a period of at least 300 million years — a very long time by Earth standards, but apparently not for the Moon. And mixed in with the rocky basaltic soils were aluminum-rich igneous fragments, probably pieces of the nearby lunar highlands. The Moon was not homogeneous and must have had a complex geologic history. It would be a challenge, and great fun, to understand.

There is no visible landmark to pinpoint the Apollo 11 landing site, but the general area can be found easily. Look eastward along the southern shore of Mare Tranquillitatis from the twin craters Sabine and Ritter (each about 30 km wide) toward the small bright crater Moltke. About two-thirds of the way to Moltke and just slightly to the north is Tranquillity Base, the Apollo 11 landing site. If you look when the angle of illumination is really shallow, you will see a low wrinkle ridge that Eagle probably landed on or near. With a higher Sun angle, just east of Sabine you may glimpse a line of three craters, 2 to 4 km in diameter, that now bear the names of Armstrong, Collins, and Aldrin.

As you observe Tranquillity Base, reflect on the fact that you are looking at basaltic rocks that are 3.7 billion years old. Although these are some of the younger rocks on the Moon, there are almost no rocks on Earth as ancient. The Moon is a museum of otherwise lost events that happened in the first billion years of solar-system history.

SABINE, RITTER, AND DIONYSIUS

A short distance from Tranquillity Base are three unusual craters that once excited passions but are now mostly forgotten. For relatively fresh craters, increased diameter changes crater morphology from simple bowls to craters with wall slumps, and finally to craters with large terraces, flat floors, and central mountains. Or at least that's how it's supposed to work, according to the system of crater classification known as the *main sequence.*

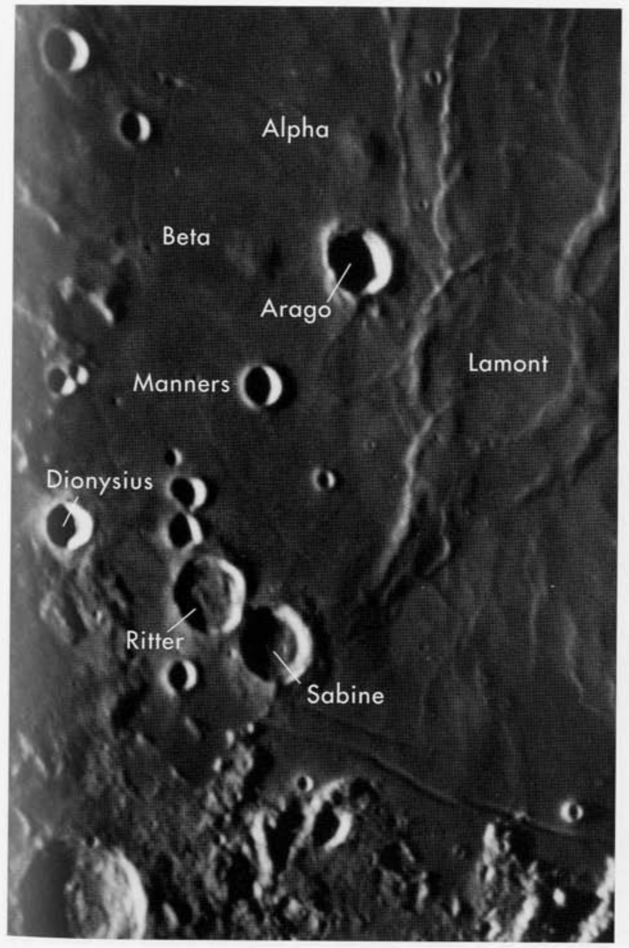


Tranquillity Base — the Apollo 11 landing site.

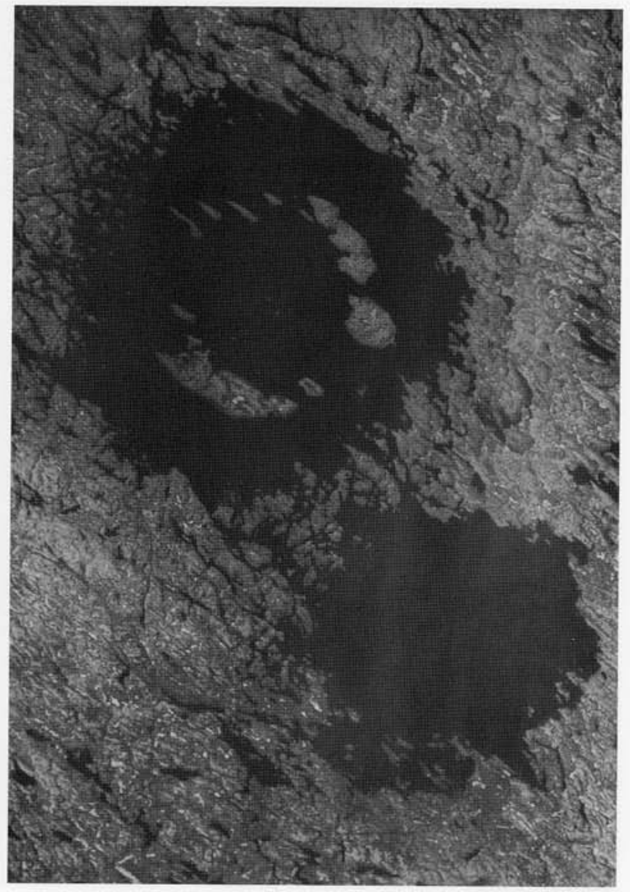
But Sabine and Ritter simply refuse to be pigeonholed into this scheme. Although their rims look fairly normal, both craters are much shallower than expected (only 700 to 750 meters, versus the 3,000 to 3,500 meters typical for craters of this diameter) and have weird floors. Sabine, the easternmost one, has an unusual ridge that resembles a thin doughnut extending around the moatlike edge of its floor. And Ritter has a lumpy floor with a possible central-ridge remnant and an elevated, arcuately bounded rough area. To believers in a volcanic origin for lunar craters, Sabine and Ritter were proof. Even USGS mappers considered volcanism to be the most likely explanation for these atypical craters.

But then the tide began to turn. Schultz, Wilhelms, and other lunar scientists noticed that many craters near edges of basins have shallow and complex floors. The idea arose that magma, rising up through basin fractures, pushed up the floors of these craters. Because radial and concentric ridges and fractures seemed to accompany the uplift, they became known as FFCs — floor-fractured craters. Sabine and Ritter can now be understood as impact craters that have been more or less modified by the intrusion of magmas. Although this is different from the old interpretation — that such craters were volcanic calderas — it does recognize the importance of igneous activity in modifying some impact craters.

There is one more question you probably will be wondering about after viewing Sabine and Ritter: What are such similar craters doing side by side if they are really random impacts? Interestingly, similar-looking craters occur on Earth too, where the impact origin of such features is beyond dispute. In Canada, the Clearwater Lakes are a 32-km- and 22-km-wide pair of craters formed by simultaneous impacts about 290 million years ago. Presumably, what happened in Canada, and on the Moon, was that gravity split an incoming projectile in half, causing two closely spaced impacts. Alternatively, the impact of a binary asteroid or comet



Western Mare Tranquillitatis.



Clearwater Lakes impact craters, Canada.

could have caused pairs of craters. These ideas would seem just short of preposterous had we not recently discovered comets shredded by gravity (Shoemaker-Levy 9) and asteroids with satellites (Ida and Dactyl).

What about Dionysius? Why is such a normal impact crater included with these misfits? Look at it under high solar illumination and note its dark rays. Dionysius is a brilliant 18-km-wide, 3-km-deep crater with short, dark rays that are most conspicuous to the west but extend in all directions. Surprisingly, none of the classic lunar observers noted this easy feature (perhaps because virtually everyone shuns the full Moon), which was apparently discovered by U.S. Air Force scientist Vern Smalley in 1965. Most likely Dionysius is simply a very large dark-halo crater, like the tiny one just east of Sabine. If this interpretation is correct, Dionysius must have excavated and scattered a localized dark volcanic ash deposit or lava flow as ray material. Other nearby smaller craters may not have dug down deep enough to tap into this dark material. While this explanation is not completely convincing, it is reasonable, given that nearby mare lavas, floor-fractured craters, and rilles are all evidence of abundant volcanism.

ARRESTING ARAGO

Continuing north along the poorly defined western shore of Mare Tranquillitatis we come to the next anomalies. (We don't bother with normal features unless they're spectacular!) The 26-km-wide crater Arago is a relatively typical Triesnecker-like complex crater except for a ridge that extends from where a central peak should be to the crest of the crater's northern rim. Although there are numerous peculiar central peaks in lunar craters, this is one of the weirdest. Naturally, the usual crowd claimed that this could only be some sort of volcanic feature, even though it doesn't look like any terrestrial volcanic landform. The ever-ingenious impactors, building on the fact that the rest of the crater is a wonderful example of impact morphology, suggested that the rebound that usually produces a central peak was unusually strong and instead resulted in peak material showering down across the crater floor, rather than sticking up in the sky. Perhaps we strain too much to understand features that we know too little about. The fallen peak would have been 12 km high and stuck far above Arago's rim, unlike any other crater. But high-resolution Apollo photography provides a better explanation. The northwest wall of the crater is displaced by a large scallop or arcuate collapse where part of the wall has tumbled onto the floor — Arago's wall terraces simply merge with its central peak.

DOMES AND RILLES

The real attraction of Arago is a pair of large domes to its north (Arago Alpha) and west (Arago Beta). These are two of the largest, steepest, and most visible domes on the Moon. Strangely, on the best topographic map of this area, made from Apollo and Orbiter photographs, they are not depicted. Both domes are rough in texture, 15 to 20 km wide, and only a few hundred meters high. In 1959 the slope of Alpha was measured at 1.4°. Halfway between Alpha and the crater Maclear are four much smaller (5 to 8 km wide) domes that are more difficult to see and are thus a greater source of delight for those observers who manage to spot them.

Although Tranquillitatis has little visible basin structure, it does have one characteristic of basins — impressive rilles. An interconnected series of rilles extends from south of the Apollo 11 site, under and near Sabine and Ritter, near Sosigenes, and past Maclear to the southern edge of the Haemus Mountains. The rilles along the southern shore of Mare Tranquillitatis are relatively broad, with flat floors. Along the western shore of the mare, however, the rilles become much more delicate and are visible only under excellent seeing conditions. Linear and arcuate rilles of this sort are common on the outer edges of maria in basins featuring distinct impact structures (the Humorum basin is the best example). Such rilles form when the weight of the mare lavas causes the basin floor to subside, fracturing the brittle lava near its edges. The absence of similar rilles on the eastern shore of Tranquillitatis suggests that only the western side sank. This idea is supported by estimates of the thickness of mare lava by University of Arkansas lunar scientist René DeHon, who found that the western third of Mare Tranquillitatis is as much as 1,500 meters thick, whereas the rest is thinner than 1,000 meters.

LAMONT — A BURIED MYSTERY

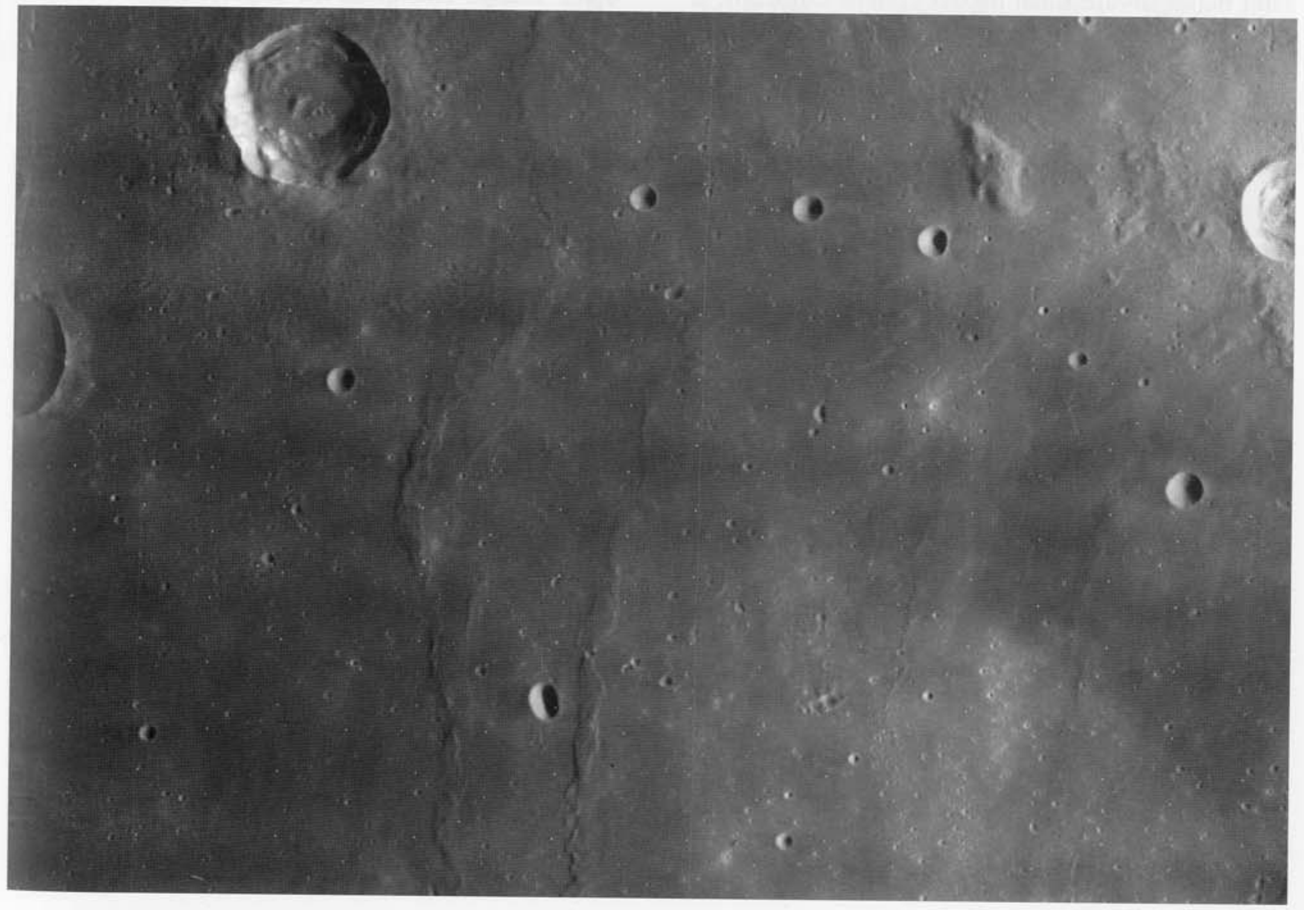
Just east of Arago, on the southwestern edge of Mare Tranquillitatis, is a unique network of concentric and radiating wrinkle ridges named Lamont. It is a 75-km-wide oval ridge surrounded by a wrinkle-ridge ring approximately 135 km in diameter. Classical selenographers considered it an "imperfect ring" and generally ignored it. But when the Lunar Orbiter spacecraft circled the Moon, Lamont's position was found to correspond to a moderate-size mascon. It was quite unusual to find one at Lamont, since all other mascons are associated with impact basins and, hence, were believed to be due to the excess mass of mare lavas and/or a rise of the dense lunar mantle under the basin.

USGS lunar geologist David Scott proposed that Lamont is a small multiring impact basin covered by subsequent Tranquillitatis mare lavas. Computations by Jet Propulsion Laboratory geophysicists suggest that the mascon can be explained by a dense layer 10 to 20 km thick somewhere between 3 and 50 km deep. So perhaps under western Tranquillitatis lies a buried basin similar to Grimaldi (but much deeper!) on the Moon's western limb. This interpretation is consistent, perhaps, with the inferred subsidence of the western portion of Mare Tranquillitatis.

Another peculiar feature can be observed near Lamont. When the illumination is somewhat low, an abrupt tonal boundary is visible northwest of Lamont running southeast to northwest. The Lamont area is slightly brighter than the region of mare on the other side of the boundary. Surprisingly, the contrast line passes across wrinkle ridges as if they weren't there. Examination of high-resolution Lunar Orbiter photographs shows that the brighter zone is full of small impact pits, indicating that this area is older. The bright halo surrounding each pit accounts for the light hue, while the sharp boundary between the light and dark zones must be the zone of contact between older pitted lavas and dark younger ones. The fact that the boundary is crossed by the wrinkle ridges suggests that both lavas were in place before the ridges formed.

THE LAMONT – GARDNER MEGADOME ALIGNMENT

Other curiosities abound. Linked to Lamont to the north-northeast is an alignment of flooded craters, ridges, and a huge dome. Only Spurr in the 1940s seems to have recognized this structure. Extending from near the young impact crater Carrel, past Jansen, to the east of Gardner is a series of 30- to 50-km-wide "almost-submerged ancient structures," as Spurr called them. Massive wrinkle ridges pass among these flooded older craters, and a somewhat sinuous rille cuts across ridges and maria north of Jansen, which is itself a lava-flooded crater whose floor is higher than the surrounding mare. But the most amazing feature of this alignment is a 70-km-wide, rough-textured dome that doesn't even have a name. I call it the Gardner Megadome, after the crater immediately to the northwest. A wrinkle ridge on the mare to the south seems to continue right onto the dome, causing an arcuate ridge that offsets its surface. A wide, rimless depression cuts the south-central part of the megadome.



Lunar Orbiter IV view of mare north of Lamont. Ross is the conspicuous crater at the top of the image.

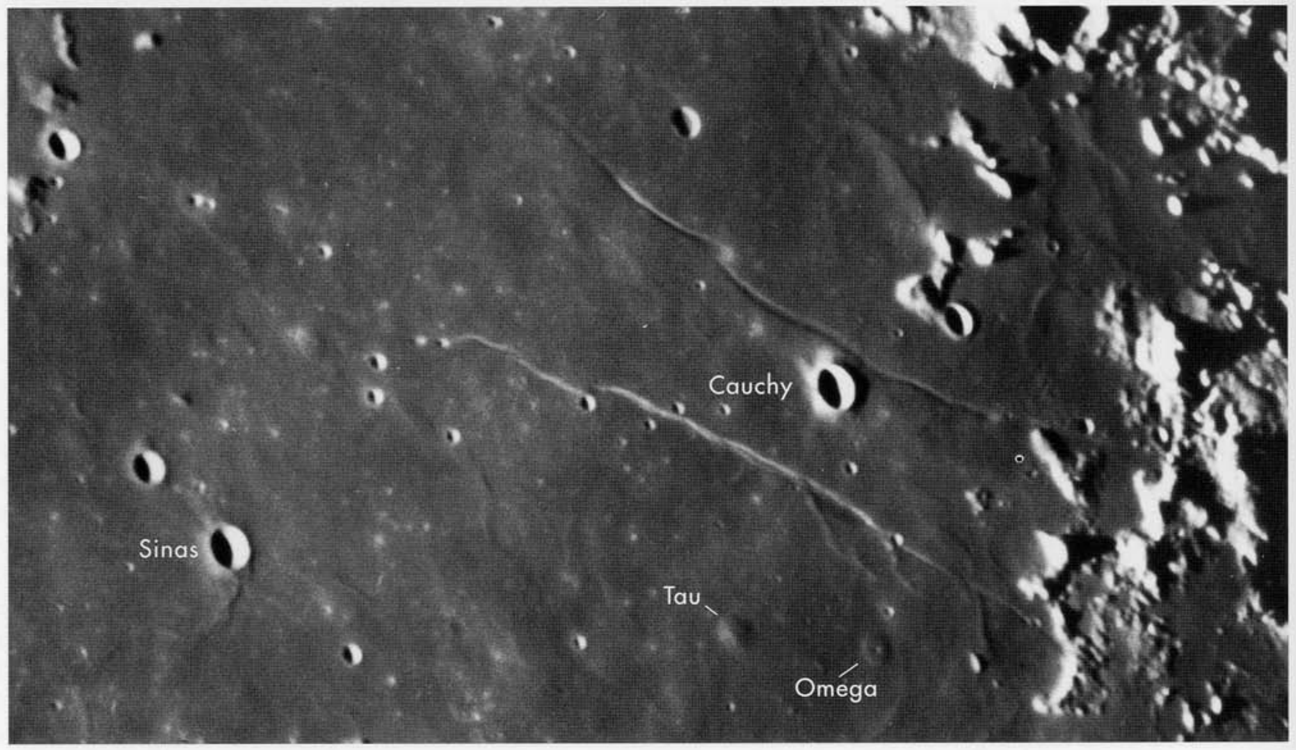
Accepting this entire alignment (from Lamont to the megadome) as one structure makes it one of the largest non-basin-related tectonic features on the Moon. But maybe it is at least related to a basin. Whitaker defined his Procellarum basin with three fragmentary rings; the intermediate ring of 2,400 km diameter passes through the northern shore of Mare Frigoris, the Oceanus Procellarum wrinkle ridges, and through Lamont! I extend Whitaker's ring to include the entire Lamont – Gardner Megadome. Perhaps Spurr's "axis of upwarping" never was upwarped but is high simply because the craters and ridges were built on a preexisting basin rim.

CAUCHY FAULTS, RILLES, AND DOMES

The Moon has very few faults (geologically speaking, anyway), but a glorious one is clearly visible cutting across northeastern Mare Tranquillitatis. The bright, 12-km-diameter crater Cauchy lies between a fault to its south and a rille to its north. The lunar surface is higher on the fault's northeastern side, as shown by the shadow it casts when the Sun is to the east. The height of the offset seems to be unmeasured but is probably only a hundred meters or so. At each end the fault bends toward small impact craters. Curiously, at this point each end of the fault becomes a rille instead. Remember that the fault near Bürg, in Lacus Mortis (discussed in Chapter 7), does the same thing. At its western end, the Cauchy fault/rille continues as two tiny, elongated and rimless collapse pits. A field of small domes extends farther west. The rille north of Cauchy is about 200 km long — nearly the same length as the southern fault/rille. Interestingly, both ends of this rille taper off to much thinner rille segments.

The existence of a rille and parallel fault is not unique on the Moon. The British lunar scientist Gilbert Fielder long ago compared the combination at Cauchy with the Straight Wall fault and the nearby rille in Mare Nubium. These features form where the Moon is under extensional stress. One reason for the stress might be that two parallel dikes of magma intruded into eastern Tranquillitatis. This idea is consistent with the presence of the small rilles at the ends of the Cauchy fault, as well as the small domes west of the fault. But why did the dikes form? Who knows, except that the two Cauchy linear features are approximately radial to the adjacent Serenitatis basin and the putative Fecunditatis basin.

South of the Cauchy fault are two domes that are conspicuous when the Sun is low. Each dome is 10 to 12 km wide. The easternmost one, Cauchy Omega, has a flat top and a small summit crater. Cauchy Tau is more dome shaped and gives the impression of having a rougher surface, like the Arago domes. Since the end of the 19th century, mare domes have been considered to be of igneous origin. Rising magma can either break through to the surface, where lava erupts from small vents, or may instead intrude rock layers, causing overlying rocks to arch upward. Apparently both processes happened near Cauchy. Smooth, pitted domes like Omega are almost certainly small shield volcanoes like those in Iceland and on the Snake River Plain of Idaho. And the rougher, uncratered lunar domes may be preexisting lunar lavas arched by intrusions. On Earth they would be called *laccoliths*, or failed volcanoes.



Cauchy rilles and eastern Mare Tranquillitatis.

Philipp Fauth's exquisite drawing of the Cauchy rilles from his 1907 book, The Moon in Modern Astronomy.

Mare Crisium.

10

Crisium Country

The Sea of Crises is no such thing — it is a place that has been mostly tranquil for billions of years. Mare Crisium (the mare's Latin name doesn't distract from the region's serenity) is easy to find but is often overlooked. Crisium is first seen soon after new Moon when long shadows creep across its mare as the Moon grows from a slim crescent. Unfortunately, at this moment of optimum illumination the Moon is low in the western sky. And 14 days later, as the sun sets on Mare Crisium, the dazzling brilliance of full Moon discourages naive observers from sleuthing along the eastern limb when the terminator returns. But both terminator crossings of the Crisium region are early evening events, so do venture out to observe them. This mare boasts both giant and tiny oblique impact features, nearly hidden basins, a completely obscured crater that may have formed yesterday (geologically speaking), and other surprises that await your investigation.

CRISIUM RINGS

Mare Crisium is easy to identify even without binoculars because it is the only lunar basin whose lava deposits don't connect to those of other maria. But its isolation from lava flooding hasn't helped to preserve Crisium's basin rings. They're there all right, but you have to look carefully to see them. The most obvious ring is the outer edge of the mare itself, which is serrated and generally marked by massifs that are high and relatively flat.

The mare surface has long been described as appearing deep. The Apollo 15 and 17 spacecraft flew directly over the southern parts of Crisium, taking detailed photographs that were used to make accurate topographic maps that show the massifs rising 2 to 5 km above the mare surface. One of the highest points is Cape Agarum, a 50-km-wide block jutting into and towering 5.5 km above the southeastern part of the mare. An arm of the mare circles behind the cape like a vast fjord. In fact, if you look closely, you'll see a number of elongated fjordlike troughs behind the massifs on most sides of Crisium. Beyond these troughs the elevation of the surface is generally lower than the massifs, which define a blocky ring 500 to 600 km wide around the circumference of the mare.

Another roughly defined ring of generally smaller massifs encircles Crisium a bit farther out. The easiest place to trace this ring is along the basin's north side, where smaller massifs border a stringy arc of dark material — Mare Anguis, the Serpent Sea. This ring is cut by the large post-Crisium crater Cleomedes, continues under Proclus, disappears among massifs in Crisium's southwest sector, passes near the mare-floored craters Firmicus and Condorcet, and is marked by a ridge on the basin's east side. These segments, fragmentary as they are, do seem to indicate a real ring, one measuring about 635 km in diameter.

Another ring segment is very well defined on the north side of Crisium, especially between the craters Geminus and Berosus. Although this ring boundary is ragged, there is a clear scarp here, with the terrain inside being lower and smoother. This difference between inside and outside is also obvious west of Geminus, even though the scarp is harder to trace there. South of Crisium, there is little evidence of this big ring, except that the outer edge of a mare patch, Mare Undarum (the Sea of Waves), is along the magic 1,075-km-wide circle that would mark the ring if it were to exist on this side of the basin.

Going back to Mare Crisium itself, a clear inner ring resides as a plexus of wrinkle ridges on the mare floor. It requires low Sun angles to see the ridges, which fit nicely in a circle about 375 km in diameter.

The recognition of basin rings was one of the most important breakthroughs in understanding lunar structure. And yet, because the rings are often hard to see, there is a good deal of disagreement among scientists. For example, three of the most authorative studies of Crisium produced these ring diameters:

HARTMANN & KUIPER	WILHELMS	PIKE & SPUDIS	RING NUMBER
—	—	1,600 km	7
1,060 km	1,090 km	1,080 km	6
—	900 km	—	5
—	760 km	740 km	4
670 km	635 km	—	3
450 km	600 km	540 km	2
—	380 km	360 km	1

Three sets of experts, three different sets of rings. Is it completely arbitrary? No. Hartmann and Kuiper discovered multiring basins and, in an effort to convince other scientists that these structures really existed, described only the most obvious rings. They didn't count wrinkle-ridge rings (ring 1) nor very dubious ones (rings 4, 5, and 7). Pike, Spudis, and Wilhelms suffer, I think, from a desire to interpret every random massif segment as a ring. Some may be real, but the differences in their ring diameters suggest the insecure status of many rings. I see good evidence for only four Crisium rings:

Geminus ring	1,075 km
Cleomedes ring	635 km
Crisium ring	500 km
Wrinkle-ridge ring	375 km

All these professional ring counters looked at only a limited selection of photographs, but the recognition of subtle features is exceedingly dependent on Sun angle. You too can go out and observe Crisium, gather new evidence, and contribute to these annular Olympics. Which rings do you see?

You may not have noticed, what with our fixation on circles, that the basin is actually not circular. The Crisium ring itself disappears on the eastern edge of the basin, and mare lavas extend 150 to 200 km east of the massif ring's expected location. Additionally, USGS mapping shows that the basin ejecta extend more to the north and south than to the east. What does this mean?

OBLIQUE INTERLUDE

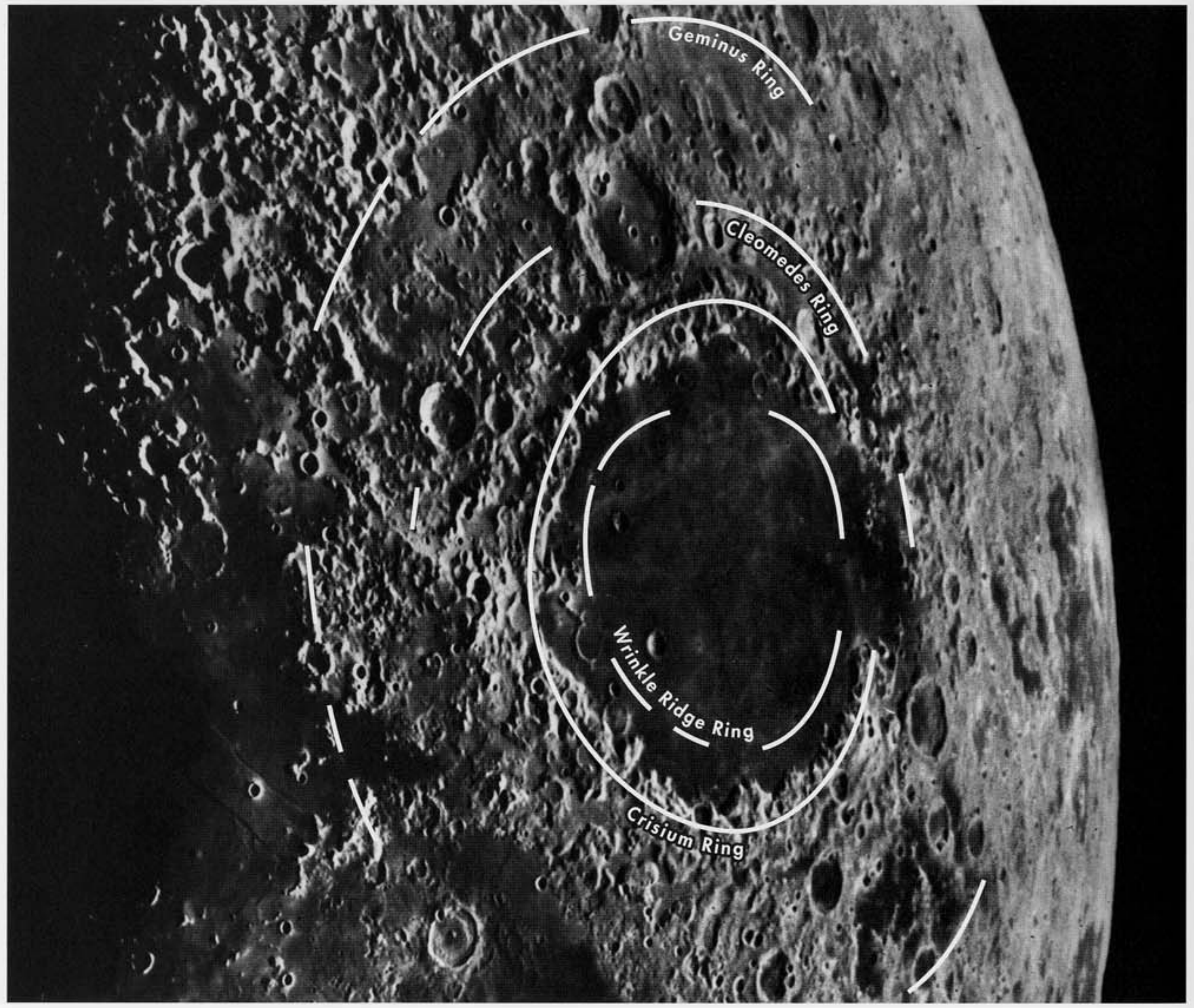
The oval shape of dusky Mare Crisium is the most conspicuous feature along the Moon's eastern rim, but from about first quarter on, a much smaller, bright crater steals the show and provides a long-overlooked clue to the irregular shape of the giant Crisium basin itself. Proclus (28 km in diameter, 2.4 km deep) is one of the very brightest craters on the Moon and is remarkable for the asymmetrical pattern of its bright rays. There is a 140° gap in the rays on the southwest side of Proclus. In fact, the countryside to the west of Proclus is noticeably grayer than the ray-covered areas and is one of the few highland regions of the Moon given a name — Palus Somni, the Marsh of Sleep.

This uneven ray pattern troubled observers. Many recognized that the Proclus rays delimited Palus Somni, but these observers failed to understand that the apparent uniqueness of the Palus was due to its lack of rays. One proposal was that the Palus had been veneered by thin coats of some liquid or plastic material. Alter suggested that Palus Somni sank at about the time of the Proclus impact. The unstated implication is that the rays originally spread out in all directions but were somehow removed in the area that subsided. Once again, a bizarre explanation represents a failure of lunar science (or maybe lunar prescience). Few observers noticed that the gray tones of Palus Somni are matched by the terrain north of the ray near the crater Macrobius, by the vague peninsula containing Maraldi and Littrow, and by the squarish block north of Mare Nectaris. Have a look for yourself.

Traditional observers based almost all their theories on raw supposition and had no secure understanding of the processes that formed rays. It turns out that rays lose much of their mystery when studied on the ground. When Shoemaker examined craters produced by nuclear explosions and Arizona's Meteor Crater, he could inspect the blocks of material that formed clots and rays beyond the crater rims. In addition, laboratory work opened up remarkable new understandings of impact processes and answered old questions.

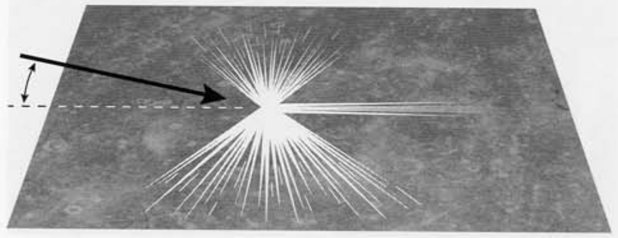
In an instantly classic study, Don Gault and John Wedekind (Caltech) reported in 1978 that the shape of an impact crater and its ejecta pattern depend on the angle at which a projectile strikes a target. Using the Ames Vertical Gun Ballistic Range, they shot millimeter-size spheres and cylinders into targets of granite, quartz sand, and volcanic pumice powder at velocities up to 7 km per second (15,000 miles per hour). Such experiments had already been crucial to understanding the physics of normal impact cratering, but Gault and Wedekind went one step further and asked, What happens when a projectile makes an oblique impact?

Surprisingly, not much changes until the impact angle is less than 45° (measured from horizontal). But at shallower angles the crater becomes increasingly elongated in the direction of projectile travel, and portions of the projectile ricochet and gouge out a series of small pits downrange from the main crater. As the impact angle decreases, the ejecta and rays undergo even more pronounced changes than the craters do. When the impact angle is less than 15°, the ejecta pattern becomes elongated in the downrange direction and a "forbidden zone," where no ejecta appears, develops in the uprange direction. For grazing impacts of just a few degrees, the rays go sideways only, producing a butterfly-wing pattern. Amazingly, examples of all of these exotic ejecta patterns can be found on the Moon, Mars, and Venus. Thus, the asymmetric Proclus ejecta and rays were formed by an oblique impact. This is perfectly natural and not at all unexpected since incoming projectiles should arrive randomly from all directions. No strange ash explosions or mysterious lava veneering of a sunken Palus Somni are required — Palus Somni is simply the ray-excluded zone of the Proclus oblique impact.



Major basin rings of Crisium.

Proclus and its rays.



Oblique impacts make elongated craters and nonsymmetrical ray patterns.

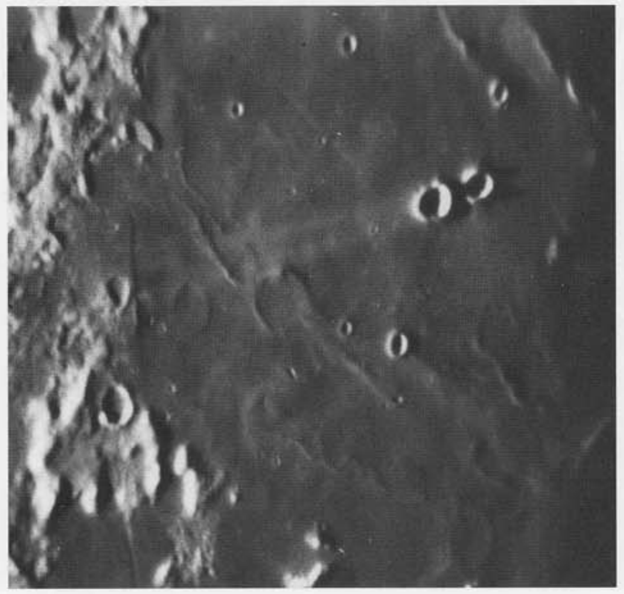
Oblique impacts also resolve the mystery of one of the most bizarre crater pairs on the Moon. South of Mare Crisium in Mare Fecunditatis are two small craters with unique parallel rays streaming from one of them. Messier is very elongated (14 by 6 km), and the irregularly shaped Messier A (13 km) has long twin tails of rays that point away from Messier. Previous explanations for this crater pair have ranged from imaginative to fantastical. All were wrong. In the 18th century, German physician and astronomer Franz von Gruithuisen proposed that the parallel rays were artificial, while other observers, perhaps in need of spectacles, claimed that sometimes the rays doubled. Additionally, the crater pair frequently have been reported to change size and shape and to be shrouded in mist. In the 1960s, British planetary observer Valdemar Axel Firsoff believed the crater Messier A (once called Pickering) to be migrating eastward, leaving behind a trail of faint ruins that are the remnants of previous positions. But the most bizarre idea came from the great meteorite collector Harvey Nininger, who proposed that a meteorite crashed through a ridge, leaving a hole on either side. Presumably a tunnel links them.

The really remarkable fact about Messier and Messier A is that the scientists Gault and Wedekind were able to beautifully mimic every one of the pair's weird features in laboratory impact experiments. A grazing impact (1° to 5°) by a projectile coming from the east excavated Messier (explaining its elongated shape and classic butterfly-wing ejecta pattern) and another part of the projectile ricocheted downrange to form Messier A and its long rays. Bigger craters formed obliquely too — look closely at the ray patterns of Proclus, Kepler, and Tycho. Maybe, on the Moon at least, truth really is stranger than fiction.

Remember the Crisium basin? It is simply a larger version of Proclus and Messier. The basin's elongated shape, low rims on the east and west, and butterfly-wing-like distribution of ejecta to the north and south are all consistent with the low-angle impact of an asteroid or comet approaching from the west. Wilhelms, who was one of the first to suggest this idea, points out that a number of other basins — Orientale, Imbrium, Humorum, Humboldtianum, and Nectaris — also have such asymmetrical features. It is possible that at least some of these oblique impact basins were formed by planetesimals in Earth orbit — leftovers from the formation of the Moon — not by random bombardment of objects that approached the Moon from a wide range of impact angles. Theoretical studies suggest that Earth-orbiting debris would spiral into the Moon, ultimately colliding at low angles.

INSIDE CRISIUM

There is sometimes such a fascination with the subtle that we neglect the obvious — like the dark, smooth plain of Mare Crisium, one of the most conspicuous features on the Moon. The mare is about 400 km wide from north to south, about the same as the state of Arkansas. Near full Moon we can see the fan of bright rays from the crater Proclus radiate over the northwestern portion of Crisium. But notice that a dark triangle of mare extends from the western shore of the mare past the crater Peirce. This appears to be a shadow zone where the rays from Proclus were blocked by a ridge near the basin rim. This ray gap is consistent with a grazing impact that ejected material at low angles.



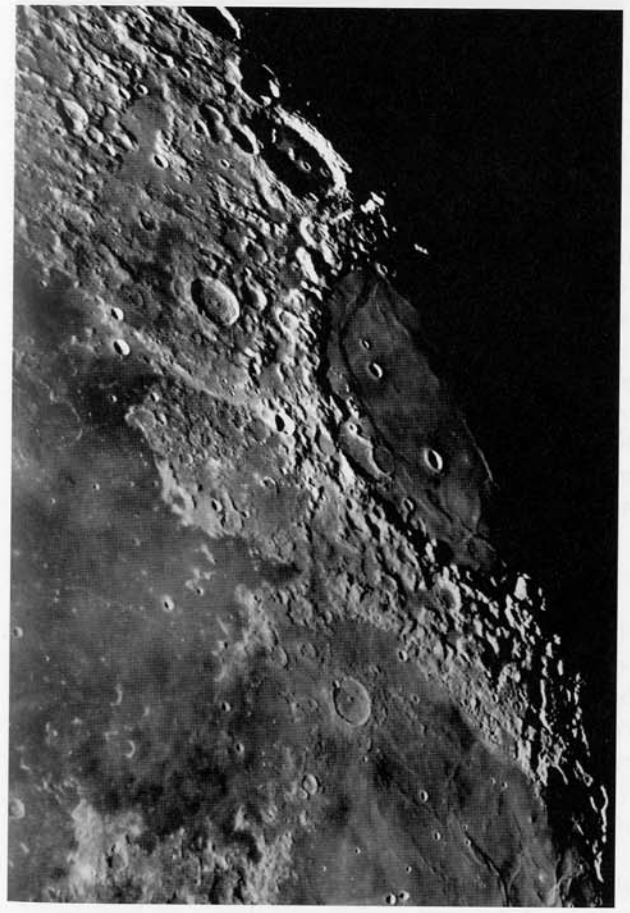
The craters Messier (the easternmost one) and Messier A.

An Apollo 11 orbital view of the Messier crater pair.

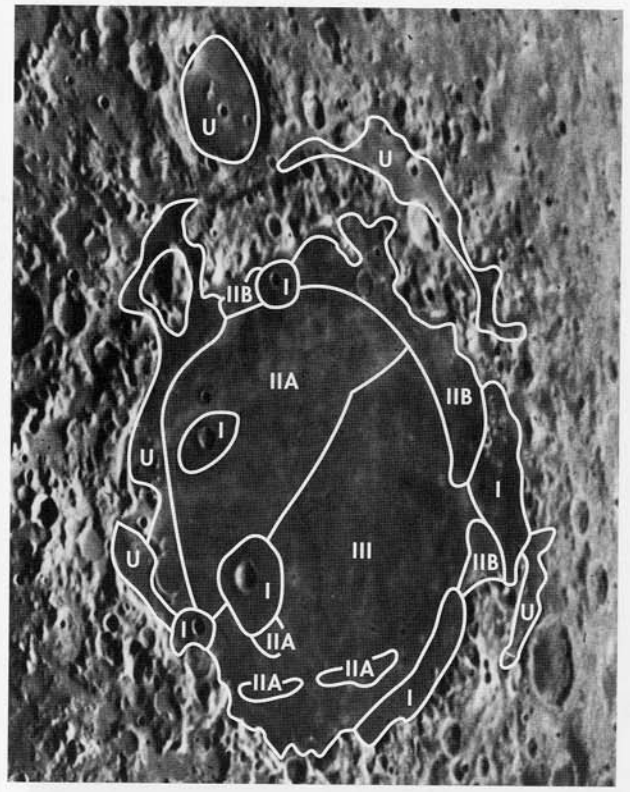
Only when the terminator is very near Crisium can its wrinkle-ridge system be seen. A complete wrinkle ring exists, as well as a north-south ridge that passes through the center of the mare. These ridges are only 100 to 150 meters high. The ring ridges are not just ridges but mark the inward edge of a bench or annular plateau. Along the southern side of the basin, the bench surface is on average about 200 meters higher than the immediately adjacent interior basin surface. In fact, all the Crisium craters that have been breached by mare lava (Lick, Yerkes, and one or two others) are sited on the shallow bench. Presumably, the interior of Crisium is so deep that craters that formed on the original basin floor are completely buried by lava.

Evidence of the nature of the bench and the thickness of lavas was unexpectedly provided by an Apollo spacecraft radar that saw through the surface lava flows to reveal the top of another lava surface about 1.4 km beneath the surface of the mare. At the boundary with the bench on the eastern side of the mare, the discontinuity is abruptly 400 meters closer to the surface. Apparently then the center of the basin dropped downward along a fault scarp. This is one of the few places on the Moon where the amount of basin-fault offset can be documented.

Although Elger and other 19th-century observers sometimes reported a light green tint for Mare Crisium at full Moon, the most important colors are the subtle ones that usually can't be seen visually. Using a telescopic spectrometer that measures light in specific wavelengths, Pieters, Head, Hawke, and their colleagues and students have done spectral mapping of Crisium that reveals the composition of the mare and the highland rocks. Like Mare Serenitatis and other basins, the oldest Crisium lavas are visible only around the edges of the mare. The unimaginatively named "Unit I" lavas (titanium-rich basalts) appear along the southeast bench. These older lavas probably extend completely under the more recent lavas, for they have been excavated by the impacts that formed Picard and Peirce on the west side of Crisium. The boundary detected by the Apollo radar is probably the contact between the buried Unit I and the overlying younger lavas. This example provides a nice case of



The western ridges of Mare Crisium.



Mare units in Crisium: From oldest (I) to youngest (III); U = undivided, and Unit II subdivided into younger (IIA) and older (IIB) flows.

agreement between completely different types of observations — an encouraging sign that we are really beginning to understand how the Moon works.

Unit II is a very-low-titanium, iron-rich basalt that covers the northeast bench of Mare Crisium, as well as the northwest half of the mare. A few arcuate exposures of Unit II occur inward from the bench on the south side, suggesting that Unit II probably extends under the topmost layer. This most recent major outpouring was Unit III lava, a low-titanium (but not very low), iron-rich basalt. Unfortunately, the spectral classifications of the western bench, Mare Anguis, and other marelike material beyond the Crisium massif ring have not been determined.

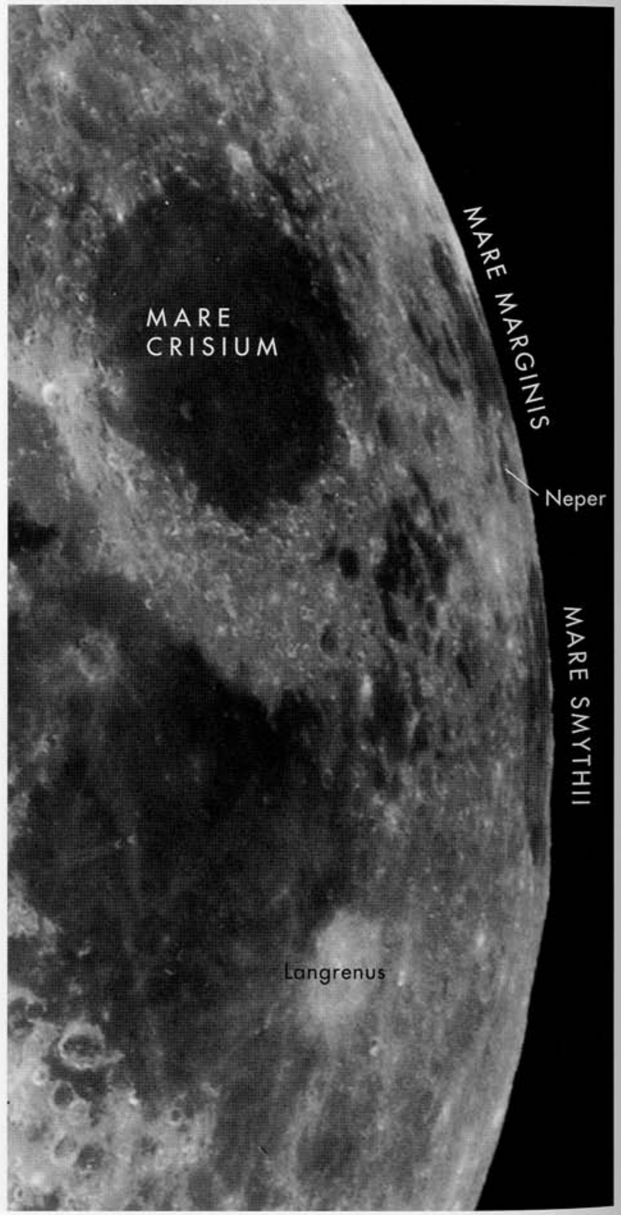
An unexpected test of these interpretations of rock types based on telescopic spectra is provided by samples from Mare Crisium. American astronauts never landed near Crisium, but a pair of Soviet automated landers did. The first of these, Luna 15, was launched at the same time as Apollo 11, apparently in a last-ditch attempt to beat Americans in returning samples from the Moon. It crashed into southern Mare Crisium, but in August 1976 the Soviets tried Mare Crisium again, and this time they were successful. Luna 24 landed near a small bright crater southwest of Cape Agarum, which is fittingly named after a headland in Russia's Sea of Azov. After drilling 2 meters into the lunar regolith, the core samples were transferred to a small capsule and were blasted off the Moon for Earth. These (the last lunar samples that Earthlings have bothered to gather) match the very-low-titanium, iron-rich basalts inferred for Unit II.

We may possess other samples from the Crisium area. A telescopic spectrum of a craterlet on the rim of Eimmart revealed one of the most unusual rock compositions on the Moon. This little crater seems to be very rich in the minerals olivine and pyroxene. Intriguingly, the very first lunar meteorite found on Earth (named Allan Hills 81005, usually shortened to AH 81005) has a similar composition. Perhaps the meteorite is a piece of Crisium material ejected by the impact that formed the little crater. Since AH 81005 has been on Earth for about 170,000 years, and since the travel time from the Moon is negligible, we could pile speculation upon speculation and guess that it is the age of the crater on Eimmart.

BORDER SEA

On the limb directly east of Mare Crisium is a patch of mare that can be seen only under favorable longitudinal libration. This piece of real estate is appropriately named Mare Marginis — it is on the margin of the Moon, where observing conditions are always *marginal.*

In spite of the difficulty, a few conspicuous landmarks will lead you to the site of an interesting feature. East of Mare Crisium are three craters that provide orientation. Condorcet is a large (75 km diameter), partially dark-floored crater, and the twins Hansen (40 km) and Alhazen (38 km) are nearby to the northeast. East of these three guardians, toward the limb, are two patches of very dark mare. This material is noticeably darker and clearly separate from the main body of Mare Marginis. Amazingly, it has no name. Whitaker likens these slivers of mare to the Cheshire Cat in *Alice's Adventures in Wonderland* — no cat, just the smile! So, by the powers vested in me as the author of a book about the Moon, I will follow the precedent set by other Moon writers and name the features Lacus Risus Felis (Cat's Smile Lake). Of course, the International Astronomical Union, which has the official prerogative to name features, may not be amused.



The eastern-limb maria Marginis and Smythii.

Beyond Lacus Risus Felis is Mare Marginis proper. It is about 200 km long from north to south and is clearly lighter hued than Mare Crisium. In fact, based on the high number of superposed impact craters, Marginis is believed to be one of the oldest maria on the Moon. Marginis mare lavas almost completely fill a low spot and also flood several craters. The most obvious is the 137-km-wide Tycho-like crater Neper. At full Moon an elongate central peak stands out as a bright ridge in a sea of gray. When the Sun is setting on Neper, telescopic observers are treated to an oblique view of an impact crater with its peak shining like a beacon in the inky darkness.

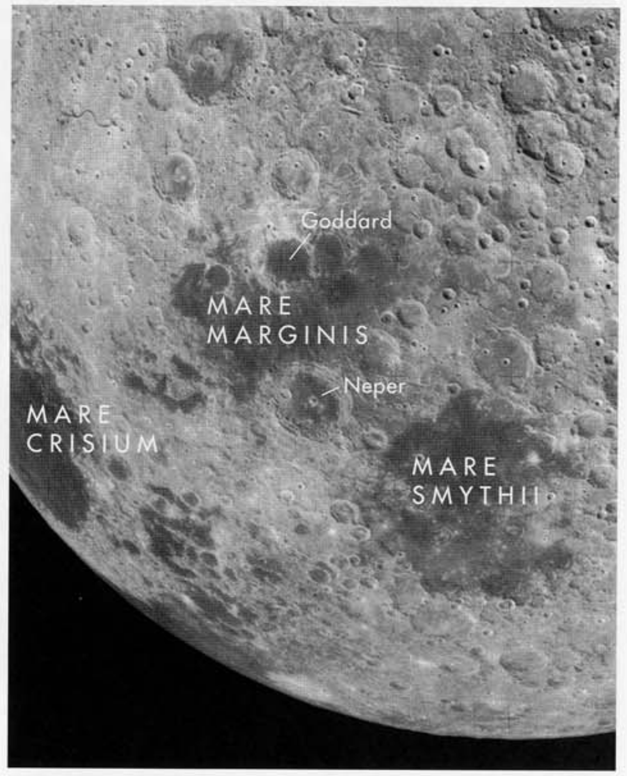
On the north side of Marginis are two other lava-flooded craters, the largest and closest to the limb being Goddard. This 90-km-wide crater is unremarkable except for a bright spot immediately to its north. Unlike virtually all similar features, this is not simply the halo of a bright crater; rather, it is the Earthward end of a set of bright swirls that extend from the lunar far side. The origin of the swirls is mysterious; the only other near-side example is Reiner Gamma in Oceanus Procellarum. The swirls around Marginis are strongly magnetized and lie exactly opposite the Orientale basin on the western limb of the Moon. Coincidence? Possibly seismic energy or magnetization was somehow concentrated antipodally during the basin's formation. Maybe there is a more local explanation. These swirls seem to merge with the ejecta blanket of the 12-km-wide far-side crater Goddard A. Lunar scientist Schultz has suggested that these swirls could be related to a comet impact that may have formed that crater. Nobody knows, but at least you can see part of a mysterious feature that is nearly on the lunar far side!

A PRIVATELY HELD MARE

On the Moon there are two maria named for individuals. Mare Humboldtianum does, of course, commemorate the famous 19th-century German explorer and naturalist Alexander von Humboldt. Mare Smythii pays homage to William Henry Smyth, a relatively obscure British astronomer and admiral in the Royal Navy. Nonetheless, the lunar Smythii is neither dead nor dull and may have a future as a site for a lunar base.

Unlike Mare Marginis, Mare Smythii is definitely contained in a multiring impact basin. A few hours after the full Moon in June 1994, I observed the shadow cast by the arcuate rim of Smythii as it fell on the mare floor. The inner basin ring that I observed has a diameter of about 350 to 400 km. Topography derived from Apollo and Clementine data indicates that the floor is deeper than anyone expected, 6 to 8 km below the highest rim. Smythii is also one of the lowest maria on the Moon, lying 4 to 4.5 km below the average lunar surface. In fact, when librations put Smythii exactly on the limb, it produces an obvious flattening, as if someone has sliced off that little bit of the Moon. Smythii also has a *mascon* (*mass concentration* — a mass of relatively dense material beneath the lunar surface), probably associated with a rise of the dense lunar mantle under the basin.

When the Sun is high, parts of the mare floor appear darker than others. This suggests that there are two different ages for the Smythii mare. The area with an intermediate albedo has a relatively large number of superposed impact craters, indicating that it is relatively old. The northern part of the floor has darker mare and formed more recently, perhaps only 1 or 2 billion years ago. Thus, one of the oldest and one of the youngest mare deposits occur in the same basin. Curiously, the very youngest mare regions on the Moon are widely separated — in Mare Smythii and in Oceanus Procellarum.



Maria Smythii and Marginis as viewed by Apollo 16.

Because Smythii is geologically diverse and situated on the lunar equator and on the limb, Spudis and University of Arizona geologist Lonnie Hood have proposed that it would be an excellent location for a lunar base. Landing sites near the lunar equator require minimum-energy trajectories (that's why most of the Luna and Apollo sites were at low lunar latitudes). Any future Moon base will have to be on the lunar near side to communicate with Earth, but radio astronomers would prefer it to be built on the far side for access to a radio-quiet sky. Spudis and Hood suggested that the solution might be to have the main base at Smythii, right at 0° latitude and 90° east longitude. Because of the Moon's 8° libration in longitude, it would be necessary to have a communication outpost at about 82° east for continuous contact with Earth. However, to keep radio telescopes from being contaminated by reruns of *I Love Lucy*, an observatory outpost would have to be 8° over the limb on the far side.

CLEOMEDES NORTH

North of Mare Crisium is a section of the Moon that lacks any recognized crater celebrities. Some large- and medium-sized features are minor points of interest, but the region is generally unspectacular. Why is that? I think it's mostly because there is no basin with its associated mountain ranges, mare lavas, domes, and rilles. This is a broad borderland between the weak, outer rings of Crisium and those of Humboldtianum. A good map will serve to identify the craters. But to preempt the wrath of reviewers who might harp on any little omission, let's at least run through the main players.

Perhaps the best-placed crater for telescopic observation north of Crisium is Cleomedes. This 125-km-wide crater has a fairly smooth, marelike floor with a ridge remnant of its cental peak. With very low illumination a small dome on the northern portion of the floor can be seen to be cut by a rille, and a short wrinkle ridge exists in the south. With its floor-covering lava, this is a miniature mare. Presumably the lava rose up basin fractures associated with the 635-km ring of Crisium that passes under Cleomedes.

Just to the north is Burckhardt, a crater with two large ears (look to see what I mean), and Geminus (85 km), a fine example of a Tycho-like crater except that it lacks rays. Next is Messala, the same diameter as Cleomedes but much older and more heavily battered by secondary and other craters. In the USGS relative-age scheme, Cleomedes is Nectarian, Messala is pre-Nectarian, and Geminus is Eratosthenian.

Another large Nectarian-age crater is Gauss (177 km), northeast of Berosus and Hahn. Gauss would be a fascinating telescopic sight if it weren't situated at 80° east longitude. This proximity to the limb robs us of a clear view of a light, smooth floor circled and cut by rilles.

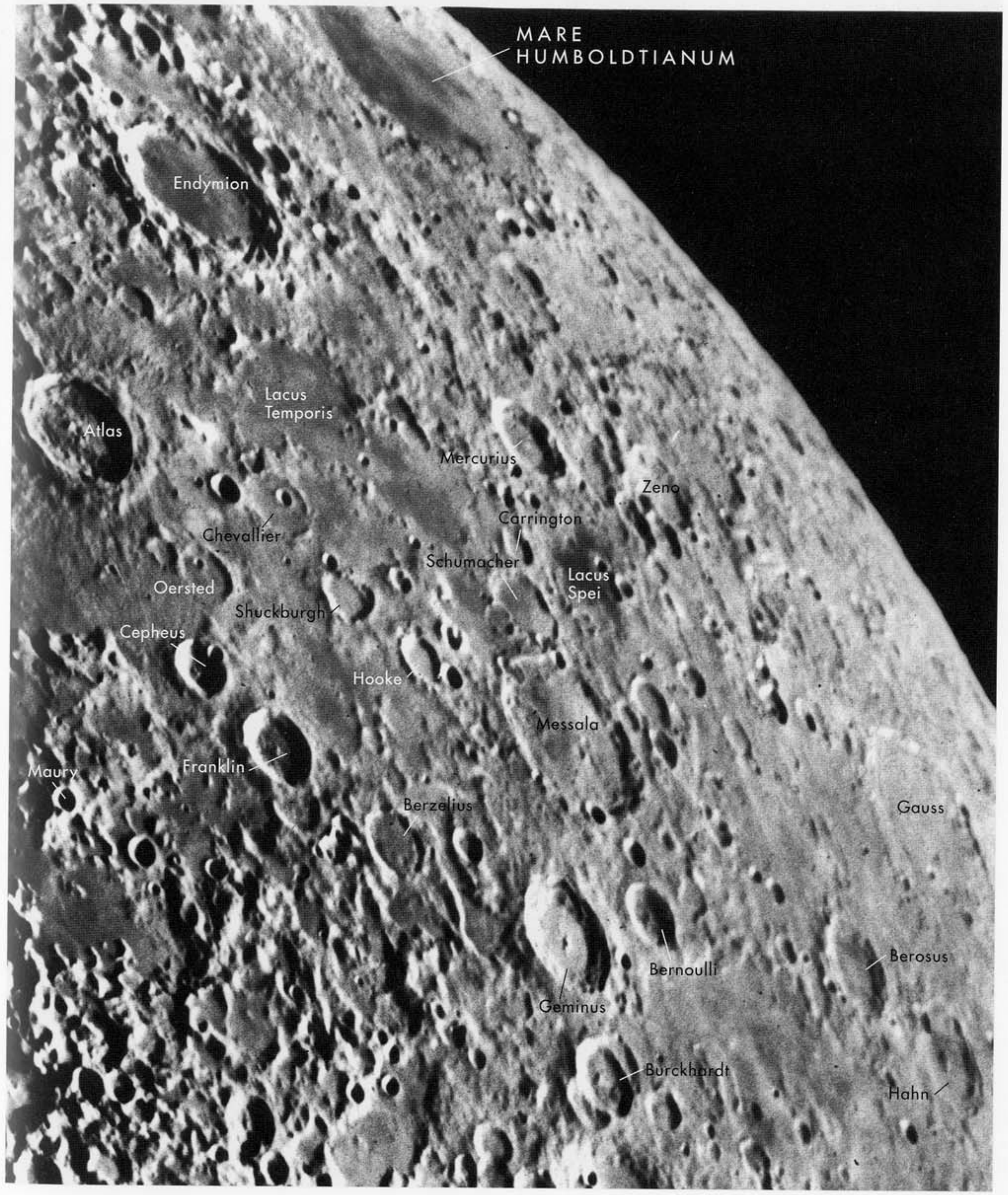
At full Moon, examine the region stretching from Lacus Mortis and Mare Serenitatis toward the limb. You'll see that it is splashed with patches of dark and grayish hued material. Typical examples are spots on crater floors (Hercules, Franklin, Bernoulli, Berosus, Hahn, Messala, Gauss, and Mercurius) and intercrater splotches such as Lacus Spei, the Lake of Hope (does it hope to grow into a mare?). Hawke points out that some of these spots are volcanic dark halo craters, like those in Alphonsus, but others are mare patches. Perhaps this region will become recognized as a cryptomare, a place where ancient dark mare material has been lightened by the dust and rays of later craters and basins.

A NEW CRATER?

Back beyond Gauss and even Riemann, beyond the regions that librations ever reveal, is one of the most talked-about craters on the lunar far side. Giordano Bruno is a relatively bright 22-km-diameter crater that is considered to be of Copernican age in the USGS classification system. Copernican-age features are younger than about a billion years old, but Giordano Bruno may be less than a thousand years old! The evidence is contained in a medieval chronicle from southern England. Just after sunset on June 18 or 19, 1178, five monks observed that the "upper horn of a new moon split and from the division point fire, hot coals, and sparks spewed out." Jack Hartung suggested that the flash and sparks were from the impact that formed Giordano Bruno.

Few scientists accept Hartung's view, principally because a crater this large should form only once every million years. Thus, there is only a 1-in-1,000 chance it would happen during the last thousand years. But the fact that an event is unlikely doesn't mean it can't happen.

Hartung also points out that other remarkable events have occurred near mid to late June. The famous explosion of some space material near the Tunguska River in Siberia on June 30, 1908, is one example. A cluster of small impacts in late June 1975 detected by seismometers left on the Moon by Apollo astronauts is another apparently rare event. Arguments have been made that all these June events are related to the Beta Taurid meteor stream, Comet Encke, and the Earth-crossing asteroids 2201 Oljato and 1978 DS. All these events and existing space debris are proposed to be the surviving remains of a single large comet that is progressively disintegrating as it travels through the solar

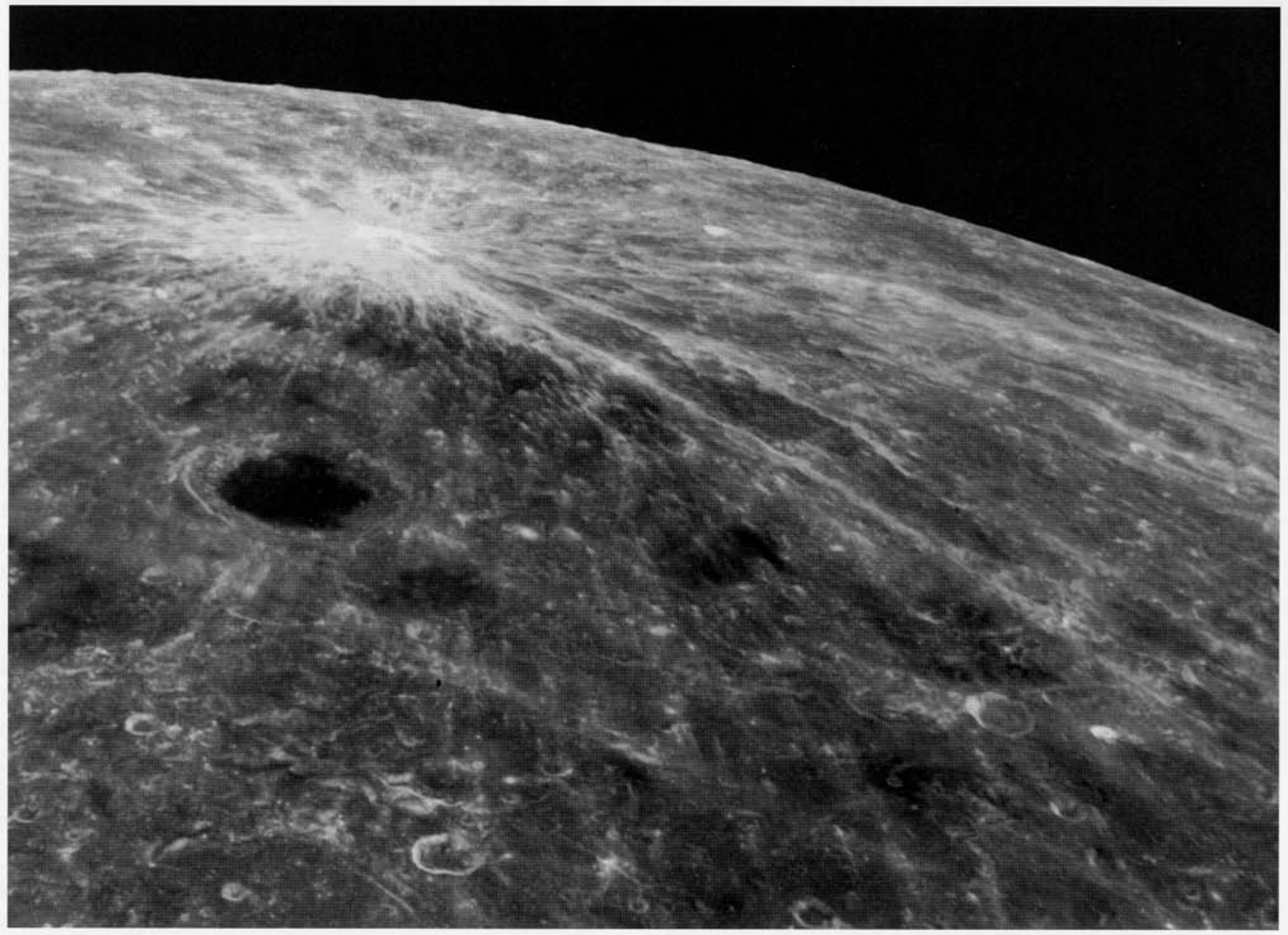


The lunar limb south of Mare Humboldtianum.

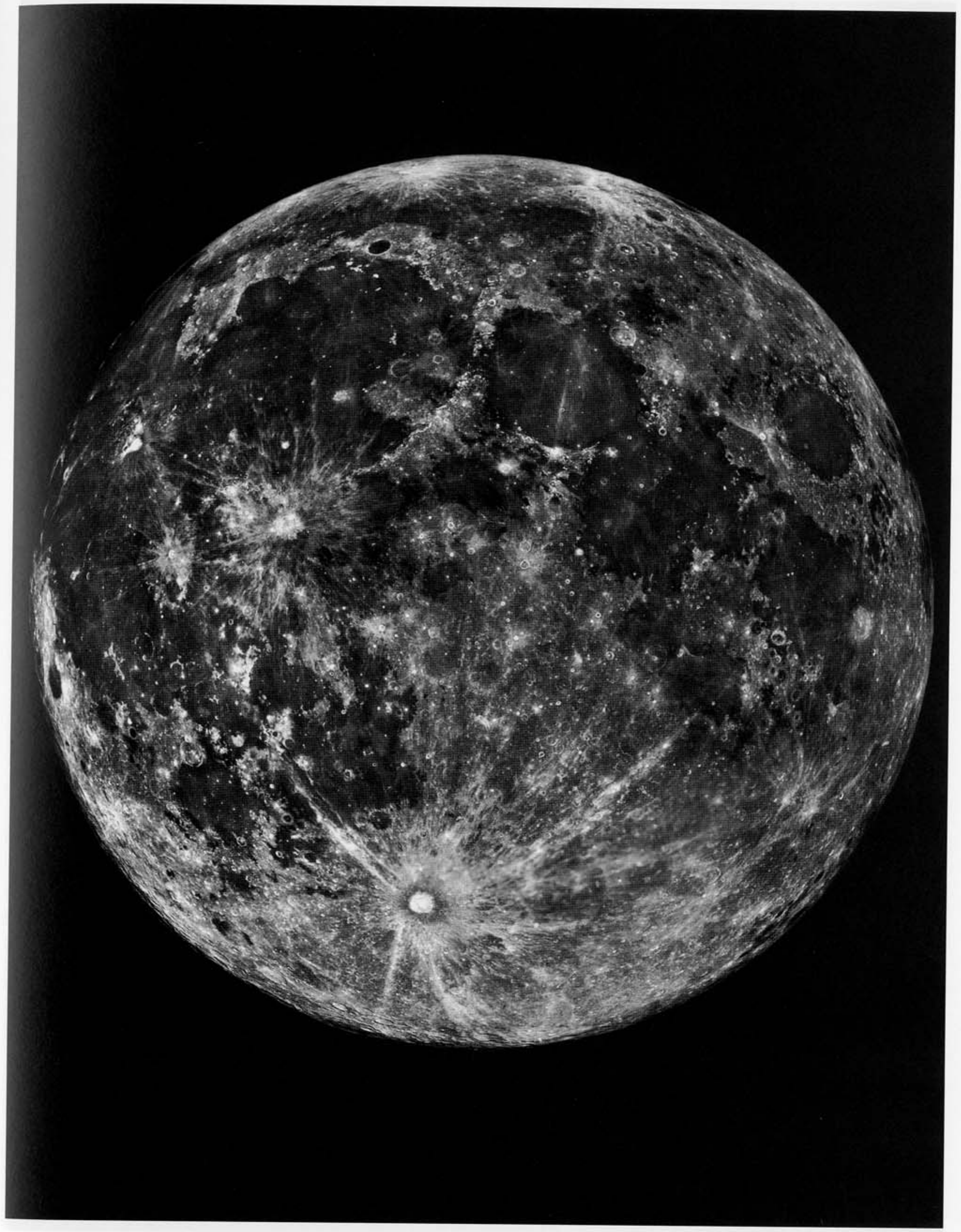
system. Perhaps Giordano Bruno marks the final resting place for the largest fragment of this putative comet.

There is other evidence supporting a young age for Giordano Bruno — the Moon is ringing like a gong that has recently been struck a mighty blow. Precise measurements of laser reflectors left on the Moon by astronauts show that the ringing must have been induced relatively recently and is consistent with an A.D. 1178 impact.

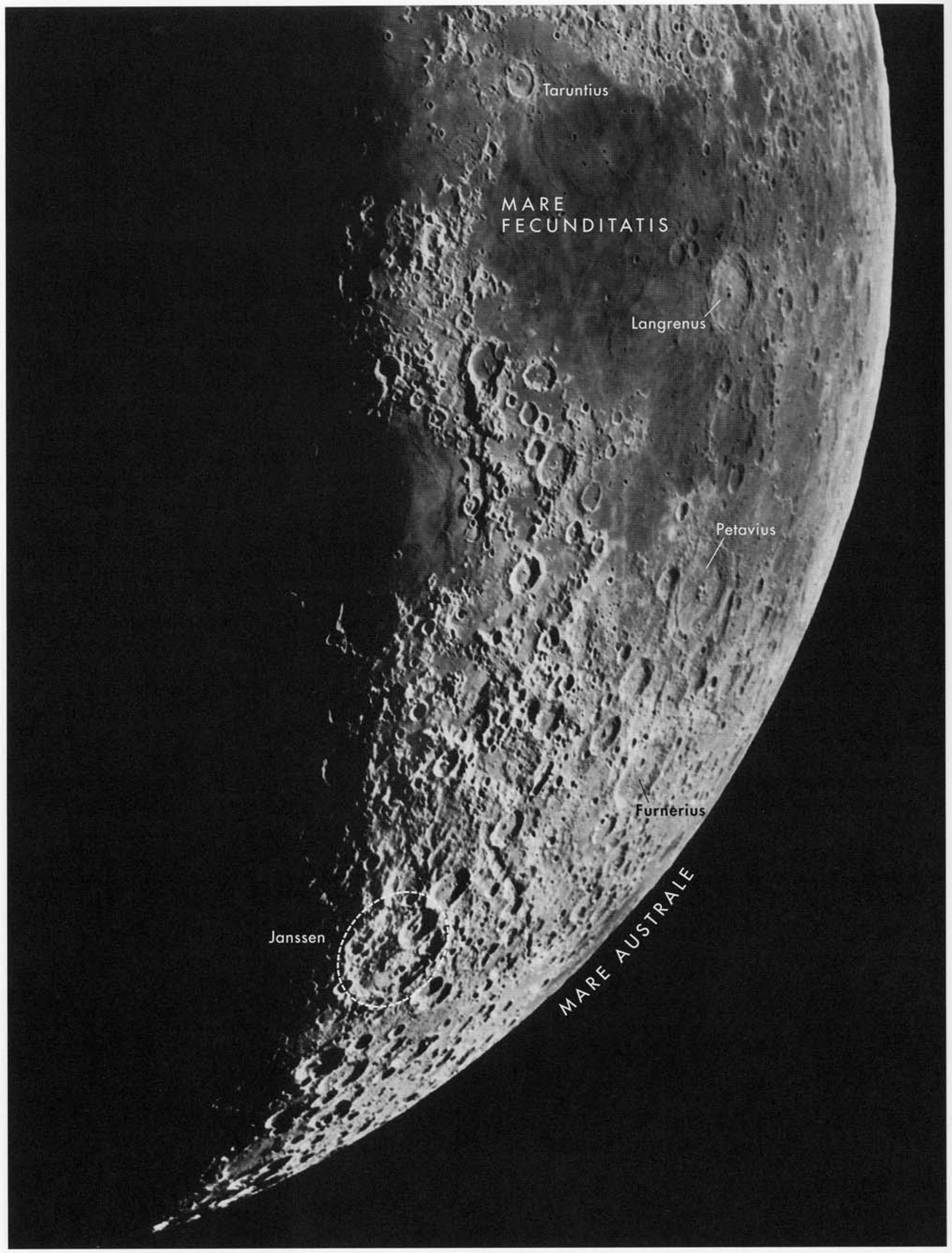
So as you prowl the limb near Crisium, imagine the slowly quieting peals of a ringing Moon, remember the incredible eyewitness story of a group of long-forgotten medieval English observers, and then snap back to the generally accepted explanation that the monks simply witnessed a meteor burning up in the Earth's atmosphere on a trajectory that carried it in front of the Moon. This theory is consistent with the lack of reports of lunar meteorites raining down on Earth in A.D. 1178. I still want to believe Hartung's innocent tale of recent bombardment simply because every time I look up at the Moon, I long to see the bright flash that would signify the formation of a new crater!



The (perhaps very) young impact crater Giordano Bruno as photographed by Apollo 8.



Ray craters like Giordano Bruno tend to be the freshest impact features. The best time to view the Earth-facing examples of young, large craters is during full Moon, when Tycho, Copernicus, and Proclus stand out boldly from the surrounding terrain.



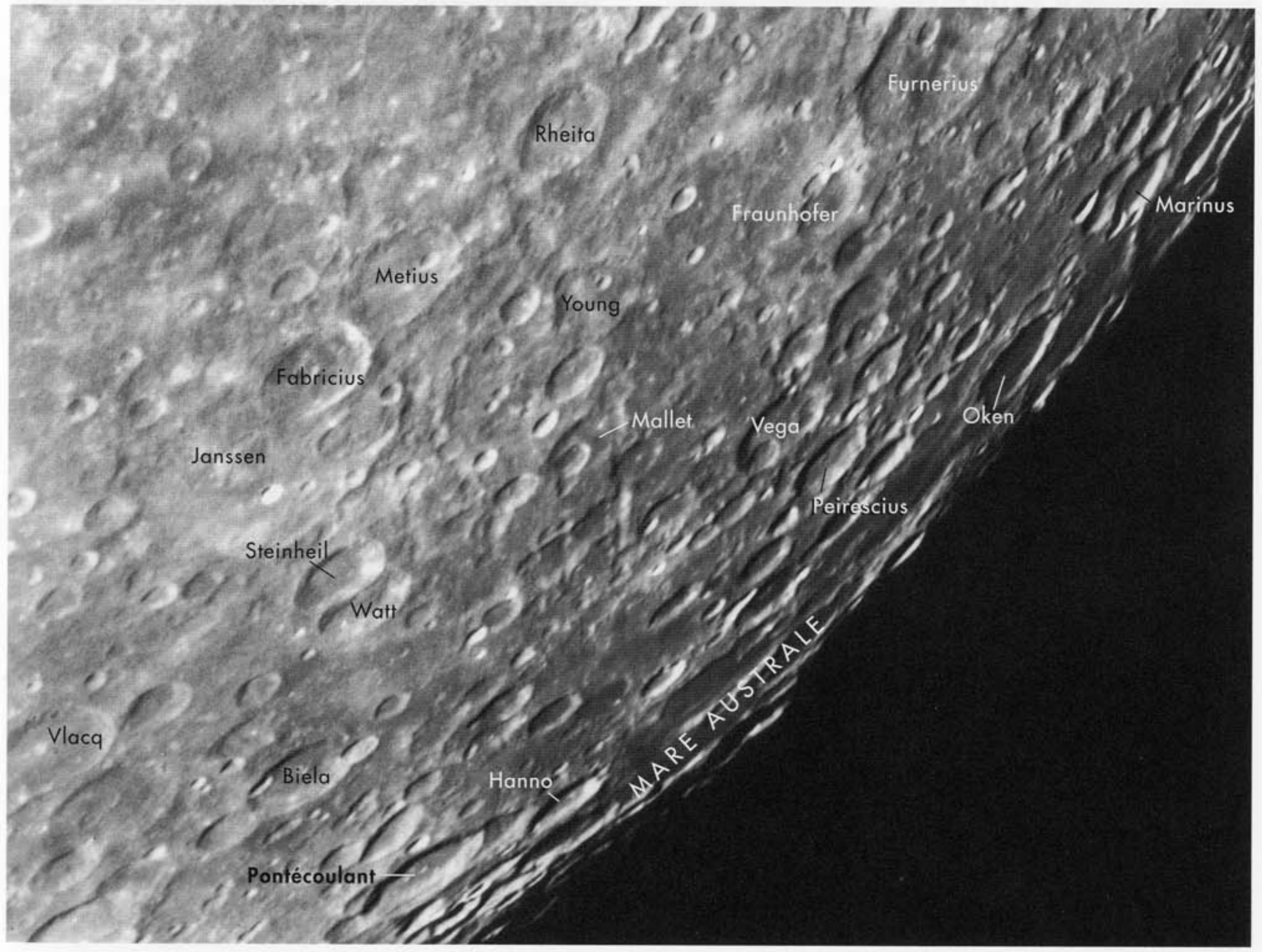
The Moon's southeast limb.

11

The Southeast Limb

The southeast limb of the Moon is almost like another planet. It lacks the clean distinction between mare lava and highland that characterizes much of the rest of the Moon, having instead a series of widespread mare deposits cluttered with old impact craters. This pattern provides insight to the possible fate of completely obliterated impact basins. The region also includes a number of large craters such as Furnerius, Petavius, Langrenus, Humboldt, and Janssen, as well as some of the best examples of secondary crater chains on the Moon. And to avoid devoting an entire chapter to a relatively featureless mare and arguably the most ill-defined basin on the lunar near side, Mare Fecunditatis will also be described.

Looking at various lunar atlases it is clear that the extreme limb of this area is much less frequently imaged than any other limb region of the Moon. Perhaps that is because sunrise occurs here when the Moon is a thin waxing crescent, often hanging low in the evening sky; and sunset occurs at full Moon when glare often discourages observers. But after our exploration of Mare Crisium, we know better!



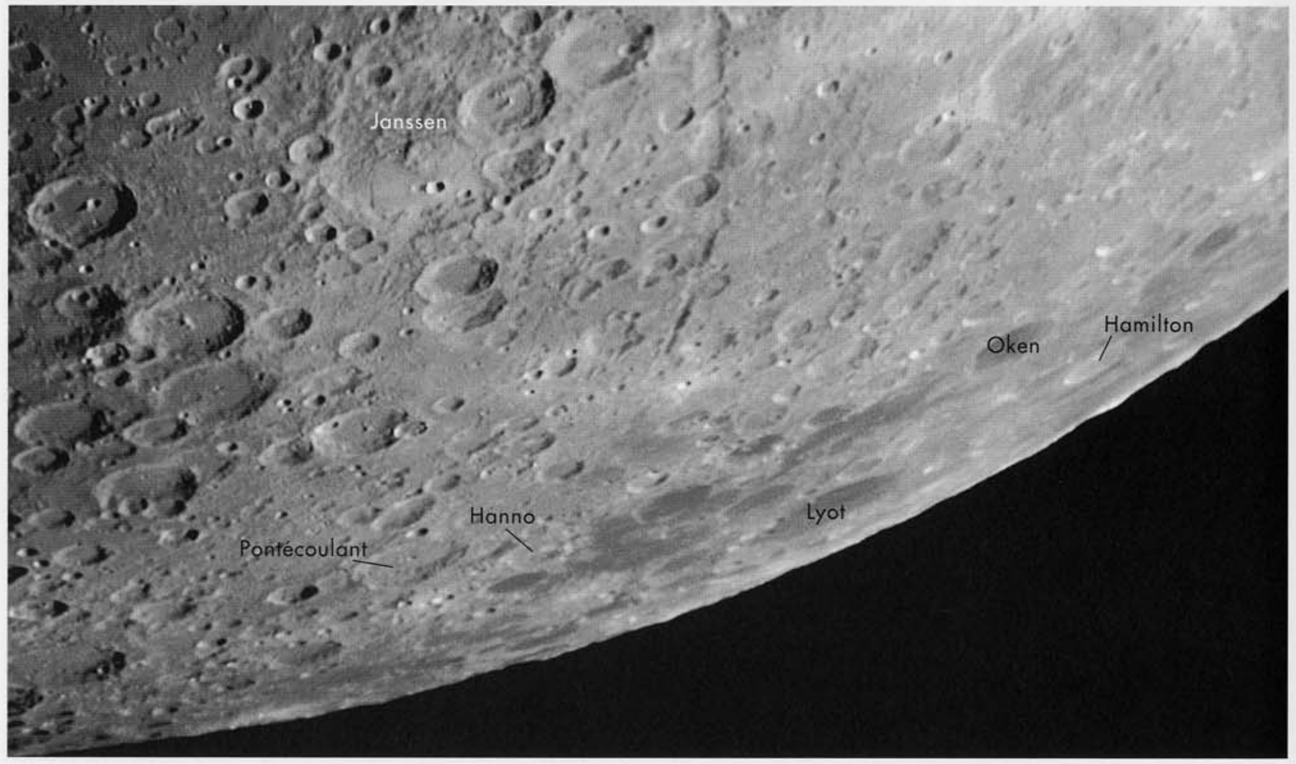
Mare Australe under low Sun conditions.

MARE AUSTRALE BASIN

Let's begin with the hardest to observe but most interesting feature of this area. Mostly the southeast limb region is nondescript, but when librations both in latitude and longitude tilt the area into view, a wide expanse of mare patches, collectively named Mare Australe, becomes visible. The remarkable nature of this "Southern Sea" was not understood until the Lunar Orbiter photographs of the region were examined by USGS scientists Desiree Stuart-Alexander and Keith Howard. They found that the mare patches on the floors of nearly 200 craters defined a circular area about 900 km in diameter, presumably delineating an ancient impact basin. Jim Whitford-Stark, then a graduate student at Brown University, realized that the putative Australe basin was approximately the same size as the Orientale basin on the western limb but was as different as could be imagined. While Orientale, the youngest large basin on the Moon, has well-defined concentric rings and massive ejecta deposits outside the rings, Australe has neither obvious ring structures nor detectable ejecta.

Undeterred by a lack of traditional evidence, Whitford-Stark elaborated on the suggestion by USGS scientists that Australe was an ancient impact basin and deduced that its history was likely different from any other known lunar basin. He proposed that very early in the Moon's history a multiring basin was formed, but because this was still a time of intense bombardment, the basin's original multiring structure was completely destroyed by later craters. A few hundred million years later, lavas rose up through basin faults and erupted onto the floors of many of the impact craters within the basin. Some of these craters were completely submerged by lavas; others were only partially filled. Australe provides a model of how the most ancient basins would be battered beyond recognition unless their low spots were later filled by mare lavas.

All this speculation based on Orbiter photographs of a feature partially out of view on the far side of the Moon doesn't belong in this book unless we can see it from Earth. Well, it's challenging, but we can. Like Orientale on the southwest limb, various aspects of Australe can be detected under high and low angles of illumination, but only during favorable librations. Under a high Sun, the basin gives itself away by its very dark surfaces; when the Sun is low, the smooth crater floors become conspicuous. You have found Australe when you see the craters north and east of the normal craters Pontécoulant and Hanno, which have low rims and dark floors. The prominently rimmed but dark-floored Oken crater (72 km) should be identifiable much of the time, but nearby Lyot (140 km) at 84° east longitude is quite challenging!



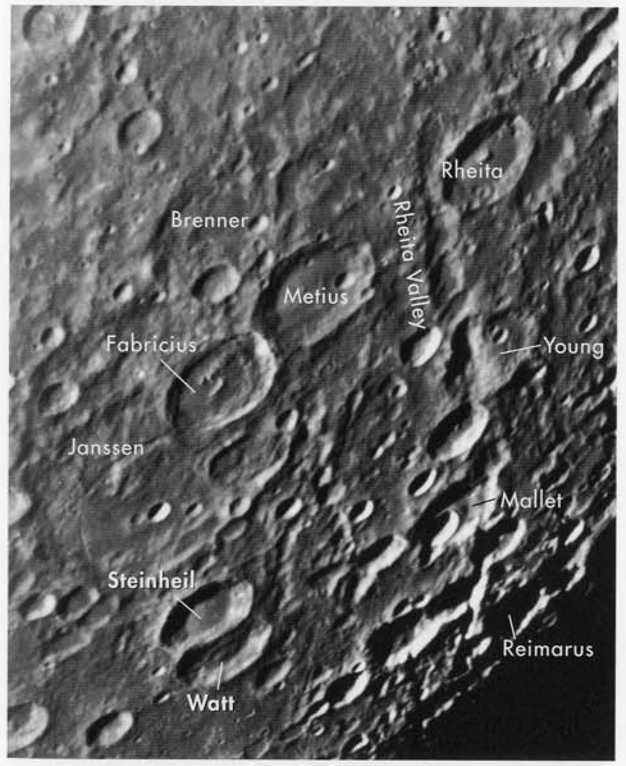
Mare Australe.

Inland from the dusky shores of Mare Australe is Janssen, a large (190 km) and unusual crater. Janssen doesn't look right — it bulges outward on its northwest rim. The key to understanding its shape is to notice that Janssen sits on top of an unnamed ancient ring that is about the same size. In turn, Janssen is overlapped by Fabricius, a rather fresh-looking, 78-km-wide crater with an elongated central peak and a peculiar massive ridge on its floor. Fabricius may explain one of the unusual features of Janssen. The large and irregular mountainous plateau near the center of Janssen might be a giant slump block dislodged from Janssen's rim by the Fabricius impact. Another example of this kind of landslide fills the floor of the nearby crater Watt — Steinheil is the culprit. But how do we explain the broad cleft or rille that slices through Janssen? This is the only major rille in the highlands, and its origin is a mystery.

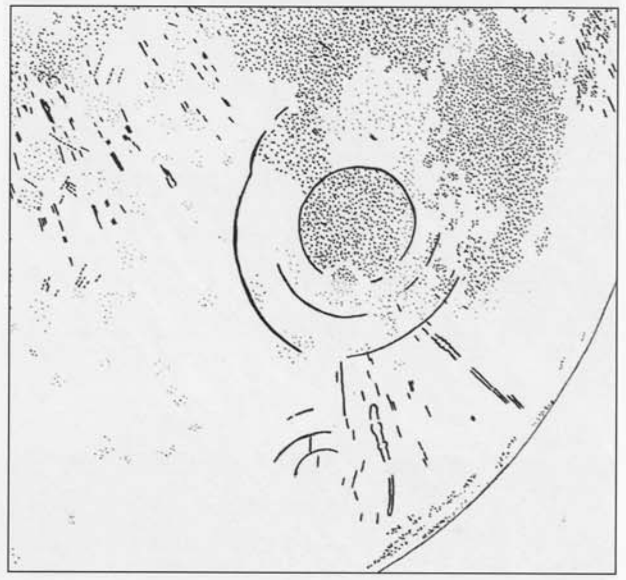
Next to Janssen is another much larger trough that we do understand, more or less. Find the crater Rheita, a typical, somewhat degraded impact crater that measures 70 km in diameter. Rheita is famous for providing its name to one of the most spectacular troughs on the Moon. The Rheita Valley is composed of more than a dozen overlapping craters that stretch away in a 330-km-long line toward the Moon's southeast limb. Shortly after the Sun rises above the Rheita Valley, its eastern walls cast a line of shadows that neatly define this linear feature. Although most early Moon mappers failed to see the connection, Baldwin realized that the Rheita Valley is simply the grandest ("almost unbelievable") of an array of great grooves radiating from the Mare Nectaris impact basin.

If you look closely you may notice that between the craters Young and Mallet the Rheita Valley changes direction, abruptly bending toward the south. The valley's character also changes, becoming a series of small craters that lack common walls. Always observant, Baldwin suggested that this narrow valley and others nearby were not radial to Nectaris and might therefore "indicate another great mountain-bordered mare forever hidden from earthbound eyes." The master was apparently wrong this time, for Lunar Orbiter pictures failed to reveal his putative back-side basin. Instead, USGS maps show that the narrow extension of the Rheita Valley is well within the field of Nectaris's secondary craters and textured terrain. In fact, Hartmann showed that the narrower Mallet Valley, as he called it, is exactly radial to the center of Nectaris, and the Rheita Valley is only tangential to the basin's inner ring. Thus the change in direction and shape of the Rheita–Mallet valleys must be due to some peculiarity of the distribution of Nectaris ejecta.

Merely using the word "ejecta" gives away the modern explanation of Rheita and the other valleys in this area, but reaching this conclusion wasn't easy. Baldwin and Urey believed that the great valleys radi-



Rheita Valley region.



William Hartmann's sketch of valleys radial to the Nectaris basin.

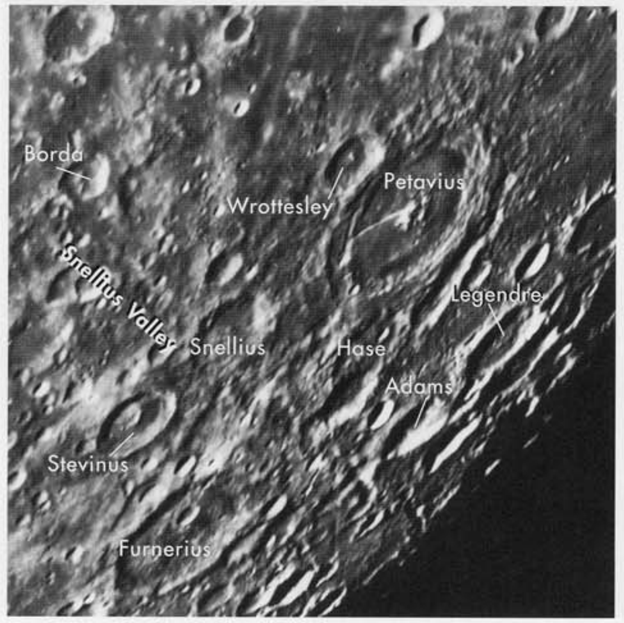
ating from basins were cut by flying ejecta. Hartmann found much evidence indicating that the crater-chain valleys were tectonic — that is, they formed by subsidence along radial fractures formed during basin impacts. But evidence from the well-preserved Orientale basin on the lunar far side strongly implies that megacrater alignments such as the Rheita Valley are essentially just secondary crater chains — monstrous versions of the lines of small secondaries radiating from young craters like Copernicus. The region around Janssen has emerged as a well-preserved museum of grooves and secondary craters formed by ejecta from the Nectaris impact basin.

Continuing northward past the Rheita Valley is a longer but more subtle crater chain that also radiates from Nectaris. This is the Snellius Valley, which cuts across its namesake crater as it traces a diagonal path between the two large craters, Furnerius and Petavius. Hartmann named this valley and described it as being composed of *craterform* (having the approximate shape of a crater) segments that make a line about 800 km long. But what accounts for the lack of normal impact-crater morphology? The craterform pits probably formed as overlapping secondary craters made by low-velocity ejecta thrown out during the Nectaris impact event. You can see the beginning of the Snellius Valley near the crater Borda, then continuing through Snellius toward the limb. At its extreme southeastern end the valley jumps sideways and continues along a parallel course. Geologists call this type of offset *en echelon* because it drives astronomers, who don't know what the word means, crazy!

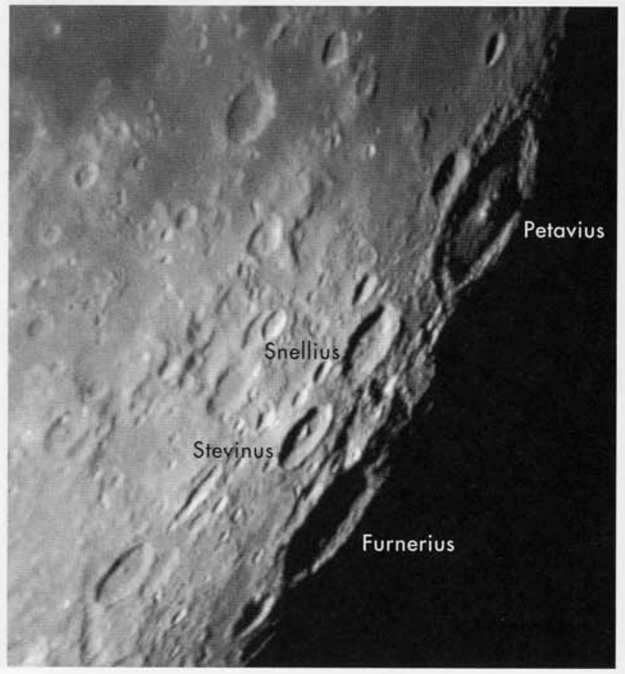
My first published discovery resulted from observations I made of the Snellius Valley. I was using a friend's 12.5-inch reflector and had optimal lighting that brought out the interconnections of the individual segments of the valley. I realized that another, much better defined but narrower valley cut obliquely across the Snellius Valley near Furnerius. The excitement of this discovery helped cement my fascination with the Moon. I suppose that my narrow valley is a secondary crater chain, but I don't know where the primary crater is — this valley isn't radial to Petavius or any obvious crater.

FURNERIUS, PETAVIUS, HUMBOLDT, AND TARUNTIUS

The large craters on either side of the Snellius Valley not only help pinpoint the valley's location but also are interesting in their own right. The somewhat battered crater Furnerius (125 km) is an excellent example of a pre-Nectarian-class crater. In the USGS age-classification sequence, the oldest features on the Moon are those that formed before the impact of the Nectaris basin, an event that occurred about 3.92 billion years ago. Furnerius is clearly older because Nectaris ejecta roughens part of its floor. And the crater has a generally subdued appearance, with a rounded rim, poorly defined terraces, and no central peak. But its floor is remarkable. It contains a smooth, marelike deposit. Under a high Sun, the floor material is of intermediate darkness, like that of an older mare surface. This isolated patch of lava is perhaps an outlier of similar-hued material in Mare Australe. Spectral mapping of the Moon by the Clementine spacecraft revealed other small patches of mare in highland regions, provoking new questions about why mare lavas erupted far from basins.



Snellius Valley.



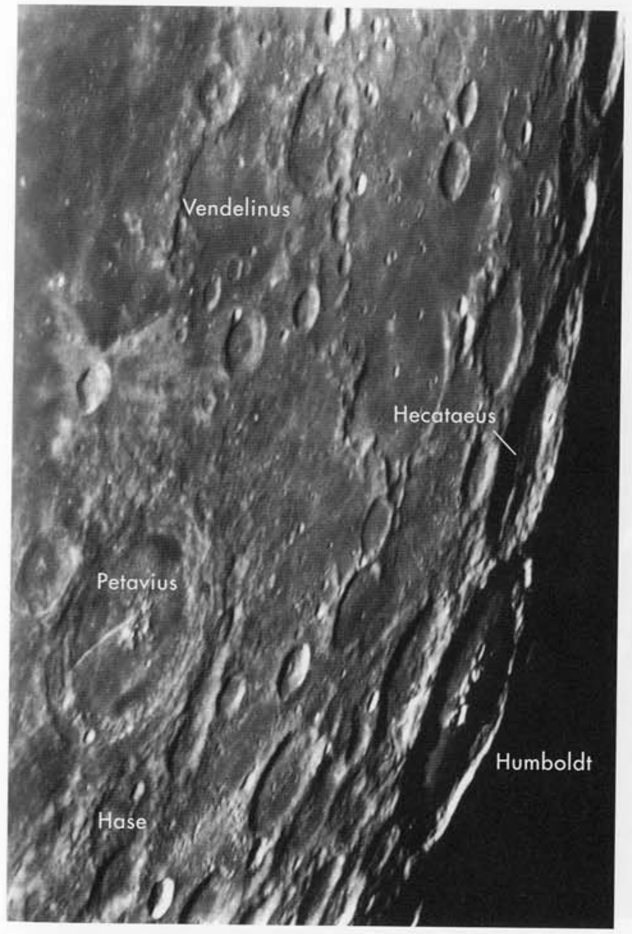
The terminator positioned near Petavius and Furnerius.

North of Furnerius is Petavius, a much more conspicuous and interesting crater that steals attention. Compared to Furnerius, Petavius is larger (177 km), younger (lower Imbrium, in USGS parlance), and, in addition, has remarkable floor features. Even a 60-mm refractor will reveal the giant cleft that emanates from the massive central peak complex and cuts across the floor toward the southwest rim. With a 4-inch aperture and good seeing, a variety of other straight and squiggly rilles can be glimpsed. The most remarkable of these is a rille that curves around the inside of Petavius's west wall, then climbs out of the crater at its south rim and disappears in Hase, a derelict neighboring crater.

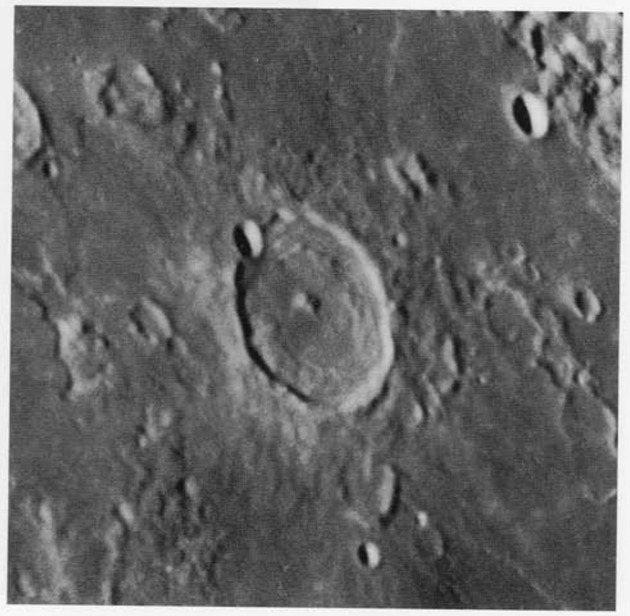
Petavius is one of the most visible examples of "floor-fractured craters" (FFCs) — a class of large craters whose original impact floors have been modified by volcanic activity and fracturing. Almost all FFCs are big and occur near the borders of maria and their enclosing basins. Once the idea that FFCs were entirely volcanic had been dismissed because of their obvious similarity to normal impact craters, the story of how they formed emerged. Schultz and his Brown University student Robert Wichman proposed the widely accepted interpretation that the appearance of FFCs is due to ponding of upward-rising magma under the crater, which lifts up the original floor, causes radial and concentric fractures, and sometimes allows lava to leak onto the crater floor.

Another beautiful example of a FFC is Humboldt, a bigger brother of Petavius, with floor fracturing and dark volcanic spots. But because it is so close to the limb, you will be lucky to find this 207-km-wide crater, much less see its floor. With its line of peaks and a diagonal of dark mare material on its near floor, Humboldt would be regarded as one of the most spectacular craters on the Moon were it better placed. Look limbward of Petavius when the libration conditions are favorable and you may just glimpse it.

A final FFC in this area is Taruntius, situated where the northern edge of Mare Fecunditatis merges with southern Mare Tranquillitatis. Taruntius is an obviously fresh impact crater — it has secondary craters and debris that radiate across surrounding maria. Its faint rays mark Taruntius as a Copernican-age crater. But something's wrong. With a diameter of 56 km, Taruntius should be about 2.3 km deep, but its depth is only 0.4 km. And a prominent ring of hills and tiny rilles circles the central peaks. These are all the characteristic signatures of a floor-fractured and uplifted crater. Schultz and Wichman attributed the uplift as



Petavius and Humboldt.



Floor-fractured crater Taruntius.

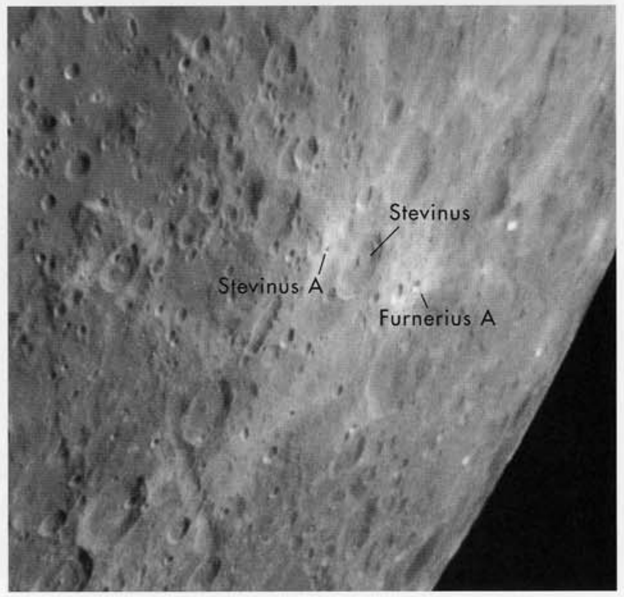
due to a 1.9-km-thick pond of frozen magma (a *laccolith*) only a few kilometers beneath the crater floor. The intriguing thing is that Taruntius's youthful age implies that magma rose near the surface in Copernican time. Under a high Sun, you can see two dark patches near Taruntius's central peak, so maybe lava or ash did erupt on to the surface a billion years ago. If so, this episode would have been one of the last gasps of volcanism on the Moon, making Taruntius a strong candidate for future exploration.

Two small craters flanking Stevinus are the sources of the most conspicuous ray systems on this quadrant of the Moon. The largest and easiest to see is Furnerius A, a 12-km-wide crater. Interestingly, the rays from this crater may stretch over 2,000 km across the lunar surface — surely some kind of record for a crater of such modest size. The second ray source is Stevinus A, an even smaller crater that is only 8 km wide.

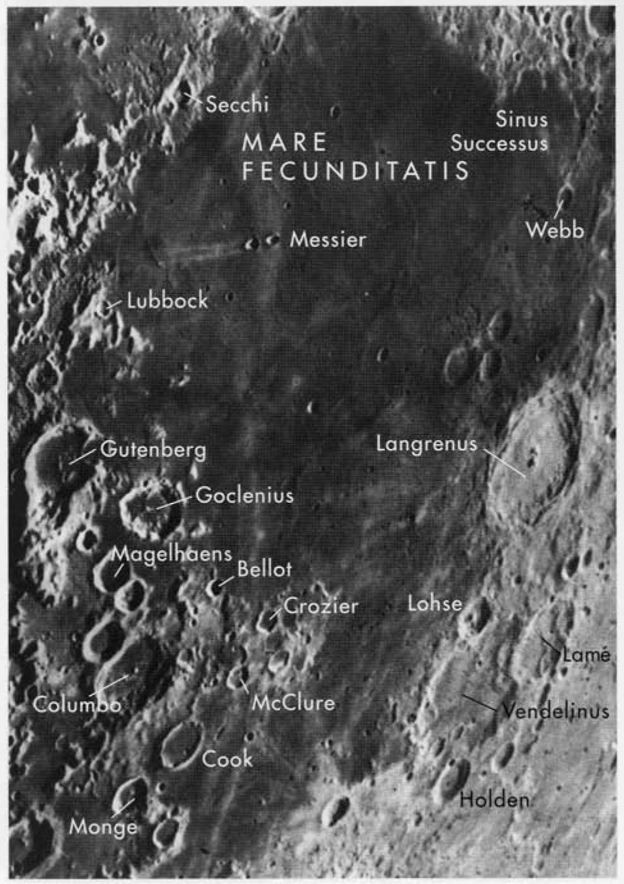
MARE FECUNDITATIS

In the naked-eye pattern known as the Lady in the Moon, Mare Fecunditatis is the bun on the back of her head. This expanse of mare material probably lies in the depression of an ancient impact basin, but there is little geologic evidence for it. In 1971 Hartmann and I listed Fecunditatis as the oldest of 31 lunar basins and estimated a diameter of about 1,000 km, based on the longest axis of the mare. We also noted that Fecunditatis has concentric wrinkle ridges that can be fit to an inner ring about 475 km wide. This ratio of inner to outer ring diameters is close to the magic value of 0.5 that is observed in impact basins throughout the solar system. In truth, as I look at the old photographs that Hartmann and I studied 25 years ago, I can't really see that the wrinkle ridges make a ring. However, new data from the Clementine spacecraft provide evidence for the reality of a basin at Fecunditatis. Topographic measures reveal that the floor of Fecunditatis is 4 km lower than the surrounding terrain, and the lunar mantle rises 15 km under the basin — similar to the mantle uplifts under well-defined basins such as Imbrium.

The surface of Fecunditatis is relatively uninteresting. The cluster of three craters near Langrenus and many of the smaller craters on the mare appear to have very low rims, as if late mare lavas flowed around the craters and partially submerged them. Only a few small features suggest source regions for the Fecunditatis lavas. Near the northwest shores of the mare are five small patches of dark material, best seen under a high Sun. Three of the patches, located near the craters Secchi and Lubbock, are centered on short, narrow depressions that are probably volcanic vents. I would guess that these patches are dark mantle material composed of volcanic ash.



Bright rays radiate from two small craters near Stevinus.

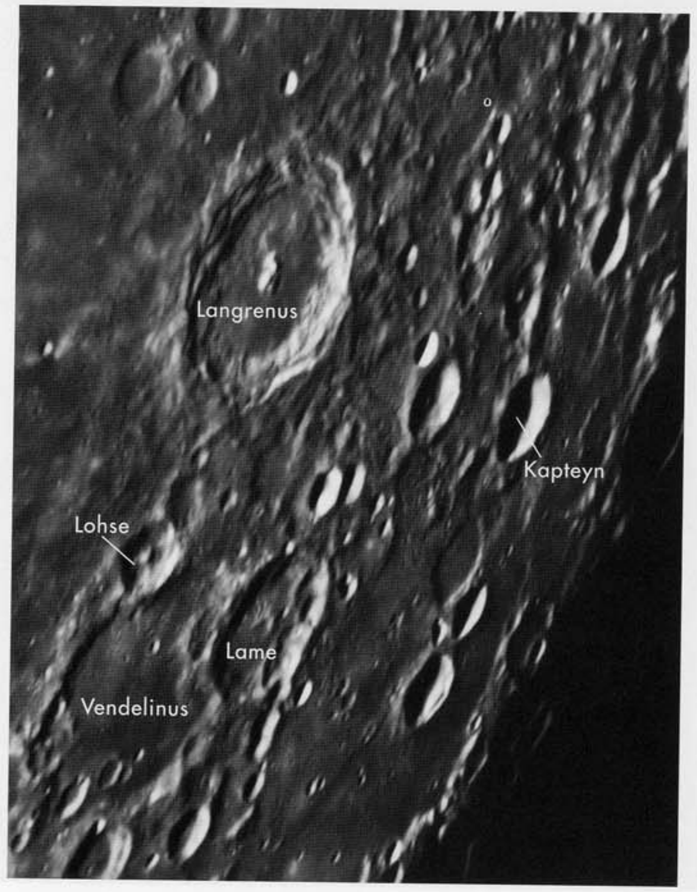


Mare Fecunditatis

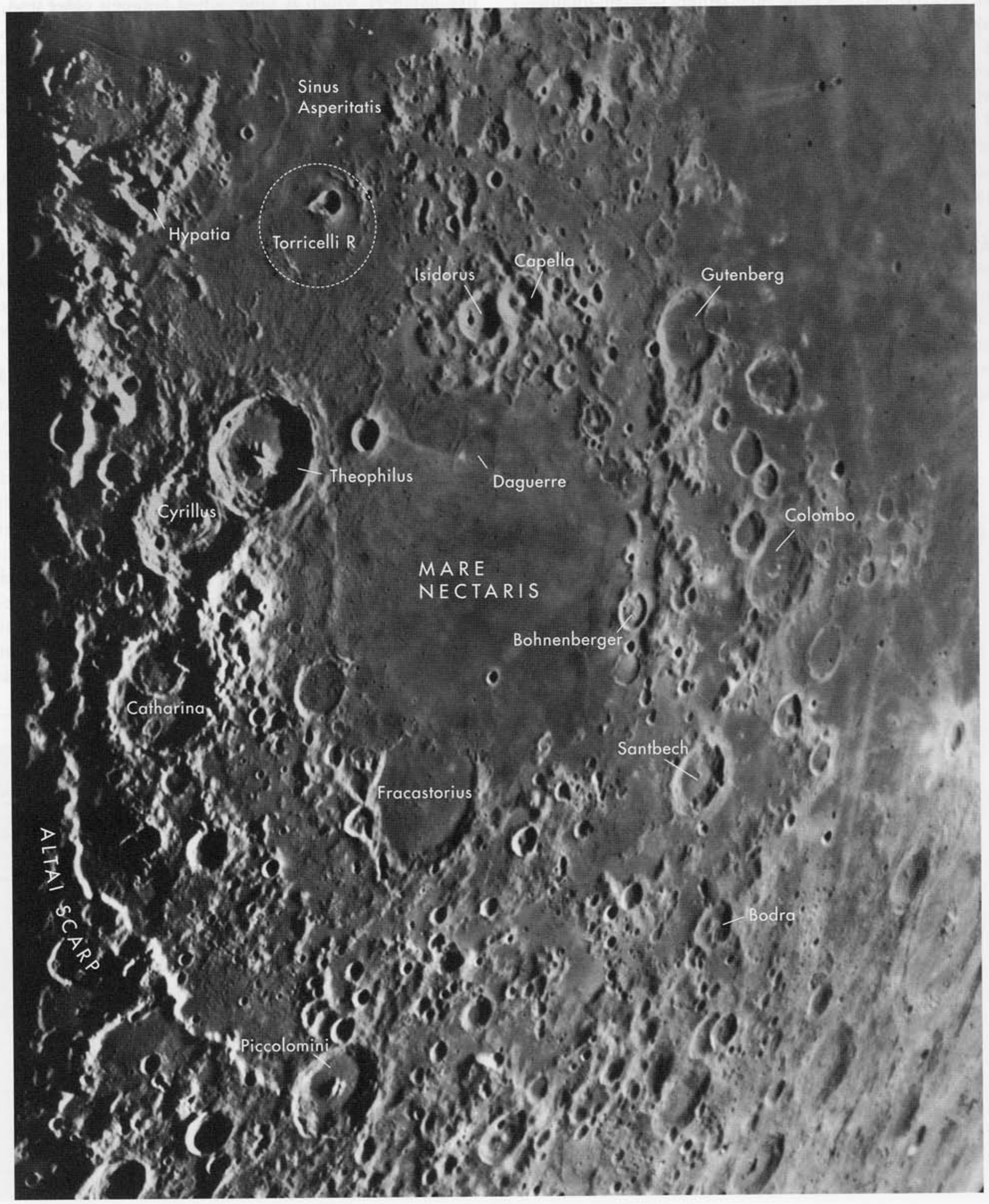
Although this mare area is not well studied, we do have tiny pieces of it brought to Earth by the Soviet Luna 16 sample return mission. The landing site is a bland plain in the northeast corner of the mare, but the returned samples are surprisingly diverse, including titanium-rich and aluminum-rich basalts. The age of the lavas is 3.40 billion years. Because of the successful sample return missions Luna 16 and Luna 20 (which touched down on the nearby highlands), a patch of Fecunditatis was named Sinus Successus. Somehow this doesn't have the romantic ring of most other lunar names, and it ignores the nearby failed Luna 18, which crashed into the mare it was intended to sample.

VENDELINUS AND LANGRENUS

Eastern Fecunditatis is bounded by two large craters, one younger and one older than the mare. Vendelinus (147 km) is a mare-filled and battered pre-Nectarian crater. Langrenus (132 km) is a glorious crater whose secondary craters gouge the surrounding mare. These secondaries and a prominent ray system led to Langrenus being classified as Copernican in age. But when the number of small craters on it was carefully counted, Langrenus, like Theophilus and some other large-rayed craters, was found to be about the same age as craters like Lambert, which is sandwiched between older and younger mare lava flows. Because Copernican-age craters are defined as being younger than the mare lavas, some of the nearly grand craters have been reclassified as Eratosthenian — they've passed their prime and are beginning the long process of erosional decay that will ultimately result in, well, nothing much. The degradation of lunar craters is due to subsequent impact cratering and volcanism. The latter seems dead on the Moon, and a glance at the maria shows that the amount of impact cratering over the last 3 billion years has been pretty minimal. So Langrenus and most other lunar features will look pretty much the same as they do now for the next few billion years or so. The Earth will churn and change constantly with mountains being formed and destroyed, and glaciers, oceans, volcanoes, and deserts coming and going. But the Moon will just sit there.



Vendelinus and Langrenus.



Mare Nectaris.

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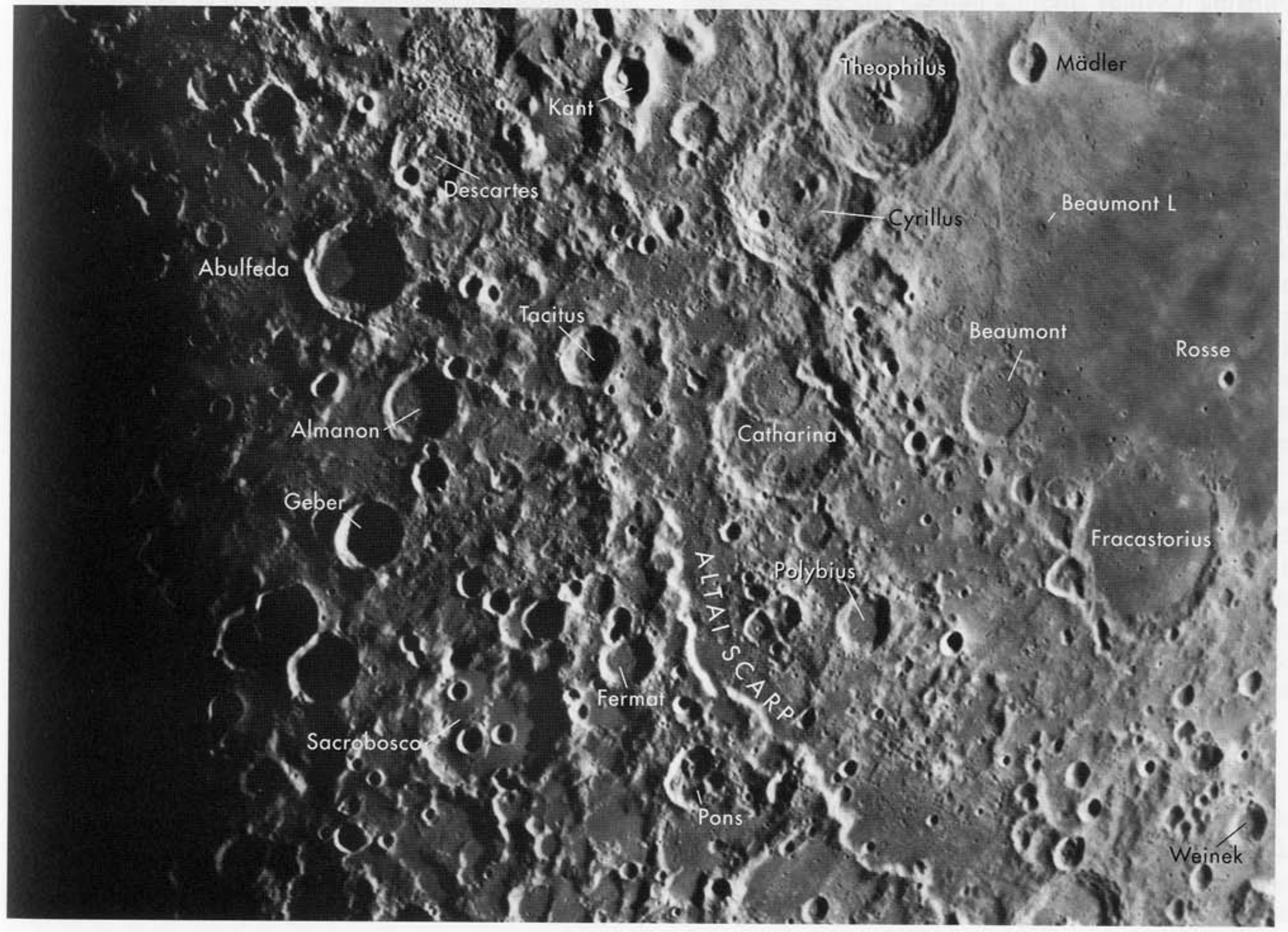
Nectaris

The Nectaris basin is one of the undervalued gems of the Moon. Some of the most dramatic and instructive landforms on the lunar surface are located within its fairly compact area. Nectaris has been relatively understudied by professional lunar scientists, perhaps because it contains only a modest pond of mare, the material we best understand. But the lack of a thick mare fill leaves the basin's scarps and rings better exposed than at any other place on the lunar near side. This broad region is also famous for the worst case of mistaken identity in lunar exploration. The Apollo 16 astronauts landed beyond the rim of Nectaris in what was supposed to be old volcanic deposits, but instead they found impact-crater debris. This surprise had repercussions in understanding planetary geology throughout the solar system, but in reality the new conventional wisdom of old plains being impact ejecta is uncertain and may even be flawed.

RINGS AND THINGS

The Nectaris basin is beautifully defined by the spectacular Altai Scarp, which forms the southwestern rim of the basin. The Scarp is a dramatic 3.5- to 4-km-high cliff that continues as a weaker and more broken scarp



Western Nectaris.

eastward under the crater Piccolomini, and on northeastward past the crater Borda for a few tens of kilometers. The northern continuation of the Altai Scarp on the western side of the basin is harder to trace, partly because of the distraction of a magnificent chain of craters: Catharina, Cyrillus, and Theophilus. But the basin rim is marked by large amorphous chunks of land called massifs, which show up especially well when the terminator is nearby — the craters Tacitus, Kant, and Hypatia lie right on the rim. An unnamed promontory near Hypatia that points toward Mare Tranquillitatis is the last well-defined portion of the main ring of the Nectaris basin, but as an imaginary arc the ring continues through a series of rilles that pass north of the crater Capella. With a telescope, try to trace all around this major basin ring — you will encounter some remarkable terrain as you do.

When Baldwin first recognized the basin structure of Nectaris, he pointed out that there were fragments of inner rings concentric to the Altai Scarp rim. He described the "great curved ridge paralleling the lava edge" between Colombo and Santbech and matched it with a similar, "diametrically opposite" short ridge linking Cyrillus and Catharina. Fifteen years later Hartmann and Kuiper found more fragments of this ring and also mapped other rings. The most obvious is the roughly circular outline of the mare shore that is bounded by a pronounced ridge (named the Pyrenees Mountains) just east of the crater Bohnenberger, and a subtle ridge on the mare's south shore on either side of the crater Fracastorius. Inside this ring is a delicate example of a wrinkle-ridge ring that extends all along the eastern and southeastern edge of the mare and then again along the western shore. A low sun angle will make this feature stand out boldly from the mare floor. And finally, some scientists think there is a subtle outer ring passing near the crater Sacrobosco and through the Apollo 16 landing site north of Descartes. I don't see any evidence of it, do you?

NECTARIS BASIN RINGS

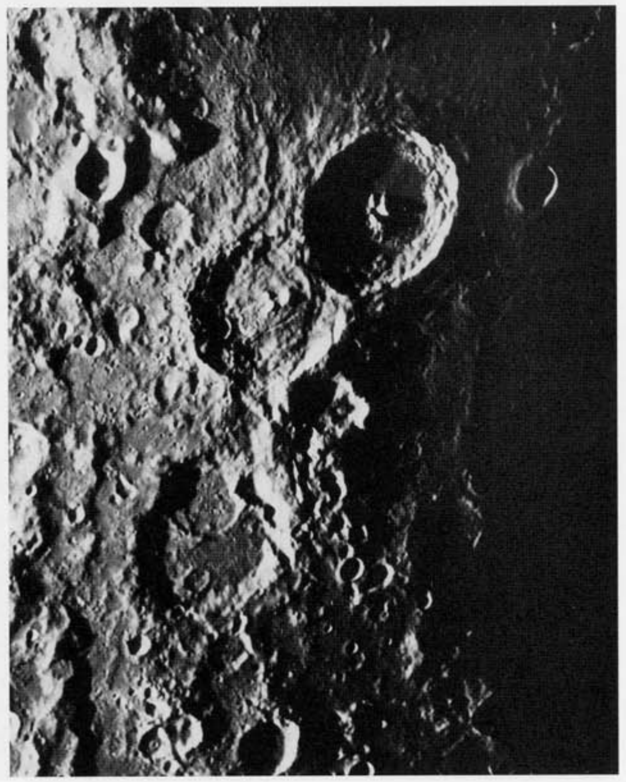
NUMBER	DIAMETER (KM)*	RING NAME
1	240	Wrinkle ridge
2	400	Pyrenees Mtns.
3	620	Santbech-Cyrillus
4	860	Altai Scarp
5	1,320	Invisible!

* *According to Spudis (1993).*

Mare Nectaris is the smallest of the circular maria on the Moon; lavas extend only 350 km from shore to shore, and their estimated maximum thickness is just 1.5 km. Altimetry measurements from the Clementine spacecraft show that Nectaris is quite deep — the bottom of the mare floor is 6.5 km below the average lunar crust elevation. Despite this depth, apparently the small pool of mare lava did not cause enough subsidence for bending at the basin margins to form concentric troughs. Maybe that's why Nectaris is one of the few basins not surrounded by arcuate graben.

MAGNIFICENT CRATERS

The Nectaris region is blessed with a number of beautiful and intriguing large craters, and a few interesting small ones. Piccolomini (88 km wide) prominently cuts the southernmost part of the Altai Scarp, but the group that first attracts the observer's eye is the magnificent chain of Catharina, Cyrillus, and Theophilus. Although they are all about 100 km in diameter, each is different. Catharina seems to be the oldest — five craters (including the 45-km-wide Catharina P) are superposed on it. Elongated craters on its northeast rim are aligned toward Imbrium, so Catharina is probably older than that basin. Cyrillus, on the other hand, is sufficiently young that traces of its terraced walls and a 2.1-km-high central peak are preserved. Although its northeastern rim has been encroached on by the formation of Theophilus, Cyrillus doesn't look as battered as might be expected. The eastern side of its floor is dominated by a large arcuate ridge that seems to turn into a valley. Southwest of the central peak, a much narrower rille squiggles across the floor for a distance of about 10 km. Are these unusual floor fractures the result of a southward shove from the formation of Theophilus? Or is Cyrillus a floor-fractured crater, with cracks due to underlying magma that warped the crater floor up and fractured it as well?



The dramatic trio (from north to south) of Theophilus, Cyrillus, and Catharina at lunar sunset.

Along with Tycho and Copernicus, Theophilus is one of the most spectacular craters visible from Earth. It is an excellent example of the Tycho class of complex-crater morphology, having the three characteristic components: terraced walls, a flat floor, and broad central peaks. Standing on the rim crest of Theophilus would be frightening, for there is a steep scarp that drops 1.5 km over a horizontal distance of just 2 km! At the bottom of this plunge is the first of a number of flat-topped or rubbly terraces that step down to the floor — a mostly smooth expanse, with hills that extend from the massive central peaks toward both the east and west walls. The smooth parts of the floor are thought to be covered by rocks that were ejected and then rained back down into the crater while still molten from the energy of the impact that formed Theophilus. Look closely around the northern outer wall of the crater, where you can see more impact melt that splashed outside the rim and collected in small smooth-surfaced ponds. This is one of the few places on the Moon where impact melt on the crater exterior is readily visible to telescopic observers.

One of the reasons that impact melts appear to the north of Theophilus is that the southern rim is quite a bit higher. According to topographic mapping based on stereo photographs taken from the Apollo 16 command module, the Cyrillus side of Theophilus's rim is as much as 1.2 km higher than its northern rim. Hawke and Head used observations such as these to suggest that the collapse that forms terraces in complex craters sloshes molten impact melt over low spots on their rims.

The so-called "discontinuous ejecta" deposits from Theophilus are wonderfully displayed on the mare surfaces to the east and north of the crater. Low lighting reveals radiating ridges and grooves that give way to a myriad of tiny secondary craters at about one Theophilus diameter beyond the rim. Because of all this ejecta-formed roughness, the mare region north of Theophilus connecting Mare Nectaris to Mare Tranquillitatis was named Sinus Asperitatis in 1976. I occasionally slip up and think Bay of Asparagus rather than Bay of Asperities.

Closer to Theophilus, in fact grading into the crater rim itself, is what modern scientists call the *continuous ejecta deposit*. This is a thin wedge of ejecta that thickens from nearly nothing 15 km from the rim to roughly 1 km before it steepens and rises to the rim crest, about 600 meters higher — another glacis.

Is Theophilus a rayed crater like Tycho and Copernicus? The answer is yes but just barely — Theophilus doesn't have conspicuous Moon-girdling rays like Tycho, nor the more spider-web-like rays of Copernicus. Under the ideal lighting conditions of full Moon, the only definite rays are just visible over Sinus Asperitatis and in southern Mare Tranquillitatis, near the Apollo 11 landing site. Closer rays radiate from the center of Theophilus, but the more distant ones seem to come from the eastern side of the crater. East of Theophilus is an enigmatic bright region that could be rays too. This roughly square patch corresponds mostly to the area of discontinuous ejecta from Theophilus but has abrupt straight boundaries on the north and east. Why?

When the shadows are mostly gone from Theophilus, keen-sighted observers may detect three or more dark-haloed spots in northwestern Nectaris. The largest is the 4.4-km-wide craterlet Beaumont L, which is about 100 km due east of Cyrillus. Another dark-haloed crater lies just north of Beaumont L. These appear to be normal impact craters that excavated dark mare material from beneath a lightened surface. Why then don't all the nearby craters of similar size do the same? And look over at the nearly buried crater Daguerre. Its northern and western rims seem to be double, which is most unusual, and there is an elongated dark halo around the northern part of its double rim. This halo is almost certainly a dark mantling deposit — such as can be seen around rilles in Alphonsus and around Serenitatis. Daguerre's rims and halos must be volcanic features. Does that mean that Beaumont L and the nearby small dark-haloed craters are also volcanic?

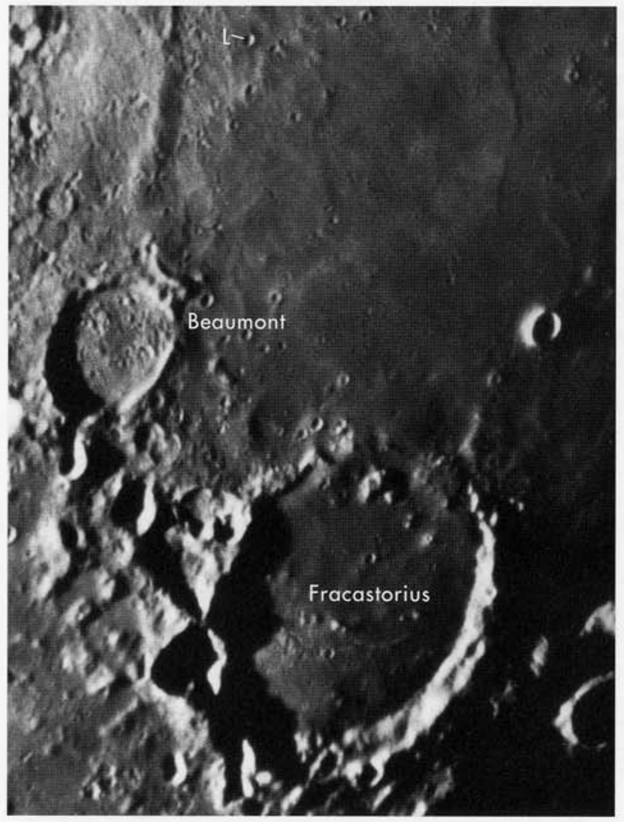
One final note about Theophilus. Its massive peak is quite bright and, according to observations made early in the last century by Pickering, it seems to change as the Sun rises and sets on it. Pickering believed that these changes were due to the falling and melting of snow each month. It makes me wonder which of the ideas of contemporary lunar scientists may prove to be just as nutty?

TILTED AND BREACHED

South and east from Catharina, the curve of the Pyrenees Mountains basin ring passes two lookalike craters, Beaumont and Fracastorius, though Beaumont might just as well be called Fracastorius Junior. Both craters obviously formed after the Nectaris basin but before the partial filling of the basin by lavas. And each clearly is tilted toward the center of the basin. This is another example of the standard basin-filling sequence:

1. an impact basin is formed;
2. craters form on the basin floor;
3. moonwide radioactive heating creates magma, which rises along basin fractures to pond in low parts of the basin floor;
4. the basin floor subsides from the weight of lavas;
5. preexisting craters tilt toward the basin center; and
6. later lavas bury the lower rims of tilted craters.

This sequence is also beautifully displayed at Mare Humorum by the craters Gassendi, Hippalus, Doppelmayer, Lee, and others. At Fracastorius there are a few twists. First, the place where the bending might be expected to be most pronounced — along the continuation of the basin ring — is marked by a rille that crosses the crater floor from east to west. This delicate feature, a mere 1 to 1.5 km wide, is only visible in good seeing. Second, as moderately high lighting shows, the southern portion of the floor of Fracastorius, all of Beaumont, and a 50-km-wide shore inside the nearby basin ring are brighter and rougher than the adjacent mare. Spurr proposed in the 1940s that this border of light gray material was "surged over" by mare lava and then upwarped, like a raised beach on Earth. Most geologists today would say that the border material (including the grayish plains on the east side of the mare) represents an earlier fill of Nectaris otherwise covered by mare lavas.



The tilted craters Fracastorius and Beaumont.

Two other tilted and breached craters are prominent on the north side of Nectaris: Daguerre (mentioned earlier) and Torricelli R in Sinus Asperitatis, north of Theophilus. Torricelli R is an 87-km-wide ruin with only part of its glacis and rim crest preserved. This crater is nearly the same diameter as Tycho, so its original depth was likely nearly 5 km before it was completely filled by mare lavas.

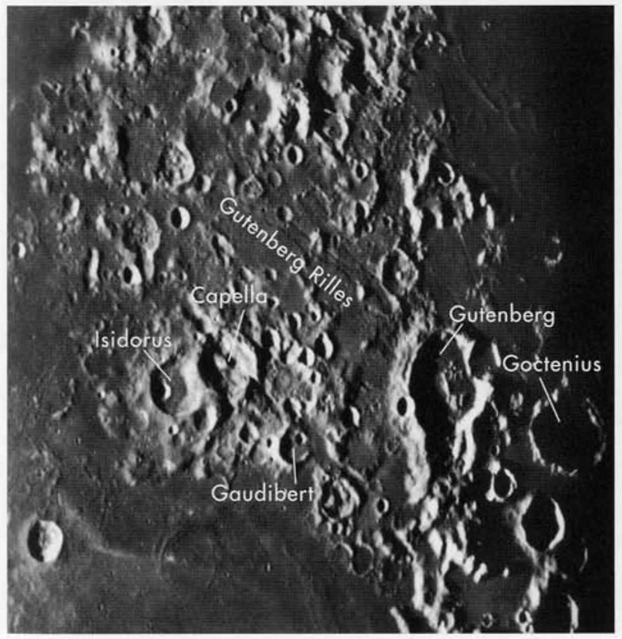
SANTBECH TO CAPELLA BACKWATERS

Interest in Nectaris is usually focused on the southwest quadrant with its mighty scarp and flashy craters. But every basin has its other side, and for Nectaris this is the seldom observed eastern and northern parts. Why is Nectaris so well defined, with three strong rings in one quadrant but none in the others? Perhaps because the older impact basins of Tranquillitatis and Fecunditatis had already thinned and weakened part of the crust to the north and east of Nectaris. If so, Nectaris, like a giant Fracastorius, may have formed on sloping ground, and its lower side initially had lower rings that were preferentially destroyed by mare flooding. Whatever the cause, only remnants of original basin rings are visible, and much of the region between the rings is flooded by Fecunditatis lavas and older gray plains. Nevertheless, some interesting sights exist in this annular backwater.

The squarish patch of highlands-like material north of Nectaris is a distinctive piece of lunar real estate, but like most bright regions of the Moon, it doesn't have an official name. I'm tired of this dark-material chauvinism — well-defined bright regions need names too! So I'm resurrecting Hevelius's 1647 designation, Colchis, for it. Colchis has many small, shallow, and distorted craters, which are probably basin secondaries. A family of three or four *en echelon* (that is, a series of parallel features, each extending a little farther than the last) rilles cut across Colchis. They have been named the Gutenberg rilles. Intriguingly, views obtained during a very low Sun show narrow rilles on the southeastern shore of Mare Tranquillitatis that have the same orientation as the Gutenberg rilles and point toward the larger, well-known rilles near the crater Moltke. On their east side, the Gutenberg rilles continue into Mare Fecunditatis and the crater Goclenius. Thus, one set of extensional rilles seems to be associated with the edges of three different impact basins: Tranquillitatis, Nectaris, and Fecunditatis.

Within Colchis lie Capella and Isidorus — two craters of nearly equal size, but they are not twins. Isidorus (42 km) is a nondescript crater with a broad, flat floor and little else of interest. Capella (49 km), however, is a minor celebrity. Capella is similar in morphology to the crater Alpetragius, located near the center of the visible hemisphere of the Moon. Each has broad inner walls and a domical central mountain but no floor. Capella has been a favorite of volcanophiles (people who think everything on the Moon is of internal origin) because a line of elongated crateriform depressions passes through it. Spurr considered the line to be a fault and the craterlike structures to be blowholes. Fielder also interpreted it as a fault stretching 280 km to the crater Gaudibert, offsetting the eastern half of Capella by 12 km. This miniature San Andreas fault implies that forces within the Moon pushed pieces of the crust past each other.

But as Spurr noted, the "fault" points back to Imbrium. That alignment plus the characteristic elongated and shallow shapes of the depressions are compelling evidence for the modern view that the feature is a secondary crater chain that originated during the Imbrium impact. The volcanoes, the fault, and the mysterious forces never were.

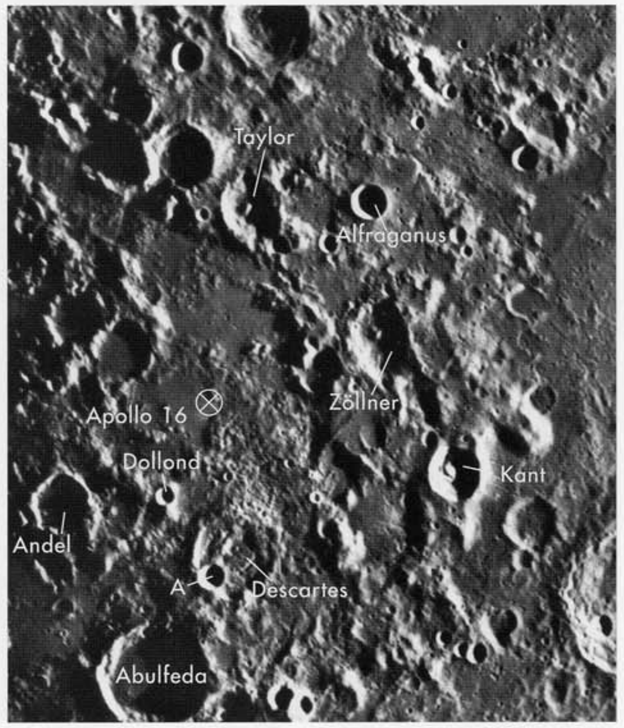


Northeastern Mare Nectaris and Colchis highlands.

"OUR MYSTERIOUS AND UNKNOWN DESCARTES"

Although maria cover only about 17 percent of the lunar surface, all the early Apollo sites were on mare material because it is relatively smooth and safe for landings. For Apollo 16, geologists finally convinced NASA engineers that it was absolutely necessary to sample the lunar highlands. As with all Apollo landing-site selections, there were competing candidates. In Wilhelms's *To a Rocky Moon*, the arguments for and against sites in Alphonsus, Copernicus, Kant, the Marius Hills, and Descartes are recounted. The last won out because of some unique features that, ironically, may not be representative of the rest of the highlands. So, what is this "mysterious and unknown Descartes" site, as astronaut John Young called it?

Few of the classical selenographers paid much attention to the bland crater Descartes west of the dramatic Theophilus. In *The Moon*, Goodacre described Descartes as "an incomplete ring-plain 30 miles in diameter. The walls are much broken and the whole formation ill-defined, and as such unsuitable for a separate name." It wasn't until USGS scientists started mapping every bit of the Moon's near side that Richard Eggleton, and later Daniel Milton, recognized an unusual patch of hilly terrain extending north 100 km from the rim of Descartes. This bumpy material is unlike anything anywhere else on the Moon and was interpreted as viscous volcanic lavas that piled up



Descartes region.

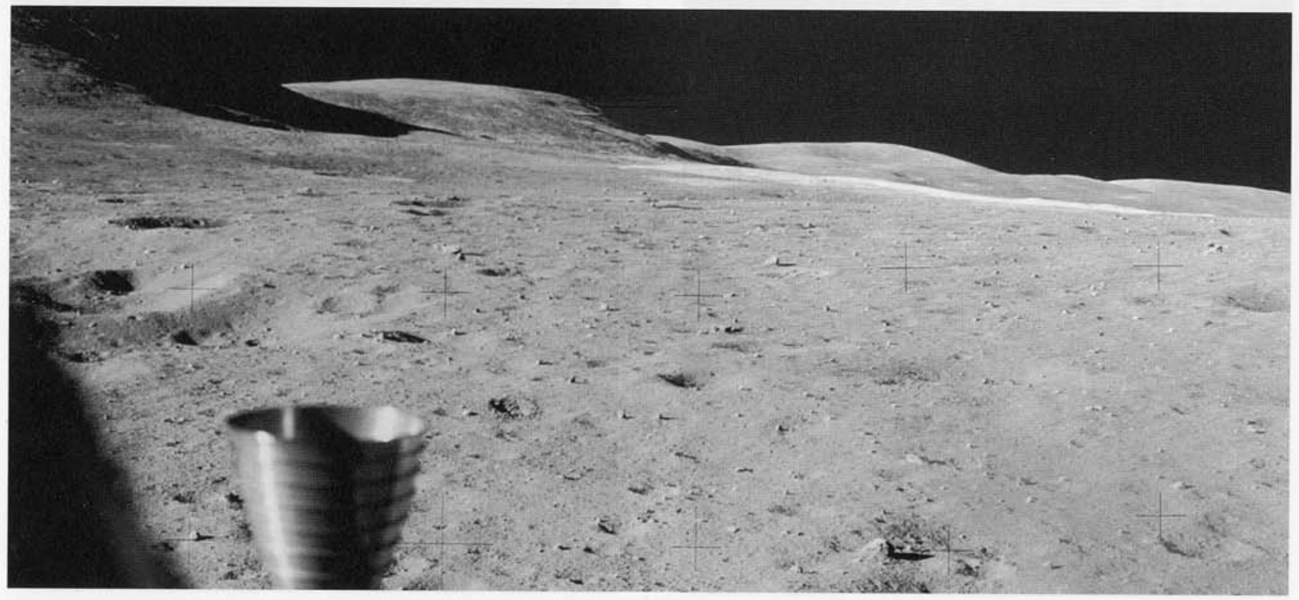
around vents rather than flowing smoothly away. Low spots in the surrounding areas are generally relatively flat and nondescript. These plains were named the Cayley Formation (after their prototype area near the crater Cayley), and at the time most lunar scientists agreed with the USGS interpretation of the Cayley as "volcanic material of high fluidity, either ash flows or lava flows of low viscosity. Chemically, probably more silicic than mare basalt." Thus, the Descartes site was exciting because it was in the unsampled lunar highlands and apparently included two different types of nonmare volcanic materials.

As soon as the Apollo 16 astronauts looked out the window of the Landing Module, Orion, they noticed light-hued rocks — the first evidence that something was wrong. When they suited up and went out on the lunar surface, it was clear that volcanic rocks were rare but that highland breccias (fragments broken by impact) were everywhere. Subsequent examination of the 95 kilograms of Apollo 16 samples confirmed the astronauts' impressions — nearly all the rocks proved to be impact breccias and impact melts. The entire reason for going to Descartes was based on incorrect interpretations!

Before Apollo 16, Wilhelms, like nearly everyone else studying the Moon, thought the Cayley Formation, and certainly the Descartes Mountains, were clearly composed of volcanic rocks. In *To a Rocky Moon*, he explains three prevailing mindsets that caused the fixation on volcanism. First, many scientists felt that the Moon had experienced widespread volcanic activity, so volcanic flows and craters should be expected. Second, all geologists are trained on Earth and thus suffer from terrestrial prejudices when interpreting other planets — on Earth volcanism is common, but impact effects are hard to find. Third, high-resolution orbital photography focused attention on details rather than on the broader view that stresses relations to major geologic structures like basins.

If volcanic activity didn't form the surfaces and rocks at Apollo 16, what did? Even before the astronauts returned to Earth, geologists were revising ideas only a week old, theorizing that the breccias must have been ejected from basin impacts. Although there were long disputes about whether the Cayley deposit is largely ejecta sent via airmail from Imbrium, or whether a small amount of Imbrium ejecta churned up vast amounts of local rocks, today most people who care accept the latter origin. The current wisdom is that the smooth Cayley plains are related to ejecta from Imbrium, while the hilly Descartes consists of underlying deposits from Nectaris.

This post-Apollo interpretation received a rather surprising challenge in 2000. Analysis of Lunar Prospector data showed a strong magnetic field corresponding almost exactly to the hilly Descartes material. It is not known how impact processes could have formed this magnetic field, but a localized mass of unerupted magma under the enigmatic Descartes hills could do it.



Shortly after setting down on the Moon, Apollo 16 astronaut John Young took this picture out the window of the lunar lander Orion. The bright material near the horizon is ejecta from the crater South Ray.

DATING WOES

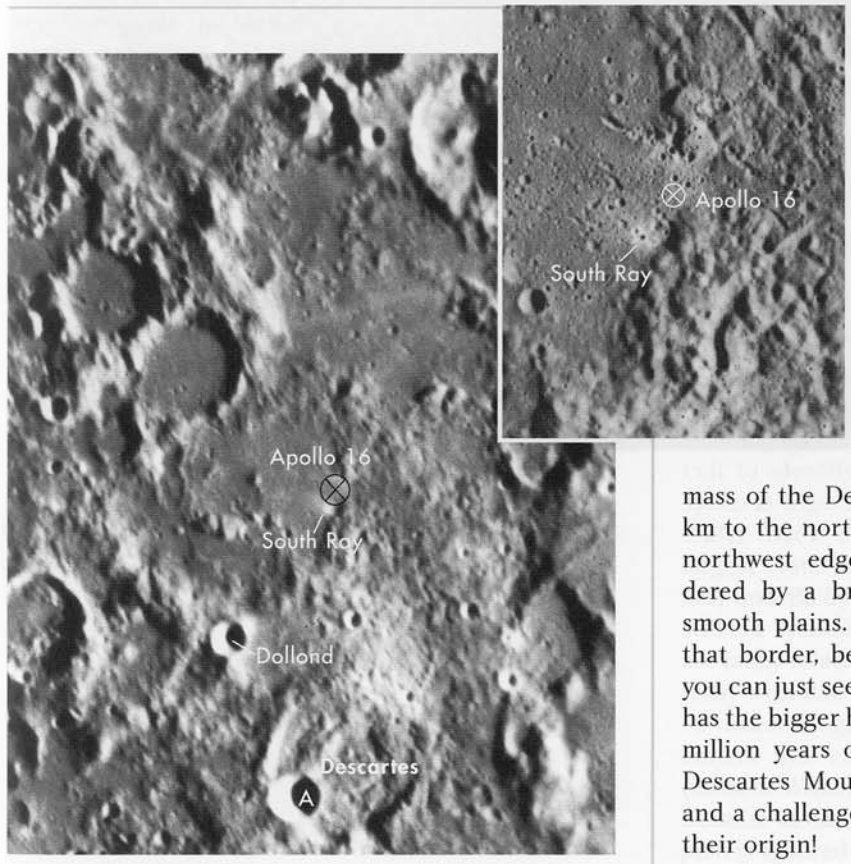
There is another problem with the widely accepted Imbrium ejecta interpretation. As Wilhelms points out, some of the Cayley samples have been radiometrically dated at 3.76 billion years, 80 million years *younger* than the Imbrium impact. Crater counts by German researcher Gerhard Neukum also show that many Cayley deposits are younger than Imbrium. In fact, different Cayley units seem to have a variety of ages, including the approximate age of the youngest big basin, Orientale. Can anyone believe that the vast Cayley deposits at the Apollo 16 site were from the Orientale impact 3,300 km away? The Cayley Formation has a complex and probably manifold origin. There is no compelling evidence that it is volcanic, but there is no easy understanding of exactly how it formed by impact processes.

Apollo 16 rocks from the Descartes Mountains are interpreted as Nectaris ejecta (probably battered by later Imbrium secondaries) and hence their age of 3.92 billion years is given as the date of the Nectaris impact. Although the radiometric dating of rocks can be very precise, there is no certainty at all of where the rocks actually came from. Commenting on the likelihood that Apollo 16 astronauts actually sampled the Descartes Mountains, Wilhelms quipped, "I doubt anyone would put much money on it." Despite the best efforts of engineers, scientists, and astronauts, there are many questions of lunar history that cannot yet be answered convincingly. One of these is the age of the Nectaris basin.

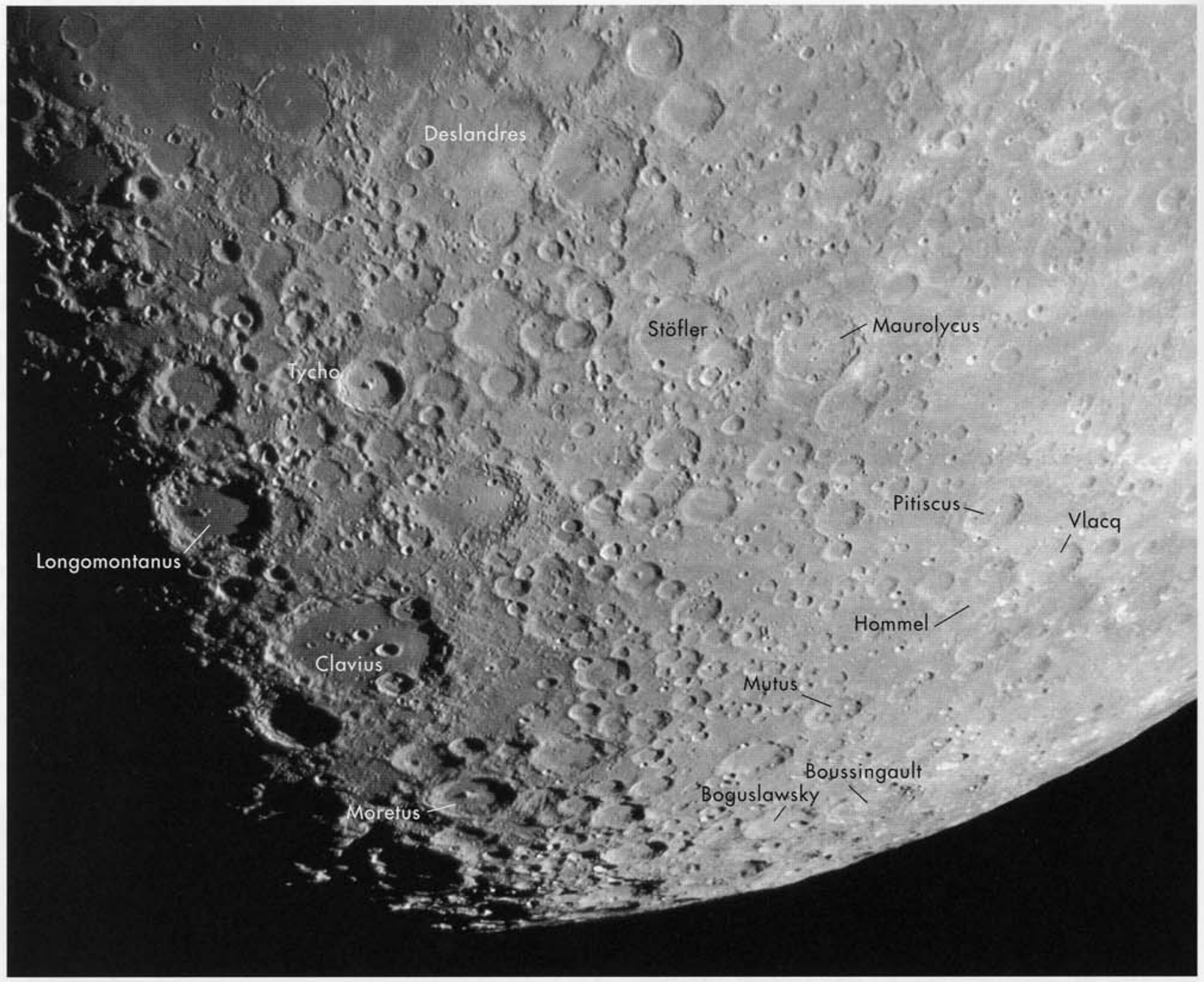
Another chronologic uncertainty is the age of Theophilus. The Apollo 16 astronauts collected tiny pieces of mare basalt that are thought to have been ejected from Mare Nectaris by the Theophilus impact. One of these mare fragments has an age of 3.55 billion years, which dates Nectaris mare deposits — thus Theophilus must be younger. Theophilus is a dramatic, fresh crater, originally mapped as Copernican in stratigraphic age but recently reclassified as Eratosthenian. Wilhelms has defined the "base" or oldest part of the Eratosthenian age as 3.2 billion years, so Theophilus is likely to be considerably younger than 3.55 billion years. The only way to accurately date a crater is to sample and radiometrically date its impact melt. Someday we'll get pieces of the impact melt pools in Theophilus and finally discover how old it really is.

YOU ARE THERE

You can find the exact site of the Apollo 16 landing with a little perseverance. When the Moon is near first quarter, locate the small bright spot halfway between the two grand craters Theophilus and Albategnius. This bright spot is near the landing site, but since the area has no big conspicuous features, it is easier to start at Theophilus and look west about two Theophilus diameters to the broad, flat-floored crater Abulfeda. Just north of Abulfeda is a poorly defined crater with a small bright crater cutting its southwest rim. The decrepit crater is Descartes (48 km wide, about 1 km deep), and the parasite is Descartes A (16 km wide, 2 km deep). Descartes has a concentric ring on its floor, reminiscent of a floor-fractured crater, but its northern rim is covered with the hilly mass of the Descartes Mountains, which extend 100 km to the north and 60 km east to west. Along their northwest edge, the Descartes Mountains are bordered by a broad patch of the Cayley Formation smooth plains. The Apollo 16 landing site is right at that border, between two bright haloed craters that you can just see. South Ray Crater (2 million years old) has the bigger halo, while that of North Ray Crater (50 million years old) is smaller and easy to miss. The Descartes Mountains are wormlike, clearly unusual, and a challenge to find. But just looking won't reveal their origin!



Close-up of the Apollo 16 landing site.



The southern highlands.

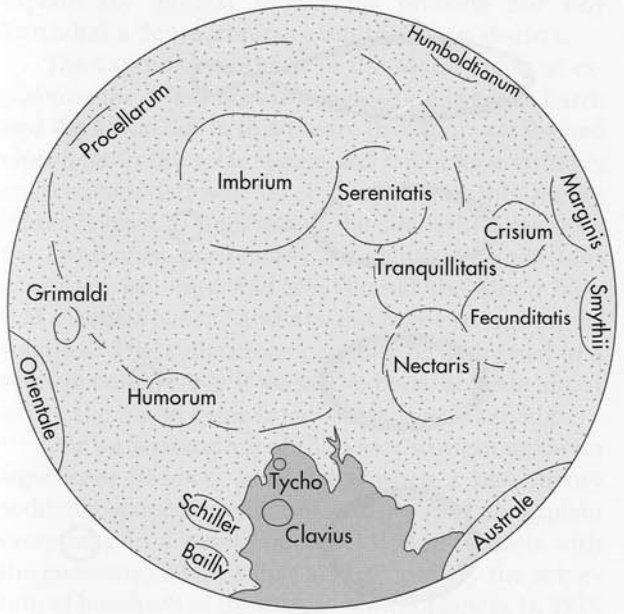
13

Cratered Highlands and Lunar Origins

The Earth-facing part of the Moon farthest from any impact basin is called the Southern Cratered Highlands. This is a region of ancient and intense cratering that has been preserved simply because it wasn't covered by basin ejecta or lava flows. It is also the highest part of the lunar near side, rising about 3 km above the average elevation of the maria surfaces. It's high not because of the pileup of crater on crater, but because it comprises the unmodified early lunar crust of lightweight, aluminum-rich rocks. The glory of this explanation is that we can be confident of the existence of this old crust, even though no astronaut ever landed near it, because of the cleverness of the geological detectives who examined only minute samples from the mare regions of the Moon. Another more visual glory is the crater Tycho — the centerpiece of the southern highlands and the source of a system of rays that girdle the Moon.

OVERVIEW OF THE CRATERED HIGHLANDS

The Southern Cratered Highlands is the oldest region on the near side of the Moon. It appears bright at full Moon and is bounded by the outer limits of basin ejecta deposits from Orientale, Humorum, Imbrium, and Nectaris. According to the USGS stratigraphic system, this area is composed of pre-Nectarian material and includes rocks dating from the very origin of the Moon to the formation of the Nectaris basin, about 3.92 billion years ago.



The southern highlands (dark gray) are the only place on the lunar near side apparently not covered by impact-basin ejecta.

The eastern and western borders of the Southern Highlands are somewhat arbitrarily defined. Although many of the craters on the southeastern side of the Moon are very similar looking, I draw a boundary that runs from west of Janssen southward to the limb. To the west the basin near Schiller roughly delineates an area foreshortened by the limb and striated by ejecta from Orientale, the youngest large basin on the Moon. To the north the Cratered Highlands reach down to the shore of Mare Nubium, while to the east they merge into a region that has been strongly affected by ejecta from the Nectaris basin.

The Cratered Highlands probably best match popular conceptions of the Moon: craters cut craters, which lie in turn on still older craters. The area around Tycho is perhaps the most heavily cratered part of the near side of the Moon. But to the east, in the area between Maurolycus and Janssen, craters appear to be more widely spaced with a smooth, light-hued surface between them. We'll explore why later.

The profusion of lookalike craters littering this part of the Moon makes finding your way around a bit challenging. Although 85-km-wide Tycho is generally easy to find, other features here are sometimes difficult to identify. Halfway toward the south pole from Tycho is a grand landmark, Clavius, the 225-km-wide crater that is commonly (and erroneously) called the largest crater on the Moon — both Deslandres (256 km) and Bailly (287 km) are bigger. More southerly still is a Tycho lookalike, Moretus (115 km). To the east are many relatively undistinguished older craters, typically with flat, peakless floors.

Interestingly, this nearly overwhelming region of craters was carefully studied by earlier observers (indeed, Wilkins's map is nearly indecipherable here because of excessive detail) but has been almost completely ignored by modern scientists. The reasons are, I think, threefold. First, the maze of similar-looking craters makes finding a particular telescopic target time-consuming; second, none of the Apollo spacecraft passed over the region; and third, there are no basins or maria, the features that we know best how to explain. With little remote-sensing data available, how do you distinguish separate geologic units in a broad, homogeneously complex expanse? The successes of the Galileo and Clementine missions during the 1990s provided high-quality images and data in many spectral bands, which should finally open up the highland to geologic exploration. Such data have already identified a chemically unique terrain on the lunar far side.

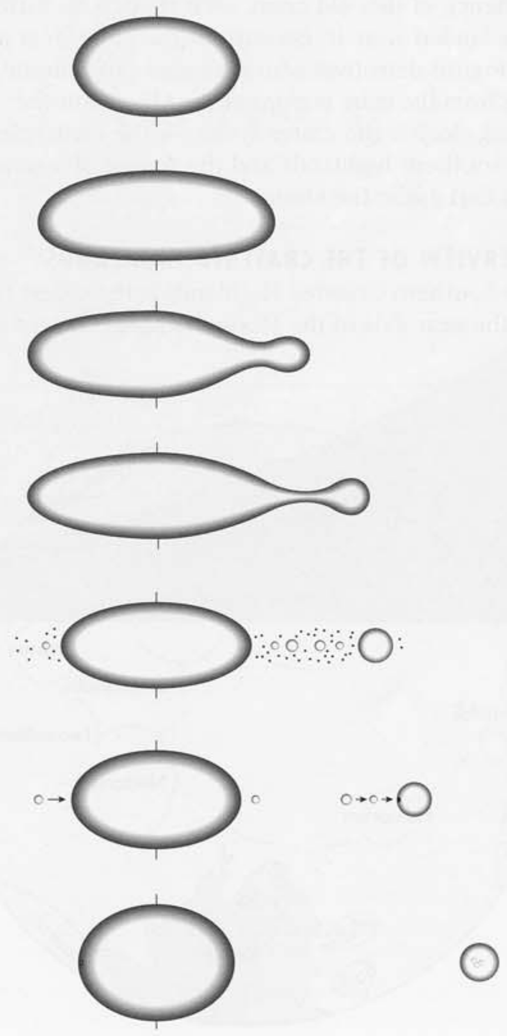
THE ORIGIN OF THE MOON

To understand the origin of the cratered highlands, we must look back to the formation of the Moon itself. Immediately after the Apollo missions, there was no consensus on the Moon's origin. In fact, Urey even commented that all the existing theories were untenable.

So what facts about the Moon does a proposed origin theory have to satisfy? Smithsonian Institution scientist John Wood (no relation to me) summarized six important ones. The first three listed here have been known for nearly a hundred years, but the others were gleaned from the Apollo program:

1. *The Moon is relatively large compared to Earth.* Most satellites in the solar system are only a few hundredths of a percent of the mass of the planets they circle, but the Moon has more than 1 percent of the Earth's mass.
2. *The Moon has a density of 3.3 grams per cubic meter, versus 5.5 for Earth.* The usual interpretation of these numbers is that Earth has a massive iron core that increases its average density, but that the Moon lacks such a core or has only a very small one.
3. *The daily rotation of Earth and the monthly orbit of the Moon around Earth give the combined Earth-Moon system a high rotational energy or angular momentum.* The Earth-Moon system's angular momentum is exceptionally high compared to other planets and their satellites.
4. *Compared to Earth and meteorites, the Moon has a pronounced deficiency of elements like potassium, sodium, and lead that vaporize at relatively low temperatures.* The most striking example is the Moon's lack of water, which is totally absent in the minerals that compose lunar rocks.
5. *Very precise laboratory measurements have demonstrated that the relative amounts of the various isotopes of oxygen differ for various types of meteorites, but their proportions on Earth and the Moon are absolutely identical.* The inescapable conclusion is that Earth and the Moon must be made of very similar material from the same source region.
6. *The uppermost 200 km of the Moon must have melted (and maybe the entire satellite did, forming a giant magma ocean) to form the Moon's thick crust of the lightweight mineral plagioclase.*

Three theories for the origin of the Moon had been debated for years, but even the Apollo data provided insufficient information to decide between them. The oldest hypothesis was proposed by George Darwin (son of the famous naturalist Charles Darwin), who suggested that the Moon spun off Earth by a process called "rotational fission." A modern version of this notion was proposed by University of Massachusetts's Donald Wise and later refined by my old friend Alan Binder. The early liquid Earth spun on its axis so rapidly (with a day lasting only 2.6 hours or so!) that it become elongated like a bowling pin around its equator and threw off a hunk of material that ultimately became the Moon. Although this idea has trouble explaining constraints 1 and 2 (the large size of the Moon and the excessive angular momentum of the Earth-Moon system), it is consistent with constraint 3 (Earth and the Moon formed of the same material).



In 1963 Don Wise (and later Alan Binder) argued that rotational fission threw the Moon out of the early molten Earth.

There were two other competing ideas for lunar origin. One postulated that the Moon and Earth formed simultaneously as twin planets, while the other proposed that the Moon was originally an independent body that formed elsewhere in the solar system but was captured when it passed too close to Earth. These now-disfavored ideas were originated by others but were promoted by the two giants of planetary science of the 1950s, Kuiper and Urey. In the 1970s NASA scientist Bevan French characterized the three traditional hypotheses — fission, twin planets, and capture — as the "daughter," "sister," and "girlfriend" theories of lunar origin! (I suppose that in the interest of political correctness, today we ought to call them the "offspring," "sibling," and "significant other" theories.)

The modern view of the "sister planet" hypothesis is that both Earth and the Moon formed together by *accretion*, the collisional sticking together of a swarm of precursor bodies (called *protoplanets*) orbiting the Sun, ranging in size from a kilometer to hundreds of kilometers. Because Earth and the Moon would have formed from essentially the same material, they should have identical ratios of oxygen isotopes. But this idea doesn't explain the angular momentum problem nor why Earth has a dense iron core but the Moon doesn't.

The capture hypothesis of the Moon excels at explaining the differences in composition between Earth and the Moon, for in this theory the Moon was formed elsewhere in the solar system and could have virtually any characteristics at all. But accepting this theory makes it hard to understand the similarities between the two bodies, particularly the identical proportions of oxygen isotopes. And why should the Moon have had a magma ocean? And why did it lose so many of its volatiles? These questions can only be addressed in a very speculative way if we say we know nothing about where the Moon came from — not very satisfying.

Our understanding of the Moon's origin made no significant headway until 1984, when a new theory suddenly gained popularity and seemed to explain everything in a novel and exciting way. It starts with the conventional idea that planets form by the accretion of hundreds of thousands of protoplanets. In 1975 Hartmann and Donald Davis suggested that if one of these colliding bodies was 4,000 km or more in diameter, it could hit the early Earth hard enough to eject some of its own mass and part of Earth's upper layers into orbit around Earth. This material would be hot (thus losing its volatiles into space), and if the collision happened after Earth's iron core formed, it would also be iron-poor. Re-accretion of the gas and particles ejected into Earth orbit would form the Moon. Although Hartmann and Davis in 1975 and Al Cameron and William Ward at the Harvard-Smithsonian Center for Astrophysics in 1976 independently proposed this theory of lunar origin, a decade passed before the idea took off like a cosmic bandwagon. Today most lunar scientists seem to believe some version of it.

To evaluate the various hypotheses about lunar origin, John Wood issued a report card with subjective grades for how well each theory explained important facts. I calculated the grade-point average from Wood's scores, which shows that the giant-impact idea ranks highest, but all the competitors receive only gentlemanly Cs. In fact, each of the other three would have received higher rankings at different times in the past, and anytime before the last decade the impact theory would have received a resounding F for physical implausibility.

FACT	HYPOTHESIS			
	CO-ACCRETION	CAPTURE	FISSION	IMPACT
Moon's mass	B	B	D	I
Angular momentum	B	C	F	B
Depleted volatiles	C	C	B	B
Depleted iron	D	F	A	I
Oxygen isotopes	A	B	A	B
Allows magma ocean	C	D	A	A
Physical plausibility	C	D–	F	A
GPA	2.4	1.7	2.3	3.4
Overall grade	C+	C–	C+	B+

Grades are based on A = the best grade, F = failing, I = incomplete (not enough evidence to decide). GPA = grade-point average — a numerical average with A = 4, B = 3, etc.
Source: John Wood (1986)

Although the traditional and the new theories all have weaknesses or uncertainties, the impact proposal ranks highest overall and is the new conventional wisdom. Thus, the current belief about the Moon's formation incorporates elements of the older ideas: the Moon includes material from the large impactor (capture hypothesis) and some blasted off Earth by a giant collision (fission hypothesis), and it all condensed from a hot vapor (twin-planet hypothesis).

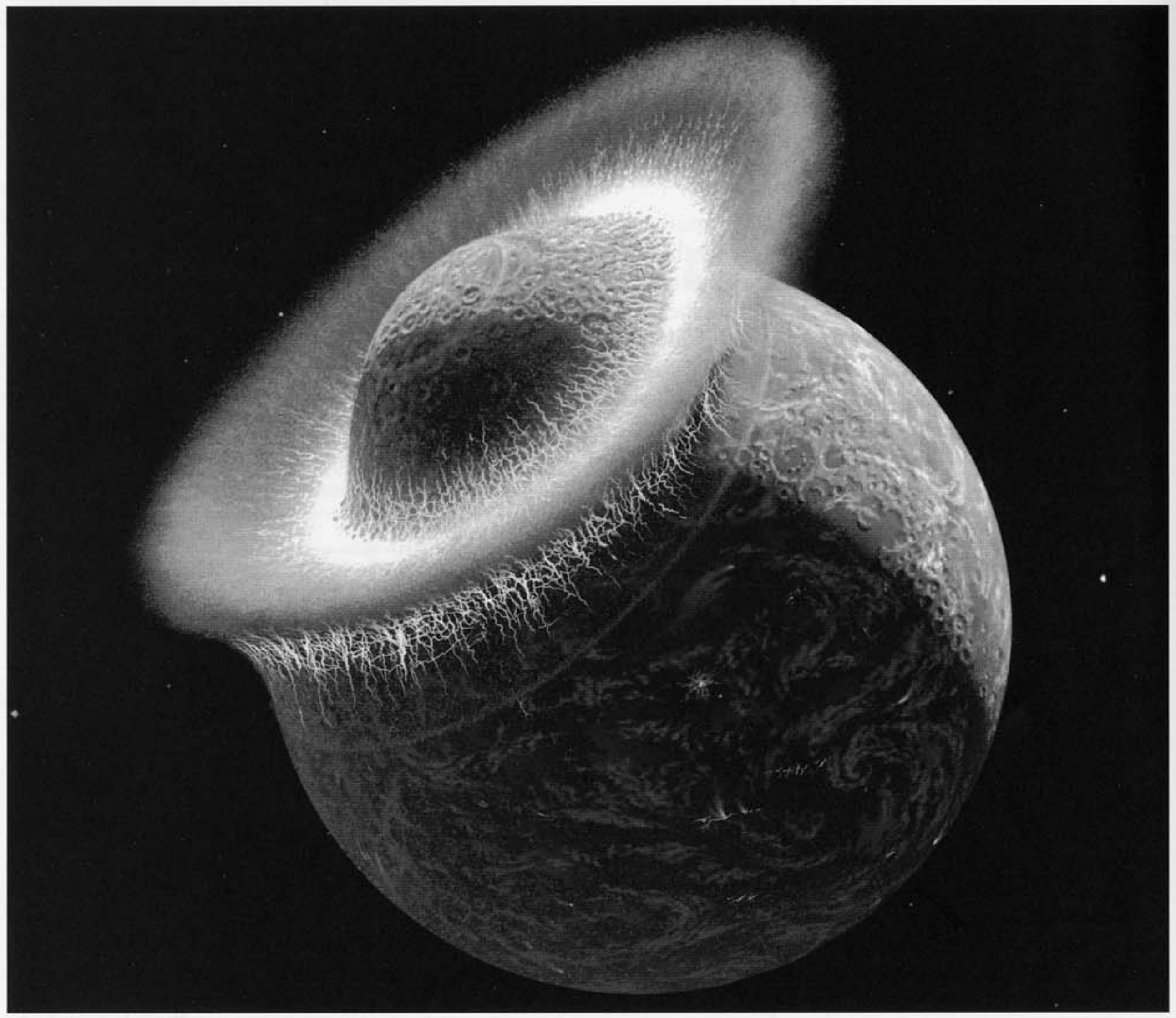
Similar giant impacts may have occurred elsewhere, causing other bizarre circumstances in the solar system. For example, the planet Uranus is tipped all the way over on its side, its pole almost coinciding with the plane of its orbit rather than being nearly at right angles like most of the other planets. And Venus rotates backward compared to the other planets. Hartmann has suggested that giant impacts knocked Uranus on its side and reversed the spin of Venus. If these ideas are reasonable, then the giant-impact origin of the Moon is neither unique nor quite so fantastic. The early solar system must have been a wild place with cosmic billiards the order of the day!

MOLTEN MOON AND FLOATING CRUST

You may have forgotten (I nearly did) that the reason we went into the origin of the Moon was to explain the high-standing crust in the Cratered Highlands. Another somewhat long story is necessary to go from the giant-collision origin of the Moon to the formation of its crust.

The accumulation of the Moon from the debris of the giant collision is thought to have happened so quickly (perhaps over a span of a few million years) that the heat generated by the accretion of all the fragments melted the Moon to a depth of at least hundreds of kilometers and perhaps even completely. This hot stage explains the Moon's depletion of volatile elements, which simply boiled off.

The composition of the lunar crust in the Cratered Highlands and elsewhere was inferred by Wood and his colleagues while examining the first samples returned by Apollo 11. Mixed in with the thousands of dark basaltic lava fragments from Mare Tranquillitatis were 61 small pieces of light gray and white rocks. These light-hued rocks are called *anorthosites*, defined as rocks with 90 percent or more of the calcium-rich whitish mineral *plagioclase feldspar*. Wood's group guessed that the white rocks were fragments ejected from impact cratering in the lunar highlands (which are much brighter than the dark maria) and were thus samples of the highlands' crust.



Don Davis's dramatic painting illustrates the collision of a giant projectile with the early Earth. Ejecta from both bodies later accreted to form the Moon.

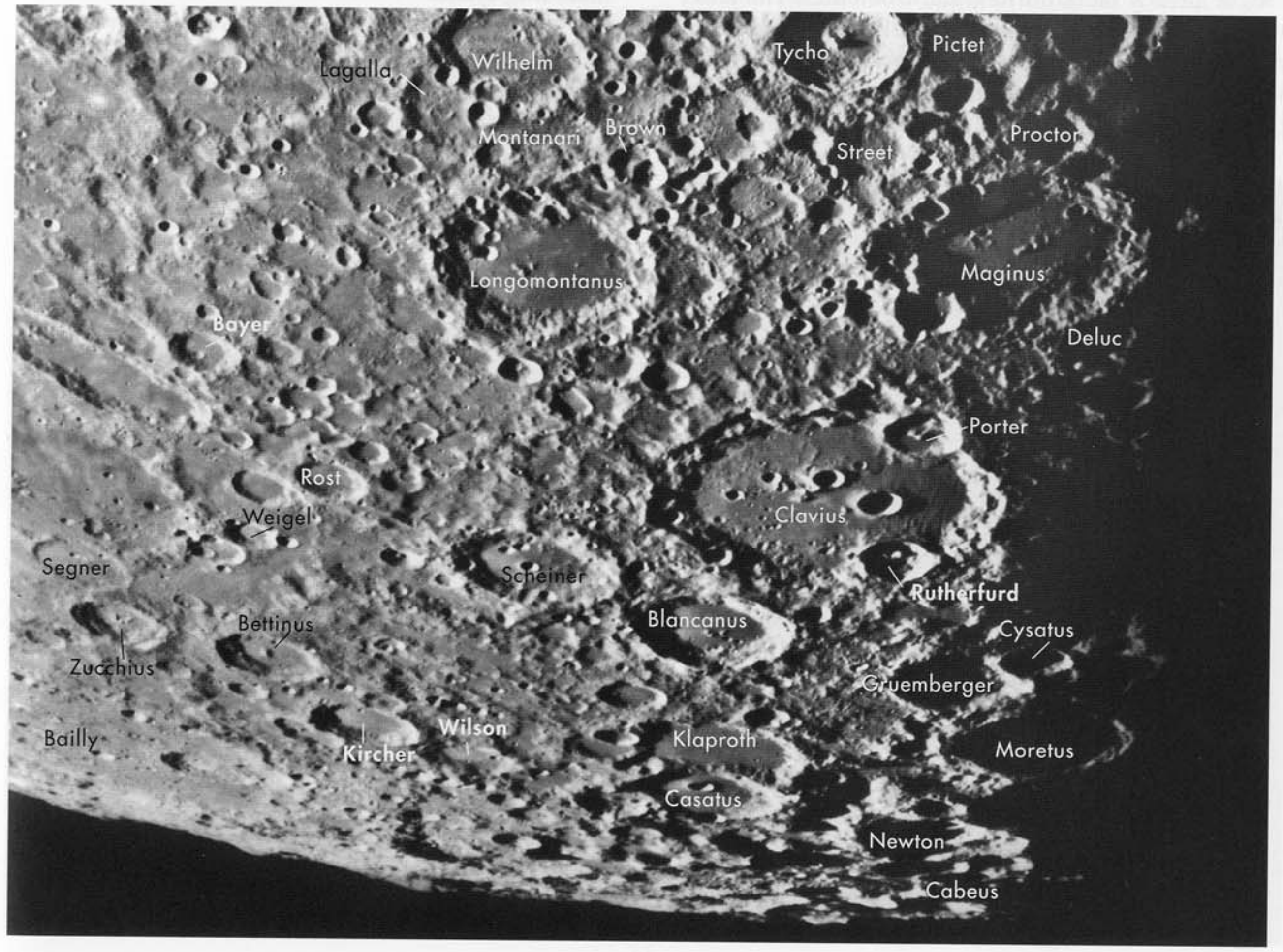
Wood's group further proposed that the lighter anorthositic crust formed by floating on top of heavier minerals, which sank as a result of "igneous activity on a grand scale, possibly the early melting of a substantial fraction of the Moon." Like the anorthosites themselves, the magma ocean was a totally unexpected discovery.

One of the obvious consequences of recognizing that the Moon had once been very hot was the abandonment of the common pre-Apollo view that the Moon was a cold, primitive, and unevolved body. That had been Urey's cherished belief, for he thought the Moon would be much more interesting if it were a little-altered sample of the primordial solar nebula. Urey, who had hectored people for more than a decade about a cold Moon, was wrong again.

So the Cratered Highlands are high because they are composed of low-density (and thus high floating) anorthosite, and because impact basins did not excavate deep holes in this part of the Moon. The highlands are bright because anorthosite is dominated by plagioclase feldspar, and because there has been no recent dark volcanism there. Remember the magma ocean with its untold billions of white plagioclase crystals splashing in pre-rocky swells when you observe the highland crust that they made.

THE HIGHLAND CRUST

Tycho is the only place truly in the lunar highlands to be visited by spacecraft. In 1968, in final preparation for the Apollo flights, NASA sent Surveyor 7 to soft-land on the northern edge of the Tycho ejecta deposits. This



The southern highlands west and north of Clavius.

robotic laboratory included an instrument that performed a chemical analysis of lunar soils near the spacecraft. Compared to lunar maria sampled by previous Surveyors (and the later Apollos), the Tycho site had only about half as much iron and titanium but considerably more calcium and aluminum.

Shoemaker, leader of the Surveyor project, was the first to understand that the Tycho rocks were fundamentally different from those in the mare. He suggested they were anorthositic gabbro and was proved correct by the tiny highland fragments in the Apollo 11 samples. Although we often say that the lunar highlands are anorthosites, as usual Shoemaker was probably right because the majority of the Apollo samples that apparently come from the highlands have enough iron and magnesium to be considered a slightly different rock, anorthositic gabbro.

The classification of highland rocks can be much more complex than the relative simplicity of mare basalts. But you can be like many lunar geologists and just remember the "ANT suite." The three most common kinds of highland rocks are anorthosites (which we've already met), norites, and troctolites. The latter two rocks are each made mostly of just two minerals. Norite contains the mineral plagioclase feldspar (as in anorthosites) plus pyroxene. Troctolites (the name always makes me think of troglodytes) are plagioclase feldspar and olivine. Of course, there are a host of other highland rock types, but they are relatively uncommon.

Almost all the Apollo samples are mare rocks, so our understanding of variations across the highland crust is necessarily based on spectral observations from ground-based telescopes and spacecraft. Fortunately, such data can often identify plagioclase, pyroxene, and olivine, so that we are able to infer the major highland rock types. And since impact craters excavate material from different depths, by looking at crater rims, central peaks, and basin rings, we can infer changes in rock types with increasing depth in the crust. One such study by Pieters suggests that norite is common in the top kilometer or two of the lunar crust, while anorthosite and troctolite are found deeper down.

TYCHO: THE METROPOLITAN CRATER OF THE MOON

Tycho is grand. It is the most conspicuous crater visible near full Moon, shining brilliantly, surrounded by a dark ring, and radiating great long rays. If we get away from the full-Moon glare so that its morphology can be seen, Tycho is revealed as the prototype of the large complex impact crater with terraced walls, a flat floor, and conspicuous central peaks — truly the "Metropolitan crater of the Moon," as Elger called it in *The Moon*.

Tycho is 85 km wide, 4.8 km deep, with a 2.25-km-high central peak. Its floor is relatively smooth on the east side, but there is a sector of roughness radiating from the central peak to the west wall. Early examination of very-high-resolution Lunar Orbiter spacecraft images of Tycho's floor showed rough textures and domelike features, which were thought to be of volcanic origin. But growing recognition of the widespread existence of material totally melted by the great energy of impact in and around fresh lunar craters led to impact melt as the accepted interpretation. It appears that both the smooth and the rough portions of Tycho's floor consist of impact-melted debris that veneer the original surface.

Unlike Copernicus, the depth of Tycho's floor is typical for a large complex crater, so there is no reason to believe that volcanism has occurred there. This must have been a great disappointment for John A. O'Keefe, a brilliant but stubborn NASA scientist who believed that *tektites* — glassy, melted, meteorite-like rocks that have been found in a half dozen or so localities on Earth — were erupted from lunar volcanoes, including Tycho.

When the Moon is full, Tycho is circled by a dusky halo, which extends out from the rim about one Tycho radius. No other rayed crater has such a conspicuous dark collar. This halo, or *nimbus*, coincides with the area immediately surrounding Tycho, which under low lighting is seen to be pockmarked with kilometer-sized secondary pits but under a somewhat higher Sun appears softened. The Surveyor 7 spacecraft landed in this area (about 25 km north of Tycho's rim), and Orbiter photographs reveal a region of striated hills interspersed with smooth ponds. The ponds are interpreted as impact-melt material that splashed all around Tycho, flowed off hills, and collected in low spots. The dark annulus maps out the distribution of a nearly continuous veneer of dark, glassy impact melt. Tycho has such a conspicuous nimbus because the crater is so young that its melt deposits have not been pulverized and mixed in with surrounding rocks by a myriad of small impacts. That steady process also contributes, in a billion years or so, to the removal of bright crater rays. The Moon deplores extremes of brightness.

The rays from Tycho that partially encircle the full Moon are not distributed equally in all directions. Look with binoculars or with a low-power telescope near full Moon and you will see bright rays that streak off to the lunar east, south, and northwest, but no bright ones go to the west. Also notice that the large nimbus of white material surrounding Tycho is twice as wide to the east as to the west. This wonderful example of a perfect impact crater must have formed from an oblique impact! When an impacting projectile skims in over the surface at angles less than 45°, ray material is concentrated in the so-called downrange direction. Thus, the Tycho impactor, probably 8 to 10 km wide, came in low over the Moon's western horizon.

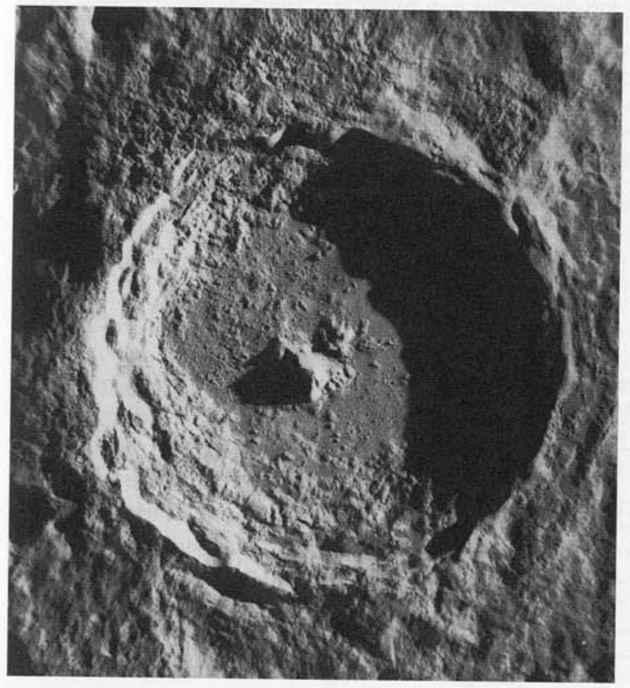
On Earth 109 million years ago, dinosaurs and other reptiles must have witnessed this devastating collision and perhaps suffered a few days later when fist-size pieces of Tycho ejecta hit the Earth.

ONWARD TO THE POLE

Halfway toward the south pole from Tycho is the grand landmark crater Clavius, famous for its large size and interesting interior. Goodacre said that under a low Sun it is "of remarkable grandeur and absorbing interest." Like Plato far to the north, Clavius has been the site of crater-counting competitions. But what the old-timers didn't notice is even more important than the mere existence of minicraters. One of the lines of small craters on the south side of its floor points directly toward the Orientale basin, and many of the craters in and around Clavius are probably basin secondaries. But why isn't Clavius a basin itself? It is one of the largest craters on the Moon that doesn't have a basin's inner ring — a feature that even a few smaller craters possess. Are there submerged rings beneath Clavius's smooth floor?

Clavius is so large that the curvature of the Moon causes the center of its floor to be noticeably higher than the edges. When the Sun is just rising, the center will be illuminated while parts of the rim are still in shadow. One other thing to observe are the ridges that

At full Moon Tycho is one of the most conspicuous lunar features. The impact melt that surrounds the crater is visible as a dark halo.



In August 1967 the Lunar Orbiter V spacecraft obtained this image of Tycho.

Tycho's ray system.

extend northward from Rutherfurd (48 by 54 km), the large crater cutting Clavius's south wall. Although they have been compared to the radial erosion ridges and dikes on terrestrial volcanoes, that origin seems very unlikely. Who knows what they are?

Immediately southwest of Clavius are two nearly twin craters, Blancanus (105 km) and Scheiner (110 km). A peculiar ridge extends from Scheiner's south wall across its floor. Orbiter photographs do not clarify the nature or origin of this feature.

Poleward of the twins is an overlapping nexus of craters that appear to be compressed into tight ovals by foreshortening. Nonetheless, there are some wondrous sites up here. Moretus is a very fresh but rayless 115-km-wide, 4-km-deep version of Tycho that would be a major attraction if it were better placed. The lunar artist Harold Hill wrote that Moretus has the highest central peak (2.12 km) of any crater on the Earthward side of the Moon. This statement was based on measurements of the peak's shadow by the great German Moon mapper Mädler about 160 years ago. I measured the peak myself in 1966, using high-resolution Lunar Orbiter photographs, and found its height to be 2.66 km, in very acceptable agreement with earlier telescopic results.

In addition to Clavius and Moretus, there are also many other interesting craters in the region that are often overlooked. In a V extending south from Tycho are two such craters, Maginus and Longomontanus. Mädler commented that even though Maginus is very large (163 km), "the full moon knows no Maginus" because the brightness of Tycho hides it. Its rim has been extensively pelted by later impacts, some of which are probably basin secondaries from Imbrium, 2,600 km to the north. The floor of Maginus is flat, relatively smooth, and contains craters whose walls appear to have been inundated by lavas. But if you look at Maginus or any of the other smooth-floored craters in the Southern Highlands, you will see that none have the dark coloration that is the signature of mare lava. What is that bright smooth material? Is it ancient lava or ejecta from giant basins?

The other side of the V south of Tycho leads to Longomontanus, a Maginus lookalike with a battered rim and smooth floor. But Longo (I feel that I'm on a first-name basis with many of these craters) teaches us something else about the Moon. Look almost anywhere on the Moon and you will see large craters with smaller ones superposed on their rims and floors. But the east rim of Longo cuts right through the middle of an older and smaller crater. This exception emphasizes the general rule that small craters overlap larger ones. Most large craters are believed to have been formed early in lunar history — later craters tend to be smaller because the sizes of the projectiles that hit the Moon must have decreased with time. This is consistent with the observation that the giant basins formed only in the first 800 million years of lunar history. Probably the large projectiles were pieces of debris left over from the formation of the planets and the Moon. The smaller projectiles may have had a variety of origins, including basin ejecta, comets, and asteroids.

THE SOUTH POLE: COLD SURPRISES

Stretching nearly 30° along the south limb are huge isolated mountains that can only occasionally be glimpsed when libration tips this part of the Moon into view. The best depiction of these Leibnitz Mountains is Whitaker's 50-year-old map that crisply shows one massive, flat-topped peak and other more ridgelike mountains. Classical selenographers found the Leibnitz Mountains relatively easy to measure because they could be seen in profile. In the early 1800s Schröter measured peaks towering to heights of 5.5 km. Sometimes these mountains are seen as brilliant, detached beacons, while their lower elevations still lie in shadow.

As soon as Hartmann and Kuiper recognized that impact basins were common on the Moon, they proposed that the Leibnitz Mountains must be the rim of a huge basin on the lunar far side, viewed nearly edge-on. Although Lunar Orbiter photographs revealed no large, mare-filled basin, the Apollo spacecraft (and later, Clementine) carried laser sensors to accurately measure the topography of the Moon. These topographic traverses revealed a broad depression up to 8 km deep that can only be a giant impact basin — and the Leibnitz Mountains do mark its rim. Named the South Pole–Aitken basin by the USGS, this 2,500-km-wide big back-side basin (or BBB, as I like to call it) is old and battered. Interestingly, the BBB is the site of most of the few patches of mare material present on the far side. Thus, the formation of the BBB probably thinned the lunar crust (to only 30 km, according to Clementine data), making it easier for magma to punch through to the surface.

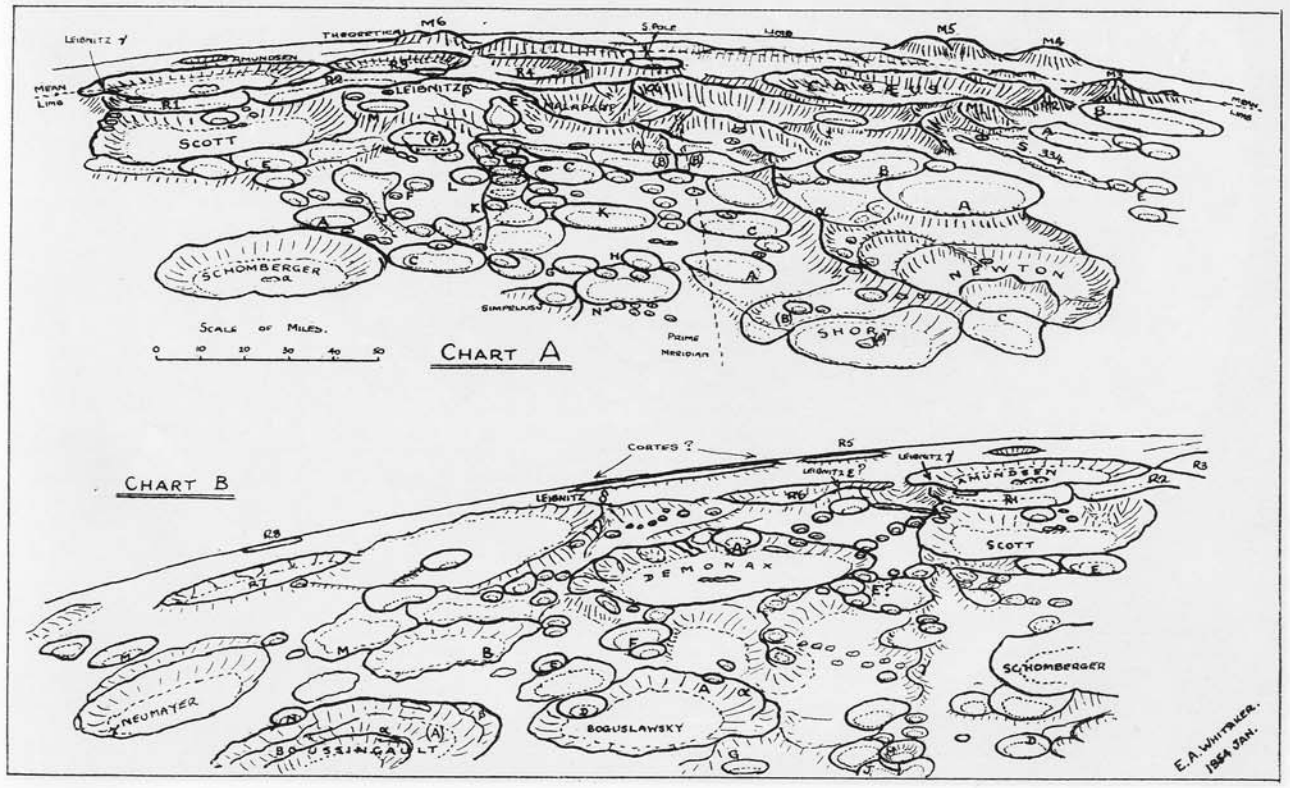
While most regions far from the orbital tracks of the Apollo spacecraft generally have been ignored, the mountainous area of the south pole has been the focus of much discussion, speculation, and engineering study. The reason for this level of interest has been visionary, but in a practical kind of way. If humans are ever going to live on the Moon, we must use resources that are found there, rather than bring everything from Earth. And probably the most important commodity is water, which we drink, use to grow crops, break down to extract air, and make into rocket fuel (both hydrogen and oxygen). The deep, permanently shadowed craters near the lunar south pole may be some of the coldest places in the solar system. If water ever existed on the Moon, some of it may still remain, perpetually frozen in dark repositories near the poles.

Since the lunar samples show that the Moon is bone dry, where would the water originally come from? As briefly mentioned in Chapter 7, an exciting and probably unavoidable source is cometary impacts. A typical comet that comes into the inner solar system is a ball of dirty ice that has a good chance of ultimately colliding with the Moon or a planet. A 2-km-wide comet contains roughly 40 million tons of water! An impact on the Moon would vaporize all the water and eject much of it into space. But some water would probably form a temporary atmosphere around the Moon, and some of the vapor would condense at cold spots at the south pole and be trapped there forever, or at least until we come to use it.

Over the last 4 billion years this scenario may have been repeated thousands of times. But there are also various processes that may have prevented any ice from being preserved. For example, sunlight striking high crater rims could reflect some heat onto the dark crater floors, but would it be enough to facilitate the escape of the water?

One of the goals of all the proposed lunar polar orbiters has been the search for water at the south pole. The Clementine spacecraft looked for ice by probing the dark crater floors with radio pulses. Some of the reflected signals were detected on Earth, and under ideal conditions these data would be capable of determining the existence of ice there. The result announced in December 1996 was that ice is probably present. Detecting it with certainty proved difficult. However, in 1998 a spacecraft specifically designed to answer this critical question was sent to the Moon and found strong evidence in favor of lunar ice. Lunar Prospector, the brainchild of Binder, detected significant amounts of hydrogen at both the north and south poles of the Moon. Since water is the most cosmically likely material to contain hydrogen, Binder and his colleagues (and many other lunar scientists) believe that the presence of water has finally been confirmed. The great surprise was also finding hydrogen at the north pole, which is flatter and contains fewer permanently shadowed crater floors than does the south pole.

One of the tallest peaks near the south pole, one that is probably part of the rim of the Big Back-side Basin, may be an ideal site for a future solar-energy farm because it is exposed to sunlight more than 90 percent of the time. Informally named Mount Clementine, it is designated "M5" on the 1954 map by Whitaker. Future mining of the polar ice may be powered by solar energy captured at Mount Clementine. Perpetual darkness and



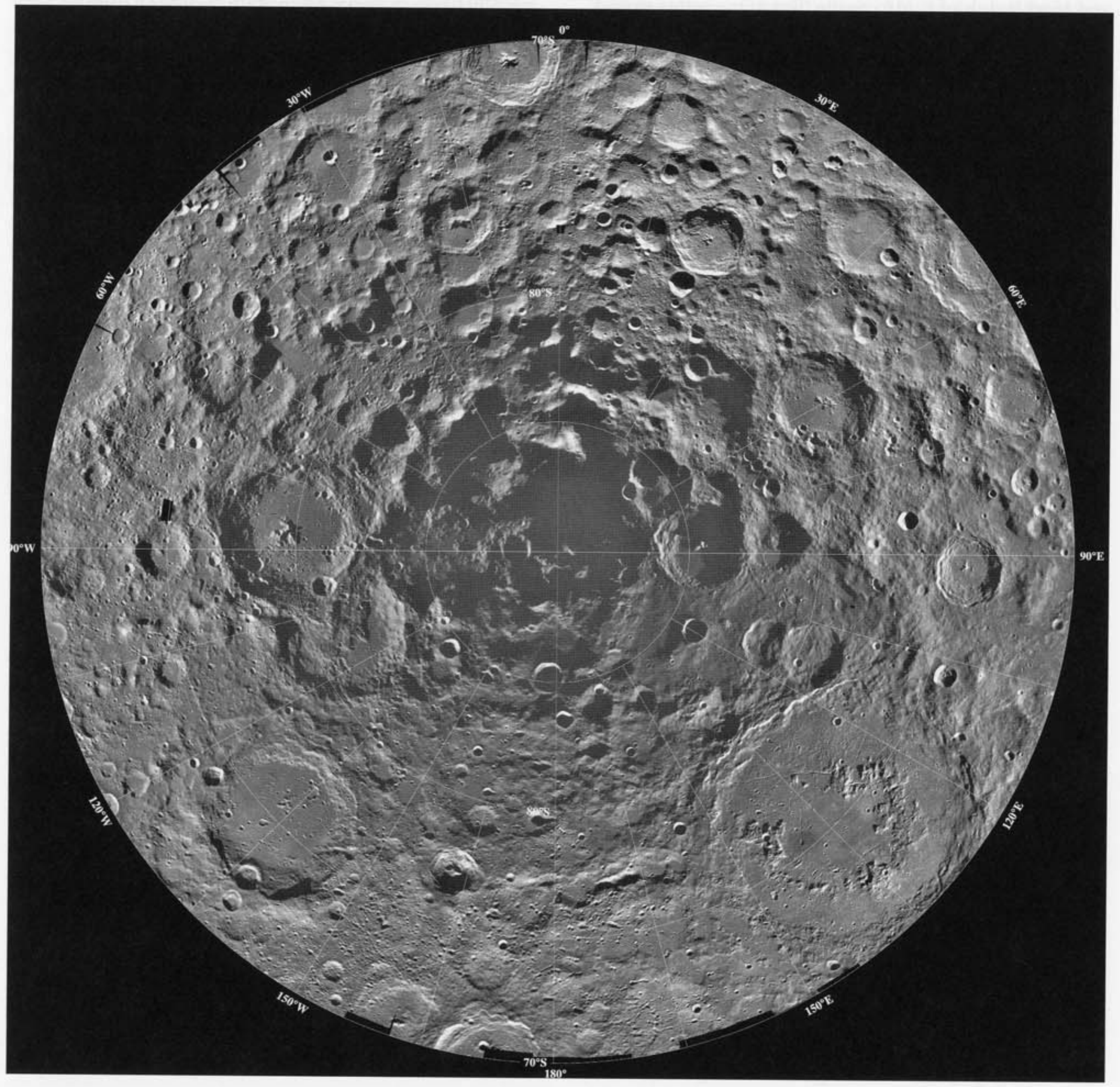
Ewen Whitaker's 1954 map of the lunar south pole is still one of the best. South is up.

nearly perpetual daylight are separated by only a few dozen kilometers on this part of the Moon!

SMOOTH FLOORS, SMOOTH PLAINS

East of a line that runs from Tycho to the Moon's south pole is a broad region not marked by anything particularly spectacular. This area is considered a classic example of lunar highlands and is similar to large tracts of the far side. The region is populated with many relatively subdued, similar-looking, 20- to 60-km-wide flat-floored craters. There are no bright ray craters or any with dramatic terraces or central peaks. The formations here are all old, softened, and nearly anonymous.

Because of the overall monotony of this stretch of highland Moon, it's hard to get your bearings. Start your explorations by locating two adjacent craters, Stöfler and Maurolycus. They are made conspicuous by their large sizes, 125 and 115 km, respectively. Another cluster of large craters lies farther to the east and consists of Pitiscus (82 km), Hommel (125 km), Vlacq (90 km), Rosenberger (95 km), and Nearch (75 km). And a last cluster, farther south and even closer to the limb, includes Helmholtz (95 km), Boussingault (130 km), and Boguslawsky (97 km) — a trio that few observers ever identify at the telescope.

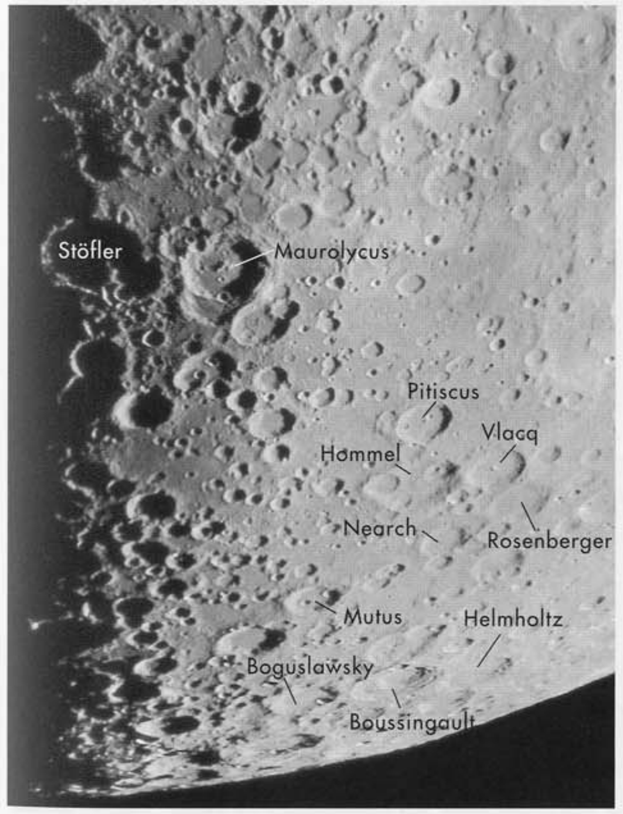


This mosaic of Clementine images shows the Moon's south pole. Moretus is the crater partially shown at the top of the image, and the conspicuous impact basin centered near 135° east and 75° south is Schrödinger.

But these craters are not what make the region interesting. The southeast quadrant is unusual in that the areas between the craters are smooth — if these intercrater plains (as geologists call them) were darker, they would be classified as mare. But because they are bright, questions arise about their origin. In the USGS stratigraphic system these plains are considered pre-Nectarian, that is, older than the oldest dated basin. Are these ancient plains the remains of the Moon's original crust that floated to the surface during the magma-ocean stage 4.5 billion years ago? Or are they light-hued lava flows that predate the mare? The latter was the prevailing view until about 1972.

Wilhelms and his USGS colleagues offered a third alternative. The surprising discovery that similar-looking rocks at the Apollo 16 landing site were not volcanic, as had been widely supposed, but were in fact impact debris convinced Wilhelms and many others that all light-hued pre-Nectarian plains are basin ejecta. Thus the plains in the southeast lunar quadrant — hundreds of kilometers south of the Descartes region, where Apollo 16 touched down — must be associated with an impact basin. But what basin? Wilhelms found one — a battered circle about 700 km in diameter stretching between the craters Mutus and Vlacq. There are even three or four hills in the area that might be the remains of a basin rim.

I thought Wilhelms's putative basin was completely imaginary until altimeter data from the 1994 Clementine lunar orbiter revealed a broad depression, 3 km deep, centered exactly at the basin's proposed location. Because Wilhelms's basin is probably the oldest one on the Moon, its impact ejecta have long since been covered by debris from other basins and cannot be the source of all the surrounding smooth intercrater plains.



The southeast quadrant of the Moon.

But if you look closely you will see that the plains are not all equally smooth. The floor of the crater Nearch is much less pitted and less rough than the floor of nearby Rosenberger. Most of the intercrater plains are rougher than many of the crater floors. To me this indicates that these regions are of different ages and were not formed by a single event.

Despite the Apollo investigations, we still don't have a sample from the smooth highland plains — we still don't know what they are made of. I believe that some of the smooth highland plains, and especially the smooth floors of most of the craters in the Cratered Highlands, may be old volcanic lava flows. Of course, volcanism has long been the refuge of scientists who really don't understand what they see on the Moon!

A LUNAR CATACLYSM?

Comparing the large number of highland craters to the far smaller number of the younger maria demonstrates that there must have been a tremendous decline in the cratering rate more than 3.5 billion years ago, the average age of the maria. During the 1960s Hartmann deduced that the rapid decline in cratering was simply the tail end of the intense bombardment that built the Moon by accretion. But by the end of the Apollo program a radically different proposal was promoted by people who had never counted a single crater.

A group of scientists at the California Institute of Technology specializing in accurate radiometric dating of lunar samples realized that lunar rocks older than about 4.0 billion years were very rare. These "inmates" of the Caltech Lunatic Asylum (as they referred to themselves in their published reports) proposed the notion that after the Moon formed about 4.5 billion years ago, the impact-cratering rate was relatively low, except for an intense spike that occurred

3.95 to 3.85 billion years ago, when nearly all the existing impact basins were formed. If most of the basins formed in a very short time, the fragmented rocks or breccias that astronauts collected at six landing sites would thus all have the same maximum age.

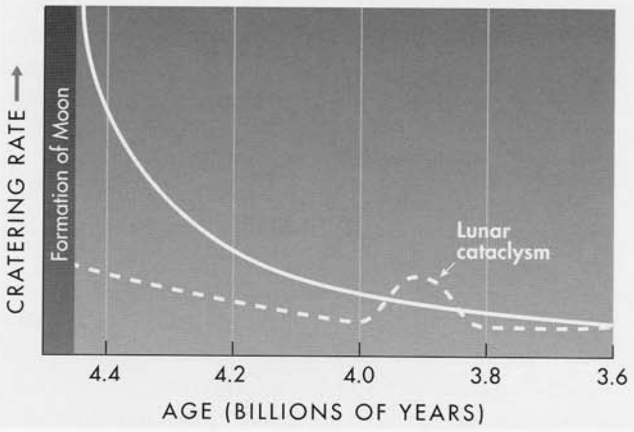
Hartmann immediately challenged this idea, calling it a misconception. One major problem with the theory is that there is no easy way to store the large projectiles that formed the 40 or so lunar basins and thousands of large craters during the 600-million-year interval between the birth of the solar system and the purported lunar cataclysm 3.95 billion years ago. Models of the formation of the planets show that all the leftover debris should have been quickly swept up by collisions with the planets or ejected from the solar system.

Hartmann believes that the absence of older lunar rocks is a natural consequence of the way the Moon formed. Prior to 4.0 billion years ago, the rate of cratering was so high that each new crater destroyed preexisting ones. This "saturation cratering" created the brecciated rocks the astronauts picked up on the Moon. But the rocks were constantly having their ages reset. If a rock were in the target area of a new impact, the extreme pressure and temperature of the collision let the argon, lead, and other elements used to date ancient rocks escape to space. In an environment of intense impact cratering, the breccias would simply assume the apparent age of the last time they were strongly shocked. Hartmann proposed that the interval 3.95 to 3.85 billion years ago marks the time when the rate of cratering finally declined enough to stop resetting all the breccia clocks.

Another possible explanation comes from Lawrence Haskin of Washington University. He proposes that Imbrium is such a giant basin that its formation would have scattered shocked fragments all over the Moon — thus contaminating the surface with rocks approximately 3.85 billion years old.

Deciding between the competing theories is important if the Moon is to serve as a guide to the solar system's history. As Australian National University's Ross Taylor, a prolific contributor to lunar studies, has pointed out, if the lunar cataclysm really occurred, then the Moon's cratering history is unique and thus cannot be used to calibrate cratering rates on Mars, Mercury, and elsewhere in the solar system. If Hartmann is correct, broadly similar cratering declines likely affected all the terrestrial planets, and 3.9 billion years probably marks the boundary between ancient cratered terrain and younger, lightly cratered materials around the solar system. Surprisingly, even though Taylor, Ryder, and others support the lunar-cataclysm idea, nearly everyone still accepts lunar-based chronologies for other planets! Someday, when geologists determine the ages of rocks on Mars and Mercury — and stratigraphically old features like the South Pole–Aitken basin — the issue of the lunar cataclysm will be resolved.

CRATERING-RATE MODELS



Did the cratering rate steeply decline (solid curve), or was it already low (dashed curve) when a spike occurred about 3.9 billion years ago?

A HELL OF A CRATER

The highlands that dominate the southern region of the Moon are chock-a-block with impact craters. Although there is little variety among many of the craters there, a few are exceptions. One is so large and battered that it escaped notice for a long time. Because it contains the relatively conspicuous 33-km-wide crater Hell, the broader crater was informally known as the Hell Plain. Later it received the official name of Deslandres. Like Clavius to the south, this crater is so large (235 km) that the first question a good lunar geologist might ask is, Why does it lack the concentric-ring structure of an impact basin? Deslandres is very shallow, so perhaps it does have an inner ring that lies buried beneath volcanic flows or impact ejecta.

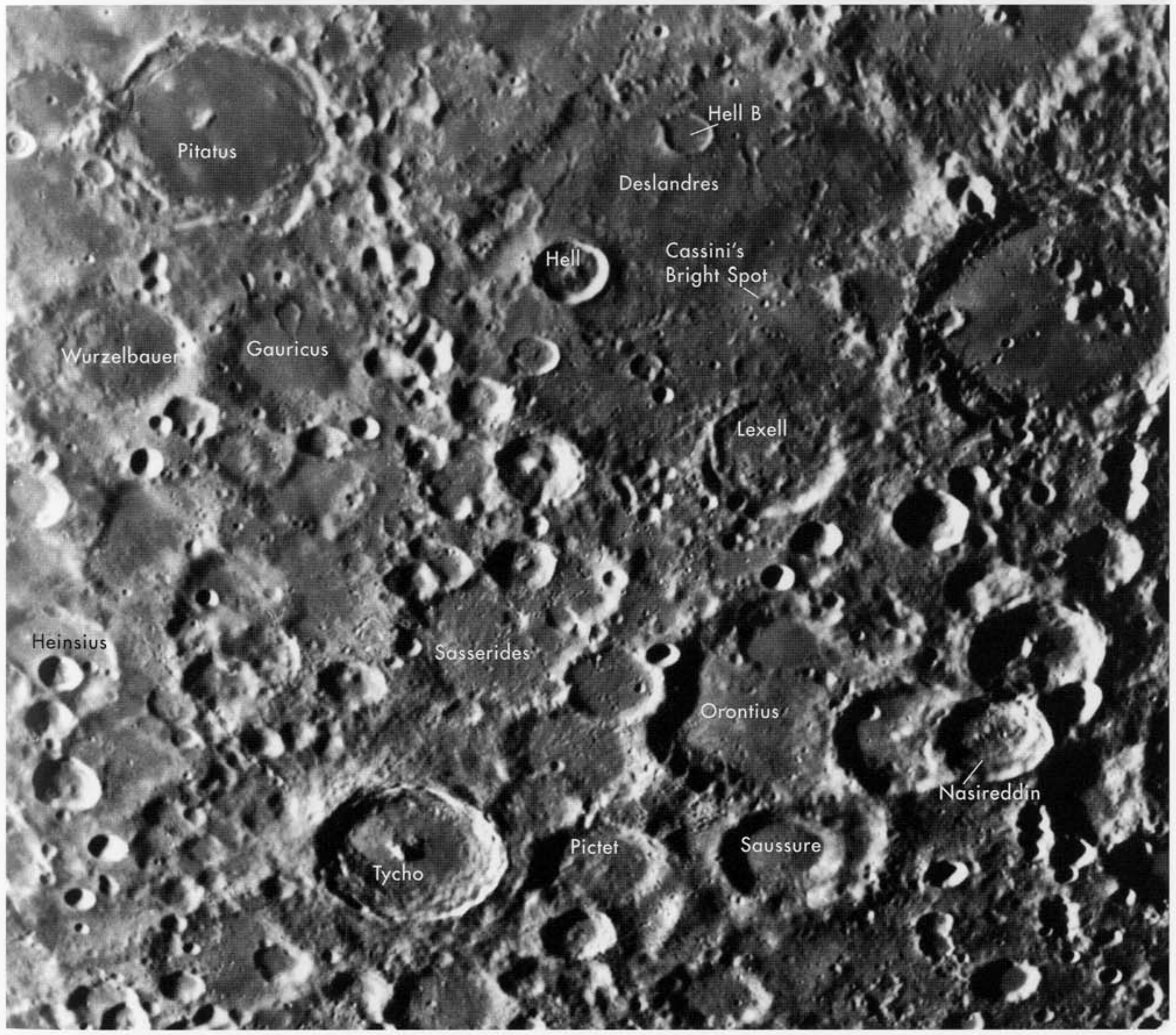
But what we can see is interesting. There is a small patch of dark mare material in the northeast corner of Deslandres, and nearby is Hell B, a 22-km-wide shallow crater with a partly broken rim. Hell B's smooth floor suggests that lava flooding occurred. At full Moon, a bright spot in east-central Deslandres contrasts with the darkness of the mare patch. In this location, the great 17th-century astronomer Giovanni Domenico Cassini thought he saw a bright cloud that soon dissipated, leaving behind a newly formed crater.

Appearing as a starlike brightening in one of Tycho's rays, Cassini's Bright Spot is a 3-km-wide fresh crater with spikes of rays extending out a few tens of kilometers. If this small crater formed at the same time as Tycho, Cassini was looking about 100 million years too late. However, the crater may very well be much younger.

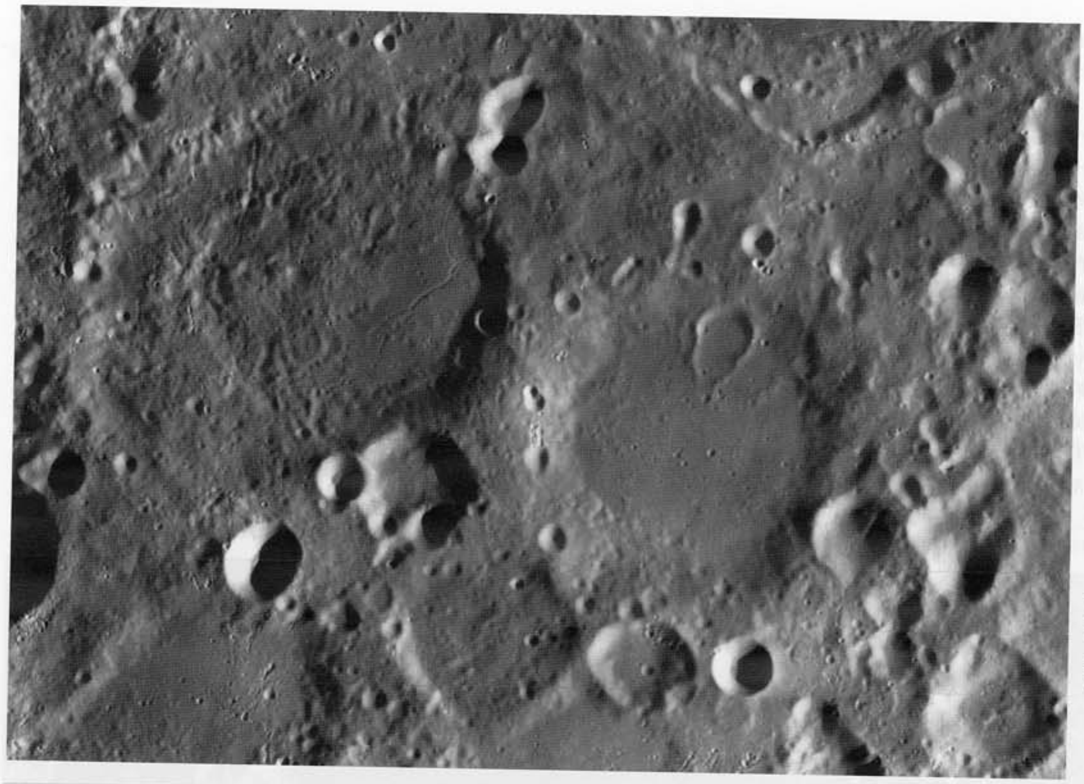
Two distinctive chains of secondary craters cross Deslandres. The one that is easier to see consists of five shallow craters in a line on the northeast quadrant of the floor. The other chain starts north of Deslandres on the shore of Nubium and cuts Deslandres's floor north and west of Hell. The USGS map of the Moon shows these as secondary crater chains associated with the Imbrium basin, but neither chain points to Imbrium or any other reasonable source.

Hell itself is a Triesnecker-class crater with smooth interior walls and a slump-filled floor. More unusual is a crater to the southeast — Hell slightly overlaps a somewhat larger, older crater whose north rim is almost completely gone. The floor of this crater is nearly filled by material of the same texture that covers Deslandres. This older crater is simply a more obscure version of Lexell, a 63-km-wide crater perched on Deslandres's southern rim. Lexell clearly slopes to the north (its northern rim is completely missing), and its floor has been embayed by the same stuff that infills Deslandres.

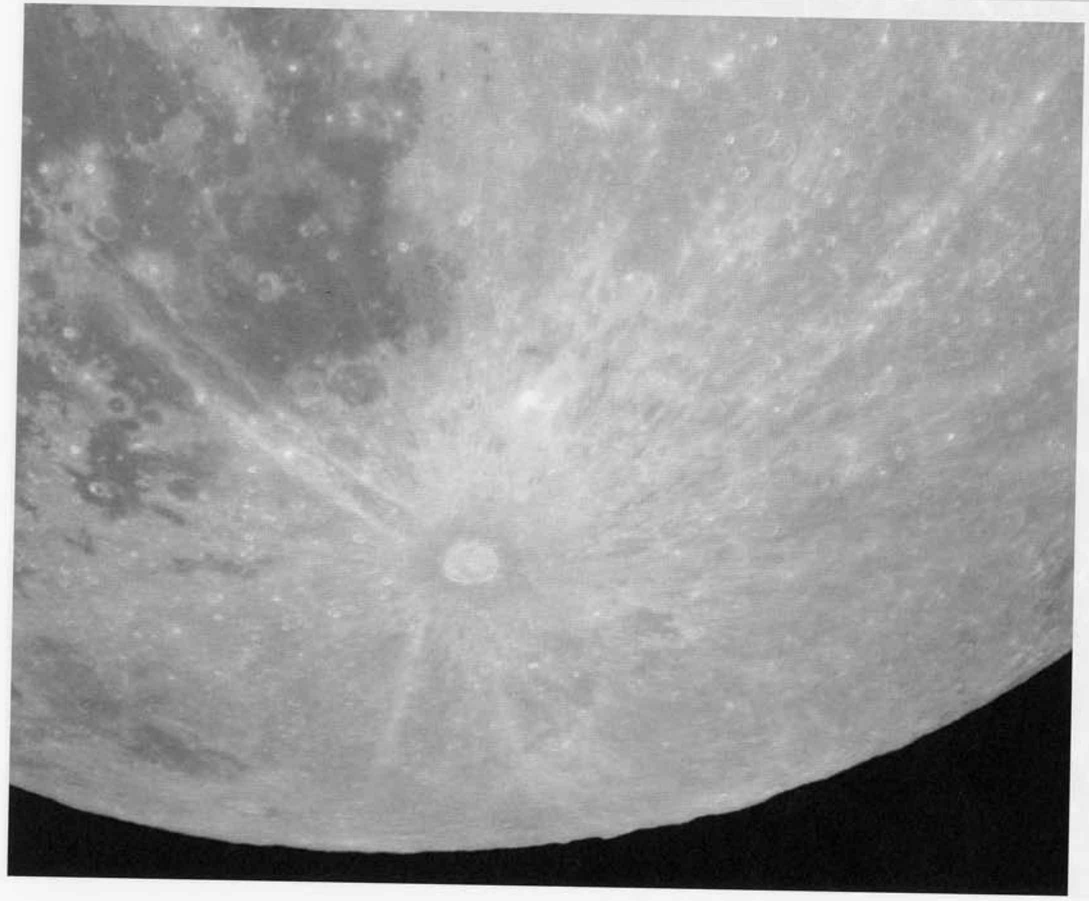
Just west of Deslandres is a woebegone crater with unique features. Gauricus (79 km) has a laid-back, evenly rounded rim that is unique on the Moon. The smoothness and lack of detail on the crater wall are contrasted with the abrupt transition to a smooth, flat



Tycho to Deslandres.



This detailed Lunar Orbiter IV image shows the large degraded craters Wurzelbauer (left) and Gauricus (right).

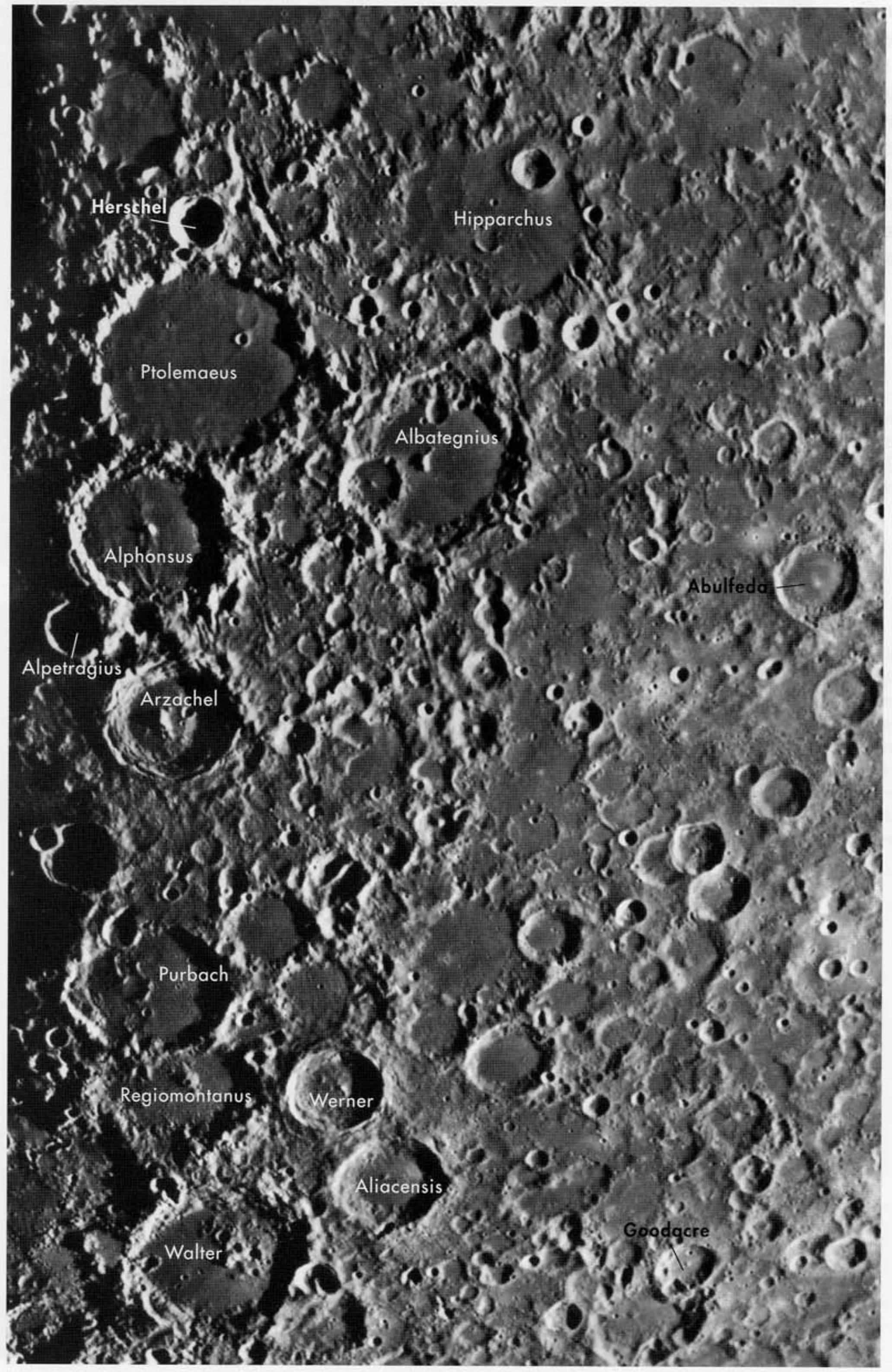


The lack of mare deposits in the southern highlands makes it nearly impossible to identify any feature except dark-rimmed Tycho. The best views of features can be had by following the night-to-night progress of the terminator as it sweeps across the region.

floor. I don't know why this crater's rim is so featureless when most craters of similar size and age carry hints of terrace slump blocks.

Another Gauricus mystery is that its floor material has apparently flooded some probable secondary craters, yet the floor does not look like mare material. However, during full Moon you can observe that parts of the floor have low reflectivity, like the nearby Mare Nubium. How can this be? Most likely the entire floor of Gauricus was flooded with mare lavas, but most of the floor was subsequently lightened and pitted by ejecta, perhaps from Tycho. Probably many highland craters harbor dark mare lavas under a dusting of obscuring ejecta.

Next to Gauricus is Wurzelbauer, another old crater whose rim is as narrow and nondescript as its neighbor's is broad and unusual. Wurzelbauer's claim to fame is its peculiar and rough central plateau. Kuiper thought that its floor was disturbed by incipient melting, and there is indeed a smooth patch with a rille on the floor's eastern quadrant. The rough floor appears to be cut by a crude arcuate trough. Is this mass of rugged material ejected from the Humorum basin impact, or is it something else? Interestingly, another lumpy set of mounds fills the floor of the nearby crater Gauricus A, just south of the parent crater. Maybe lumps are contagious!



The Great Peninsula.

14

The Great Peninsula

Most of the highlands of the Moon are either located on the far side or are scrunched so close to the limb that specific craters are often hard to identify. But almost right in the middle of the Moon there is one place where the highlands are well displayed without foreshortening. Extending north from the cratered region surrounding Tycho is a 750-km-wide squared-off peninsula of highlands surrounded on three sides by impact basins and their lavas. Alter called this the Great Peninsula, noting that it was the "greatest intrusion of continental terrain into a dominantly mare region." He was right, except that the mare came later and, flowing into impact basins, intruded onto the highlands. This area is also visible with the naked eye at full Moon. It makes up the face of the "Lady in the Moon," with maria Serenitatis, Tranquillitatis, and Nectaris forming her hair.

The Great Peninsula is dominated by its largest and most famous crater, Ptolemaeus, which is part of a conspicuous crater trio that includes Alphonsus and Arzachel. Older large craters like Hipparchus, Albategnius, Purbach, and Regiomontanus help to fill the western half of the peninsula. Strangely, the eastern side is marked only by smaller, monotonous features of little interest. The entire Great Peninsula has been scoured by Imbrium basin ejecta and secondary crater, and many of the large craters have unusual floors. One of these craters, Alphonsus, was alleged to have been the site of minor volcanic activity in 1958.

CRATERS, EJECTA, AND MEGAREGOLITH

The Great Peninsula has had a tumultuous history. The region's preexisting topography was swept away by the giant excavation that formed the Gargantuan basin. Over the next few hundred million years the area was repeatedly scoured, shaken, and buried by ejecta from the surrounding basins: Nubium, Tranquillitatis, Serenitatis, Nectaris, and lastly Imbrium. And throughout these epochs it was bombarded by thousands of crater-forming projectiles. This was not a quiet neighborhood.

These giant cratering events helped to form the upper layers of the Moon. Every impact digs a hole and spreads excavated debris in rings around the crater. Because big holes eject lots of material over great distances, basin ejecta should dominate the Moon-wide debris layer. Based on measurements of the number and sizes of impact craters and basins on the Moon, lunar scientists estimated how thick the resulting ejecta layer would be if it were spread uniformly over the Moon. The answer is approximately 2 km! Naturally, this material is not spread evenly but is thickest near the biggest basins and thinnest in the region near Tycho, the point on the Earth-facing side of the Moon most distant from the basins. This debris layer is called the *megaregolith*, because it is simply a much larger version of the same sort of breaking, fracturing, pulverizing, and melting of lunar rocks by innumerable tiny impacts that generate the lunar soil layer, or *regolith*.

Since the highest rate of cratering occurred during the first 600 million years of lunar history, most of the megaregolith was formed at that time. Naturally, a thinner layer would be expected for a younger surface. In fact, the cratering rate diminished so rapidly that the lunar maria (roughly 3.5 billion years old) have no megaregolith, simply a 5- to 10-meter-thick regolith. Incidentally, the existence of the megaregolith was confirmed by seismometers placed on the Moon by Apollo astronauts. As seismic waves from lunar quakes travel near the lunar surface, they slow down. This behavior is consistent with the existence of a layer of broken rocks and dust about 1.5 km thick. It's wonderful when theory and completely independent observations agree!

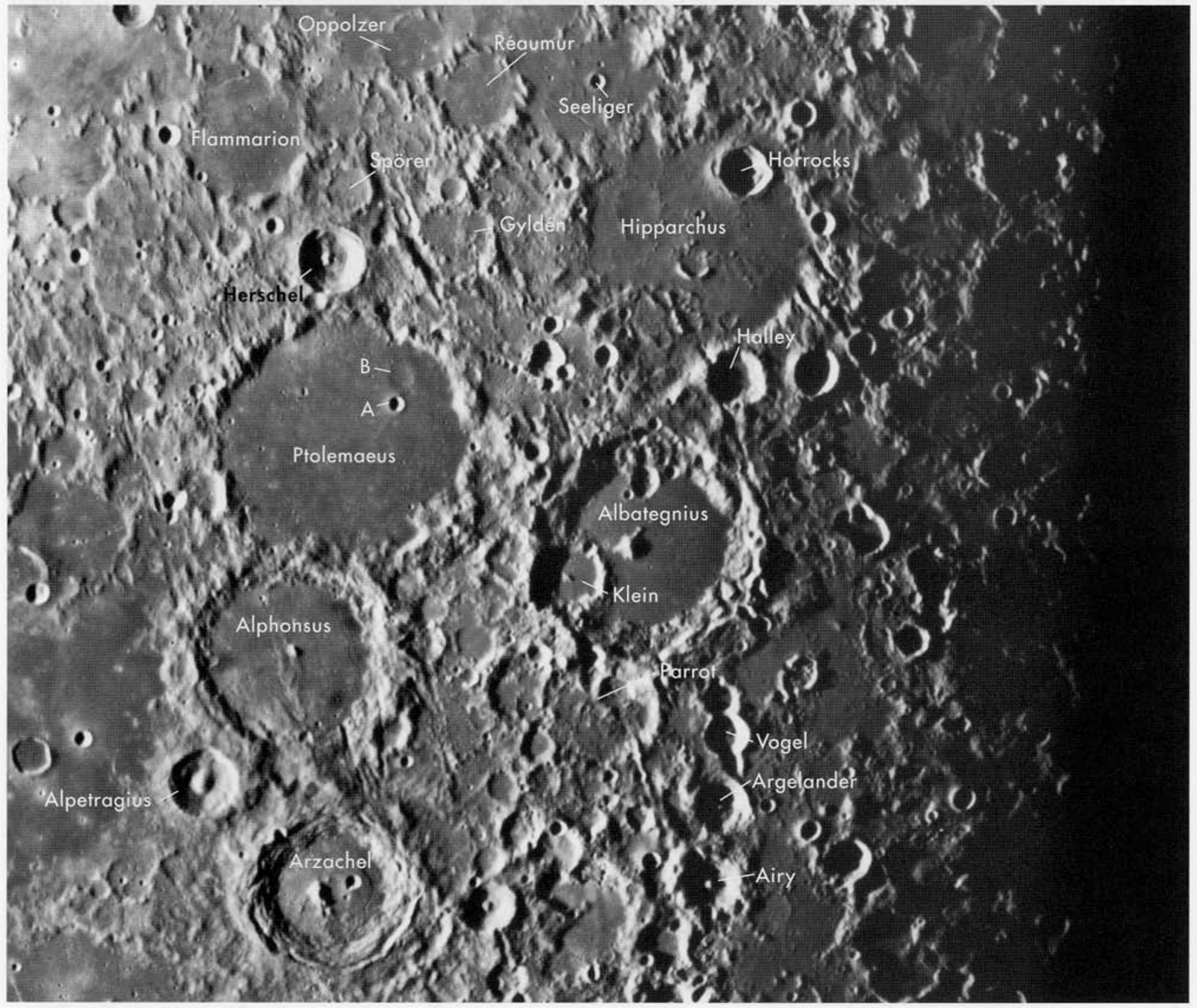
From the scientist's point of view the megaregolith provides an important means of sampling rocks originating deep within the lunar crust. All sampling of the lunar surface by Apollo astronauts and by remote sensing from Earth measures the regolith, which masks the more ancient bedrock below. But any brecciated lunar regolith fragment may contain a piece of crust brought to the lunar surface from tens of kilometers below by a great impact. Thus, searching for small pieces of crustal rock in larger regolith samples is a major activity among scientists trying to look farther down into the lunar crust and farther back into lunar history. Successful searches abound. For example, unusual fragments in some possible megaregolith samples excavated by North Ray crater at the Apollo 16 site are among the oldest (4.25 billion years) pieces of rock returned from the Moon.

The megaregolith may have an effect that is measurable with Earth-based telescopes. The 1.5- to 2-km thickness of fragmented rock overlying bedrock gives the lunar highlands two distinctly different layers. This may help to account for some of the subtle differences in geometry between highland and maria impact craters. About 20 years ago, my Brown University colleagues Mark Cintala and Jim Head and I discovered that central peaks are more common in fresh craters formed on mare material compared to ones on the highlands. Similarly, terraces are much more common in fresh mare craters than highland craters. We speculated that the differences are due to the strength of rock layers — the megaregolith of the highlands is very fragmental and weak compared to the more coherent mare lavas. Thus, the megaregolith would absorb and dissipate impact energy, which in the coherent lavas would rebound, forming a central peak, or cleanly fracture, forming terraces.

PTOLEMAEUS

Although it is shallow and lacks rays and a central peak, Ptolemaeus is one of the most familiar craters on the Moon. One reason is that it is large — 153 km wide, 2.4 km deep — and well placed for telescopic observation. It also has enigmatic features that are only fleetingly visible.

When the Sun shines moderately high over Ptolemaeus, the relatively large (9 km) bright impact crater



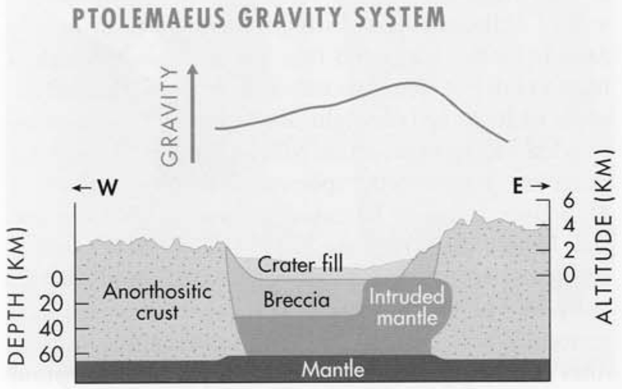
Ptolemaeus, Alphonsus, and Arzachel.

Ptolemaeus A and perhaps three or four craterlets a few kilometers in diameter are visible on its floor. But when the Sun is low, the real action starts — all sorts of shallow "saucers," or hollows, typically 5 to 10 km in diameter, become visible. The largest and easiest to see are Ptolemaeus B (about 18 km across) to the north of A and a smaller one that is south of A and connected to it by a low ridge. The other fairly obvious saucer is on the southwest portion of the floor and is conspicuous under a very low Sun.

In the hour or so it takes the terminator to sweep across Ptolemaeus's floor, additional saucers seem to appear from nowhere and then quickly disappear. The champion saucerologist seems to have been Wilkins, the indefatigable British Moon mapper. His 1955 chart depicts more than two dozen saucers as dashed rings. How many can you see?

So what are these saucers adorning the floor of Ptolemaeus? A commonly held view has been that they are craters covered by subsequent lava flows. This suggestion seems best because there is evidence that some of the saucers are definitely buried features. For example, to the east of Ptolemaeus A there is a faint chain of saucers that appears to be radial to the Imbrium basin. Considering that the area around Ptolemaeus is cut by many Imbrium secondary crater chains, it seems likely that this saucer chain originated with the Imbrium impact but was subsequently covered by some material. But what? Is the material lava or perhaps pulverized ejecta that arrived from Imbrium moments after the crater chain formed? A view of Ptolemaeus at full Moon reveals that its floor is not dark like maria but bright like the highlands. So most likely Imbrium ejecta ponded in Ptolemaeus, filling it enough to hide a central peak and nearly burying earlier impact craters and gouges on its floor.

This explanation is the best we can do, yet nearby Albategnius (136 km) also has a smooth floor with similar, but little-known, saucers and saucer chains. But based on the small number of fresh impact craters on it, the floor of Albategnius is significantly younger than the Imbrium impact — the material partially filling Albategnius could not have come from Imbrium.



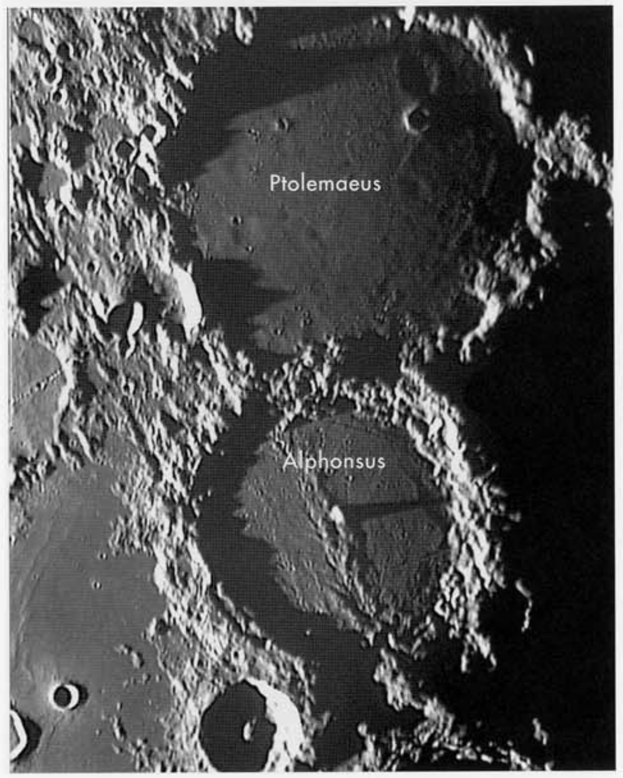
The observed gravity variations over Ptolemaeus can be explained by a dense uprising of mantle material under the crater floor.

Maybe the light material in Albategnius and Ptolemaeus is a light-hued volcanic deposit. The idea of volcanic fill is consistent with a strong gravity anomaly at Ptolemaeus that is thought to be due to an intrusion of dense mantle material that nearly reaches the bottom of the original crater floor on the eastern side. The intrusion could be the magma chamber that fed surface lava flows.

One more thing about the floor of Ptolemaeus: during the 1930s German observers reported that its color changes from gray after sunrise to olive green near full Moon, then to a yellow hue near sunset. This was cited by Firsoff as evidence of the existence of some primitive form of lunar vegetation (lichen was proposed) that would green up in response to sunlight and then wither away at sunset. Sadly for potential lunar vegetarians, Apollo samples contain neither green cheese nor green lichen.

ALPHONSUS — VOLCANISM THEN AND NOW?

Moving southward we find Alphonsus, a spectacular crater 118 km in diameter, with a rim that clearly over-

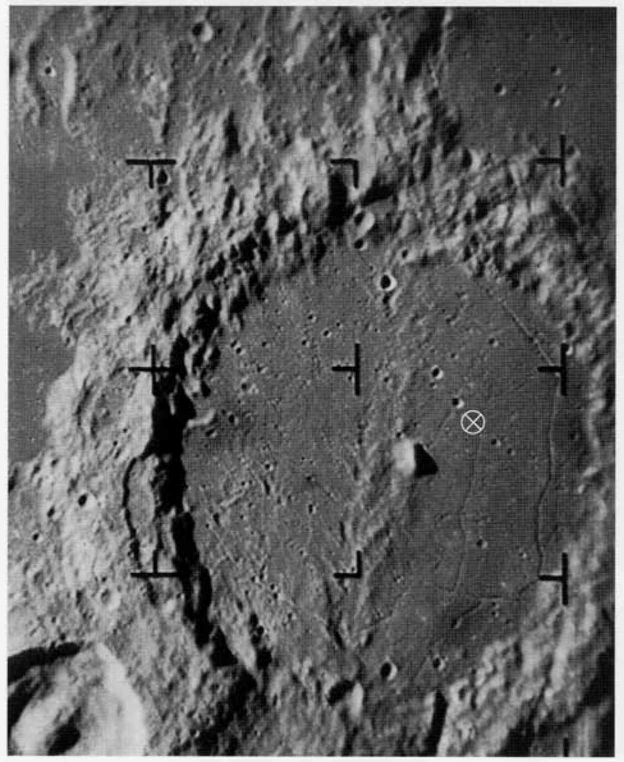


Sunset on Ptolemaeus and Alphonsus.

laps that of Ptolemaeus. Although Alphonsus is thus younger, it too has been pummeled by the formation of the Imbrium basin, whose ejecta cut irregular chains through the crater's southern rim. Like Ptolemaeus, the floor of Alphonsus is relatively smooth and light hued, but it also contains rilles, dark spots, a central peak, and a unique central ridge.

Alphonsus was first seen well in television images transmitted by the Ranger 9 spacecraft before it hard-landed (as its planned crash landing was euphemistically called) on the crater floor. The TV pictures confirmed what is visible at the telescope — certain features are of volcanic origin. Most conspicuous are six dark patches along the east and west inner walls. The five dark spots along the east wall are connected by a thin rille, and each one has a small crater (1.0 to 1.5 km wide) at its center. These are clearly not impact features. The dark patches are most certainly deposits of ash erupted from small volcanic craters.

In 1973 Brown University's Jim Head and Thomas McGetchin of MIT proposed that these very flat little pits are lunar cinder cones. Now, anyone who has tried to climb the steep-sided Sunset Crater near Flagstaff, Arizona, knows that cinder cones are anything but flat! But that's on Earth. The shape of a volcano or any other landform depends on many different factors. Cinder cones are formed by the low-energy, nearly vertical ejection of small clots of magma (cinders), which are carried through the air on ballistic trajectories. When the cinders land they tumble downhill, coming to rest at their angle of repose. On the Moon the process may be different. Will the energy of eruption be the same? Will the size of the cinders be altered? Will the angle of repose change? We don't know about all of these factors, but we absolutely do know that the Moon doesn't have any air, so there will be no air resistance to slow down the flying cinders. And the Moon's gravity is only one-sixth that of Earth, so an eruption of the same energy on the Moon should propel cinders six times farther than on Earth. Models of small volcanic eruptions under lunar conditions (low gravity and no air resistance) nicely match the observed low cones and broad ash patterns of the dark halo craters in Alphonsus. This was one of the first convincing examples of comparative planetology — knowledge of a geologic process on one planet (Earth) helped us understand an unusual feature on another planet (the Moon).



Ranger 9 transmitted this image of Alphonsus from an altitude of 415 km before crash landing on March 24, 1965. The impact site is indicated.

There is one footnote to the dark-halo story, courtesy Thomas McCord. While at MIT he pioneered a method of deducing the compositions of lunar and planetary surfaces from their reflectivity at different wavelengths and showed in 1968 that the dark spots in Alphonsus contained mare material. More recent spectral studies by Hawke and his University of Hawaii colleagues confirmed this by finding high concentrations of olivine and pyroxene (important minerals in mare basalts) in the halo material. Thus, explosive eruptions of marelike material occurred within at least one highland crater.

The eruptions that produced the dark halos on the floor of Alphonsus are undated but probably occurred 3 to 4 billion years ago. Does activity still continue there? On October 26, 1956, Alter used the 60-inch telescope at Mount Wilson, California, to take a series of photographs of Ptolemaeus, Alphonsus, and Arzachel. Upon examining his pictures, Alter believed that those taken in blue light showed the rilles near the northeastern wall of Alphonsus less distinctly than those in nearby Arzachel. Alter suggested that volcanic gas had leaked from a craterlet along the rille and obscured the surface while he took the blue-light photographs. This observation led a Russian scientist, Nikolai Kozyrev, to initiate a program of systematic spectroscopic observations of Alphonsus to see if he could determine what the gas was. Finally, on November 3, 1958, Kozyrev obtained a spectrum that seemed to show emission bands apparently due to the absorption of gaseous carbon. The announcement of this "eruption" caused a sensation. Alter excitedly proclaimed, "With the possible exception

of the Russian photographs of the far side of the Moon, Kozyrev's spectrum is the most important single lunar observation ever made." Wow! (See the September 1999 issue of *Sky & Telescope*, page 118, for a more detailed account of this story.)

The seemingly fantastic conclusions of Alter and Kozyrev have to be kept in context. Most Russian and British scientists of the 1950s believed that lunar craters were volcanic in origin. The proposal that the central peak of Alphonsus was an active volcanic cone, and that the enclosing crater was a volcanic caldera, was not as outlandish then as it might seem now. Modern lunar scientists have generally forgotten (or are ignorant of) this pre-Apollo episode because the volcanic origin of craters has been completely discredited. We still don't know what, if anything, Kozyrev and Alter observed, but, thanks to Hawke's spectral studies, we do know that the central peak of Alphonsus is virtually pure anorthosite — an uplifted portion of the ancient lunar crust. It is certainly not a volcanic peak. Nonetheless, Kozyrev's peculiar observation was partially responsible for Ranger 9 being targeted at Alphonsus.

Another consequence of Kozyrev's report was the plan to establish America's first Moonbase on the floor of Alphonsus in 2015 AD. At least that's the scenario depicted in Ben Bova's 1987 book *Welcome to Moonbase*. The book is a fictional guide for future "Luniks" arriving at their new home. Alphonsus was selected for the lunar base because it is near the center of the Moon and thus easily accessible from Earth and because the escape of Kozyrev's gases provided a source for extraction of hydrogen, carbon, and nitrogen. I hope and yearn for there to be a lunar base someday, but there is no compelling reason for it to be at Alphonsus.

Nikolai Kozyrev.

ARZACHEL AND ALPETRAGIUS

The three craters Ptolemaeus, Alphonsus, and Arzachel make a very attractive trio near the center of the Moon. There is a progression of morphology from wide, battered, and shallow to small, round, deep, and relatively fresh. Arzachel has a broad, wreathlike, terraced inner wall, with elongated depressions along the crest of the southern rim. The smooth floor hosts an off-center central peak, various low hillocks on the south and west, and an arcuate rille along the east wall. This rille is unusual because at sunset a long shadow is cast toward the eastern wall of Arzachel — the crater floor west of the rille must be higher than the floor east of it, so perhaps the rille is also a fault.

Nearly nestled between Arzachel and Alphonsus is a prominent crater with arguably the most unusual

Alphonsus, Alpetragius, and Arzachel as imaged by Lunar Orbiter IV.

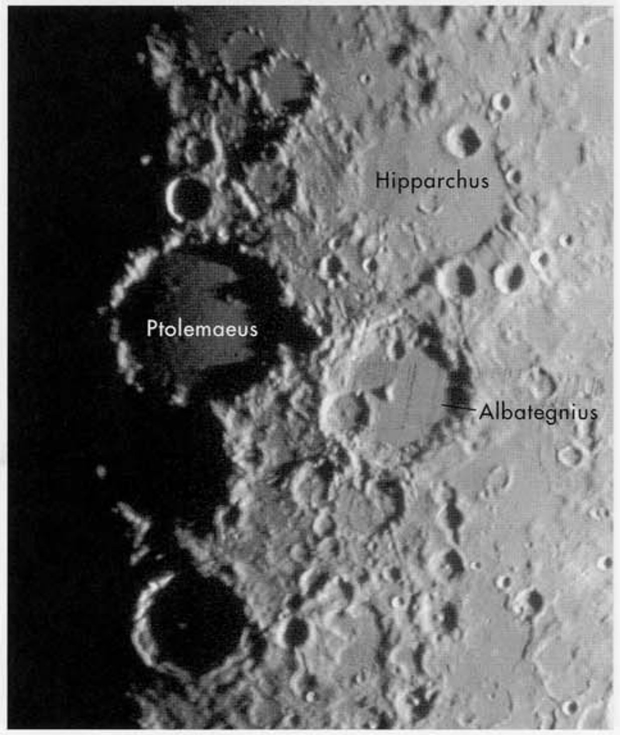
central peak on the Moon. Alpetragius is 40 km wide and nearly 4 km deep, but it has no floor. Instead there is a broad domical peak. Kuiper noted that sometimes Alpetragius looks like a bird's nest with two eggs, one of which is the landslide on the north wall. But I only see one egg — and it's an ostrich egg! An instructive comparison is with Herschel, just north of Ptolemaeus, which is nearly the same diameter and depth (41 km wide, 3.8 km deep). Herschel is a normal Triesnecker-class crater, with small central peaks, terraced walls, and a flat floor with an irregular outline.

Central peaks form by the rebound of the underlying rocks compressed by the force of impact. Considering that such peaks usually occupy only about 30 percent of a crater's floor, there must have been some unusual aspect of the Alpetragius impact that accounts for its wide peak. Naturally, the proponents of volcanic origins for lunar craters regarded the peculiar peak as proof of their ideas. Spurr thought the peak was a "protuberant dome" that had solidified rather than bursting to form a crater. This idea stems directly from the early 19th-century "craters of elevation" theory, which postulated that terrestrial volcanoes are giant bubbles formed by the upheaval of the crust. But long ago, observations showed that no Earthly volcanoes formed from bursting bubbles; it's very doubtful that any ever did on the Moon either.

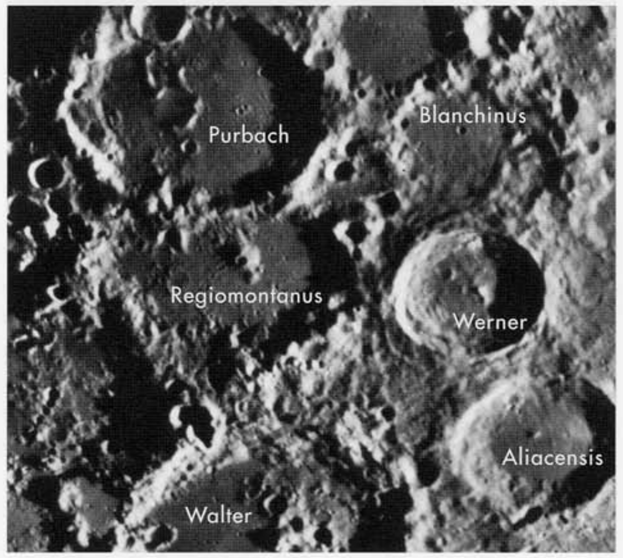
Before the Sun rises over Ptolemaeus and Alphonsus, be careful not to confuse them with a similar pair to the east. Hipparchus (150 km) is a heavily damaged version of Ptolemaeus, with a large floor and rim cut by Imbrium ejecta. Nearby is Albategnius, whose off-center, arcuate peak gives it a resemblance to Alphonsus.

Another impostor crater in this region is Werner (70 km wide, 4.2 km deep), south of the Hipparchus-Albategnius chain. This crater looks very much like Tycho, and I admit to being fooled more than once when viewing the terminator just before first quarter. At this time Tycho is still in shadow, and Werner is a passable imitation — at least for a moment or two.

Immediately west of Werner is Regiomontanus (125 km), an old, battered crater that has been the subject of controversy. For those who claimed that lunar craters were volcanoes, Regiomontanus was regarded as prime evidence because its central peak is topped by a prominent pit. Volcanists interpreted this peak as a true volcanic cone. Supporters of the impact origin of craters responded that it's hardly surprising that somewhere on the Moon a random impact would occur atop a central peak. High-resolution Lunar Orbiter images revealed that most of the other suspected peak pits are more apparent than real, but the Regiomontanus pit is indisputable and looks for all the world like a normal impact crater. Someday lunar geologists will pick up samples from the crater and at last solve the riddle. But if you can't wait, just remember that we understand the origin of central peaks in terrestrial and lunar impact craters, and that there's no way that the impact crater Regiomontanus could have formed without a rebound peak.



Ptolemaeus east.

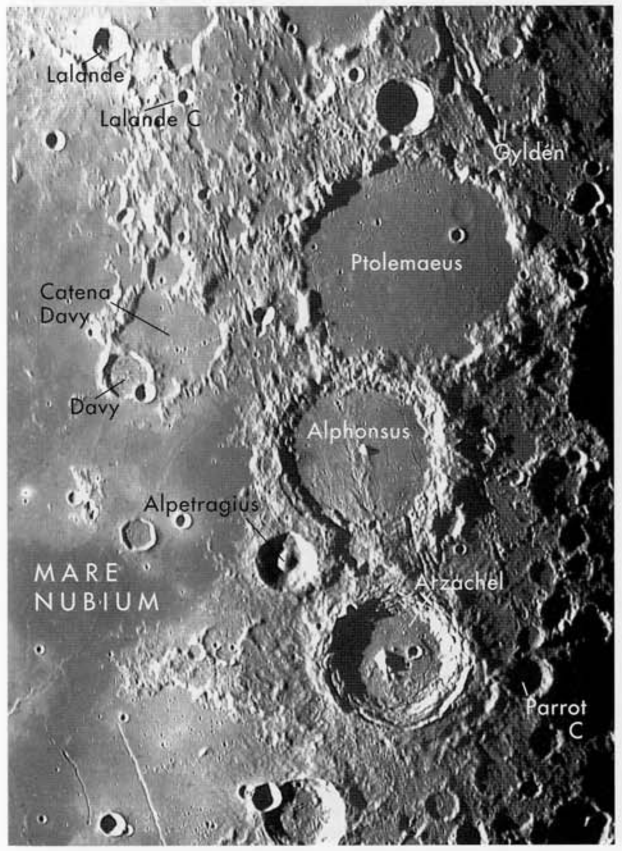


Regiomontanus and Werner.

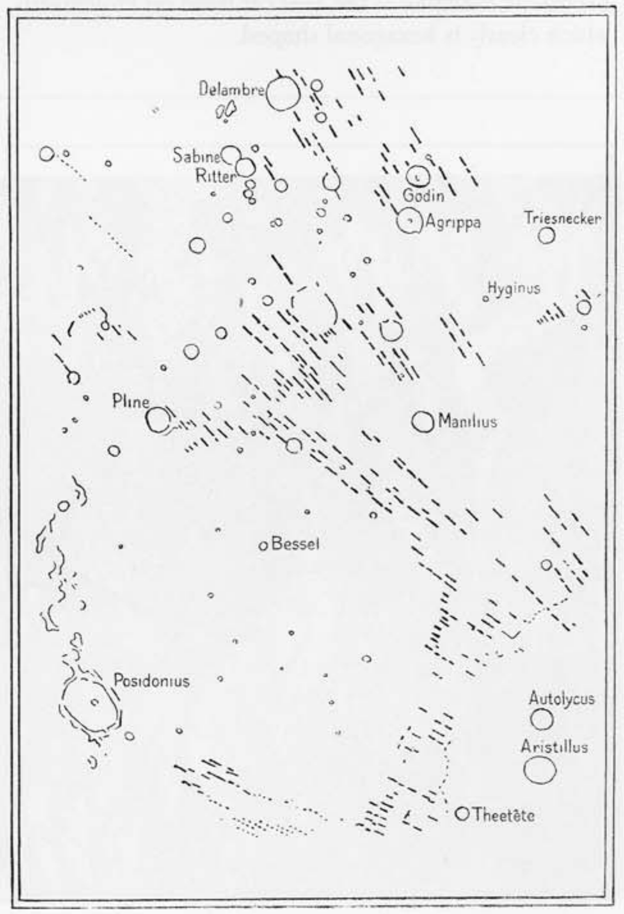
STRAIGHT RIMS AND LINEAMENTS

The western half of the Great Peninsula is one of the best places on the Moon to see the linear features that were named Imbrium sculpture by Gilbert. In addition to the furrows that cut into the rims of Ptolemaeus and Alphonsus, long troughs cross the nearby highland terrain. The longest is west of Ptolemaeus and Alphonsus, extending about 225 kilometers from the small crater Lalande C to the rim of Alphonsus. Look at this trough and you will see that it is made up mostly of coalescing craters with smooth floors. A similar furrow runs from east of Alphonsus nearly 200 km to the south-southeast. It is overlaid, and thus interrupted, by the younger crater Parrot C, just east of Arzachel. A few other shorter troughs are visible near the craters Hipparchus and Albategnius.

You don't have to be a certified lunar scientist to see that these troughs are radial to the Imbrium basin, though no one noticed before Gilbert, just over a century ago. But people weren't very interested in the Moon then nor 40 years later when French astronomers Gabriel Delmotte and Maurice Darney rediscovered "le Système Imbrien." Baldwin's independent recognition of the network of troughs also made little impact on traditional lunar mappers, but Urey and Kuiper, who brought respectability to lunar studies, immediately understood the importance of these troughs. Even so, the exact mechanism for forming these features proved elusive. Kuiper, who prided himself on his acuity at the telescope, believed that he could see massive blocks at the downstream end of some of the troughs. One example he cited is the short valley that cuts through the crater Gyldén, just northeast of Ptolemaeus. At its southern end the valley narrows to a hill that casts a shadow. This hill is Kuiper's block, which he believed ploughed 100 km across the lunar surface before coming to rest remarkably undamaged. Examination of telescopic and Lunar Orbiter spacecraft photographs provides no convincing evidence for the block's existence. It's difficult to understand how such a brilliant scientist could propose such a physically implausible scenario, but lacking an understanding of secondary-crater formation (an idea that wasn't developed until a decade or so later), gouging was the only known way that flying debris could be imagined to form furrows.



Imbrium lineaments.



Gabriel Delmotte's "Système Imbrien." Note that south is up.

But there was an alternative explanation. The Imbrium sculpture is not the only example of straight features on the Moon. Assiduous mappers found more and more linear troughs and segments of crater rims, and for a while the traditional search for ever-smaller craterlets was replaced by the mapping of these so-called *lineaments*. The scientific framework for understanding lineaments was provided by Spurr, a retired American mining geologist who was so captivated by the famous Mount Wilson Observatory photograph of the Mare Imbrium quadrant of the Moon that he wrote an entire book devoted to the interpretation of that single image! Spurr applied his knowledge of terrestrial geology to the Moon, and in four turgid and rambling self-published volumes, he presented evidence that lunar craters and other landforms were all caused by internal activity. He believed that the lunar surface recorded the effects of the "crusting over of a fluid sphere."

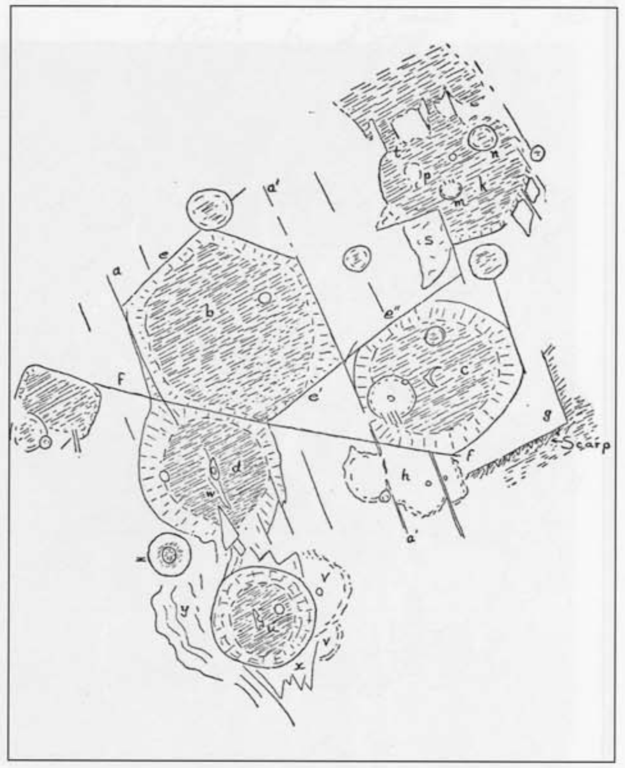
While Spurr's arguments for the volcanic origin of craters have been rejected, his observations of a Moonwide network of lineaments — or the "lunar grid system," as he called it — persist. Following in the footsteps of earlier observers such as Elger, Spurr noted that many lunar craters have polygonal outlines. One of his classic examples is the area centered on Ptolemaeus, which clearly is hexagonal shaped.

And there is a hint of a hexagon shape in neighboring Albategnius. To the south the straight-sided craters Purbach and Walter provide additional convincing examples that lineaments do exist on the Moon. Spurr argued that the straight edges of crater rims and the linear troughs mark a Moonwide system of faults that formed as the molten lunar globe shrank. He believed that Ptolemaeus and other straight-sided craters resulted from the collapse of volcanic bubbles bounded by preexisting faults. Spurr's interpretation may be crazy, but the lunar grid has a mapable reality.

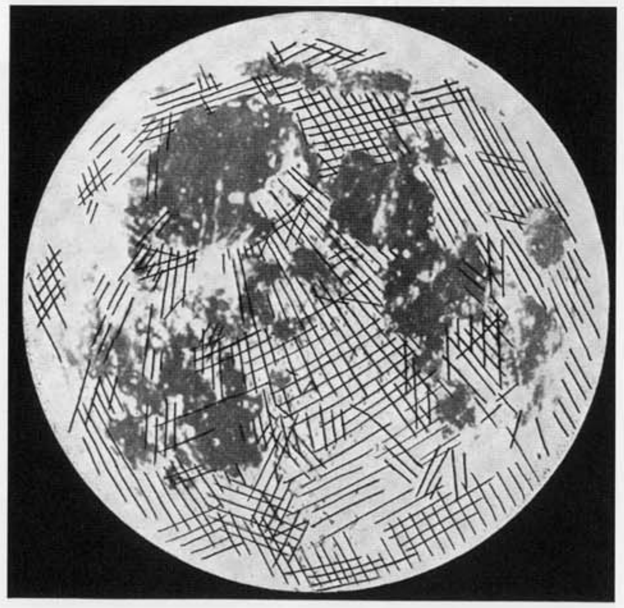
Strangely, Spurr didn't make a global map of the lunar grid, but many of his followers did. Although Russian scientists made a series of ever more stylized and unnatural-looking lineament maps, in 1964 my colleague Robert Strom of the Lunar and Planetary Laboratory in Tucson, Arizona, became king of the gridders when he published a whole series of large maps showing families of lineaments. But my favorite grid map is Fielder's because it displays a regularity of spacing and coverage that clearly reflects the influence of an idealized model over the reality of the lunar surface.

The quest to map the lunar grid was another example of a dead-end exercise that simply did not repay the effort — a case of mistaking activity for accomplishment. Like the earlier competition to chart the maximum number of tiny craterlets, grid mapping did little to enhance our understanding of the Moon.

Most grid elements are due to secondary ejecta and fracturing associated with Imbrium and other impact basins. Other parts of the grid pattern, if they exist, may well be derived from stresses present early in lunar history. After the Moon formed, it spiraled outward from Earth. During this time, the tidal forces induced by its proximity to Earth would have been 10 to 100 times greater than would be required to cause pervasive faulting in the Moon. It's possible that these early stresses influenced the shapes of lunar crater rims, just as on Earth localized stresses helped to square the rim of Meteor Crater in Arizona. The process is not mysterious.



Josiah Spurr's sketch of Ptolemaeus and nearby straight-sided craters.

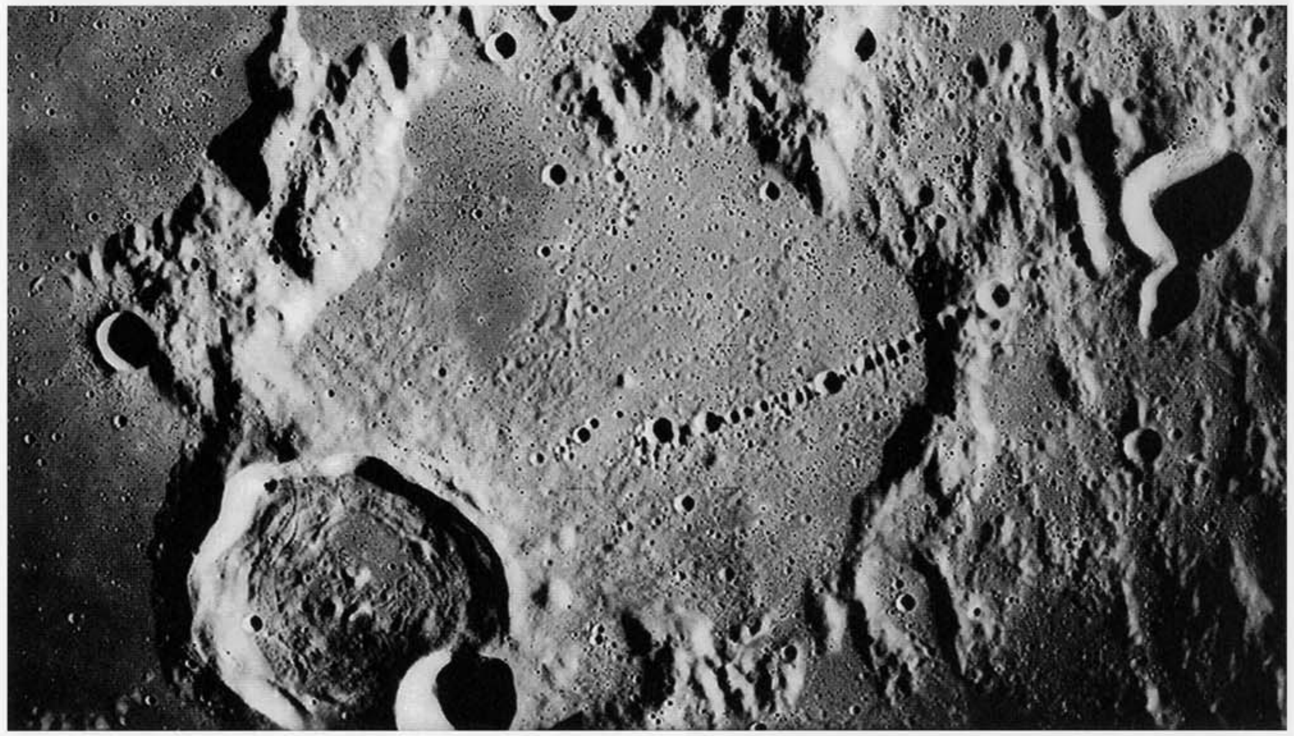


Gilbert Fielder's chart of the (idealized) lunar grid system.

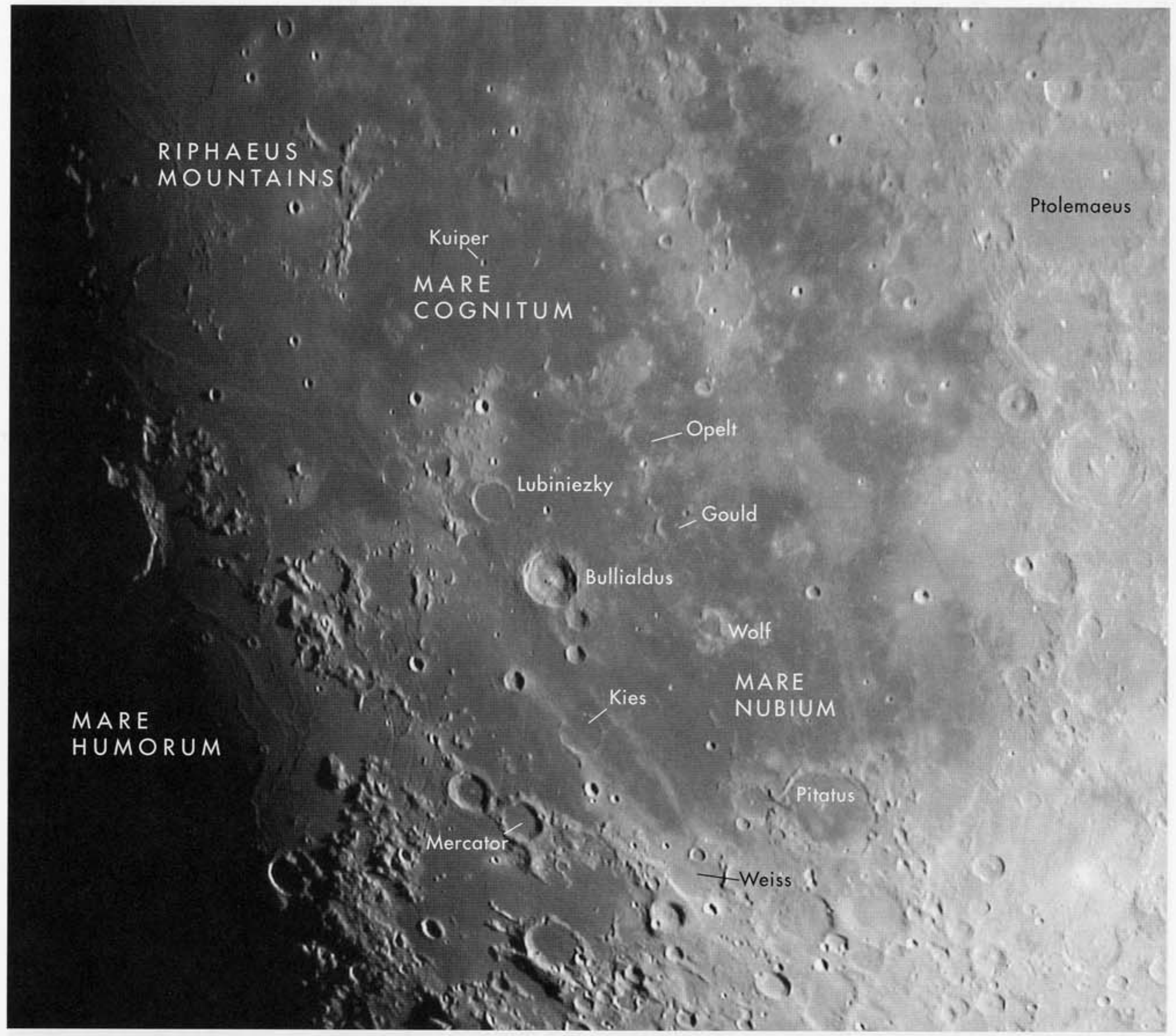
DAVY'S WEIRD CHAIN

As you look at various alignments near Ptolemaeus, you may notice a small one in the squared-off old crater embracing the northeastern rim of Davy, on the northeastern shores of Mare Nubium. This so-called Davy crater chain (also labeled as Catena Davy on some Moon maps) is a 45-km-long alignment of more than a dozen small craters, most of them 1 to 2 km wide. The crater chain has been a mystery for many years. It is apparently not volcanic, since the craters don't look like the volcanic pits found along the Hyginus rille and elsewhere. And there is no obvious source crater if the feature is a secondary crater chain. Robert Wichman (then at the University of North Dakota) and I proposed an explanation, as did Melosh and Whitaker of the University of Arizona. Suppose a comet or small asteroid passed so close to Earth that it was torn apart by Earth's gravity, with the resulting pieces dispersing into a line. If such a train of particles hit the Moon, it could produce a crater chain like the one near Davy.

This may seem like a preposterous idea, but we have actually witnessed just such an event. In 1992 Comet Shoemaker-Levy 9 passed perilously close to Jupiter and was gravitationally shredded into a "string of pearls" of 23 or more cometary fragments. These pieces sequentially collided with Jupiter in July 1994, in rapid-fire succession — on average one every 7 hours. Each impact created a flash as the speeding comet fragment was instantaneously transformed into heat. The aftereffect was a series of dark splotches in Jupiter's atmosphere that persisted for many days. Crater chains on Jupiter's icy moons Callisto and Ganymede were probably also formed by collisions of this kind. The process seemed so bizarre that no one even thought of it, but we know it did occur on Jupiter in 1994 and apparently in the Moon's past as well.



Davy (the large crater at lower left) and its associated crater chain, as photographed by Apollo 16.



Mare Nubium region.

15

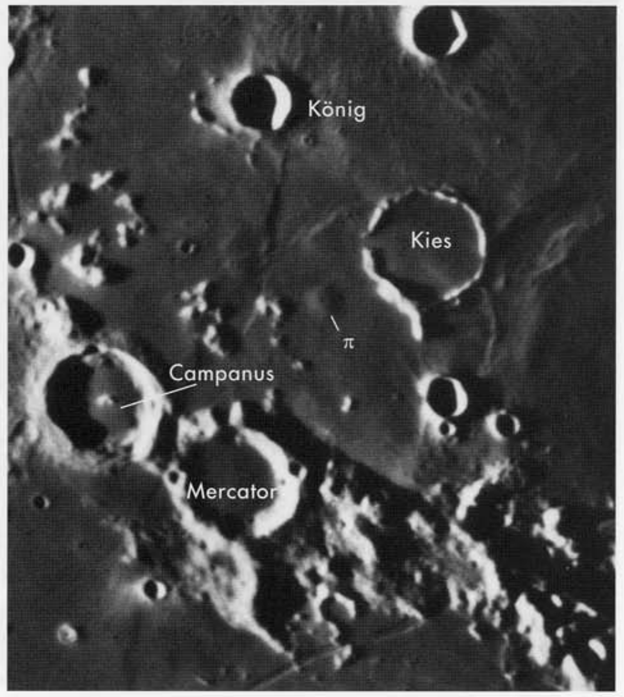
Mare Nubium

Nubium means "clouds," but if the lunar mare of that name really shares any similarities with terrestrial clouds, it is because its boundaries are soft and ambiguous. The reason for Nubium's lack of definition is easy to spot — it doesn't have the conspicuous surrounding rim of a typical impact basin. Even the most enthusiastic sketchers of basin rings struggled to find a single, halting ring to define the 700-km-wide Nubium basin. A portion of a basin rim is apparent only in one location along the southern shore of Nubium, where a 130-km-long ridge stretches between the ruined crater Weiss and the lava-floored crater Mercator. Assuming that Mare Nubium does mark a basin, it must be an ancient one whose only heritage is a low spot that puddled younger lava flows.

On the classic 1837 Moon map by Beer and Mädler, the region labeled Mare Nubium is restricted to an area in the south — modern usage has extended the name to include the entire expanse of lava flows that stretches all the way to Copernicus. In 1964 the northern part of Mare Nubium was given the name Mare Cognitum (Known Sea), an homage to the revealing photographs from Ranger 7, the first spacecraft to provide successful close-up images of the Moon. Fittingly, a small crater near the Ranger 7 impact point has been named Kuiper, after Gerard Kuiper, the team leader of the Ranger project. I remember being thrilled by Kuiper's first words when interviewed on the day of the impact: "This has been a great day for America, and a great day for science."

Mare Nubium has been relatively neglected by lunar scientists; only Spurr described it in detail. He pointed out that Nubium is not a well-defined feature and is only separated from Oceanus Procellarum by an arbitrary line. While there is some truth in this statement, for the purposes of this chapter I consider Nubium to be the area extending all the way to the eastern rim of the Humorum basin, northwest to the Riphaeus Mountains, and north to the unnamed mare patch west of Ptolemaeus. Spurr also observed that Nubium lavas must be thin because the partial rims of many older craters protrude through them. Louisiana Moon mapper René DeHon calculated that most of the Nubium lavas are less than 500 meters thick. Spectral mapping, both by ground-based telescopes and the Jupiter-bound Galileo spacecraft, showed that many Nubium-area lavas are low- to medium-titanium basalts like those sampled at the Apollo 12 landing site near the northern portion of the mare between Fra Mauro and Lansberg.

When the terminator is near, Nubium appears crossed by a number of wrinkle ridges that form no particular pattern. Many ridges clearly mark the rims of buried craters — examples include the five or six structures linking the ruined craters Opelt, Gould, and Wolf. Other craters have completely lava-flooded interiors, but rims that are largely intact. Lubiniezky and Kies are both 44-km-wide examples. Kies is famous as the guidepost to one of the easiest volcanoes to find on the Moon. Just west of the crater is an 11-km-wide dome called Kies Pi, which contains a tiny summit pit. Kies Pi, a few other nearby domes, and another low dome described later in this chapter are the only known structures of this kind south of the lunar equa-



Kies and nearby dome Kies Pi (π).

tor. Thus, the formation of volcanoes seems to require different circumstances than the formation of lavas, which are common in the five southern-hemisphere lunar maria.

THE STRAIGHT WALL

The absolute best example of a lunar fault is found along the eastern shore of Mare Nubium — the Straight Wall. This well-known lunar feature is a long, thin line that never fails to impress; even casual Moongazers enjoy this magnificent sight. The view is best when the Sun has risen over it and the terminator is a little to the west in central Nubium. Under these conditions the wall casts a shadow that stretches along the entire 120 km of its length. This dramatically demonstrates that the lunar surface must be lower on the west side of the fault than on its east. Various authors report that the scarp is 250 to 300 meters high, but my measurements of its shadow length suggest that it may rise as much as 450 meters above the basin's western floor. In spite of appearances the Straight Wall is not a sheer cliff, though it is relatively steep — rising above the mare plain at an angle greater than 20°.

The Straight Wall and ghost crater rims of Mare Nubium.

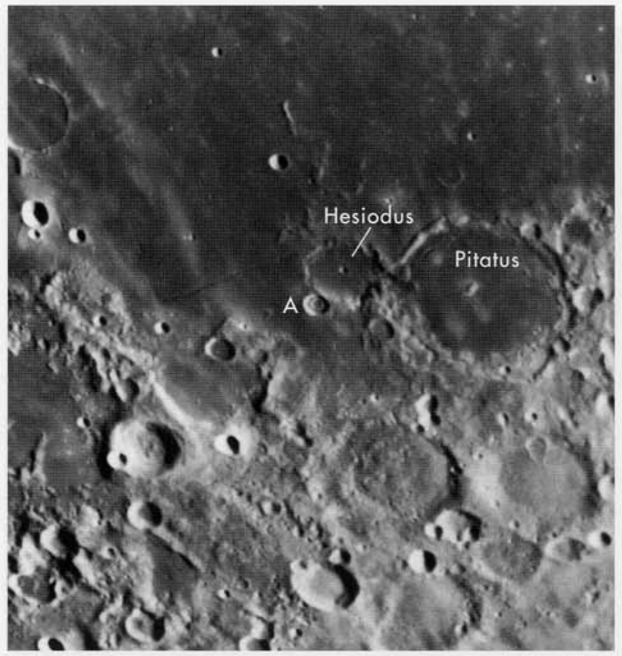
The Straight Wall (dubbed the Railway by Elger, who was a railroad engineer) is labeled as Rupes Recta or the Straight Scarp on modern Moon maps. It terminates in the south against a jumble of short ridge segments that the 17th-century selenographer Christiaan Huygens likened to the handle of a sword, with the Straight Wall being the blade. If you widen your view you will notice that the Wall slices through the lava-flooded floor of an old, unnamed ruined crater that I call "Ancient Thebit," after the 57-km-wide crater Thebit on its rim. To the east the rim of 200-km-wide Ancient Thebit is well defined, but its west rim is marked only by arcuate wrinkle ridges.

Although some researchers have noted that the Straight Wall is roughly radial to the Imbrium basin and thus perhaps related, it clearly has a much closer relation to Ancient Thebit. I believe that Ancient Thebit formed on the edge of the Nubium impact basin and that subsidence of the basin lowered the crater's western wall, which was ultimately buried by the lava flows that flooded the basin. This is essentially the same sequence as Sinus Iridum on the Imbrium basin and Fracastorius on the rim of the Nectaris basin. The basinward portion of Ancient Thebit's floor faulted downward to accommodate the basin's sinking. This is again very similar to Fracastorius, which is cut by a delicate crack where the mare subsided.

Finally, if you look very closely under good seeing conditions, you should see a tiny crack roughly parallel to the Straight Wall just west and north of the bright crater Birt. Each end of this rille, known as Rima Birt, terminates in a tiny pit. The pit on the northern end sits on top of a dome that is noticeably darker than nearby mare. Rima Birt is a challenge for telescopic observers *and* for scientists who try to explain why it is there. Because the tiny pit at the rille's northern end is located near the rim of Ancient Thebit, we can speculate that fractures associated with the rim provided an easy path for lavas to erupt onto the lunar surface, producing a dome, collapse pits, a lava channel, and perhaps a small pyroclastic deposit.

THE SOUTHERN RIM

Across the southern shore of Mare Nubium are some minor oddities worth finding. The biggest is Pitatus, a 97-km-wide crater with a nearly pulverized rim and a floor completely covered by lava except for one lonely, off-center peak. Interestingly, a narrow rille skirts the inner wall of Pitatus. Although this cleft system has been known at least since Elger, few observers commented that the eastern part of the rille appears to be outlined by whitish deposits and that its northwestern portion appears to crack a low rise. Lunar Orbiter photographs show that a series of rilles encircle the entire floor and that tiny rilles connect the peak to southwestern and southeastern rims. Clearly volcanism filled Pitatus and made the rilles. The white rille



Pitatus and Hesiodus A.

Lunar Orbiter IV view of Pitatus, Hesiodus, and Hesiodus A.

rims could be sulfur or other volcanic emanations like those that sometimes occur along lava channels in Hawaii. It would be very surprising, however, if such deposits survived 3 billion years of bombardment by solar wind and micrometeorites.

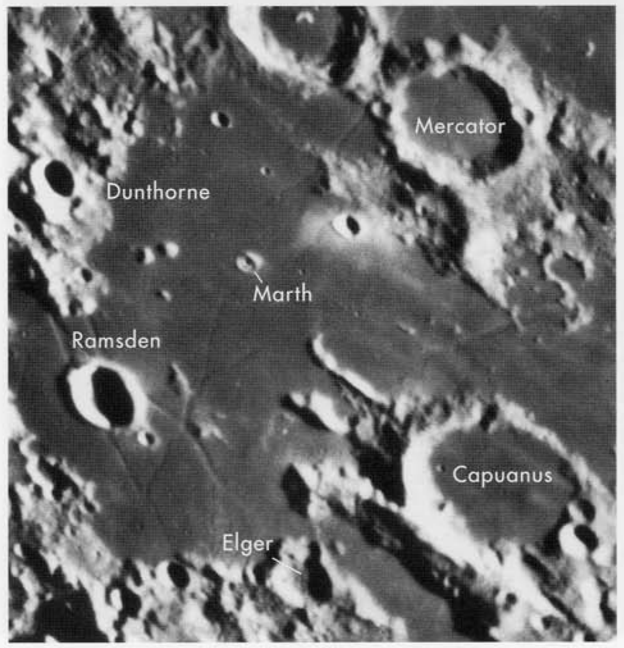
Immediately west of Pitatus is Hesiodus, an absolutely nondescript battered crater whose only claim to fame is that it marks the location of a truly unusual little crater: Hesiodus A. Located on the southwest rim of Hesiodus, Hesiodus A is a 14.5-km-diameter crater that looks just like a normal simple impact crater when the Sun is low. But as the Sun rises, lo and behold, Hesiodus A reveals a perfect little doughnut or circular ridge. And inside the doughnut are two or three tiny central peaks. Hesiodus A is the most easily observed concentric crater on the Moon. I once wrote a short paper cataloging 51 concentric craters. Nearly all occur near mare edges and have diameters of 2 to 20 km. The inner doughnuts cannot be impacts that just happened to be centered on preexisting craters. They must be formed by some sort of volcanic extrusions or annular intrusions, neither of which have many analogues on Earth.

On the west side of Hesiodus is a straight rille like those commonly found paralleling the edges of maria. But this independent-minded rille slices through the rim of the Nubium basin (look to see the down-dropped blocks of highland material) and enters a backwater of mare material (Palus Epidemiarum) between Capuanus and Mare Humorum. This rille serves as a pointer to a nexus of intersecting rilles at the crater Ramsden. The shortness and angular intersections of the Ramsden rilles are very similar to the Triesnecker rilles. Scientists have no good explanation for either of these unusual rille concentrations. Perhaps the rilles occur over a low broad dome whose uplift cracked the existing mare surface into characteristic patterns similar to those on the top of a loaf of yeast-rich bread.

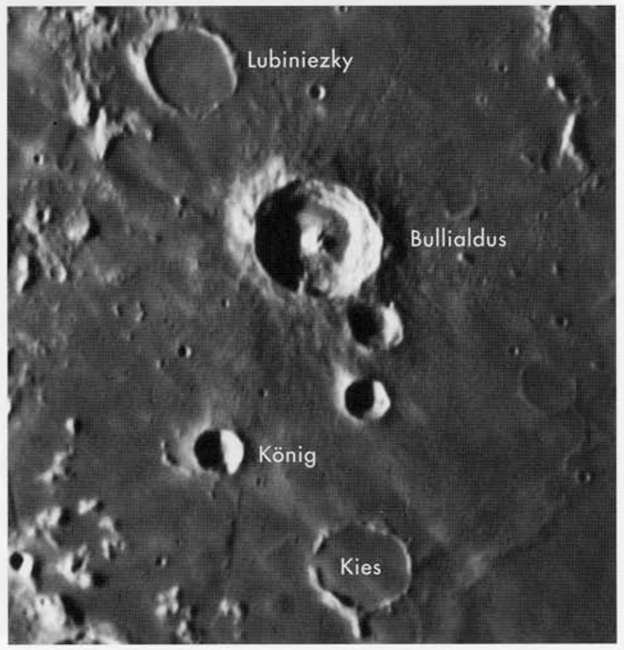
A small crater northeast of Ramsden provides a challenge for visual observers equipped with 8-inch or larger telescopes. The 7-km-wide crater Marth appears to be a normal little impact crater, but if you look very closely you'll see that it is a concentric crater similar to Hesiodus A. There are hints that Marth sits atop a slight rise and that lavas from that rise have filled nearby delicate rilles. Before leaving this interesting little area, notice the small domes on the floor of the crater Capuanus. With the dome near Kies and the other rilles and concentric craters nearby, this area was clearly a center of minor volcanic activity 3.5 billion years or so ago.

BULLIALDUS

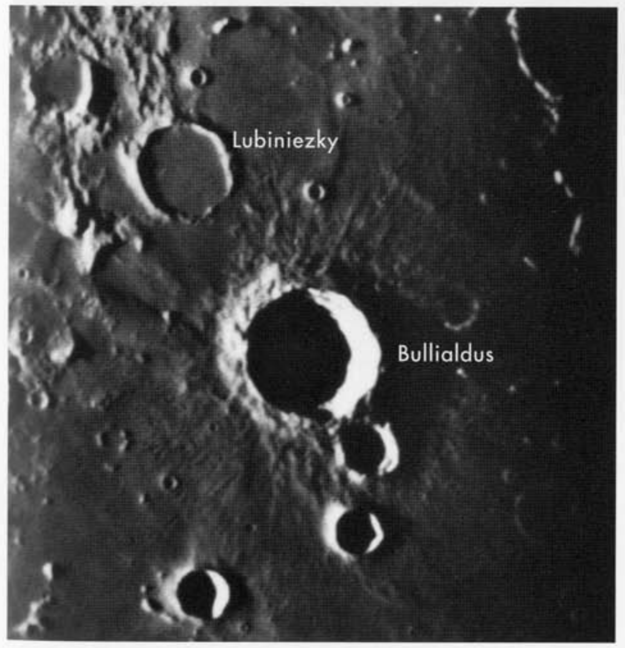
Between mare-flooded Kies and its near twin Lubiniezky is Bullialdus (61 km wide, 3.5 km deep) — one of the finest Tycho-like craters in the southwest quadrant of the Moon. It is also one of the few. Only 13 relatively fresh craters larger than 60 km in diameter adorn the entire lunar near side. Bullialdus has the same morphology as Tycho — a wide, terraced inner wall, flat floor, and a clump of central peaks — but it's much less bright and lacks rays. Thus, Bullialdus is early Eratosthenian to late Imbrian in stratigraphic age, with a probable absolute age between 3.0 and 3.6 billion years.



Ramsden rilles.



Bullialdus.



Sunset terminator approaches Bullialdus.

When the terminator is near Bullialdus, telescopic observers are offered a dramatic view of the crater's "exterior deposits," as lunar geologists describe them. The advancing terminator first reveals the thick wreath that makes up the outer rim. It never ceases to amaze me that crater rims do not rise smoothly from the mare, as observations made when the Sun is higher suggest, but abruptly turn up. Beyond this rim wreath are linear ridges radiating away from Bullialdus. These filaments of ejected material give way to alignments of tiny secondary craters. If you look closely you'll see that the secondaries extend about 1 Bullialdus diameter away from the crater's rim, except to the northwest. There the secondaries are covered by the same lavas that filled Lubiniezky and embayed the ejecta ridges from Bullialdus. These younger lavas are daubed by the much younger bright rays from Tycho.

The story of Bullialdus is not all told, however. Telescopic images obtained through a series of spectral filters provided Pieters and her colleagues with information from which they inferred general rock compositions. Once again we must descend into the nomenclatorial morass of rock names. Basically, Pieters found that the crater wall is a gabbro or basalt, not surprising considering that Bullialdus impacted into mare rocks! The interesting observation is that the central peaks seem to be made of two similar but different types of *norite*, rocks that include the minerals plagioclase and calcium-poor pyroxene. These central peaks were probably excavated from about 6 km below the lunar surface, so Bullialdus excavated different rock layers beneath the mare lavas that fill the Nubium basin.

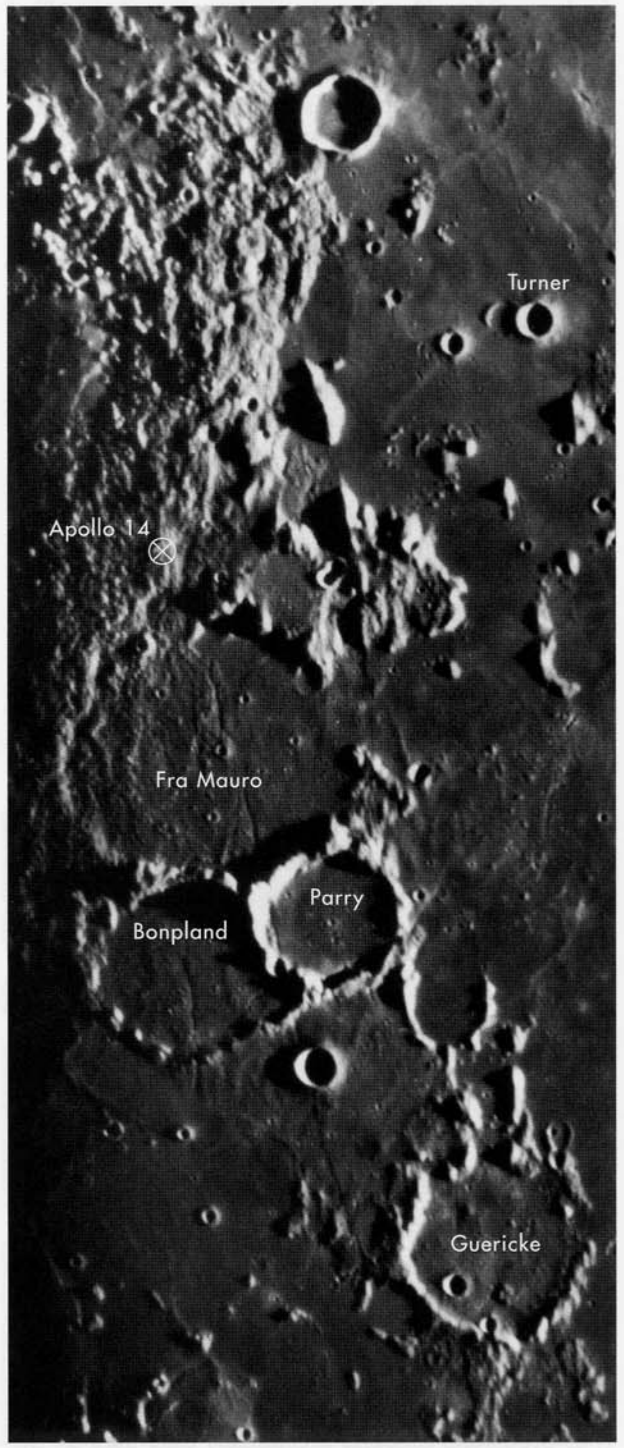
Pieters also recognized another spectral unit — a fresher gabbro that cuts across the western wall of Bullialdus. She interpreted this rock type as a dusting of ray material from Tycho, which the Surveyor 7 lander showed to be gabbroic. But another possibility exists, I think. That same western wall cuts through a mare ridge that extends from Mercator and Campanus, past König, and north of Bullialdus. Can you see it? This ridge could have a somewhat different composition than the adjacent mare basalts, and this may be what the spectral images detected. Perhaps someday lunar geologists will discover whether the fresher gabbro is a massive wall layer ("By Luna," they'll say, "Wood was right!") or is merely a scattering of Tycho ejecta ("That Pieters was one smart cookie!").

FRA MAURO AND IMBRIUM

South of Copernicus and west of Ptolemaeus lies a complex of old and battered craters that are often passed over but are of fundamental importance to understanding the Moon's history. The craters Parry, Guericke, Bonpland, and Fra Mauro were described by early mappers like Goodacre as ruins that "point eloquently to the destructive forces of erosion or submersion," but the selenographers of that time seldom discussed what caused those forces. Each of these craters has gaps and gouges cutting its rim, and a broad longitudinal ridge of hummocky material extends from the north across the western half of Fra Mauro.

Gilbert, in the 19th century, noticed that the striations near Fra Mauro were radial to Mare Imbrium, as did Baldwin six decades later. But it was the definition of a lunar stratigraphy by Shoemaker and Hackman in 1962 that moved mission planners to select this site for the Apollo 14 landing. The USGS mappers named the hilly, bumpy, and radially lineated material in this area the Fra Mauro Formation and proclaimed that it was the main ejecta from the excavation of the Imbrium basin. The goal of Apollo 14 was to sample Fra Mauro to see if it really was ejecta and, if so, to determine the age of the Imbrium impact by dating shocked and melted debris.

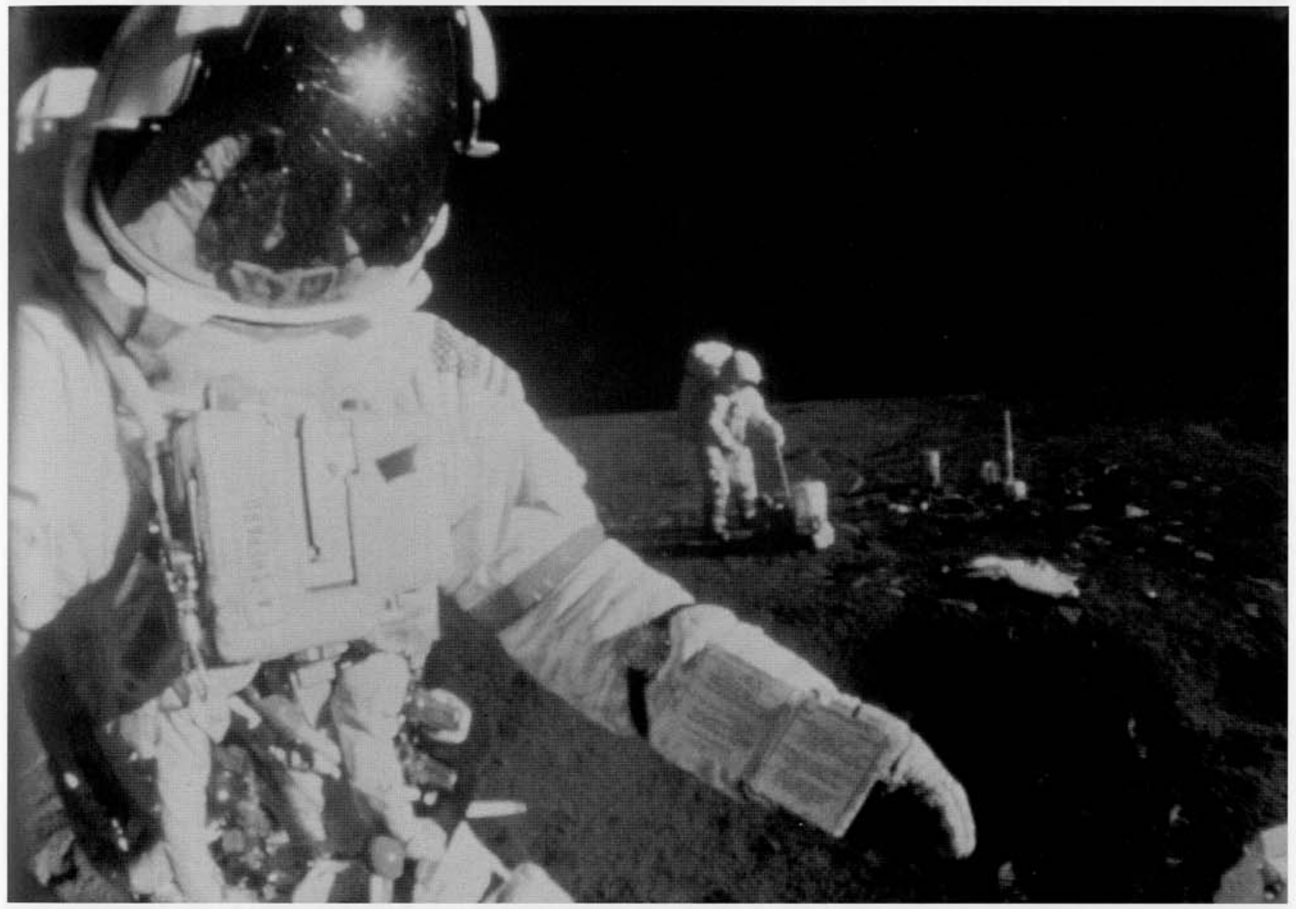
On January 31, 1971, the lunar module Antares brought the Apollo 14 astronauts down on the Fra Mauro Formation just 40 km north of the crater of the same name. The rocks they brought back were, exactly as predicted, breccias presumably excavated by the



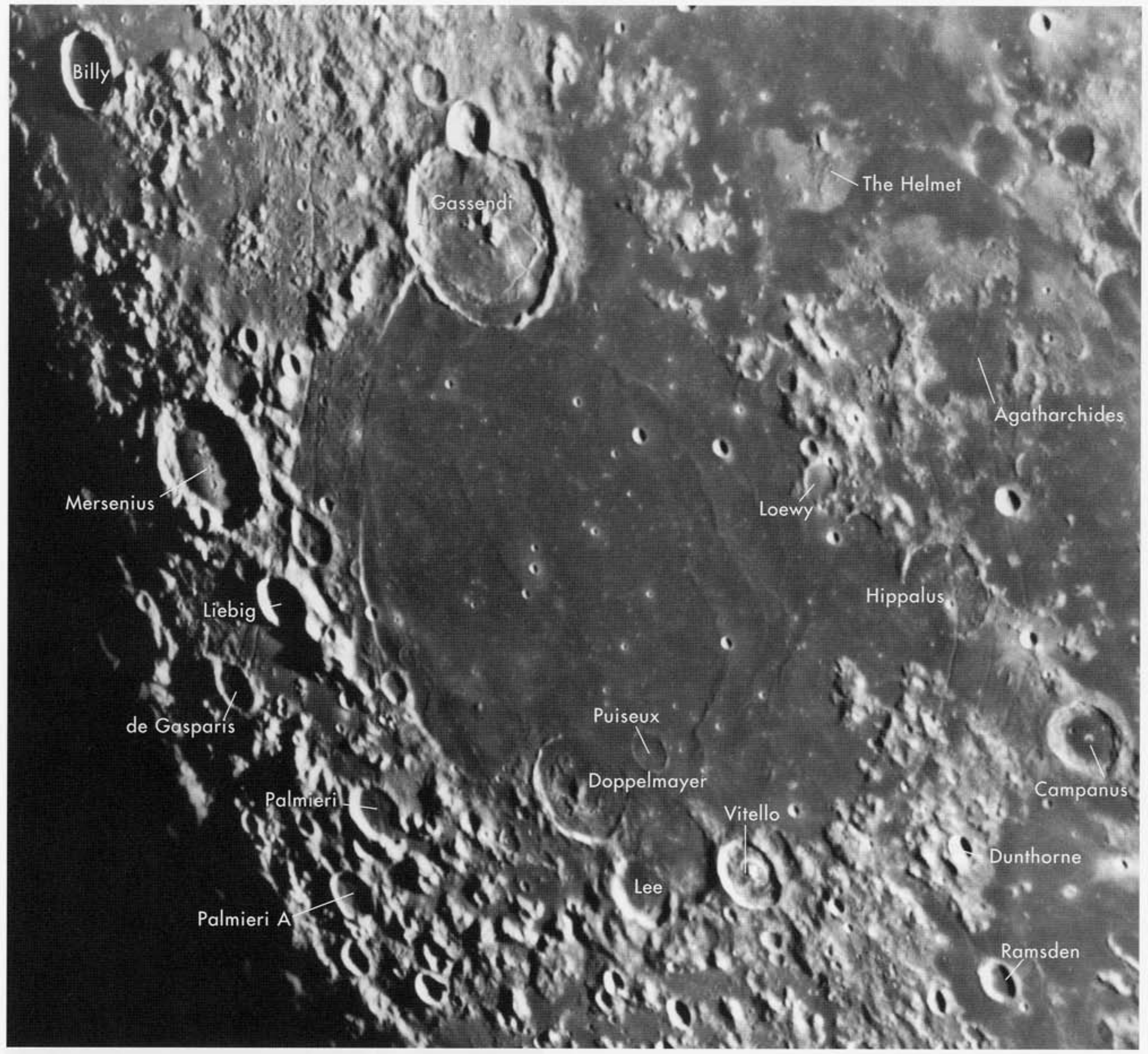
Fra Mauro.

Imbrium impact. These breccias included fragments from multiple previous brecciation events — there are fragments within fragments within fragments, mixed with and embedded in a matrix formed by impact melting. The impact of the Imbrium basin–forming projectile shocked and melted the existing target rocks (which had probably already been brecciated from previous cratering) and threw them hundreds of kilometers to the Fra Mauro site. There the incoming debris smashed into the local rocks, creating more breccias and more melting. Naturally, lunar geologists argue whether most of the brecciation in the Apollo 14 rocks is from the initial Imbrium impact or if it occurred largely as the result of the secondary cratering at Fra Mauro. Esteemed lunar scientists Eggleton and the USGS's Terry Offield (primary ejecta) and Hawke and Head (local ejecta) have taken the opposing sides of this issue. The truth is probably a combination of the two ideas. The ages of the breccias center around 3.85 billion years, which is the inferred age of the Imbrium impact event as dated by samples retrieved later by Apollo 15.

USGS Moon mappers interpreted the Fra Mauro Formation as primary ejecta from the Imbrium basin because it buries prebasin craters out to a distance of nearly 600 km from Imbrium's rim. While the signs of this burial are best seen in the area of the Fra Mauro crater, pieces of similar ridged and lineated terrain are visible to the southeast of the Apennine Mountains and north of Mare Frigoris. Presumably thick deposits of Fra Mauro ejecta are also buried by the lavas of Oceanus Procellarum and Mare Serenitatis.



Apollo 14 astronauts Alan B. Shepard Jr. (foreground) and Edgar D. Mitchell explore the Moon north of the crater Fra Mauro.



Mare Humorum.

16

Humorum

The western side of the Moon is dominated by ill-defined expanses of mare material, with Oceanus Procellarum oozing into Imbrium, Nubium, and all the little named and unnamed mare patches near Copernicus. In this subhemisphere of ambiguity, Humorum stands out as a coherent, distinct, and well-defined region. In fact, Humorum is arguably the best place on the near side of the Moon to learn about basins because it has a nearly complete inventory of impact-basin features.

Finding your way around Humorum is easy. The dark circular patch of the mare can be seen with the naked eye. And because the basin itself is relatively small, the entire region fits within a telescope's field of view, even at moderate magnifications. Four conspicuous craters provide orientation. Cutting the north rim of the basin is the 110-km-wide crater Gassendi, with its shallow floor and tight arc of central peaks. Directly across the mare surface on the basin's southern rim is Doppelmayer. This is a smaller (64 km) version of Gassendi. It has a similar shallow floor, big central peak, and lacks a rim on the mare-facing side.

West of Mare Humorum is another conspicuous crater, Mersenius. This 84-km-wide crater lies just beyond the basin rim and has broad walls and a wide floor. Marking the eastern shore of Humorum is 58-km-wide Hippalus. Like Doppelmayer, Hippalus has a breached rim, but in this case the floor has been completely covered by mare lavas. Hippalus is also cut by one of a family of three arcuate rilles concentric with the shore of Humorum.

BASIN STRUCTURES

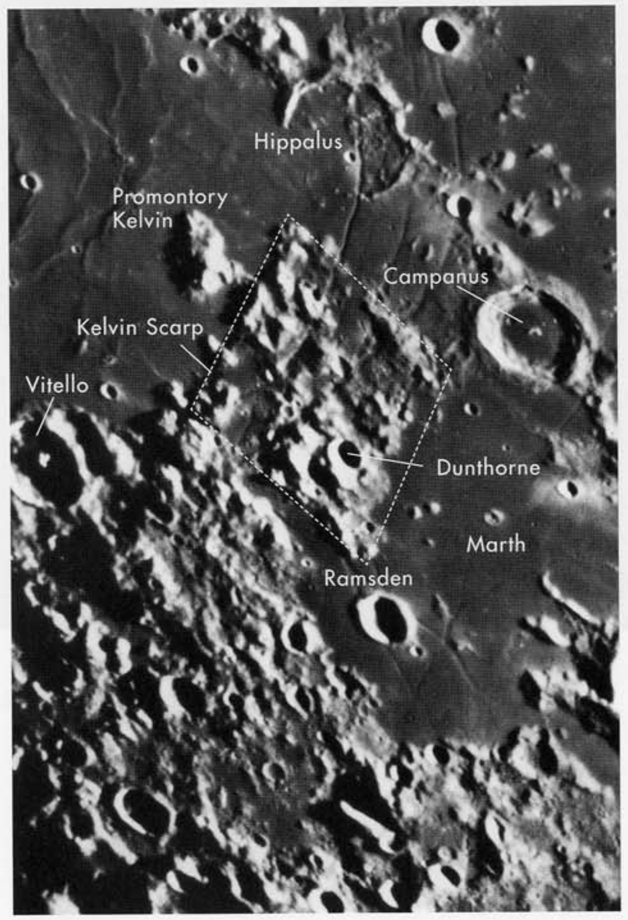
Humorum lacks basin rings as striking as Nectaris's Altai Mountains or Imbrium's Apennines. The basic structure is there but more subdued and harder to see, especially in the east where basin rings have been obscured or destroyed by lava flooding from Mare Nubium. The most obvious basin-ring structure is the edge of Mare Humorum itself. The roughly circular mare fill is sharply bounded on the west by an arc of mountain ridges that become progressively lower and more degraded from north to south. This is the main basin rim, measuring about 425 km across.

Fragments of a larger basin ring occur as isolated ridges west of the mare. One piece can be found southeast of the crater Billy. A second, lower ridge is northwest of Mersenius, and a third, broader ridge is east of Vieta. Two low scarps just east of the bright crater Palmieri A continue the arc. The ring defined by these relicts can't be mapped very well on the east side of Humorum but appears to be about 800 km wide. In his book *The Geology of Multi-Ring Impact Basins,* Paul Spudis includes two additional rings. There are some hints of Spudis's smaller ring, which measures roughly 570 km in diameter, but his proposed 1,200-km outer ring is very difficult to discern.

Inside the main rim, elements of a smaller circle are easy to see, but you may not recognize them as pieces of a basin ring. The largest of a family of arcuate wrinkle ridges on the east side of Mare Humorum defines part of a 340-km-wide ring. A low, curving scarp on the west side of the mare marks its opposite side. This ring is similar to wrinkle ridge rings in Serenitatis and Crisium. The visible fault that defines the western portion of this wrinkle-ridge ring (named the Liebig Scarp after a nearby crater) confirms what is merely conjecture at the other deep basins — inner rings mark the edges of down-dropped central blocks.

Paul Spudis.

One of the most striking examples of straight-sided lunar terrain occurs at the southeast edge of Humorum, between the craters Campanus and Vitello. A square patch of hilly, uplandlike material is sharply defined, especially on the Humorum-facing side (Kelvin Scarp). It is somewhat less distinctly delineated on the other three sides by abrupt, linear changes in elevation where the hills drop down to the mare surface. This region has no name, but Spurr — who wrote thick, long-ignored books with dense texts and awful drawings — called it a rectangular block, which he thought was fault-bounded and uplifted. In this case he was probably right. Directly opposite the rectangular block, the northwest edge of Humorum is also bounded by straight line segments. Such features were once widely discussed as components of a Moonwide grid pattern, perhaps dating to an early period of rapid lunar rotation that induced stresses and faults. But most straight edges are actually parts of local systems of radial and concentric features centered on impact basins. Spurr's rectangular block is unusual, but it appears to be simply part of Humorum's multiring structure.

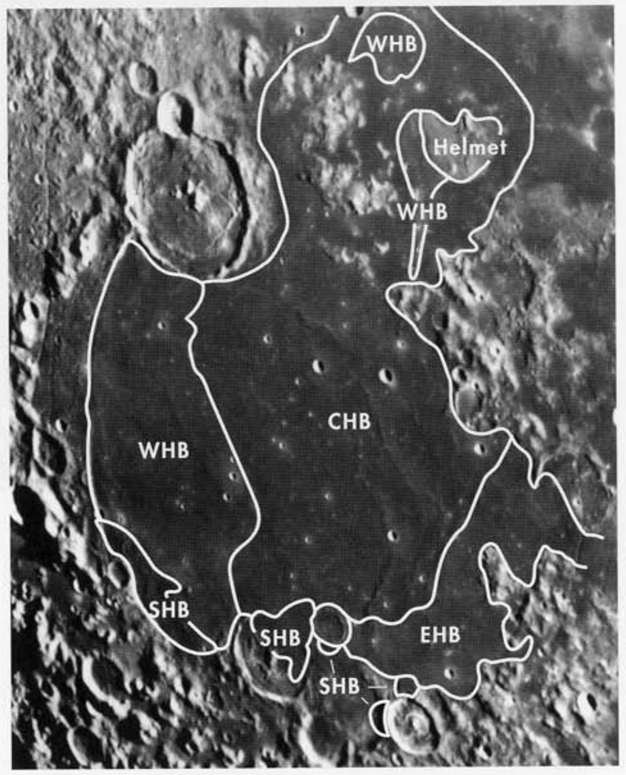


Spurr's rectangular block.

MARE HUMORUM

With the collecting of lunar rocks by Apollo astronauts, chemical and petrologic analysis of the Moon became the central focus of lunar studies. At about the same time, multispectral telescopic measurements of the lunar surface identified regions of the Moon with color characteristics similar to the Apollo samples. Spectral observations by Pieters and others showed that Mare Humorum harbors four major lava color types.

The southeastern arc of the mare is similar to low-titanium basalts found at the Apollo 12 site. Informally these can be called East Humorum Basalts (EHB), naturally, because that's where they're found. The second color type in this name game is the Central Humorum Basalt (CHB) because it occurs in a central zone that widens from Doppelmayer to Gassendi. This type of rock appears to have more than twice as much titanium as EHB and perhaps should be considered medium-titanium basalts. It seems to be unique to the western side of the Moon, having been identified only in Humorum and eastern Mare Procellarum. The third color type, West Humorum Basalt (WHB), occupies the western third of Mare Humorum. WHB is similar to the lavas in the central part of Mare Serenitatis and much of western Procellarum. WHB is fairly similar to EHB, both being low in titanium. Only a spectral expert can tell them apart — and I'm not one.

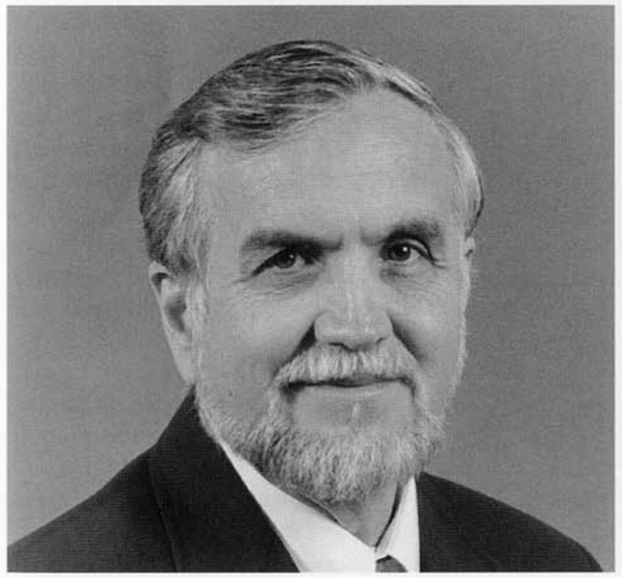


Geologic sketch map of Mare Humorum.

The fourth and final color type, the South Humorum Basalt (SHB), is clearly related to the volcanic landforms along the southern shore of the mare, though some interesting findings suggest these features could be ash deposits rather than lava flows. This area showed up as a thermal anomaly in infrared images made in the 1960s. Ash would act as insulation, retaining the Sun's heat after nearby lavas had reradiated it back into space.

You can recognize some of these mare spectral types at the telescope, especially under a high Sun. In particular, the EHB lava is noticeably lighter hued than the adjacent CHB lava. Look carefully and you will see that the EHB areas are bounded by the easternmost wrinkle ridge, the one that marks the inner ring of the basin. Hawke and his students and colleagues at the University of Hawaii discovered that three small craters located in the EHB area had excavated underlying highlands material. This confirms that the area outside the wrinkle ridge is a shallow bench, with lava thicknesses less than 1.25 km; otherwise the small craters would not have highland spectral signatures. The Hawaii group also found that craters inside the wrinkle ridges (in CHB) haven't excavated highlands material, so the central part of the basin must be deeper. It's wonderful when observations make geologic sense!

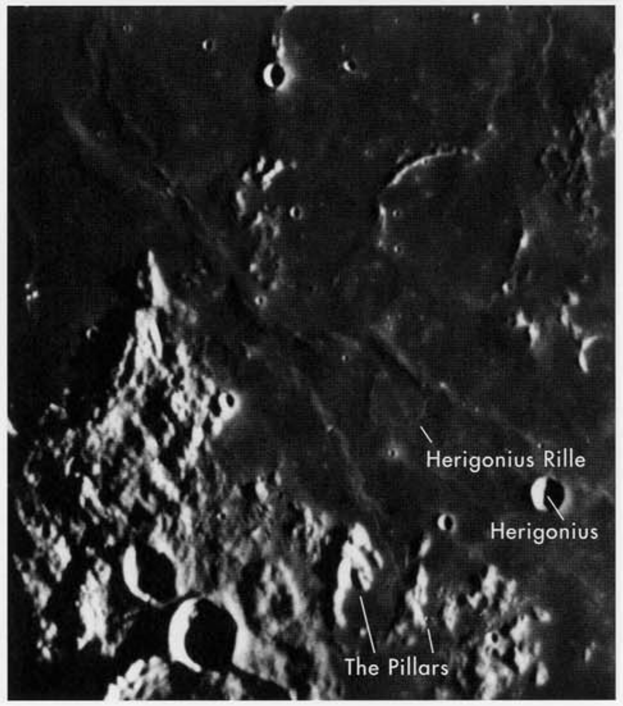
Because the EHB and WHB units have many tiny impact craters, they must be older than the sparsely cratered CHB. A reasonable geologic interpretation would be that the EHB and WHB lavas covered the entire floor of the Humorum basin. The weight of these lavas caused the central part of the basin to sink, and the new hollow thus created was filled by the later CHB lavas. But where did these flows of lava come from? They must have come up basin fissures that were covered by the final lavas that seeped out. Such burial of source fissures probably occurred at all the maria.



Ronald Greeley.

But Spudis and Ronald Greeley of Arizona State University have discovered volcanic vents that probably fed at least some of the Humorum lavas. Most of the tiny volcanic cones and sinuous rilles that issue from them are too small to be seen through a telescope, though you can see the lava flows themselves. Find the 15-km-wide crater Herigonius in the mare to the northeast of Gassendi. One rille has a source covered by Herigonius, but the Herigonius Rille (which is visible in telescopes) originates just to the west. Slopes in this region tilt toward the center of Humorum, and the rilles pass between sets of elongated hills that I call the Pillars (from the Pillars of Hercules or the Straits of Gibraltar between Africa and Spain).

Although the rilles are hard to detect when the Sun is high, the dark mare lavas (CHB) that pass through the Pillars and wrap around the southern end of Gassendi are readily visible. It looks like these same CHB lavas flowed through a tiny breach in Gassendi's southernmost rim, depositing the dark material that ponded on that crater's floor. That such a tiny gap could

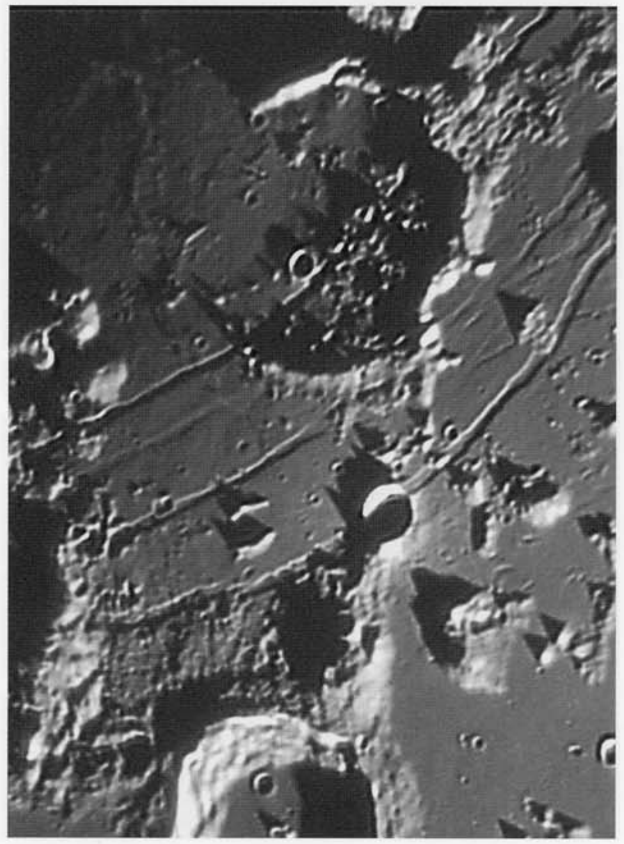


A winding, narrow rille (indicated) threads the Pillars.

allow mare material to spill into Gassendi testifies to the very fluid nature of lunar lavas. But perhaps there's more to this story, as we shall see later in the chapter.

Let's now look at some much more conspicuous rilles. Low light angles clearly show three arcuate rilles just east of Humorum and obviously related to it. Each of the curving rilles between Hippalus and Campanus is 3.0 to 3.5 km wide and roughly 200 km long — there are no troughs of this size on Earth. These arcuate rilles formed by the extension or stretching of the crustal rocks as the center of the Humorum basin subsided, probably due to loading from the weight of early EHB and WHB lava flows.

The wrinkle ridges on the eastern half of Humorum's mare formed in CHB lavas, whereas the concentric rilles on the east and the Liebig Scarp to the west cut the outer EHB and WHB lavas. Because the CHB lavas are believed to be younger than the surrounding ones, the concentric rilles and the fault scarp must have formed after the EHB lavas were emplaced but before the ridges formed. This deduced sequence is a nice example of stratigraphic interpretation, where different lava flows provide chronological markers for tectonic activities, such as the formation of rilles and ridges.



The ruined crater Hippalus and Mare Humorum's concentric rilles. (North is to the upper right.)

Remember the fourth spectral type? It is visually conspicuous because of its dark appearance. The SHB occupies discrete areas along the southwestern and southern shores of Humorum. The largest of these dark surfaces occurs exactly along a narrow straight rille that cuts the southwest shore of Humorum — a feature barely visible with a 6-inch telescope in excellent seeing. The line of dark material surrounding this rille is undoubtedly a deposit of volcanic ash. Radar images used by Pieters and her colleagues show that this material is very smooth, just as expected for ash. Presumably the ash erupted along the rille, as often happens in Hawaii when the first, gas-rich phase of an eruption shreds the erupting magma into fragments.

While this explanation is probably correct for this particular area, high-Sun photographs reveal that the dark mare material in Humorum is part of a larger region that includes the dark patches between the craters Liebig and Palmieri and southeast of Doppelmayer and Vitello. It is possible that all these areas are covered by ash, but this explanation troubles me because they don't appear to have obvious volcanic source vents.

Only one of these mare types in Humorum is similar to any of the Apollo samples. We need to go back to the Moon, and next time we'll be better prepared. The spectral imaging techniques that were just coming into use during the Apollo days should prove invaluable for pinpointing the areas of maximum scientific interest that will be targets of future exploration.

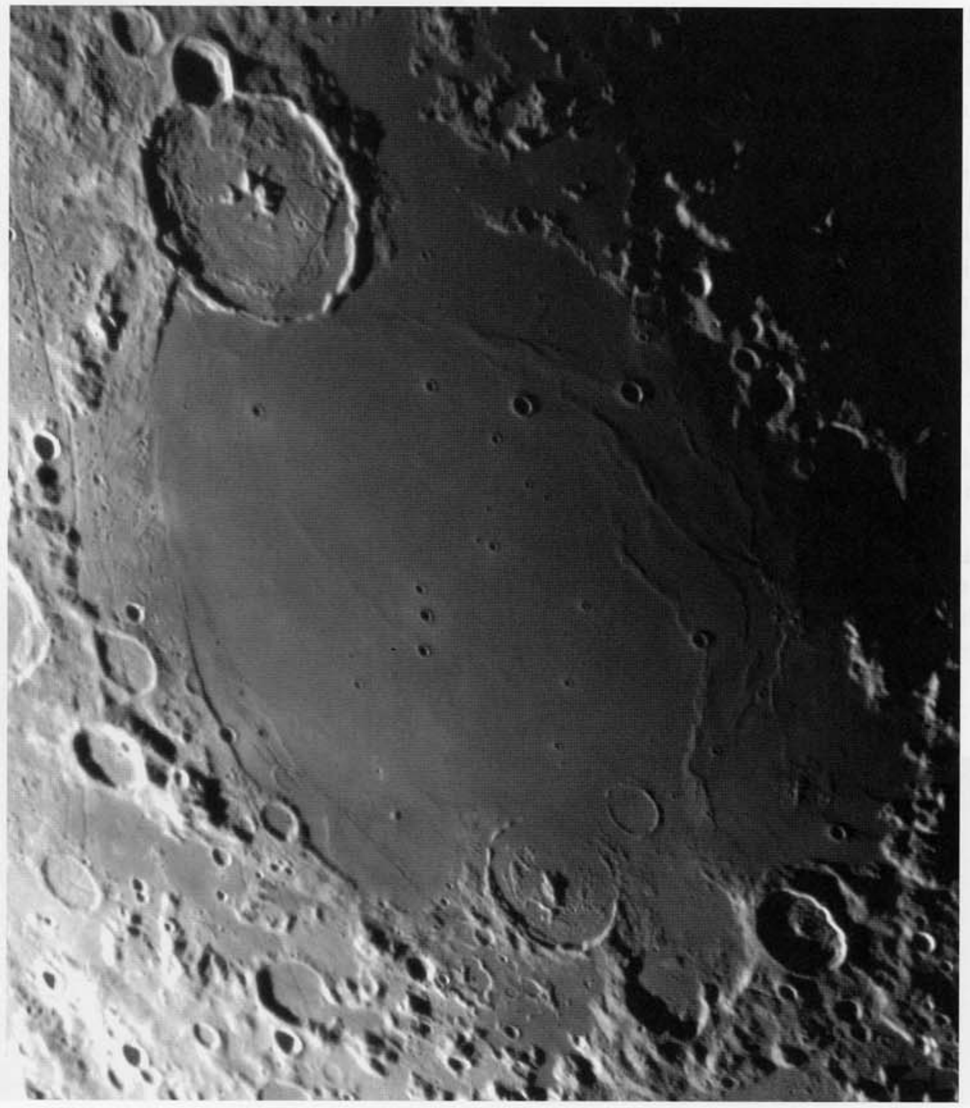
GASSENDI AND SIMILAR CRATERS

Nearly 100 years ago Elger stated that Gassendi was "one of the most beautiful telescopic objects on the moon's visible surface, and structurally one of the most interesting and suggestive." And he was right. Gassendi is large enough (110 km across) to display details that demonstrate the crater does not have a typical impact-crater morphology. Gassendi is quite shallow (2.8 km deep), with poorly defined rim slumps, a conspicuous cluster of central peaks, and a network of rilles that range from easy to very difficult to detect telescopically.

Because Gassendi doesn't look like a normal impact crater, it has sometimes been considered volcanic in origin. But it and nearby craters Vitello and Doppelmayer are now recognized as FFCs. Schultz, now at Brown University, proposed that some impact craters on the margins of basins are intruded by magma that rose up through basin fractures into the breccia and fracture zones underlying the craters. This caused the crater floor to uplift and fracture, with mare lavas often erupting onto the crater's floor. Floor uplift explains the shallowness of Gassendi and these other FFCs. Hawke and his colleagues at the University of Hawaii have discovered that the east wall of Vitello is composed of pure anorthosite, which confirms that these features are simply strongly modified impact craters. Thus, Vitello is not volcanic; instead it was impact-excavated out of the anorthositic crust that formed in the early Moon's magma ocean.

Doppelmayer, Hippalus, and other craters on the south and east shores of Mare Humorum have missing rim segments and are flooded by mare lavas. According to Goodacre in *The Moon*, "The erosive activities of the once liquid surface of the Mare are well displayed in the existence of many partially ruined rings around its margin." Although there have been many similar speculations that lava flows destroyed wall segments, that explanation seems less likely when it is noted that the rims of these breached craters systematically decrease in height toward the basin center. Undoubtedly, these craters were formed on the original floor of the Humorum impact basin, and as the floor later subsided, the craters tilted inward, with later mare lavas overflowing the low spots.

Like the other large craters on the edge of Mare Humorum, Gassendi tilts down toward the center of the basin. Its southern rim is very low and appears to be breached. However, high-resolution images show that the rim is indeed continuous. So the marelike lava that ponds on the southern part of the crater floor could not have swept through a small pass, as I speculated earlier. Instead, the lavas must have welled up through fractures under Gassendi's floor. This seems to be the correct answer, but I don't feel comfortable with it. If the source regions for the dark CHB in the area really are the volcanic vents Greeley and Spudis



A magnificent view of the volcanic rilles in western Humorum, Gassendi, and other features of the mare.

mapped north of the Pillars, then there shouldn't be any fractures or vents near southern Humorum that could supply magma to Gassendi. As Kuiper used to say, "We don't pretend to know all the answers."

The final large crater near Humorum is Mersenius, a famous feature just outside the Humorum basin rim. Look closely at Mersenius and you'll notice that it has been strangely modified. At the telescope when the Sun is low you can easily see that the floor is bowed upward. With excellent seeing conditions (or on Lunar Orbiter photographs) you can make out a series of rilles. Perhaps mare magma rose up through basin fractures under Mersenius, doming its floor and making irregular fractures. In any case, Mersenius lacks the massive central peak that must have once existed inside it — most likely it is covered by the same lavas that partly fill the crater. In addition, if you look closely at the floor of Mersenius, you may see evidence of violence and turmoil from far away. A line of small overlapping craters on the floor points accusingly back toward the Imbrium basin. Are these far-flung secondary craters from that huge blast?

INDEPENDENT-MINDED RILLES

Whereas the Hippalus rilles on the eastern side of Humorum are well-behaved basin rilles concentric with the center of subsidence, the rilles on Humorum's western margin aren't. A long rille cuts through rubbly terrain west of Gassendi, bends through Humorum's basin rim, curves slightly south of Mersenius, and slices across the floor of the 30-km-wide crater de Gasparis. At various places this so-called Mersenius Rille spawns other rilles that trend in the same direction.

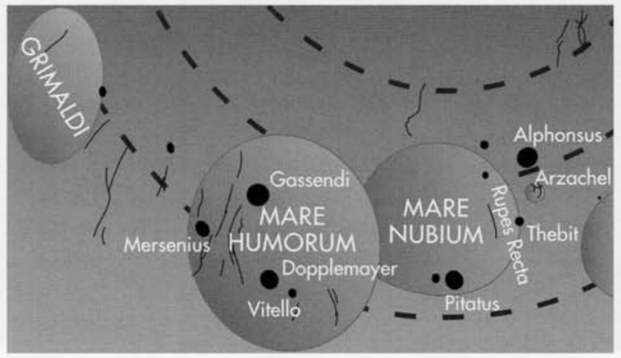
De Gasparis is the Grand Central Station of rilles, however, for it is crisscrossed by five troughlike rilles. Farther south is Palmieri, which is similarly traversed. None of these rilles on Humorum's western rim is concentric to the basin. In fact, they hardly seem to notice it is there. Why?

I think the most likely explanation presents itself if you look at a map of the rilles along the western shore of Oceanus Procellarum. This big-picture perspective shows that the western Humorum rilles are just part of a series of linear rilles (including those near Sirsalis, Hevelius, Olbers, Vasco da Gama, and Galvani) that are all approximately perpendicular to the rim of the putative Gargantuan basin. Other rilles that seem oblivious to local basins, such as those near Gutenberg and Taruntius and the Cauchy Fault (all near Mare Fecunditatis), are also radial to Gargantuan. This most giant and most ancient of lunar near-side basins (if it exists) could account for the emplacement of all these rilles.

According to recent work by Head and Lancaster University's Lionel Wilson, linear rilles are probably surface subsidences caused by near-vertical sheets of magma known as *dikes*, which rose almost to the surface. The Sirsalis Rille (Rima Sirsalis), whose northernmost extent reaches Procellarum, and other radiating rilles are thus the surface manifestations of the tips of long dikes that, along the lower topography of the original floor of Gargantuan, broke through to the surface. Such breakthroughs would cause the volcanic fissure eruptions whose lavas make up Oceanus Procellarum. Head and Wilson calculate that the Sirsalis dike is 600 meters wide and rose to within 2,400 meters of the surface before solidifying.

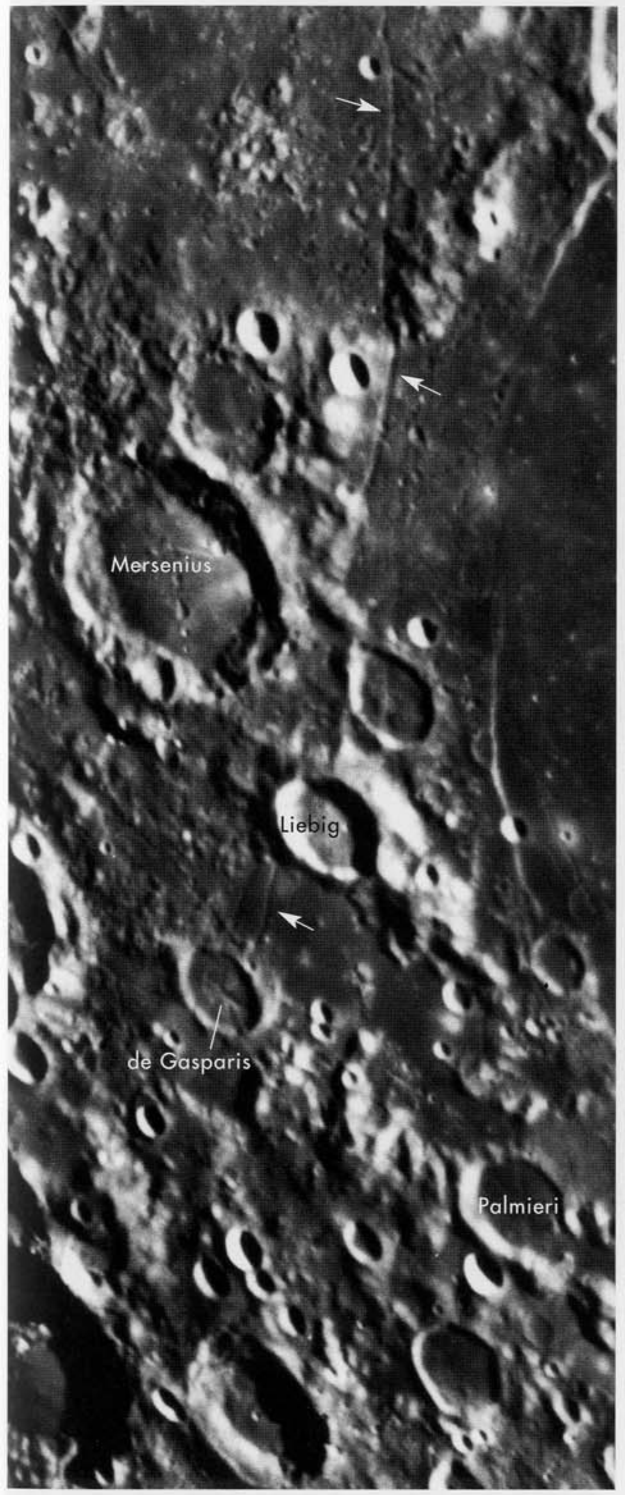
THE HELMET

A final noteworthy little landform in the Humorum region is not mentioned in any of the classic Moon books. The low "swampy" area east of Gassendi contains a number of ridges that are presumably pieces of otherwise obliterated craters. One grayish region has been dubbed "the Helmet" by Pieters and her coworkers. The Helmet stands out like a beacon in multispectral images because it differs from mare and highlands in being strongly absorbent in the ultraviolet region of the spectrum and more reflective in near-infrared wavelengths. This is nothing to get excited about; it just demonstrates yet another type of lunar material that Apollo astronauts weren't able to sample. Many mysteries await the next generation of lunar explorers, whenever they arrive.

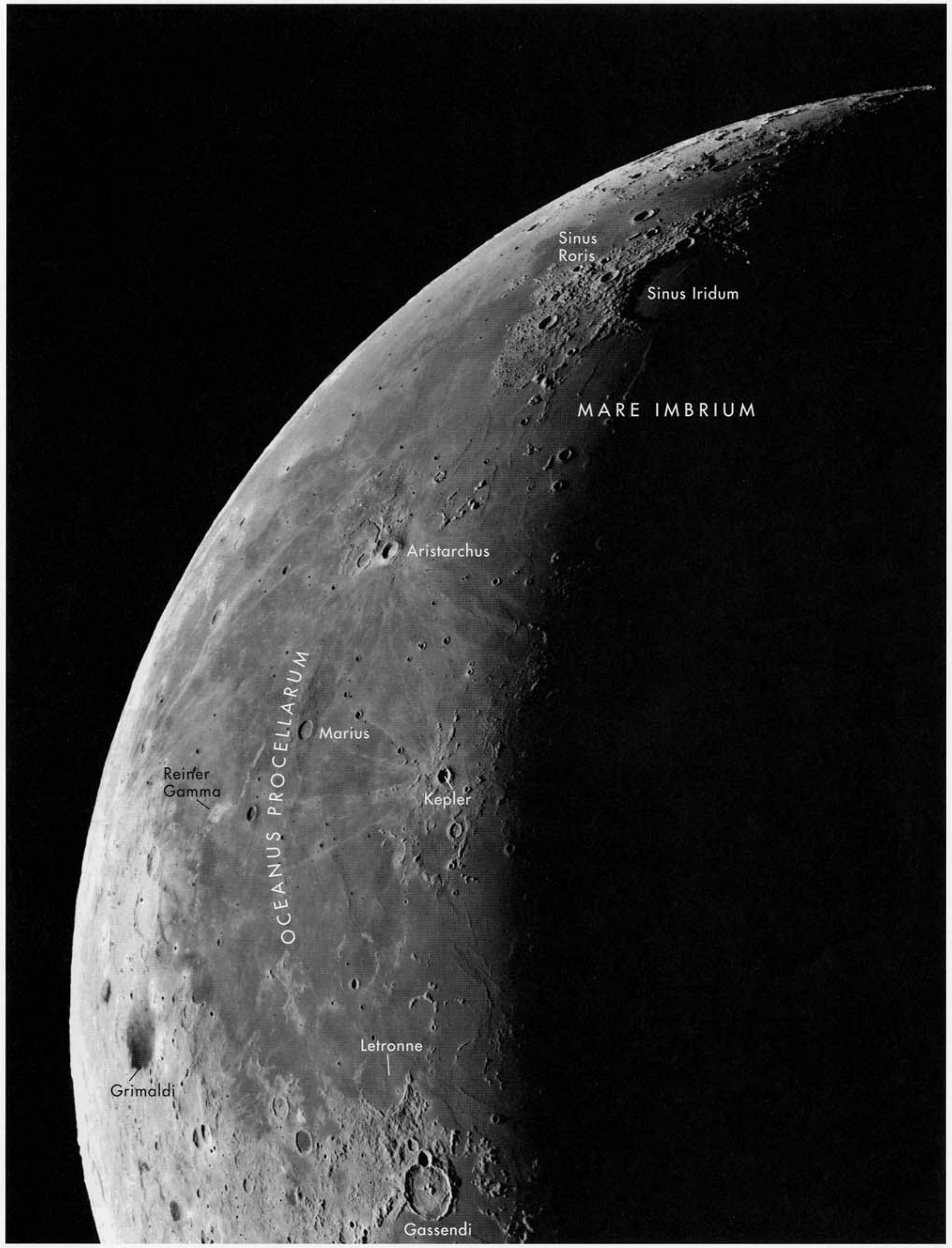


Mersenius and many other rilles are radial to the proposed Gargantuan/Procellarum impact basin.

The Helmet. (South is up.)



Mersenius rilles (arrowed).



Oceanus Procellarum.

17

Procellarum: The Biggest Basin?

Classical selenographers didn't appreciate the significance of Procellarum. All they really noticed was that it was a sea so large that they called it an ocean — an ocean of storms. Stretching 2,000 km north to south across the western side of the Moon, Oceanus Procellarum is neither circular nor is it partially surrounded by a mountainous ring like maria Imbrium, Nectaris, Crisium, and Humorum. A less obvious difference, discovered through the careful tracking of Lunar Orbiter spacecrafts, is that Procellarum also lacks a mascon gravity anomaly. So what is this largest and most unusual mare?

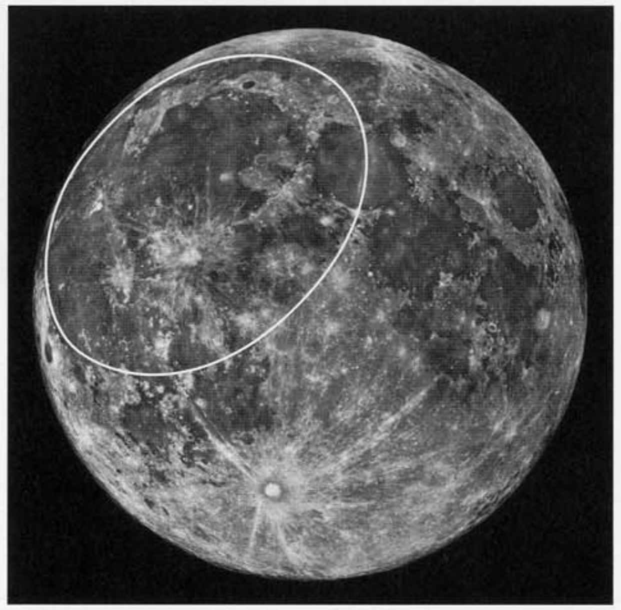
GARGANTUAN

A clever way to account for these anomalies was suggested by the British geologist Peter Cadogan. He noticed that the highland-mare border on the west side of Oceanus Procellarum defined an arc that could continue through the northern edge of Mare Frigoris and extend farther along an abrupt northwestern termination of the southern highlands north of the crater Ptolemaeus. Cadogan speculated that these arc segments were the remnants of a 2,400-km-wide Gargantuan basin formed by a giant impact about 4.3 billion years ago.

Gargantuan, if real, would solve a number of problems. The reason that Procellarum isn't a circular mare patch is that it occupies only a portion of the Gargantuan depression. Low parts of the giant basin are filled by the mare basalts south of Mare Imbrium and the arcuate trough of Mare Frigoris. The subsequent formation of the Imbrium basin obliterated part of Gargantuan. And perhaps Gargantuan lacks a surrounding mountain rim because it formed so early in lunar history that the Moon was warm and still plastic enough to deform, allowing the rim to subside. This fits with Cadogan's idea that Gargantuan lacks a mascon because the lunar crust was not yet sufficiently rigid to support any excess mass.

The existence of Gargantuan would solve other problems as well. Two fundamental discoveries of the Apollo program were that the Moon has a 60-km-thick crust of anorthosite, but, strangely, the average thickness of that crust is 8 km greater on the far side than on the near side. Cadogan's explanation of this discrepancy was that Gargantuan both excavated a deep

Peter Cadogan.



Cadogan's map of the proposed Gargantuan basin.

hole on the near side (thinned that crust) and redistributed its ejecta (crustal rocks) to the far side.

Finally, Gargantuan — in its role as explainer of all things — provides an answer to the riddle of the composition of the Apennines. After the discovery of the anorthositic lunar crust from Apollo 11 samples, the Apollo 15 mission to the Apennine rim of the Imbrium basin was expected to bring back samples of uplifted anorthositic crustal rocks. And it did; for example, the astronauts brought home the famous genesis rock. However, the Apennines were found to have a considerable amount of KREEP rocks, which are high in radioactive and rare-earth elements. Sensors on the orbiting command modules of the Apollo flights also detected high levels of radioactivity over Procellarum and Imbrium. Cadogan proposed that a massive outpouring of KREEP-rich lavas erupted onto the floor of the Gargantuan basin, and that even though these lavas have been covered by later mare basalt lavas, the underlying radioactivity is still detectable. And the Apennine rim? It's KREEP-rich because the Imbrium basin was excavated in post-Gargantuan lavas that contained KREEP.

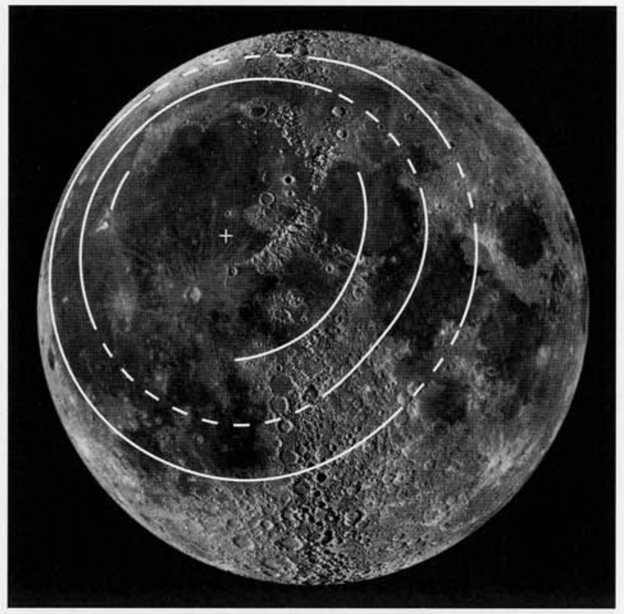
Another, even larger ancient impact basin exists on the lunar far side — the South Pole–Aitken basin (or BBB for big back-side basin) discussed in Chapter 13. This is one of the largest impact basins in the solar system and is 2,500 km wide and 13 km deep. It has not been extensively flooded with lavas, presumably because the thicker crust of the lunar far side was harder for rising magmas to penetrate.

Cadogan suggested that the far-side crust was thicker because of the piling up of ejecta from Gargantuan. But wouldn't the South Pole–Aitken basin make a similar hole in the far-side anorthositic crust and transfer its ejecta to the Earth-facing hemisphere of the Moon? In fact, analysis of the recent Clementine data suggests that the South Pole–Aitken basin has a remarkably thin crust that is only 20 km thick and that the extra volume of back-side crust is about equal to material missing from the South Pole–Aitken basin hole. The near-side cratered highlands also have a thick crust (as much as 95 km thick in places), so it is possible that Gargantuan and the BBB both engaged in the wholesale redistribution of lunar rocks.

Whitaker was actually the first person to notice that Oceanus Procellarum is part of a giant ancient basin. But he delayed publishing his map until after Cadogan did and originally did not consider the broader significance of the proposed basin. Whitaker's Procellarum basin is much better defined than Cadogan's Gargantuan and encompasses fragments of at least three concentric rings, the largest of which is 3,200 km in diameter and includes much of the Moon's Earth-facing hemisphere!

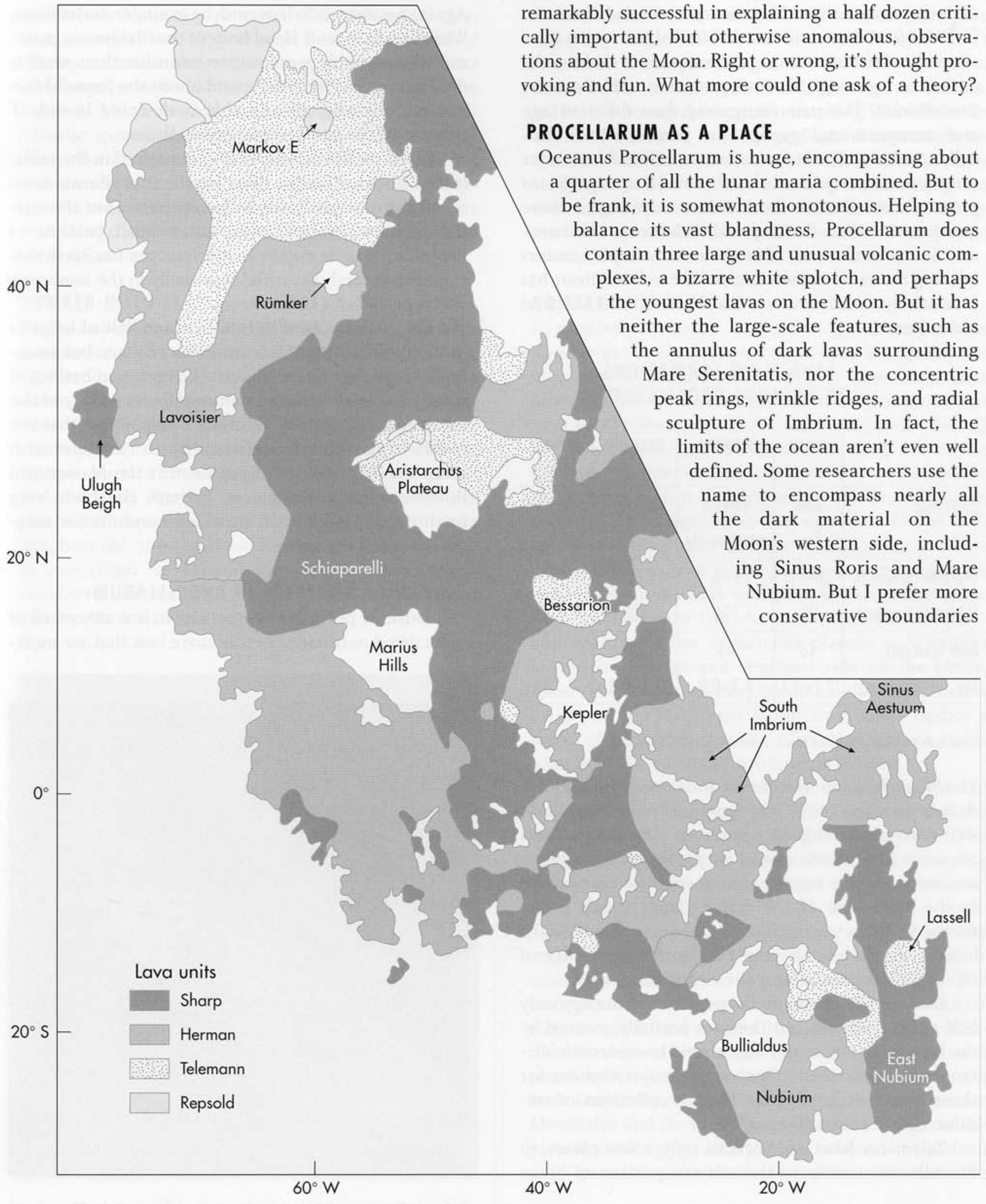
Gargantuan and Procellarum provide a fine example of the relationship between different scientists' training and interests and their perspective and treatment of new information. Cadogan is a geochemist who was intimately involved with the analysis and interpretation of lunar samples. Whitaker's expertise is the mapping of lunar features. Cadogan used Gargantuan to explain fundamental problems of lunar structure and composition, whereas Whitaker's initial concern was simply to find an origin for troubling ridges and other lunar topography that didn't seem related to known basins. Cadogan quickly published his paper on Gargantuan because it was an exciting solution to many Apollo-era problems. Whitaker delayed because describing an ancient basin at the limits of credibility didn't seem very important at the time and probably wouldn't have been accepted for publication.

Gargantuan is also of interest in light of the "giant impact" theory for the Moon's origin. The Gargantuan and South Pole–Aitken basin events are simply smaller giant impacts. Apparently, the early Earth (and later the Earth-Moon system) experienced a series of catastrophic impacts that diminished in size during the first half billion years of solar-system history. If the Moon had been hit by a projectile only somewhat larger than those that formed Gargantuan and the South Pole–Aitken basin, the impact would have shattered the Moon into a ring of rubble surrounding Earth. And while a Saturn-like ring would be marvelous, I prefer the Moon.



Whitaker's map of the Procellarum Basin.

STRATIGRAPHY OF OCEANUS PROCELLARUM BASALTS



Major lava units in Oceanus Procellarum as determined by Whitford-Stark and Head.

The Gargantuan basin is an example of a truly outrageous hypothesis, startling in its magnitude and innovation and rich with consequences. Even though the idea has often been ignored or criticized, it is remarkably successful in explaining a half dozen critically important, but otherwise anomalous, observations about the Moon. Right or wrong, it's thought provoking and fun. What more could one ask of a theory?

PROCELLARUM AS A PLACE

Oceanus Procellarum is huge, encompassing about a quarter of all the lunar maria combined. But to be frank, it is somewhat monotonous. Helping to balance its vast blandness, Procellarum does contain three large and unusual volcanic complexes, a bizarre white splotch, and perhaps the youngest lavas on the Moon. But it has neither the large-scale features, such as the annulus of dark lavas surrounding Mare Serenitatis, nor the concentric peak rings, wrinkle ridges, and radial sculpture of Imbrium. In fact, the limits of the ocean aren't even well defined. Some researchers use the name to encompass nearly all the dark material on the Moon's western side, including Sinus Roris and Mare Nubium. But I prefer more conservative boundaries and see Oceanus Procellarum extending from the Rümker volcanic lump southward to the flooded crater Letronne. Its western margin is well defined by the highland-mare boundary, but to the east it oozes imperceptibly into both maria Imbrium and Nubium.

Whitford-Stark and Head of Brown University used a variety of remote-sensing information to deduce the definitive geological interpretation of Oceanus Procellarum. The pair recognized four different age and compositional groups (or *formations*) of Procellarum lavas. These formations resulted from major eruptions of particular lavas that make up significant parts of Procellarum. From oldest to youngest these groups are called the Repsold, Telemann, Hermann, and Sharp formations, after the nearby impact craters bearing the same names. Each of these formations has a relatively consistent set of observed and inferred characteristics:

LAVA-FLOW FORMATIONS IN OCEANUS PROCELLARUM

	SHARP	HERMANN	TELEMANN	REPSOLD
Brightness	dark	darkish	bright	bright
Craters	few	intermediate	many	?
Titanium content %	3–11	1–6	<2	?
Thickness (meters)	25	150	250	125
Area (percent)	43	45	11	1
Age (billion years)	2.7±0.7	3.3±0.3	3.6±0.2	3.75?

Data from Whitford-Stark and Head, 1980; ? = not determined

The Sharp lavas are the easiest to see because they are darker than the other lava flows on which they lie. A well-defined, triangular patch of Sharp-age lavas occurs in Sinus Roris. Under very tranquil atmospheric conditions you may be able to spot the narrow rille in the mare west of the crater Sharp, which is the source for these young lavas. Another exposure of Sharp lavas is the dark material at the southwestern edge of Oceanus Procellarum near the crater Damoiseau.

Lavas of the Hermann Formation now occupy only half of Procellarum, but they are partially covered by the later Sharp lavas and may extend considerable distances beneath them. One of the major sources for these lavas was the Marius Hills, a collection of volcanic domes and sinuous rilles.

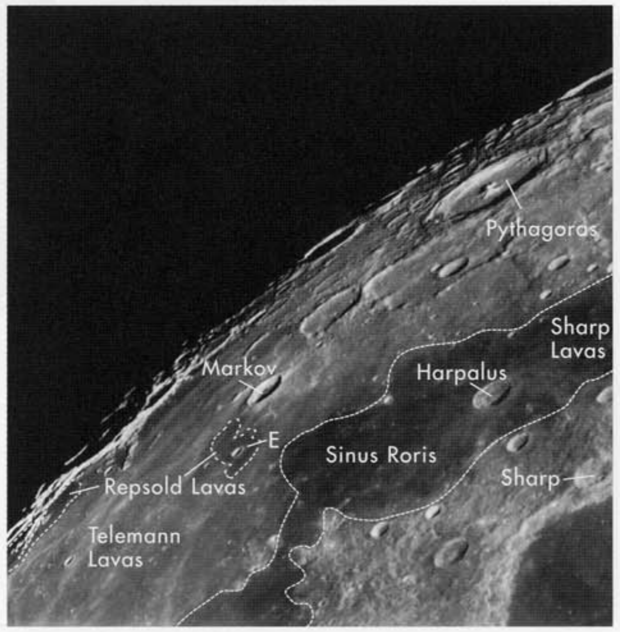
Telemann lavas are seen in only a few places in Procellarum, mostly in the western portion of Sinus Roris. They are the older, brighter, more heavily cratered, and topographically higher basalts that the Sharp lavas butt up against. The Aristarchus plateau seems to have been a source for the Telemann lavas. Again, because it is covered by younger formations, Whitford-Stark and Head believe that Telemann material was probably much more extensive than what is now exposed. Little can be said about the Repsold formation, a geological unit that is detected in only 1 percent of the vast Oceanus Procellarum.

Based on the information summarized in the table, it took about 1 billion years for the Procellarum lavas of various compositions to be erupted onto the surface. As we will see later, other small patches of Procellarum lavas may be much younger. On Earth volcanism has rarely occurred repeatedly in the same area over a period of a billion years.

The mapping by Whitford-Stark and Head helps to explain the history of Oceanus Procellarum, but amazingly they never mentioned the Gargantuan basin and whether it might have somehow influenced any of the area's volcanic activity. Whitaker's map shows that the middle ring of his Procellarum basin coincides with many wrinkle ridges and passes near the Marius and Rümker volcanic complexes. Perhaps the basin ring fractures of Gargantuan provided conduits for magmas to reach the surface.

VOLCANIC COMPLEXES IN PROCELLARUM

Volcanism is pervasive on the Moon, but almost all of it occurred as broad sheets of mare lava that are mostly flat and monotonous. But in Oceanus Procellarum, there are three unique, large volcanic complexes. Nobody really knows how they formed. Back in the early days of modern lunar studies (1968), USGS scientist Jack McCauley proposed that this concentration of volcanism in northern Procellarum formed above convection zones that brought magma up from the lunar mantle. A terrestrial analogy would be Iceland, which formed as a hot spot on the mid-Atlantic spreading ridge. We really don't believe that ocean-floor spreading occurred on the Moon, but there must have been some other feature (perhaps associated with Gargantuan, as suggested by Whitaker) that resulted in localized volcanism at these three locations.



Dark, young Sharp lavas partially cover older Telemann lavas. The crater Markov E has excavated darker Repsold material from beneath the Telemann lavas.

RÜMKER HILLS

The so-called Rümker Hills are the smallest and northernmost of three volcanic complexes. Although Lunar Orbiter images show that Rümker includes about a dozen low, coalescing domes, telescopic observations when the Sun angle is low reveal that the most important topographic feature is a mound with a somewhat bumpy surface measuring about 65 km across. Unfortunately, Rümker is relatively small and poorly placed for easy observation. In the four classic books that bear the title *The Moon,* Rümker is not shown at all in one (Elger 1895), and the others (Neison 1876, Goodacre 1930, and Wilkins and Moore 1955) depict it incorrectly as a ruined crater.

The Rümker Hills.

Rümker gives the impression of being older than the surrounding mare lavas, but none of the mare wrinkle ridges cross it. The most noticeable feature of Rümker is a diamond-shaped depression on its eastern flank. Besides being lower, this area is smoother. The relatively high-Sun Lunar Orbiter images don't emphasize this aspect, and it isn't mentioned in any of the scientific literature I've read. The depression misled early selenographers into mistaking Rümker for an old battered crater, but to a geologist a depression on the flank of an obvious volcanic mound immediately suggests a *caldera* or volcanic collapse crater. If it is a caldera (and there really is no other evidence to support this speculation), it would be one of the largest on the Moon.

ARISTARCHUS PLATEAU

A relatively straight wrinkle ridge extends from Rümker to the northeastern tip of what is arguably the most unusual feature on the Moon — the Aristarchus plateau. With all the strange and weird landforms that exist on the Moon you may think I exaggerate, but all the other candidates are simply the largest or most unusual examples of standard features — whereas the Aristarchus plateau is unique. An elevated diamond bounded by straight sides that measures 170 by 200 km, it is darker than the surrounding maria. At its southeastern corner is the brightest large crater on the Moon, Aristarchus, and next to that is the older, dark-floored crater Herodotus. But the most remarkable feature of the Aristarchus plateau is Schröter's Valley, the biggest and strangest rille on the Moon. About 100 km east of the plateau are the ruined crater Prinz and the Harbinger Mountains, which harbor a maze of beautiful sinuous rilles that are probably somehow related to the Aristarchus plateau.

The plateau itself was almost completely ignored by classical selenographers, who were dazzled by Aristarchus and fascinated by Schröter's Valley. The plateau is roughly 2 km higher than the surrounding Telemann-age mare, which embays it on the north and east; thus the plateau is older than 3.6 billion years. The plateau's surface has smooth areas (especially inside the bend of Schröter's Valley), but overall it is undulating and marked by small hills and ridges. The eastern portion of the plateau (north of Aristarchus) is more irregular and apparently higher than the remainder. An unusual thin ridge (the Agricola Mountains) parallels the north boundary of the plateau. Hartmann and Kuiper speculated that because the Agricola Mountains and the northern and southern edges of the plateau are roughly radial to Mare Imbrium, the plateau must be associated with the formation of the Imbrium basin. It probably was, but it is unclear why there would be only one such uplifted block. Is the plateau, as McCauley speculated, an outpouring of lava above a hot spot — a lunar Iceland? Or is it controlled by the conjunction of fractures associated with both Gargantuan and Imbrium? Maybe it's just something we aren't clever enough to figure out.

One obvious difference from any other place on the Moon is the distinctive color of the Aristarchus plateau, compared to the gray of surrounding mare lavas. An unusual, delicate reddish hue was first noticed in 1647 by Hevelius and was confirmed in an Apollo color photograph. In 1912 the plateau was also found to be the darkest spot on the Moon when photographed through an ultraviolet filter. (It is also rather dark in visible wavelengths.) The plateau became known as "Wood's Spot" after the discoverer of the UV anomaly, the astronomer R. W. Wood. He suggested that the feature might be a deposit of sulfur, which was known to be very absorbant in ultraviolet light. Even though R. W. Wood was not related to me, I still think that Wood's Spot is a fine name, but sadly it has fallen out of use. Most reports describe the plateau as ruddy, but other observers report a yellowish tint reminiscent of hot-dog mustard, and I have seen a pronounced olive tone in telescopic views when the Moon was nearly full. What color do you see?

Other unusual features emphasize the uniqueness of the Aristarchus plateau. It is a very poor reflector of radar waves, meaning that it has a smooth surface and lacks abundant fist-sized or larger rocks. During lunar eclipses it cools more than other dark regions, and high-resolution spacecraft photographs show that the sharpness and depths of small craters are subdued, a strong implication that the plateau is mantled by a few tens of meters of volcanic ash. The dark color (and the presumed volcanic mantling) extends eastward to the adjacent Harbinger Mountains. Spectral studies suggest that this material is an iron-rich volcanic glass, perhaps tiny glass spheres like those found at some Apollo landing sites.

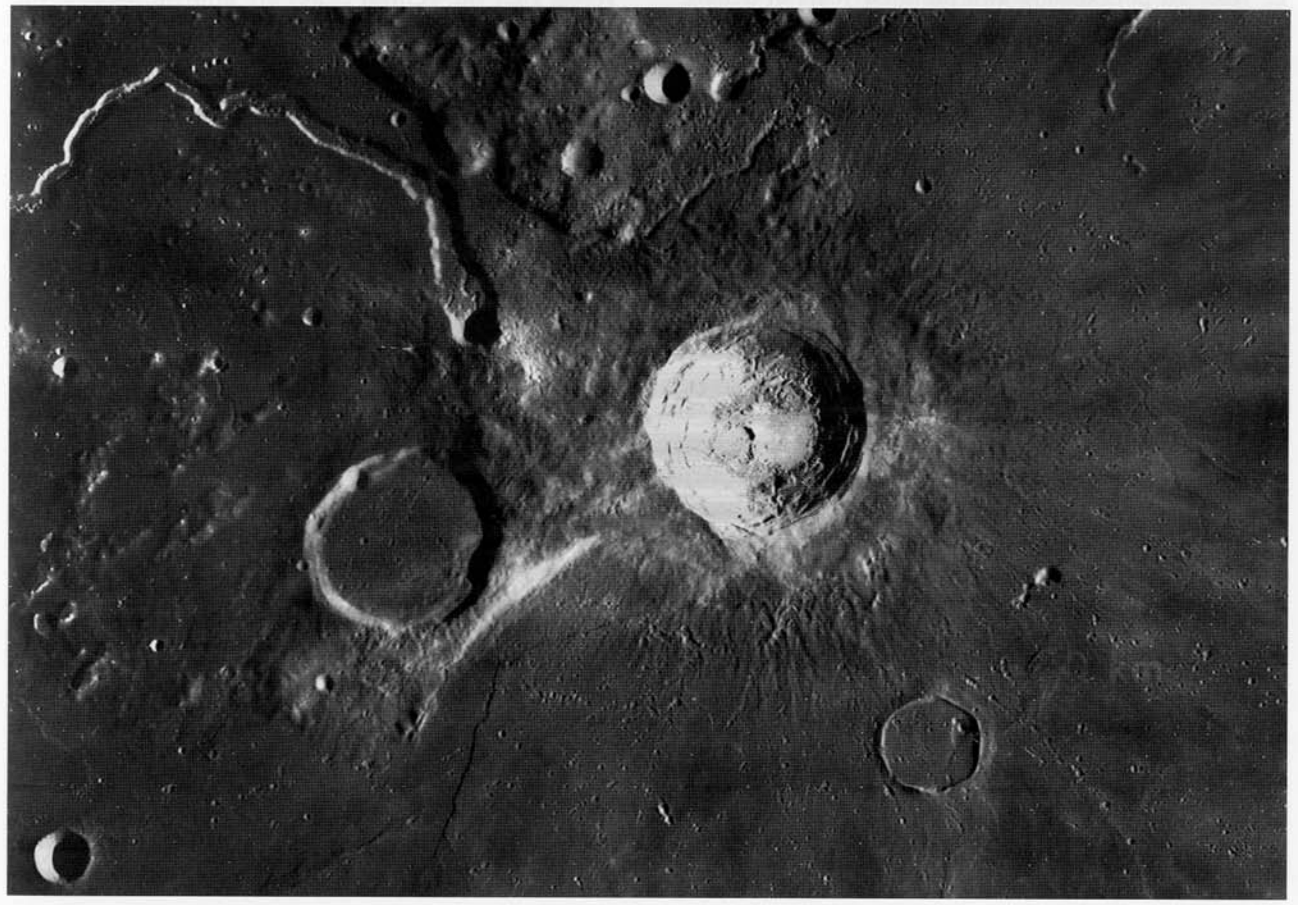
The most likely source for much of the volcanic mantle is the Cobra Head, a 9-km-wide volcanic crater that is the source of the sinuous rille known as Schröter's Valley. This crater, on the north side of a 30-km-wide hill or dome, lies at the head of a shallower and broader elliptical area, which continues northward as the large valley discovered by Schröter in 1787 (and by Huygens in 1686). Schröter's Valley is the largest and most unusual sinuous rille on the Moon. It extends for 160 km, measures about 10 km wide near the Cobra Head, and has a flat-bottomed floor 200 to 1,000 meters deep. For much of its length, the rille is closer to 5 km wide, and it narrows to the point where it is barely visible when it reaches the surrounding mare. The drop in elevation from the Cobra Head to the mare is about 2 km, corresponding to an average slope of less than 1°.

The Aristarchus plateau.

Although it was once proposed that the rille was cut by a swiftly flowing current of volcanic ash and gas, the currently accepted view is that it was formed by rapidly flowing lava. Head and Wilson have used physical models to argue that the formation of the Cobra Head and the very large Schröter's Valley would require phenomenal rates of volcanic activity, with 10 million to 10 billion kilograms of basalt erupting every second! Such a high eruption rate for lava flows would undoubtedly propel millions of volcanic droplets into the lunar sky, just as the biggest Hawaiian eruptions spew fire-fountains of volcanic glass hundreds of meters above their vents. Whitford-Stark and Head calculated that lava from the Aristarchus plateau region could have covered all of Oceanus Procellarum to a depth of 200 meters. But spectral images show that the dark mantling material abruptly stops at the edge of the plateau, which must be older than the adjacent lava flows. A continuation of the volcanic mantling material that drapes the plateau is probably buried under later Sharp and Hermann lava flows.

CONTINUING VOLCANIC ACTIVITY?

Aristarchus is such a brilliant crater that it commands attention, and some observers have reported temporary changes there. Sir William Herschel, the discoverer of Uranus, believed that Aristarchus was an active volcano, and there have been many more recent reports of flashes, obscurations, and red and violet glows near the crater and elsewhere on the plateau. The most credible report was made by observers using the Lowell Observatory's 24-inch refractor to make Moon maps in preparation for the Apollo program. On October 30, 1963, James Greenacre and Edward Barr saw three sparkling reddish orange spots, the first on the southwest rim of Aristarchus, the second near the Cobra Head, and the third near the first bend of Schröter's Valley. One month later, Greenacre and Barr plus three other observers, this time at two telescopes,



Aristarchus, Herodotus, and Schröter's Valley as imaged by Lunar Orbiter IV.

saw two more pinkish-red scintillating spots in nearly the same locations. On the first occasion, the red spots had disappeared after 20 minutes — this time they persisted for 75 minutes.

The interpretation offered by Greenacre, and later by Hartmann and others, is that eruptions of incandescent lava were responsible for the red glows. But it is highly unlikely that three widely separated points tens of kilometers apart would erupt simultaneously and then repeat the performance precisely one month later! Almost certainly these skilled observers were tricked by turbulence in Earth's atmosphere, the chromatic aberration of their refracting telescope, or sunlight glancing off bright lunar slopes that was dispersed into tiny spectra.

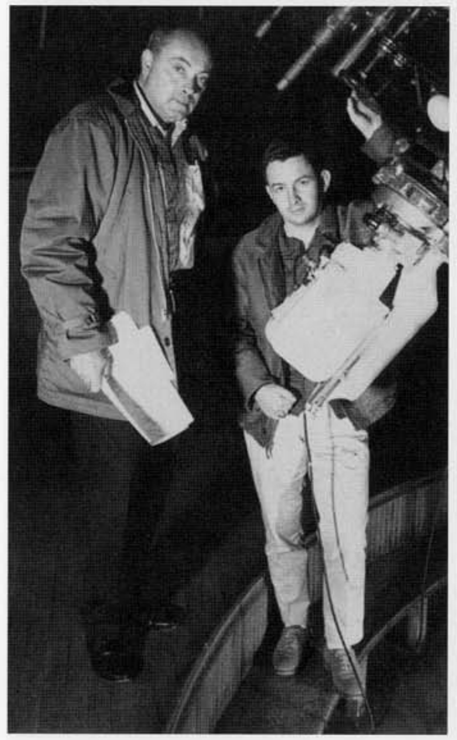
But maybe there is more to it than that. A spectrometer on the Apollo 15 Command Module detected radon gas near Aristarchus. In addition, NASA scientist Winifred Cameron determined from hundreds of reports that transient lunar phenomena (TLPs) like the Aristarchus glows preferentially occur at times of maximum tidal stress in the Moon. While thermal studies have established the extreme unlikelihood of present-day volcanism on the Moon, it is possible that gases generated by the radioactive decay of uranium and thorium could be released periodically. Two hundred years of debate about purported changes on the Moon could be due to insignificant releases of gases from the decay of radioactive elements — the last gasps of an old geezer.

ARISTARCHUS AND HERODOTUS

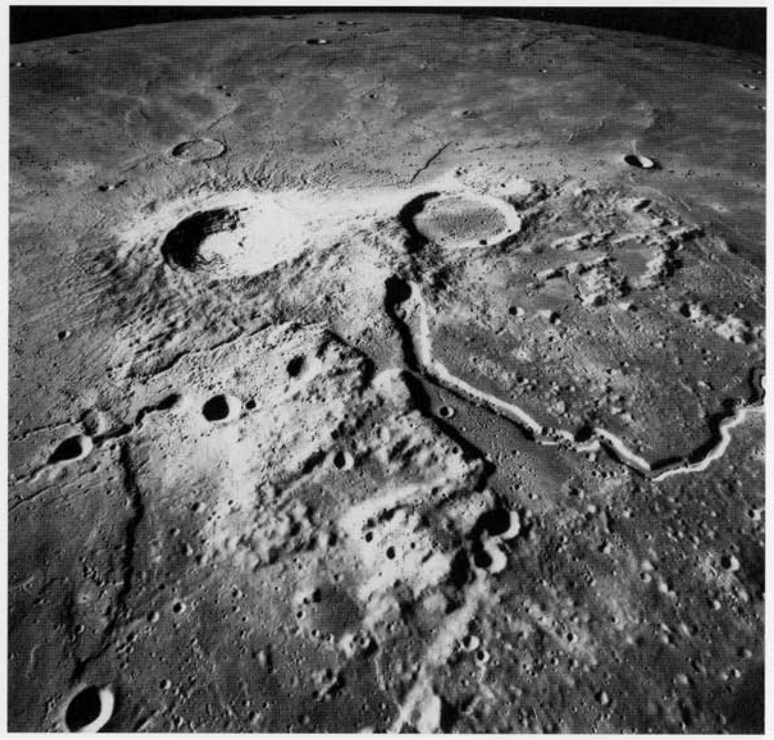
After all the discussion about the peculiar volcanic features of the Aristarchus plateau, let's not forget Aristarchus itself. Aristarchus is a 40-km-wide complex impact crater of the Tycho type. Although Aristarchus is brighter than Tycho, it has a slightly larger number of superposed impact craters and thus is somewhat older, having formed about 500 million years ago.

Aristarchus has razor-sharp rim crests, terraced walls, and a small central peak protruding from a flat floor. One of its most remarkable features is a series of radial dark bands that stretch up the west wall. Keen-eyed amateur astronomers have observed these features for more than a century and offered various theories to account for them, including the notion that the bands are vegetation. More prosaically, the bands are now interpreted as raylets of glass-rich impact ejecta — fallback material excavated by the Aristarchus impact. Detailed infrared measurements of Aristarchus's interior revealed three different types of lunar highland crust. The impact that created Aristarchus penetrated whatever mare material was at the target site and cut into a complex basement of highland rocks. High-resolution Clementine images reveal that the central peaks are anorthosites — the primitive calcium-rich slag from the magma ocean.

The rays of Aristarchus extend 125 to 150 km beyond the crater's rim to the south and east, interfingering with rays from Copernicus and Kepler. High-resolution satellite images show that Aristarchus, like Tycho, is surrounded by a dark halo (only partially in this case) caused by splashes of impact melt. The real peculiarity is that rays do not appear to lie over the surrounding plateau, though some short ray streamers do seem to extend beyond the northeast edge of the plateau. This is truly remarkable. If the rays don't extend over the plateau, the surface of the plateau must be younger than Aristarchus, which is unbelievable. Satellite pictures do show some evidence of Aristarchus secondary craters on the plateau, but the secondary impacts dug up dark mantle material rather than bright crustal rocks, so the rays aren't bright.



James Greenacre (left) and Edward Barr stand at the eyepiece end of the Lowell Observatory's 24-inch refractor.



This detailed photograph of Aristarchus and Schröter's Valley was taken from orbit by Apollo 15.

Now on to Herodotus. What can you say about an old, degraded crater in the shadow of the most brilliant crater on the Moon? Not much besides recite its dimensions. Herodotus is 35 km across and 1.3 km deep. Schröter's Valley does not penetrate the rim, but one of the rays of Aristarchus crosses the southern part of its otherwise featureless floor.

PRINZELY RILLES

East of the Aristarchus plateau are the breached and flooded crater Prinz, the Harbinger Mountains, and a bevy of sinuous rilles that extend to the north. The rim of Prinz (47 km) tapers from a height of about 1 km to just one low remnant on its southern side. Similarly, a tiny hill is all that shows of its central peak. Did Prinz form on a slope or was the crater tilted so that its southern rim subsided below the mare lavas?

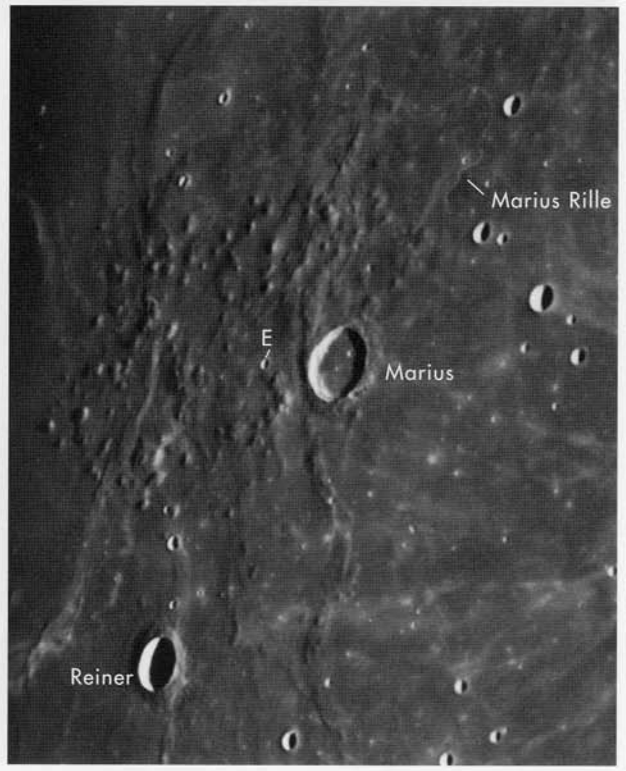
The Prinz rilles help to answer this question. These four large sinuous rilles are miniature versions of Schröter's Valley — beginning with a broad Cobra Head–like depression (just barely visible in a 6-inch telescope) that wiggles away downhill from its source. I propose that the Harbinger Mountains are an uplifted area of older, pre-Imbrian rocks. The uplift tilted Prinz, allowing lavas to flood in. And the cause of the uplift? The rise of a large pond of magma that ultimately escaped to the surface, forming the rilles.

MARIUS HILLS

The third volcanic complex in Oceanus Procellarum is unlike the stump of Rümker or the uplifted block of the Aristarchus plateau. The Marius Hills may be a place where a concentrated rise of magma within the lunar crust resulted in very slight updoming of the mare crust and the formation of about 300 small domes or hills. These hills are of two types: low domes typically 3 to 10 km wide and a few hundred meters high, and steeper hills up to 1,000 meters high that often rise out of the low domes. All these hills seem to be steeper and rougher than normal lunar domes, and very few have summit craters. The Marius Hills are undoubtedly small volcanoes, but they are not just little shield volcanoes like those in Iceland and elsewhere on the Moon — they are cones, not domes. The entire region also has a strong positive gravity anomaly, implying that there is a substantial root of dense unerupted magma below the surface.

Two long sinuous rilles are faintly visible near the Marius Hills. One looks like a strand of curly hair on the mare northeast of the Hills. This rille starts at a barely visible Cobra Head–like depression and meanders for a distance of about 275 km while maintaining a width of only about 300 meters. Another rille of similiar size hugs the western edge of the Marius Hills complex, and narrower rilles originate in the middle of the complex. Whitford-Stark and Head proposed that the Marius Hills were the source of much of the 3.3-billion-year-old Hermann Formation, whose lavas cover nearly half of Oceanus Procellarum.

Using Clementine multispectral data, Wilson and colleagues from England and the Netherlands discovered six chemically distinct volcanic units in the Marius Hills. The most common lava flows have some of the highest levels of iron oxide detected on the Moon. The European researchers also noticed that most of the domes and hills are overlapped by the surrounding lava flows, which, therefore, must be younger. The



The Marius Hills.

cones appear to be coated by a glassy material that is interpreted as pyroclastic deposits (ash).

A speculative geologic history of the Marius Hills would start with early gas-rich magma rising from the lunar mantle, producing pyroclastic eruptions, which built the steep-sided cones. Rising magma with less gas constructed the gently sloped domes. Later lavas flowed from the rilles and spread between and around the hills and farther out onto the surrounding plains. From comparisons with Earth volcanism we believe that the cones are built up from small amounts of relatively slowly erupting magma, whereas rilles and mare flows result from much larger batches of rapidly rising magma. It seems that over time the magma plumbing became more efficient at transporting magma to the surface.

In the 1960s the Marius Hills were proposed as a landing site for the robotic Surveyor spacecraft, and later were a highly favored candidate site for Apollo 15 and 16. The USGS geologists believed that the hills included some of the youngest volcanic rocks on the Moon and thus would make an excellent landing site. But other locations were selected. Someday in this new century, lunar geologists will sample the Marius lavas and learn their ages, compositions, and maybe even figure out why they exist at all.

This spectacular Lunar Orbiter IV photograph shows the Marius Hills. Marius E is the largest crater near the right-hand edge of the picture.

REINER GAMMA

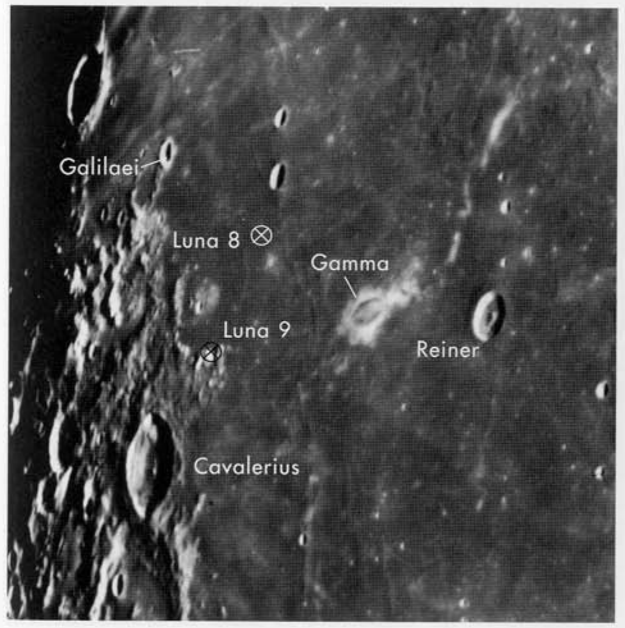
Light or dark, all features on the Moon can be interpreted in terms of their geologic associations except for one — *swirls*. These are bright, irregular markings that occur in only a few locations and appear to have no relation to their settings. Reiner Gamma, located in western Procellarum, is the only swirl on the Earth-facing side of the Moon. It appears as an oval patch of bright material with a discontinuous tail that points toward the Marius Hills. With high-Sun lighting, small splotches to the southwest are also visible.

For decades telescopic observers hunted fruitlessly for some subtle topography that would indicate that Reiner Gamma was simply the peculiar ray pattern of an impact crater. But it seems to just be a splash on the mare surface. Apollo-mission magnetometer readings deepened the mystery by detecting one of the strongest local magnetic fields on the Moon at Reiner Gamma. The other swirls (all on the lunar far side) were also found to be *magcons*, concentrated areas of intense magnetism.

Thirty years after the Apollo missions there still is no compelling explanation for Reiner Gamma and the other swirls, but there are some interesting ones. Peter Schultz and Lynn Srnka of the Lunar and Planetary Institute in Houston, Texas, proposed that the splotches and magnetic anomalies were the result of cometary impacts. But if their speculative and complex hypothesis is correct, why aren't there bright swirls all over the Moon? Various studies have shown that impacts from comets should be just as common as those from asteroids.

An alternative theory for the splotches came from Lonnie Hood and his colleagues. They noticed that most of the areas with unusual magnetic fields and bright swirls are located on exactly the opposite side of the Moon from the most recent impact basins: Orientale, Imbrium, Serenitatis, and Crisium. Hood and his group suggest that the magnetic fields date from 3.8 to 4.0 billion years ago, when these basins formed, but that the swirls appeared much later, perhaps resulting from nearby normal impact craters that deposited bright secondary rays and scattered bright ejecta. Normally, ray material is darkened by the constant solar wind of ions that transform impact-melted glassy rock debris into darker minerals. Hood speculates that the localized magnetic fields could have deflected solar wind from certain areas, thus preserving the bright material. In this theory the swirl shapes map out partial arcs of the local magnetic field.

This sounds plausible, even if it is speculative. But now for the "oops factor" — Reiner Gamma, the best-known swirl, is not antipodal to any impact basin! So how do we explain its magcon? We can't. Reluctantly, we must leave Reiner Gamma with Elger's summary description: "ill-defined white spots of doubtful nature."



Reiner Gamma.

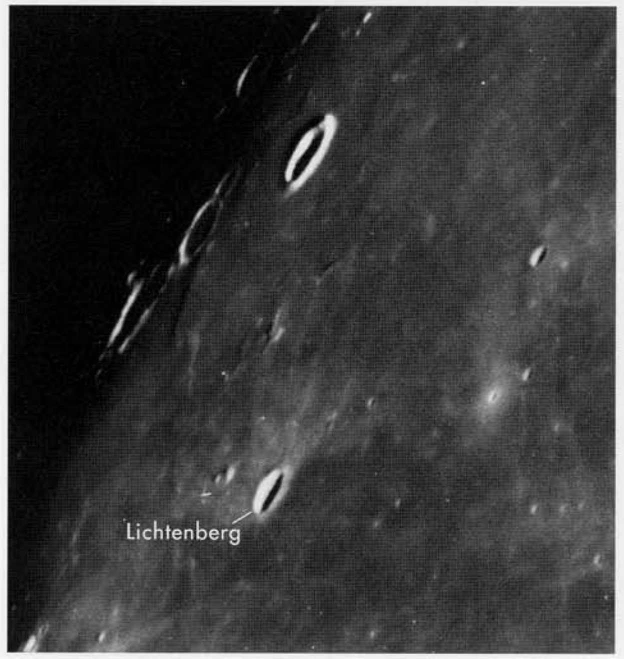
A Lunar Orbiter IV view of Reiner Gamma.

THE YOUNGEST LAVAS ON THE MOON?

One of Shoemaker's first contributions to lunar science was developing a mathematical understanding of how impact craters and crater rays form. Shoemaker realized that fresh-looking craters like Copernicus and Tycho have long, bright rays, but that the rays of older craters were somehow eroded away. Rays thus provide a way to identify the youngest craters on the Moon.

A first observation about rays is that they indiscriminately cover everything, both highlands and mare. But in 1965 the USGS Moon mapper Henry Moore discovered that some of the bright rays from the 20-km-wide crater Lichtenberg (located near the Moon's western limb, northwest of the Aristarchus plateau) were apparently covered by a patch of dark lava in Oceanus Procellarum. In 1965, when no one knew the actual age of the Moon, this was simply regarded as evidence that relatively recent volcanism had occurred on the Moon.

As Apollo samples were dated, it became clear that there were no mare lava samples younger than about 3.1 billion years, and crater counting showed that large unsampled areas were only a half billion or so years younger. A conventional wisdom soon emerged that held that lunar volcanism occurred during a short (on a lunar time scale) interval from about 3.9 to 2.5 billion years ago. But in 1983 Schultz and Spudis presented evidence that lunar volcanism started earlier and lasted longer. The lavas near Lichtenberg were apparently the youngest on the Moon. A crater the size of Lichtenberg should have lost its rays by its billionth birthday — the crater must be younger than that, and so must the mare lavas.



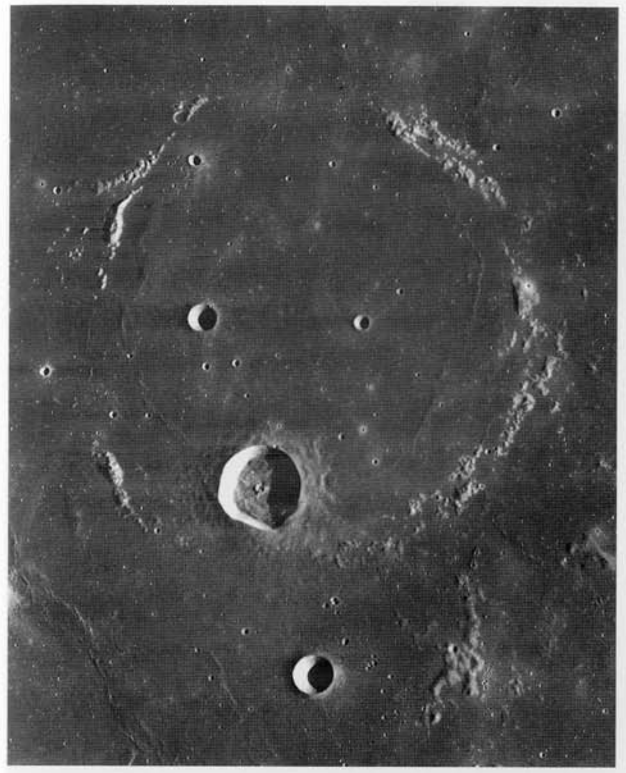
Rays from the crater Lichtenberg are covered to the south and east by younger dark lava.

Look at bright-rimmed Lichtenberg with your telescope and you'll easily see the dark lavas that cover the rays southeast of the crater and in fact go right up to its rim. Clearly the lavas are younger than the bright-rayed crater. Why does it matter that there is very young volcanism on the Moon? Because melting rock requires a heat source and all theoretical models of lunar evolution allow for heat-generating radioactivity only in the first billion years or so of the Moon's life. We can't explain how magma was produced 1 billion years ago, so there is something wrong with our understanding. Interestingly, since Mädler's observations in the 1830s, some observers have occasionally glimpsed a reddish tint or glow in this area of young lava. (Schultz and Spudis suggest an age of 900 million years.) It would be wonderful, but wildly unlikely, if volcanism still occurred on the Moon from time to time.

SOUTHERN PROCELLARUM

The northern part of Oceanus Procellarum is filled with lava flows, large volcanic complexes, and simple impact craters of no particular interest. The southern part of the ocean is different. There is one significant fresh crater, Kepler (31 km wide and 2.75 km deep), with a bright ray system like a miniature Copernicus. But southern Oceanus Procellarum is characterized mainly by the arcuate remnants of older craters that have been partially buried by lavas. Examples include the Flamsteed P ring, Letronne, and Wichmann R. The most likely explanation for the occurrence of so many flooded craters in the south may be that the south is covered by a thin veneer of lavas, whereas mare lavas in the north completely bury older craters.

In pre-Apollo days, when the origin of lunar craters was vociferously debated, flooded craters like Flamsteed P were generally interpreted as ancient impact craters whose walls had been mostly eroded by mare lavas. But those who argued that craters were volcanic in origin believed that these were volcanic craters caught in the act of growing and thus were among the youngest landforms on the Moon. Fielder, an early proponent of impact origins for lunar craters (who changed his mind in favor of volcanism), considered flooded craters to be a unique type of crater. He named them "elementary rings" because of their uncomplicated shape. Fielder and a half dozen or so other scientists (including O'Keefe, of tektite notoriety) believed that the rings were made of lava extruded from circular fractures above underground magma reservoirs. Their most compelling evidence came from the high-resolution Lunar Orbiter photographs that show that the base of the wall of Flamsteed P has a pronounced lobe that had clearly slid onto the adjacent mare. Fielder believed that this lobe could only be lava, and asserted that "the conclusion that the ringwall of Flamsteed P is a youthful volcanic feature is inescapable."

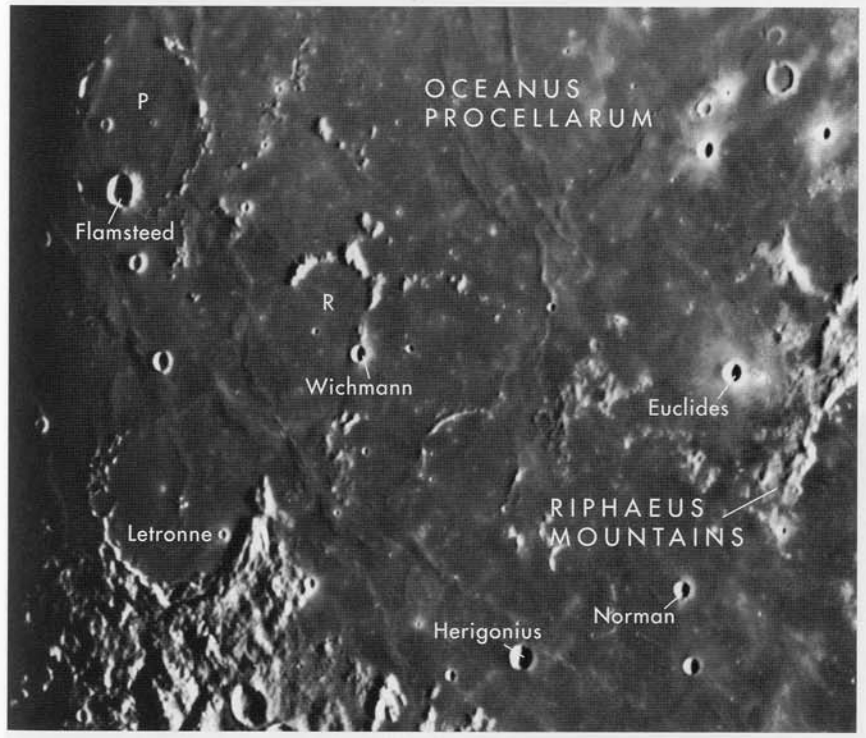


Flamsteed and the large flooded crater Flamsteed P as imaged by Lunar Orbiter IV.

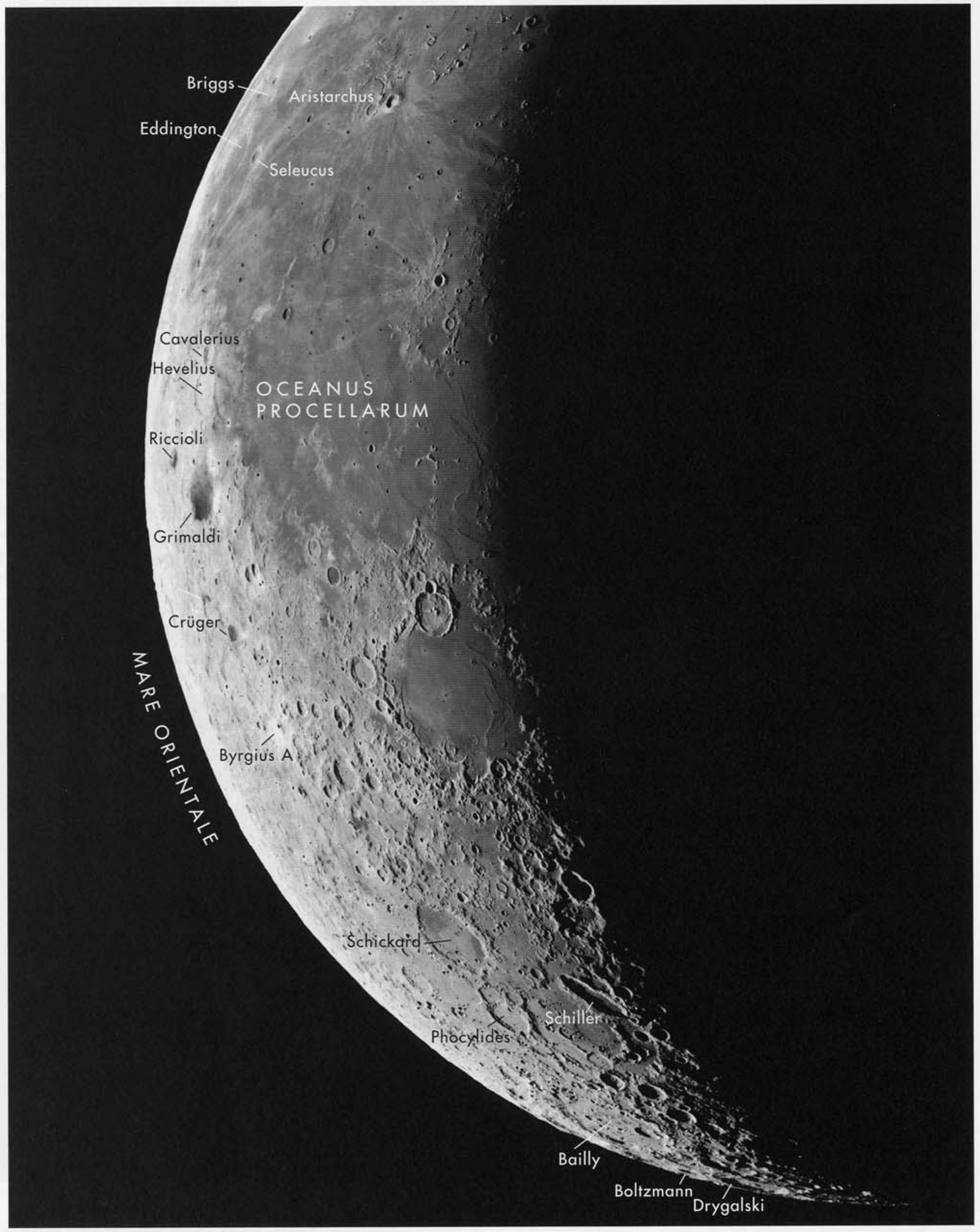
Inescapable, but almost certainly wrong. Observations by Hartmann and Spencer Titley of the USGS demonstrated that such lobes occur at the bottom of many slopes, including relatively fresh impact craters and individual hills. The lobes are rocks that have slid down the wall, perhaps due to jostling by moonquakes. Similar deposits occur at the bases of nonvolcanic hills on Earth. Another volcanic interpretation bites the dust!

Letronne is a beautiful example of an impact crater that formed on a regional slope. Sometime after Letronne's formation, Procellarum lavas breached its northern wall and inundated the interior so that only three tiny remnants of its central peak remain. Looking at the nearby carcasses of many old craters indicates that the destruction of crater walls must have been an efficient process. But how exactly did it happen? When a lava flow on Earth encounters an obstacle, the flow submerges it, flows around it, or sometimes carries it down stream. On the Moon, it seems that some other process destroyed the missing walls. Portions of crater walls are often completely missing, as if they dissolved. I really don't know how to explain this phenomenon.

According to crater counts by Schultz and Spudis, three areas of southern Procellarum have patches of lava that are as young as the ray-covering lavas near Lichtenberg. The young spots are the western floor of Letronne, inside the Flamsteed P ring, and northeast of the ring — all about 1 billion years old. Adding the Lichtenberg flows and one other young area near Gruithuisen that Schultz and Spudis measured suggests that Oceanus Procellarum has more areas of young volcanism than any other region on the Moon. Most thermal models of the Moon show that by 1 billion years ago the only sources of molten material would have been at depths of 400 to 500 km. Perhaps deep fractures from the Gargantuan impact provided conduits to the surface for these lavas.



Southern Procellarum.



The Moon's western limb.

18

The Western Rim

Our perspective from Earth's surface squeezes all the Moon's near-limb craters into narrow ellipses so foreshortened that they become hard to recognize. The difficulty of mapping this region was demonstrated by one confused drawing published in the mid-1960s that mislocated the large crater Einstein by hundreds of kilometers.

Although views provided by the Lunar Orbiter satellites finally clarified the geography of the limb regions (and, of course, the lunar far side), visual observers are still frustrated by the compressed view. Fortunately, the Moon's librations help considerably. As described in Chapter 10, librations in longitude — the side-to-side "no" movement of the lunar face — extend our view nearly 8° east and west.

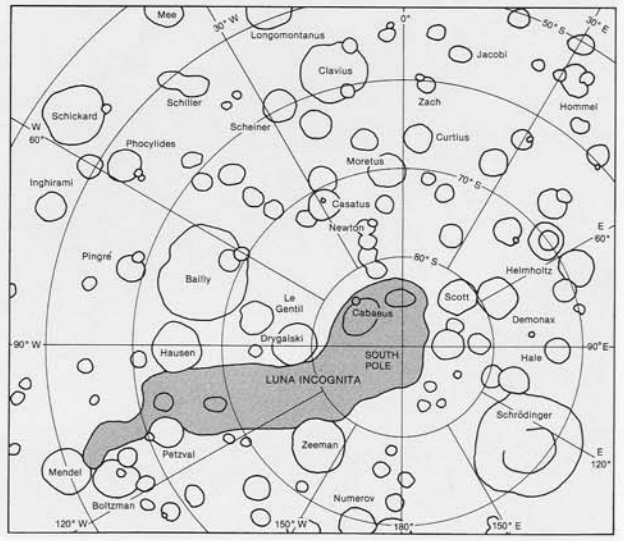
In this chapter we will start near the south pole and then slide north along the limb, pausing at some often-overlooked wonders hiding behind Humorum and the vast Procellarum ocean. Thus, I will violate the promise I made in the introduction that regions would be defined by natural surface features. Instead, this chapter will describe the western edge of the Moon, which has only one unifying feature — its entire length is observable in a single night.

BAILLY AND BEYOND

Southwest of Tycho and west of Clavius are some of the largest craters on the Moon, a pair of overlooked basins, and two contenders for the title of Most Bizarre Lunar Crater.

A bright ray tangential to Tycho's western rim streaks southward toward the limb. When the Moon's south pole is tipped steeply toward the Earth, this ray can be seen pointing toward a great crater plain with its far rim nearly on the limb. This vast crater is Bailly, a 300-km-wide and nearly 6-km-deep depression with a relatively flat floor punctuated most noticeably by a 65-km-wide bright crater, Bailly B. Bailly presented a challenging playing field for amateur astronomers competing to chart details — the record was 140 individual features. Under favorable illumination Bailly is a marvelous site, with hills and rims intermixed with black shadows, but what is important to lunar geologists is that it is an ancient multiring impact basin, not just a large crater. In 1971 Bill Hartmann and I came to this realization when we found a battered inner ring and hints of an outer ring while examining Lunar Orbiter photographs. Bailly is the smallest of the multiring basins, but its abysmal location (from the point of view of terrestrial observers) had disguised its true nature.

Just beyond Bailly is Hausen, a huge (167 km wide and 5.6 km deep!), relatively young Tycho-like crater. Because Hausen is right on the limb, terrestrial observers usually see only its rim in profile, if they notice anything at all. Somewhere back near Hausen are the Doerfel Mountains. This "magnificent range," as Goodacre described it in *The Moon*, was said to consist of three massive peaks that pierce the lunar sky from behind Bailly and two other limb craters, Boltzmann and Drygalski. This is a case where Lunar Orbiter photographs don't help much. Although these high-resolution satellites imaged most of the Moon's surface, the one region not covered is a long strip extending from the south pole to just west of Hausen. But a 20-year campaign of careful observing by a coordinated band of amateur astronomers filled in much of this "luna incognita." Their map, however, does not give any clues about the true nature of the Doerfels. Elsewhere on the Moon isolated mountain peaks are remnants of large impact basins. But when the

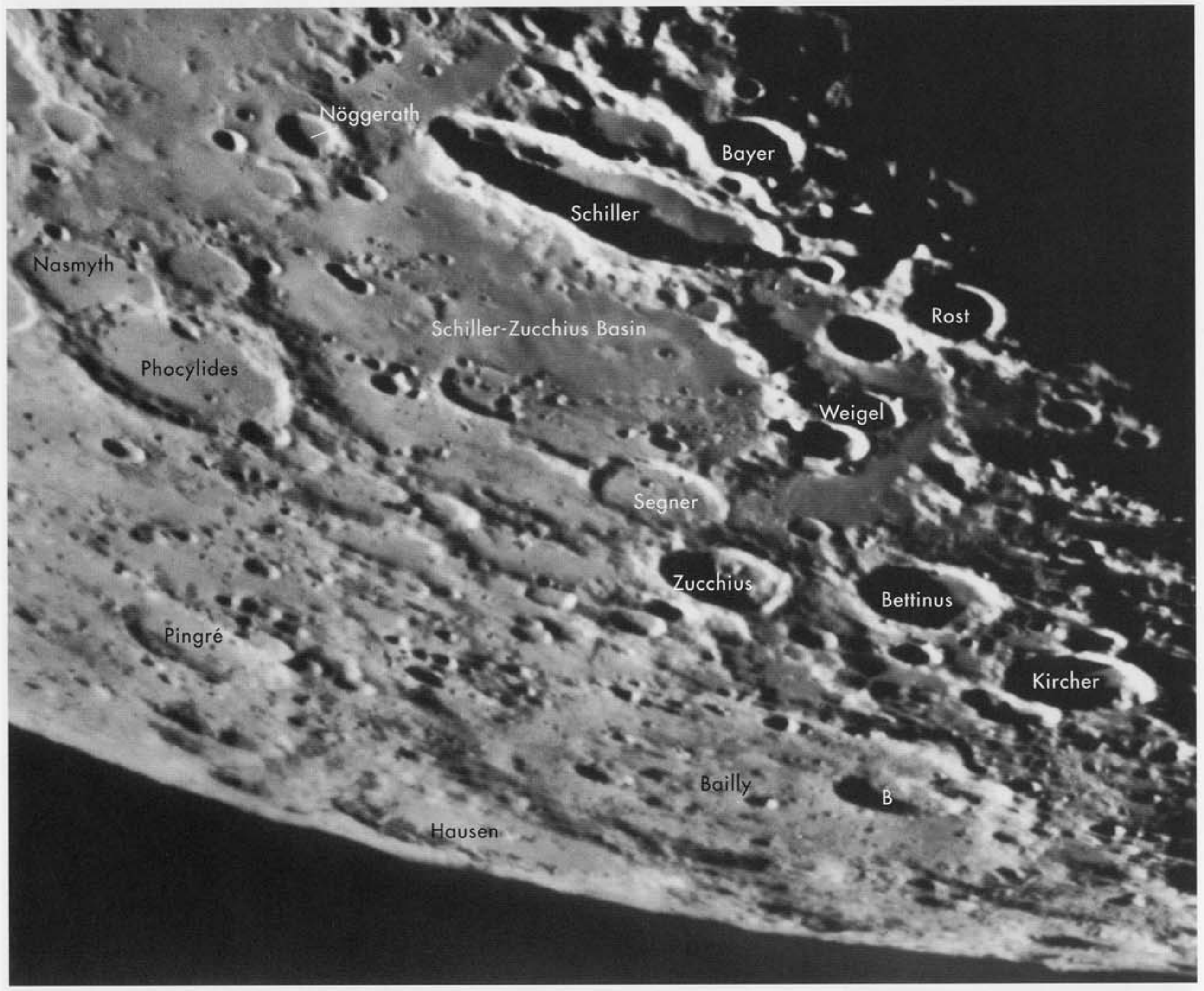


John Westfall's map of the Moon's south polar region showing Luna Incognita, the last region of the Moon's surface to be mapped.

Clementine lunar orbiter finally imaged this area in 1994, it failed to locate a conspicuous basin. The Doerfels, if they exist at all, appear to be a mixture of massifs from the newly discovered Bailly-Newton basin and crater rims. Because of the uncertainty, the name Doerfel was officially transferred to a 68-km crater in the area of the putative peaks.

Moving away from Bailly and the limb we find three relatively conspicuous and similar-sized craters — Kircher (73 km), Bettinus (71 km), and Zucchius (64 km). All have smooth, flat floors and are typical examples of somewhat degraded Tycho-class craters. Zucchius touches Segner (67 km), a crater nearly identical in size but shallower. These craters are markers for a simple basin that was long overlooked because of its proximity to the enigmatic crater Schiller. This Basin Near Schiller, as Hartmann and I called it (renamed the Schiller-Zucchius basin by USGS mappers) is most conspicuous as an anomalous patch of light-hued, smooth, marelike material. Closer inspection reveals a semicircular ridge cut by Segner and partially surrounded by a larger, more poorly defined scarplike ring. Under a low Sun a possible third ring is suggested by a shallow depression in the basin center. Thus, the Schiller-Zucchius basin is a two-ring structure with diameters of 165 and 325 km, and a possible third 85-km-wide inner ring. The basin is fairly heavily battered by craters that are probably large secondaries from the Orientale basin just over the limb to the west.

The crater Schiller is definitely not circular. It measures about 180 km long by 70 km wide and appears to be composed of three or four overlapping craters. Crater counting gives an age of 3.7 billion years for the smooth material on Schiller's floor. One proposal asserts that this unusual crater is a giant volcanic collapse pit, like the 100-km-long by 35-km-wide Toba caldera in Indonesia. The lack of surrounding massive ash deposits and the impactlike wall terraces make this theory unlikely. Another suggestion is that Schiller resulted from a succession of two or more separate impacts and that subsequent lava flooding somehow removed the intervening rims. But there is little evidence that any of the postulated craters overlap any of the others, implying that the craters formed simultaneously.



The Basin Near Schiller.

Laboratory experiments performed by Gault during the 1970s provide a possible explanation for Schiller. Gault and colleagues at NASA showed that when projectiles impact at a very low angle (2° or 3°), a line of overlapping elliptical craters results. However, Schiller is considerably larger than other oblique impact craters on the Moon. Could a grazing impact account for a crater as big as Schiller? The dozens of large elongated craters on Mars point to an answer. Pete Schultz proposed that the Martian low-angle impacts resulted when small moons about the size of Phobos and Deimos spiraled in and crashed onto the planet's surface. Perhaps Schiller marks the final resting place of a small former satellite of our Moon.

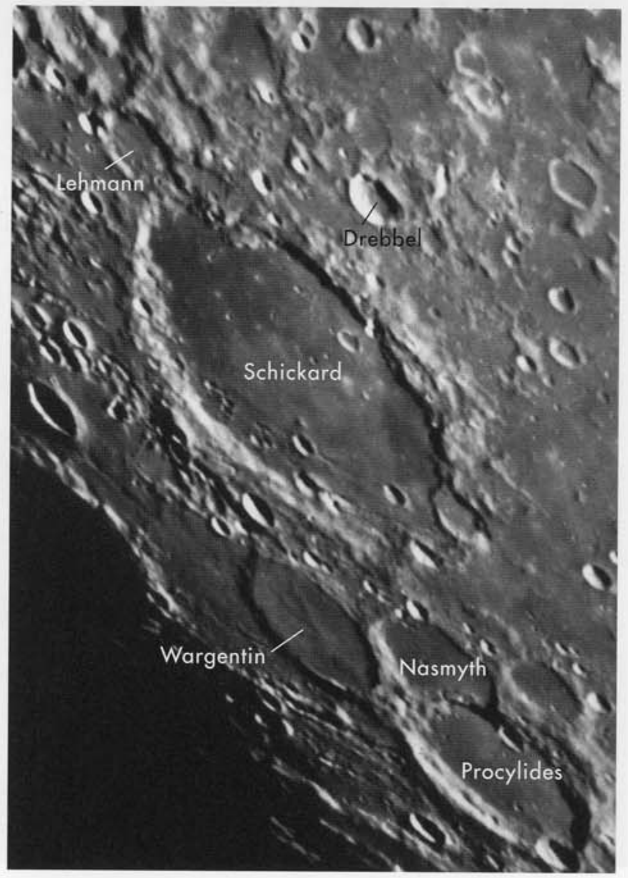
SCHICKARD AND WARGENTIN

Near the elongated crater Schiller is a cluster of conspicuous craters, two of which are wondrously unusual. The normal specimens, which we shall pass over quickly, are Phocylides (114 km diameter) and Nasmyth (77 km), two forgettable flat-floored ring plains that look like the sole and heel of a shoe. But their companion, 84-km-wide Wargentin, is remarkable. Unlike its neighbors, Wargentin is virtually filled to its rim with lavas — it's a plateau rather than a depression.

In *The Moon* Elger compares Wargentin to a "shallow oval dish turned upside down." The material filling the crater's floor rises entirely to the crests and perhaps even overflows the western and northern rims, but the southern rim (especially near Nasmyth) rises a few hundred meters above the elevated floor. This filling is widely considered to be lava, though a feeble argument has been made that it is ejecta from the nearby Orientale basin impact — an argument that conspicuously fails to account for the fact that other nearby craters aren't filled. A low, forked ridge (like a bird's foot, according to Elger) extends along the elevated floor much like a wrinkle ridge on mare surfaces. If the fill in Wargentin is lava, then the same awkward question put to the Orientale-ejecta theory has to be asked: Why did this unusual volcanic event affect just Wargentin? Well, perhaps it didn't. Read on.

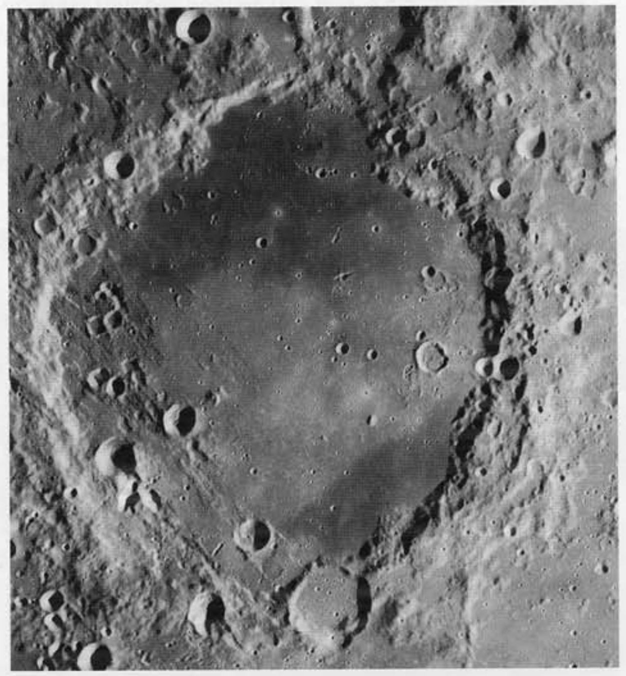
The giant (227 km diameter) crater Schickard poses additional questions, but at least we have some answers. Schickard is about the same diameter as Clavius but is older and shallower (about 1.5 km versus 5 km deep). Schickard is remarkable for its zebralike coloring. Its floor is dark on both ends but is striped by a wide diagonal of lighter material. Telescopic measurements by Hawke and colleagues at the University of Hawaii, and from the Galileo spacecraft flyby, confirm what is inferred from visual observation near full Moon — the dark material has the spectral characteristics of lunar mare lavas, while the older, light swath resembles highland material. Crater counts suggest that the age of the light material coincides with the formation of the Orientale basin, 3.84 billion years ago. Furthermore, ridges and lines of secondary craters on the southwest portion of Schickard's floor occur only on the light material, and dark-haloed craters have brought up dark mare material from under the light plains.

Putting the pieces together, a likely chronology is that some time after Schickard formed it was flooded by mare lavas that rose up through fractures under the crater, just like the history proposed for Wargentin. Soon afterward the formation of the Orientale basin showered a thin veneer of excavated highland material across the crater's floor and scoured it with chains

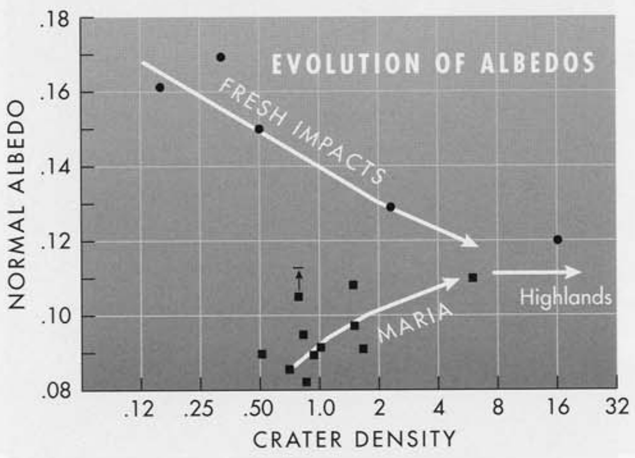


Wargentin and Schickard.

of secondary craters. Forty million years later (3.8 billion years ago), additional mare material erupted onto the northern and southern portions of Schickard's floor, covering the Orientale ejecta. Sometime later, small craters impacted into the central swath of light material, excavating underlying mare lava that is still visible as dark halos around small craters. And, of course, the *thin* veneer of Orientale ejecta in Schickard is further circumstantial evidence that the *thick* deposit in Wargentin is not ejecta.



Schickard as imaged by Lunar Orbiter IV.



The brightness, or albedo, of lunar materials starts as either fairly dark (mare) or fairly bright (crater rays) but over time evolves toward a uniform reflectivity of 11 percent.

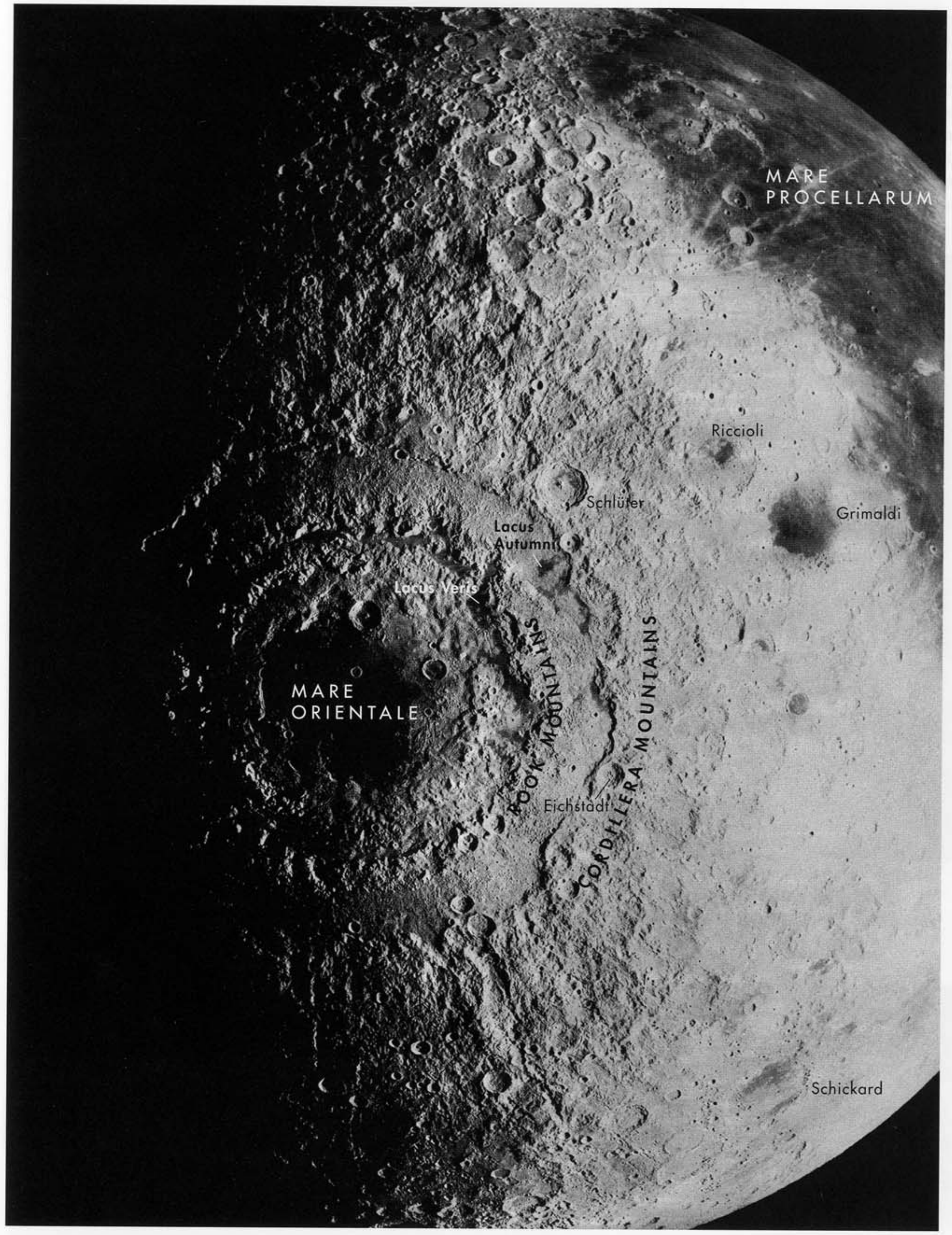
LIGHT PLAINS AND CRYPTOMARIA

Many craters in this region and elsewhere on the Moon have smooth flat floors, almost all of which are light-hued. In 1971 Hartmann and I examined the reflectivity, or *albedo*, of various materials with different ages across the lunar surface. We found that with time dark material lightens and bright material darkens. Thus, we proposed that mare lava exists under many light plains and that the period of mare formation and eruption may have been much more extensive than generally thought. This suggestion has been confirmed by studies of dark-haloed craters and the discovery of tiny fragments of mare lavas mixed in with ancient lunar-highland rocks. Head and his students have recently named such older and lightened mare material "cryptomare" or "hidden mare," and this new name has washed across the research firmament as a great new idea, even though Spudis and Schultz had earlier recognized the existence of buried mare. Cryptomaria are evidence for early basaltic volcanism, pushing back the time of initiation (and thus the duration) of mare volcanism. Basaltic volcanism earlier than that sampled by Apollo astronauts means that the Moon was hot earlier than was suspected.

OBSERVING ORIENTALE

The linear crater chain crossing Schickard is just one of many in this area that radiate from Orientale, the youngest basin on the Moon. Orientale is centered at 95° W, just beyond the western limb of the Moon, but favorable librations tip the Moon so that the main rings and mare lava flows occasionally come into view. In fact, the true multiring nature of the basin was discovered by Hartmann by examining Earth-based photographs projected onto a sphere. But we had to wait for the spectacular Lunar Orbiter photographs in 1967 to appreciate the fully glory of the Orientale basin.

Orientale is what the Imbrium basin would look like if it were stripped of its thick lava flows. As discussed in Chapter 2, the Orientale basin is a nearly pristine multiring basin. The Cordillera Mountains, with their rugged massifs and a dramatic scarp facing the basin center, define the outer ring. The next ring is made of more massifs and is called the Outer Rook Mountains. The dark mare lavas forming Lacus Veris leaked to the surface just inside the Outer Rooks, presumably along deep fractures associated with the basin ring formation. Encircled by the Outer Rooks is a diffuse collection of smaller mountains and hills that are generally thought to mark two additional rings. One of these, the Inner Rook ring, is relatively well defined while the innermost, unnamed ring is only



Lunar Orbiter view of the Orientale basin.

partially defined by the edge of Mare Orientale — the thin sheet of lava that fills the center of the basin.

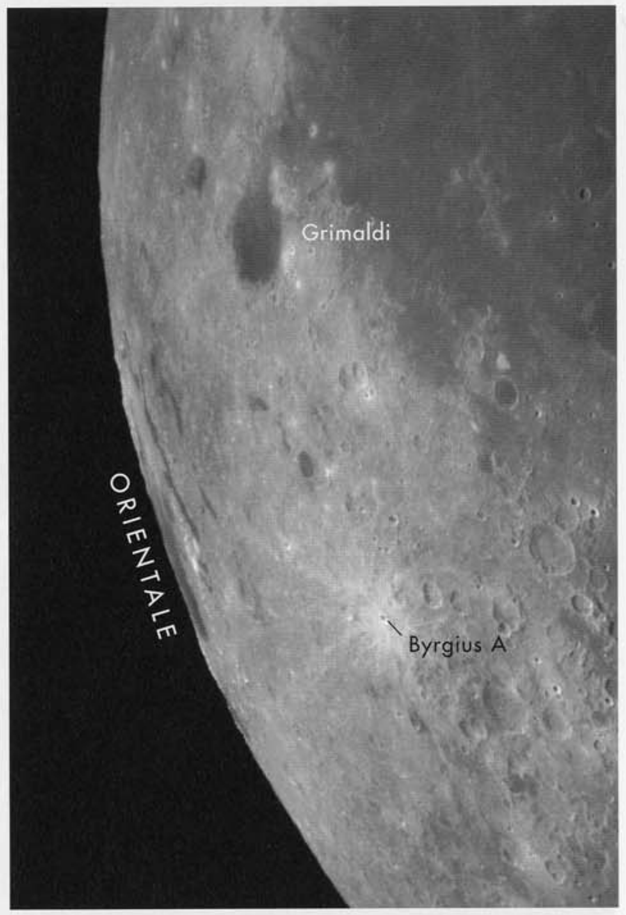
ORIENTALE RING DIAMETERS

Cordillera	930 km
Outer Rook	620 km
Inner Rook	480 km
Unnamed	320 km

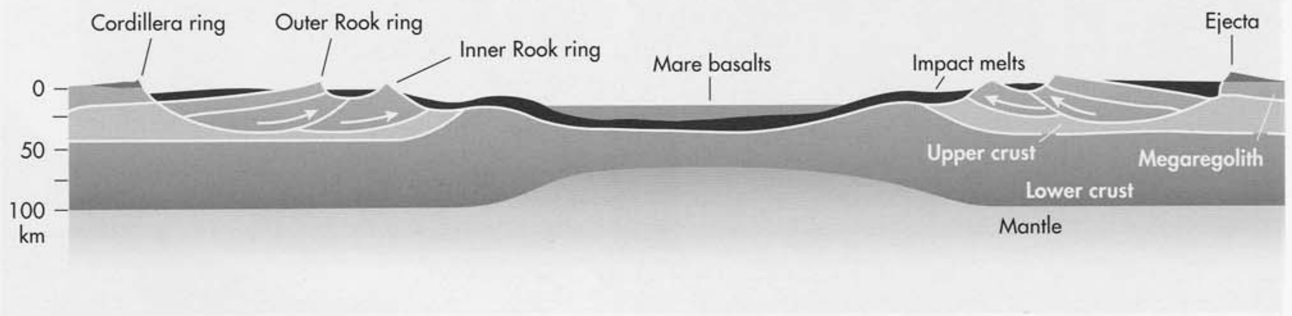
The Cordillera peaks rise 1.25 km above the surrounding highlands, and the floor of Mare Orientale is about 6 km below the peaks. Thus, this vast hole — more than 900 km wide — is very shallow, with only 6 km of total relief. But what about when it formed? How deep was the original crater? This would depend on which mountain ring represents Orientale's true rim. If the Cordillera ring defines the original crater, the depth must have been immense. However, if either of the Rook rings is the true rim, the crater would be much smaller and thus less deep. Lunar scientists have long debated which is correct.

Careful scrutiny of Lunar Orbiter images and chemical mapping using multispectral images from the Jupiter-bound Galileo spacecraft and telescopic measurements help to answer these questions. Multispectral data showed that the Inner Rook Mountains are composed of the same anorthositic rocks thought to make up much of the upper crust of the Moon. But the massive deposit of radially textured ejecta outside the Cordillera ring are dominated by anorthositic norites (which have less aluminum than pure anorthosite) and probably came from deeper within the lower crust. Thus, Orientale did not appear to excavate further down than the lower crust (35 to 50 km), which is consistent with the smaller-diameter models.

The sketch below shows one hypothetical cross-section of Orientale, with the Outer Rooks marking the crater of excavation and the Cordillera ring being equivalent to a terrace in a Tycho-like crater. The mantle is depicted as bulging up under the center of the basin, probably in response to the thinning of the crust by the impact. High-density mantle rising toward the surface accounts for the gravity anomaly or mascon measured over Orientale by the Orbiter spacecraft.



Orientale during a favorable libration.



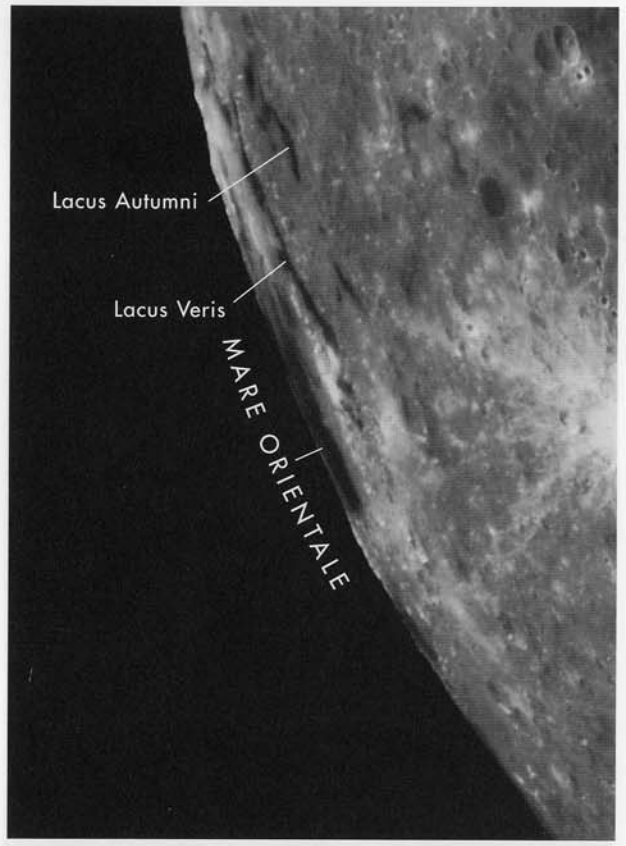
Schematic cross section of the Orientale basin.

This high-powered science is all well and good, but what can we see from Earth? Longitudinal librations (the Moon shaking its head back and forth) regularly bring Orientale into view. With a high Sun over the western limb the dark mare lava flows stand out distinctly against the bright, anorthositic crust. Lacus Autumni is a patch of mare just inside the northern part of the Cordillera Mountains, while Lacus Veris is a much longer ribbon of mare that follows the inside of the Outer Rook Mountains. When librations are very favorable, Mare Orientale itself can be seen bordered by a low white range — the Inner Rooks. The Rook and Cordillera mountains are sometimes visible in profile as bumps on the limb of the Moon.

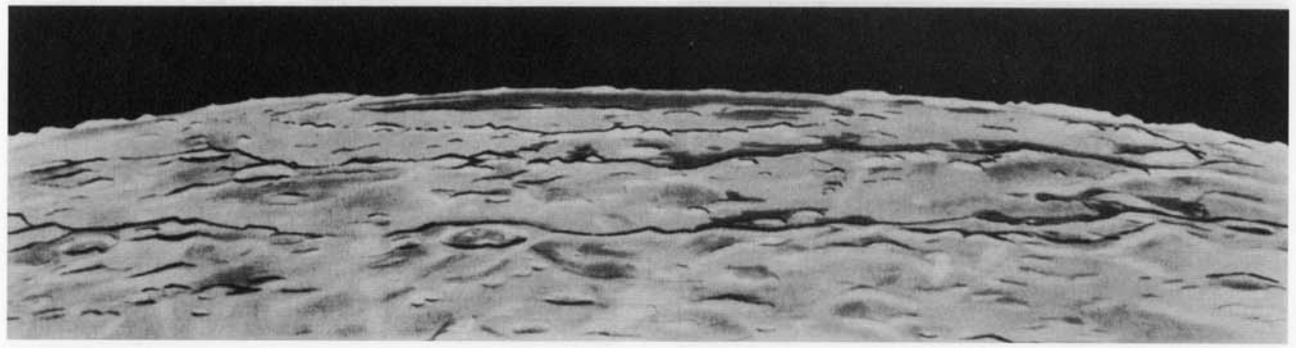
When the lighting angle is low *and* the libration angle is favorable (a fairly rare coincidence) observers can view the actual arcs of the three main rings. Moderate Sun angles reveal the heavily striated ejecta that buries and entangles craters hundreds of kilometers beyond the Cordilleras. If you are fortunate enough to observe Orientale's rings, lavas, and debris, and you understand what you saw, you can consider yourself a member of a small lunar elite.

Another somewhat mysterious range of mountains has been noted north of the Corderillas. Schröter depicted a line of mountains up to 6 km high, which he called the D'Alembert Mountains. Measurements of photographs in the 1950s found peaks even higher, but uncertainty about their precise location led to the removal of the name. Are they actually part of Orientale's Corderilla? Urey pointed out that the D'Alembert Mountains and Mare Orientale are only 500 km apart but have elevations that differ by nearly 10 km. Urey claimed that this staggering difference in elevation required that the outer "parts of the Moon are now, and have always been since these inequalities were formed, more rigid and hence colder than the outer parts of the Earth."

This observation was one of the cornerstones of Urey's belief that the Moon formed cold and never heated up. The discovery, first from chemical measurements by Surveyor spacecrafts and then from Apollo samples, that the lunar maria are basalts formed from high-temperature melting destroyed Urey's arguments. But how do we explain the great difference in heights? Well, Urey was partly right. At least since the time that the still-deep basins formed about 4 billion years ago, the Moon must have been sufficiently cool for its crust to support significant elevation differences. But just



Under a high Sun, the dark patches of mare are the most conspicuous features of the Orientale basin.

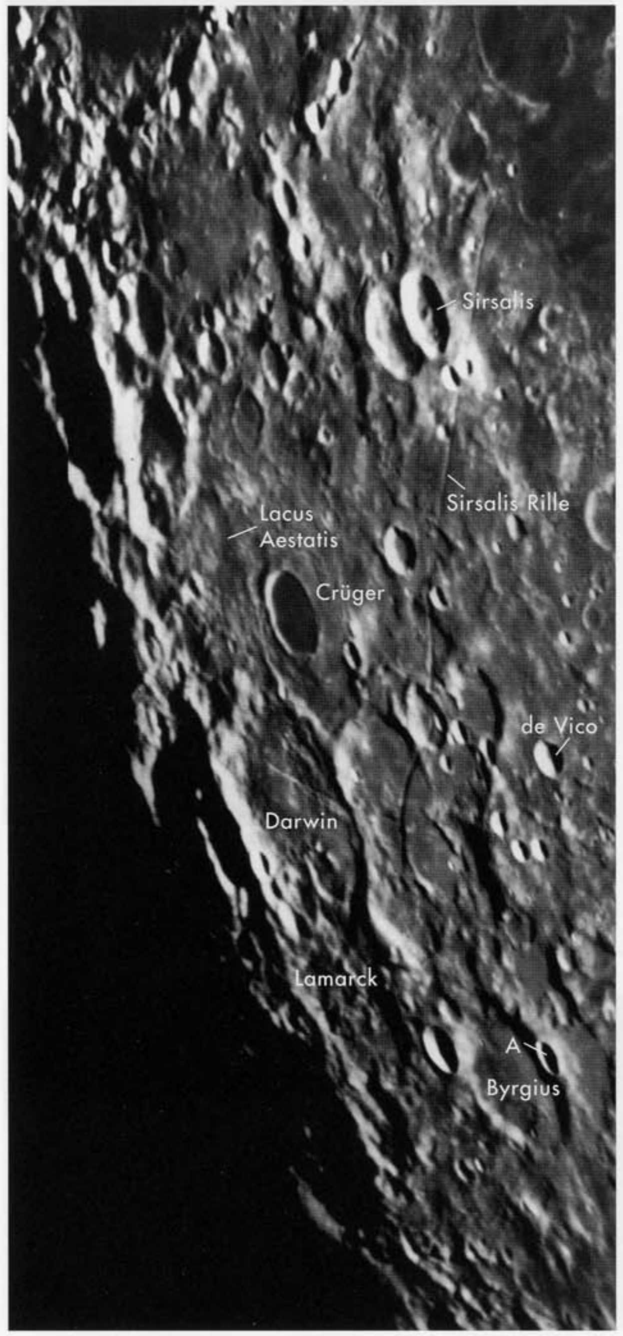


Orientale seen under a low Sun, as sketched by Bill Hartmann. North is to the right.

500 million years earlier, immediately following its formation, the Moon was completely molten, so it must have cooled very quickly!

CRÜGER AND THE SIRSALIS RILLE

Between Mare Humorum and the limb-hugging Orientale are a few craters of interest, most conspicuously the brilliant 19-km-wide Byrgius A. When the Sun is high, this small crater's white interior and compact, bright ray system (the only one in this corner of the Moon) is so prominent that as early as 1645 Langrenus mapped this otherwise obscure crater and even named it Malvezzi.



Crüger and the Sirsalis rille.

About 230 km north of the Byrgius beacon is another crater that is remarkable because of its albedo. Crüger has a dark, mare-covered floor surrounded by a narrow bright rim. A hundred years ago observers thought Crüger had a small central hill, but careful telescopic observations confirm what Orbiter images show easily — the peak is actually a small bright crater. Crüger is 45 km across but only 500 meters deep. Is it a standard impact crater flooded with lava nearly to its rim crest, like a Wargentin wannabe? Or is it perhaps a large secondary crater formed from debris excavated during the Orientale impact? Or is it entirely of volcanic origin — a collapsed caldera flooded with lava from its last eruption? We don't know; any of these origins is possible.

The area immediately north of Crüger includes an isolated patch of mare material (Lacus Aestatis) and the lava-flooded interior of an older impact crater, so Crüger could be an impact crater filled with later lava that regionally leaked to the surface. But look for the low hills near Crüger and the odd ridges that fill part of the old crater Darwin just to the south. These are ejecta deposits from Orientale, so Crüger might also be related to that basin-forming catastrophe. But Crüger has a twin in Billy (46 km), located on the southwestern shore of Oceanus Procellarum. And Gambart and about 30 other similar, smooth-walled and dark-floored craters also seem to have a family relationship. There is no real evidence that these craters are volcanic calderas, but if any large features on the Moon are volcanic, these Crüger types seem to be the most likely candidates.

The only detailed study of Crüger's origin conducted by Hawke and his colleagues concluded that Crüger is a lava-flooded impact crater. One piece of telling evidence came from telescopic spectral measurements of the crater's walls, which appear to be norite-rich anorthosite. That's typical lunar crust material, likely to be excavated to form the rim of an impact crater, but not expected if Crüger were a caldera. See, we can answer some questions!

The highlands bordering the western side of Oceanus Procellarum are cut by a multitude of long, nearly straight rilles. A fine example slices through old craters south of Crüger and angles north-northeast past the conspicuous crater Sirsalis before disappearing along the Procellarum shore. This is not a sinuous rille like those around the northern side of the Aristarchus plateau but rather a flat-floored linear trough. This rille

appears to be roughly radial to the Imbrium basin, but its shape was controlled by something else. While a student at the University of Massachusetts, Matt Golombek (later of Mars Sojourner fame) measured the angles of the rille's walls and deduced that it formed in material that progressively thickened from 2.0 to 3.5 km deep in the direction of Orientale. Golombek concluded that the rille's width and the slopes of its walls were determined by the thickness of Orientale ejecta through which the rille cuts and which increase toward the basin.

Further evidence about the nature of this rille was provided by the Lunar Prospector spacecraft, which mapped a strong magnetic anomaly associated with it. The magnetism indicates the existence of a volcanic dike that failed to reach the surface.

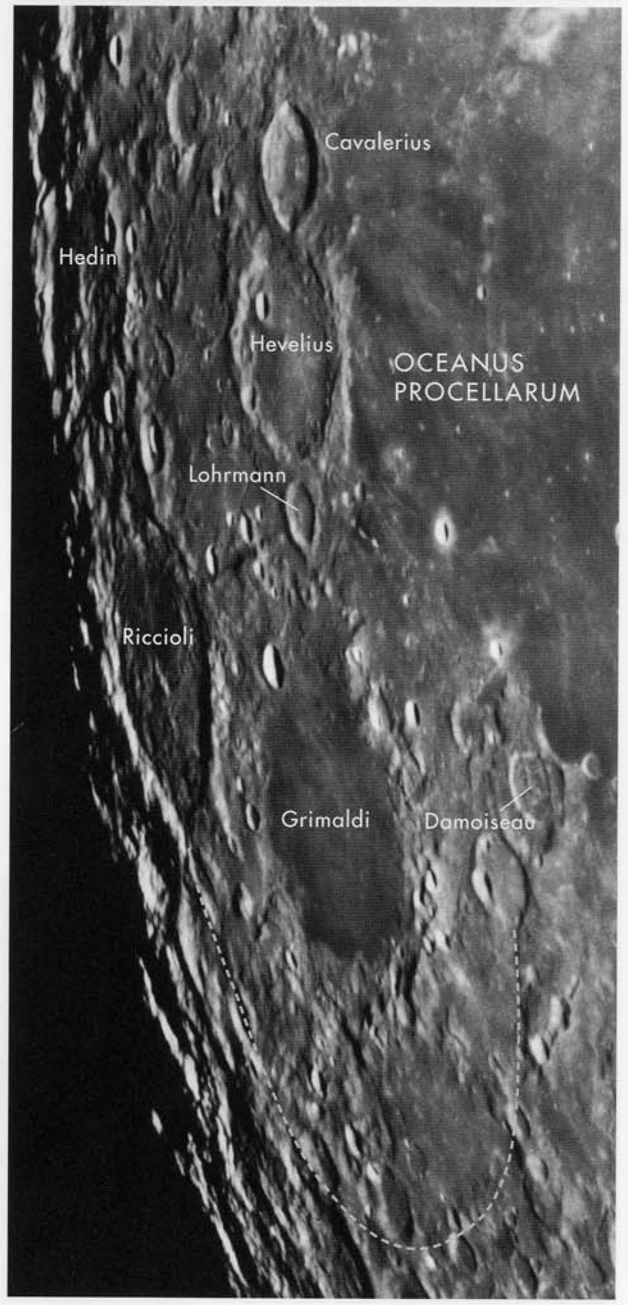
GRIMALDI BASIN

Grimaldi and Riccioli were 17th-century Moon mappers whose scheme for naming craters is the basis for our present nomenclature. Modestly, they commemorated themselves with two large, battered, and partially mare-filled depressions near the lunar equator, west of Oceanus Procellarum. Most of the floor of 145-km-wide Riccioli is covered by striated ejecta that points back to its source — the Orientale basin. A central peak barely emerges from the debris-covered floor, which is cut by linear rilles that can sometimes be glimpsed. Because Riccioli is near both the lunar equator and the limb, it was proposed by NASA's Paul Lowman as a potential site for a future astronomical observatory. Being on the equator it could see the entire sky, and being on the Earth-facing hemisphere (but just barely) it would have easy line-of-sight data transmission to Earth.

Grimaldi is another example of a multiring basin that no one recognized until the basin paradigm was discovered. Grimaldi's 230-km-diameter rim is actually the inner ring of a 430-km-wide basin whose largest ring is best seen to the north and east, where a plain of smooth, light material is bounded by an irregular scarp. Grimaldi is a relatively old feature (about 4 billion years), and its degradation has been enhanced by ejecta bombardment from Orientale.

Matt Golombek.

Marelike fills in Grimaldi and Riccioli provide targets for dating by crater counting and for determining basalt composition by spectral mapping. The modeled ages are 3.25 billion years for the western part of the Grimaldi lavas, with the eastern portion perhaps being



Grimaldi and vicinity. The dashed line indicates a portion of the Grimaldi basin.

750 million years younger. If this latter age is correct, this is another young age for mare material in the Procellarum region. Small impact craters superposed on Riccioli's lava patch yield an age of 3.48 billion years. The ages of the mare deposits of this pair of craters are consistent with a very simple observation — no ejecta from Orientale covers these lava patches, so they must be younger than Orientale (3.84 billion years).

Telescopic spectral studies and data from Galileo's 1990 lunar flyby suggest that these small mare units are medium- to medium-high-titanium basalts like those in Mare Orientale and nearby Oceanus Procellarum. These spectral similarities suggested to the Galileo team that the western limb of the Moon has had a more homogeneous source for lavas than did the rest of the more variegated Earth-facing hemisphere.

The mare in Grimaldi holds other surprises. As the Lunar Orbiter and Apollo spacecraft flew over Grimaldi, they were pulled closer to the surface by a locally enhanced gravity field. Grimaldi is the smallest crater or basin to have a mascon. One explanation for this is that the 140-km-wide sheet of mare lava blanketing the basin floor provides the necessary excess mass to attract the spacecraft. Another idea is that the dense mantle, normally about 60 km below the lunar crust, domes up closer to the surface in response to the intense compression and sudden release of pressure that follow a basin-forming impact. Probably each of these ideas is part of the explanation.

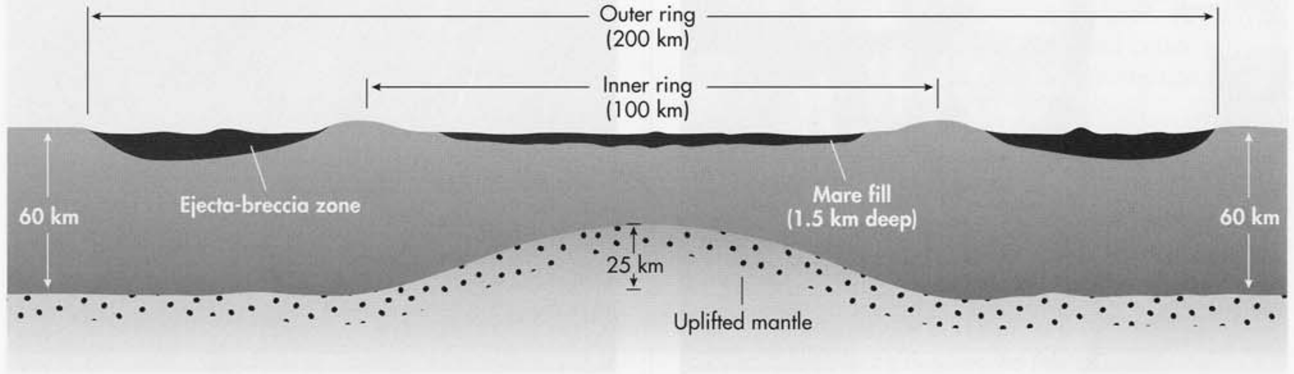
The dark floor of Grimaldi has also been the site of several reports of bright flashes. The most famous observer was astronaut Schmitt, who saw a flash in Grimaldi when it was illuminated by earthshine during the Apollo 17 mission. Curiously, a flash of bright light was seen in nearby Riccioli during the Apollo 16 flight. And Walter Haas, the dean of American amateur planetary astronomers, reported that the floor of Grimaldi sometimes looked greenish. The astronaut observations make these lunar transient phenomena reports less dubious than most. Readers may want to check this area for possible repeats of flashes and colors, and while doing so you may even notice on the northern part of Grimaldi's mare a flat pitted dome that is inconspicuous on Lunar Orbiter photographs because of their high Sun view.

Just north of Grimaldi is the 106-km-wide crater Hevelius, with the younger, Eratosthenian-age crater Cavalerius perched on its northern rim. Hevelius is distinguished by two telescopically visible rilles that form an X pattern on its floor. Under very low solar illumination a broad, low dome is visible just south of the central peak.

Beyond Hevelius are other rilles and linear crater chains that point accusingly back to Orientale. Craters here are subdued if not battered, and there are no big names. This is the outermost area of the nearly continuous ejecta from Orientale, which USGS scientists have named the Hevelius formation. The Sirsalis rille to the south also cuts through the Hevelius formation, which often consists only of irregular patches of low hills and rough surfaces that formed as ground-hugging ejecta lost speed and swirled to a stop. You wouldn't have wanted to be in this area 3.84 billion years ago.

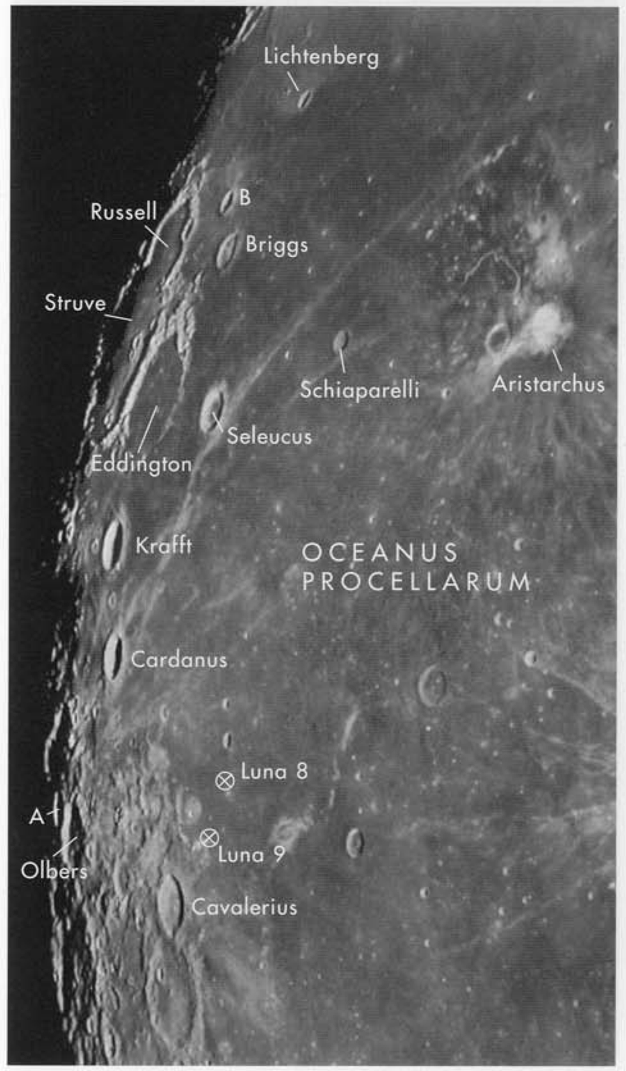
THE NORTHWESTERN PROCELLARUM MARGIN

Sliding along the Moon's curved limb from Hevelius toward the north pole, there is little highland region to be seen since Oceanus Procellarum stretches nearly to the limb. However, this is the site of a historical event. Just north of Cavalerius, on the border of Oceanus Procellarum, the Soviet spacecraft Luna 9 made the first lunar soft landing on February 3, 1966. About 70 km north lie the remains of its predecessor, Luna 8, which crashed into Oceanus Procellarum in a failed landing attempt. Future scavengers will probably cash in by selling these artifacts to wealthy lunarians.



Hypothetical cross section of the Grimaldi basin.

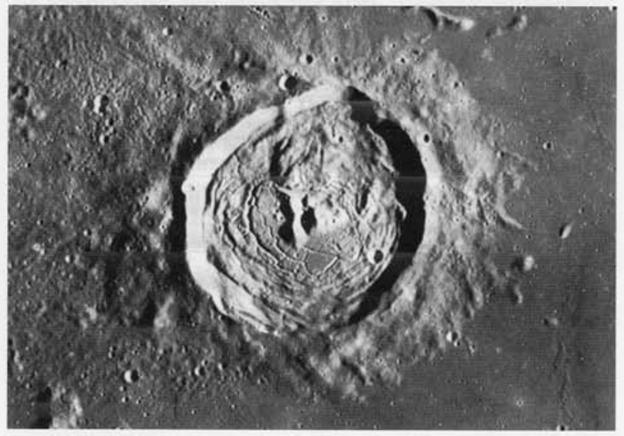
The most interesting natural structures here are twin craters along the shoals of the ocean. Cardanus and Krafft are two similar-sized (about 50 km wide) craters. They even look alike when the Sun is low and both are filled with shadow. But under a high Sun, Krafft is hard to make out except for a small bright crater on its floor, while Cardanus is conspicuous with its bright rim crest and inner walls. Notice that the bright rays that touch Cardanus actually originate at Olbers A, 170 km south-southwest. Both of the twins are surrounded and partially overlapped by lavas from Oceanus Procellarum. But look closely when there is low Sun and you may see that part of the ejecta from Cardanus covers older mare material to the south — Cardanus appears to have formed between successive eruptions in Oceanus Procellarum. The final feature of note about the twins is that they are linked by a linear rille made of overlapping craters. High-resolution Lunar Orbiter photographs show that the chain continues onto the floor of Krafft. This is obviously a secondary crater chain; it's not radial to Cardanus yet could not have come from anyplace else. What a strange Moon!



Western Procellarum.

Three giants of early 20th-century astronomy are honored by giant craters along an otherwise bland stretch of northwestern Oceanus Procellarum. The astronomers Struve, Russell, and Eddington made discoveries about stellar structure and evolution that are still valuable, but their craters have seen better days. All three are mere ruins that have been flooded by mare lavas that invaded along their southern walls, now largely missing. It must have been a fantastic spectacle when mare lava cascaded into the once-deep crater Eddington. Struve was shallowed before these lavas, however, for you can see a roughness under a low Sun (and brightness when the Sun is high) along its southeastern floor due to secondary craters and striated terrain — the farthest reach of Orientale's ejecta blanket in this direction. Sticking out from under the northern end of Russell is half a crater. This is one of the best examples on the Moon of a smaller crater being impacted by a larger one and surviving to tell the tale.

Virtually all the larger craters along the difficult-to-see highland margin of northwestern Oceanus Procellarum have shallow floors cut by concentric and radial rilles. This is the greatest concentration of FFCs on the Moon, but most are visible only on Lunar Orbiter photographs. Examples include Vasco da Gama, Dalton, Balboa, Lavoisier, and a number of unnamed craters. Fortunately, one example is clearly visible. If you look at the craters in the mare near Eddington and Russell, you'll see that all are pretty ordinary impact craters except for Briggs. This sharp-



The floor-fractured crater Briggs as imaged by Lunar Orbiter IV.

rimmed 37-km-wide crater is clearly much shallower than its neighbors. In fact, it's only 1.25 km deep — normal impact craters of similar diameter are two to three times deeper. As explained in Chapter 11, floor-fractured craters are thought to have uplifted floors resulting from magma intruding beneath them. The observation that FFCs are abundant along the edge of Oceanus Procellarum is consistent with the interpretation that Procellarum lavas fill the Gargantuan impact basin. Fractures bounding this proposed giant basin would have supplied conduits for the rising magma that uplifted and fractured the crater floors. The existence of the Gargantuan basin is consistent with so many geologic observations that it is quite astonishing that so few lunar scientists accept it.

ORPHAN RAYS

Most of what I have described in this book are things that lunar science understands. But there are still enough mysteries for new lunar researchers to unravel someday. For instance, when the Moon is nearly full, look at the long, bright rays that extend from near the northwest limb across Oceanus Procellarum. One peculiar ray seems to extend from near the crater Cardanus, pass Seleucus crater, and skirt the northern end of the Aristarchus plateau. The ray is very unusual and is perhaps composed of unrelated ray segments. For example, the southwestern end of the ray is broken and not very straight; like other nearby rays, it probably is from the very bright crater Olbers A that is scrunched near the limb. But between Cardanus and Seleucus the ray bends in a shallow arc opening to the northwest and then abruptly straightens and heads northeasterly across Procellarum for another 400 km. Why does the ray bend? I don't know, but individual linear segments with the bend are radial to Olbers A, and the long stretch of the ray does radiate from there. Note that another ray segment passes south of Seleucus, grazes Schiaparelli, and disappears at the Aristarchus plateau. This ray does not point back to Olbers A and has no obvious source.

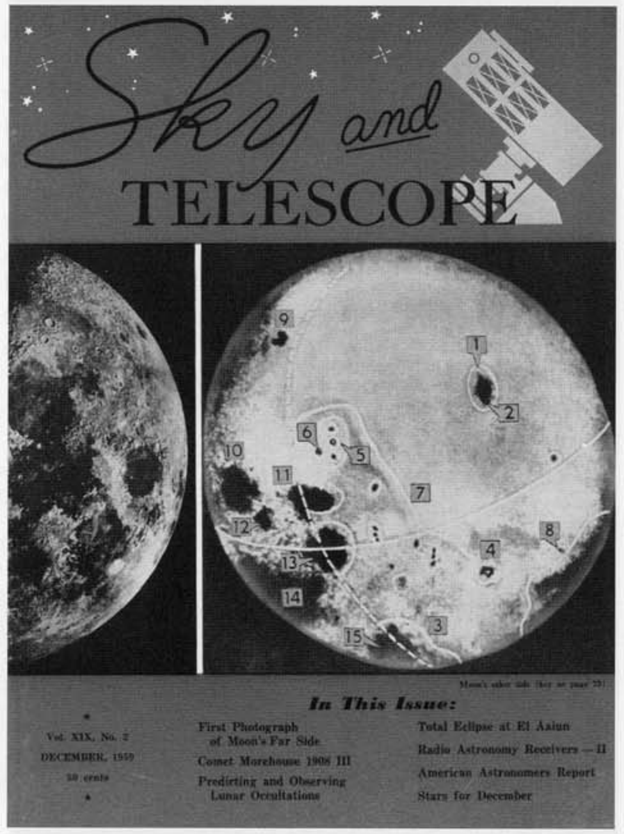
To the north another strange ray appears as a straight line stretching from near the small crater Briggs B to south of Lichtenberg. While this ray also lacks a source, the mare material north of it seems darker than that to the south. In 1966 Wilhelms proposed that this strange ray was actually a "very long linear fracture" that was the source of the lava that buried ejecta from the young crater Lichtenberg. Alas for this fractured theory, this ray was measured by the German selenographer Julius Franz early in the 20th century. He projected it and a faint companion south of Struve around to the far side of the Moon and predicted a source crater at 107° W, 19° N. Lunar Orbiter photographs reveal the fresh ray crater Ohm at 113° W, 18° N! Sadly, Franz never lived to be vindicated, but the strange ray is perfectly normal, luring us around the limb to the far side.

AN UNSEEN MOON

After 40 years of planetary exploration, humans have sent spacecraft to all of the Sun's planets except remote Pluto. From Mercury's shriveled surface to Neptune's giant blue spot, we're at least partially familiar with them all. But there is one part of the solar system that is rarely seen and all but forgotten — the far side of the Moon.

This is ironic, for the lunar far side was the very first piece of celestial real estate to be photographed at the dawn of the Space Age. In October 1959 the Soviet Union flew the gutsy Luna 3 mission, which swept behind the Moon and radioed back to Earth grainy photographs of the lunar far side. Amazement at this feat was profound — space exploration had revealed what had been forever hidden from humans. But it wasn't until the American Orbiter program of 1966 and 1967 that we got good views of the far side, showing an unfamiliar face lacking the widespread dark maria common on the near side. (Wilhelms used these images to make the first geologic map of the far side.) The Apollo astronauts also took spectacular photographs of the far side, but because their landings were all on the near side, nearly all subsequent lunar studies have been of the familiar side facing the Earth. And the far side has languished just beyond the limb of our consciousness.

This should have changed on January 25, 1994, with the launch of the Clementine spacecraft, but it didn't. Clementine was wondrously efficient in imaging the Moon, obtaining more than 2 million digital images that, for the first time, covered every piece of the lunar surface. USGS scientists in Flagstaff, Arizona, painstakingly assembled mosaics of these tiny images into composite photographs of both the near-side and far-side lunar hemispheres. When I first saw these mosaics I was amazed by the profound difference between the two lunar faces. I knew that maria were much less common on the lunar far side, but the Clementine mosaics made that fact dramatically visible. Then I realized that I had never seen a photograph of the entire lunar far side before! No one had, because none previously existed. All the studies of the far side had been made by mentally piecing together the various Orbiter and Apollo oblique images of bits and pieces of the far side. With Clementine, for the first time we can see the lunar far side as a whole — and it is an unfamiliar world, deserving our attention as much as another planet might. But not in a book that focuses on what you can see with your own eyes.



Sky and TELESCOPE

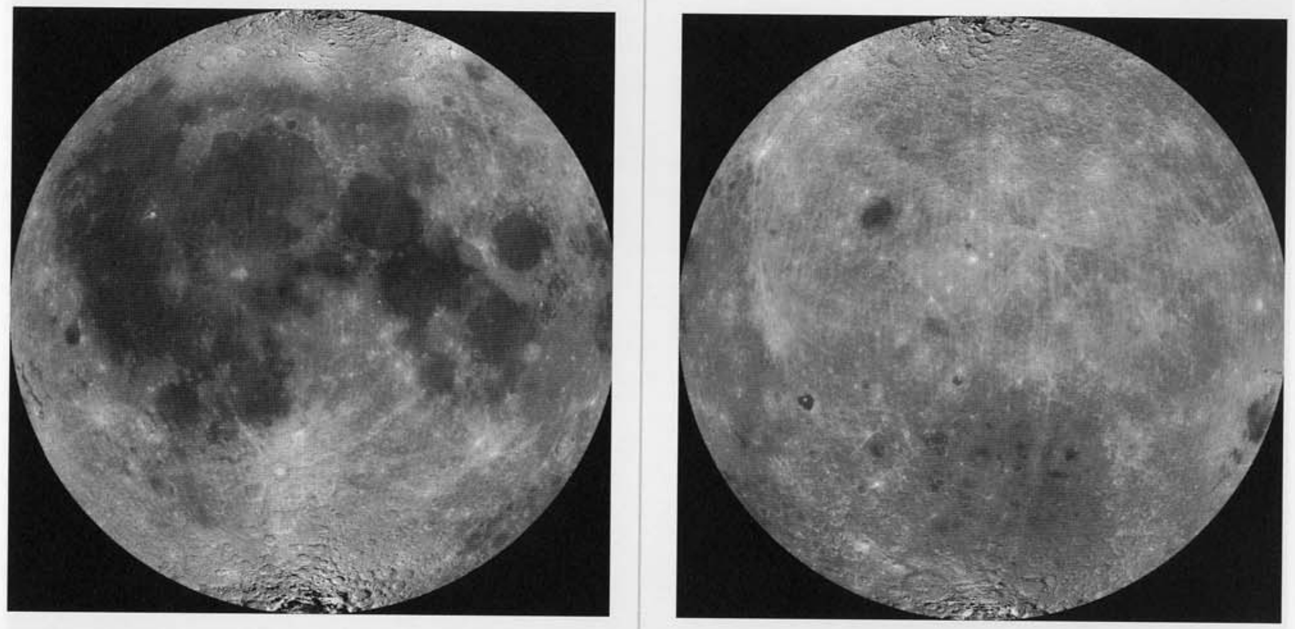
In This Issue:

Vol. XIX, No. 2
DECEMBER, 1959
50 cents

First Photograph of Moon's Far Side
Comet Morehouse 1908 III
Predicting and Observing Lunar Occultations

Total Eclipse at El Aaiun
Radio Astronomy Receivers — II
American Astronomers Report
Stars for December

The first image of the Moon's far side was featured on the front cover of the December 1959 issue of Sky & Telescope.



These mosaics made from Clementine images show the near (left) and far sides of the Moon.

Moonrise over the Valley of the Moon, California.

19

Beyond the Moon

Lucy, our hominid ancestor who walked the East African plains 3.5 million years ago, saw the same Moon that we see today. But the difference in perception is chasmal. Finally, we humans have a reasonable understanding of when and how the Moon formed, what it is made of, and how it evolved. But, like Lucy, we are — or should be — still in awe of this desolate world that lights our nights. As Anaïs Nin wrote in her *Diary*, "Most peoples' possession of knowledge deprives them of a sense of wonder. . . . I say that after we know all there is to know, there is still wonder and mystery of a deeper kind."

We know that the Moon formed 4.5 billion years ago, apparently by the accretion of ejecta from a giant collision between a huge protoplanet and Earth. The remaining heat of that collision and energy from intense cratering melted the newborn Moon, causing a scum of light, aluminum-rich material to float to its surface. The Moon's proximity to Earth relentlessly drove tempestuous tides until gradual cooling froze the anorthosite crust into immobility. Continuing impacts, some nearly large enough to tear the Moon asunder, carpeted its surface with craters of all sizes. For more than 500 million years great torrents of magma rose up through basin fractures and erupted onto basin floors, creating an awesome but unobserved sight, for no life existed yet on Earth. Although small lava flows leaked out onto various lunar maria for another billion years, for the last half of the solar system's history the Moon has simply orbited Earth unchanged but for the occasional addition of new craters from the impacts of asteroids and comets.

It's been more than a decade since I began writing Chapter 1. (I hope you have made faster progress reading this book!) Since then, the Galileo spacecraft has flown past the Moon twice, the military's Clementine orbited the Moon for two months, and the "faster, cheaper, and better" Lunar Prospector appears to have discovered water ice at the lunar poles. We have gone from the complete abandonment of the Moon to the collection of very significant data and new discoveries. Sadly, all these lunar explorations were merely fortuitous sideshows. Galileo and Clementine were focused on other aims (Jupiter and the testing of Star Wars sensors, respectively), and Prospector's target was less important than the demonstration that something useful could be accomplished in space at low cost. How far our once-great prowess in space has fallen. We no longer explore the Moon for its own sake — we now do it only when it is simple, convenient, or cheap. In 1961 President Kennedy dared us to go to the Moon, "not because it is easy, but because it is hard." Now we are back to a more typical ennui, apparently waiting for the Moon to come to us. Kennedy must be rolling in his grave.

In the decades since Apollo 17 left the Moon, we humans have sent Vikings to Mars; Venera and Magellan to Venus; Mariner 10 to Mercury; Voyagers to Jupiter, Saturn, Uranus, and Neptune; Galileo to Jupiter and the asteroids Gaspra and Ida; Vega and Giotto to Halley's Comet; and Cassini enroute to Saturn. We also gained human space-flight experience with Skylab, Mir, the Space Shuttle, and the International Space Station. Thus, most of the revolution in our understanding of the solar system has come since the last Apollo mission. But Apollo gave us the keys to the solar system — the knowledge that ancient impact cratering and volcanism have been the two most important processes in forming and modifying planets.

The Moon and Earth are an instructive pair for planetologists to ponder. Earth is the largest of all the rocky planets, while the Moon is the smallest well-studied planetary object. The Moon is largely covered with an ancient impact-cratered crust. Lava flows were active mostly during the Moon's first billion years, but only a few types of lava and resulting volcanic landforms exist. The Moon is dead.

By contrast, our planet is in constant agitation. As heat continues to escape from its interior, Earth's thin plates skate around its surface, colliding, subsiding, and shearing out of each other's way. Volcanism formed all the ocean floors and leaks out along the edges and in the interiors of many continents. A moderate range of temperatures permits water to exist as a liquid, gas, and solid, each form contributing to geologic erosion and redistribution of surface materials. Even more remarkable is the pervasive and exuberant presence of life, which occupies nearly all of the surface. Pity the poor future inhabitants of all the other moons of the solar system, whose planets won't be nearly as fascinating to observe.

THE MOON — SO WHAT?

Was the Apollo exploration of the Moon worthwhile? That is a question often asked by nonscientists. John Logsdon, whose doctoral thesis while at New York University is the classic study of the political aspects of the decision to go to the Moon, did not judge Apollo an unqualified success. Logsdon conceded that it was a political success because it demonstrated the preeminence of the United States in space, but he faulted Apollo for failing to build an infrastructure of spacecraft and technology that would lead to future space activities. As for the scientific value of Apollo, he applied the words of physicist Freeman Dyson: "All was good science, but it was not great science. For science to be great it must involve surprises, it must bring discoveries of things no one expected or imagined." At best, Logsdon grudgingly accepted that Apollo was a scientific success, even if no scientist received a Nobel Prize for Apollo-related research.

Well, there are no Nobel Prizes for geology, or for the remarkable feats of engineering that made the Apollo missions possible. If there were, Shoemaker would have won several for his many fundamental contributions to planetary science, and Wernher von Braun would have won for his brilliance in rocketry. Dyson's remark is the view of a brilliant physicist commenting upon a completely different discipline. Apollo did yield the unexpected surprises that Dyson cites as a qualification for science to be great. Through Apollo we learned that the Moon is ancient (talk about a surprise; even the lunar gods Shoemaker and Baldwin mistakenly thought mare lavas were less than a billion years old); that lunar rocks not only lack water but also are vastly depleted in all volatile elements; that impact cratering has been the major geologic process throughout lunar history; and that the Moon is made of rocks that have oxygen isotopes identical to Earth rocks. These unexpected discoveries have led to a completely new theory for the origin of the Moon and the early history of Earth — the giant-impact theory. Surely that must satisfy Dyson's requirement that great science involves unimagined surprises.

The greatest scientific value of human exploration of the Moon is that it allowed us to understand how planets work. Living on Earth is like being a scientific billionaire — we have such an overwhelming abundance of geologic and biologic riches that we failed to recognize that only impact cratering and volcanism are universal geologic processes. The Moon is our Rosetta Stone for the solar system. The magnificent images of Mercury, Venus, Mars, 100 planetary satellites, and a comet and asteroids from dozens of robotic probes are understandable only because of what we learned from the Moon. When people cavalierly devalue our knowledge of the Moon, they are also implying that understanding Earth and the solar system is not important. I vehemently disagree.

Amazingly, Logsdon also questions the importance of Apollo in human history and in the history of human exploration. Perhaps his reticence should be considered a welcome relief from President Nixon's bombast that the first landing on the Moon was the greatest day since creation. But what other historic deed can be considered more important than the Apollo landing? What other achievement in exploration? Thousands of years from now, when humans (if we still exist) wander across the solar system and the galaxy, the flight of Apollo 11 will be mythical in its importance. As the 19th-century Russian space visionary Konstantin Tsiolkovsky said, "Earth is the cradle of mankind, but we can't stay in the cradle forever." Apollo was the first halting step out of the cradle. I'm anxious for the next.

Earthrise as captured by Apollo 17.

Apollo 17 astronauts Ronald E. Evans and Harrison H. Schmitt departed the Moon on December 14, 1972. No one has been back since.

Photograph and Illustration Credits

The author gratefully acknowledges the following sources of the photographs and illustrations listed below. Full citations appear on pages 197–202. Special thanks are due to the University of Arizona Lunar and Planetary Laboratory (UA/LPL); Brown University/NASA Northeast Regional Planetary Data Center (Brown/NASA); and Lick Observatory, whose images comprise a substantial part of this book.

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Dedication and acknowledgments. Pages x, xi: Gary Seronik (5).

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CHAPTER 1

Opposite page 1: Gary Seronik.
Page 1: Vatican Observatory.
2: UA/LPL (3).
3: left, NASA: right, Gary Seronik.
4–7: Gary Seronik (8).

CHAPTER 2

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23: table, source: C. R. Neal and L. A. Taylor, *Geochimica et Cosmochimica Acta.*
24: left, Sky Publishing diagram, source: H. Hiesinger et al., *Journal of Geophysical Research;* right, NASA.
25: Don Davis (2).

CHAPTER 3

26: Lick Obs.
27: H. P. Wilkins and P. Moore, *The Moon.*
28: left, Gilbert, *The Moon's Face;* right, Patrick Moore.
29: left, *Sky & Telescope* archives; right, Yerkes Observatory.
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36: UA/LPL.
37: H. C. Urey, from Z. Kopal, *Physics and Astronomy of the Moon.*

CHAPTER 4

38: Mount Wilson and Palomar Observatories.
39: Thomas Gold.
40: Ewen Whitaker.

41: top, NASA; bottom, Ewen Whitaker.
42: UA/LPL.
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48: left, Sky Publishing diagram, source: Charles Wood; right, Carlé Pieters.
49: Charles Wood.
50: left, Carolyn Shoemaker; right, Brown/NASA.
51: left, Gary Seronik; right, UA/LPL.
52: top, B. Ray Hawke; bottom, UA/LPL.
53: table, source: E. M. Shoemaker and R. J. Hackman, from Z. Kopal and A. K. Mikhailov, *The Moon.*
54: table, source: D. E. Wilhelms, *Geologic History of the Moon;* bottom, Don Davis (2).
55: Don Davis (2).

CHAPTER 6
56: Lick Obs.
57: UA/LPL.
58: USGS.
59, 60, 61, 62: UA/LPL.

CHAPTER 7
64, 65: top, USGS/NASA; bottom, Lick Obs.
66: UA/LPL.
67: top, Don Wilhelms; bottom, UA/LPL.
68, 69: UA/LPL (3).
70: USGS.
71,72: UA/LPL (4).

CHAPTER 8
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77: left, Sean Solomon; middle, John Michael Jemail; right, Lick Obs.
79: top left, *Sky & Telescope* archives; bottom left, W. G. Lohrmann, *Topographie der sichtbaren Mondoberflaeche;* bottom right, NASA.
80: left, Ernst E. Both; right, UA/LPL.

CHAPTER 9
82: UA/LPL.
83: NASA.
84: UA/LPL.
85: left, UA/LPL; right, NASA/JSC.
87: Brown/NASA.
88: UA/LPL.
89: P. Fauth, *The Moon in Modern Astronomy.*

CHAPTER 10
90: UA/LPL.
91: table, sources: W. K. Hartmann and G. P. Kuiper, *Communications of the Lunar and Planetary Laboratory I;* R. J. Pike and P. D. Spudis, *Earth, Moon and Planets;* and D. E. Wilhelms, *Geologic History of the Moon.*
92: UA/LPL. **93:** left, Gary Seronik; right, Sky Publishing diagram, source: D. E. Gault and J. A. Wedekind, 9th LPSC.
94: left, UA/LPL; right, NASA.
95: left, UA/LPL; right, Sky Publishing diagram, source: UA/LPL and C. M. Pieters et al., 10th LPSC.
96: Gary Seronik.
97: NASA.
99: UA/LPL.
100: Brown/NASA.
101: Lick Obs.

CHAPTER 11
102: Lick Obs.
103: UA/LPL.
104: Gary Seronik.
105: left, UA/LPL; right, William Hartmann.
106: left, UA/LPL; right, Gary Seronik.
107: UA/LPL (2).
108: left, Gary Seronik; right, UA/LPL.
109: UA/LPL.

CHAPTER 12
110, 111: UA/LPL.
112: table, source: P. D. Spudis, *Geology of Multi-Ring Impact Basins;* right, Lick Obs.
114, 115: UA/LPL (3).
116: NASA.
117: bottom left, UA/LPL; inset, Brown/NASA.

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118: Gary Seronik.
119: Sky Publishing diagram, source: Charles Wood.
120: Sky Publishing diagram, source: D. U. Wise, *Journal of Geophysical Research.*
121: table, source: J. A. Wood, from W. K. Hartmann et al., *Origin of the Moon.*
122: Don Davis.
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125: left, Brown/NASA; right, Lick Obs.
127: Ewen Whitaker.
128: USGS.
129: Gary Seronik.
130: Sky Publishing diagram, source: G. Ryder, 20th LPSC.
131: UA/LPL.
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134, 136: UA/LPL.
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141: left, Craig Zerbe; right, A. Dauvillier, *Le volcanisme lunaire et terrestre.*
142: left, J. E. Spurr, *Geology Applied to Selenology;* right, G. Fielder, *Structure of the Moon's Surface.*
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144: Gary Seronik.
145, 146: UA/LPL.
147: left, UA/LPL; right, Brown/NASA.
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151: NASA.

CHAPTER 16
152: UA/LPL.
153: Paul Spudis.
154: left, UA/LPL; right, Sky Publishing diagram, sources: UA/LPL and C. M. Pieters et al., 6th LPSC.
155: left, Arizona State University; right, UA/LPL.
156: Stephen Keene.
157: European Southern Observatory.
158: left, Sky Publishing diagram, source: D. E. Wilhelms, *Geologic History of the Moon;* right, UA/LPL.
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CHAPTER 17
160: European Southern Observatory.
161: left, Tom Bayley; right, Sky Publishing diagram, sources: P. H. Cadogan, *Nature,* and Lick Obs.
162: Sky Publishing diagram, sources: Ewen Whitaker and Lick Obs.
163: Sky Publishing diagram, source: J. L. Whitford-Stark and J. W. Head, *Journal of Geophysical Research.*
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165, 166: UA/LPL.
167: Brown/NASA.
168: left, William Cannell; right, NASA.
169: UA/LPL.
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171: left, UA/LPL; right, Brown/NASA.
172: UA/LPL.
173: top, Brown/NASA; bottom, UA/LPL.

CHAPTER 18
174: European Southern Observatory.
175: John Westfall, *Sky & Telescope.*
176, 177: UA/LPL.
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185: left, UA/LPL; right, Brown/NASA.
186: Sky Publishing Corp.
187: USGS (2).

CHAPTER 19
188: Christine Churchill.
190, 191: NASA.

Selected References

For readers who are interested in the sources of the major statements or in learning more about particular themes that appear in this book, here is a listing of some of the works I consulted. Notice that many of the references are from the 1970s and 1980s. That doesn't mean that I haven't kept up with the latest developments; rather, this was the golden age in which our modern understanding of the Moon developed. The Introduction also includes a list of some of the books and maps that I routinely use — many of these titles are still available and comprise the beginning of a great lunar library.

The works below are listed alphabetically by author; the chapters of this book in which they are referenced are listed in boldface at the end of each entry. The first six works are so important that I consulted them in nearly every chapter:

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Index of Selected Features

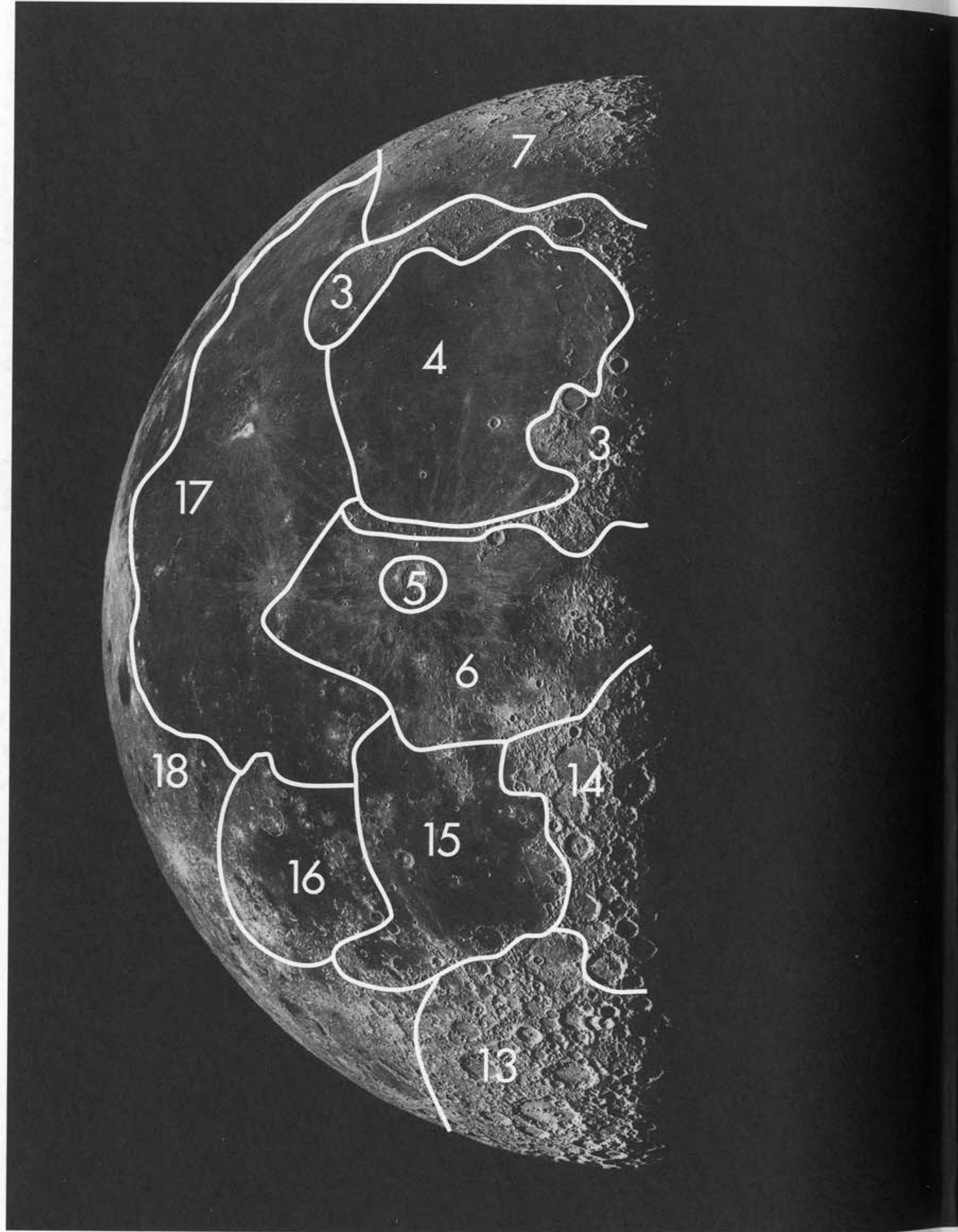
Here is a listing of the lunar features described in this book. Each entry includes the page number where the most extensive discussion is given, along with the chart number on which the feature appears in Antonín Rükl's superb *Atlas of the Moon*, soon to be available in an updated edition from Sky Publishing. Unless otherwise designated, the feature can be assumed to be a crater.

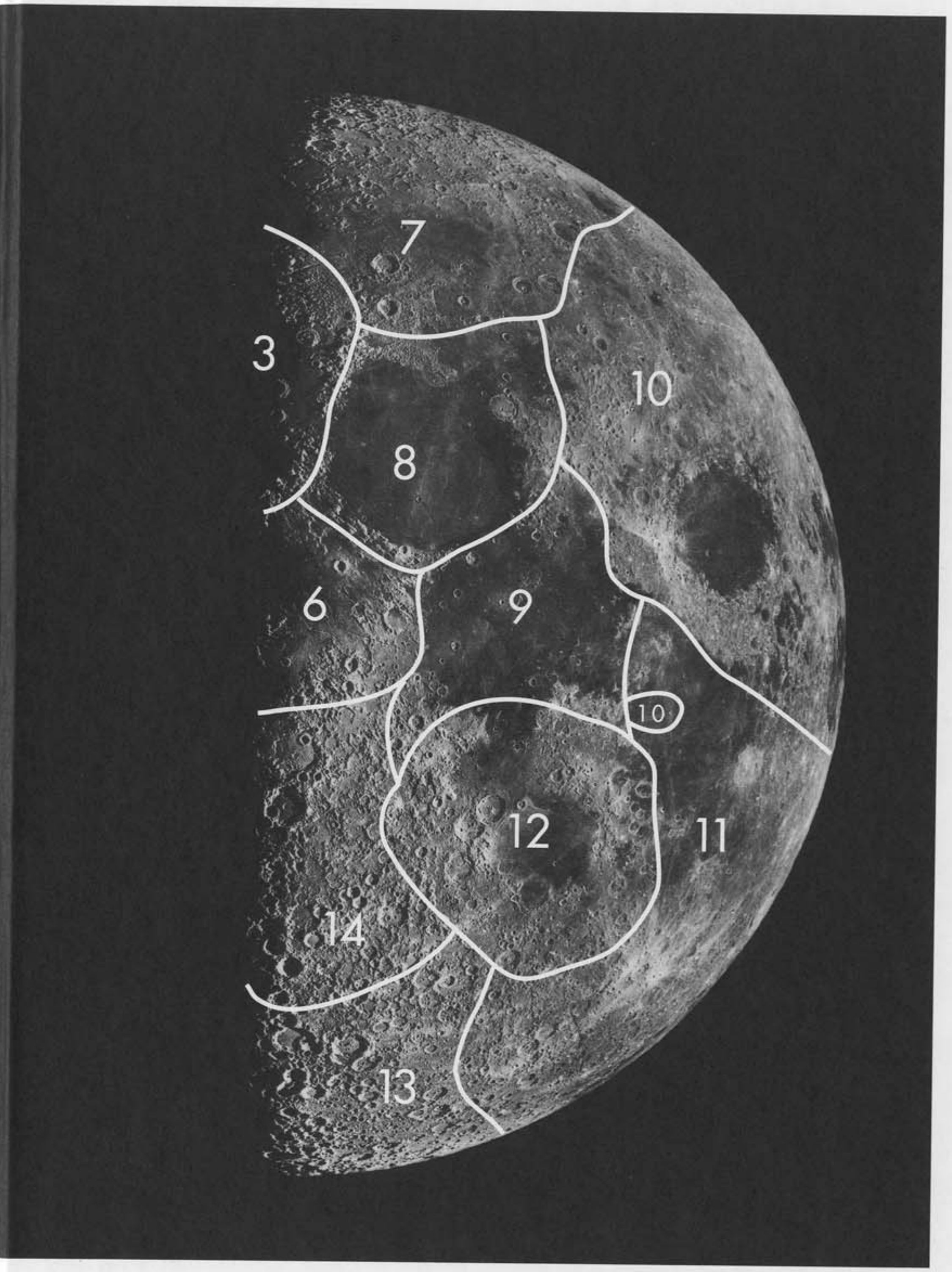
So, for example, if you are interested in observing Albategnius, you will find it described on page 137, though the crater may also be mentioned briefly elsewhere. If you plan on using the Rükl atlas at the telescope, turn to charts 44 and 45 to find Albategnius. (Note that in Atlas of the Moon, charts covering the Moon's libration zones are given Roman numerals.)

Index of Selected Topics

Information on specific lunar features can be found in the preceding index. Most of the topics indexed below are also discussed (albeit in less detail than on the pages cited here) elsewhere in the book.

CHAPTER KEY





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ISBN 0-933346-99-9
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