National Aeronautics and
Space Administration

Educational Product	
Teachers and Students	Grades 5-college

Planetary Geology

A Teacher's Guide with Activities

in Physical and Earth Sciences

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Activities in Planetary Geology for the Physical and Earth Sciences

Editors

Ronald Greeley and Kelly Bender
Department of Geology
Arizona State University
Box 871404
Tempe, Arizona 85287-1404

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

Acknowledgments

This book is the second edition of NASA SP-179, first printed in 1982. It has been updated to take into account planetary missions that have flown throughout the solar system since the first edition. Both editions are outgrowths of various short courses in Planetary Geology that have been held over the last two decades, and from activities developed in the classroom. *Activities in Planetary Geology* was developed for the National Aeronautics and Space Administration with the guidance, support, and cooperation of many individuals and groups.

NASA Headquarters

Solar System Exploration Division
Office of Planetary Geoscience
Education Office

Production

Photographic Support

Bill Knoche, ASU
Daniel Ball, ASU

Graphics

Sue Selkirk, ASU
Mary Milligan

Word Processing

Carol Rempler, ASU
Byrnece Erwin, ASU
Kelly Bender, ASU

Activity Contributors

Ms. Kelly Bender
Department of Geology
Arizona State University
Tempe, AZ 85287

Dr. Richard D'Alli
Department of Psychiatry
Duke University Medical Center
Durham, NC 27706

Prof. Ronald Greeley
Department of Geology
Arizona State University
Tempe, AZ 85287

Ms. Lee Ann Henning
Fort Hunt High School
Fort Hunt, VA

Mr. William Johnson
Fairfax High School
3500 Old Lee Highway
Fairfax, VA 22030

Ms. Deana Cooper
Highland High School
Gilbert, AZ 85234

Mr. David Nelson
Department of Geology
Arizona State University
Tempe, AZ 85287

Dr. Robert Pappalardo
Department of Geological Sciences
Brown University
Providence, RI 02912

Mr. David Rood
2060 John Dodgen Way
Marietta, GA 30062

Prof. Peter H. Schultz
Department of Geological Sciences
Brown University
Providence, RI 02912

Guide to Activity Level

	Unit 1			Unit 2			Unit 3			Unit 4					Unit 5		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	Geologic Events	Aerial Photos	Stereo Photos	Impact Cratering	Compar. Cratering	Rainy Day Craters	Coriolis Effect	Storm Systems	Wind Tunnel	Landform Mapping	Mars Geology	Venus Geology	Outer Planet Sats.	Planets in Stereo	Intro. to Mapping	Moon Mapping	Mars Mapping
Grade Level																	
● K – 4	√																
▲ 5 – 8	√	√				√	√				√						
■ 9 – 12	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
★ College	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Form of Activity																	
Individual Student Activity	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Group Student Activity	√			√	√	√	√		√	√	√	√	√	√	√	√	√
Instuctor Demonstration				√	√		√		√								

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Introduction

Many earth science courses include an introduction to the solar system. The challenge of earth science is to understand the natural processes that shape not only our planet, Earth, but all objects in the solar system. But there are more compelling arguments for including planetary science in the classroom. Those arguments, some of which are outlined below, inspired NASA to conduct short courses in planetology for earth science teachers at the secondary and college levels. This book is an outgrowth of these short courses.

The Planetary Perspective

Few processes can be understood in isolation from other natural phenomena. Planet Earth is no exception. The forces that drive Earth's evolution and shape its surface have most likely operated elsewhere in the solar system. Earth scientists attempt to recognize those forces on all planets and explain why they are manifested on our world in ways that seem familiar, and on other worlds in ways that may not.

Earth scientists are also concerned with earth materials, the building blocks of this planet. If there is one illuminating result of space exploration, it is the emergence of a unifying vision of the birth and growth of planets. Pictures of the planets sent back by spacecraft strongly suggest a close relationship among the inner planets. Rocks and soil brought back from the Moon bear remarkable similarity to Earth materials. Even spacecraft pictures of the outer planet satellites, many of which are planets themselves by virtue of their size, have astounded scientists with their exotic, but recognizable surfaces.

The American geologist T. C. Chamberlain (1843–1928) once wrote that when approaching a scientific problem, it is important to maintain several working hypotheses. Prior to manned and unmanned space travel there were only terrestrial examples of planet-making materials and processes. It is now possible to devise general theories from a collection of working hypotheses. The multiple working hypotheses come from the scenes of extraterrestrial environments.

A major goal of science is prediction. Once generalized theories are formulated, then experiments are designed to test the theories through their predictions. Some experiments that could address the questions of earth scientists simply cannot be performed on Earth because of their monumental proportions. What could be more illustrative, elegant, or challenging than to consider the other planets as great experiments running under conditions different from those on Earth? The result is to gain insight into planetary scale problems and to escape the limited Earthbound view of nature.

Apollo 17 was launched December 7, 1972. Here astronaut Harrison Schmitt works with a lunar scoop in the Moon's Taurus-Littrow mountains.

Earth scientists are painfully aware that the processes active on Earth today have wiped clean much of the record of Earth's own history. However, relics and indirect evidence of our own past are often preserved on other planetary surfaces. A common tactic used by scientists to understand complex systems is to study simpler, analogous systems. While the Earth is a complex, turbulent, and delicately balanced system, the other planets may represent stages in the evolution of that system that have been arrested in their development or ventured down different pathways.

Finally, the study of the Earth and planets on a grand scale is not without practical benefits. Better analysis of the atmosphere, sea, and solid crust proves to be of technological, economic, and cultural value. But meteorologists have observed Earth's weather since Ben Franklin's day; what has been missing is another model, another atmosphere to study, where the variables are different, but the dynamics are as definitive. We may have found those requirements in the atmospheres of Venus, Mars, and the outer planets.

We are living in a time of revolutionary discoveries in earth science. It is possible that the fundamental work in earth and planetary sciences over the last three decades will someday be likened to Galileo turning the first telescope toward the heavens. From a scientific standpoint, earth science is a special case of the more general planetary or solar system sciences. This is the motivation to study other worlds—to learn more about that celestial neighborhood in which we occupy a small, but life-sustaining place.

About This Book

Science education is an integral part of scientific endeavors. When the National Aeronautics and Space Administration was created by an act of Congress in 1958, its charter required the agency to "…provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof." Part of that responsibility includes introducing students to the scientific results of planetary exploration. This volume is designed to help meet this goal.

The activities are written either to supplement or to introduce topics usually encountered in earth science courses. Consistent with the rationale outlined above, most activities deal with new concepts in planetary geology, but, when generalized to include terrestrial processes, can illustrate broad problems in the earth sciences. The exercises are not keyed to any particular text; rather, each addresses concepts as independent units. The exercises are grouped into five units: 1) introduction to geologic processes, 2) impact cratering activities, 3) planetary atmospheres, 4) planetary surfaces, and 5) geologic mapping. Although each exercise is intended to "stand alone," students will benefit from having worked some of the prior exercises. For example, it would be difficult for students to work exercises in planetary geologic mapping without some knowledge of geologic processes and planetary surfaces. The suggested introductory exercises are noted at the beginning of each exercise. Depending on the level of the student and the context of the exercise, the sequence of the units is somewhat cumulative.

Depending on the instructor, activities can be adapted to most levels of instruction by modifying the questions and adjusting the expectations for answers. A list of suggested correlations of activities with topics commonly covered in earth science courses is included for the convenience of the instructor.

Special Note to the Instructor

Each activity includes an introduction with instructor's notes, a "blank" exercise sheet which can be copied for classroom use, and an answer key to the exercise.

It is our hope that this book will be a valuable resource in teaching the physical, earth, and space sciences. Enclosed is an evaluation card. We would appreciate your returning this card with your comments.

A Note About Photographs

An essential part of Planetary Geology is the use of spacecraft photographs. Ideally each student-team should have access to glossy photographic prints for use during the laboratory exercises. Photocopies of the pictures in this book (such as Xerox copies) generally lack sufficient detail to be useful. Offset printing is slightly better, but again this process is at least three generations removed from the original product.

Glossy prints or copy negatives can be obtained for a nominal cost (in some cases for no charge) from various sources. Each spacecraft photograph caption in this book contains the necessary picture identification numbers to help you in obtaining the photos. Usually the mission name (Apollo, Viking, etc.) and frame number is sufficient identification.

Listed below are sources of space photography. Instructions for ordering photography will be provided upon written request. Be sure to include your name, title, the fact that the photographs will be used at a non-profit educational institution, and specific photograph numbers.

For planetary mission photography, contact:

National Space Science Data Center
Code 633
Goddard Space Flight Center
Greenbelt, MD 20771

For Earth photography, contact:

EROS Data Center
U.S. Geological Survey
Sioux Falls, SD 57198

For photographs indicating Arizona State University as their source, contact:

Arizona State University
Space Photography Laboratory
Department of Geology
Box 871404
Tempe, AZ 85287

Introduction to Geologic Processes

Of the terrestrial planets, the Earth is the most complex and diverse. Because we live on this planet, we have the opportunity to study the geologic processes that have formed and continue to shape its surface. The four main geologic processes that act on the Earth's surface are **volcanism**, **tectonism**, **gradation**, and **impact cratering**.

Volcanism is the eruption of molten material onto the surface. On the terrestrial planets, the molten material (or magma) is composed of melted rock and gases. On icy satellites the material is predominantly liquid water or slushy ice, with some fraction of rocky material. Tectonism involves the movement of rock by folding, fracturing, or faulting. Earthquakes are a manifestation of tectonism. Volcanism and tectonism are processes driven by internal planetary activity. Gradation involves the erosion, movement, and deposition of surface materials. The major agents of gradation are running water, ice, gravity, and wind. Gradation is controlled by the surface environment of a planet or satellite. Factors controlling surface environment include gravity, temperature, and the presence of an atmosphere. Material falling from space such as meteoroids and comets result in impact cratering, the fourth principal geologic process.

By recognizing the morphologies (shapes) of landforms produced by each of these four processes, it is possible to begin to unravel the history of a planetary surface. Planets and satellites have different geologic histories, with each of the processes playing a part. However, the extent to which any process has operated on a surface varies from planet to planet. The exercises in this unit are designed to introduce the student to the landforms produced by each process. Today, impact cratering (emphasized in Unit Two) is relatively rare in the solar system, but historically it has played a major role in shaping planetary surfaces and in the formation of features now seen.

2.0 hours each part (with instructor modification for grade level)

Geologic Events on Earth

Instructor Notes

Suggested Correlation of Topics

The Earth, geography, gradation, impact cratering, earth science introduction, tectonism, volcanism

Purpose

The objective of this exercise is to show the frequency and distribution of events on Earth resulting from the four major geologic processes. In this exercise, the student will process and analyze a geologic data set to produce graphic and written results. Locating event sites will improve world geography skills.

Materials

Suggested: magazines and newspapers, glue or tape, paper, colored pens or pencils, straightedge or ruler, atlas or world almanac (one atlas per student group). Substitutions: wall-size world map can substitute for an atlas.

Background

This exercise illustrates the general frequency and distribution of volcanic, tectonic, gradational, and impact cratering events. It is important that students have an introduction to these processes through lectures, videos, or slides before working the assignment. Volcanic and tectonic events (volcanic eruptions and earthquakes) are typically large in scale and short in duration. That is, each event often results in great disruption over a large area, but last only a short time. However, over long periods of time, these processes can produce large landforms such as mountains, plains, ocean basins and islands. Impact cratering is of short duration and the frequency of impacts is very low compared to a human lifespan. Early in Earth's history, impact cratering was much more common, but now there are fewer objects in space to act as impactors. Gradation occurs at all scales from the erosion of mountain ranges to the grinding of sand grains in streams. Gradation on Earth occurs on time scales from seconds to centuries or more.

Teacher Recommendations

Part One of the exercise requires the student to collect data in the form of pictures and newspaper articles. This part can be done in several ways: it can be assigned as a take-home exercise, the instructor can collect magazines and newspapers to enable completing the exercise during a single class period, students can use a library (make photocopies instead of cutting up papers), or it can be omitted. Finding pictures that illustrate landforms created by all four processes can be frustrating. Many magazine advertisments with landscapes as the background will be useful. Make sure only one representation of an individual event is used; for example, a major earthquake will get extensive coverage by the media—but only one picture of that earthquake's effects should be used. Encourage the students to explain the types of landforms they select and help them classify the formation processes. Impact cratering occurs so infrequently that it is unlikely to be represented in magazines; however, pictures of the Moon show craters and it is up to the instructor to decide if such pictures can be used. It is recommended that the exercise be limited to the Earth. Suggested modifications of *Part One* for different grade levels are as follows:

Grades K–4: Eliminate procedure B; use procedure D and questions 1, 2, 5, and 6 for class discussion. Work in groups, completing the exercise in class.

Grades 5–8: Retain or eliminate procedure B at instructor's discretion; modify procedure D to the writing level of the students; use questions 5 and 6 for class discussion. Work in groups, completing the exercise in class.

Grades 9–12: Use exercise with no modifications. Work individually, in class or as homework.

College: Increase the number of pictures and articles needed. Have students compile a list of all the surface features produced by each process and then apply the lists to the region in which they live (i.e., list the volcanic, tectonic, gradational, and any impact features in the local geographic area). Photos of these features can be added to the scrapbook. Work individually, in class or as homework. Lengthen the time span of exercise (collect articles over a period of a month or more) as appropriate.

The second part of the exercise requires the student to analyze a data set and produce a graph of the results. In addition, the student is required to use geography skills to plot the location of the geologic events. To classify the list according to process, note that earthquakes are tectonic events; eruptions of ash and lava are volcanic events; landslides, mudslides, avalanches, flooding, hurricanes, and the formation of sinkholes are gradational events. The meteorite fall is the only impact event listed. The locations listed are general, so encourage the students not to spend too much time in finding the exact location when plotting the event on the world map. For example, if the listing is Sumatra, Indonesia, then anywhere on that island will do. Question 3, which follows the plotting portion of the exercise, can be used to lead into a discussion about plate tectonics after noticing the distribution of events around the Pacific (the "Ring-of-Fire"). For all grade levels discussion is suggested following the exercise.

Suggested modifications of *Part Two* for different grade levels are as follows:

Grades K–4: Do procedures A, B, and C using only the North American entries. Use questions 1 and 2 for class discussion. Work in groups completing the exercise in class. The instructor will need to teach how to make a bar graph and help with geographic skills. Instead of the world map provided, use a U.S. wall map and mark it with adhesive dots.

Grades 5–8: Do procedures A, B, and C using a limited number of regions from the list. Eliminate questions 3 and 4. Work in groups completing the exercise in class.

Grades 9–12: Use exercise with no modifications. Work individually, in class or as homework.

College: Expand question 3 by providing students with a map showing the lithospheric plates of the Earth. Discuss which processes are found mainly at plate boundaries, and have students try to explain any exceptions. Work individually, in class or as homework. If you have access to the Internet, then the exercise can be done using up-to-date events, and can be used over the course of a month (the minimum suggested interval) or a year.

Science Standards

- Earth and Space Science
  - Structure of the Earth system
  - Earth's history
  - Changes in Earth and sky
  - Origin and evolution of the Earth system
- Physical Science
  - Interactions of energy and matter

Mathematics Standards

- Statistics
- Measurement

Answer Key

Part One

1. (Answers will vary.) Volcanism, tectonism, gradation.
2. (Answers will vary.) Impact cratering.
3. (Answers will vary.) Tectonism, gradation, volcanism.
4. (Answers will vary.) Impact cratering.
5. Answers will vary, but should indicate tectonism and gradation occur more often than volcanism and impact cratering (which is very rare).
6. **a.** Answers will vary, however, volcanoes tends to form large features over a short period of time.

   b. Answers will vary, however, gradation can level mountains and fill in large bodies of water over the course of millions of years.

   c. Answers will vary. Location of population centers in relation to known areas of volcanism and tectonism and the ability to predict activity due to these processes will control their impact on society (which can be great over a short time period, or have no effect during centuries of dormancy). Large gradational events, such as floods, can do as much damage to property and cause as much loss of life as large earthquakes or volcanic eruptions.

Part Two

North America:	**B.** 6 tectonic, 8 gradation, 4 volcanic, 1 impact.
South America:	**B.** 6 tectonic, 4 gradation, 3 volcanic, 0 impact.
Europe:	**B.** 1 tectonic, 1 gradation, 0 volcanic, 0 impact.
Africa:	**B.** 2 tectonic, 1 gradation, 0 volcanic, 0 impact.
Asia:	**B.** 9 tectonic, 6 gradation, 4 volcanic, 0 impact.
Antarctica:	**B.** 1 tectonic, 0 gradation, 0 volcanic, 0 impact.
Australia:	**B.** 6 tectonic, 0 gradation, 1 volcanic, 0 impact.
Atlantic Islands:	**B.** 8 tectonic, 0 gradation, 0 volcanic, 0 impact.
Pacific Islands:	**B.** 28 tectonic, 3 gradation, 8 volcanic, 0 impact.
Complete data set:	**B.** 67 tectonic, 23 gradation, 20 volcanic, 1 impact.

1. Tectonism.
2. Impact cratering. Not many objects in space act as meteorites, most burn up in the atmosphere before impact, many land in the oceans.
3. Volcanism and most tectonic events border the Pacific Ocean (the "Ring-of-Fire," related to plate tectonics). Most tectonic events are related to plate boundaries, but due to the limited numbers, will appear to be randomly distributed except for those in the Pacific. Gradation events are randomly located. With only one event it cannot be determined from the data, but impact cratering is also random.
4. Gradation. No. On the Earth, water and wind work to physically and chemically break up the surface and then move the materials to new locations for deposition. Lacking wind, water, and ice, gradation on the Moon occurs by physically breaking up the surface during impacting events. The surface materials are only transported if they are thrown out by an impacting event.

Name ______________________________

Geologic Events on Earth

Purpose

To learn about the frequency and distribution of events on Earth that result from geologic processes: **volcanism**, **tectonism**, **gradation** and **impact cratering**. In addition, you will learn to recognize the **landforms** produced by these processes.

Materials: Part One

Magazines and newspapers; glue or tape; paper.

Introduction

Volcanism is the eruption of melted rock (called **magma**) and its associated gases onto the surface of the Earth. Volcanism commonly produces volcanoes and volcanic flows. Tectonism involves the movement of rock by fracturing and faulting, which results in earthquakes. Gradation involves the erosion, transportation, and deposition of surface materials. On Earth, water, wind, gravity and ice are the major agents of gradation. Impact cratering occurs when material from outside the Earth's atmosphere (meteoroids, comets) strike the surface.

Procedure

A. Cut out magazine pictures illustrating each of the four processes: volcanism, tectonism, gradation, impact cratering. Try to find at least two pictures showing landforms produced by each process.

B. Go through recent newspapers and collect articles describing activities related to the four geologic processes.

C. Put the pictures and articles together in a "scrapbook," with one process per section (e.g., the volcanic pictures and articles together on a page or two).

D. Study the pictures and write short descriptions of the surface features produced by each process.

Questions

1. For which process(es) was it easiest to find pictures of the resulting landforms?

2. For which process(es) was it most difficult to find pictures of its resulting landforms?

3. Which process(es) was it easy to find articles about in the newspaper?

4. Which process(es) was it difficult to find articles about in the newspaper?

5. Based on the number of pictures and articles you found for each process, what can you say about the frequency of activity for each process (how often does each occur)?

6. **a.** In your opinion, which process has the greatest effect on the surface (in terms of changing the appearance of the surface) over a short time period?

   b. Which has the greatest effect over a long time period (thousands of years or more)?

   c. Which process has the greatest effect on society?

Materials: Part Two

Atlas or World Almanac; colored pens or pencils; straightedge or ruler

Procedure

A. The list on the following pages documents the major geologic events recorded on Earth from August 1992 to July 1993. Fill in the blank to indicate whether the event is related to volcanism (V), tectonism (T), gradation (G), or impact cratering (I).

B. Count the total number of events of each type. Using your straightedge, make a bar chart to illustrate the results.

C. On the world map provided (Figure 1.1), mark with a dot the location of each event listed. Color code each dot by process (red for volcanic, blue for gradation, green for tectonic, and black for impact events).

Questions

1. Over the given year, which process occurred most frequently?

2. Which process occurred least? List some reasons why you think this process does not happen more often.

3. Examine the world map you completed. Do the events appear to be randomly distributed on Earth? Describe the distribution of events for each process as illustrated by your map.

4. The Moon has no atmosphere or water. On Earth, which process uses these agents? Can this process occur on the Moon in the same way it does on Earth? Why or why not?

Major Recorded Geologic Events on Earth, August 1992–July 1993

North America

_____ 08/07/92 earthquake, Gulf of Alaska

_____ 08/19/92 Mount Spurr erupts ash near Anchorage, Alaska

_____ 08/24/92 hurricane Andrew hits Florida, winds up to 200 mph

_____ 09/01/92 earthquake, near Nicaragua in the Pacific Ocean

_____ 09/02/92 earthquake, in St. George, Utah

_____ 09/02/92 earthslides destroy homes in St. George, Utah

_____ 09/16/92 Mount Spurr erupts ash near Anchorage, Alaska

_____ 09/30/92 earthquake near the Aleutian Islands, Alaska

_____ 10/09/92 27 lb. meteorite impacts car, Peekskill, New York

_____ 12/11/92 storm causes flooding in New Jersey and Long Island

_____ 12/30/92 snow avalanche, Utah

_____ 01/18/93 wet soil causes homes in California to slip downhill

_____ 03/07/93 sinkhole in Florida destroy part of a street

_____ 03/24/93 flooding, West Virginia

_____ 05/13/93 earthquake, Gulf of Alaska

_____ 05/15/93 earthquake, southern Mexico

_____ 06/25/93 flooding occurs along the Mississippi and Missouri Rivers

_____ 07/31/93 Sequam erupts ash and lava, Aluetian Islands, Alaska

_____ 07/31/93 Veniamin erupts ash and lava, Alaskan Peninsula, near Aluetians

South America

_____ 10/17/92 earthquake, northern Colombia

_____ 10/18/92 earthquake, northern Colombia

_____ 11/28/92 earthquake, Pacific Ocean off coast of Chile

_____ 12/07/92 rain causes mudslide in Llipi, Bolivia

_____ 01/14/93 Galeras Volcano erupts, southern Colombia

_____ 02/24/93 earthquake, Chile-Argentina border

_____ 03/11/93 rains cause major avalanche, Andes Mountains, Peru

_____ 03/29/93 landslide, southern Ecuador

_____ 04/18/93 earthquake, Andes Mountains, central Peru

_____ 04/20/93 Lascar Volcano erupts lava, northern Chile

_____ 05/09/93 rains cause landslide, southern Ecuador

_____ 06/07/93 Galeras Volcano erupts ash, Colombia

_____ 07/11/93 earthquake, central Chile

Europe

_____ 10/23/92 earthquake, Caucasus Mountains, Georgia

_____ 01/27/93 snow avalanche, Ossetia, Russia

Africa

_____ 09/11/92 earthquake, near Kinshasa, Zaire

_____ 10/12/92 earthquake, Cairo, Egypt

_____ 04/22/93 rains cause flooding in the Sudan

Asia

_____ 08/19/92 earthquake, central Kyrgyzstan

_____ 09/14/92 Indus River floods in Pakistan

_____ 11/06/92 earthquake, Aegean Sea, near Turkey

_____ 12/08/92 earthquake, Nicobar Islands, Indian Ocean

_____ 01/15/93 earthquake, Hokkaido, Japan

_____ 01/18/93 snow avalanche, Ankara, Turkey

_____ 01/19/93 earthquake, Sea of Japan

_____ 02/07/93 earthquake, Noto Point, Japan

_____ 02/21/93 snow avalanche, northern Iran

_____ 03/20/93 earthquake, Tibet

_____ 04/22/93 Sheveluch Volcano erupts ash, Kamchatka Peninsula, Russia

_____ 04/29/93 rains cause mudslides near Tokyo, Japan

_____ 06/08/93 earthquake, Kamchatka Peninsula, Russia

_____ 06/23/93 Mount Unzen Volcano erupts, Japan

_____ 07/04/93 Klyuchevskoy Volcano erupts, Kamchatka Peninsula, Russia

_____ 07/12/93 earthquake, Japan

_____ 07/14/93 extensive flooding, Punjab, Pakistan

_____ 07/15/93 Klyuchevskoy Volcano erupts lava Kamchatka Peninsula, Russia

_____ 07/27/93 extensive flooding, southern China

Antarctica

_____ 11/04/92 earthquake, Balleny Islands, Antarctica

Australia

_____ 10/23/92 earthquake, Papua New Guinea

_____ 11/01/92 earthquake, Papua New Guinea

_____ 12/18/92 earthquake, Papua New Guinea

_____ 01/13/93 earthquake, Indian Ocean south of Australia

_____ 03/06/93 earthquake, Solomon Islands, South Pacific

_____ 03/09/93 earthquake, Macquarie Island, Indian Ocean

_____ 07/16/93 Manam Volcano erupts ash and lava, Papua New Guinea

Atlantic Islands

_____ 08/28/92 earthquake, north of Ascension Island in the South Atlantic

_____ 11/21/92 earthquake, South Sandwich Islands, South Atlantic

_____ 01/10/93 earthquake, South Sandwich Islands, South Atlantic

_____ 03/09/93 earthquake, South Sandwich Islands, South Atlantic

_____ 03/10/93 earthquake, South Sandwich Islands, South Atlantic

_____ 03/20/93 earthquake, South Sandwich Islands, South Atlantic

_____ 04/05/93 earthquake, South Sandwich Islands, South Atlantic

_____ 05/02/93 earthquake, South Sandwich Islands, South Atlantic

Pacific Islands

_____ 08/02/92 earthquake, Halmahera, Indonesia

_____ 08/02/92 earthquake, Flores Sea, Indonesia

_____ 08/19/92 Mount Pinatubo erupts ash, Philippines

_____ 08/28/92 rain causes avalanches on Mount Pinatubo, Philippines

_____ 08/28/92 Mount Pinatubo erupts lava, forming dome in its crater

_____ 09/11/92 Hurricane Iniki hits Hawaii, winds up to 160 mph

_____ 09/26/92 earthquake, Halmahera, Indonesia

_____ 10/11/92 earthquake, Vanatu Islands, South Pacific

_____ 10/15/92 earthquake, Vanatu Islands, South Pacific

_____ 10/17/92 earthquake, Vanatu Islands, South Pacific

_____ 10/22/92 earthquake, Kermadec Islands, South Pacific

_____ 11/04/92 earthquake, Vanatu Islands, South Pacific

_____ 11/08/92 earthquake, Fiji Islands, South Pacific

_____ 12/12/92 earthquake, Flores, Indonesia

_____ 12/20/92 earthquake, Banda Sea, north of Australia

_____ 12/31/92 earthquake, Kermadec Islands, South Pacific

_____ 01/04/93 earthquake, Tonga Islands, South Pacific

_____ 01/20/93 earthquake, Sumatra, Indonesia

_____ 01/20/93 earthquake, Banda Sea, near Indonesia

_____ 02/02/93 Mount Mayon erupts ash and lava, Philippines

_____ 02/13/93 earthquake, near Fiji, South Pacific

_____ 03/01/93 earthquake, Irian Jaya, New Guinea

_____ 03/01/93 Mount Mayon erupts ash and hot rock, Philippines

_____ 03/03/93 Mount Mayon erupts ash, Philippines

_____ 03/03/93 rains on Mount Mayon cause lahars (hot mudslides), Philippines

_____ 03/06/93 earthquake, Fiji, South Pacific

_____ 03/12/93 earthquake, Fiji, South Pacific

_____ 03/21/93 Mount Mayon erupts ash, Philippines

_____ 03/21/93 earthquake, Fiji, South Pacific

_____ 03/24/93 Mount Mayon erupts ash, Philippines

_____ 03/26/93 Mount Mayon erupts ash and lava, Philippines

_____ 04/17/93 earthquake, Fiji, South Pacific

_____ 04/20/93 earthquake, northeastern Indonesia

_____ 05/11/93 earthquake, Mindanao, Philippines

_____ 05/16/93 earthquake, Tonga Islands, South Pacific

_____ 05/18/93 earthquake, Pacific Ocean, near the Philippines

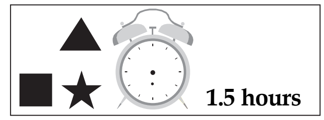
_____ 06/06/93 earthquake, Mariana Islands, North Pacific

_____ 06/18/93 earthquake, Kermadec Islands, South Pacific

_____ 06/30/93 earthquake, Vanuatu Islands, South Pacific

(**Source**: *Geochronicle*, *Earth Magazine* 01/93, 03/93, 05/93, 07/93, 09/93, 11/93, 01/94)

Figure 1.1 *Map of the Earth to be used for plotting locations of geologic events. Use the following scheme: red dots for volcanic, blue dots for gradational, green dots for tectonic, and black dots for impact events.*



Geologic Landforms Seen on Aerial Photos

Instructor Notes

Suggested Correlation of Topics

Geomorphology, gradation, impact cratering, tectonism, volcanism, photography

Purpose

The objective of this exercise is to introduce students to landforms produced by the four major geologic processes using aerial photographs.

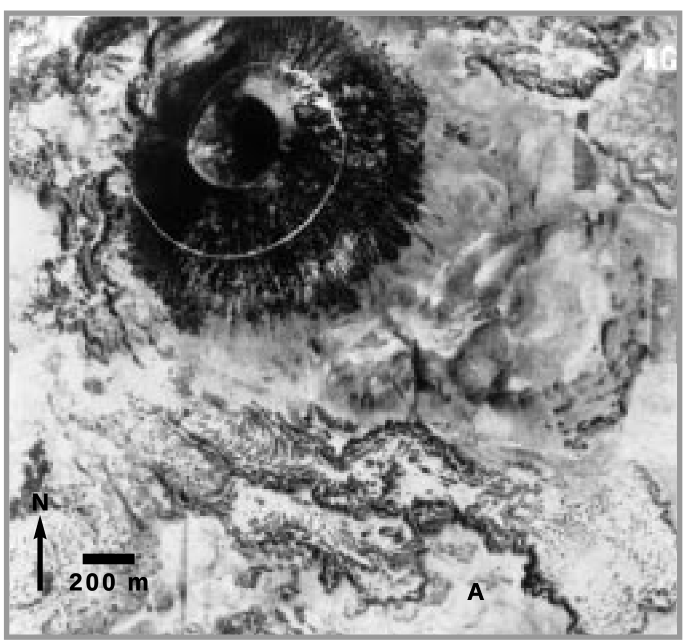
Materials

Ruler (metric)

Background

Geologic processes often result in distinctive landforms or surface features. For example, steep, conical hills with small summit craters are distinctive as volcanic in origin. Aerial photographs, commonly taken from airplanes, are used to study landforms on Earth. Depending on the camera used and the height of the airplane, areas shown in the photograph can range in size from a city block to an entire city. Aerial photographs are either "vertical" (viewed straight down on terrain from above) or "oblique" (viewed to the side).

In this exercise, students will study a series of aerial photographs of different terrains on Earth. In answering questions about the areas, they will become acquainted with landforms resulting from the four major geologic processes. Students should be introduced to these processes (gradation, impact cratering, tectonism, and volcanism) before beginning this exercise. A very brief statement about the four geologic processes is provided in the student section. Questions 2 and 6 require student knowledge of simple trigonometry.



Answer Key

1. **a.** The volcano has a circular base and a circular crater. The sides of the cone are gullied from erosion.

   b. A road.

2. **a.** ~564 m.

   b. 30.6°.

3. **a.** They are somewhat rugged.

   b. The source of the lava is probably at the base of the cinder cone near the road.

4. **a.** They are both generally conical in shape, with a central depression at the top.

   b. Mt. Tavurur is much larger, and its crater is more irregular.

5. The crater is scalloped, suggesting that it has been reshaped several times by multiple eruptions.

6. x=~446 m, 27.7°.

7. The slopes of a volcano may be affected by the following: Single versus multiple eruptions, type of material (ash versus lava), viscosity ("runnyness") of the lava (dependent on its temperature and composition), length of lava flows, erosion by wind or rain after volcano is formed.

8. It cuts through the mountains and is expressed as a depression or trough. The rocks along the fault were ground together and weakened, so that they were more easily eroded than the rocks away from the fault.

9. **a.** A road would have been cut and separated.

   b. There are at least two off-set features (drainage valleys) along the fault: near the middle of the photo, and near the bottom of the photo (harder to see the offset) .

10. Blocks A and C must move apart in the horizontal plane (← →). The area is undergoing extensional stresses.

11. **a.** The alluvium is material eroded from the mountains.

    b. All three erosional agents have acted to produce materials eroded from the mountains, but water was the main agent.

    c. All three agents, but mostly water.

    d. It would be eroded by the agents of wind, water, and gravity. For example, sand dunes are visible alongside the fans, evidence of erosion by the wind.

12. **a.** It removes material from its banks, and carries material from one place to another. It deposits material to form sandbars (erosion, transportation, deposition).

    b. The channels change position with time. Dry and semi-dry (ponds present) channels are visible in the foreground of the photo.

13. **a.** It is roughly circular, with squared sides.

    b. The walls are gullied, indicating erosion by running water. The flat bottom suggests it has been infilled.

14. About 48 times. (Crater diameter is about 1200 m.)

15. **a.** Meteor Crater is much wider and the sides are not as steep. Impact craters excavate (occur at ground level and dig out below ground level), volcanic cones and craters are built up above ground level (positive relief features).

    b. They have the same circular shape and have a crater in the center.

16. **a.** Circular. Somewhat subdued appearance: the rim appears worn, and not very distinct. The center of the crater seems to have been partly filled in with sediment and sand dunes.

    b. Meteor Crater appears to be more distinct and deeper than Roter Kamm.

17. **a.** The crater is much wider and not nearly as high or steep.

    b. They are both very circular and have raised rims.

18. **a.** River valley—gradation

    b. Graben—tectonism (rivers are flowing into this graben)

    c. Lava flow—volcanism

    d. Cinder cone—volcanism

    e. Lava flow—volcanism

    f. Lava flow in a pre-existing river valley—gradation, followed by volcanism

Answer Key, continued

g. Graben—tectonism (lava flows have entered parts of this graben)

19. Near letter G, volcanic material flowed into the pre-existing graben valley in two separate places. The flow spread out in a fan shape.

20. _3_ River and stream valleys formed

_5_ dark (black) volcanic materials were deposited

_4_ medium gray volcanic flows were deposited

_1_ light gray plains formed

_2_ tectonism produced grabens

21. On Earth they have been obliterated by tectonic processes and agents of gradation (wind and

Name ______________________________

Geologic Landforms Seen on Aerial Photos

Purpose

By studying aerial photographs you will learn to identify different kinds of geologic features, tell how they differ from one another, and learn the processes involved in their formation.

Materials

Ruler (metric)

Introduction

The four major geologic processes (**gradation**, **impact cratering**, **tectonism**, and **volcanism**) each produce distinct landforms. A **landform** can be identified based on its shape and form, or its **morphology**. Volcanism is the eruption of melted rock (called **magma**) and its associated gases onto the surface of the Earth. Volcanism commonly produces volcanoes and volcanic flows. Tectonism involves the movement of rock by fracturing and faulting, which results in earthquakes. Gradation involves the erosion, transportation, and deposition of surface materials. On Earth, running water, wind, gravity and ice are the major agents of gradation. Impact cratering occurs when material from outside the Earth's atmosphere (such as meteoroids and comets) strike the surface. The aerial photographs in this exercise will help you recognize landforms and the geological processes that formed them. These processes act on other planets, where they can generate similar landforms.

Questions

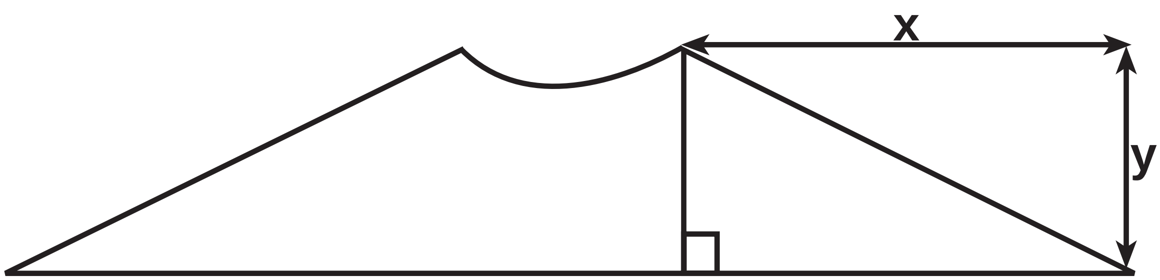
Volcanism

1. Examine the **cinder cone** of Mount Capulin, New Mexico, shown in Figure 2.1. The depression at its summit is referred to as a volcanic crater.

   a. Describe the general shape of the cone and the volcanic crater at the top.

   b. What is the white spiral line from the base of the cone to the crater rim?

   Based on the elevation of Mt. Capulin (334m) and the information provided by the aerial photo, the slope of the volcano's sides can be calculated. This simple sketch of Mt. Capulin will help.



2. **a.** Using your ruler and the scale bar on Figure 2.1, determine (in meters) the distance x, measured from the base of the cone to the edge of the crater at the top of the cone.

   b. The height y of the cone is 334m. Use trigonometry to estimate the average slope of the volcano's sides.

Examine the lava flow labeled A.

3. **a.** Does its surface appear rugged or smooth?

   b. Trace the flow back to its point of origin. Where is the probable source of the flow?

Study Mt. Tavurur volcano, New Guinea, in Figure 2.2.

4. **a.** How is the volcano similar to Mt. Capulin?

   b. How is it different?

5. Mt. Tavurur has erupted many times during its formation. How does the shape of the summit crater support this statement?

6. As you did for Mt. Capulin, estimate the slope of Mt. Tavurur's flanks. Draw and label a sketch similar to the one provided for Mt. Capulin. The height of Mt. Tavurur is 225m. Measure length x from the edge of the volcano at the ocean to the rim of the summit crater.

Sketch area

7. List some factors that might affect the slope of a volcano.

Tectonism

Southern California is cut by many faults. These are usually visible on aerial photographs as straight or gently curving linear features, often forming distinct divisions between landforms. Examine Figure 2.3, an oblique view of the San Andreas fault (arrow). A fairly straight valley trends from the bottom toward the top of the photo. (The dark line to the left of the fault is a canal lined with vegetation.) Over time, the ground to the left of the fault is moving away from us with respect to the ground to the right of the fault.

8. In what way does the fault affect the morphology of the mountains in this photo?

Tear a piece of paper in half. Place the two halves side by side and draw a line from one piece across onto the other. Making certain that the edges of the pieces remain in contact, slide the paper on the left away from you and the paper on the right towards you. This motion illustrates what occurs along the San Andreas fault and how it affects the features along it. This type of fault is called a **strike-slip fault**.

9. **a.** What would have happened if the line on the paper was actually a road crossing a fault?

   b. Are there any features like this in Figure 2.3?

One landform distinctive to tectonism is called a **graben** (see Figure 2.4). A graben is a valley bounded on both sides by **normal faults**. The movement along these faults is vertical, with the central block moving downward in relation to the sides.

10. For block B to have enough space to move down, what has to occur to blocks A and C in Figure 2.4?

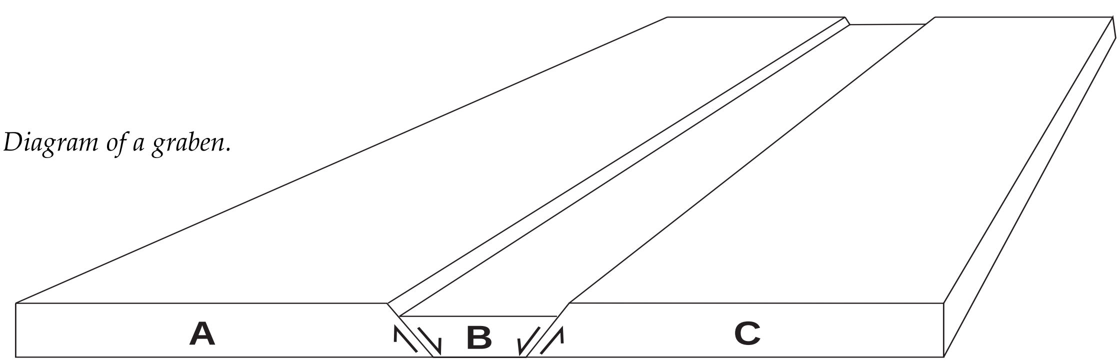


Figure 2.4. *Diagram of a graben.*

Gradation

Figure 2.5 is a vertical photo of alluvial fans at Stovepipe Wells, Death Valley, California. These features result from the build up of alluvium (gravel, sand, and clay) that accumulates at the base of mountain slopes. "Fan" describes the general shape of the feature.

11. **a.** What is the source of the alluvium that makes up the fans?

    b. Which agents of erosion (wind, water, and/or gravity) might have generated the alluvium?

    c. Which agent(s) deposited it?

    d. Once deposited, how might the alluvium be further eroded?

Figure 2.6 is a photograph of the Delta River, a braided stream in central Alaska. This river carries melt water and silt from glaciers to the Pacific Ocean. Rivers of this type are usually shallow. Because they are laden with sediments, they often deposit the sediments to form sandbars. These sandbars redirect the river flow, giving the river its branching, braided appearance.

12. **a.** How is the Delta River an agent of gradation that works to change the surface?

    b. Do the individual river channels appear to be permanent, or do they change position with time? How do you know?

Impact Craters

Examine the photographs of Meteor Crater, an impact crater in Arizona. Figure 2.7 (a) is a vertical aerial photograph, and Figure 2.7 (b) is an oblique view.

13. **a.** Describe the crater's general shape.

    b. Meteor Crater is one of the best preserved craters in the world. However, it has been eroded somewhat. List some evidence for this.

14. The meteor that impacted here was about 25m across. Measure the diameter of Meteor Crater. How many times bigger than the meteor is the crater?

15. **a.** Describe how the morphology of Meteor Crater is different from the volcanic landforms shown in Figures 2.1 and 2.2.

b. How is it similar?

Examine the view of Roter Kamm impact crater, Namibia, Figure 2.8.

16. **a.** Describe its morphology?

    b. Compared to Meteor Crater, does it look fresh or eroded? Explain.

17. **a.** How is Roter Kamm crater different from the volcanic landforms of Figures 2.1 and 2.2?

    b. How do they look similar?

Synthesis

Different processes produce landforms that are different in morphology. Linear, straight features are generally tectonic in origin. More sinuous features (such as river valleys) are typically formed by gradational processes. Volcanism forms flows in irregular patches and cones.

A part of central Arizona is shown in Figure 2.9. Represented here are landforms shaped by three of the four principal geologic processes. For each labeled landform, identify its type and the process that formed it.

18. A.

    B.

    C.

    D.

    E.

    F.

    G.

19. Identify a place in the photograph where a pre-existing graben has affected the morphology of a later volcanic flow. Sketch what you see, and describe in words what happened. (Use the sketch area on the next page.)

Sketch area

20. Determine the sequence of events that affected this region. Order the events below from first occurring (1) to most recent (5).

___ river and stream valleys formed

___ dark (black) volcanic materials were deposited

___ medium gray volcanic flows were deposited

___ light gray plains formed

___ tectonism produced grabens

21. Large impacting objects such as asteroids have rarely fallen to Earth in the last few million years, but billions of years ago they were very common. Assuming that throughout the geologic history of Earth, as many impacts have occurred as on the Moon, then why do we see so few craters on the Earth today, while so many remain visible on the Moon?

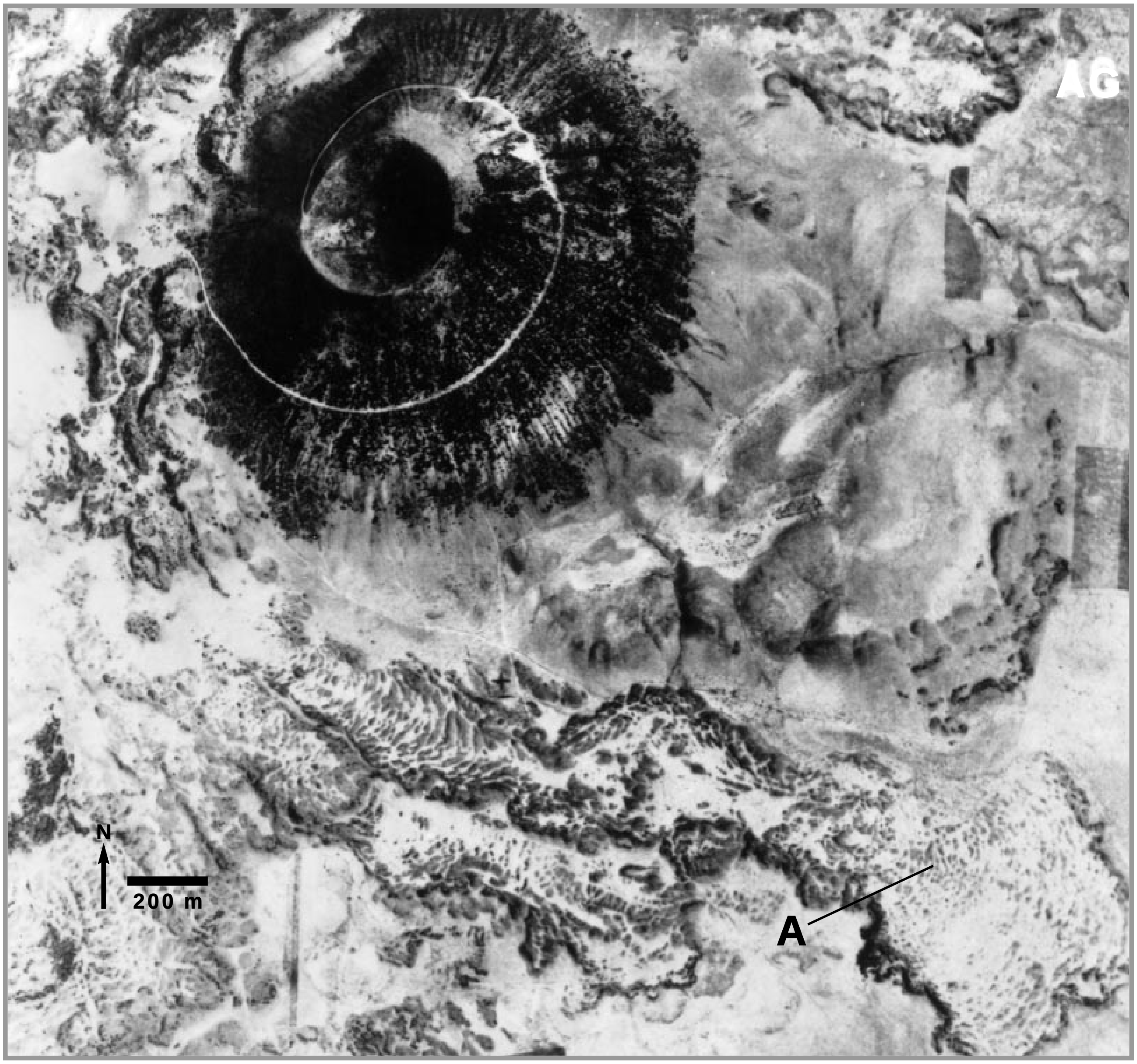


Figure 2.1. *Mount Capulin, New Mexico; vertical aerial photograph. (University of Illinois Catalog of Stereogram Aerial Photographs #105.)*

Figure 2.2. *Mt. Tavurur. Vertical view of a composite volcano on the eastern Pacific island of New Britain, Papua, New Guinea. (Univ. Of Illinois Catalog of Stereogram Aerial Photographs, #102.)*

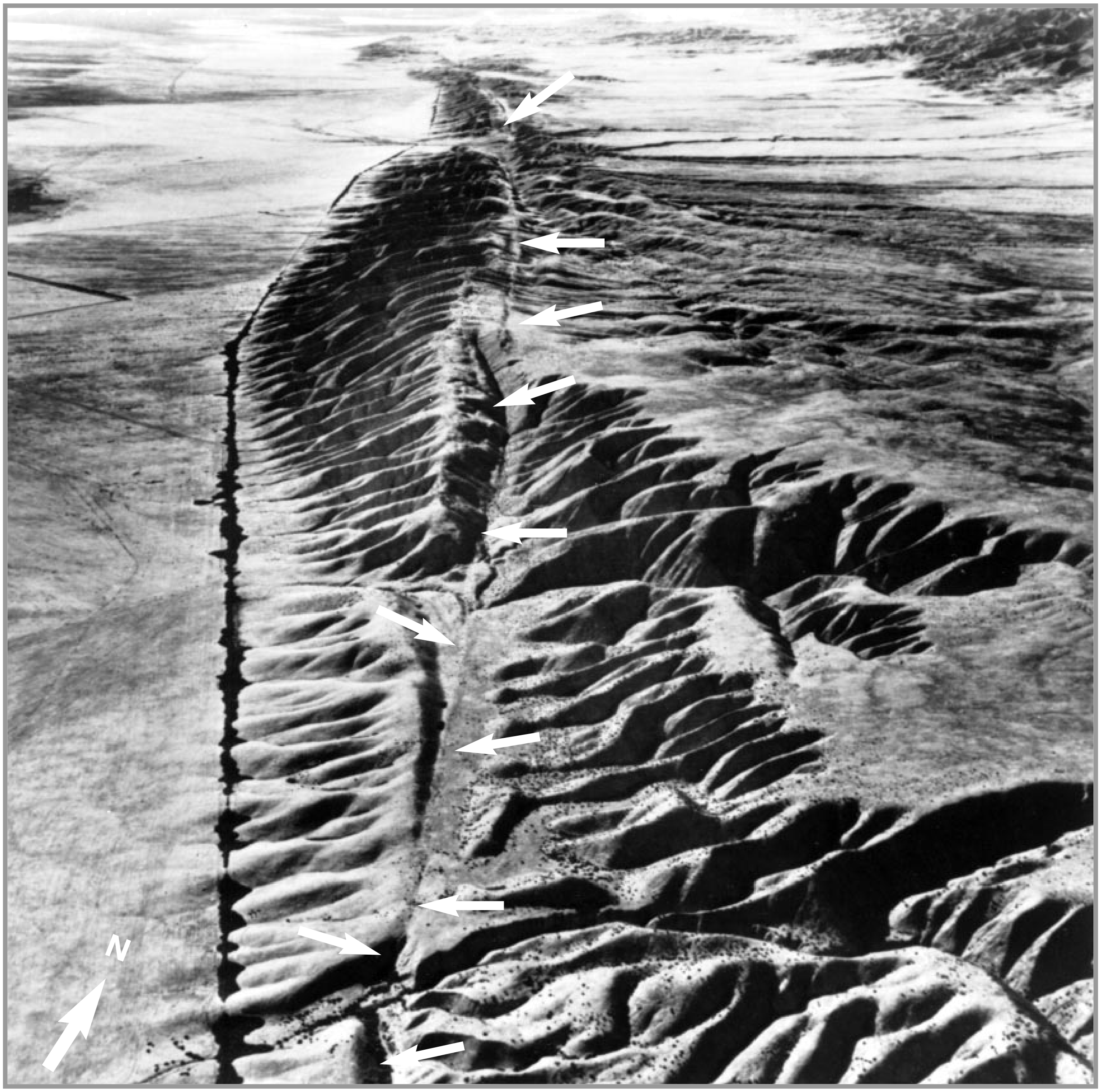


Figure 2.3. *Oblique aerial view of a part of the San Andreas fault north of Los Angeles. North is to the top right. The foreground is approximately 3.5 km across. (photograph by Robert E. Wallace, U.S. Geological Survey).*

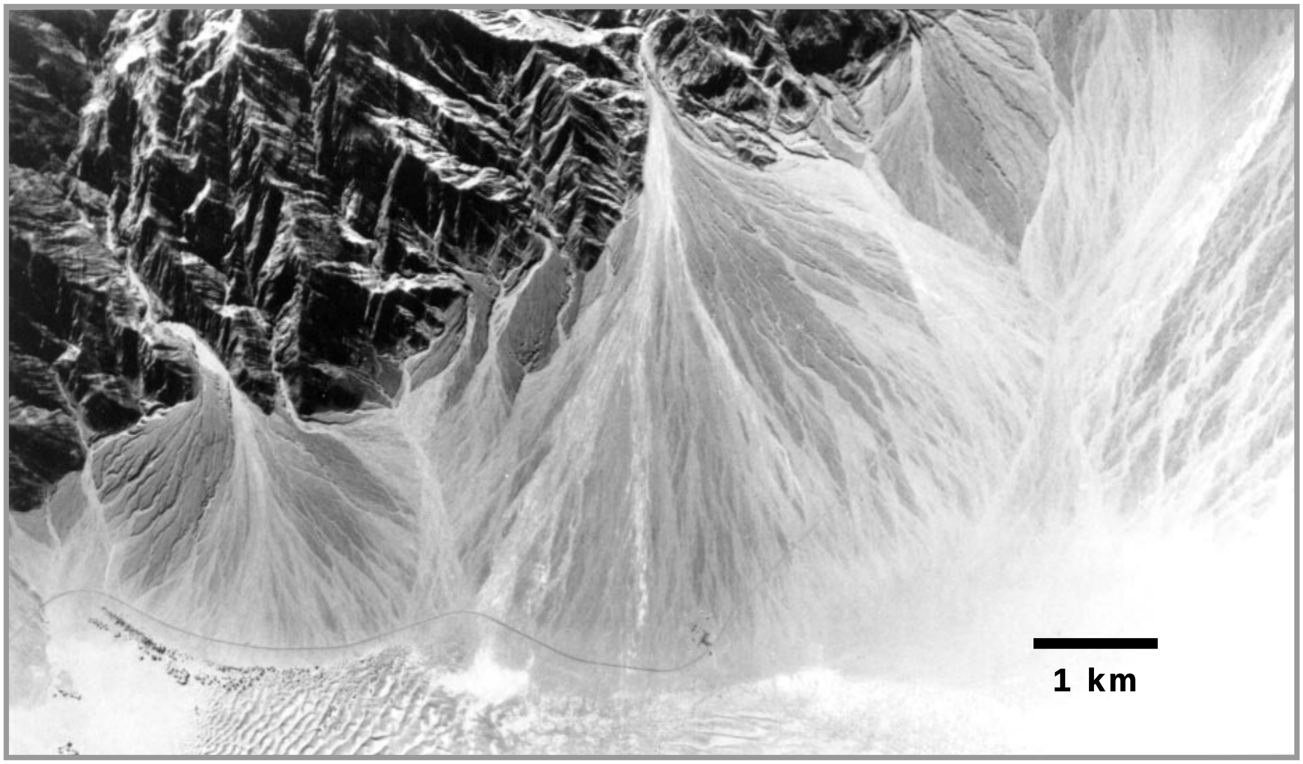


Figure 2.5. *Vertical view of alluvial fans near Stovepipe Wells, Death Valley, California. Panamint mountains lie to the south. North is to the bottom left. (University Of Illinois Catalog of Stereogram Aerial Photographs, #125).*

Figure 2.6. *The Delta River, a braided stream in central Alaska. North is to the top. (U.S. Navy photograph courtesy of T. L. Péwé, Arizona State University).*

Figures 2.7.a., 2.7.b. *Meteor Crater, Arizona: (a) vertical view, (b) oblique view. One of the best preserved meteor impact craters in the world, Meteor Crater was formed about 20,000 years ago. North is to the top. (a, University of Illinois Catalog of Stereogram Aerial Photographs, #5; b, Photograph courtesy U.S. Geological Survey.)*

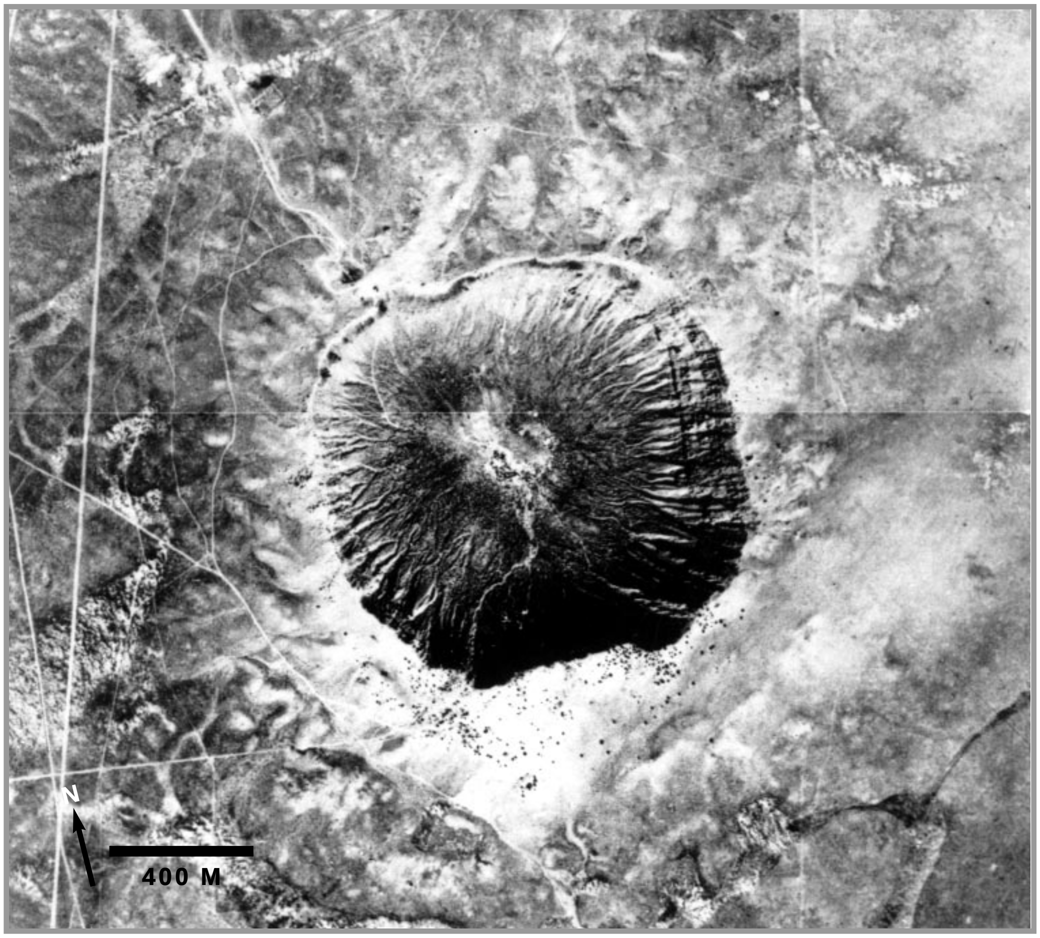


Figure 2.8. *Roter Kamm crater, Namibia. This impact crater is 2.5km across and formed more than one million years ago. North is to the top. (Photograph courtesy Robert Deitz; from Meteoritics, vol. 2, pp. 311-314, 1965.)*

Figure 2.9. *Mosaic of Landsat frames showing north-central Arizona. North is to the top.*

Exercise Two is suggested as an introductory exercise.

■ ★ 2.0 hours

Geologic Landforms Seen on Stereoscopic Photos

Instructor Notes

Suggested Correlation of Topics

Gradation, impact cratering, tectonism, volcanism, photography, scientific tools

Purpose

The objective of this exercise is to use stereoscopic (“three-dimensional”) photographs in understanding the four major geologic processes (gradation, impact cratering, tectonism, and volcanism).

Materials

Pocket stereoscope, protractor, ruler, calculator

Background

Before working this exercise, students should be introduced to the concept of stereoscopic viewing. Objects appear “three-dimensional,” that is they show depth, because we view them with each eye from slightly different perspectives. Stereoscopic photographs appear three-dimensional because they consist of two images of the same feature taken from two different perspectives. When viewed in a stereoscope, the features appear to have depth. The stereo images have different degrees of “vertical exaggeration,” the apparent increase in vertical relief that results when viewing images obtained from viewing perspectives separated by a large distance. These ideas are further explained in the student part of this activity.

This exercise uses pairs of stereoscopic photographs that illustrate landforms shaped by the four principal geologic processes: volcanism, tectonism, gradation, and impact cratering. Students should be introduced to these processes through lecture before working the exercise (see introduction to Unit One).

Parts A through D concentrate on specific examples of the four geologic processes and generally increase in difficulty; part E involves synthesis of the preceding parts. Starred (*) questions might be omitted at the high school level. In some instances, in-depth material that pertains to specific questions is found in the instructor answer key.

It is best for students to work this exercise in pairs or small groups. If the availability of images or stereoscopes is limited, then students might move among work stations prearranged by the instructor.

When first trying to view stereo photographs, some students may become frustrated. Encouragement and patience are important in getting this exercise started. It is helpful to have the students place their index fingers on the same object within each photo of the stereo pair and then adjust the position of the stereoscope until their fingers appear to overlap. When they remove their fingers, the stereo effect should become apparent. However, vision problems may prevent some students from seeing in stereo at all. These students should not be penalized, but should analyze the photographs “monoscopically,” while working with other students who can achieve the stereo effect.

The instructor may wish to explore some additional demonstrations to illustrate aspects of stereo photography. If a stereo pair is cut along the dividing line and the left and right images are switched, inversion occurs; that is, mountains become depressions, and valleys become ridges. If you have a camera (an instant camera is best), you can make your own stereo pairs. Take two photos of your classroom (or any other object) from positions a few feet apart. Place the photos side by side under a stereoscope and adjust them until they align and the stereo effect is seen. The further apart the photos are taken, the greater the vertical exaggeration.

Answer Key

1. **a.** Sketch should show steep sides and a relatively flat top.

   b. The crater is roughly circular, but is irregular in detail, with multiple scallops.

   c. The scalloped outline reflects craters from multiple eruptions.

   d. Gullies have been carved down its flanks by runoff of rainfall, waves have eroded the visible base of the volcano, and the inlet has cut into volcanic material.

   e. The flanks have been eroded to form deep parallel gullies. The easily eroded material is unlikely to be rock but is probably ash.

   f. Rainfall is typically greatest on the windward side of a high-standing volcano. This is because air cools as it rises up the mountain's flanks, promoting condensation and precipitation of water. The air is relatively dry as it passes over the other side of the volcano.

2. **a.** Wind blows from the southwest (lower right). The dunes show slip faces on their northeast sides.

   b. A dune in the center of the photo will migrate towards the northeast (the upper left of the photo).

   c. In the lower right, dunes coalesce into linear ridges (called "transverse dunes"). Crescent shaped ("barchan") dunes form toward the center, near a dark area blown free of dunes. Toward the upper left of the photo, dunes are U-shaped and convex the opposite way from the dunes in the lower right.

   d. Sand supply, consistency of wind direction, wind velocity, and the presence of vegetation all affect dune morphology.

3. **a.** The sketch should show a tree-like "dendritic" pattern of smaller branches that join into the main trunk stream.

   b. South. The downhill direction is indicated by the direction small streams flow near their intersection with the larger one. A "Y" pattern typically results, with the Y pointing downstream.

   c. Material is eroded from the rock cliffs of the waterfall and washed downstream. Gradually the cliffs will retreat in the upstream direction, lowering the overall topography of the region. This process is termed "headward erosion."

   d. The ridge is becoming more narrow as debris is washed down the steep slopes to either side during rains. Some of this material is visible in fans near the bases of the steep slopes. Eventually the more resistant material atop the ridge will be eroded through, and the less resistant material beneath will erode away relatively rapidly.

4. **a.** Gray. The white layers form ridges but the gray material is eroded out into valleys. In some locations, white layers have sheltered and protected the gray material from erosion. No river channels are apparent in the white material; gullies indicate that the gray material erodes easily.

   b. SSW **c.** N65W

   d. 35m **e.** 220m

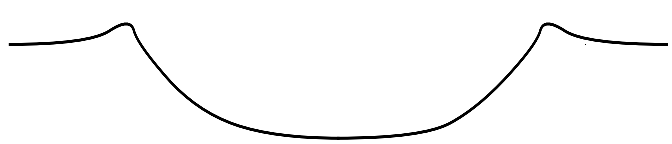
   f. The stereo view reveals that the strata are probably not curved, but have a constant strike, and a constant dip to the south-southwest. As the river cut downward, it exposed portions of the white layers to the south that are still buried elsewhere. Therefore, the apparent curvature in the monoscopic photo is a geometric consequence of the river having cut into the dipping strata, exposing the white layer at different elevations.

5. **a.** About 1200m. **b.** About 240m.

   c. Large vertical exaggeration (appears as deep or deeper than wide).

   d. The crater shows a raised rim that stands above the surrounding plain. The rim rises 30 to 60m above the surrounding plain.

   e. Sketch should include bowl shape, rim-to-rim width of about 1200m [6cm] depth of about 200m [1cm], and raised rim.



   f. Similarities: Roughly round shape overall, steep and gullied interior walls, highest

Answer Key

along rim, relatively flat along crater bottom. Differences: volcanic crater is irregular in outline and shows multiple scallops, sits atop an edifice; impact crater lies principally below surrounding plains, has a raised rim, is round to squared off in shape.

6. **a.** Steeply tilted.

   b. Roughly north-south strike; eastward dip.

   c. Erosion has destroyed most of a volcanic plain that once was continuous across the region.

   d. As is true of most places on Earth, impact craters have been long since destroyed by deposition of sediments, by tectonism, by volcanic flooding, and by gradation.

   e. Top to bottom: 2, 1, x, 4, 3

Name ____________________

Geologic Landforms Seen on Stereoscopic Photos

Purpose

By using stereoscopic pairs of aerial photographs, you will learn to recognize some of the **landforms** that result from the four major geologic processes: **volcanism**, **gradation**, **tectonism**, and **impact cratering**.

Materials

Stereoscope, protractor, ruler, calculator.

Introduction

Because our eyes are separated by a short distance, we view the world from two slightly different perspectives simultaneously. This enables us to perceive a scene in three dimensions. In other words, we are able to perceive the distances to objects and depth within them. When you look at a photograph, your eyes see the distance to the flat photo, rather than the relative distances of objects within the image. The photo appears flat, even though it is an image of the three-dimensional world. To perceive apparent depth in photographs, geologists obtain two pictures of the same object or region from slightly different perspectives, as illustrated in Figure 3.1. When the images are viewed simultaneously, one with each eye, a "three-dimensional," or stereoscopic, effect results.

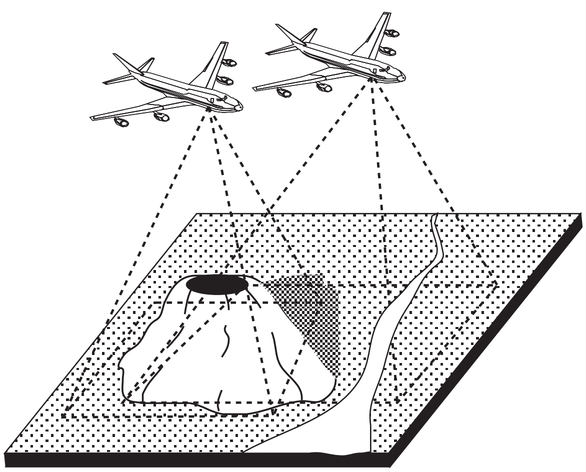


Figure 3.1. Stereoscopic photographs are typically obtained from airplanes. The farther apart two photographs are obtained, the greater the vertical exaggeration of the resulting stereoscopic images.

This perception of vertical relief in aerial photos can greatly aid the geologic interpretation of landforms in the image. Most stereoscopic photographs are obtained from aircraft. Because the distance the plane moves between subsequent photos is much greater than the distance between a person's eyes, the apparent vertical relief of the stereo photos is exaggerated, appearing much greater than the actual relief. This **vertical exaggeration** increases the farther apart the photographs are taken.

***Figure 3.2.** Using the pocket stereoscope. The stereoscope is aligned horizontally and centered along the seam separating the image pairs.*

Figure 3.2 shows how to set up a pocket stereoscope. Place the stereoscope over a stereo pair with the seam of the photos in the middle of the stereoscope. Look through the lenses at the two photos, so that each eye sees just one photo. Pick out a feature that is visible in both photos, relax your eyes, and allow your focus to change until the two images appear to merge. You may need to adjust the position of your stereoscope slightly as you look through it to help the photos merge. When they do merge, you should see a stereoscopic effect. This may take time and patience. Some of the photographs are stereo "triplets" with one photograph in the middle and additional photographs on both the right and left sides. The stereoscope should be positioned to view the middle and right photos as one image pair, and the middle and left photos as another image pair.

Questions

Volcanism

1. Figure 3.3 shows a volcano on the island of New Britain, north of Australia. First study the photos "monoscopically," without the stereoscope. In the photos, water appears black. The top of the high-standing volcano shows a circular depression termed a summit crater.

   a. Sketch how the volcano might look from the ground.

Sketch area

Now position the stereoscope over the left dividing line and view the volcano in stereo. Reposition the stereoscope over the right seam and view this portion of the volcano in stereo.

b. Observe and describe the shape of the summit crater.

c. Do you think the summit crater formed by a single eruption or from multiple eruptions? Explain.

d. List at least two pieces of evidence that the volcano has been eroded.

e. Do you think the volcano is made of hard rock that is difficult to erode or soft ash that is easy to erode? Explain.

***f.** Why is the volcano more heavily forested on one side than the other?

Gradation

2. Figure 3.4 shows a portion of White Sands, New Mexico, an area affected by **aeolian** (wind) processes. The crescent-shaped features are dunes composed of sand. Most sand **dunes** have a gentle slope on their **windward** side and a steeper slope to the **leeward** side. High velocity winds blow sand up the windward side to the brink of the dune; sand then slides down the leeward **slip face** of the dune.

   a. Examine the photographs stereoscopically and identify the slip faces on the dunes. From which direction is the wind blowing?

   b. Consider one of the dunes near the center of the photo. Where will its sand go in time?

   c. How does the **morphology** of the sand dunes change across the photo? Use sketches of at least two dunes to illustrate your answer.

Sketch area

Sketch area

***d.** What factors might affect the dune morphology across the region?

3. Examine Figure 3.5, which shows a system of canyons cut by rivers and streams in northwestern New Mexico. The gradation is affecting relatively flat-lying sedimentary rocks.

   a. Look at the places where smaller tributary streams join larger rivers. In the space below, make a sketch of the pattern you see.

Sketch area

   b. Which direction does the water flow in the prominent river that crosses the central portion of the photo?

   c. Identify a place in the photograph where you might expect a tall, steep waterfall. How would such a waterfall aid the process of erosion in this area?

   d. Over time, what will happen to the high standing, narrow ridge that separates two east-west trending valleys in the central portion of the photo?

Tectonism

Most rocks on Earth are laid down in relatively flat layers. Sedimentary rocks (such as those in Figure 3.5) are laid down over broad areas by wind or water, in layers called **strata**. Tectonism deforms such rocks in various ways. Tectonic stresses in the Earth can pull or push on rocks until they break, moving along faults. Broad-scale tectonic deformation can also cause originally horizontal rock layers to be tilted.

4. Figure 3.6 shows Lookout Ridge, Alaska, an area affected by tectonic deformation. Notice that the white and gray sedimentary rocks have been steeply tilted, now standing nearly on their ends.

   a. Which rock layers are more easily eroded, the white or the gray? Support your answer.

b. Examine the broad, steep face that is shown by one of the white layers near the center of the stereo photo. When rainfall lands on this surface, in which direction would it run down? This is the **dip** direction of these tilted rocks.

c. Examine the overall trend of the visible edges of the tilted strata. Use a protractor to measure the direction of this trend, and report your answer in terms of the number of degrees west of north. (For example, N20W would mean the trend is 20° west of north.) This is the **strike** direction of the tilted rocks.

d. Notice the small-scale faults that cut and displace the white and gray strata near the center of the stereo image. Use the scale bar on the photograph to estimate the amount of displacement along these faults.

e. A greater displacement of strata can also be observed in the southeast corner of the left hand monoscopic image. Use the scale bar to estimate the amount of displacement there.

***f.** In the right hand image, the strata appear to curve as they cross the prominent river that cuts north-south across the photo. Using information available to you from the stereo scene, explain this apparent curvature.

Impact Cratering

5. Figure 3.7 shows Meteor Crater, Arizona. The impact crater is about 20,000 years old and is one of the best-preserved impact structures on Earth. In this stereo pair you can see the crater floor, walls, rim, and remnants of **ejecta**, material thrown from the crater by the impact. Some ejecta appears as irregular bright patches around the crater.

a. Using the scale bar on the photograph, determine the diameter of the crater in meters.

b. Before erosional infilling, an impact crater in Meteor Crater's size class has a diameter about five times greater than its depth. Based on this, how deep was Meteor Crater when it formed?

c. Based on the appearance of Meteor Crater in these stereo images, and considering your previous answers, is the vertical exaggeration of this stereo pair large or small?

d. What do you notice about the elevation of the rim of the crater compared to the elevation of the surrounding plain?

e. Sketch a non-exaggerated profile across Meteor Crater in the space below. Use a scale of 1cm = 200m. The present depth of the crater is about 85% of its original depth, due to erosional infilling. Use your answer from 5.b. to determine the present depth to use for your profile.

Sketch area

f. List some similarities and differences in the morphology of Meteor Crater compared to the volcanic summit crater seen in Figure 3.3.

Synthesis

Planetary surfaces represent combinations of some or all of the four geologic processes. In the following questions, you will synthesize information from the previous questions and photographs.

6. Examine Figure 3.8, which shows the Caballos mountains of southwestern New Mexico. The two nearly featureless "islands" of high standing rock are volcanic in origin. Beneath them are rocks that were laid down as sedimentary strata.

   a. Examine the strata of Figure 3.8, comparing this scene to Figures 3.5 and 3.6. Are the strata of the Caballos mountains tilted or flat-lying?

   b. Estimate the strike and dip directions of the strata in the region beneath the western "island" of volcanic rock.

   c. What is the most likely explanation to account for the isolated islands of volcanic plains?

   d. Why are no impact craters visible in this area?

e. Determine the sequence of events that affected this region by numbering the events below from 1 (first event) to 4 (most recent event). Mark with an "x" the one event that did not occur in this region.

___ Tectonic forces caused folding and tilting of the rocks.

___ Sedimentary strata were laid down horizontally.

___ Volcanic plains were faulted and tilted.

___ Erosion by rivers and streams dissected the region.

___ Volcanic plains were laid down horizontally.

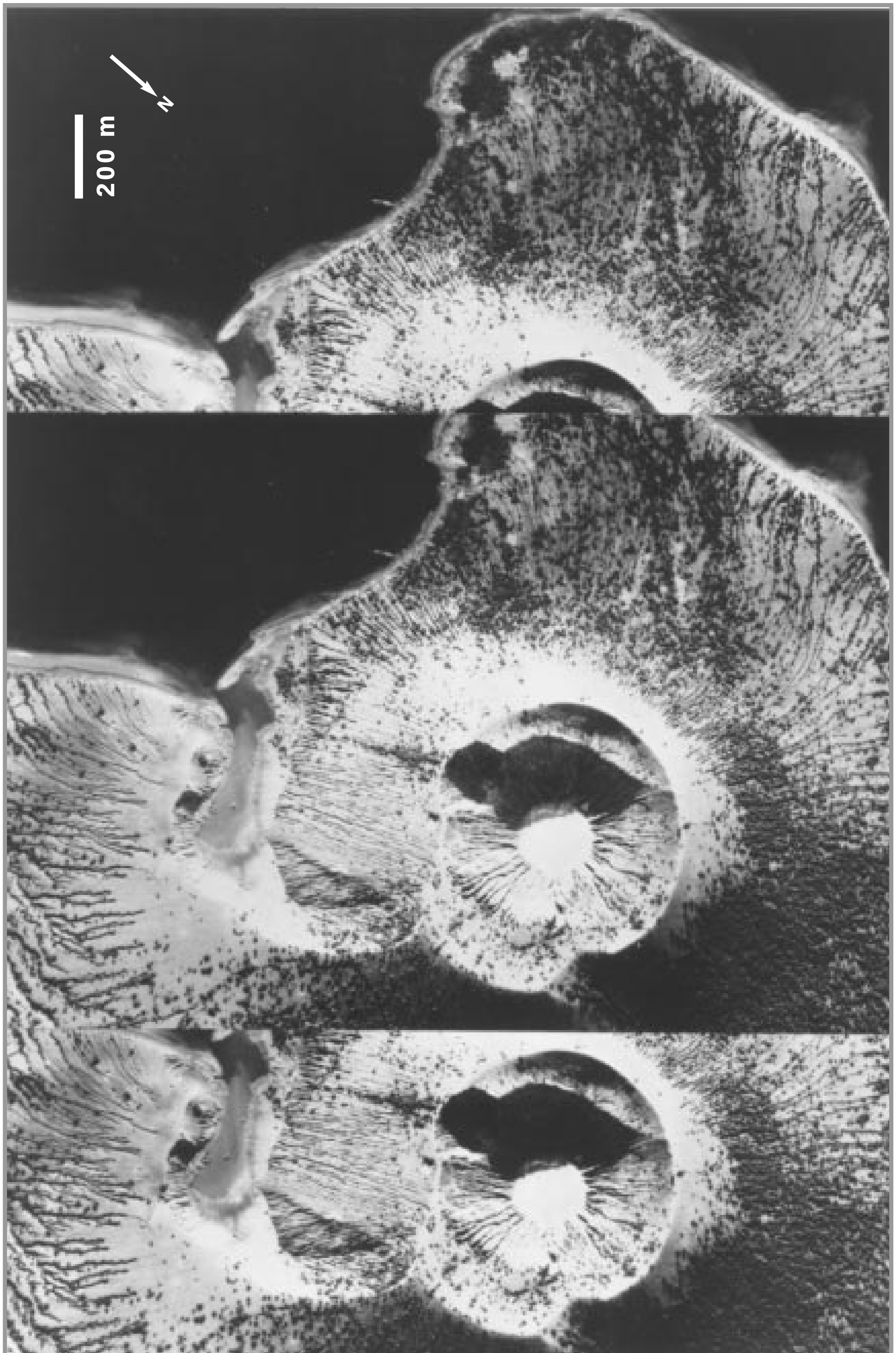


Figure 3.3. *Gazelle Peninsula, island of New Britain, New Guinea. (University of Illinois Catalog of Stereogram Aerial Photographs #107).*

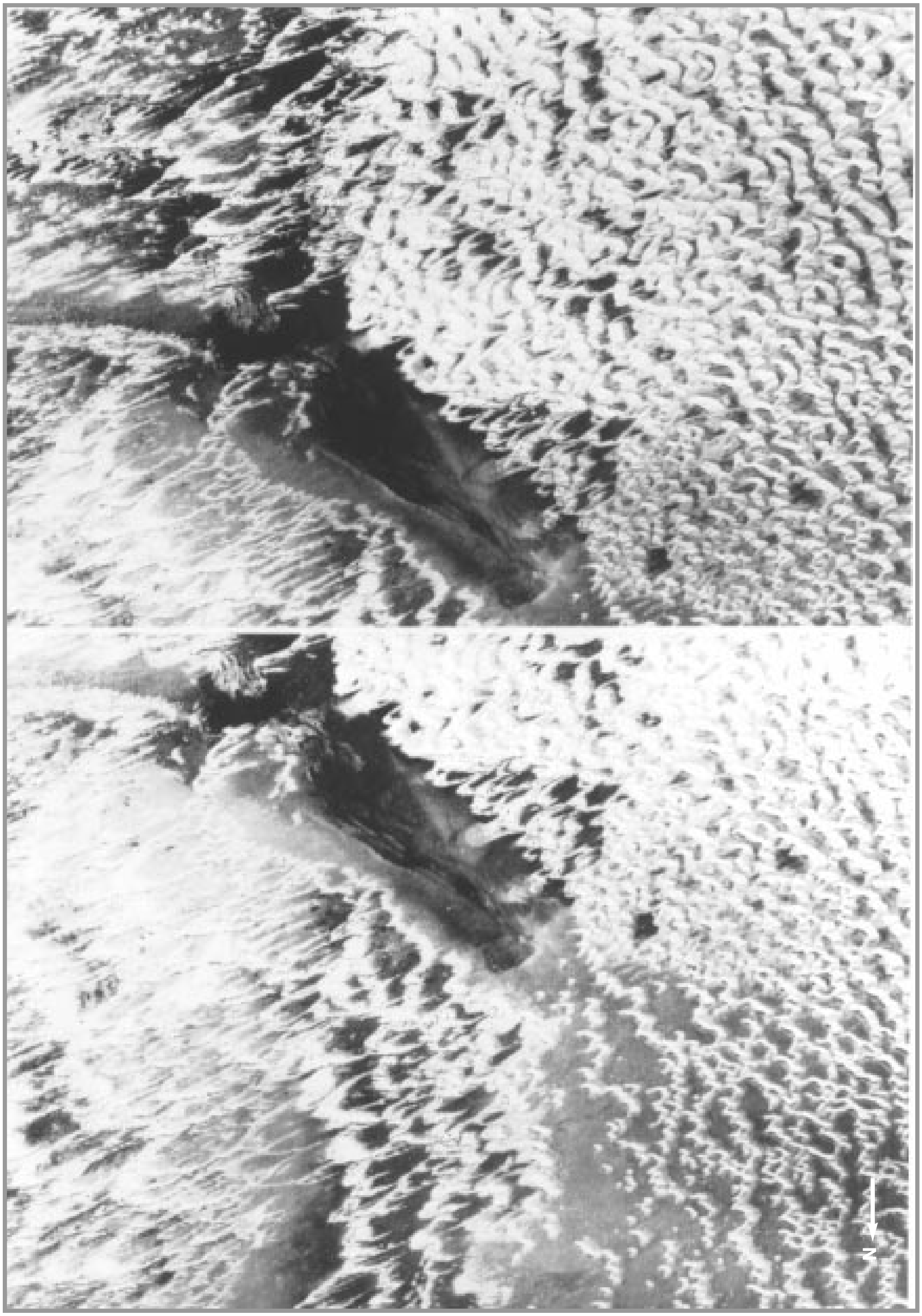


***Figure 3.4.** White Sands, Tularosa Basin, New Mexico. North is to the left (University of Illinois Catalog of Stereogram Aerial Photographs #509).*

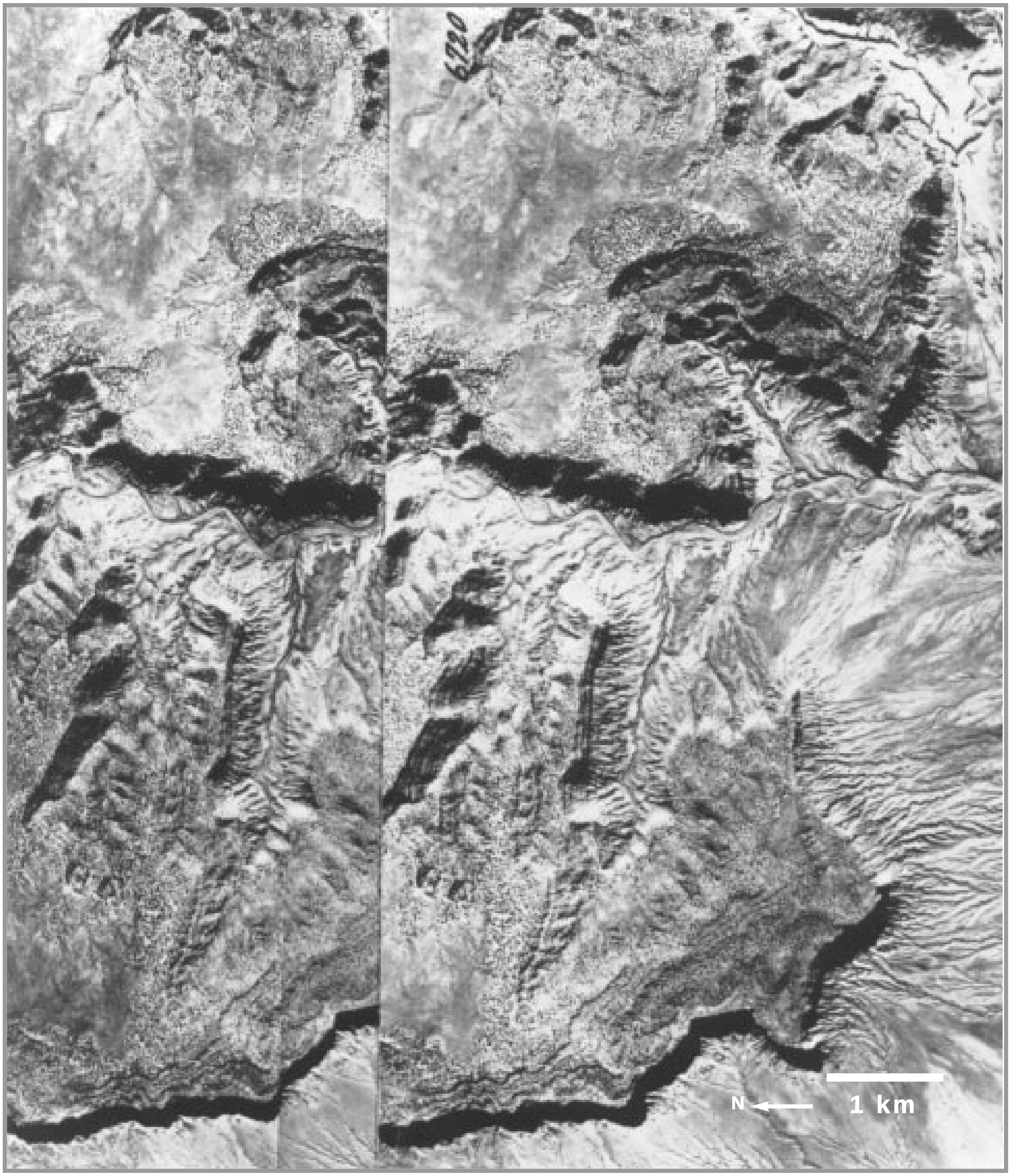


Figure 3.5. *Monument Rocks, San Juan County, New Mexico. North is to the left. (University of Illinois Catalog of Stereogram Aerial Photographs #521).*

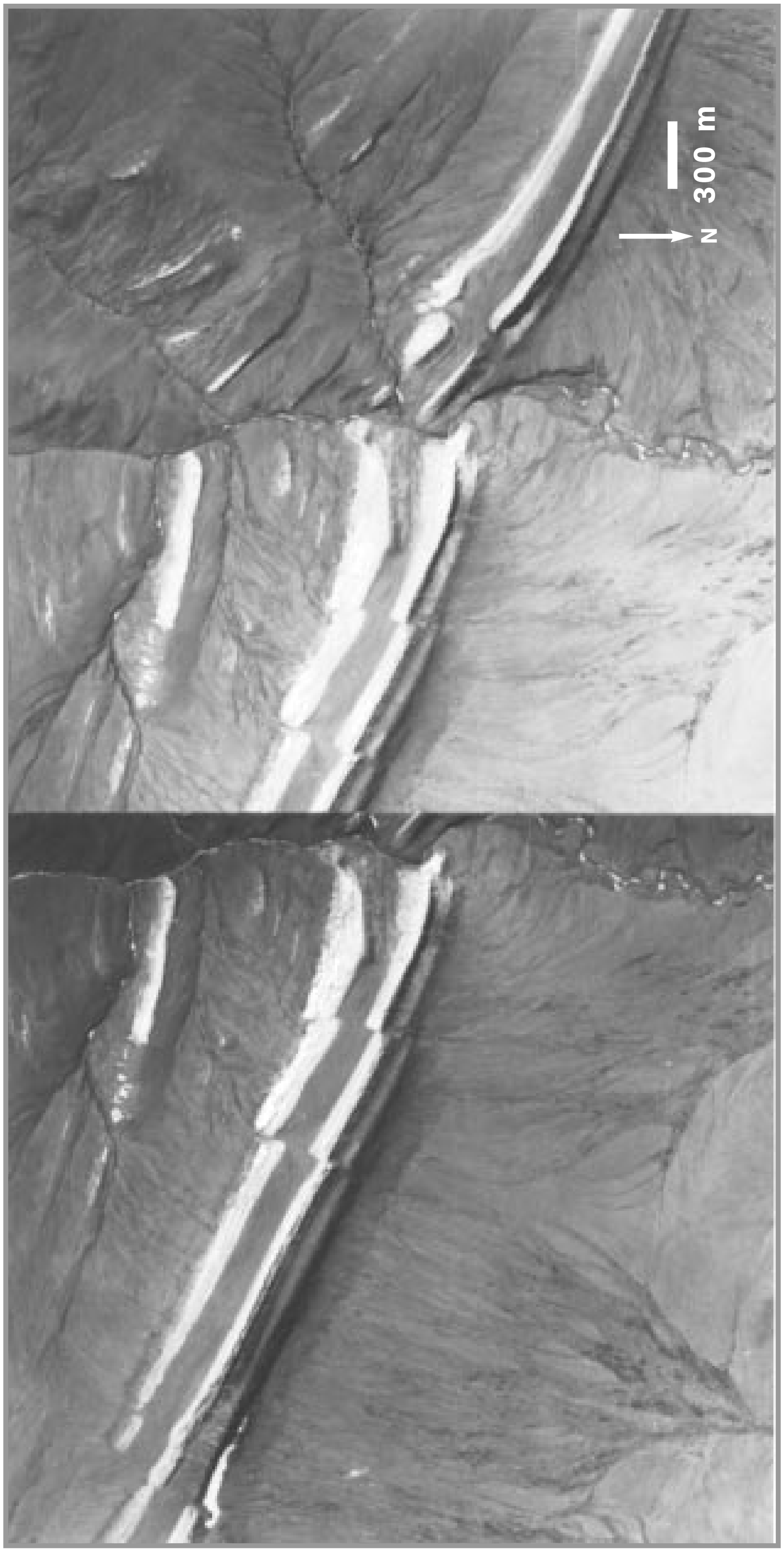


Figure 3.6. *Lookout Ridge, Alaska. North is to the bottom. (University of Illinois Catalog of Stereogram Aerial Photographs #156).*

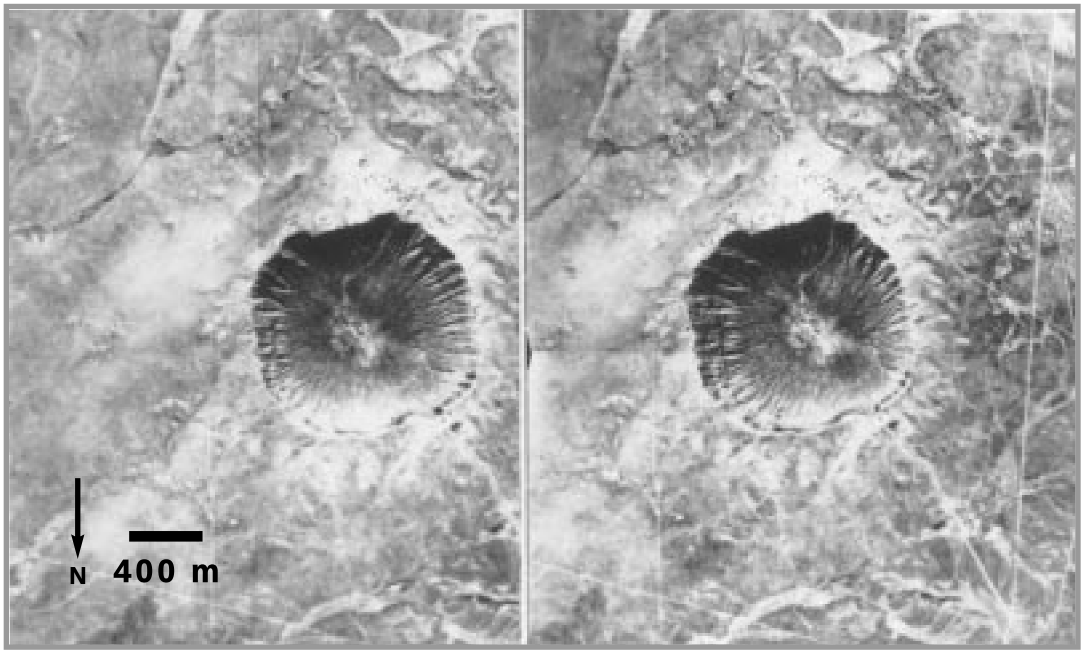


Figure 3.7. *Meteor Crater, Arizona. North is to the bottom. (University of Illinois Catalog of Stereogram Aerial Photographs #5).*

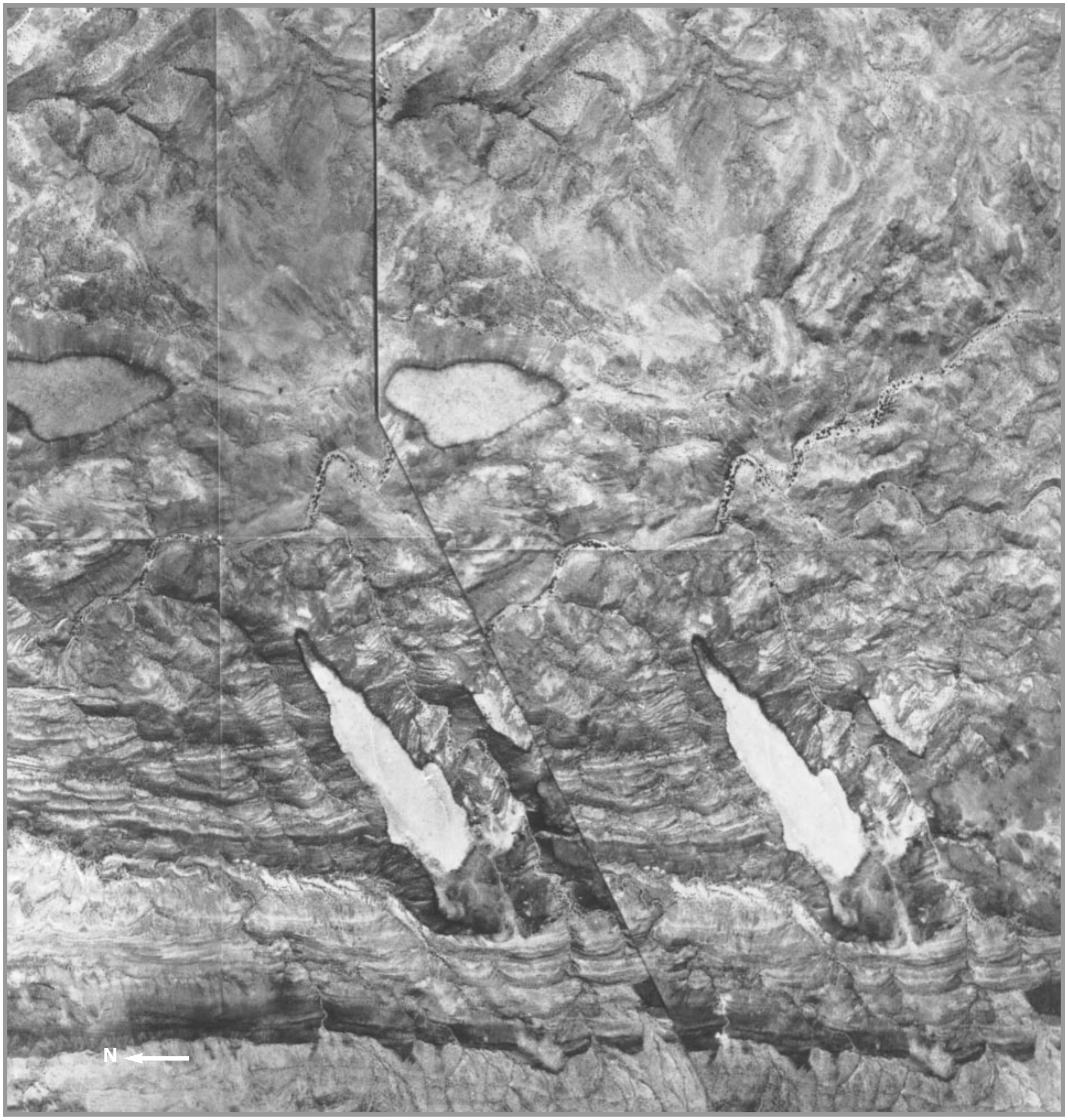


Figure 3.8. *Sierra Caballos Mountains, New Mexico. North is to the left. (University of Illinois Catalog of Stereogram Aerial Photographs #138).*

Introduction to Impact Cratering

The following activities demonstrate the fundamental principles of impact crater formation. The activities are simulations; true impact or volcanic events take place under conditions different from the classroom. Although some aspects of the simulations do not scale directly, the appearance of the craters formed in these activities closely approximates natural, full size craters. These laboratory exercises can be used to stimulate discussions of planetary landscapes, terrestrial craters, and the evolution of planetary surfaces.

In these experiments, students will study the craters formed when objects of different masses and traveling with different velocities strike a target of fine sand. This activity demonstrates important concepts: first, there is a relationship between the velocity and mass of the impactor and the size of the crater formed; and second, craters can be divided into distinct zones: floor, wall, rim, ejecta. The "Rainy Day" experiment illustrates the relation between crater frequency and relative surface age, as well as demonstrating the effect of illumination angle on identifying craters.

On Earth, volcanic explosion craters are often formed when magma rises through water-saturated rocks and causes a phreatic, or steam explosion. Volcanic explosion craters from phreatic eruption often occur on plains away from other obvious volcanoes. Other volcanic eruptions can cause mild explosions, often in a series of events. Some volcanic craters form by collapse with little or no explosive activity. Volcanic craters are typically seen either on the summits or on the flanks of volcanoes. Volcanic craters have also been identified on the Moon, Mars, Venus, and Io. The exercise comparing these cratering processes will help the student learn to identify the differences in the resultant craters.

■ ★ 2.0 hours

Impact Cratering

Instructor Notes

Suggested Correlation of Topics

Craters on planets and satellites, gradation, impact mechanics, physics

Purpose

This exercise demonstrates the mechanics of impact cratering and will show the student impact crater morphologies. Upon completion of this exercise the student should understand the relationship between the velocity and mass of the projectile and the size of the resultant crater. The student should also be able to identify the morphologic zones of an impact crater and, in certain cases, be able to deduce the direction of the incoming projectile.

Materials

Suggested: If performed as an instructor demonstration: one set of the following:

- sand (very fine and dry), tray (e.g., kitty litter box), dyed sand, slingshot, scale, ruler, lamp, calculator, safety goggles, drop cloth, fine screen or flour sifter
- projectiles: 4 different sizes of steel ball bearings; 4 identical ball bearings of one of the intermediate sizes, one each of the three other sizes (sizes should range from 4mm to 25 mm)
- 3 identical sized objects with different densities (e.g., large ball bearing, marble, balsawood or foam ball, rubber superball)

If performed by students: enough sets of the above list for all students/groups.

Substitutions: dry tempera paint can be dry-mixed with sand to make dyed sand (but do not get this mixture wet!), a thick rubber band can be substituted for a slingshot.

Background

This exercise demonstrates the mechanics of impact cratering and introduces the concept of kinetic energy (energy of motion): KE = 1/2 (mv^2), where m = mass and v = velocity. The effects of the velocity, mass, and size of the impacting projectile on the size of the resultant crater are explored. By the conclusion of the exercise, the student should understand the concept of kinetic energy, and know that the velocity of the impactor has the greatest effect on crater size [KE = 1/2 (mv^2)].

Use of a slingshot to fire projectiles is required in this exercise. It is the instructor's decision whether this exercise should be done as a demonstration or by the student. Students should be supervised carefully at all times during the firing of the projectiles and everyone should wear protective goggles. Place the tray on a sheet of plastic or drop cloth; this will make cleanup easier. Fill the tray completely with sand, then scrape the top with the ruler to produce a smooth surface. The dyed sand is best sprinkled on the surface through a fine screen, or a flour sifter.

This exercise requires the calculation of kinetic energies. All of the velocities necessary for these calculations have been provided in the student's charts. Calculation of velocity for dropped objects is simple using the formula:

$v = (2ay)^{.5}$ where v is the velocity, a is the acceleration due to gravity (9.8 m/s^2), and y is the distance dropped

Calculation of the velocity for objects launched by a slingshot is a time consuming procedure for values used in only two entries in the exercise; however, it is an excellent introduction to the physics of motion and can be done in a class period before performing this exercise. The procedure for calibrating the slingshot and for calculating velocities of objects launched by the slingshot follows the answer key (where it may be copied for student use).

Advanced students and upper classes can answer the optional starred (*) questions, which apply their observations to more complex situations.

Science Standards

- Earth and Space Science
  - Origin and evolution of the Earth system

Mathematics Standards

- Geometry
- Computation and Estimation
- Measurement

Answer Key

1. **a.** The crater.

   b. Undisturbed surface layer of sand.

   c. No.

   d. Thick and continuous near the crater, thin and discontinuous far from the crater.

2. Not much, although the ejecta of the 65° impact may be slightly oblong.

Part B

	Velocity (m/sec)	Mass (kg)	KE (Nm = kg m2/sec2)	Crater Diameter (cm)
Shot 1	1.4	~0.002	0.00196	~2
Shot 2	6.3	~0.002	0.03969	~4
Shot 3	14*	~0.002	0.196	~5
Shot 4	69*	~0.002	4.761	~11

* velocities are approximate; NM = Newton x meter

Part C

	Velocity (m/sec)	Mass (kg)	KE (Nm = kg m2/sec2)	Crater Diameter (cm)
Shot 1 (4 mm)	6.3	~0.00034	0.0067473	~2.5
Shot 2 (8 mm)	6.3	~0.002	0.03969	~3.5
Shot 3 (18 mm)	6.3	~0.028	0.55566	~7
Shot 4 (25 mm)	6.3	~0.067	1.329615	~7

Part D

	Velocity (m/sec)	Mass (kg)	KE (Nm = kg m2/sec2)	Crater Diameter (cm)
Shot 1 (steel)	6.3	~0.028	0.55566	~7
Shot 2 (glass)	6.3	~0.008	0.15876	~6
Shot 3 (wood)	6.3	~0.002	0.03969	~3.5

3. As impact angle decreases toward 10°, ejecta becomes more oblong pointing downrange. Ejecta is absent on the uprange side of the crater.

4. **a**. Low angle.

   b. Entered from the east and bounced off the surface leaving two craters with an oblong ejecta pattern.

5. **a.** The higher the kinetic energy, the larger the crater.

   b. Higher velocities produce larger craters.

   c. Larger masses produce larger craters.

   d. Larger sizes (of the same density material) produce larger craters. Mass (density) is the controlling factor. Size (radius) is not a factor in the equation for kinetic energy.

   Instructor's note: Impacting objects in space have different densities. For example, meteorites occur as high density objects (iron meteorites) or as lower density objects (stony meteorites). Comets are composed mostly of water ice and have relatively low density. Like the foam ball, impacting comets might not form a crater at all.

   e. Velocity of the projectile is most important, as shown by the kinetic energy equation.

*6. Craters are better preserved on flat terrain. In rugged areas, craters can be modified by landslides (mass wasting).

Calibrating the Slingshot

Objective

To determine the initial velocity of a mass that is propelled by a slingshot.

Background

This procedure applies two physical laws, Hooke's Law and the Law of Conservation of Energy. Hooke's Law (F=kx) states that the force (F) applied to an elastic material depends upon how stiff the material is (k) and how far you pull the elastic material (x). The stiffness of the elastic material (k) is small if the elastic material is soft, and large if the elastic material is stiff. The Law of Conservation of Energy (W = PE = KE) states that there is a relationship between work (W) performed on a system (the force applied to an object to move it a certain displacement in the same direction as the force is acting) and the potential energy (PE, stored energy) of a system and the kinetic energy (KE, energy of motion) of the system. The equations for Hooke's Law, work, and potential energy are derived from a graph of force versus elongation.

The velocity term that we want to solve for is found in the kinetic energy portion of the Law of Conservation of Energy.

KE = $1/2\ mv^2$, where m is the mass of the object being launched and v is the velocity.

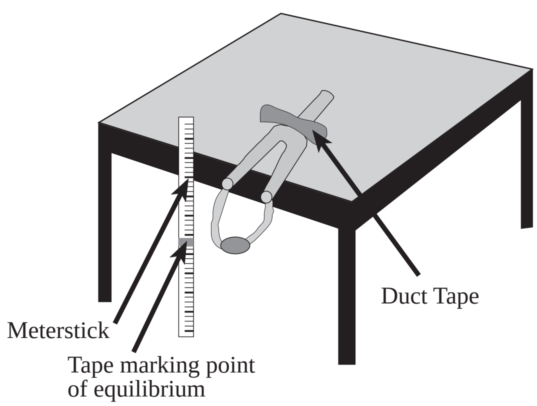
The potential energy of elasticity is a combination of Hooke's Law and work.

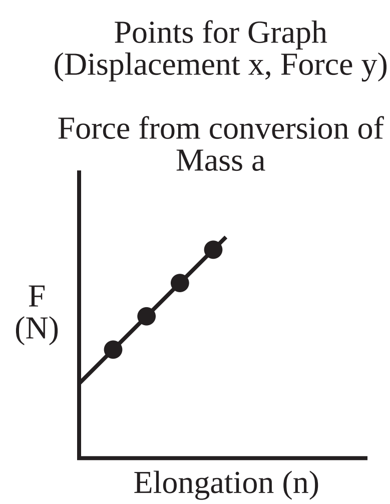
PE = $1/2kx^2$ where k is the spring constant and x is the elongation distance of the slingshot—how far back it is pulled.

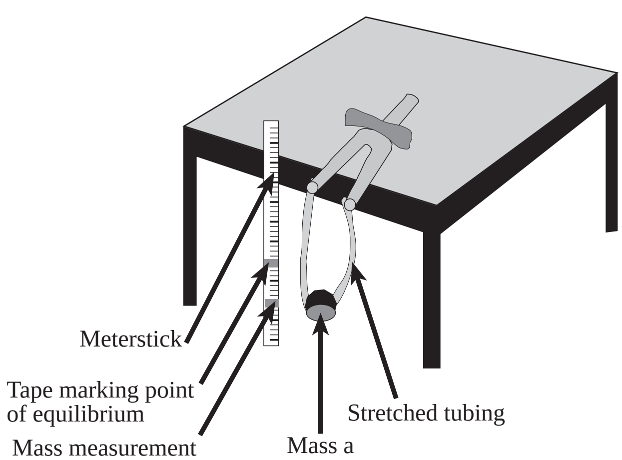
Because the Law of Conservation of Energy states that the potential and kinetic energies of a system are equal, we can set these equations equal to each other.

$1/2mv^2 = 1/2kx^2$; solving for v gives: $v = (kx^2/m)^{.5}$

We will control x (the distance pulled back) and will measure m (the mass of the object being launched). But to solve for v (the velocity) we must first calibrate the slingshot by experimentally solving for the spring constant, k.







How to Solve For k

1. Place the slingshot on the edge of a table or counter so that the elastic band hangs free. Immobilize the slingshot by placing a large weight on it or by duct-taping it to the counter. Rest a meter stick on the floor and tape it along side the slingshot. Pull down on the elastic tubing of the slingshot until all the slack is taken out, but do not stretch the tubing. Mark this point on the meter stick. This is the point of equilibrium.

2. Place slotted masses in increments of 100, 150 or 500 grams (depending on the stiffness of the slingshot) in the pocket of the slingshot until it begins to elongate or stretch past the point of equilibrium. This initial mass is called the "preload force" and is not counted as a recordable force in the data table. (On the graph of force versus elongation, the preload force will appear as a y-intercept.) Once the slingshot starts to elongate or stretch, begin recording the amount of mass you are adding to the pocket and how far from the point of equilibrium the pocket is displaced. Maximize your range of data! Keep taking measurements until you have 7 or 8 data points.

3. Convert the mass from grams into kilograms and multiply by 9.8 m/s^2 to get force in the unit of Newtons.

   example: 150 g (1 kg/1000g) = .150 kg; .150kg(9.8 m/s^2) = 1.47 N

   Convert the elongation measurements from centimeters to meters. Now you are ready to graph force (in Newtons) versus elongation (in meters).

4. Graph force (on the y-axis) versus elongation (on the x-axis). The graph will be a linear function with the slope representing the spring constant, k (in N/m). If you are using a computer graphing program it will automatically calculate the slope and y-intercept of the graph. If you are graphing on graph paper, calculate the slope of the graph using two data points and the equation: slope = $(y_2\text{-}y_1)/(x_2\text{-}x_1)$

   example: (3,5) (4, 6) slope = (6-5)/(4-3) = 1/1 = 1 N/m, in this case k = 1 N/m

   If the graph has a y-intercept, disregard it (it is simply part of the preload force).

   The slope of the line is the value of the spring constant, k, and can now be used in the velocity equation above.

Name ______________________________

Impact Cratering

Purpose

To learn about the mechanics of **impact cratering** and the concept of **kinetic energy;** and to recognize the **landforms** associated with impact cratering.

Materials

For each student group: Sand, tray, colored sand, drop cloth, screen or flour sifter, slingshot, safety goggles(one for each student), triple beam balance, ruler, lamp, calculator

Projectiles: 4 different sizes of steel ball bearings: 4 identical ball bearings of one of the intermediate sizes, one each of the three other sizes; 3 identical sized objects with different densities (large ball bearing, marble, wood or foam ball, rubber superball)

Introduction

Impact craters are found on nearly all solid surface planets and satellites. Although this exercise simulates the impact process, it must be noted that the physical variables do not scale in a simple way to compare with full-size crater formation. In other words, this exercise is a good approximation but not the real thing.

Impact craters form when objects from space, such as asteroids, impact the surface of a planet or moon. The size of the crater formed depends on the amount of kinetic energy possessed by the impacting object. Kinetic energy (energy in motion) is defined as: $KE = 1/2\ (mv^2)$, in which m = mass and v = velocity.

Weight is related to the mass of an object. During impact the kinetic energy of the object is transferred to the target surface.

Safety goggles must be worn whenever the slingshot is in use!

Procedure and Questions

Part A

Place the tray on the drop cloth. Fill the tray with sand, then smooth the surface by scraping the ruler across the sand. Sprinkle a very thin layer of the colored sand over the surface (just enough to hide the sand below) using the flour sifter. Divide the tray (target area) into four square shaped sections, using the ruler to mark shallow lines in the sand.

In one section produce a crater using the slingshot to launch an intermediate size steel ball bearing straight down (at 90°, vertical) into the target surface. The slingshot should be held at arms length from sand surface (70 to 90 cm) facing straight down into the tray. Do not remove the projectiles after launch. ***Use the space on the following page to make a sketch of the plan (map) view and of the cross section view of the crater.*** Be sure to sketch the pattern of the light-colored sand around the crater. This material is called **ejecta**. Label the crater floor, crater wall, crater rim, and ejecta on the sketch.

1. **a.** Where did the ejecta come from?

   b. What would you expect to find beneath the ejecta?

Sketch area

c. Would you expect the ejecta to be of equal thickness everywhere?

d. What is the ejecta distribution and thickness in relation to the crater?

In the next section of the target tray, produce a crater using the slingshot to launch a steel ball bearing (the same size as above) at 65° to the surface. The angle can simply be estimated. The end of the slingshot should still be 70 to 90 cm from tray. Be certain no one is "down range" in case the projectile ricochets. ***Sketch the crater and ejecta in plan view on the space provided below.***

Sketch area

2. Is there an *obvious* difference between the two craters or ejecta patterns?

In the third section of the target tray, produce a crater using the slingshot to launch a steel ball bearing (the same size as above) at 45° to the surface. Again, estimate the angle. The end of the slingshot should still be 70 to 90 cm from the tray. Be certain no one is "down range" in case the projectile ricochets. ***Sketch the crater in plan view on the space provided on the following page.*** As above, label the parts of the crater.

Sketch area

In the fourth section of the target tray, produce a crater using the slingshot to launch a steel ball bearing (the same size as the previous exercise) at about 5 to 10° to the surface. Again, estimate the angle, and make sure not to hit the rim of the tray. The end of the slingshot should still be 70 to 90 cm from tray. Be sure no one is "down range" in case the projectile ricochets. ***Sketch the crater in plan view and cross section on the space provided below.***

Sketch area

Examine the sand craters and your sketches.

3. How does ejecta distribution change with impact angle?

Examine Figure 4.1, a photograph of the lunar crater Messier.

4. **a.** Was this a high angle or low angle impact?

b. Did the meteoroid which formed Messier impact from the east or west?

Part B

Remove the four steel ball bearings from the sand tray and thoroughly mix the sand and colored sand to produce a uniform mixture. Smooth the target surface with the ruler. The remaining experiments will be performed without a colored upper layer of sand. Divide the target area into four sections as before.

Produce four craters on the smooth target surface, using the same four identical steel ball bearing as in *Part A.* Find the mass of one of the projectiles before launching it and enter the value in the table below.

- Make the first crater by dropping the projectile from a height of 10 cm above the surface. Measure the diameter of the crater formed and enter the value in the table.
- For the second crater, drop the projectile from a height of 2 meters. Measure the crater diameter and enter it in the table.
- The third projectile should be launched with the slingshot 70 to 90 cm above the tray and with the rubber tubing pulled back slightly (extended ~3 cm). Measure the crater diameter and enter it in the table.
- For the last crater, extend the slingshot ~15 cm. The slingshot should still be 70 to 90 cm above tray. Measure the crater diameter and enter it in the table.
- Calculate the kinetic energy of each projectile and enter the values in the table.

Part B

	Velocity (m/sec)	Mass (kg)	KE (Nm = kg m2/sec2)	Crater Diameter (cm)
Shot 1	1.4			
Shot 2	6.3			
Shot 3	14*			
Shot 4	69*			

** velocities are approximate*

Part C

Remove the projectiles and smooth the target surface with the ruler. Divide the target into four sections. Find the mass of each projectile and enter the values in the table below. Produce four craters by dropping 4 different sized steel ball bearings from a height of 2 meters above the target surface. Measure the crater diameter produced by each impact. Enter the projectile mass and resultant crater diameters in the table below. Calculate the kinetic energy of each projectile and enter the values in the table on the next page.

Part C

	Velocity (m/sec)	Mass (kg)	KE (Nm = kg m2/sec2)	Crater Diameter (cm)
Shot 1 (smallest)	**6.3**			
Shot 2 (next larger)	**6.3**			
Shot 3 (next larger)	**6.3**			
Shot 4 (largest)	**6.3**			

Part D

Remove the projectiles and smooth the target surface with the ruler. Divide the target into three sections. Find the mass of each projectile and enter the values in the table below. Produce three craters by dropping 3 identical size, but different mass, projectiles from a height of 2 meters above the target surface. Measure the crater diameter produced by each impact. Enter the projectile mass and resultant crater diameters in the table below. Calculate the kinetic energy of each projectile and enter the values in the table below.

Part D

	Velocity (m/sec)	Mass (kg)	KE (Nm = kg m2/sec2)	Crater Diameter (cm)
Shot 1 (steel)	**6.3**			
Shot 2 (glass)	**6.3**			
Shot 3 (wood)	**6.3**			

Examine the results of parts B, C, and D. Use the completed tables to answer the following questions.

5. **a.** How does kinetic energy of the projectile relate to crater diameter?

   b. How does velocity relate to crater size?

   c. How does mass relate to crater size?

d. How does the size of the projectile relate to crater size?

e. Which is the most important factor controlling the crater size; the size, mass, or velocity of the projectile?

******Part E*

Remove all projectiles from the sand tray and smooth the target surface. Divide the sand into two equal halves. In one half form a ridge of sand about 10 cm high and 15 cm wide, and leave the other half smooth. Use intermediate size steel ball bearings and form one crater on the side of the ridge. Form another crater on the flat section, launching it with the slingshot from 70 to 90 cm above the tray. Compare the two craters.

*6. What can you say about crater preservation on rugged terrain versus smooth terrain?

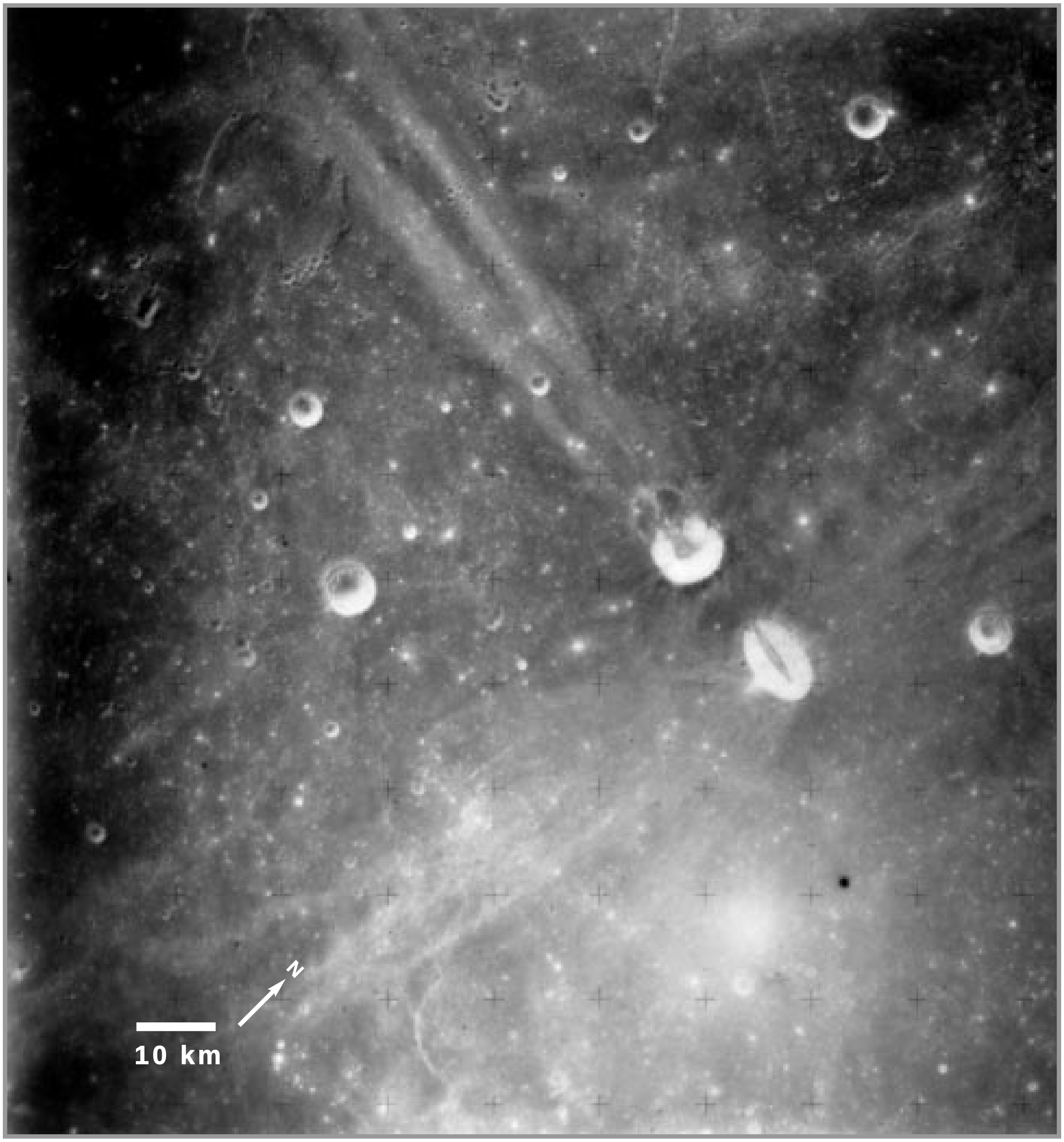


Figure 4.1. *Apollo 15 photograph of lunar craters Messier A and B. The small crosses are camera registration marks. North is to the upper right corner of the photo. The oblong crater (Messier A) is 11 kilometers in diameter. (Apollo Metric frame AS152674).*

Exercise Four is suggested as an introductory exercise.

■ ★ 2.0 hours

Comparative Cratering Processes

Instructor Notes

Suggested Correlation of Topics

Craters on planets and satellites, gradation, impact mechanics, physics

Purpose

The objective of this exercise is to learn how different cratering processes produce different surface features. This exercise will explore three cratering processes: impact, volcanic explosion, and volcanic eruption.

Materials

Suggested: For each student group (or single set if done as instructor demonstration):

- tray (kitty litter box)
- very fine dry sand
- safety goggles (for everyone)
- marbles
- slingshot
- video camera
- VCR (4-head is best for stop action) and TV
- black posterboard (2′ x 3′)
- 3-foot-long narrow diameter flexible plastic tubing(surgical tubing)
- bicycle pump
- thin skinned balloons
- hose clamp
- sheet of clear heavy plastic (to protect camera)

Substitutions:

- instant camera with cable release
- 3 packs of instant black and white film
- high intensity strobe light (variable to at least 15 flashes per second)

  [Note: strobes can be dangerous to persons with epilepsy]
- 2 boxes or stacks of books: one for the camera, one for the strobe

Background

Impact craters are found on nearly all solid surface planets and satellites. However, other geologic processes, such as volcanic explosions and eruptions, can form craters as well. The differences between craters formed by impact and explosion can be very slight. Non-explosive volcanic craters can usually be distinguished from impact craters by their irregular shape and the association of volcanic flows and other volcanic materials. An exception is that impact craters on Venus often have associated flows of melted material.

This exercise demonstrates three processes that can form craters. Because the simulations in this activity do not scale in size to natural geologic events, the variations noted by the students may be very slight.

The use of the slingshot in this exercise can be dangerous. This exercise can be done as a demonstration to avoid accidents and to expedite its completion.

Science Standards

- Earth and Space Science
  - Energy in the Earth system

Mathematics Standards

- Geometry

Instant Camera Instructions

Instant cameras give the students an opportunity to have an instant and permanent record of the exercise. Action is "stopped" by use of the strobe light and students can reshoot if necessary. If using a instant with an electric eye, set the film speed setting to 75 (even though the film speed is 3000) and the exposure control on front of the camera to "Darker." This permits a longer exposure and a smaller f/stop (larger lens opening). If the Instant does not have an electric eye, but has numbered settings, set the number to "6" and flip the exposure from "I" to "B" before each picture. If the resulting photographs are too light, increase the number accordingly. Focus the camera on the target surface and place the black posterboard and the strobe light as shown in Figure 5.3. The flash rate on the strobe should seem like rapid blinks. Too many flashes during the exposure produces a dispersed cloud; too few, and the event may be missed entirely. In using the camera, it is best if you have a cable release attached to the Instant—this will help eliminate jarring the camera unnecessarily. If the camera does not accept a cable release, be sure that the camera is on a firm surface; push the button and release carefully. To get good photos, the film must be exposed long enough to catch 2 flashes from the strobe light (about 1/8 second). Start the exposure just before the marble is fired and stop it right after it appears to hit the sand. Be sure the student photographers know how to operate the camera before starting the activity. Although the instructions and precautions may seem involved, this exercise can be done easily and successfully with a little practice.

Answer Key

1. **a**. Answers will vary, student may say in straight lines or arcs.

   b. (See Figure 5.1) The formation of an impact crater is a relatively well ordered event in which the ejecta leaves the surface at approximately a 45° angle from the horizontal (upper left picture Figure 5.1). As the crater enlarges (middle left), the inverted cone sheet of ejecta, called the ejecta plume, enlarges. Ejecta falls first close to the crater, and as crater formation continues (bottom left), the ejecta strike the surface at increasing distances. Note how the base of the ejecta plume has enlarged with time.

2. **a.** Ejecta from the vertical impact are thrown out at about a 45° angle. The sheet of ejecta moves outward in a symmetrical pattern, producing the appearance of an enlarging, inverted cone. For the 45° impact, the ejecta cone becomes asymmetrical and distorted in the down-range direction.

   b. (See Figure 5.2) As the angle of impact departs from the vertical, the ejecta cone or plume becomes asymmetric. For the relatively low velocities represented in the figure (20 m/s), asymmetry is not apparent until the impact angle is greater than 20°. At 20° (upper right), the sequence of ejecta remains relatively symmetric. At 60° (lower left) and 75° (lower right) from the vertical, the ejecta cone is distorted in the downrange direction. For impacts of much greater velocities (2 km/s), the asymmetry does not occur until much larger departures (80°) from the vertical.

3. **a.** (See Figure 5.1.) The upper and middle right pictures in the figure show the relatively chaotic and dispersed nature of the ejecta caused by this type of cratering process.

   b. In appearance, the crater shape is similar. However, the ejecta pattern is chaotic and dispersed with ejecta thrown at all angles. Note that the ejecta pattern and crater appearance will vary with different depths of burial of the balloon.

4. (See Figure 5.1) The bottom right picture shows the formation of the eruptive crater. Ejecta is blown straight up and lands right around the crater.

5. **a.** All three craters contain similar parts: crater, rim, ejecta.

   b. Answers will vary, but many students will note that the explosive and volcanic craters are not as symmetrical as the impact craters. The volcanic eruption crater will be the most irregular.

   c. All craters formed have raised rims.

   d. Answers may vary. The crater ejecta patterns will probably be widest.

   e. Impact has the greatest effect.

6. **a.** Olympus Mons (Figure 5.5) is volcanic; Timocharis crater (Figure 5.6) is of impact origin.

   b. Timocharis has well developed ejecta patterns; the crater on Olympus Mons is irregular in outline and shows no ejecta patterns.

   c. Impact craters have large, well-defined ejecta patterns; the ejecta patterns of volcanic explosion craters may not be as well-organized; volcanic eruption craters have little ejecta or poorly organized ejecta patterns.

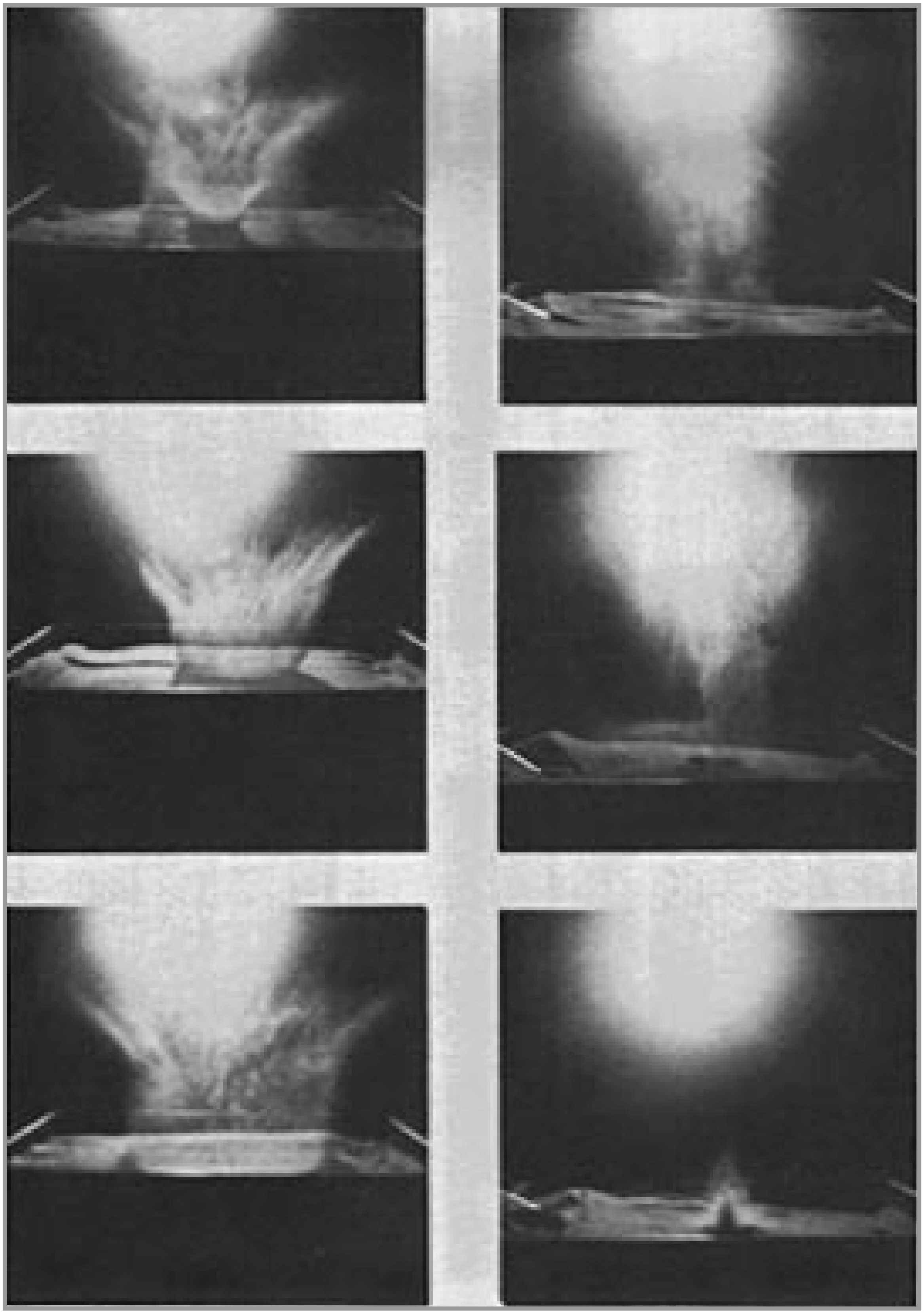


Figure 5.1. *Comparison of the formation of an impact crater (left side), a low-energy explosion crater (top two photos on the right side), and simulated volcanic eruptive crater (bottom right). All craters were formed in a sand box and recorded using a strobe light.*

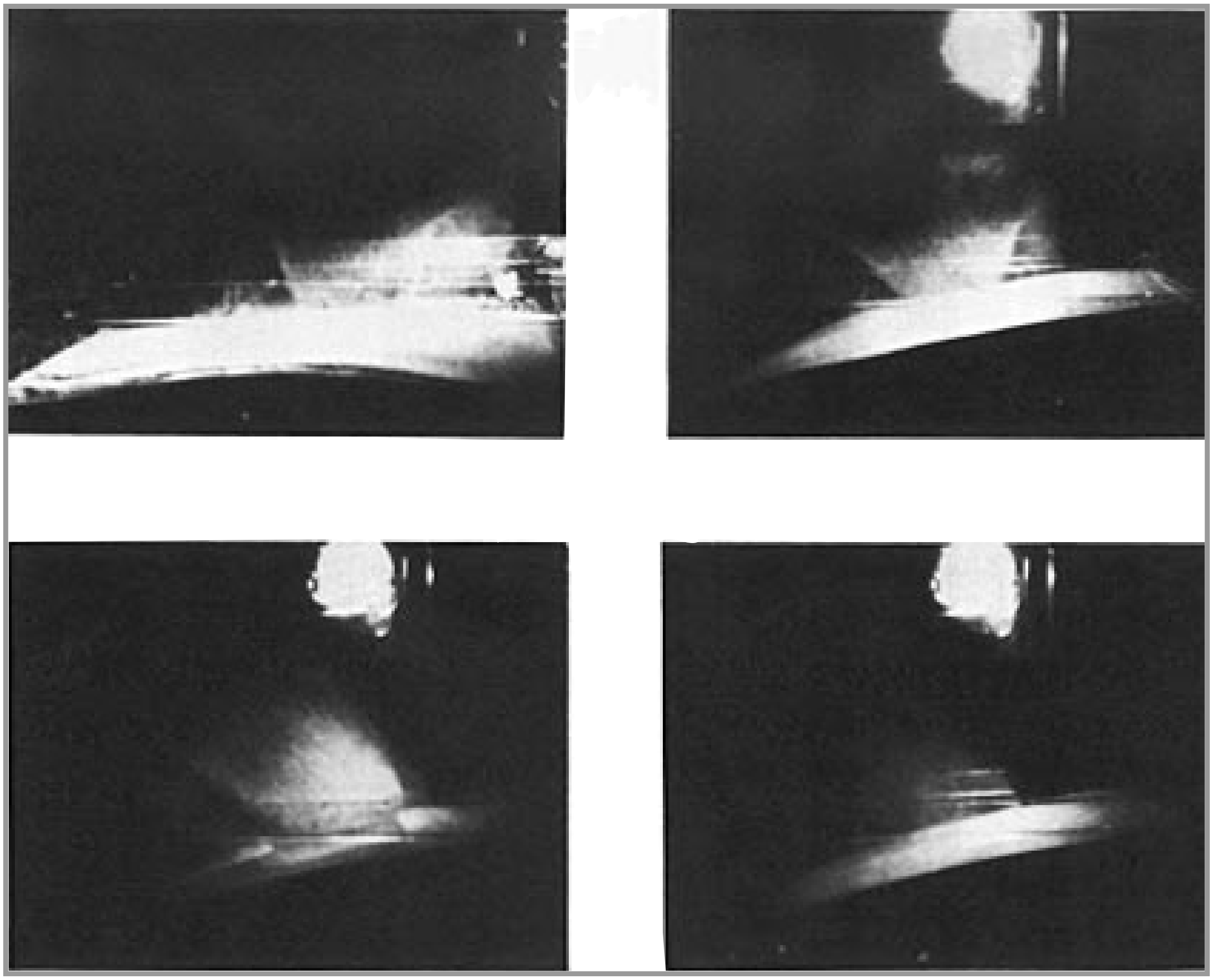


Figure 5.2. *Strobe light instant photographs of impacts into fine sand at different angles of incidence. Photograph records two flashes of the strobe light in each illustration. The upper left image is for a vertical impact, upper right is at 20° from vertical, lower left is at 60° from vertical, and the lower right is 75° from vertical.*

Name ____________________

Comparative Cratering Processes

Purpose

To illustrate the similarities and differences in craters formed by three different cratering processes: impact, volcanic explosion, and volcanic eruption.

Materials

For each student group: tray (kitty litter box), very fine sand, safety goggles (for all students), marbles, slingshot, video camera, VCR and TV, black posterboard (2′ x 3′), 3-foot-long narrow diameter flexible plastic tubing, bicycle pump, thin skinned balloons, hose clamp, sheet of heavy clear plastic (to protect the camera)

Introduction

In examining a planetary surface, it is important to identify the processes that shaped the surface. Not all craters form by impact processes; some result from volcanic explosions and volcanic eruptions. This exercise examines the crater forms which result from these three processes: impact, explosion, and eruption.

Procedure and Questions

Part A: Impact Cratering Process

Use Figure 5.3 to set up the equipment for this part of the exercise. **All students must wear safety goggles during this part of the exercise.** Hold the slingshot 70 to 90 cm above the target. While video taping the tray, fire a marble straight down (vertically) into the sand tray using the slingshot . The goal is to photograph the **ejecta** (material thrown out of the crater) while it is airborne and after it has landed. You may need to repeat this part several times to get a good photographic record.

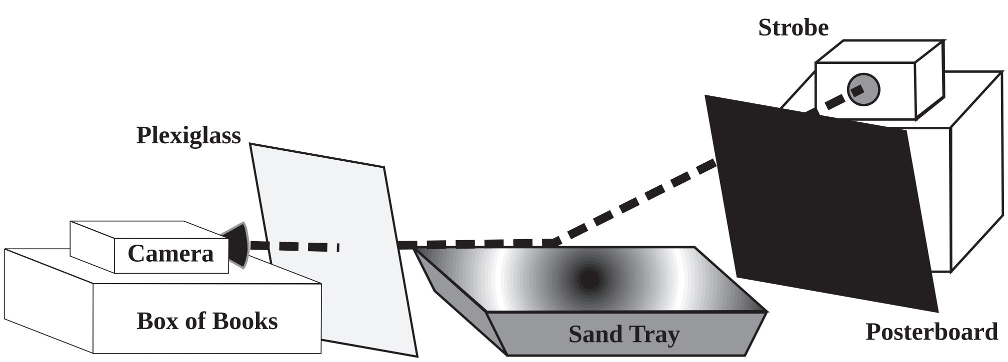


Figure 5.3. *Diagram showing the setup for photographing the impact experiment.*

1. **a.** Before examining the video or photographs, describe how you think the ejecta will appear, and what path you think the ejecta took in the air.

   b. Observe the video or photographs. Sketch the crater, the path the material appears to take in the air, and the pattern of ejecta deposited on the surface based on the photographic record and your observations. Use the pause or stop action ability of the VCR to view the tape.

Sketch area

Remove the marble and smooth the sand surface. Record another impact while firing the marble at an angle of 45° into the target surface. The slingshot should be 70 to 90 cm from the target. Be sure that no one is down range and that you stand to one side and fire into the tray between the camera and posterboard. The projectile flight path should parallel the posterboard.

2. **a.** How are the ejecta paths through the air different from those during the vertical impact?

   b. Sketch the crater, the path the material appears to take in the air, and the pattern of ejecta deposited on the surface, based on the photographic record and your observations.

Sketch area

Part B: Volcanic Explosive Cratering Process

Set up the equipment as shown in Figure 5.4. Place the bike pump where the person stood in Part A. Attach the plastic tube to the bicycle pump. Check for air leaks. Next, pull the balloon tightly over the other end of the tube and slip on the clamp. You are using only a small portion of the balloon and the balloon should burst easily when the pump is used. Bury the tube in the sand but turn up its end in the center of the box so that it is almost vertical and about 2 centimeters below the surface of the sand. Smooth the surface of the sand over the tube. Start your video or photographing and then give a quick, hard, single push of the bicycle pump. If the balloon did not burst, check for air leaks or tighten the clamp on the balloon and try again.

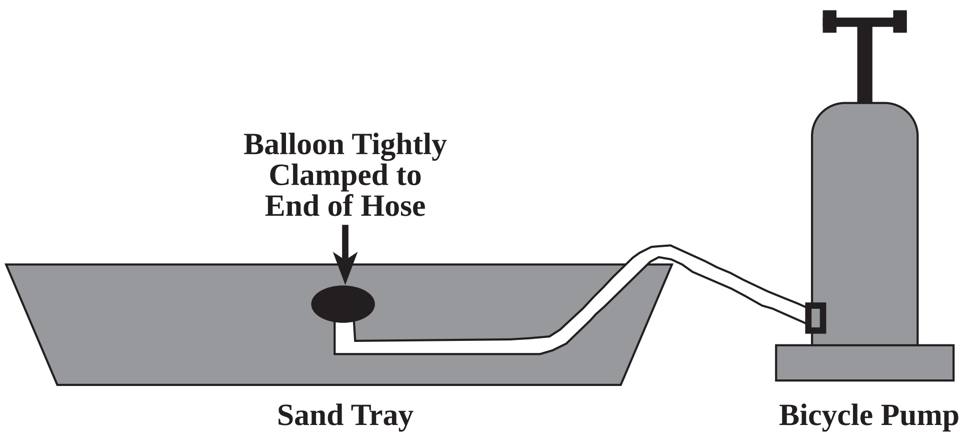


Figure 5.4. *Diagram showing the setup for photographing the explosive experiment.*

3. **a.** Sketch the crater, the path the material appears to take in the air, and the pattern of ejecta deposited on the surface based on the photographic record and your observations.

Sketch area

b. How does the resulting low-energy explosion crater compare with the impact crater?

Part C: Volcanic Eruptive Cratering Process

Remove the burst balloon and the clamp from the end of the tube. Rebury the tube in the sand, this time without a balloon. Again make sure the end is turned up almost vertical in the center of the sand tray and that it is only about 2 centimeters below the surface. Smooth the surface of the sand over the end of the tube. Start video taping or photographing before pushing the pump. Do not push as hard as for the balloon. Push the pump two more times for a total of three pushes.

4. **a.** Sketch the crater, the path the material appears to take in the air, and the pattern of ejecta deposited on the surface based on the photographic record and your observations.

Sketch area

Compare the craters and features formed by each of the three processes.

5. **a.** How are all three similar?

   b. How are they different?

   c. Which craters have raised rims?

   d. Which crater formed the widest ejecta pattern?

   e. Which process affected the surrounding material most?

Examine Figures 5.5 and 5.6.

6. **a.** Which feature is probably volcanic in origin? Which feature is probably impact?

   b. What evidence did you use to reach your conclusion?

   c. If you were searching for a crater produced by an explosion, what features would you look for that would distinguish it from a crater formed by volcanic eruption or impact?

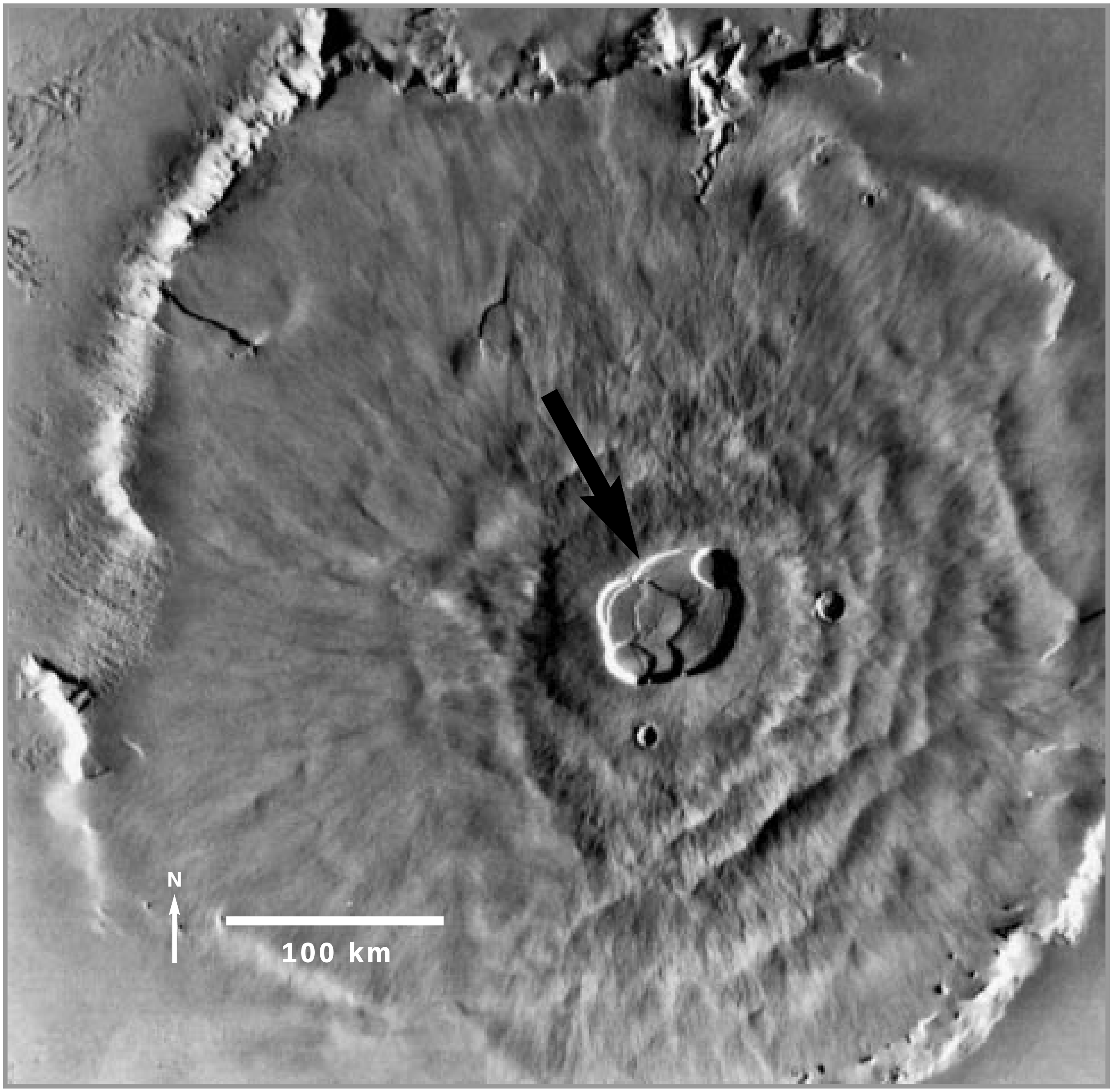


Figure 5.5. *Olympus Mons, Mars, showing the 80-km in diameter summit crater (arrow). North is to the top. (Viking MDIM mosaic 211-5360.)*

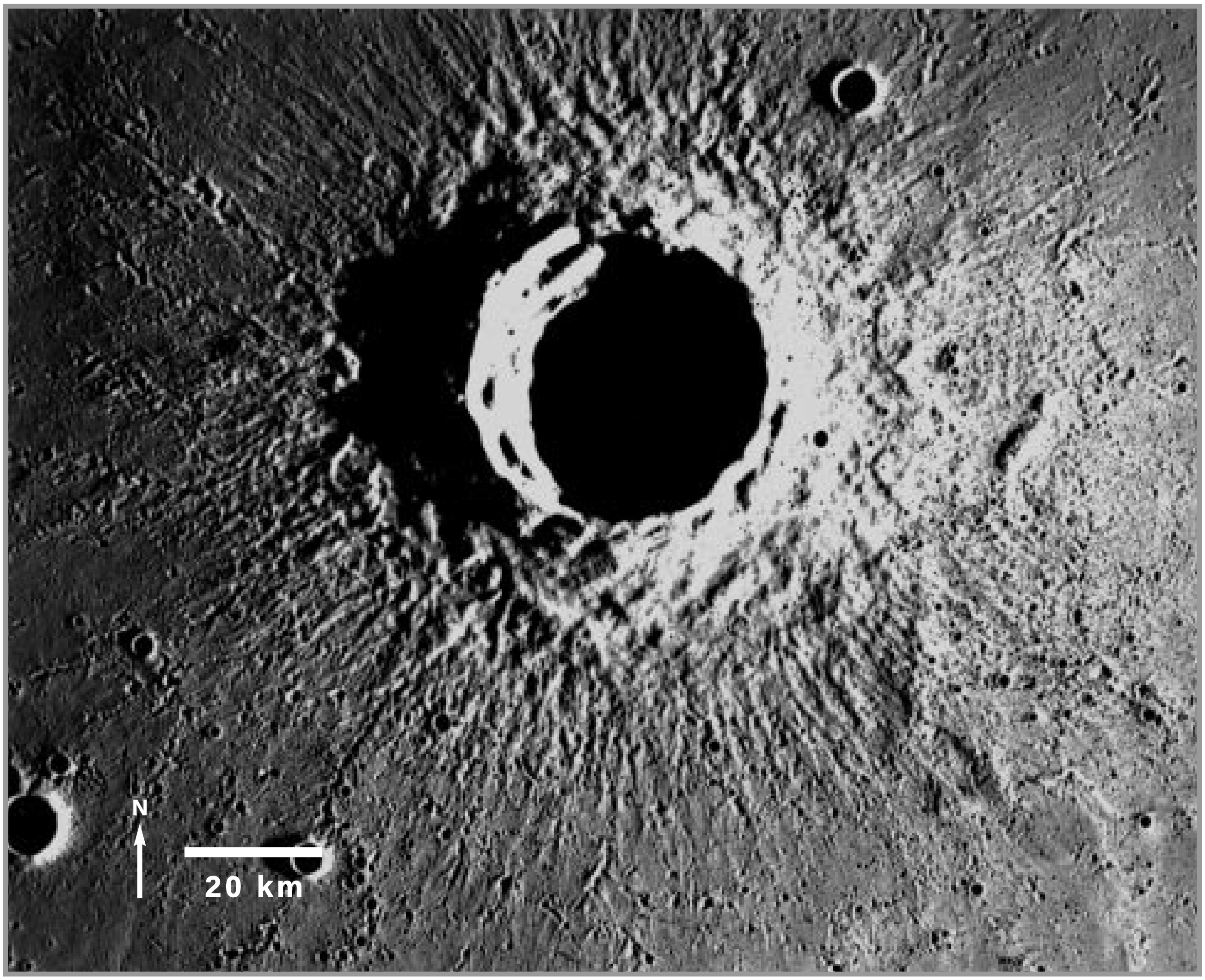


Figure 5.6. *Timocharis, Moon. North is to the top. The crater is 33 kilometers in diameter. (Apollo 15 metric frame AS15 0598.)*

Impact Cratering on a Rainy Day

Instructor Notes

Suggested Correlation of Topics

Craters on the planets and satellites, gradation, impact mechanics

Purpose

The objective of this exercise is to illustrate the way in which planetary surfaces are modified by multiple impacts and how surfaces can be dated through analyses of craters. The effects of multiple impacts and illumination angle are explored.

Materials

Per student group: watering can, duct tape, pin, fine mesh screen, water, 4 large petri dishes, very fine sand, portable light source (flashlight or flood lamp)

Background

Impact craters are found on terrestrial planets and nearly all satellites. Many surfaces have large numbers of craters. This indicates that the surface is very old, as it has accumulated craters over a long time period.

This exercise demonstrates the effect of continuous cratering, using sand and 'raindrop' impactors. Craters formed early will be degraded, or even removed, by subsequent crater formation. After a period of time the surface will reach equilibrium, in which old craters are destroyed as rapidly as new craters are formed. This exercise also explores the effect of illumination angle in viewing and identifying craters. More detail is shown when the illumination angle is low and features cast shadows than when the illumination angle is high. Advanced students and upper grades can attempt to answer the optional starred (*) questions , which apply what they have observed in this exercise and other general planetary background information to more complex planetary surfaces.

Figures 6.1 and 6.2 show sample experiments.

Science Standards

- Earth and Space Science
  - Earth's history

Mathematics Standards

- Geometry

Answer Key

1. **a**. During a slow, steady rain, many craters will be similar in size.

   b. Although craters typically are not clustered, a few clusters may develop. They may overlap.

2. **a.** The large crater formed by the finger becomes degraded (eroded) by the rain impacts.

   b. It becomes less sharp and distinct.

   c. It would probably disappear.

   d. There are more overlapping craters in this dish.

3. **a.** The large craters become degraded (eroded). Yes.

   b. Tiny craters should be found in both dishes, with the dish exposed for four minutes having the greater number.

   c. The change in appearance between the surfaces in these two dishes is not as distinct as the change between the previous two surfaces. Students may say the dishes appear almost identical. The longer the surface is exposed to cratering, the more difficult it becomes to distinguish the "age" difference between them (the surfaces are approaching equilibrium).

4. **a.** Small craters are nearly invisible. Little detail visible.

   b. Shadows help define many surface features. Small craters are more obvious.

   c. Shadows are long, hiding some small craters.

   d. Very long shadows. Edge of dish blocks the view of some craters.

5. **a.** A range of crater sizes in various states of preservation; large number of craters per unit area; similarity of terrain at different locations.

   b. Younger; it is much less heavily cratered.

   ***c**. 6.3 : mainly impact cratering, some volcanism in dark areas near limb. 6.4: volcanic plain with relatively few impact craters.

*6. **a.** Surface features near the terminator are illuminated by low sun angle and show more topographic detail. However, very near the terminator less topography is discernible than at a slight distance from the terminator. When the shadows cover half or more of the crater floor, the illumination is too low.

   b. The surface near the limb is illuminated by a nearly overhead sun and the craters appear "washed out" (lacking detail); however, the different albedo variations of the surface are visible.

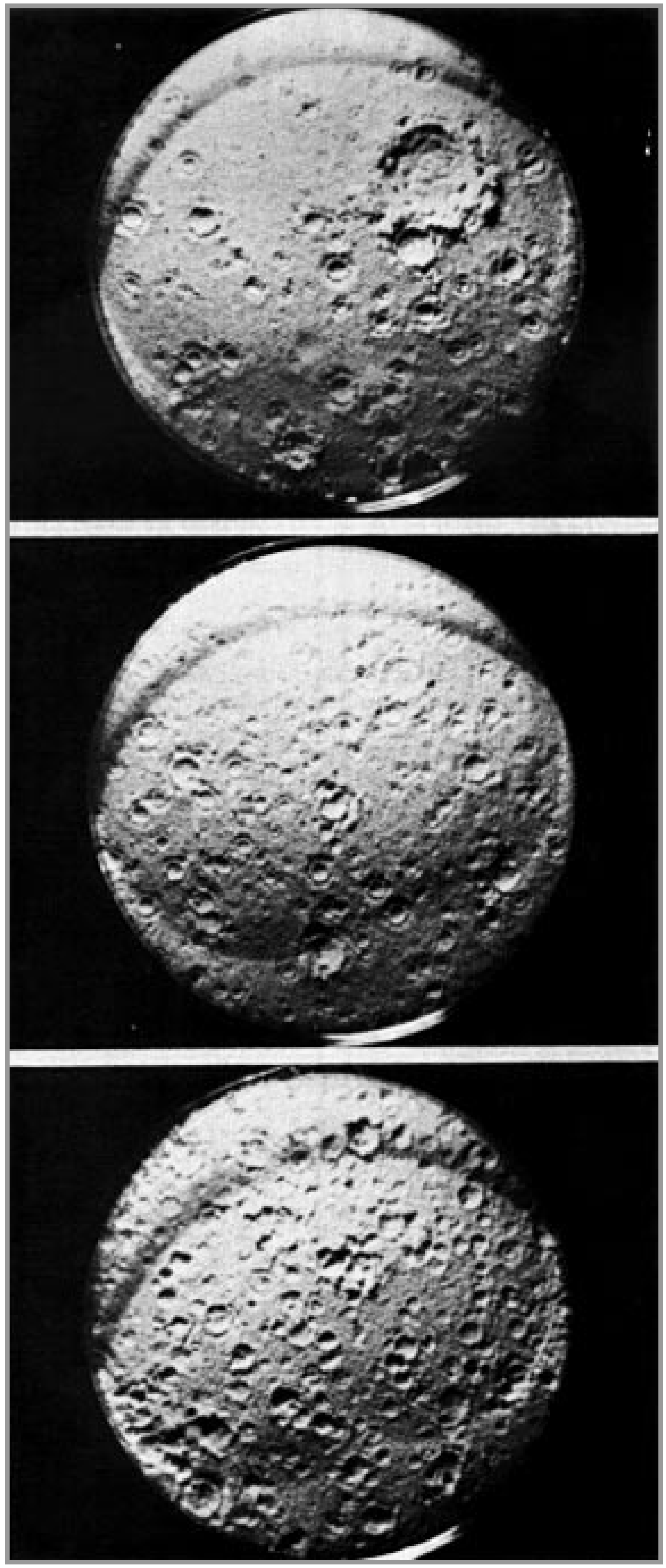


Figure 6.1. *Different sand surfaces exposed for different lengths of time to rain: 5 seconds (top), 30 seconds (middle), and 2 minutes (bottom).*

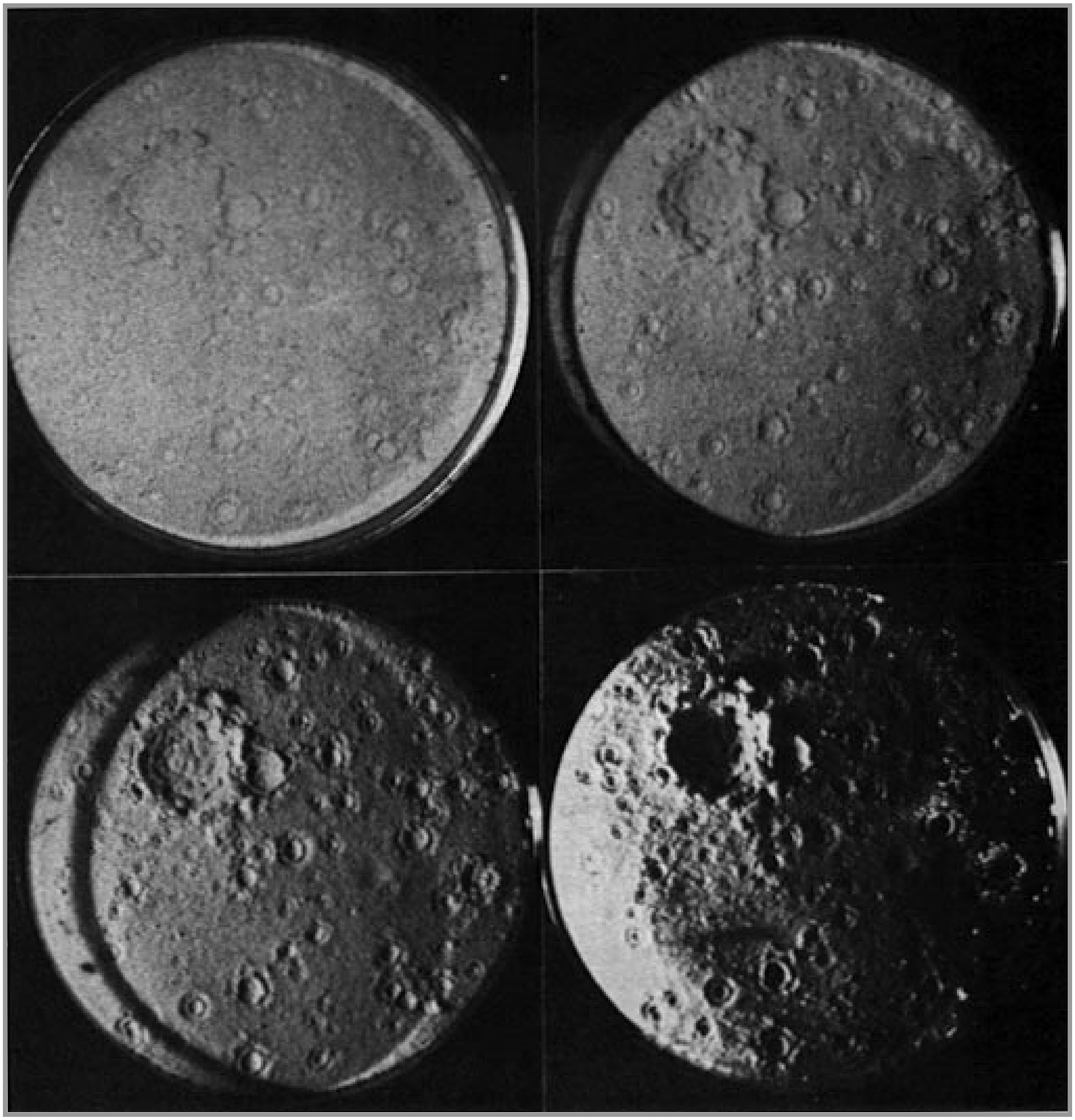


Figure 6.2. *Illustration of the effect of lighting angle on the identification of surface features. The craters are illuminated from directly overhead (upper left), 60° from the horizontal (upper right), 30° from the horizontal (lower left) and 5° from the horizontal (lower right).*

Name ______________________________

Impact Cratering on a Rainy Day

Purpose

To learn how planetary surfaces are modified by multiple impacts and how surfaces can be dated by analysis of craters. In addition, to understand the effects of illumination angle on the detection of craters.

Materials

For each student group: Watering can, duct tape, pin, fine mesh screen, 4 petri dishes, very fine sand, flashlight.

Introduction

Impact craters are formed when meteoroids, asteroids, or comets impact planetary surfaces. As the number of impact craters increases on a surface, the appearance of the surfaces changes. After a period of time, **equilibrium** is reached, in which old craters are destroyed as quickly as new craters form.

Procedure and Questions

A. Place a piece of duct tape over the end of the watering can. Using the pin, poke one or two holes in the tape. Fill the can with water, but don't make it too heavy to hold for long periods of time. Fill each petri dish with fine sand. Place one dish on the floor on top of a drop cloth or newspaper.

B. When making "raindrops" pour the water from the can very slowly, as single drops. Make each drop from the can hit the mesh screen to break it into smaller drops. Move the screen so that the drops are hitting dry screen as much as possible. As the holes of the screen fill with water, move the screen around so drops fall on dry spots of screen. This activity works best if one person holds the watering can and a second person holds screen. Holding the watering can at chest level, with the screen ~30 cm below the spout, "rain" on the petri dish for about 5 seconds, or until several craters have formed.

1. **a.** How do the crater sizes vary?

   b. Are the craters clustered together? Do they overlap?

Save all your "rained" on dishes for use in Question 4.

Make a crater in the second dish with your finger. Place this dish in the rain for approximately 30 seconds.

2. **a**. What does the surface look like?

   b. What happened to the large crater you formed?

c. What do you suppose would happen to the large crater if you left it in the rain for 5 minutes (10 times as long)?

d. Are there more or fewer overlapping craters here than in the first dish?

Make another “finger” crater in each of the other two dishes. Place one dish in the rain for two minutes; the other for four minutes. Make sure you pour the water slowly or you will form a lake in the petri dish!

3. **a**. What has happened to the large craters? Does this agree with your prediction from question 2c?

b. Which dish has the most small craters?

c. Is there a marked difference between the two dishes, allowing you to easily tell which dish spent the most time in the rain?

The **angle of illumination** affects the visibility of surface features. Surfaces lit from directly overhead (noon time) appear different from those lit at an angle, as during sunrise or sunset. Line up the four petri dishes with their raindrop craters. Turn off the overhead lights. Use the flashlight and shine the light across the surface of the dishes, estimating the illumination angle. Try shining the light from the following angles and describe what you see. Examine the dishes from two locations—from the position of the flashlight and from directly above the dishes.

4. **a.** 90° (directly above the craters)

b. 45°

c. 20°

d. 10°

Examine Figures 6.3 and 6.4.

5. **a.** Based on Figure 6.3, list the evidence you see on the Moon for long term impact cratering.

b. Is the surface shown in Figure 6.4 older or younger than the surface seen in Figure 6.3? How can you tell?

***c.** What geologic process(es) formed the surface seen in Figure 6.3? What process(es) formed the surface seen in Figure 6.4?

Figure 6.3 shows both the **limb** and the **terminator** of the Moon. The limb is the horizon, seen in the upper left corner. The terminator is the boundary between the day and night side, seen in the lower right. When examining spacecraft images, scientists are concerned with many aspects of the surface imaged. One aspect of interest is **topography,** the ruggedness of the surface. Another aspect is **albedo,** a measure of how the surface reflects light; albedo is a function of the composition and physical properties (such as grain size) of the surface.

*6. **a.** What part of Figure 6.3 gives the best topographic information? Is the illumination angle at this location high or low?

b. What part of Figure 6.3 gives the best albedo information? Is the illumination angle at this location high or low?

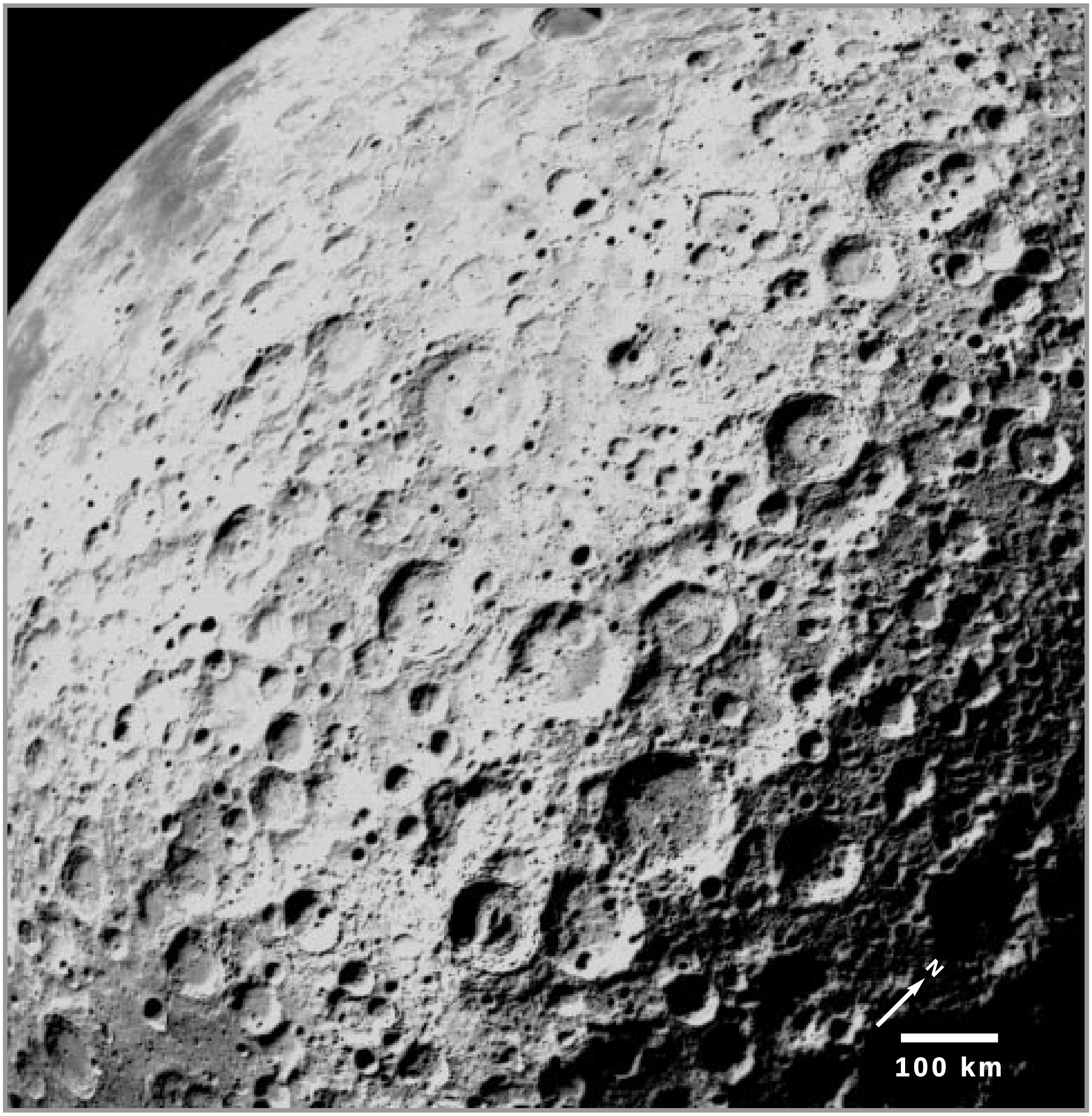


Figure 6.3. *Photograph of the lunar highlands. Mare Marginis is the darker surface visible on the limb (lunar horizon, upper left). (Apollo metric photograph AS16 3003.)*

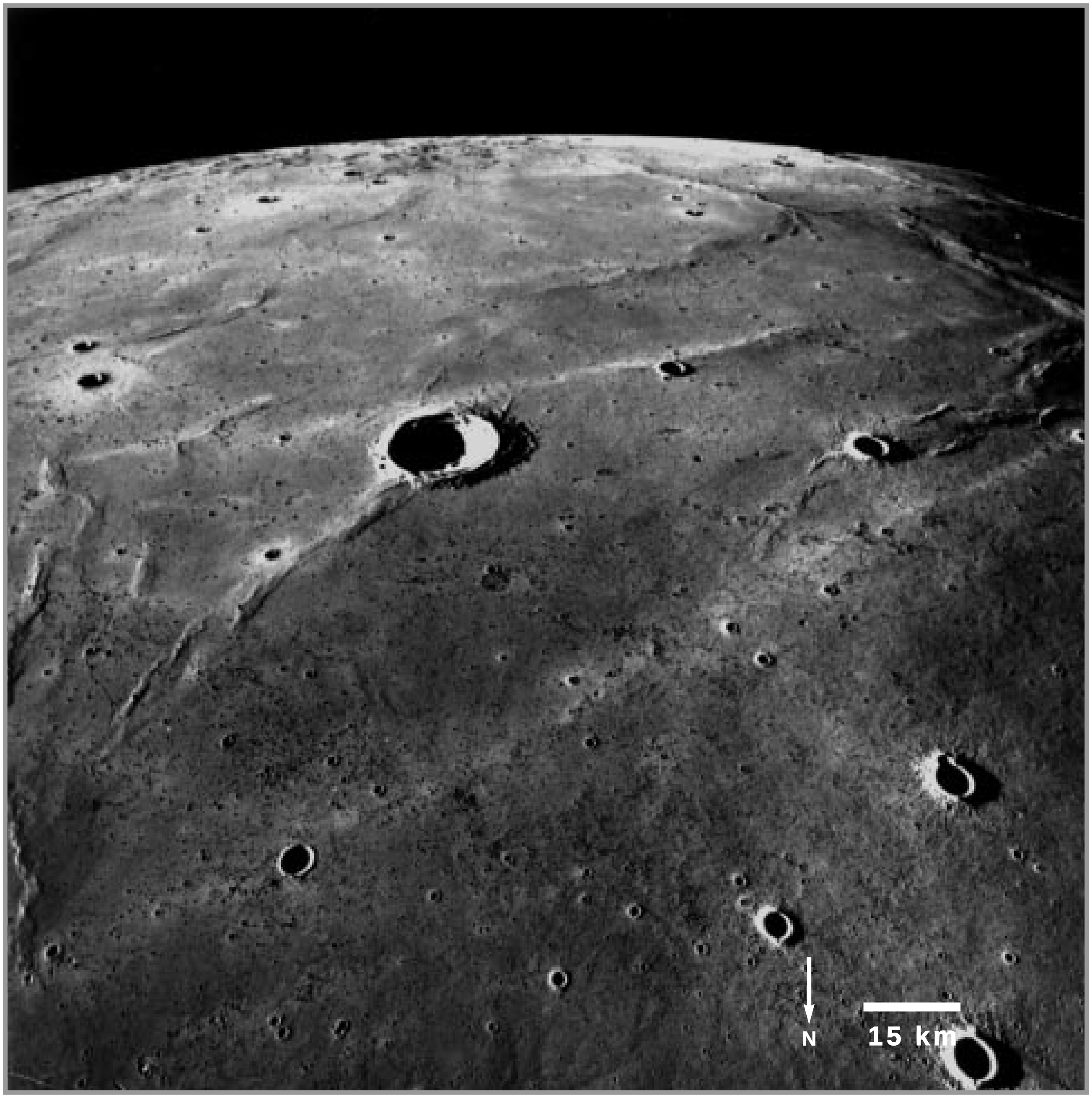


Figure 6.4. *Photograph of lunar maria, looking south across Oceanus Procellarum. The large crater is Schiaparelli. (Apollo metric photograph AS15 2617.)*

Introduction to Planetary Atmospheres

Earth is not unique in possessing an atmosphere. Venus, Mars, Pluto, and two of the satellites of the outer planets—Titan (a moon of Saturn) and Triton (a moon of Neptune) have atmospheres that envelop their surfaces. In addition, the giant planets of the outer solar system—Jupiter, Saturn, Uranus, and Neptune—are composed predominantly of gases. Other bodies in the solar system possess extremely thin atmospheres. Such bodies are the Moon (sodium gas), Mercury (sodium gas), Europa (oxygen) and Io (sulfur).

The compositions of planetary atmospheres are different, for a variety of reasons. First, surface gravity, the force that holds down an atmosphere, differs significantly among the planets. For example, the large gravitational force of the giant planet Jupiter is able to retain light gases such as hydrogen and helium that escape from lower gravity objects. Second, the distance from the sun determines the energy available to heat atmospheric gas to a planet's escape velocity, the speed at which gas molecules overcome a planet's gravitational grasp. Thus, the distant and cold Titan, Triton, and Pluto are able to retain their atmospheres despite relatively low gravities. Finally, we know that the chemistry and geologic history are different for each planet. Because atmospheric makeup is generally related to chemistry and temperature during planetary formation and the subsequent escape of interior gases, the constituents and total pressures of planetary atmospheres are likely to be different. Moreover, on Earth, atmospheric composition is largely governed by the by-products of the very life that it sustains.

From the perspective of the planetary geologist, atmospheres are important in the ways they shape planetary surfaces. Wind can transport particles, both eroding the surface and leaving deposits. Frost and precipitation can leave direct and indirect marks on a planetary surface. Climate changes can influence a planet's geological history. Conversely, studying surface geology leads to an understanding of the atmosphere and climate of a planet—both its present state and its past.

1.0 hours

Coriolis Effect

Instructor Notes

Suggested Correlation of Topics

Air and its movements, atmospheres, circulation of air or sea, meteorology, ocean currents, physics: forces and mechanics, planetary rotation

Purpose

The objective of this exercise is to demonstrate that an object which moves in latitude over the surface of a rotating planet experiences the Coriolis effect, an apparent deflection of its path from a straight line. Upon completion of this exercise the student should understand the concept of the Coriolis effect and be able to understand viewing an event from different frames of reference.

Materials

Suggested: lazy susan type turntable (must be able to be rotated clockwise and counterclockwise), paper, tape, markers (3 colors)

Background

The Coriolis effect is caused by an "imaginary" force but has very real effects on the weather of Earth and other planets. On Earth, which spins counterclockwise as viewed from above its north pole, objects are deflected to the right in the northern hemisphere and to the left in the southern hemisphere. This deflection is only apparent, however, as an observer watching from space would see the object's path as a straight line. It is because we are viewing in the frame of reference of the rotating Earth that we see the apparent deflection.

This exercise demonstrates the Coriolis effect by using a rotating turntable. Students will draw straight lines while spinning the turntable in different directions. To their surprise the resultant lines will be curves on the paper covering the turntable. This apparent deflection, the Coriolis effect, only occurs in the frame of reference of the turntable. The students, in a different frame of reference, know that the path of the marker used to draw the line was straight. On the sphere of the Earth, we occupy the same reference frame as the motion, so we "see" the Coriolis effect in action. To an outside observer, who is occupying another reference frame, there is no deflection and the motion is a straight line.

This concept has important implications for the motion of ocean currents, storms on Earth, and even missiles, but is unimportant at smaller scales. In combination with pressure effects, the Coriolis deflection gives rise to a counterclockwise rotation of large storms, such as hurricanes, in the northern hemisphere, and clockwise rotation in the southern hemisphere. This could be illustrated to students through pictures of hurricanes or other large storms found in newspapers, magazines, or elsewhere in this lab manual.

Students should work in pairs, one spinning the turntable at a constant speed and the other marking the line. Instructors should note that the spinning of the Earth once a day on its axis is called rotation. Students can experiment with rotating their turntable faster or slower to see the effect on the drawn lines. A faster spin will result in greater deflection. If time or materials are a problem, this exercise can be done as a demonstration by the instructor.

Vector motion of the surface of a sphere is complex. The magnitude of the Coriolis effect is controlled by rotation about the vertical axis. On Earth the vertical axis of rotation is a line connecting the geographic north and south poles. On a rotating sphere, the maximum rotation is at the poles; there is no rotation about the vertical axis at the equator. To visualize this, imagine two flat disks glued onto the surface of a sphere, one at the north pole and one at the equator. As the sphere rotates, the disk at the north pole rotates around the vertical rotation axis of the sphere. The vertical axis of the sphere is also the axis of rotation of the disk. If viewed from above, the disk spins in one spot, just as the sphere does. The surface of the disk at the equator is parallel to the vertical rotation axis of the sphere. When the sphere rotates, this disk revolves around the axis. There is no spin or rotation of the disk at the equator. The magnitude of the Coriolis effect increases from the equator where it has no effect to the poles. The turntable is equivalent to the disk at the pole of the sphere, and illustrates the maximum Coriolis effect.

The Coriolis effect operates on Mars in a similar way as on Earth. Because Mars rotates at about the same rate and in the same sense as Earth, Mars has large-scale weather systems just like on the Earth. Students might try to predict the direction that the Coriolis effect would deflect objects on Venus or Uranus, which spin clockwise as viewed from "above" (north of) the solar system. Advanced students and upper grades can answer the optional starred (*) question, which applies their observations to more complex situations.

Science Standards

- Earth and Space Science
  - Origin and evolution of the Earth system

Answer Key

1. The line is straight.
2. Unlike the real Earth, this model is not rotating.
3. The line was deflected to the right.
4. Counterclockwise.
5. It would be deflected to the right.
6. It was deflected to the left.
7. Clockwise.
8. It would be deflected to the left. [The direction of travel does not matter in the deflection, all directions of travel are deflected to the right in the northern hemisphere and to the left in the southern hemisphere.]
9. Objects in the northern hemisphere are deflected to the right, while those in the southern hemisphere deflect to the left.
10. The streaks form a curved path.
11. The streaks are curved because there is a Coriolis effect on Mars.
12. Yes; for there to be a Coriolis effect on Mars, the planet must rotate.
13. The wind blew from the north.
14. The wind is being deflected to the left.
15. Deflection to the left indicates we are looking at the southern hemisphere of Mars.

*16. The Coriolis "force" is an imaginary force because objects affected by it are really following a straight path. It is an apparent deflection we see from the vantage point (frame of reference) of the rotating Earth.

Name ____________________

Coriolis Effect

Purpose

By tracing an object as it moves across the surface of a rotating and a non-rotating model, you will demonstrate the true and apparent motions of objects as they move across the real Earth. This apparent motion is known as the **Coriolis effect**.

Materials

For each student group: Turntable which can be spun both ways, paper, tape, colored markers (3)

Introduction

The Coriolis effect is the name given to the imaginary force that deflects objects, such as rockets or large storms, which move over the surface of some planets. It is important in causing the swirling motion of storms, including hurricanes. The Coriolis effect occurs on Earth and other planets because the planets rotate.

Questions

Cover the turntable with the paper, taping it to the edges of the turntable. Use one of the markers to draw a straight line all the way across the turntable. This shows the path of clouds or objects moving on a non-rotating planet.

1. Observe and describe the shape of the line you drew. Looking down on your line, is it straight or curved?

2. What is wrong with (missing from) this model of the Earth that might affect how objects truly move over the Earth's surface?

Now spin the turntable counterclockwise. This is the direction that the Earth turns (or rotates), when viewed from the north pole. The turntable is modeling the northern hemisphere of the Earth. Draw a straight line across the turntable using a different colored marker, while spinning it at a constant speed. Be sure to watch that your marker follows a straight path! Label the beginning of the line you drew with an arrow pointing in the direction the marker moved. Note that the line you drew is a curve.

3. With the starting point of the line directly in front of you, in which direction was line deflected? (Which way does the arrow point—right or left?)

4. Which direction does the line curve (clockwise or counterclockwise)?

5. If you were in an airplane that takes off from Miami, Florida and is flying to Toronto, Canada, would your plane be deflected to the left or to the right as it flew?

Now spin the turntable clockwise. This is the direction that the Earth turns (or rotates), when viewed from the south pole. The turntable is modeling the southern hemisphere of the Earth. Draw a straight line across the turntable using a different colored marker, while spinning it at a constant speed. Be sure to watch that your marker follows a straight path! Label the beginning of the line you drew with an arrow pointing in the direction the marker moved. Note that the line you drew is again a curve.

6. With the starting point of the line directly in front of you, in which direction was line deflected? (Which way does the arrow point—right or left?)

7. Which direction does the line curve (clockwise or counterclockwise)?

8. If you were in a cruise ship that set sail from Cape Town, South Africa and was sailing for Rio de Janeiro, Brazil, would your ship be deflected to the left or to the right as it traveled?

9. What is the difference between the way objects move over the Earth in the northern hemisphere compared with those in the southern hemisphere?

Examine Figure 7.1, which shows part of Mars. The bright streaks associated with some craters can be used as wind direction indicators. They are deposits of dust that can form downwind from craters.

10. Does the group of streaks form a straight or a curved path (as a whole group)?

11. What does the shape of the wind streaks indicate about the existence of a Coriolis effect on Mars?

12. Does Mars rotate? How do you know?

13. From which way did the wind blow to make the streaks in Figure 7.1?

14. Imagine you are on the part of Mars shown in this figure, standing with the wind to your back. Which way is the wind being deflected, to your left or your right?

15. If Mars rotates in the same direction as the Earth (from west to east), is this a picture of the northern or southern hemisphere of Mars?

Optional Question

*16. Why is the Coriolis "force," which causes objects to deflect from a straight path on a rotating planet, sometimes called an imaginary force?

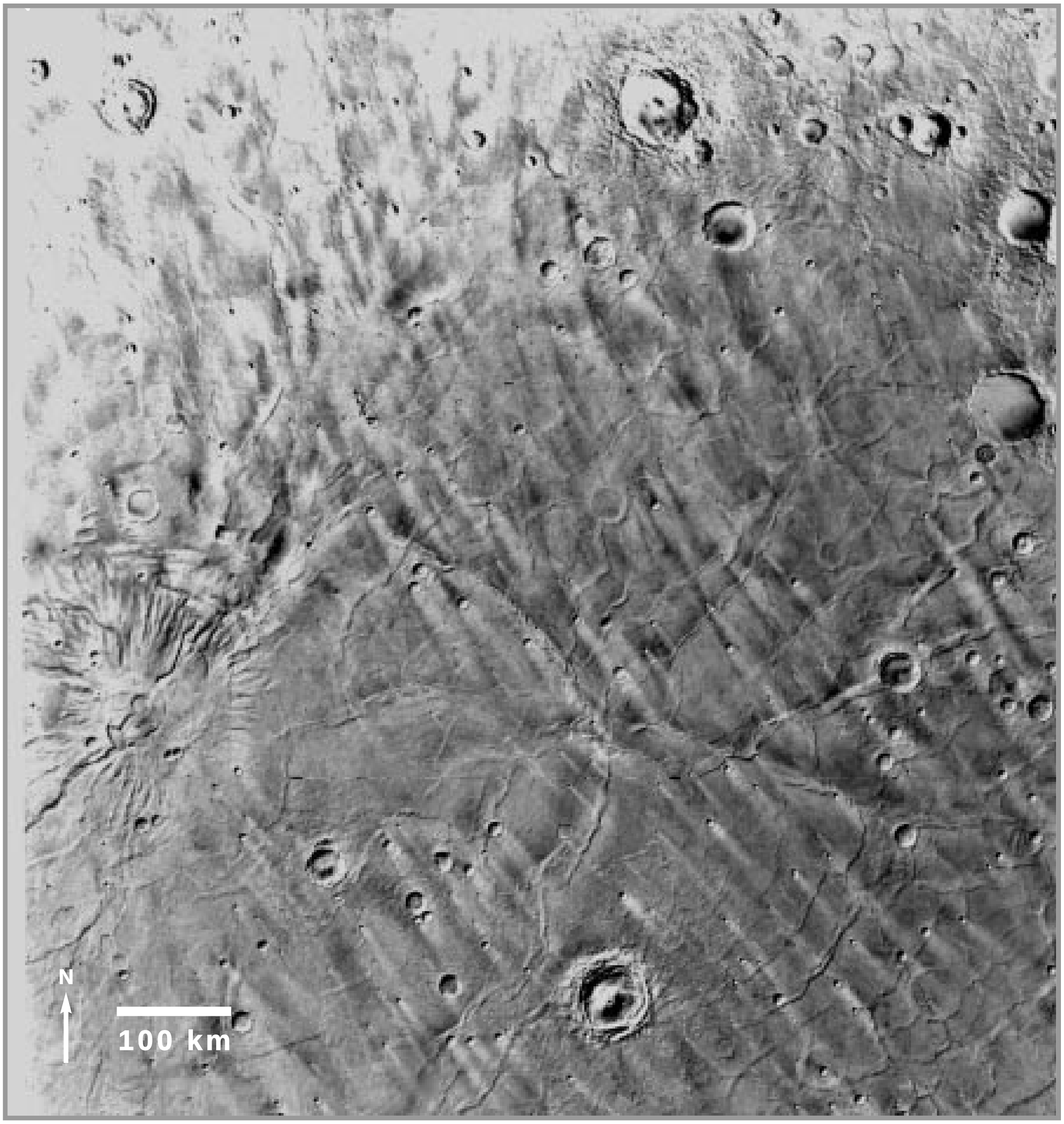


Figure 7.1. Centered at 20˚, 250˚W, this mosaic is of a region on Mars called Hesperia Planum, site of much aeolian (wind) activity. Note the bright streaks associated with some of the craters; they can be used as wind direction indicators. North is to the top. Viking Orbiter mosaic 211-5478.

Exercise Seven is suggested as an introductory exercise.

■ ★ **1.0 hours**

Storm Systems

Instructor Notes

Suggested Correlation of Topics

Air and its movements, air masses, atmospheres, Coriolis effect, cyclonic storms, geography, meteorology, rotation of planets, weather forecasting, weather satellites, winds

Purpose

The objective of this exercise is to demonstrate the fundamentals of atmospheric circulation as they apply to Earth and other planets. Upon completion of this exercise the student should understand the fundamental controls on atmospheric circulation, especially planetary rotation and the Coriolis effect. In addition, the student will be able to make simple weather predictions based on satellite photographs.

Materials

World map

Background

Earth's weather patterns are complex, but some basic meteorological concepts can be understood by examining photographs of the Earth taken from space. Furthermore, comparing Earth's cloud patterns to those of other planets which have very different atmospheres—Mars, Venus, and Jupiter—sheds light on some basic principles of atmospheric circulation.

A fundamental concept of this exercise is that air moves from areas of high pressure toward areas of lower pressure. An analogy can be made to water flowing from a high pressure hose, or dye dissipating in water.

The simple Hadley cell circulation model of Figure 8.1 introduces atmospheric circulation. The pattern is driven by solar energy, which heats the equatorial regions. As the planetary comparisons of this lab indicate, rapid planetary rotation disrupts this simple pattern into multiple circulation cells and turbulent eddies. This occurs on Earth giving rise to cyclonic storms, which are low pressure centers that result in inclement weather. The tilt of a planet can also affect the atmospheric circulation pattern, because the region of maximum solar heating will change with the season of the year. Venus rotates very slowly (once in 243 Earth days) and is tilted only 3° with respect to the plane of its orbit. Thus, Venus has a relatively simple pattern of atmospheric circulation which approximates a Hadley cell.

The Coriolis effect, introduced in the previous laboratory exercise, is an imaginary force that causes deflection of air parcels due to a planet's rotation (Figure 8.2). On a planet rotating toward the east (such as the Earth and most other planets), this causes rightward deflection and counterclockwise rotation of winds in the northern hemisphere, and the opposite effect in the southern hemisphere (Figure 8.3). The slow rotation of Venus makes the Coriolis effect unimportant there. However, like Earth, Mars has a 24 hour rotation period and the Coriolis effect is important.

To some students it will be readily apparent which way a storm is spiraling. Others may first want to sketch the spiraling clouds. If your pencil moves clockwise as it moves in toward the center of the spiral, then the clouds spiral clockwise, and vice versa. This exercise calls on students to locate and predict the weather in various cities around the world. Using a world map to locate the cities and then finding them on the Earth photo is a good lesson in geography. Additional cities can be added by the instructor if time permits.

Jupiter is a giant gas planet that has no solid surface; instead its atmosphere gets progressively denser with depth. At great depth within the atmosphere the pressure is so tremendous that the gases of the atmosphere are compressed into a liquid, and below this is the solid core of the planet. Jupiter rotates very rapidly, once in about 9 hours 55 minutes; Jupiter also has a large supply of internal heat. These factors contribute to complex, turbulent flow in the atmosphere. Neighboring bands in Jupiter's atmosphere typically have winds that blow in opposite directions. Vortices (spots) in the atmosphere are generally not Coriolis-induced; instead they develop along boundaries between bands as a result of the opposing winds. Imagining that a storm rotates like a pinwheel can help to reveal the directions that winds to either side are blowing. Most of Jupiter's spots are temporary features, appearing and disappearing as winds and eddies shift slightly. The Great Red Spot of Jupiter, observed from Earth for more than 300 years, is a notable exception.

Science Standards

- Earth and Space Science
  - Energy in the Earth system
  - Origin and evolution of the Earth system

Answer Key

1. **a.** It spirals counterclockwise.

   b. The Coriolis effect deflects any northern hemisphere storm into a counterclockwise spiral.

2. **a.** They spiral clockwise.

   b. The Coriolis effect deflects any southern hemisphere storm into a clockwise spiral.

3. The feature is a storm front, usually associated with precipitation, wind, and cooler temperatures.

4. **a.** Continued clouds and showers; cool.

   b. Continued clear and warm.

   c. Partly cloudy and hot.

   d. Increasing clouds with rain likely; cooler.

   e. Continued clear and cool.

5. The air pressure will decrease as the cyclonic storm over the eastern United States, a center of low pressure, passes through.

6. **a.** It is a cyclonic storm.

   b. It must be in the northern hemisphere because the clouds spiral counterclockwise.

7. **a.** No.

   b. Venus has a more simple circulation pattern.

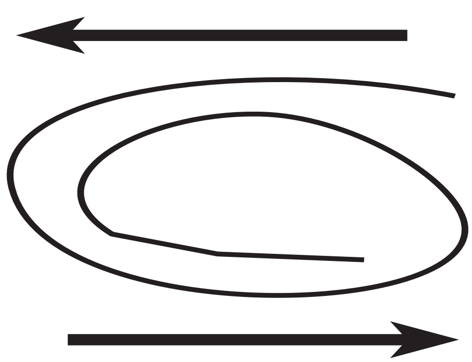
   c. Venus must rotate more slowly than the Earth, because it does not show evidence for Coriolis–induced storms. Also, its simple cloud banding reflects a single equator-to-pole circulation cell.

8. **a.** Jupiter rotates quickly. It shows well-defined banding and a turbulent, complex pattern of atmospheric circulation.

   b. The GRS lies in Jupiter's southern hemisphere.

   c. Counterclockwise.

   d. No; the rotation is incorrect.

9. 

Name ____________________

Storm Systems

Purpose

By examining photographs of Earth, Mars, Venus, and Jupiter, you will recognize wind circulation patterns and the influence of **rotation** and the **Coriolis effect** on planetary atmospheres.

Materials

World map.

Introduction

Our lives are affected every day by the weather—on some days more than others! Being able to predict the weather is a convenience, but being able to predict severe weather is important to public safety. Furthermore, understanding the Earth's weather patterns is critical to agriculture, transportation, and the military. To gain insight into Earth's weather and circulation patterns, it is useful to examine the atmospheres of other planets, comparing them to each other and to Earth.

Atmospheric circulation is caused by differences in heating, primarily between the poles and equator. On an ideal non-rotating planet (Figure 8.1), warm air would rise over the equatorial regions, lowering the air pressure there. Air in each hemisphere would then circulate to the cool polar regions where it would sink, increasing air pressure there. To complete the cycle, the cold high-pressure air would travel at ground level back toward the equator. This simplified pattern of circulation is called a Hadley cell, named after the British scientist who first proposed the model. On a real planet, the pattern of atmospheric circulation is complicated by rotation, which breaks the circulation into several cells from pole to equator and results in an ever-changing pattern of turbulent swirling clouds, called **eddies.** Also, if a planet is tilted with respect to its orbit around the Sun, the latitude of maximum solar heating changes as the planet goes through its yearly cycle of seasons.

Air moves from regions of high pressure to regions of low pressure. The pressure difference, or gradient, is the driving force for atmospheric circulation. However, other effects prevent the direct motion of a given air mass from high to low pressure. Friction between the ground and the atmosphere modifies air motion, as does the presence of mountains or other topography. Furthermore, the Coriolis effect deflects air masses as they move. On a planet that rotates in the normal sense (toward the east), a parcel of air is deflected to the right of its direction of motion in the northern hemisphere and to the left in the southern hemisphere. Figure 8.2 shows this effect.

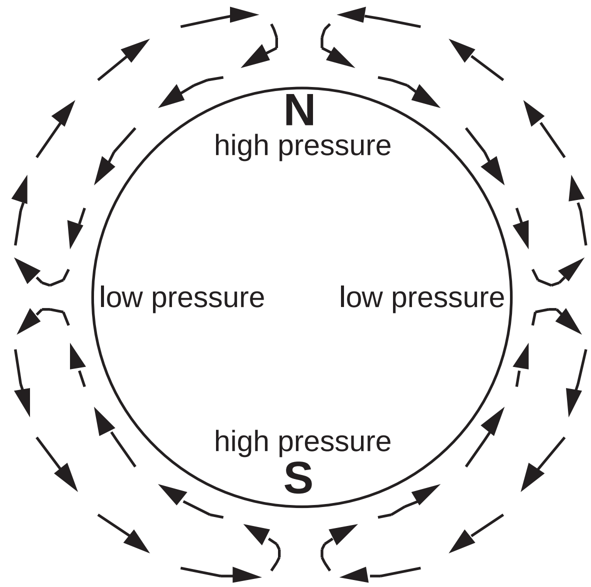


Figure 8.1. *The idealized Hadley cell model of atmospheric circulation. Although unrealistically simplified, this pattern of airflow would develop on a planet if it were spinning very slowly and if the axis were at right angles to the orbital plane (that is, if there were no seasons). The Sun would always heat the planet most strongly at the equator. Air would rise along the equator and lower the pressure locally. Colder, dense air would sink at the poles, raising the air pressure there. This air would return toward the equator along the ground. Rapid planetary rotation breaks up this circulation pattern into several cells and produces turbulent eddies.*

Cyclonic storms are the fundamental mechanism for turbulent, inclement weather on Earth. These are huge, well-organized centers of low pressure which develop along the boundaries between air masses. As a cyclone intensifies, so does weather activity along the boundary, or **front.** In addition to its clouds, a storm front commonly brings with it precipitation, wind, and cooler temperatures.

The motion of air parcels on Earth generates such low pressure centers. Air parcels can approach low pressure cells from all directions. Because of the Coriolis deflection, a circulation of winds is set up around the low pressure centers (Figure 8.3). The result is a counterclockwise spiral of air into a low center in the northern hemisphere, and a clockwise spiral in the southern hemisphere.

Procedure and Questions

Examine Figure 8.4, using the world map to help identify the land masses that are visible.

1. Notice the well-defined spiral pattern of clouds southwest of the Baja peninsula, Mexico.

   a. Which way is this cloud pattern spiraling, clockwise or counterclockwise?

   b. Why?

2. Now examine the two cloud spirals over the southern Pacific Ocean.

   a. Which way are these clouds spiraling, clockwise or counterclockwise?

   b. Why?

3. Notice the long line of clouds stretching over the southern Pacific Ocean. What is this feature and what kind of weather is likely associated with it?

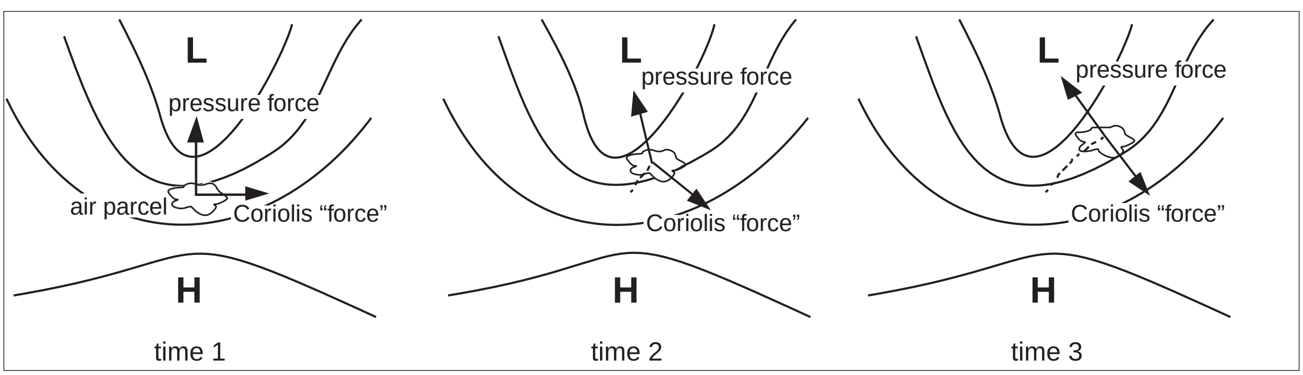


Figure 8.2. *As a small mass of air, called an air parcel, moves under the influence of a pressure gradient, its path is not a direct one from high to low pressure. The curved lines around the low pressure centers (L) are contours of equal pressure, or isobars. The low pressure center can be considered a "well" or sink for air, and the high pressure center (H) can be considered a "ridge" or source of air. If you were riding along an air parcel in the northern hemisphere, you would be deflected to the right of your direction of motion as the air parcel drifts from high pressure toward lower pressure. Thus, the final motion is nearly parallel to the isobars, rather than across them. In the southern hemisphere, the mirror image of the diagram is observed, with the Coriolis "force" causing air parcels to deflect toward their left.*

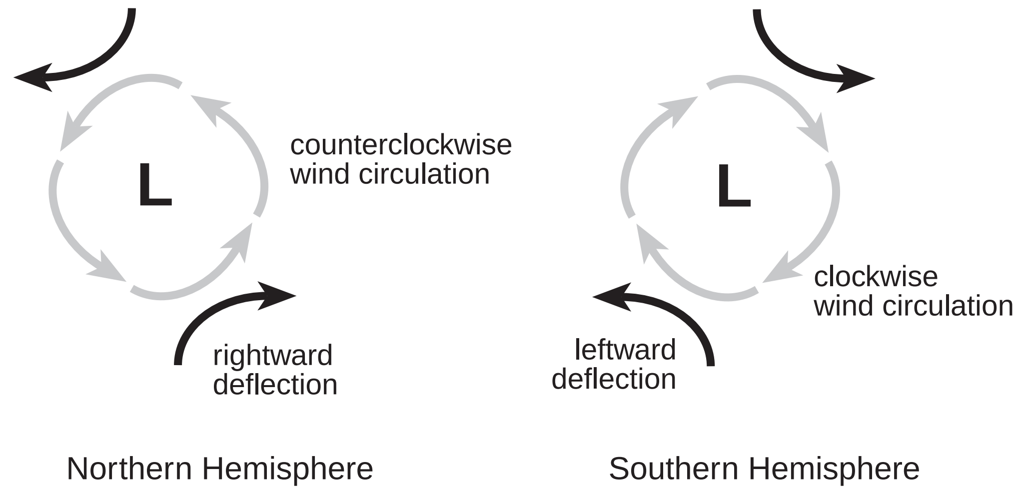


Figure 8.3. *A simplified illustration of how low pressure cells (cyclones) develop. Air parcels heading toward lows are deflected by the Coriolis effect to set up a counterclockwise circulation pattern in the northern hemisphere, and a clockwise pattern in the southern hemisphere.*

4. As Earth rotates from west to east, frictional drag pulls the atmosphere along more slowly in the same direction. Assuming that the storm system off of southern Chile will reach the coast by tomorrow, and noting that this photo was taken in September, determine a likely weather forecast (temperature, clouds, and precipitation) for the next 24 hours in each of the following locations:

   a. Indianapolis (40°N, 86°W)

   b. El Paso (32°N, 106°W)

   c. The Galápagos Islands (0°N, 91°W)

   d. Tierra del Fuego (54°S, 68°W)

   e. Buenos Aires (34°S, 58°W)

5. Will the air pressure become higher or lower in Bermuda during the next 24 hours? Explain.

6. Look at Figure 8.5, taken by a spacecraft in orbit over Mars. Like Earth, Mars rotates west to east.

   a. What do you think this cloud feature is?

   b. In what hemisphere is the feature? How do you know?

7. Examine the atmosphere of Venus as seen in Figure 8.6.

   a. Can you identify any obvious spiraling clouds that might be due to the Coriolis Effect?

   b. Compare the photos of Venus and Earth, and recall the simple Hadley cell circulation model of Figure 8.1. Does Venus appear to have a more simple or more complex pattern of atmospheric circulation than Earth?

   c. How does the circulation pattern support the proposition that Venus rotates slowly?

Jupiter is a gaseous planet, having no solid surface (but likely possessing a solid core). Although the planet is composed mostly of hydrogen and some helium, its visible clouds probably consist of ammonia (NH_4), ammonium hydrosulfide (NH_4HS), and water (H_2O). The Great Red Spot (GRS) is a great storm in the clouds of Jupiter.

8. Base your answers to the following questions on the Voyager photos of Jupiter shown in Figures 8.7 and 8.8.

   a. Does Jupiter rotate quickly or slowly? Justify your answer.

   b. Does the GRS lie in the northern or southern hemisphere of Jupiter?

   c. In which direction do winds around the GRS rotate?

   d. Is the GRS a Coriolis-induced storm? Support your answer.

9. The winds of Jupiter commonly blow in opposite directions in neighboring bands. That is, winds blow to the east in one band and to the west in the neighboring band. These opposing winds can act to create swirling eddies and storms. Draw a sketch of the GRS. Indicate with arrows the directions that winds along its northern and southern edges are blowing.

Sketch area

Figure 8.4. *Earth as seen from the Geostationary Operational Environmental Satellite, GOES-7. The picture was taken at 6 p.m. Greenwich Mean Time on September 25, 1994, soon after the start of northern hemisphere autumn. The north pole is toward the top.*

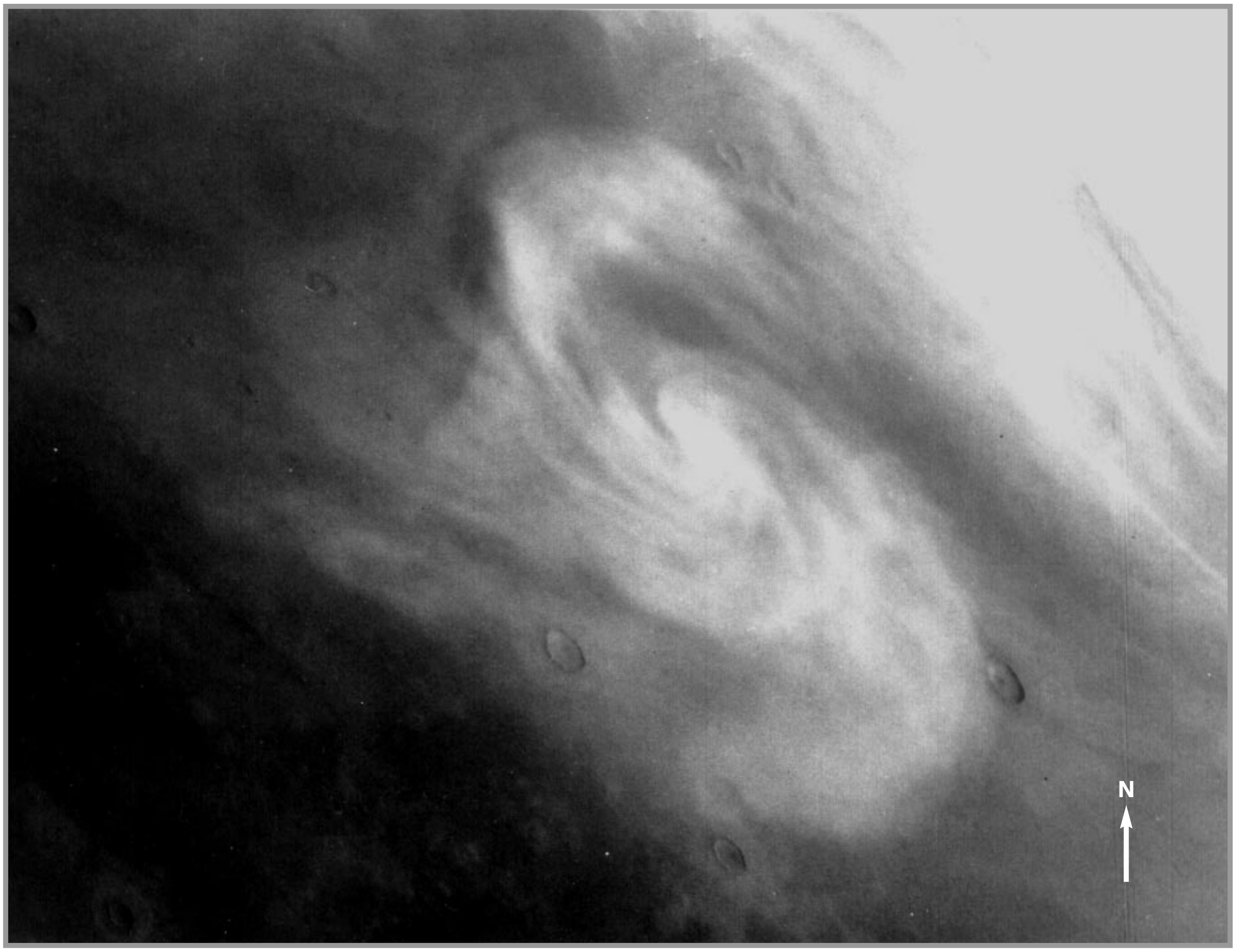


Figure 8.5. *Viking Orbiter image 78A42, showing a water frost cloud pattern over the surface of Mars. North is toward the top.*

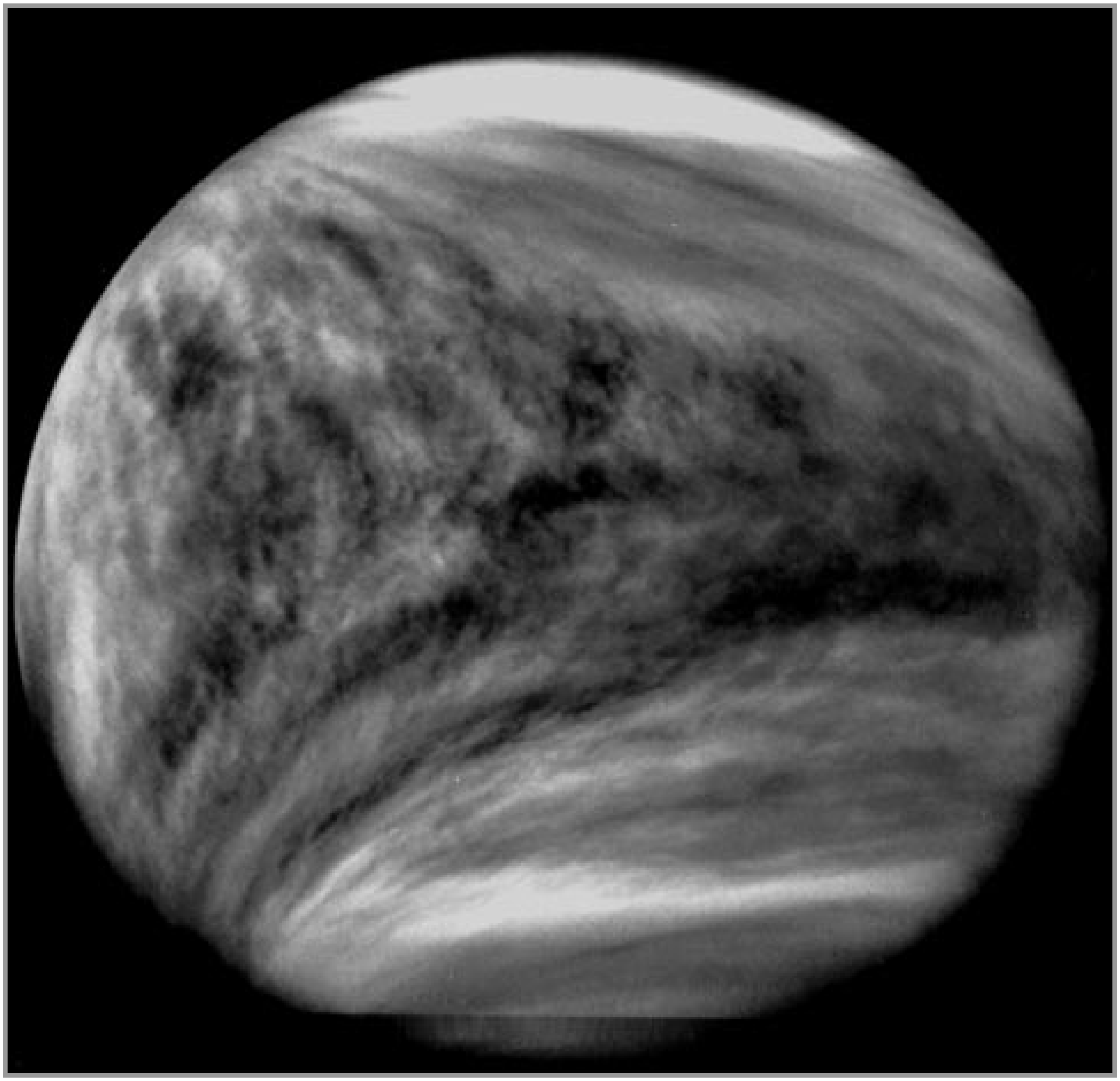


Figure 8.6. *Patterns of cloud motion on Venus are revealed in this ultraviolet image, taken by the Pioneer Venus orbiter in 1979. Venus is unusual in that the planet and its atmosphere rotate from east to west. The surface of Venus cannot be seen through the thick clouds. North is toward the top; the horizontal black line is missing data. Pioneer Venus image 0202-79-046-0830, courtesy of Larry Travis.*

Figure 8.7. *Jupiter as seen by the Voyager 1 spacecraft from a distance of 54 million km (34 million miles), as it approached the planet on January 9, 1979. The Great Red Spot (GRS) is a large vortex just below center. North is toward the top.*

Figure 8.8. *Closeup of the Great Red Spot (GRS) seen by Voyager 1 on February 25, 1979 from a distance of 9.2 million km (5.7 million miles). The spot is about 25,000 km (16,000 miles) across, and could hold two Earths side-by-side. White ovals and turbulent, swirling eddies are also visible.*

■ ★ 1.0 hours

Aeolian Processes

Instructor Notes

Suggested Correlation of Topics

Aerodynamics, air and its movements, arid lands, climate, deserts, environments, erosion, landforms, meteorology, weather, wind and its effects

Purpose

The objective of this exercise is to demonstrate the process of wind erosion and deposition around surface features such as hills and craters.

Materials

- 3-speed fan
- 6-foot-long table (or longer)
- chair
- drop cloth
- sugar (5-pound bag); very fine sand can be substituted
- small ball (tennis or racquet ball)
- drinking glass
- metric ruler
- pencil
- tape
- ribbon or string (approximately 15 cm-long)
- 3 to 5 obstacles, different sizes and types; rocks, ruler, key, etc.

This exercise works well for groups of students. In addition, it can be a demonstration by the instructor. This exercise is only a general simulation of the complex interaction of the wind and a planetary surface. The wind produced by the fan has a "spin" to it because of the fan blades. For increased simulation accuracy, the wind can be stabilized by removing the "spin". To stabilize the wind, an open gridwork, such as toilet paper tubes glued together, must be placed between the fan and the experiment. Because the gridwork will slow the wind, as well as stabilize it, higher fan speeds will be necessary for material movement. Commercial three speed fans may not have sufficient wind velocities. Sugar is much easier than sand to move with the wind velocities produced by a commercial fan. Both materials are messy to work with, so have a dust pan and broom on hand.

For more accurate simulation of the effects of wind on planetary surfaces, it is recommended that a wind tunnel be constructed. The directions for constructing a wind tunnel are included here. The construction of the wind tunnel is time consuming, but can be used for quantitative experiments, or for science-fair projects.

Wind Tunnel

Materials:

1. Wardrobe box from a moving company
2. 3-speed 50 cm box fan
3. Wind stabilizer (open ended milk cartons or cardboard tubes glued together along their lengths)
4. Base for inside box, approximately 15 cm high and 50 cm wide
5. Masking tape
6. Clear plastic wrap (for the side 'windows')
7. Sand collection tray (such as a kitty litter box)
8. Dark-colored posterboard

Construction:

Figure 9.1 shows the set-up for the wind tunnel. Moving company wardrobe box (or similar size box 61 cm x 50 cm x 122 cm) is kept intact (do not remove the flaps). Three windows are cut out, one on each side and one on the top. The two side windows are sealed with clear plastic wrap (or clear acrylic panels) and taped from the inside. The width of the plastic wrap determines the height of the window. A convenient length is 40 cm. The top window is left unsealed so that you can look more closely at the sand crater and perhaps take pictures during different stages of the experiment. A base is placed on the floor of the wind tunnel in order to raise the floor area to nearer the center of the fan. Fifteen centimeters above the floor is sufficient. The base should fit snugly within the tunnel, to help stabilize the box and to prevent the base from being moved by the wind from the fan. The sand collection tray is placed behind the base to catch some of the sand or sugar. The posterboard is placed on top of the base and should be taped down along the sides to prevent it from becoming airborne during the experiment. The wind stabilizer is placed directly against the base within the tunnel and the fan is placed immediately behind the wind stabilizer. The fan should be within the flaps at one end of the box, and directed to blow into the tunnel.

Science Standards

- Earth and Space Science
  - Energy in the Earth system
  - Origin and evolution of the Earth system

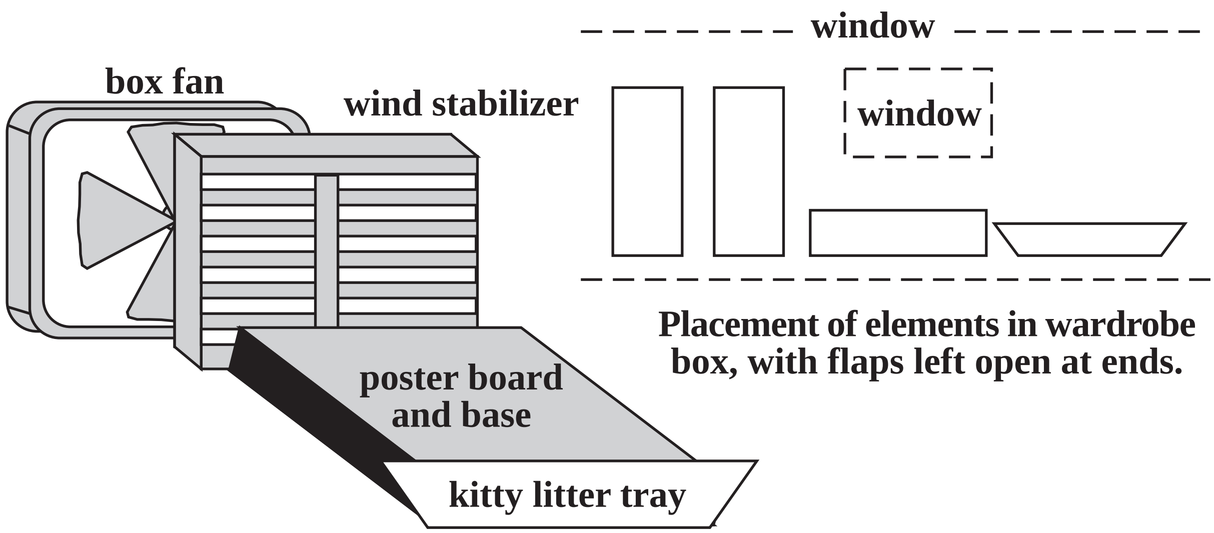


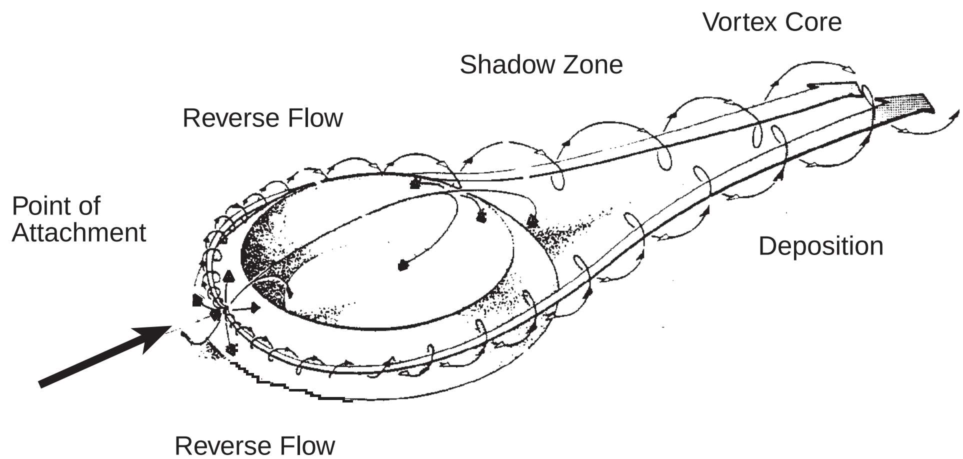
Figure 9.1. *Diagram of wind tunnel construction.*

Answer Key

1. Sketch of cone
2. Answers will vary, depending on fan speed and material (sugar or sand) used. Usually travels entire distance of table and beyond (a meter or more).
3. Answers will vary, but may see a sheet of sugar/sand with ripple-like features developing perpendicular to the wind direction.
4. Answers will vary, depending on fan speed and material used. Usually 1/3 to 1/2 meter for the initial bounce. The second one is shorter (less energy).
5. Answers will vary, depending on fan speed and material used. Usually a few centimeters.
6. Sketch (NOTE: sketches are not provided within this answer key, as the variation in fan velocities will control the speed of erosion and deposition).
7. Sketch
8. Erosion occurs at the front and sides of the cone.
9. Deposition occurs behind the cone.
10. The sketch below represents the aerodynamic characteristics of a crater when wind blows across it from left to right. Experiments to visualize this model were done at the NASA Ames Research Center. For a cone, the reverse flow (seen within the crater) does not occur.
11. Sketch
12. Depending on the shape and positioning of the obstacles, sugar will initially pile up against the obstacle (on the front and sides), some sugar will also be deposited behind each obstacle. With time the sugar will be removed from the front and sides, but will remain in the lee of (behind) each obstacle. For discussion, talk about windbreaks, such as snow fences, and other obstacles man puts in the path of the wind to control drifting sand and snow.
13. Sketch
14. Sketches, see answer 10 above for wind movement arrows.
15. Students should see sugar within the crater moving from the back of the crater towards the front (reverse flow). Once the back rim of the crater has been removed by erosion this motion will decrease dramatically and may not be observed by the student.
16. Sketches, see answer 10 above for wind movement arrows.
17. Answers will vary, should be the same for both crater shapes.
18. **a.** Answers will vary, but should have produced something similar to the windstreaks seen in the figure (most likely during Part Two).

    b. The average prevailing wind has come from the east (from right to left).

    c. The bright crater tails are most likely depositional zones of bright surface materials.



Name ______________________________

Aeolian Processes

Purpose

In this experiment you will investigate the process of wind erosion and deposition around features such as craters and hills.

Materials

For each student group: 3 speed oscillating fan, long table, chair, drop cloth, sugar, small ball (tennis or racquet ball), drinking glass, metric ruler, pencil, tape, ribbon or string (~15 cm long), 3 to 5 obstacles (small rocks, keys, ruler, eraser, etc.).

Introduction

Wind is an important agent of gradation in many arid and coastal regions of the Earth and on Mars and Venus. During wind erosion, small particles are moved in **suspension, saltation, or traction**. Very small particles can be carried by the wind without touching the ground until the wind slows or stops and drops the particles. This is termed suspension. Most sand (and sugar) sized particles are bounced along the surface. This is termed saltation. Particles too large to be picked up by the wind or bounced along the surface may be pushed along the surface by the wind or by the impact of particles in saltation. This is termed traction. Eventually the particles are deposited by the wind in some new location. Wind erosion and deposition of particles result in distinctive landforms, such as dunes and windstreaks. Venus and Mars have wind related features similar to those seen on Earth.

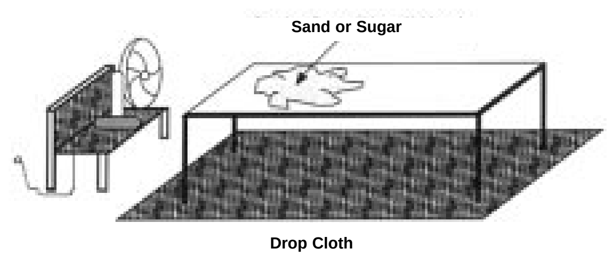


Figure 9.2. *Diagram of the experimental set-up.*

Procedure and Questions

Place the fan on the chair, centered at the end of the table. Make sure the center of the fan is even with the surface of the table (see Figure 9.2). Direct the wind by tilting the fan towards the surface of the table at an angle of 15 to 20 degrees from vertical. Tape a piece of ribbon or string on the end of a pencil. Turn the fan on medium speed. Holding the pencil perpendicular to the surface of the table with the string along the table, move the pencil around the table to locate the "dead spots" produced by the fan. Locate the area near the fan where the air movement is greatest; this spot is where all sand piles should initially be placed.

Part One

Form a 5 centimeter high cone of sugar in the identified spot. Make an initial sketch of the top view and side view of the cone in the space provided.

1. Initial Sketch (use Sketch Area A):

   Turn on the fan at a speed (usually medium) that results in moderate movement of material. Leave the fan on for three minutes. Answer the following questions while the fan is blowing.

2. How far down the table surface has the sugar traveled after one minute?

Sketch Area A

3. Describe the pattern the sugar has formed at the far end of the table after 2 minutes.

4. What is the average length of the bounce of a sugar grain leaving the cone of sugar? Is the second bounce of a sugar grain longer or shorter than the first bounce?

5. How high above the table does the sugar rise (in centimeters).

After three minutes turn off the fan and make a sketch of the cone. Include both a top and side view.

6. Second Sketch (use Sketch Area A):

Turn the fan back on for another two minutes. Be sure to note the saltation of the sugar grains at the far end of the table. Sugar from the cone will hit sugar grains on the table and make them move along in saltation or traction. After two minutes turn the fan off and make a final sketch of the top and side views of what remains of the cone of sugar.

7. Final Sketch (use Sketch Area A):

Compare your previous two sketches with the final one.

8. From where has most of the sugar been eroded on the cone?

9. Has any sugar been deposited around the cone? If so, where?

10. Based on your three sketches of the sugar cone, diagram the effect the cone has on the wind movement. Do this by imagining you can see the wind. Draw arrows to show how you think the wind moves around the cone.

Part Two

Clean up all the sugar on the table. Form another 5 cm high cone of sugar in the spot of greatest wind movement. Place obstacles (keys, small rocks, eraser, etc.) at different locations on the table downwind of the cone of sugar. Place the obstacles at different orientations to the wind. For example, with a long side parallel, perpendicular or at an angle to the wind; flat or on its side. Turn on the fan at the same speed as in part one. After three minutes turn the fan off and observe the deposition and erosion of sugar around the obstacles.

11. Make a sketch (include both a top and side view) of each obstacle and the sugar surrounding it. Add arrows to indicate the movement of the wind around each obstacle. (use Sketch Area B).

Sketch Area B

12. Where does most of the deposition occur at the obstacle? Where does most of the erosion occur?

Part Three

Remove the obstacles and clean up all the sugar on the table. Form a thin (few grains thick) layer of sugar 20 cm by 20 cm in size and make a 3 cm high cone of sugar in the center. Make sure the cone is in the spot of maximum wind. Use the ball to form a bowl-shaped crater on the pile. Remove the ball and make an initial sketch of the crater. Include a top and side view.

13. Initial Sketch (use Sketch Area C):

    In this part of the activity, you will be turning the fan on and off for three one-minute intervals to monitor the progress of erosion of the crater. Turn on the fan at the same speed used previously, producing moderate movement of the sugar. After one minute, turn off the fan and observe what changes have occurred to the crater and the surrounding area. Sketch what you observed. Include a top and side view, as well as arrows indicating the wind movement over and around the crater.

14. a. Sketch after first one-minute interval (use Sketch Area C):

    b. Sketch after second one-minute interval (use Sketch Area C):

    c. Sketch after final one-minute interval (use Sketch Area C):

15. How is the movement of the wind around the crater different from the movement of the wind around the cone in Part One?

Sketch Area C

Part Four

Clean up all the sugar on the table. Form another thin layer of sugar 20 cm by 20 cm in size and make a 3 cm high cone of sugar in the center. Make sure the cone is in the spot of maximum wind. Use the bottom of the drinking glass to form a flat-bottomed crater that goes all the way down to the table surface. Make an initial sketch of the crater and its surroundings. Turn the fan on and off for three, one-minute intervals and sketch what you observe. Include top and side view, as well as arrows indicating the wind movement over and around the crater. (Use Sketch Area D, placing two sets of sketches in each box provided.)

16. **a.** Initial Sketch (use Sketch Area D):

    b. Sketch after first one-minute interval (use Sketch Area D):

    c. Sketch after second one-minute interval (use Sketch Area D):

    d. Sketch after final one-minute interval (use Sketch Area D):

17. Based on your observations and sketches, are there any differences in erosion and deposition of sugar between the bowl-shaped crater and the flat-bottomed crater? If yes, explain.

The wind is at work on other planetary surfaces besides Earth. Examine the photograph of Mars (Figure 9.3).

18. **a.** Do you see anything similar to what you produced on the table?

b. From which direction do you think the wind was blowing?

c. Are the light areas behind the craters zones of erosion or deposition? Recall the obstacles in Part Two.

Sketch area D

Figure 9.3. *Wind streaks on Mars located on plains between Tartarus Montes and Orcus Patera. The picture center is approximately 19°N, 183° W. North is to the top. Viking Orbiter photograph 545A52.*

Introduction to Planetary Surfaces

The three decades from the mid-1960s to the mid-1990s have revolutionized our understanding of the planets and their satellites. During this period, spacecraft made an initial reconnaissance of all of the planets except Pluto, returning a wealth of information, much in the form of images. The surfaces revealed in these images range from the subtly familiar, such as the riverlike valleys of Mars seen by the Viking Orbiters, to the wildly exotic, like the ice cliffs of Miranda, a satellite of Uranus.

What we understand of the histories of the planets and their satellites is based on observations of their surfaces. For example, Mars shows a myriad of landforms that were shaped by running water in the past, even though liquid water is not stable near the surface of Mars today. Thus, planetary scientists conclude that Mars had a wet early history, and that its climate somehow evolved to make Mars the frozen desert that it is today. Many of the icy satellites of the outer solar system show evidence for extensive flows of icy material, even though these moons are frozen solid today. Thus, some energy source increased the internal temperatures of these satellites in the distant past.

This unit introduces students to the interpretation of geologic landforms and processes on the planets and satellites through five exercises. First, the overall geology of the terrestrial planets is introduced. Then, individual activities concentrate on the geology of Mars and Venus. Next, students are led through the outer solar system using some of the spectacular images from the Voyager mission. Finally, the types of landforms and processes introduced in preceding activities are reviewed through analysis of stereoscopic planetary images.

Exercise Two is suggested as an introductory exercise.

■ ★ 1.5 hours

Landform Mapping: The Terrestrial Planets

Instructor Notes

Suggested Correlation of Topics

Planetary comparisons, geomorphology

Purpose

The objective of this exercise is to recognize and compare the similarities and differences among the surfaces of the terrestrial planets at a global scale.

Materials

Suggested: clear acetate or overhead transparency film, overhead projector markers, metric ruler, drawing compass (a single compass can be used by a group of students).

Substitutions: tracing paper, colored pens or pencils, pen and string (as a compass).

Background

This exercise views Mercury, Venus, Earth, Moon, and Mars at the global scale. At this scale only the largest and most prominent landforms and terrains are visible. This provides a starting point for more detailed study of planetary surfaces in later exercises or as provided by the instructor. Note that the Moon, although not actually a planet, is typically grouped with the terrestrial planets when considering its geology.

This exercise is best worked in pairs or small groups of students. When the students are working on question 16, encourage them to compare the images side by side in ordering the surfaces from least to most complex. The starred question can be used for more advanced students or for class discussion.

Science Standards

- Earth and Space Science
  - Origin and evolution of the Earth system

Mathematics Standards

- Connections
- Number and number relationships

Answer Key

1. The highlands are bright, rugged and heavily cratered. The plains are dark, flat, smooth and less cratered.
2. The highlands.
3. The highlands.
4. Younger.
5. Cratered plains and rayed craters.
6. Older than the lunar plains. (Lunar plains are often called maria.)
7. All three surfaces have craters, although Mars has the least. Mars has more extensive smooth plains than the Moon or Mercury; no obvious volcanoes or canyons are visible on either Mercury or the Moon. Only Mars shows polar ice caps.
8. Mars has a dynamic atmosphere (including dust storms). Gradation by running water occurred on Mars, but water never flowed on the Moon. Volcanic activity has been more extensive on Mars. Tectonism has occurred on Mars. On the Moon, impact cratering and plains volcanism have been the major geologic processes; on Mars, all four major geologic processes have worked to shape the surface.
9. Younger.
10. The southern region is older.
11. Mars.
12. **a.** Both are long and relatively narrow. The canyon on Mars is straight, the one on Venus is arcuate. [If the student says the Venus canyon is bright and the Mars canyon is dark, remind them of the differences in imaging systems: radar vs. optical camera.]
13. Younger.
14. **a.** Smooth plains, canyons (deep ocean trenches and rifts in Africa), volcanoes (represented by islands) and rough "highlands" (mountain ranges).

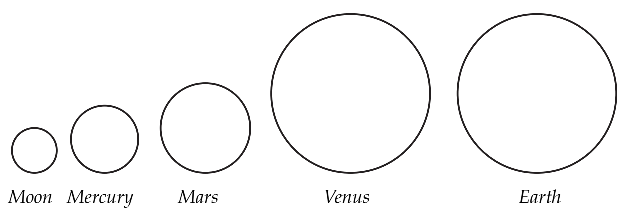
    b. Continents, mid-ocean rift/ridge zones.
15. **a.** Similarities: if Earth's continents are thought of as "highlands," both can be divided into high– and low-standing regions; low-lying regions are relatively smooth. Differences: the Moon is dominated by craters; lowlands on the Moon are formed by large impacts flooded by volcanic material; no linear mountain chains on the Moon; no prominent arcuate ridges or trenches on the Moon.

    b. Students will have difficulty finding any similarities between Earth and Mercury. Differences: Mercury is dominated by craters (impact cratering is the prominent geologic process); on this image of the Earth, impact cratering is the only geologic process that is *not* apparent.

    c. Similarities: both have volcanic and tectonic landforms. Differences: no continents or mid-ocean ridge system on Mars, no craters seen on this global view of Earth.

    d. Similarities: both show arcuate mountain ranges; both show expansive smooth regions; neither shows very large craters. Differences: more extreme topography on Earth, continents and deep ocean basins, compared to more uniform topographic level on Venus; no mid-ocean ridge systems on Venus.
16. **a.** Oldest to youngest: Mercury, Moon, Mars, Venus, Earth.

    b. Answers will vary based on students perception of "most complex." Earth has the most active geologic history reflected on its surface, however, some students may argue that Venus is more complex. Least to most complex: Mercury, the Moon, Mars, Venus, Earth.
17. (This representation is ~1/3 the size of what student answer should be.)



*18. Answers may vary. In general it is true that the larger the terrestrial planet, the more complex its surface. This is not strictly true, however: the Moon, despite its smaller size, is arguably more complex than Mercury. Students might wish to debate the relative complexity of Earth and Venus, or Venus and Mars, as seen at the global scale.

Name ______________________________

Landform Mapping: The Terrestrial Planets

Purpose

To examine and compare global-scale surfaces of the terrestrial planets.

Materials

Clear acetate, overhead projector markers, metric ruler, compass.

Introduction

At a global scale, only the largest planetary **landforms** and regions are visible and can be identified. Such landforms include large volcanoes, canyons, impact craters, plains regions, mountains, and highlands (topographically "high standing" regions). Although the Moon and planets formed at the same time (about 4.5 billion years ago) their surfaces differ in age. This difference is due to variation in the levels of geologic activity on each body since their formation. The four main geologic processes (**volcanism, tectonism, gradation,** and **impact cratering**) have worked to alter the original surfaces. In comparing planetary surfaces, relative ages are usually determined from impact craters. In general, older surfaces show more craters, larger craters, and more degraded craters than younger surfaces.

Questions

Moon

Examine Figure 10.1. Place a piece of clear acetate over the photo. Trace the outline of the Moon. Divide the Moon by its two major regions—highlands (light) and plains (dark)—by outlining the light-toned and dark-toned areas. On the Moon, the plains are called "maria" (which means "seas" in Latin) for their fanciful resemblance to oceans.

1. Describe the characteristics of each region.

2. Which of the two regions appears to be most heavily cratered?

3. Which region on the Moon is older—the plains or the highlands?

4. Some large, young craters have bright ejecta deposits that form a star-like pattern of rays around them. Trace two such craters and their deposits onto your acetate map. Are these craters older or younger than the plains?

Mercury

5. Examine Figure 10.2. What landforms and regions do you observe on Mercury?

6. Based on the number of craters, do you think the surface of Mercury is older, younger, or about the same age as the plains on the Moon?

Mars

Examine Figure 10.3. Mars has a thin atmosphere, seasonal dust storms and polar ice caps (notice the bright south polar ice cap near the bottom of the figure). At one time, Mars had liquid water on its surface, although today Mars is too cold to have liquid water and only has ice. The darker spots within the bright region of the upper left of the image (marked A–D) are large volcanoes. Images sent back from surface landers and other remotely acquired data show that the lighter toned areas are relatively dusty and the darker toned areas are sandy or bare rock. Near the center of the image is Valles Marineris (marked E), a large canyon system of probable tectonic origin.

7. List similarities and differences in the features found on Mars compared to those on the Moon and Mercury.

8. Why is the surface of Mars different from the Moon? (List reasons that support your answer.)

9. Based on the number of impact craters, do you think the surface of Mars seen here is older, younger, or about the same age as the highlands on the Moon?

10. Based on the number of impact craters, which part of Mars is older, the northern or the southern region?

Venus

Although the atmosphere of Mars is relatively cloud free, the thick cloud cover on Venus completely hides the surface from viewing by cameras. Using **radar,** which can penetrate through clouds, the Magellan spacecraft sent back radar images of the surface of Venus. In general, these radar images show rough topography (such as mountains, **rift zones,** crater rims and **ejecta**) as bright, and smoother material (plains) as dark. A volcano (A), a crater (B), and a canyon (C) have been labeled on the image.

11. Which planet looks more like Venus at the global scale: Mercury or Mars?

12. Compare Valles Marineris on Mars to Artemis Corona (the canyon marked C) on Venus. How are their morphologies the same? How are they different?

13. Based on the number of craters, do you think the surface of Venus is older, younger, or about the same age as the highlands on the Moon?

Earth

Figure 10.5 shows a digital representation of the Earth, shown as it might look from space if it had no clouds and no oceans. In this way, Earth's landforms can be compared to those of other planets.

14. **a.** List some major landforms on Earth that are comparable to what you have seen on the other planets.

    b. List some different types of landforms you can see.

15. List some similarities and differences between the landforms of the Earth and:

    a. Moon

    b. Mercury

    c. Mars

    d. Venus

16. Based on the number of craters, the number of geologic processes evident and the different types of landforms seen on the images, list the five surfaces you have examined in order :

    a. From oldest to youngest.

    b. From least complex to most complex.

17. Examine the table on the next page. Using a compass, draw circles showing the relative sizes of Mercury, Venus, Mars, the Moon, and Earth in the sketch area below. Let the diameter of Earth equal 6 cm.

Sketch area

	Mercury	Venus	Earth	Moon	Mars
Mean Distance from Sun (millions of km)	57.9	108.2	149.6	384,400 km from Earth	227.9
Equatorial Diameter (km)	4880	12,104	12,756	3476	6787
Equatorial Diameter (Earth diameters)	0.38	0.95	1.000	0.272	0.53
Mass (relative to Earth)	0.055	0.815	1.000	0.0123	0.108
Volume (relative to Earth)	0.06	0.88	1.000	0.0203	0.15
Density (g/cm^3)	5.4	5.2	5.5	3.34	3.9

*18. Before the initial reconnaissance of the solar system by spacecraft was completed, it was traditionally believed that the geological complexity of surface features on a solar system body would be related to the size of the body, larger planets being more geologically complex. Is this true of the terrestrial planets? Support your answer.

Figure 10.1. *Photograph of the Moon. North is to the top. (Courtesy of Ewen A. Whitaker, University of Arizona.)*

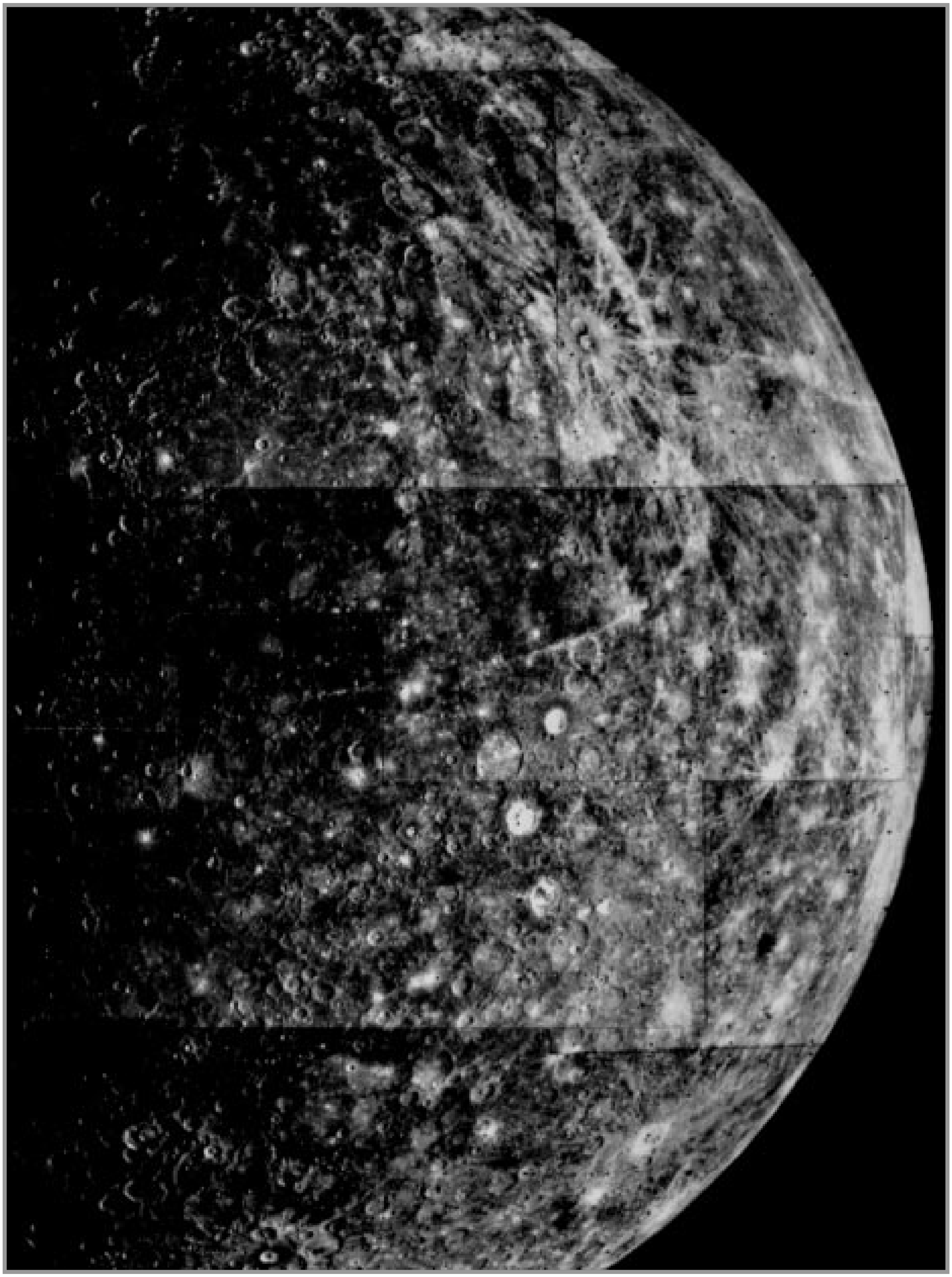


Figure 10.2. *Mariner 10 mosaic of Mercury. North is to the top. (NASA P-14580.)*

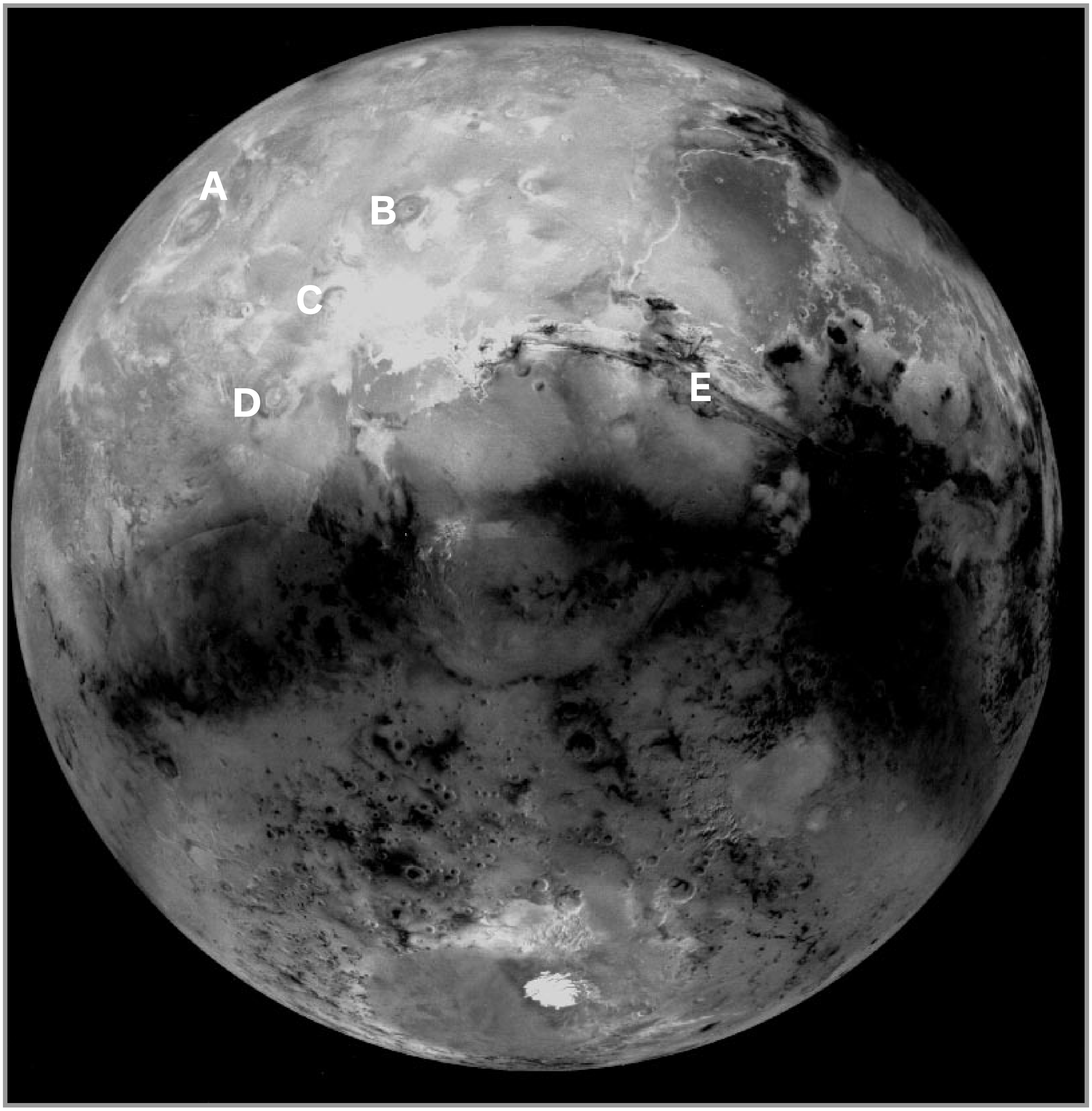


Figure 10.3. *Viking Orbiter global mosaic of Mars, centered at -30°, 90°. North is to the top. (Courtesy U.S. Geological Survey, Flagstaff, Arizona.)*

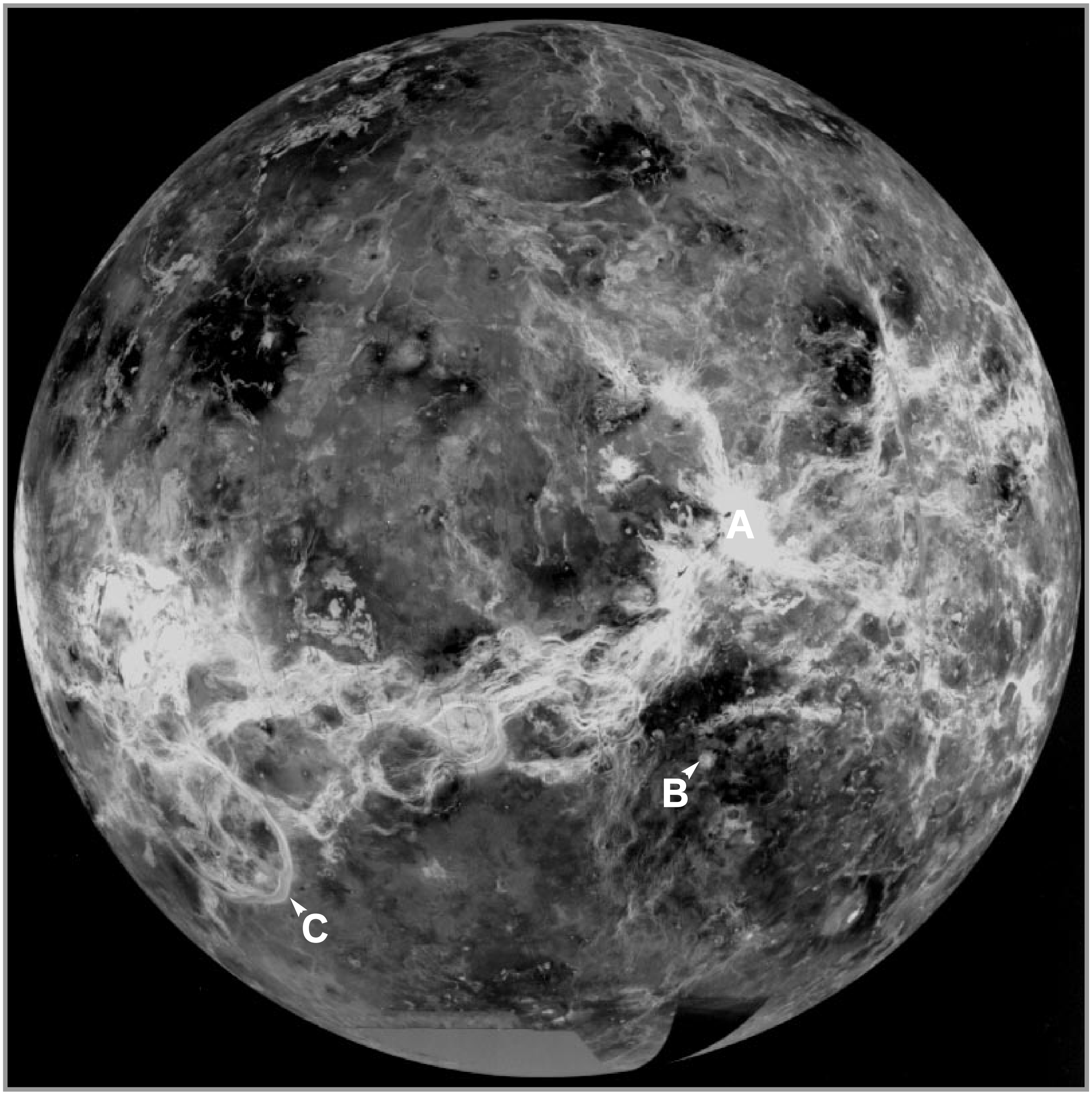


Figure 10.4. Magellan radar mosaic of Venus. North is to the top. The smooth gray and black sections at the bottom of the figure are portions of the south pole that were not imaged by the spacecraft. (NASA P-39225.)

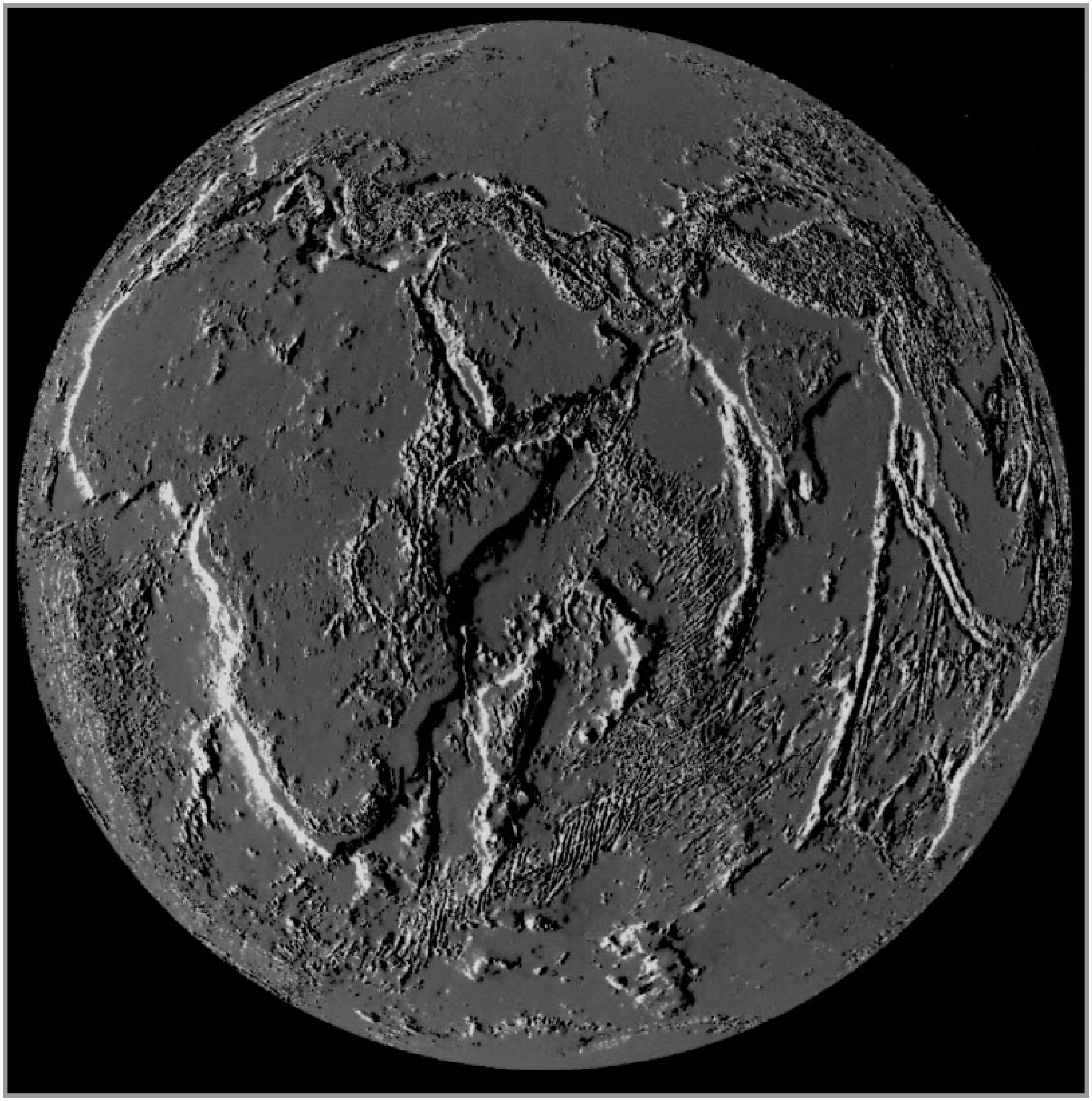


Figure 10.5. *Global representation of the Earth in which higher standing topography is shown as brighter, centered at 0°, 50°. North is to the top. (Courtesy U.S. Geological Survey, Flagstaff, Arizona.)*

Exercise Two is suggested as an introductory exercise.

1.0 hours

Geologic Features of Mars

Instructor Notes

Suggested Correlation of Topics

Mars, geomorphology, gradation, impact cratering, tectonism, volcanism

Purpose

By examining images of martian surface features, students will learn to identify landforms and interpret the geologic processes which formed them.

Background

To perform this exercise students should have been introduced to the four geologic processes—gradation, impact cratering, tectonism, and volcanism.

In many ways Mars is similar to Earth. Martian volcanoes, although apparently extinct, are similar to those on Earth. Mars does not experience plate tectonics like the Earth, but it does have familiar tectonic features, such as rift zones. Gradation on Mars is also similar to the forms observed on Earth, although liquid water is not stable on the surface of Mars today. On Mars, as on most other worlds, impact cratering is much more conspicuous than on Earth. The number, size, and freshness of craters, and their relation to other geologic features, can be used to determine the relative ages of Martian surfaces.

A more detailed description of the processes that have acted on Mars is presented in the students' introduction.

Science Standards

- Earth and Space Science
  - Energy in the Earth system
  - Origin and evolution of the Earth system
  - Earth in the solar system

Answer Key

1. It is approximately circular, but has numerous over-lapping craters within it and at the margins.

2. Answers will vary, but should include: a) erosion, b) tectonism (faulting).

3. Geologically young because there are few impact craters. Younger than the surface of the moon.

4. *Answers will vary*. The sharp, straight cliffs and the large dimensions suggest tectonic processes; the stream patterns on the south side are indicative of modification by running water.

5. Ius Chasma is larger by several times.

6. **a.** Northeast (to the top of the photo).

   b. Craters are numerous and degraded, indicating this is a relatively ancient region.

   c. The craters are older than the valleys which cut across the center rims. However, there are also a few fresh, young craters superposed on the channels, indicating that these impacts occurred after channel formation.

7. **a.** The diffuse streaks of bright material are found on the southeast side of craters.

   b. The wind blew from the northwest.

8. **a.** Like Olympus Mons, Apollinaris Patera has radial flow patterns and a basal scarp (cliff). Apollinaris Patera has more craters, a large flow trending to the south, and a less complex caldera than that of Olympus Mons. Olympus Mons is a much larger edifice.

   b. Volcanism, considering its characteristics described above.

   c. Impact formed Reuyl crater, indicated by the ejecta pattern and central peak.

   d. Gradation by running water, indicated by the meandering pattern and tributary channels.

   e. Water that once flowed through Ma'adim Vallis may have deposited sedimentary material onto the floor of Gusev crater.

9. Answers will vary. D, A (C), C (A), B. D is a very old degraded crater. The flows from A are modified at their southern part by sediments from crater D due to flow of water in channel C. So A preceded C. (This is very difficult to see and students may reverse the order of these two events.) Crater B is fresh in appearance—rim is not eroded—and thus is probably very young.

Name ______________________________

Geologic Features of Mars

Purpose

To learn to identify landforms on the surface of Mars and the geological processes that produced them.

Introduction

In many ways Mars is similar to Earth. The same four geologic processes that shape Earth—gradation, impact cratering, tectonism, and volcanism—have left their mark on Mars. Volcanism has produced vast lava flows, broad shield volcanoes, and plains of volcanic material. Mars has some of the largest volcanoes in the solar system, including Olympus Mons, a massive volcano many times larger than the Island of Hawaii. Olympus Mons is only one of four huge volcanoes in a 3000 km-wide region called Tharsis. These volcanoes erupted repeatedly over many millions of years, growing higher with each lava flow. Enormous collapse calderas are found on the summits of each of the volcanoes.

Gradation is the dominant geologic process acting on Mars today. Mass movement is the displacement of material by landslides or slumping through the action of gravity. Aeolian (wind) activity is also a continuing process of gradation. Sand and dust particles carried by the wind form dunes and windstreaks. Although temperatures below freezing and low atmospheric pressures do not allow liquid water on the surface of Mars today, gradation processes involving running water were important on Mars in the past. Valley systems cut through many of the cratered terrains of Mars and have characteristics analogous to water-cut valleys on Earth. A mystery concerning water on Mars is "Where did it go?" Some water probably seeped into the ground and is frozen there today as ice, and some likely escaped into space over time. Moreover, the polar caps contain some water ice. Mars, like the Earth, has seasons. The polar caps shrink during local summer and grow during local winter.

Although Mars does not have plate tectonics like the Earth, there are many tectonic features that show its surface has been deformed. Stresses can be caused by subsurface uplift or by the addition of mass (such as lava flows) that weigh down an area. Extensional stresses have led to the formation of great valleys such as Valles Marineris, the longest canyon system in the solar system.

As on the Moon, Mercury, Venus, and most of the outer planet satellites, impact craters are found on the surface of Mars. Craters can be used to determine the relative ages of martian surface materials; in general, older surfaces have craters which are more numerous, larger, and more degraded than those on young surfaces. Moreover, the principles of superposition and cross-cutting relations indicate that a feature which at least partly covers another feature is the younger. Thus, if a valley cuts through a crater, the crater must be older. Individual craters are degraded or destroyed over time by gradational processes and further cratering. Therefore, crisp craters with upraised rims and steep sides are young, while less distinct and eroded craters with partial rims are probably older. Through a combination of these principles, the relative ages of geologic features can be determined, and a sequence of geologic events developed.

Questions and Procedures

Examine Figure 11.1: Olympus Mons is a shield volcano 600 km in diameter, towering 25 km above the surrounding plain. Around its base is a steep cliff as high as 6 km. It has a summit caldera some 80 km wide.

1. Examine the caldera (labeled A) and describe its shape.

2. Suggest some ways in which the scarp around Olympus Mons might have formed.

3. Do you think the surface of Olympus Mons is geologically old or young, compared to the surface of the Moon? Explain your answer.

Examine Figure 11.2: Ius Chasma is part of the western end of Valles Marineris, the largest Martian canyon. Smaller valleys join the main east-west chasm.

4. Which of the four geologic processes might be responsible for the formation of Ius Chasma?

5. Compare the size of Ius Chasma and its tributaries to the size of the Grand Canyon of Arizona. Which is larger, and by how much?

Examine Figure 11.3: Valleys west of Chryse Planitia. Similar to some river systems on Earth, these martian channels have a branching pattern.

6. **a.** In what direction did the water flow?

   b. Based on the number and morphology of craters, is this a relatively old or young region of Mars?

   c. Are the craters you observe older or younger than the valleys? Use the principle of cross-cutting relations to justify your answer.

Examine Figure 11.4: The Hesperia region in the southern hemisphere consists of cratered plains which have been modified by aeolian processes. Wind-produced features, called bright windstreaks, are associated with many craters.

7. **a.** Describe the appearance and orientation of the windstreaks.

b. If windstreaks are dust deposits formed downwind from the craters, what wind direction is indicated here? (Remember that wind direction refers to the direction from which the wind blows.)

Examine Figure 11.5: Apollinaris Patera and surrounding region. All four geologic processes can act to shape a planetary landscape. For the following, you will use the knowledge from previous questions to identify Martian landforms and describe the geologic processes that created them.

8. **a**. Compare Apollinaris Patera (marked A on Figure 11.5) to Olympus Mons (Figure 11.1). How are they similar, and how are they different?

   b. What process do you think formed Apollinaris Patera? How can you tell?

   c. What process do you think formed Reuyl crater (marked B on Figure 11.5)? Justify your answer.

   d. Ma'adim Vallis is the channel in the southeast part of the photograph, marked C. Which of the four processes do you think formed Ma'adim Vallis? Justify your answer.

   e. Consider the relationship between Ma'adim Vallis and Gusev, the 160 km diameter crater marked D. What could be the origin of the material that comprises the floor of Gusev? (Hint: the region slopes to the north.)

9. Based on your observations, what is the probable order of occurrence of A, B, C, and D in Figure 11.5 (i.e., which came first, second, third, last)? Give evidence for your answer.

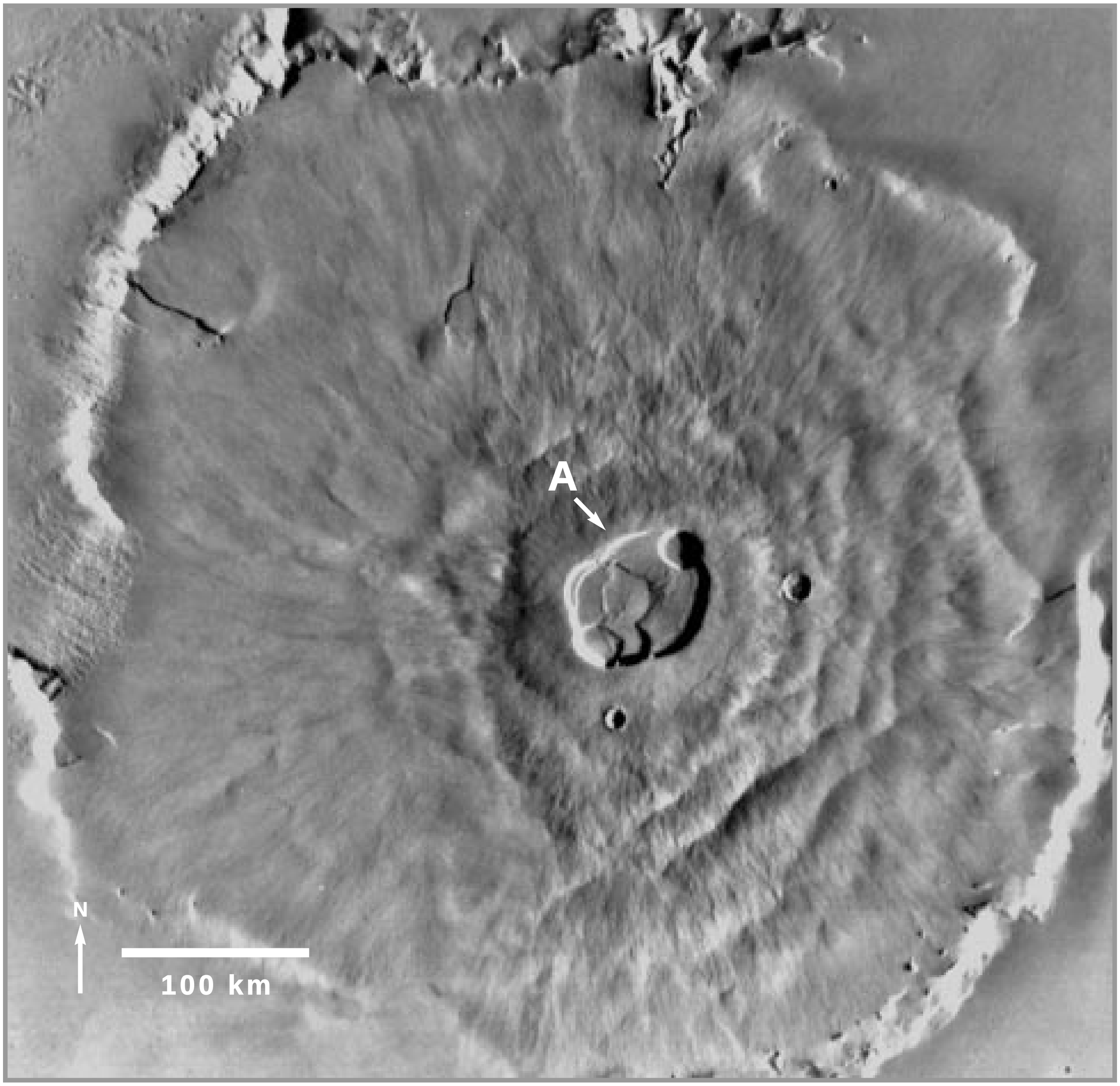


Figure 11.1. *Martian shield volcano, Olympus Mons. The summit caldera is about 80 km in diameter. (Viking MDIM mosaic 211-5360)*

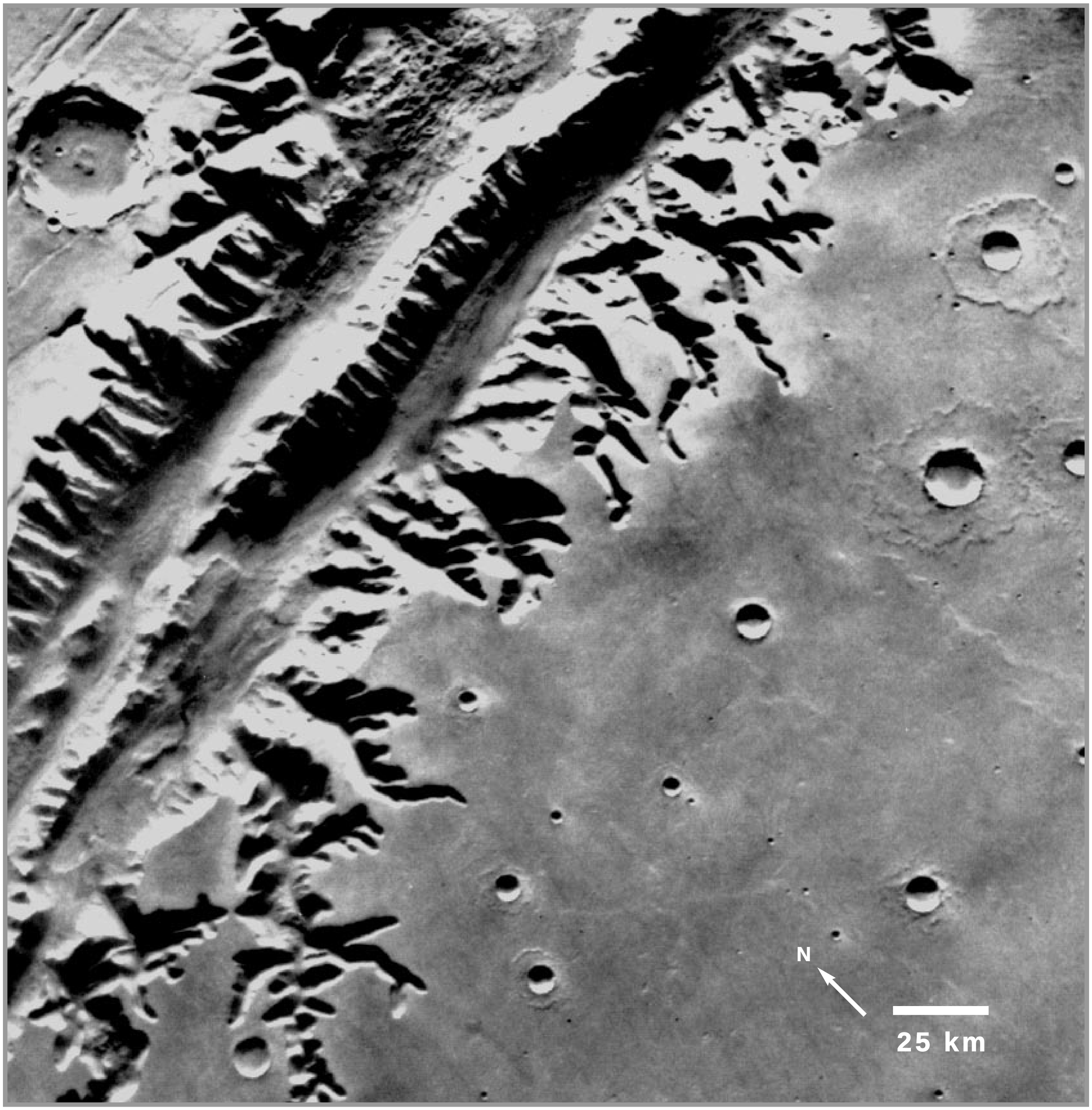


Figure 11.2. *Ius Chasma, part of the Valles Marineris system. (Viking image 645A57.)*

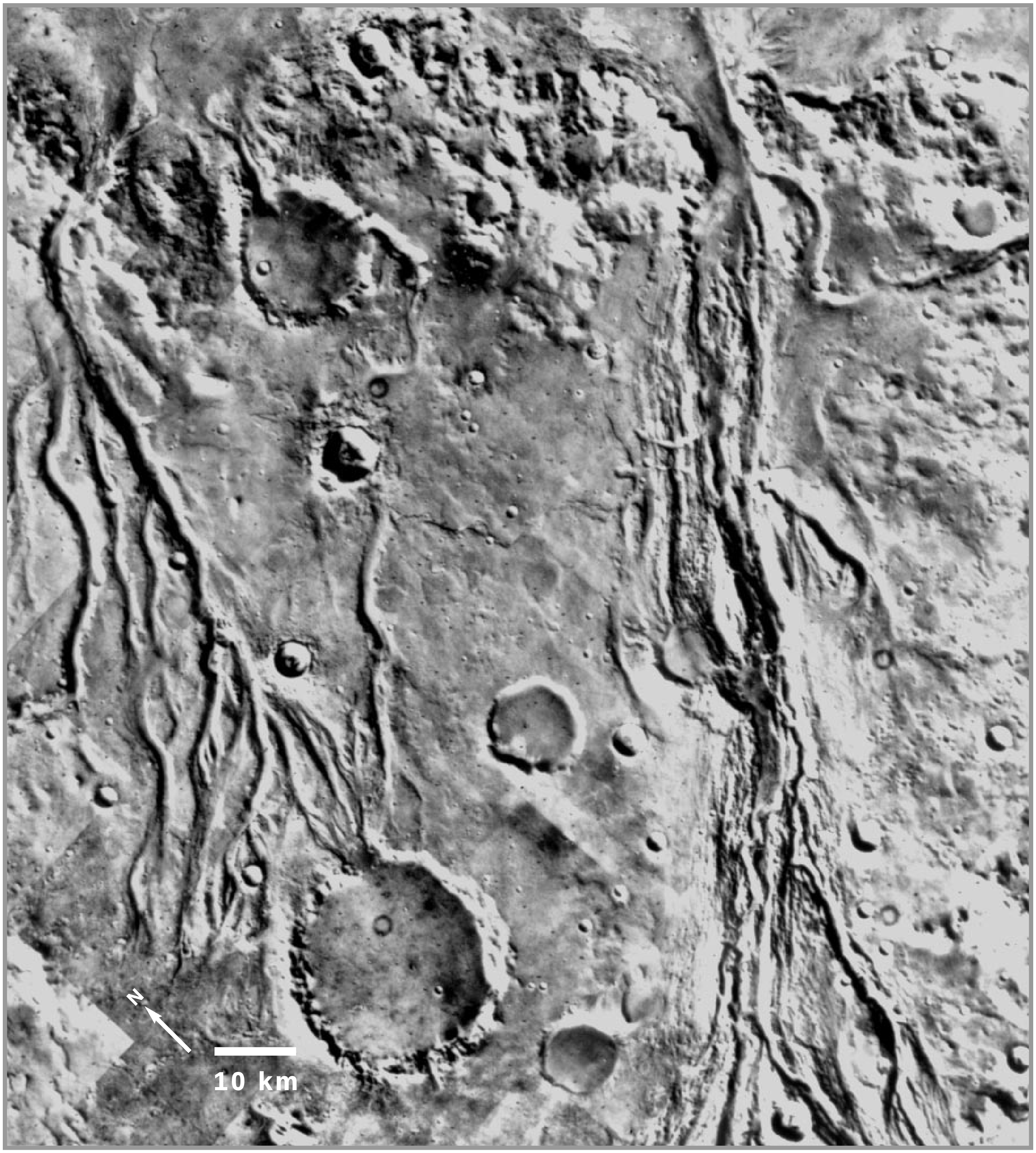


Figure 11.3. *Valleys on western Chryse Planitia near the Viking Lander 1 site. The large crater at left center is 28 km in diameter. (Viking mosaic P-17698.)*

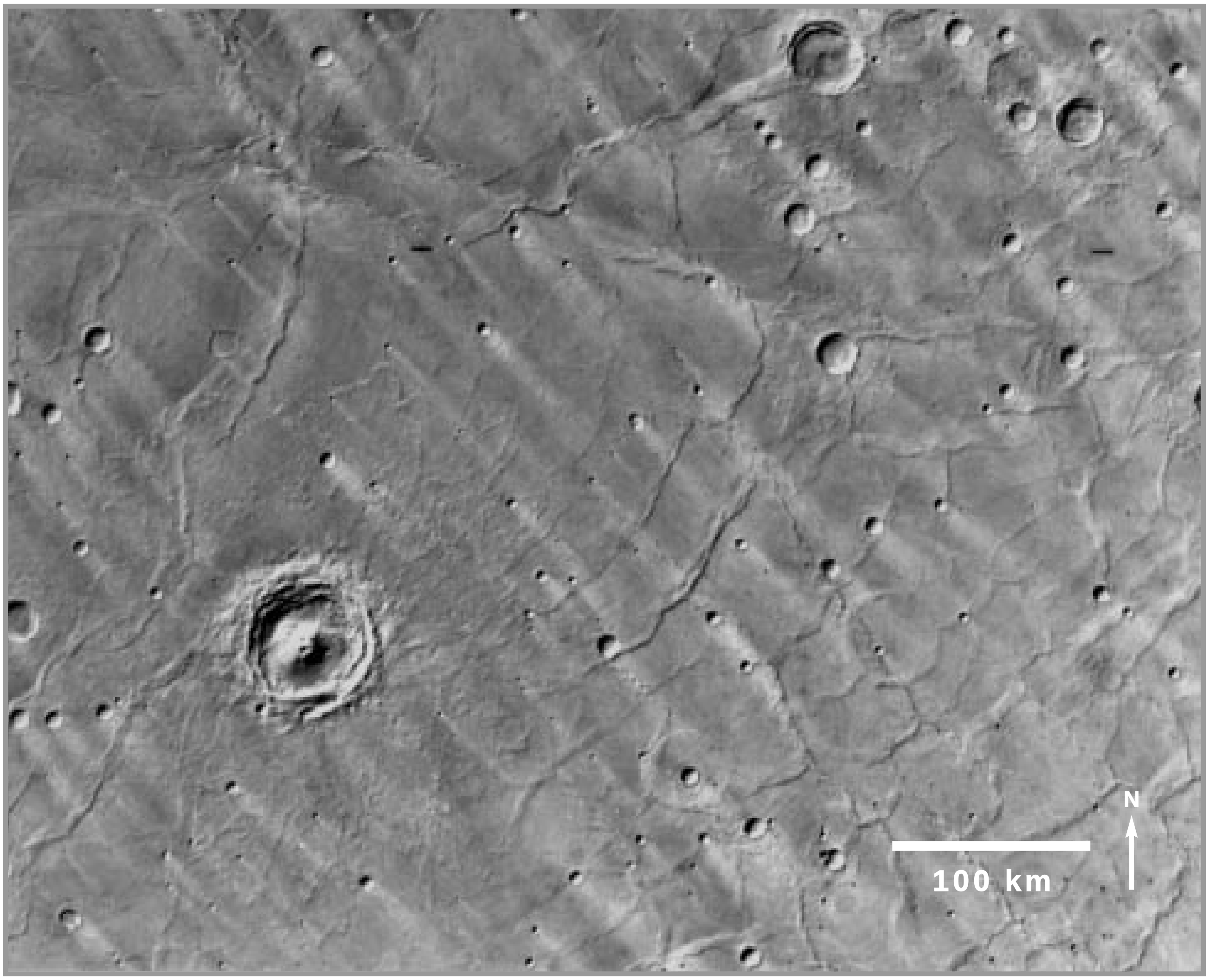


Figure 11.4. *Hesperia Planum, showing bright windstreaks associated with some of the craters. Location: 24° S, 245° W. North is to the top. (Viking MDIM Volume 4.)*

Figure 11.5. *Apollinaris Patera and surrounding region centered at 10° S, 190° W. (Viking MDIM Volume 4.)*

Exercise Two is suggested as an introductory exercise.

1.0 hours

Geologic Features of Venus

Instructor Notes

Suggested Correlation of Topics

Venus geomorphology, impact cratering, radar, remote sensing, tectonism, volcanism

Purpose

The objective of this exercise is to introduce the student to the remote sensing technique of radar imaging and to introduce the surface features found on Venus.

Materials

Suggested: clear acetate or overhead projector film, overhead projector markers, tape, 25 cm piece of string

Substitutions: tracing paper, pencil, ruler

Background

This exercise introduces the use of radar images for geologic feature identification. Most people are not familiar with radar as an imaging system. Consequently, the student introduction contains extensive information to aid in completing this exercise. With completion of the exercise, the student should be able to recognize and identify some of the major geologic features found on Venus and understand the use of radar as a remote sensing technique.

The explanation of radar and radar imaging in this exercise is highly simplified, focusing only on surface roughness. Factors such as wavelength, incidence angle, polarization and signal processing are not presented, although these factors are very important controls on the appearance of radar images. Students may only be familiar with the use of radar for weather satellites, air traffic control monitors, and police speed guns. Air traffic control radar and police speed guns work because the metal in cars and airplanes is highly reflective at radar wavelengths. Because radar is an active system (it emits energy), it is not dependent on the sun or good weather for use; it can be used at night and is an important safety measure for air travel. Weather satellite radar systems use relatively short wavelengths, small enough for individual ice crystals and water droplets in clouds to reflect the signal back to the satellite, producing the images we see on the evening newscast. The Magellan spacecraft at Venus used a longer wavelength system that penetrated the thick cloud cover that shrouds the planet.

The vertical stripes on some images of Venus (most obvious in figures 12.4, 12.5 and 12.9) are artifacts of the Magellan imaging system. Each stripe represents a single orbit of the spacecraft. Black stripes are present where the spacecraft did not image.

Teacher Recommendations

The instructor is encouraged to present the electromagnetic spectrum before working this exercise, and to explain the radar part of the spectrum. The exercise is divided into three parts. The first part examines Venus features and asks the student to answer questions based on the images. The second part has the student identify various features within a region of Venus. The third part has the student design a rover journey to some of the features identified in part two. The “rover” part of this exercise will produce many and varied paths, depending on features identified, features chosen for a rover visit, and the rover starting point. The map in the answer key identifies all the features students are asked to locate, and includes two sample rover paths. The test for rover path accuracy is in the distance used (25 cm maximum) and whether the rover stays on the dark (smooth) plains while traveling to the selected features of interest. This exercise can be done in groups or by individual students. A further suggestion for this exercise is to plot all the rover paths on a single page (or on an overhead projector viewgraph) and have the class decide on the path that is best, providing the most interesting scientific results with the least risk to the rover. Such a discussion closely simulates planning meetings for NASA missions. For further interdisciplinary application, rover groups could assign different tasks within each group: someone to draw a picture of the rover, someone to draw pictures of what the rover might see, a science group to plan the rover path, a "reporter" to write up a travelogue of what the rover did and saw, and any other tasks that the students consider to be important to the mission.

Science Standards

■ Earth and Space Science

- Origin and evolution of the Earth system

Mathematics Standards

■ Measurement

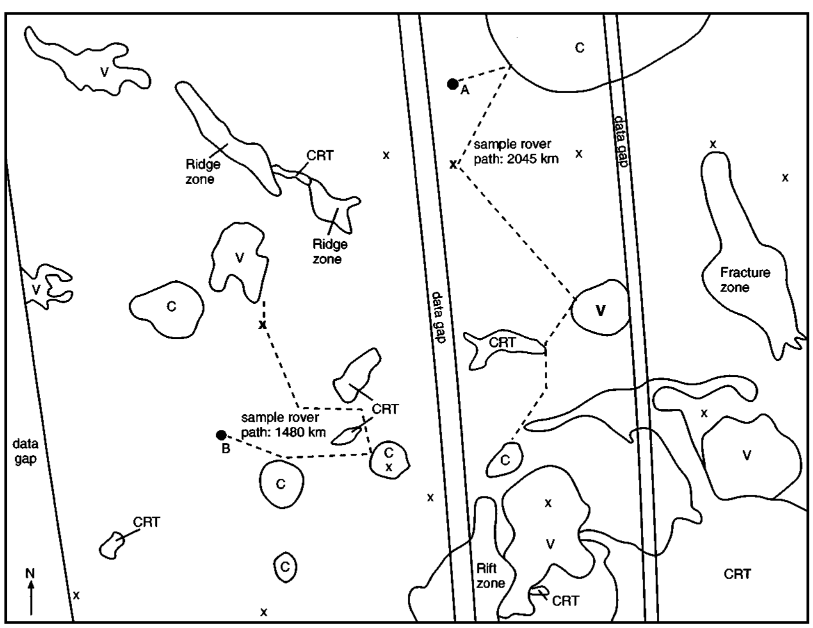
Answer Key

1. **a.** The ejecta, rim, and central peak consist of broken rock fragments and have a rough texture which appear bright in the image. The crater floor is smooth and appears dark in the image.

   b. Feature A has a rough texture.
2. Crater is older. It had to already be there to be rifted by later tectonic activity.
3. No. The same tectonic activity that formed the complex ridged terrain has not affected the volcanic plains, meaning that the plains are younger, and that either that style of tectonism has ceased, or that it is episodic and has not occurred since the plains were emplaced.
4. Almost all appear to have a central summit crater, and to be cone shaped. Some are brighter than others indicating differences in texture.
5. Flow textures are both rough (bright) and smooth (dark). The flows have lobate outlines and contain "feeder" channels (usually dark in tone) that supplied the lava to the flow front.
6. ~200 km in diameter
7. a. Flows are rough (bright on the image).

   b. ~150 km

NOTE: On the student maps, they will label all tectonic zones as "rift zones." On the answer key, these zones are marked as rift zones, ridge zones, and fracture zones. Ridge zones have positive relief, rift zones have negative relief, and fracture zones have not had any displacement (neither positive nor negative).



Name ____________________

Geologic Features of Venus

Purpose

To learn about geologic features on Venus and the use of radar images.

Materials

Clear acetate, overhead projector markers, tape, 25cm piece of string

Introduction

Radar is an imaging and detection system that uses the microwave section (~1mm to ~1m wavelengths) of the **electromagnetic spectrum.** By changing the wavelength used by radar, different objects can be detected. Radar is an active system in that the signal energy is transmitted from and received by the instrument. Our eyes are a passive system, we only receive reflected energy (as from the sun or a light bulb). Because radar produces and receives its own energy, it is not generally dependent on environmental conditions for its use. It can be used during the day and at night, and because radar wavelengths can penetrate clouds, it can be used during most kinds of weather.

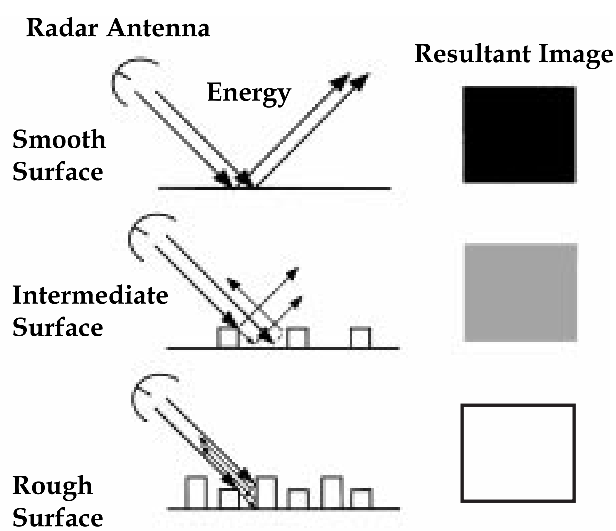


Figure 12.1. *Diagram of radar reflectance and effect on resultant image. Smooth surfaces reflect the incident energy away from the antenna, producing a dark tone (non-return) on the image. A rough surface scatters the incident energy, some of which will be returned to the antenna and produce a bright tone on the image.*

All electromagnetic energy interacts with the objects and surfaces it encounters by being absorbed, transmitted, or reflected. We see only the light that is reflected (bounced) toward our eyes. The radar system will only “see” the radar waves reflected back to the antenna (Figure 12.1). The more energy reflected back to the antenna, the brighter the tone created in the resultant image. In general, smooth surfaces are dark in a radar image and rough surfaces appear bright. One way to think about radar is that it shows how the surface “feels” (rough or smooth), whereas a conventional photograph shows how a surface “looks” (color and brightness). Because we are not accustomed to thinking about a surface in terms of its texture, working with radar images can be difficult at first.

Figures 12.2 a and b show the same area of the Mojave Desert of California. Figure 12.2a is a visible wavelength Landsat satellite photo and 12.2b is a Seasat radar image. The feature marked A is a lava flow. In the Landsat photo it is dark, because the rocks are dark in visual appearance; but on the radar image the lava flow is very bright, because the surface is very rough and scatters the radar energy back to the antenna. The feature marked B is a dry lake bed. In the Landsat photo it is light, because the materials are light colored sands and clays. In the radar image, the lake bed is very dark and difficult to distinguish from the surrounding dark area. This is because both the lake bed and the surrounding sands are very smooth. Mountains appear bright in the radar image. It is easier to distinguish mountains from the surrounding sand deposits in the radar image than in the Landsat photo. Because of the radar’s sensitivity to surface texture, it is able to image structural features (such as faults and fractures) that may be undetected in a visible wavelength photo. Note that a cinder cone within the lava flow (marked C) is easier to see in the radar image than in the Landsat photo.

Radar was used to image the surface of Venus because thick cloud cover makes the use of visible wavelength imaging impossible. The Venus radar images in this exercise were acquired by the Magellan spacecraft, which orbited Venus from 1990 to 1994. The vertical black stripes on some images are missing data, places where the spacecraft did not image the surface.

Questions and Procedures

Part A

Figure 12.3 shows two impact craters on Venus. They are surrounded by smooth volcanic plains, which are dark on the radar image. The crater rims are easily identified, as are the **ejecta** deposits.

1. **a.** Describe the ejecta, rim, floor, and central peak of the smaller crater in terms of texture.

   b. The ejecta of the larger crater is different from that of the smaller crater. Part of the ejecta of the larger crater was molten, melted rock and formed flows. What is the texture of the ejecta flow labeled A?

The right side of Figure 12.4 shows a rift zone on Venus. Although the rift zone appears almost flat in the image, the topography of this area is more like the Grand Canyon of Arizona, with steep cliffs and deep valleys. The other bright lineaments in this figure are fractures and faults.

2. Note the crater at A. Is it younger or older than the rift? How do you know?

Figure 12.5 shows an area of "complex ridged terrain," the term used for some mountains and highlands on Venus. This area has been fractured, faulted, rifted, uplifted and surrounded by younger smooth (dark) plains. The deformed area is very bright in the radar image because the complex structures have produced very rough terrain.

3. Does the tectonic activity that formed the complex ridged terrain appear to have affected the volcanic plains? What does this indicate about tectonic activity in this area and the age of the volcanic plains?

Figure 12.6 shows many small (1–10 km in diameter) volcanoes, constituting a "volcanic shield field." Volcanism has played a major role in the formation of the surface of Venus, and shield fields are common.

4. List any similarities and differences among the individual volcanoes.

Most dark (smooth) plains on Venus are volcanic. However, not all volcanic flows on Venus are dark; some are bright. Figure 12.7 shows an area of volcanic flows.

5. Describe the field of flows shown in the image. Include information as to texture, outline, and any other interesting features.

So far all the figures have shown features that can be found on Earth as well as on Venus. Figure 12.8 shows features that may be unique to Venus. Termed "coronae" (the singular is "corona"), these features are identified by circular sets of fractures. Some form low, circular domes that can have associated volcanic flows (for example, the flows to the north and northwest of the corona marked A); or the centers may have subsided, leaving bowl-shaped depressions, which can be filled by lava flows. Radial fractures commonly surround coronae, giving a "buglike" appearance.

6. What is the diameter of the largest corona in the image?

7. **a.** Are the flows to the north and northwest of the corona labeled A rough or smooth in texture?

   b. How far from the letter A did the volcanic material flow to the northwest?

Part B

Figure 12.9 shows part of the Carson Quadrangle of Venus, centered at 11°S, 345°E. The area shown is equal to about two-thirds of the continental United States. All the types of features shown in the previous figures can be found on this image; however, due to their small size, shield fields are very difficult to see. The black areas are regions that were not imaged by Magellan. The bright circular spots are where meteoritic material struck the surface without forming an impact crater. These are called "splotches." Be sure to note the difference in scale between this figure and the previous ones.

Tape a piece of clear acetate to the figure. Draw a box outlining the image. Trace the scale bar and north arrow. On the acetate, identify all the features listed below.

A. Identify as many coronae as you can. Trace their outline and place a "C" within the outline.

B. Identify and mark with an "x" all the craters in the image area.

C. Outline and label with the letters "CRT" all areas of complex ridged terrain.

D. Outline and label with an "R" all rift zones.

E. Outline and label with a "V" areas of volcanic flows. Do not include the extensive smooth plains flows. Look for the variation in texture as seen in Figure 12.7.

Part C

One day, planetary scientists hope to send a robotic rover to the surface of Venus. Because the surface temperature is about 470°C (~870°F), people will probably never set foot on this planet. In this part of the exercise you will plan a rover journey.

In planning the rover path remember these rules: 1) the robotic rover can only travel on smooth terrain (dark plains); 2) it cannot cross rift zones or complex ridged terrain; 3) it must travel in straight lines (turns are allowed, but the path will be lines and angled turns rather than curves); and 4) the rover can *cross* the black non-imaged parts of the image, but you cannot drive for any great distance inside the black areas, because there may be unknown obstacles.

You should develop a rover path to include a visit to at least 1 crater, 2 coronae, the edge of a region of complex ridged terrain, and an area of volcanic flows (not including the smooth plains). Spacecraft and rover engineers designed the rover to travel a maximum distance of 3430 km (a distance of 25 cm on the image) starting from either landing point A or B. Because of the high temperatures on the surface and the limited fuel carried by the rover, 3430 km is the maximum lifetime-distance expected of the rover. Optimizing your path to travel less than 3430 km is highly recommended by the design team. Use the string (or a ruler), the image, and your acetate map with the features identified to plan a rover path to visit the five features listed above.

You may choose any individual feature to visit, but you must begin at either point A or B, and you must complete the path to all five features in 3430 km (25 cm) or less. You do not need to return to the starting point. If you are having difficulty in planning the rover path, ask your instructor to check that you have identified all possible locations for each type of feature. Once you have settled on the features to visit and the rover path, trace the path onto your acetate "map."

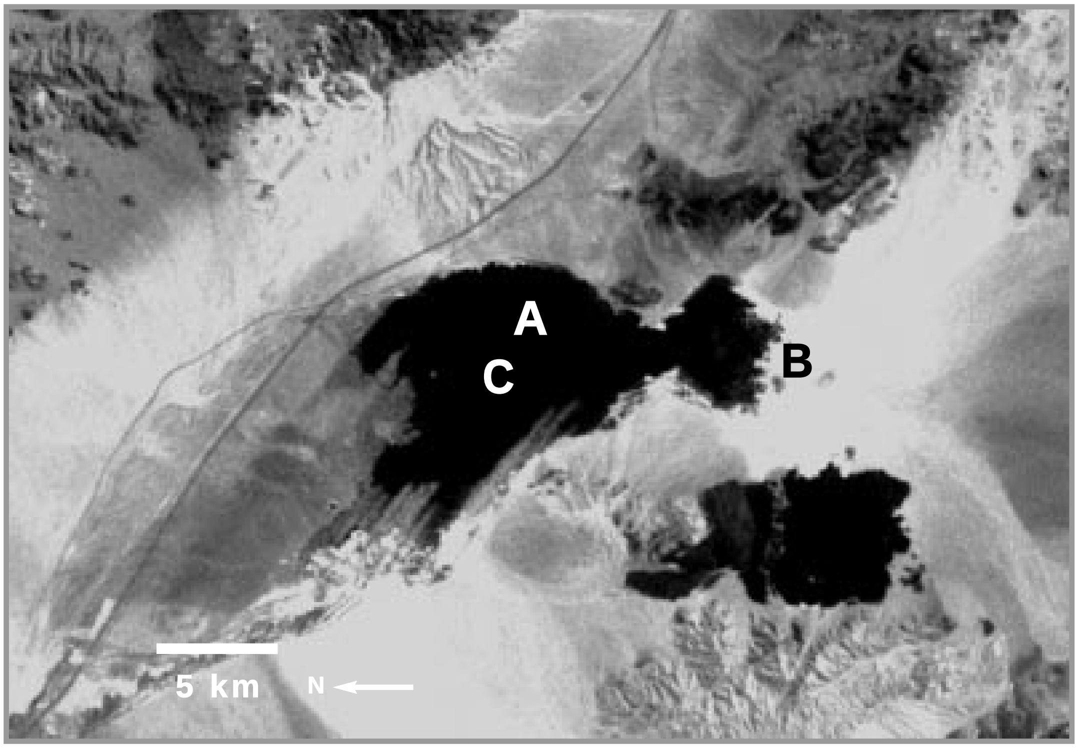


Figure 12.2.a. *Landsat photo of part of the Mojave Desert, CA.*

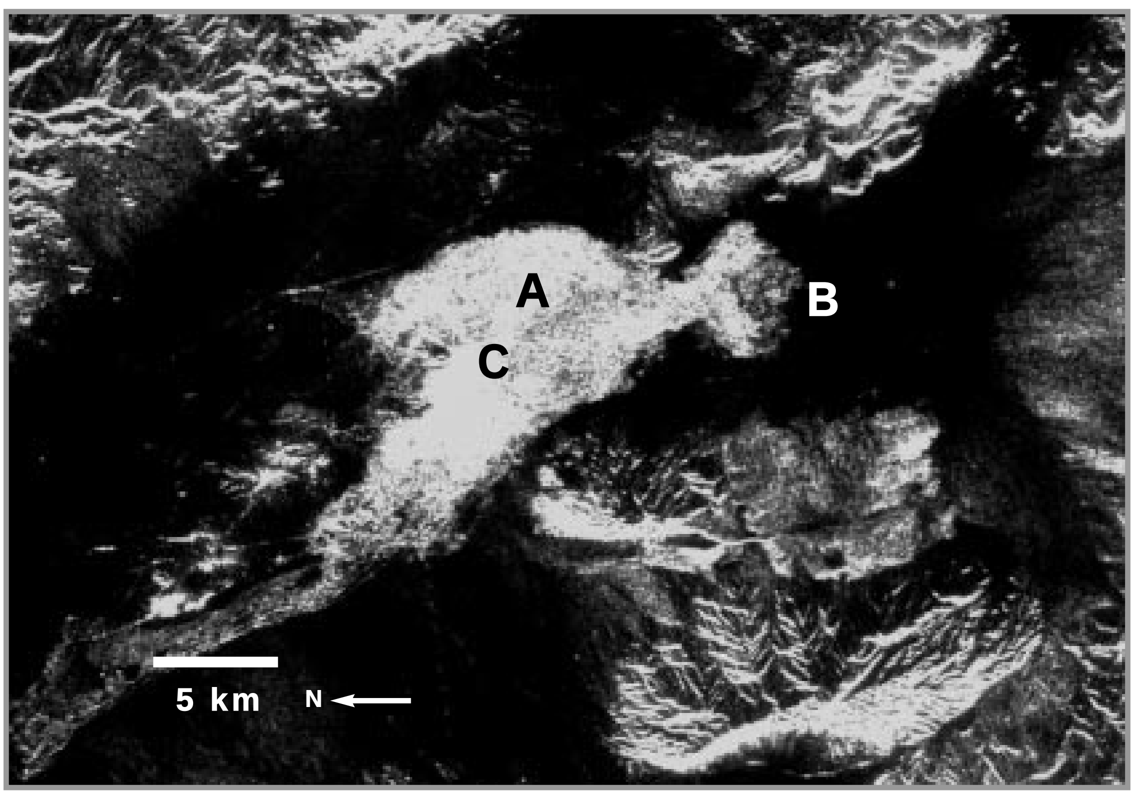


Figure 12.2b. *Seasat radar image of the same part of the Mojave Desert, CA as shown in Figure 12.1a. The feature labeled A is the Pisgah lava flow. The feature labeled B is a dry lake bed. The feature labeled C is a cinder cone.*

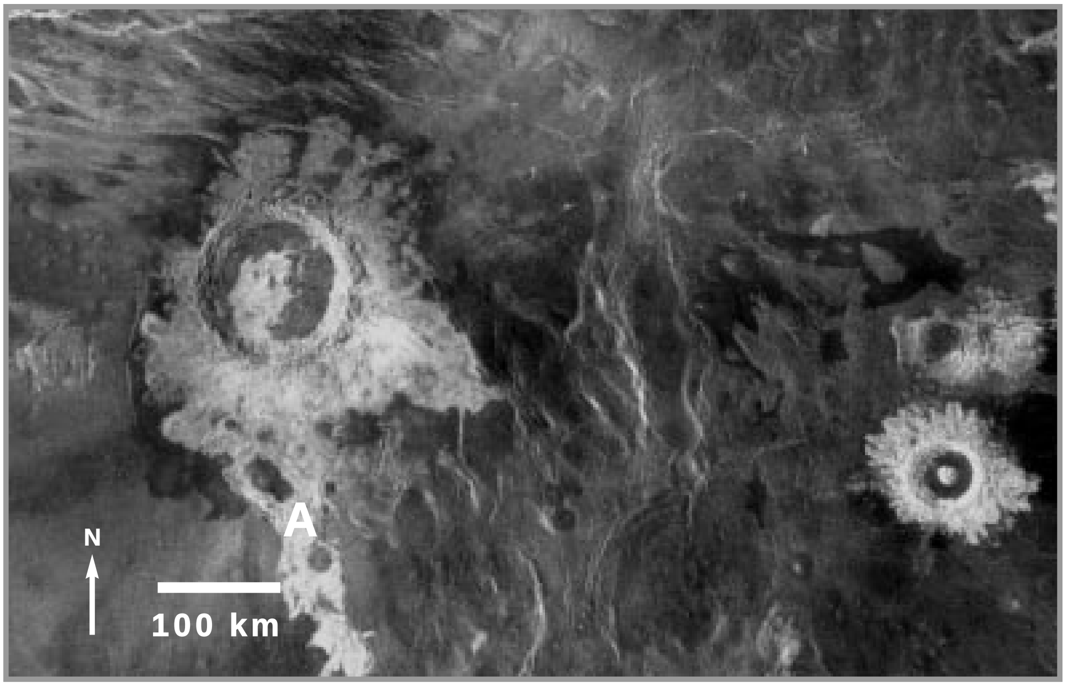


Figure 12.3. The prominent circular features in this image are impact craters. Magellan radar image (F-MIDR 30N287). North is to the top.

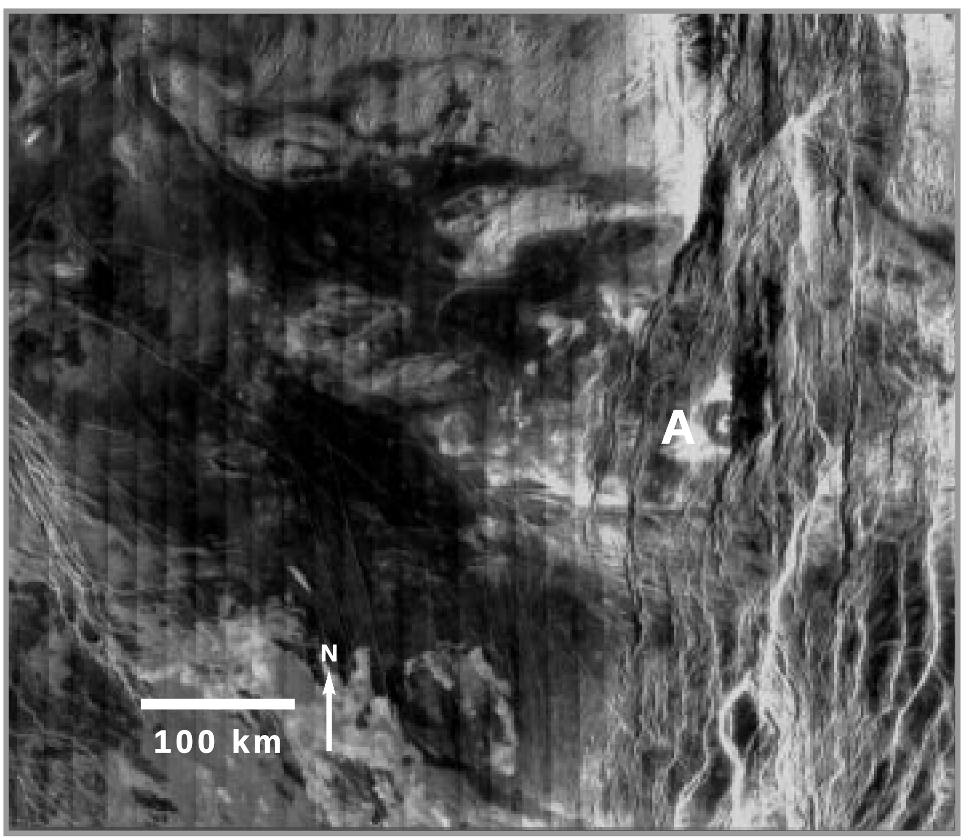


Figure 12.4. *The right side of this image shows a major zone of rifting. Note that the crater labeled A has been cut by the rift, with part of the crater visible on both sides of the rift. The thin linear features in the southern portion of this image are faults and fractures. Magellan radar image (F-MIDR 30N281). North is to the top.*

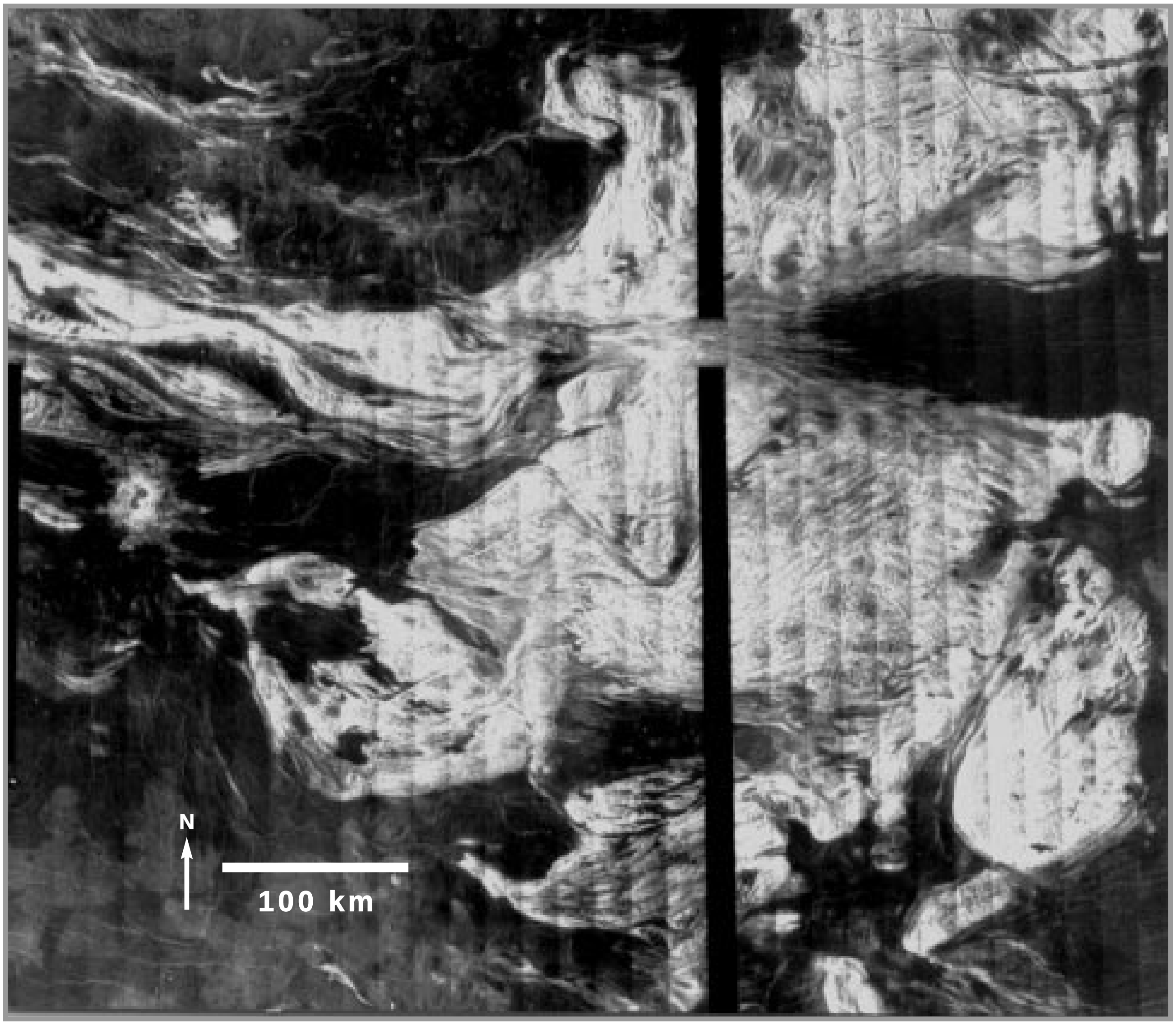


Figure 12.5. *This image shows the terrain termed "complex ridged terrain" or "tessera" on Venus. Considered by many to be the oldest surface terrain, it has been subject to extensive faulting and fracturing. It generally forms highlands above the surrounding volcanic plains. Magellan radar image (F-MIDR 30N123). North is to the top.*

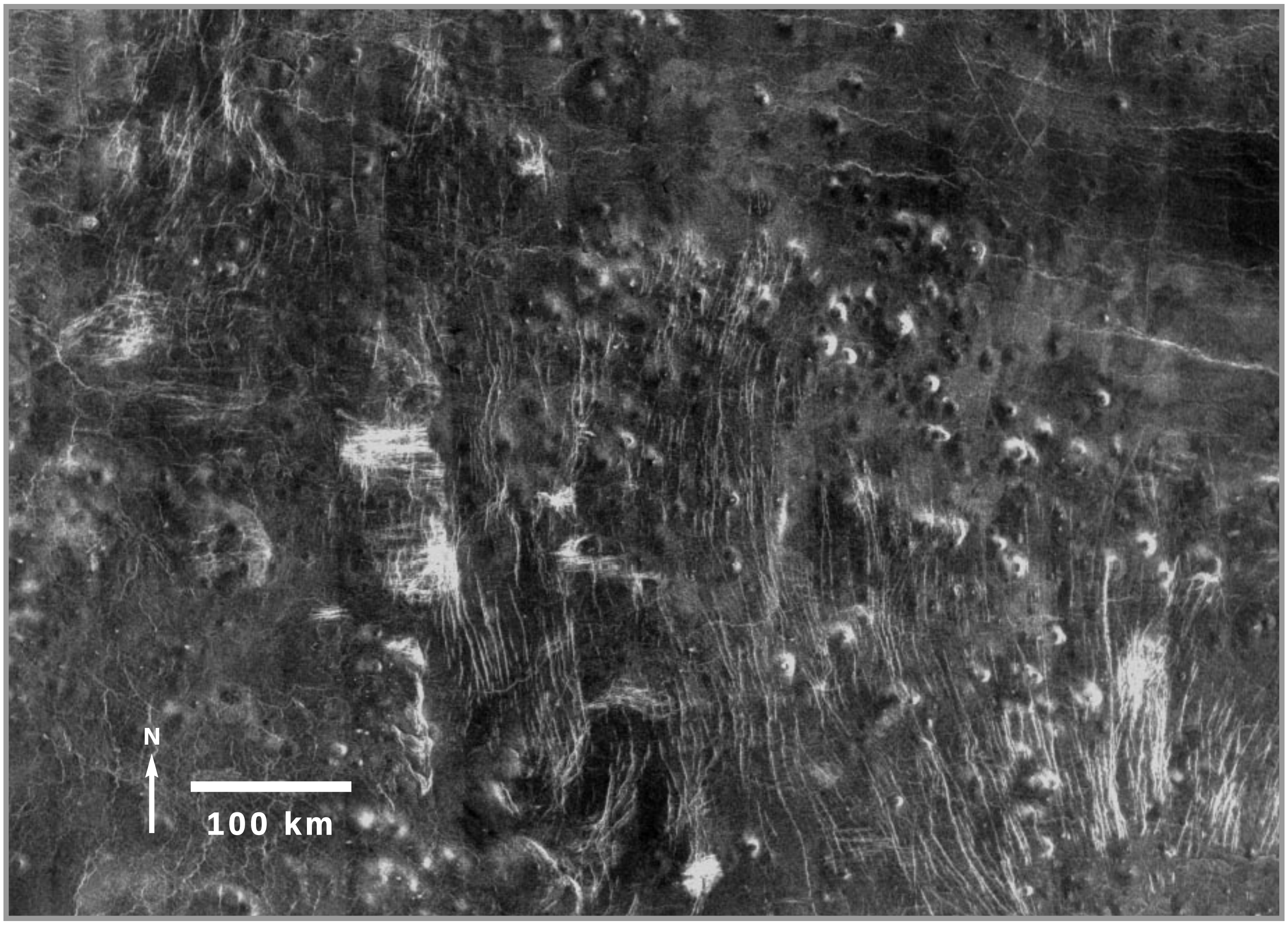


Figure 12.6. *Volcanoes come in all sizes on Venus. The ones in this image range from 1 to 10 kilometers in diameter. While volcanoes of this type and size are sometimes found as an isolated structure within the volcanic plains, they are generally found in clusters, termed "shield fields," like the field shown here. Magellan radar image (F-MIDR 45N119). North is to the top.*

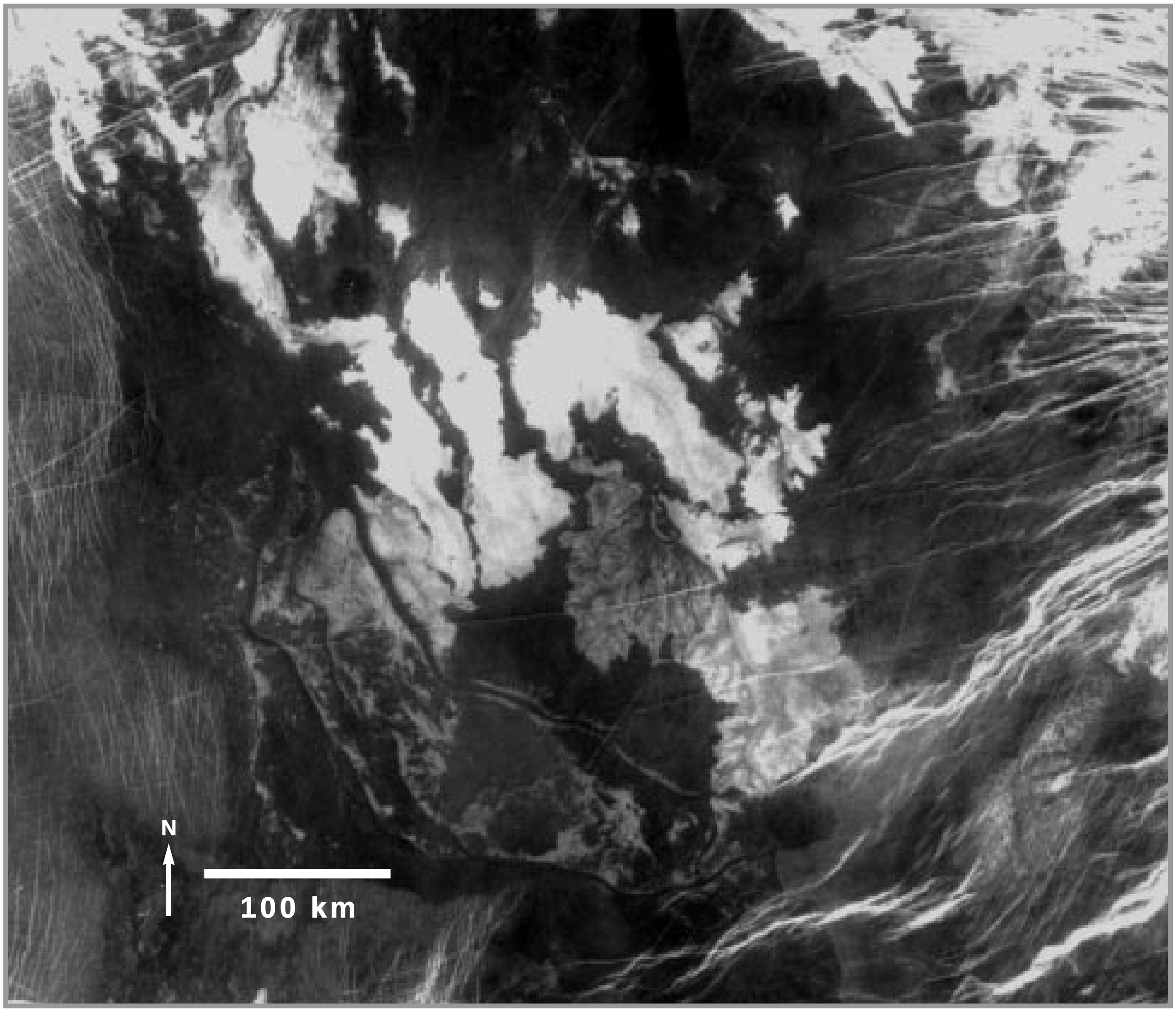


Figure 12.7. *This image shows an area of young volcanic flows. Magellan radar image (F-MIDR 20S180). North is to the top.*

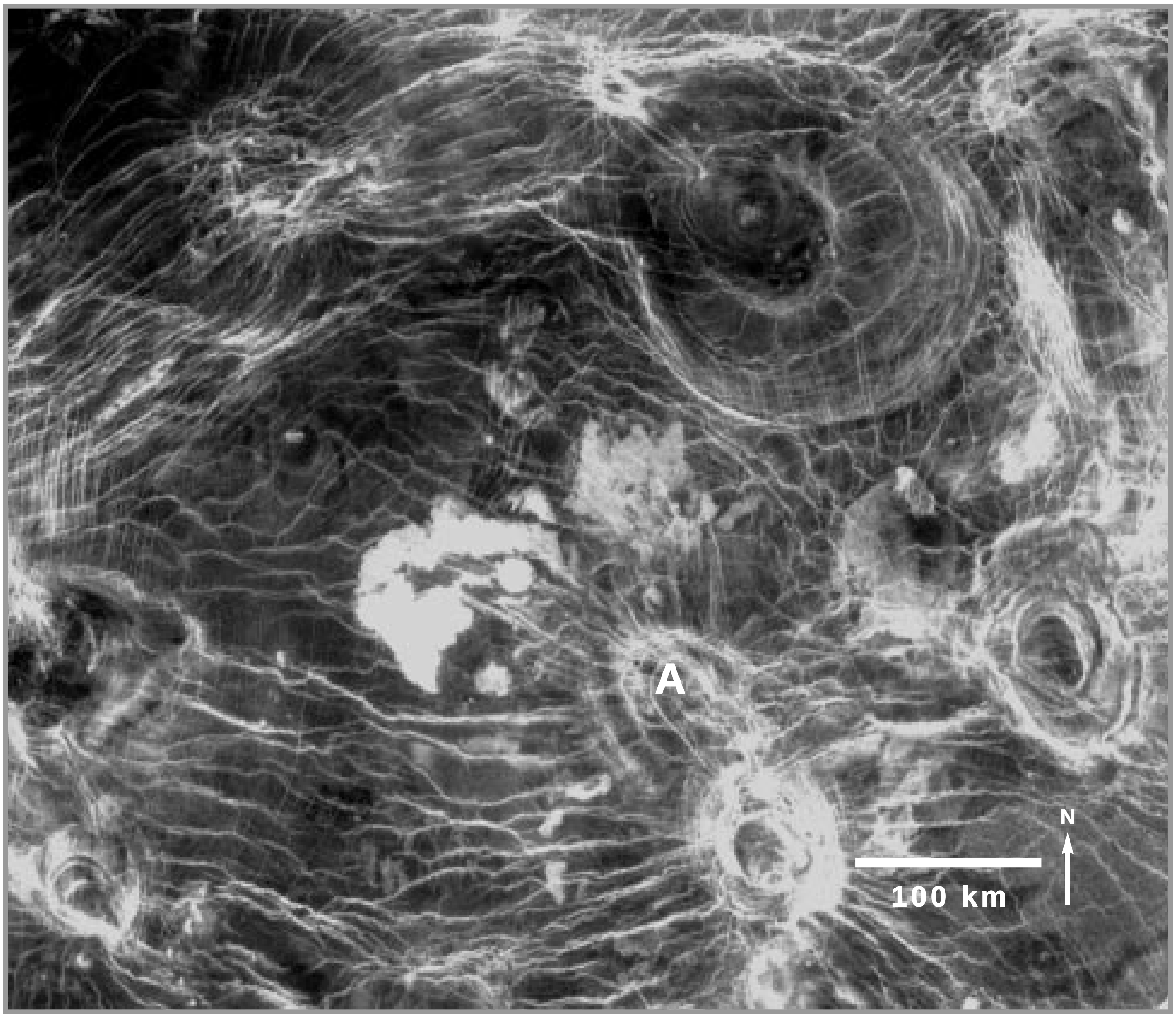


Figure 12.8. The circular features in this image are termed "coronae" (singular: "corona"). Interpreted to have formed by the rise and then subsidence of subsurface plumes of material, these features are easily identified by the characteristic circular and radial fracture patterns. Some coronae have been the site of volcanic flows, such as at the corona labeled A. Magellan radar image (F-MIDR 40N018). North is to the top.

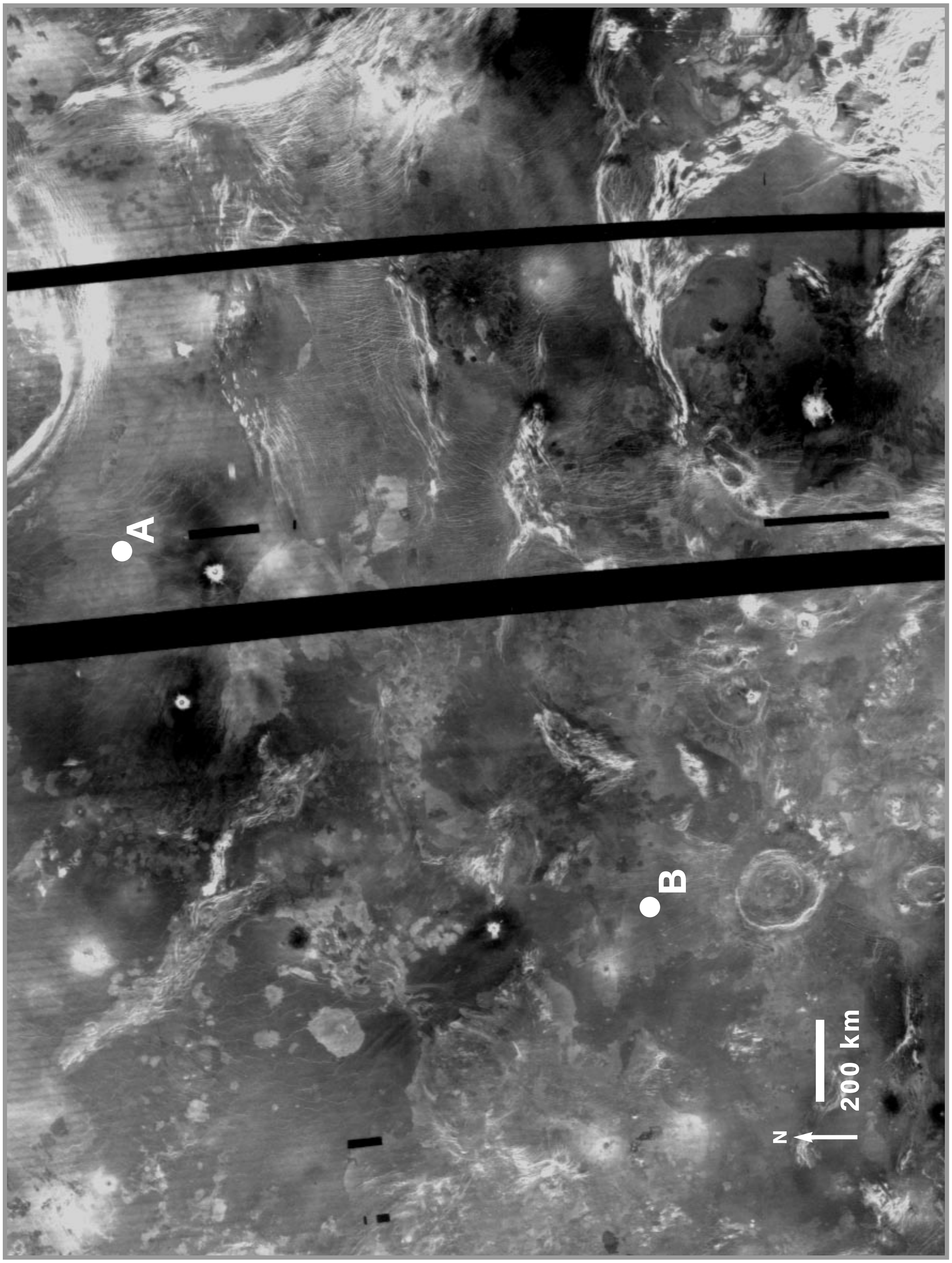


Figure 12.9. *Magellan radar image of part of the Carson Quadrangle, Venus (C2-MIDR 00N337;2). North is to the top.*

Exercises Two and Fifteen are suggested as introductory exercises.

■ ★ 2.5 hours

Geologic Features of Outer Planet Satellites

Instructor Notes

Suggested Correlation of Topics

Comparative planetology, geological mapping, geomorphology, impact cratering, outer planets, tectonism, volcanism

Purpose

This exercise allows the student to develop skills in image interpretation and comparative planetology by analyzing similarities and differences in the landforms and the geological histories of four outer planet satellites. Incorporated are skills of geological mapping, description, and interpretation of tables.

Materials

Clear acetate or overhead projector transparencies (2 sheets per student or group), overhead projector markers (colored markers can be used for added clarity)

Substitutions: Tracing paper, pencils (colored pencils for added clarity)

Background

Reconnaissance of the giant, gaseous outer planets of the solar system and their major satellites was undertaken by the two Voyager spacecraft, launched in 1977. Voyagers 1 and 2 flew past Jupiter and its major satellites in 1979, then explored Saturn and its moons in 1980 and 1981. Voyager 2 flew past Uranus and its satellites in 1986 and explored the Neptune system in 1989. These spacecraft enabled the discovery of the spectacular diversity in the geology of the outer planet satellites.

This exercise uses Voyager images of four of these moons—Ganymede and Io at Jupiter, and Enceladus and Rhea at Saturn—to illustrate this diversity. Most of the outer planet satellites are composed of mixtures of rock and ice. The ice typically is water ice, but more exotic ices, such as methane, are present in some satellites, especially those circling planets farthest from the sun. Io is unusual in being a rocky world, and in the predominance of active volcanism which shapes its surface today. Ganymede and Enceladus show widespread evidence for past volcanism, but the "lava" that once flowed on these satellites is comprised of ice, rather than rock. Ganymede and Enceladus show clear evidence for tectonism, expressed as grooves and ridges. Tectonism has affected Io and Rhea to lesser degrees, and its expression will probably not be apparent to students from the images supplied in this exercise. The most observant students, however, may notice small grooves on Rhea and Io. The abundant cliffs on Io may be tectonic in origin, or they may be related to sublimation of a volatile material and subsequent collapse, a form of gradation.

In general, gradational processes on outer planet satellites are not apparent at the scale of Voyager images and are not specifically addressed in this exercise. However, in discussing the morphologies of craters on Rhea, it would be useful to point out to students that the principal cause of crater degradation on that satellite is the redistribution of material by impact cratering. New craters pelt older ones, creating ejecta and redistributing material to subdue the forms of fresh craters over time. To a lesser extent, mass wasting probably acts to modify crater shapes through the action of gravity.

There are many opportunities for class discussion of specific topics only touched upon by this exercise. For example, question 5 regarding the morphologies of craters on Ganymede might initiate discussion on what could cause their different appearances. Where relevant, information that will help the instructor guide discussion is included in square brackets within the answer key.

It may be interesting to consider the sources of heat for driving the volcanism and tectonism on outer planet satellites. The gravitational pull on a satellite by the parent planet about which it orbits and by neighboring satellites can cause tidal heating of the satellite. Heat is generated as the satellite is squeezed by gravitational stress as it moves in a slightly elliptical orbit about its primary planet. This is the principal source of heat for Io, and may have driven activity on Ganymede and Enceladus in the past. Rhea has been relatively inactive; however, poor resolution Voyager views of Rhea's opposite hemisphere provide tantalizing hints that volcanism and tectonism indeed have affected Rhea to some extent.

The instructor may choose to show Voyager images of other icy satellites, such as Iapetus, a moon of Saturn that shows one bright, icy hemisphere while its other half is as dark as charcoal; Miranda, a moon of Uranus that shows spectacular regions of volcanism and tectonism juxtaposed within ancient cratered terrain; or Triton, Neptune's large moon which has active geysers likely propelled by liquid nitrogen that shoots up into a tenuous atmosphere. Also, this exercise has neglected enigmatic Titan, the largest moon of Saturn, which possesses an atmosphere of nitrogen, methane, and organic compounds so thick as to hide its surface. Pluto and its satellite Charon have not yet been visited and photographed by spacecraft. These two objects are small and icy, akin to many outer planet satellites; thus, information about them is included in Table 1.

This exercise is designed for individual completion by each student. Instructors may wish to have students work together in groups, perhaps with each student of a group being responsible for a specific satellite. Where relevant questions are encountered, encourage students to separate their *description* of a satellite surface from their *interpretation* of the geological history of the surface; questions here attempt to distinguish the two. Note that some questions ask for the student to report a radius value when given a satellite's diameter, requiring some simple math.

If the mapping exercises are done on clear acetate as recommended, then they can be overlain on an overhead projector to compare student maps and prompt discussion of mapping choices. The final question (number 20) works well when done together as a class discussion. It may be useful for the class to construct a chart that summarizes the radii, densities, and compositions of each satellite (compiling information from questions 1, 6, 11, and 16). This will facilitate discussion of how these parameters might affect satellite activity. It will be found, however, that there are no obvious correlations from the satellites introduced in this exercise.

It would be useful to review with students the processes of impact cratering, volcanism, and tectonism (as introduced in Unit One) before proceeding with this exercise. Discussion of geologic mapping and stratigraphic relations (introduced in Unit 5) would be helpful as well. Exercise 10 is a good complement to this one, as it investigates the terrestrial planets at the global scale.

Science Standards

- Earth and Space Science
  - Origin and evolution of the Earth system

Mathematics Standards

- Computation and estimation

Answer Key

I. Ganymede

1. Ganymede orbits the planet *Jupiter*. Its radius of *2631* km makes it the largest satellite in the solar system, bigger even than the planet Mercury. Its density of *1.94* g/cm^3 means that it is composed of a *roughly equal mixture of rock and ice.*

2. **a.** The bright terrain has a high albedo and shows few craters. It contains sets of parallel and intersecting grooves, and also shows smooth areas. Some of the bright material is contained within narrow lanes that cut across the dark terrain.

   b. The dark terrain has a low albedo and shows many craters. Few grooves are seen on the dark terrain. The dark terrain can form "islands" within the bright terrain.

3. **a.** The dark terrain is older, as it is the more heavily cratered and is cross-cut by swaths of bright terrain.

   b. Although the ages of individual crater ejecta deposits will vary depending on the age of a crater, ejecta from crater "A" is superimposed on both bright and dark materials, indicating that the ejecta is younger than these other materials.

4. The bright terrain includes smooth patches and is only lightly cratered, suggesting that it is volcanic in origin and that bright terrain volcanism probably erased preexisting dark terrain craters. The bright terrain contains numerous grooves, which are probably of tectonic origin. [The grooves probably formed by extensional tectonism (rifting), meaning that the bright material was pulled apart, and fault valleys formed the grooves.]

5. **a.** This 100 km diameter crater shows a central dome. [Crater domes might form in large craters either by rebound upon impact or from later magmatism.] It also shows very small craters around it, some aligned in chains. [These smaller craters are secondaries—formed as chunks of ejecta were thrown from the large crater as it formed.]

   b. This 23 km diameter crater shows bright rays emanating from it. [Bright rays are created by ejecta thrown from relatively fresh craters, and they disappear over time as subsequent smaller impacts pelt this material.]

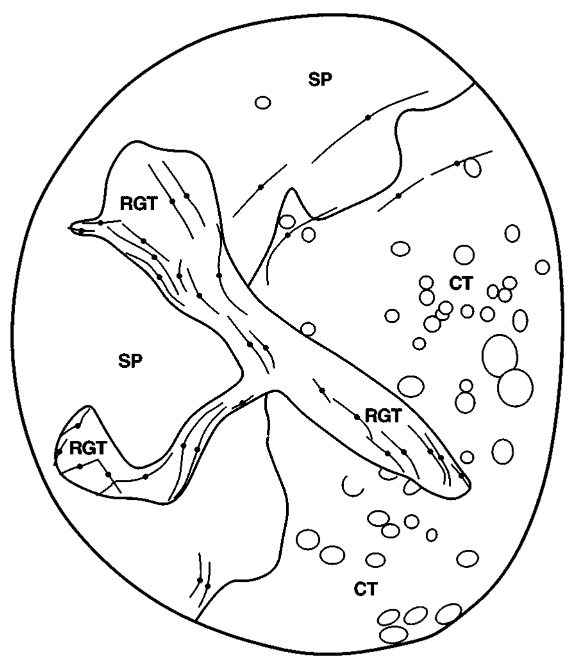
   c. This 50 km crater has been cut by a dark terrain groove.

   d. This 10 by 60 km feature is probably an impact crater that formed by an oblique (low angle) impactor which skimmed the surface of Ganymede as it hit. [Students may notice that some craters in the bright material have dark floors. Dark craters can form in bright material either because the impactor was a dark asteroid rather than a bright comet, or because the craters punch through bright material to throw out underlying dark material in their ejecta.]

II. Enceladus

6. Enceladus orbits the planet *Saturn* and has a radius of only *251* km. Its density of *1.24* g/cm^3 means that it is composed of *mostly ice*. Its albedo of *95%* is *higher* than the albedo of any other satellite.

7. The largest craters on Enceladus show central mounds. [The mounds might be due to central volcanism or slow rebound of the crater shape because of a warm satellite interior.] Some medium-sized craters in the bottom third of the image appear to have been cut in half. [They were probably disrupted by tectonism and/or partially flooded by volcanism.]



Geologic Sketch Map of Enceladus

Answer Key (continued)

8. Grooves and ridges are predominantly concentrated in a band that runs across the satellite.

9. (Answers will vary)

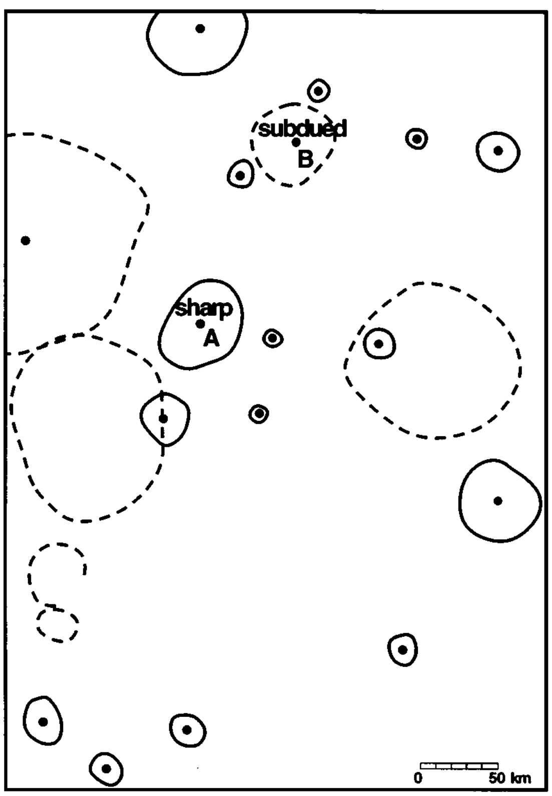
   a. *Cratered terrain:* Characterized by numerous craters, with few obvious grooves.

   b. *Ridge-and-groove terrain:* Characterized by approximately parallel-trending ridges and grooves that curve gently and has few craters.

   c. *Smooth plains:* Smooth-appearing plains with little evidence for topography other than a few tectonic features.

10. **a.** The cratered terrain is oldest, as it is the most heavily cratered and it appears to be cross-cut by the ridge-and-groove terrain.

    b. It is difficult to be certain of the relative ages of the smooth plains and the ridge-and-groove terrain. The smooth plains may be the youngest, having flooded the region neighboring the ridge-and-groove terrain. On the other hand, preexisting smooth plains may have been tectonically deformed to create the ridge-and-groove terrain. (Answers will vary.)



Rhea Crater map

III. Rhea

11. Rhea orbits the planet *Saturn* and has a radius of *764* km. Its density of *1.33* g/cm^3 means that it is composed of *ice with minor amounts of rock.*

12. Impact cratering.

13. **a.** (See question 14.a. below.)

    b. (See question 14.a. below.)

    c. Craters probably have sharp-appearing morphologies when they first formed, i.e., when they were "fresh." Over time, craters become more and more subdued or "degraded."

14. **a.** [Because subdued craters may be difficult to find, several are indicated on this sketch map.]

    b. Central peaks are more apparent in fresh craters.

    c. The fact that peaks are most apparent in fresh craters suggests that central peak topography, like the rest of the crater, becomes more subdued and less prominent over time as subsequent impacts redistribute material.

    d. The transition diameter is between ~10 and 20 km.

15. **a.** Rhea shows abundant evidence for cratering, and is more heavily cratered than the surfaces of the other two satellite. Unlike Ganymede and Enceladus, this part of Rhea shows no smooth terrains and essentially no grooves. Like Enceladus, Rhea's surface is of uniform albedo; this is in contrast to the surface of Ganymede, which shows bright and dark terrains.

    b. Rhea has had a less active geological history. It is dominated by the external process of cratering. Unlike Ganymede and Enceladus, it does not show widespread evidence for the internally-driven processes of volcanism and tectonism.

IV. Io

16. Io is a satellite of the planet *Jupiter.* Its density of *3.57* g/cm^3 means that it is composed of *rock*. This density is unusual in that it is *higher* than that of any other outer planet satellite. Io is *1815* km in radius.

Answer Key (continued)

17. **a.** Volcanism.

    b. It shows a somewhat irregular, scalloped shape of three coalescing circles.

    c. A caldera.

18. Volcanism is the principal process shaping the surface of Io, as demonstrated by the abundance of flow-like features, smooth materials, and irregularly-shaped calderas that are commonly associated with high and/or low albedo materials. No impact craters can be confidently identified on Io, and they have presumably been erased by volcanism.

19. Craters on Rhea are a) generally more circular; b) more numerous; c) commonly have smaller craters superimposed on them; d) show a range of morphologies from sharp to subdued (a range of degradation states); e) show central peaks. Some craters on Io are associated with bright and/or very dark materials.

20. (Answers may vary—acceptable alternative answers are provided in parentheses.)

	Ganymede	**Enceladus**	**Rhea**	**Io**
Impact Cratering	**2 (3)**	**3 (2)**	**1**	**4**
Volcanism	**3 (2)**	**2 (3)**	**4**	**1**
Tectonism	**1 (2)**	**2 (1)**	**4 (3)**	**3 (4)**

Name ______________________________

Geologic Features of Outer Planet Satellites

Purpose

To recognize the similarities and differences in the processes affecting the outer planet satellites, and in the resulting landforms.

Materials

Acetate (2 sheets), overhead transparency markers

Introduction

Planetary geologists study the solid surfaces of solar system objects. This includes the planets of the inner solar system and the moons, or **satellites**, of all the planets. The giant gaseous planets of the outer solar system—Jupiter, Saturn, Uranus, and Neptune—have a total of 62 satellites.

The outer planets are far from the warmth of the Sun, so the satellites that circle them are very cold—so cold that many are composed partly or mostly of **ice**. Much of the ice in these satellites is water ice, the kind in your freezer. But some satellites probably contain other types of ice, including ammonia, methane, carbon monoxide, and nitrogen ices. These are compounds that you may know as liquids or gases in the warm environment of Earth.

Some outer planet satellites display many **impact craters**, and some are less cratered. In general, an older surface shows more and larger impact craters than a younger surface. Also, younger features and surfaces will cut across or lie on top of older features and surfaces. Relatively fresh or large craters commonly show a blanket of bright **ejecta**, material thrown from the crater as it was formed.

The surfaces of outer planet satellites can also be shaped by **volcanism** and **tectonism**. Volcanism can erase craters while creating regions that appear smooth. On a rocky satellite, the volcanic lava will be rocky; on an icy satellite, an icy or slushy "lava" might emerge from the satellite's relatively warm interior. A centers of volcanism is sometimes marked by an irregularly shaped volcanic crater termed a **caldera**. Tectonism can create straight or gently curving grooves and ridges by faulting of the surface. Commonly, an area smoothed by volcanism will be concurrently or subsequently affected by tectonism. A volcanic or tectonic feature must be younger than the surface on which it lies.

The **density** of a planet or satellite provides information about its composition. Density is a measure of the amount of mass in a given volume. Rock has a density of about 3.5 g/cm^3, and most ices have a density of about 1 g/cm^3. This means that a satellite with a density of 3.5 g/cm^3 probably is composed mostly of rock, while a satellite of density 1 g/cm^3 is composed mostly of ice. A satellite with a density of 2 g/cm^3 probably is composed of a mixture of nearly equal amounts of rock and ice.

The **albedo** of a satellite is a measure of the percentage of sunlight that the surface reflects. A bright satellite has a high albedo, and a dark satellite has a low albedo. Pure ice or frost has a very high albedo. If a satellite's surface is icy but has a low albedo, there is probably some dark material (such as rock) mixed in with the ice.

Even if the albedo of a satellite is completely uniform, the apparent brightness of the surface can change based on the positions of the Sun and the observer. The lit edge, or **limb**, of a planet or satellite typically appears bright. The surface looks darker as the day/night line, or **terminator**, is approached because that is where shadows are longest.

Properties of the Major Satellites* of the Solar System and Pluto

Planet	Satellite	Diameter (km)	Mass ($x10^{23}$g)	Density (g/cm^3)	Albedo (%)
Earth	Moon	3476	735	3.34	12
Jupiter	Io	3630	894	3.57	63
	Europa	3138	480	2.97	64
	Ganymede	5262	1482	1.94	43
	Callisto	4800	1077	1.86	17
Saturn	Mimas	394	0.38	1.17	60
	Enceladus	502	0.8	1.24	95
	Tethys	1048	7.6	1.26	70
	Dione	1118	10.5	1.44	50
	Rhea	1528	24.9	1.33	60
	Titan	5150	1346	1.881	20
	Iapetus	1436	18.8	1.21	4 (leading), 50 (trailing)
Uranus	Miranda	492	0.69	1.15	32
	Ariel	1158	12.6	1.56	31
	Umbriel	1170	13.3	1.52	20
	Titania	1578	34.8	1.70	28
	Oberon	1522	30.3	1.64	23
Neptune	Triton	2706	214	2.07	73
	Proteus	416	~0.4?	~1.5?	6
Pluto		~2360	~130	~2	~50
	Charon	~1180	~110	~1.3	~40

* Only satellites larger than about 400km diameter are listed here, in order of increasing distance

Questions and Procedures

I. Ganymede

1. The Table will help you to fill in the blanks:

   Ganymede orbits the planet____________. Its radius of _______ km makes it the largest satellite in the solar system, even bigger than the planet Mercury. Its density of ______ g/cm^3 means that it is composed of_____________ .

Examine Figure 13.1a, which shows part of the Sippar Sulcus region of Ganymede, and compare what you see to the **geomorphic** sketch map of the area (Figure 13.1b). Notice that the surface of Ganymede can be divided into two principal geologic units, bright terrain and dark terrain. The dark terrain is believed to be a mixture of ice and rock, while the bright terrain is probably composed mostly of ice.

2. List and describe the many characteristics of the bright and dark terrains. Be as detailed as possible. Include factors such as albedo, number of craters, general surface appearance, and other characteristics that are apparent.

   a. bright terrain:

   b. dark terrain:

3. **a.** Which of Ganymede's two principal terrain types is older? How can you tell?

   b. What is the age of the ejecta for the crater marked "A" relative to the bright and dark terrain? How can you tell?

4. Many researchers believe that the bright terrain of Ganymede was shaped by both volcanism and tectonism. What is some evidence that this is true?

5. All the craters you can see in Figure 13.1a probably formed by the impacts of comets or asteroids. Many show small central pits, created as a result of impact into an icy target.

Four craters that show unusual morphologies are indicated in Figure 13.1b with the letters **A** through **D**. Describe the shapes and characteristics of these interesting craters. Include the *dimensions* of each crater using the scale bar, and also describe the *characteristics* that make it peculiar compared to most other craters on Ganymede.

A: ____

____

____

B: ____

____

____

C: ____

____

____

D: ____

____

____

II. Enceladus

6. Enceladus orbits the planet __________ and has a radius of only _______ km. Its density of_______ g/cm^3 means that it is composed of __________ ______________________. Its albedo of __________ is __________ than the albedo of any other satellite.

Now make a geological sketch map of Enceladus. Use as a guide the map of Ganymede in Figure 13.1. Tape a piece of acetate over the photograph of Enceladus, Figure 13.2. Trace the outline of the satellite. You will find that it is simple to trace the satellite's limb, but the terminator is not as clearly defined. Next, outline the most prominent craters on the satellite, you will have to decide which craters should be included.

7. Locate and describe two unusual looking craters.

   Grooves on Enceladus are probably tectonic features; next map their locations. This symbol (-●-) is one way of mapping a groove. Draw a thin line along each groove you see, and place a dot near the center of each line to indicate it is a groove.

8. Where do grooves (and the ridges between them) occur on Enceladus?

The surface of Enceladus can be divided into three different types of terrain. Think about the features you have mapped so far, and decide on how to divide the surface into three terrains. Decide on names that describe your units. (For example, "cratered terrain.")

Draw boundaries around the different units. There might be only one patch of each unit, or there could be more than one patch. To complete the map of Enceladus, label the units with the descriptive names that you have given them.

9. List the names of your three units. Following each name, describe the characteristics of each unit as *you* defined it in making your map of Enceladus.

   A: ____

   ____

   ____

   B: ____

   ____

   ____

   C: ____

   ____

   ____

10. **a.** Which is the oldest of these three major units on Enceladus? How can you tell?

    b. Which is the youngest of these three major units on Enceladus? How can you tell?

III. Rhea

11. Rhea orbits the planet __________ and has a radius of _______ km. Its density of ______ g/cm^3 means that it is composed of ____________________.

12. Examine Figure 13.3, which shows a part of Rhea's surface. What is the principal geologic process that has shaped this part of Rhea?

13. Notice the **morphologies** (shapes) of the craters that you see in Figure 13.3. The 60 km crater **A** shows a sharp and distinct morphology, with steep and well-defined slopes. On the other hand, the 65 km crater **B** is more difficult to identify, as it is rounded and indistinct. Keep in mind that the cratered surface of Rhea seen is probably about 4 billion years old.

    a. Lay a piece of acetate over Figure 13.3, taping it at the top. Trace the rectangular outline of the photo, and also trace and label the scale bar. With a solid line, trace the outline of crater A, and label the crater "sharp." Next locate and trace the outline of crater B, but this time use a dashed line. Label this crater "subdued."

    b. Locate one additional sharp crater, outlining it with a solid line. Find an additional subdued crater, and outline it with a dashed line.

c. The terms "sharp" and "subdued" are descriptive terms, used to describe the morphologies of craters. Sharp-appearing craters are sometimes referred to as "fresh," while subdued-appearing craters are commonly referred to as "degraded." What do the terms "fresh" and "degraded" imply about how a crater's morphology changes with time on Rhea?

14. Notice that some of Rhea's craters, including crater **A**, show central peaks. These form upon impact, due to rebound of the floor during the "modification stage" of the cratering process.

a. On the acetate, outline as many central peak craters as you can confidently identify. Retain the scheme of outlining each sharp crater with a solid line, and each subdued crater with a dashed line. Put a dark dot in the middle of each central peak crater that you identify.

b. Are central peaks more recognizable in sharp or subdued craters?

c. Based on your answer to part b, what can you infer about how the topography of a central peak changes over time?

d. Central peaks form only in craters above a certain diameter. This "transition diameter" from simple, bowl-shaped craters to more complex, central peak craters depends on surface gravity and material properties, so it is different for each planet and satellite. Estimate the transition diameter for craters on Rhea based on the smallest central peak craters that you are able to identify.

15. Consider the surface of Rhea (Figure 13.3) in comparison to the surfaces of Ganymede (Figure 13.1) and Enceladus (see Figure 13.3 and your sketch map).

a. Compare and contrast the general appearance of the surface of Rhea to the surfaces of Ganymede and Enceladus.

b. What do the differences in surface appearance suggest about the geological history of Rhea as compared to the histories of Ganymede and Enceladus?

IV. Io

16. Io is a satellite of the planet __________. Its density of ______ g/cm^3 means that it is composed of ______________________. This density is unusual in that it is ___________ than that of any other outer planet satellite. Io is _____________ km in radius.

Examine Figure 13.4, which shows part of the surface of Io. The very high albedo material is considered to be sulfur dioxide frost. When the two Voyager spacecraft flew by Io in 1979, they photographed nine actively erupting volcanoes.

17. Examine the feature in the far northeast corner of the image, which shows a central depression with relatively low albedo (dark) material radiating from it.

a. What process created this feature?

b. Describe in detail the shape of the central depression. Use a sketch if you like. (Use the sketch area below.)

Sketch area

c. What kind of volcanic "crater" is this central depression?

18. Examine the other craters and surface features seen in Figure 13.4. What is the principal process shaping the surface of Io? List some observations that support your answer.

19. Contrast the characteristics of craters that you see on Io to those on Rhea. List at least four differences between Io's volcanic craters and Rhea's impact craters.

20. On the chart below, rank the relative importance of impact cratering, volcanism, and tectonism on the four outer planet satellites that you have studied, based on the images you have seen. Use numbers from 1 (for the satellite most affected) to 4 (for the satellite least affected).

	Ganymede	**Enceladus**	**Rhea**	**Io**
Impact Cratering				
Volcanism				
Tectonism				

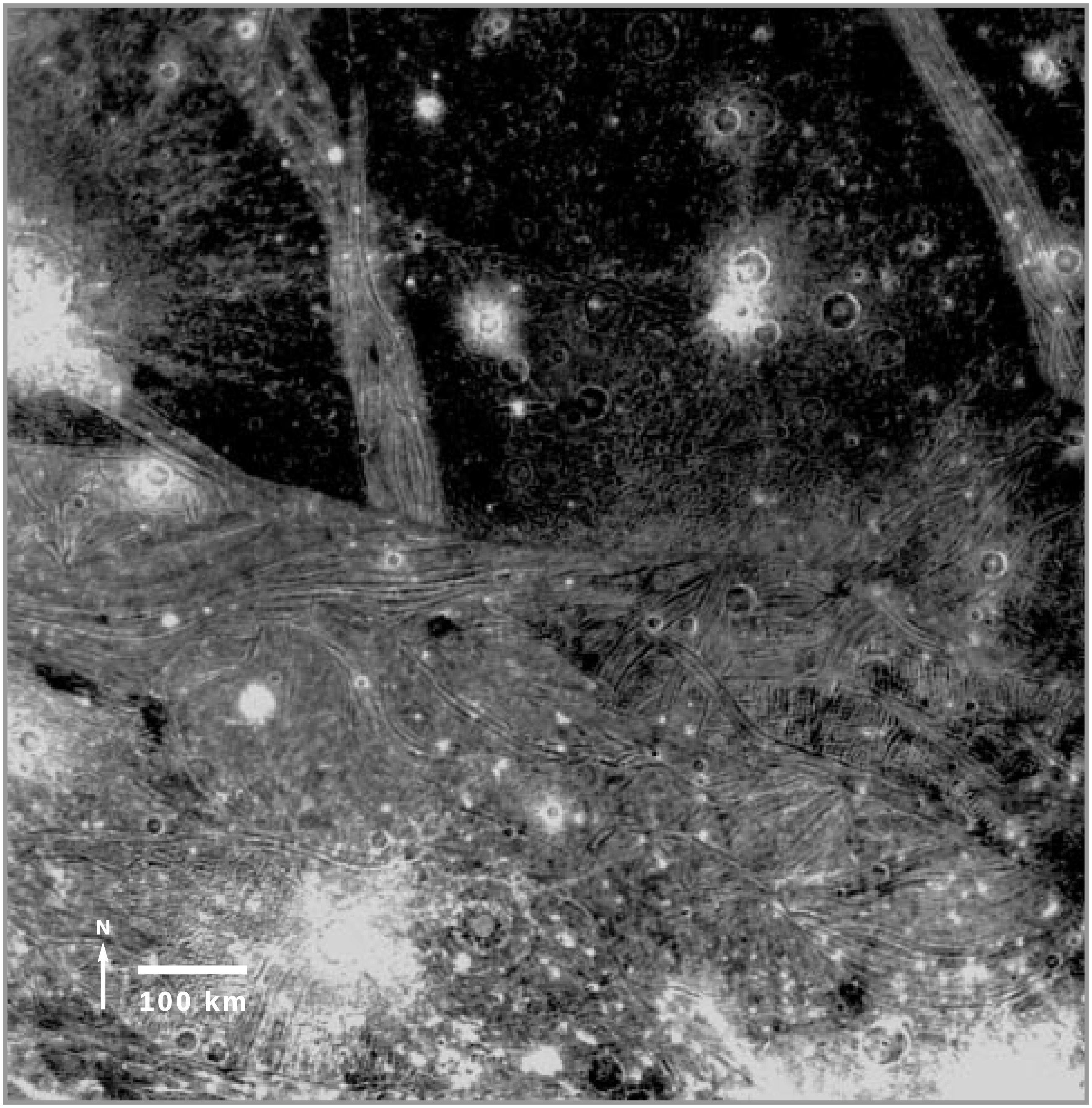


Figure 13.1.a. *Voyager 2 image of Ganymede (FDS 20636.02) at a resolution of 1.5 km/pixel, showing part of Sippar Sulcus in lower half.*

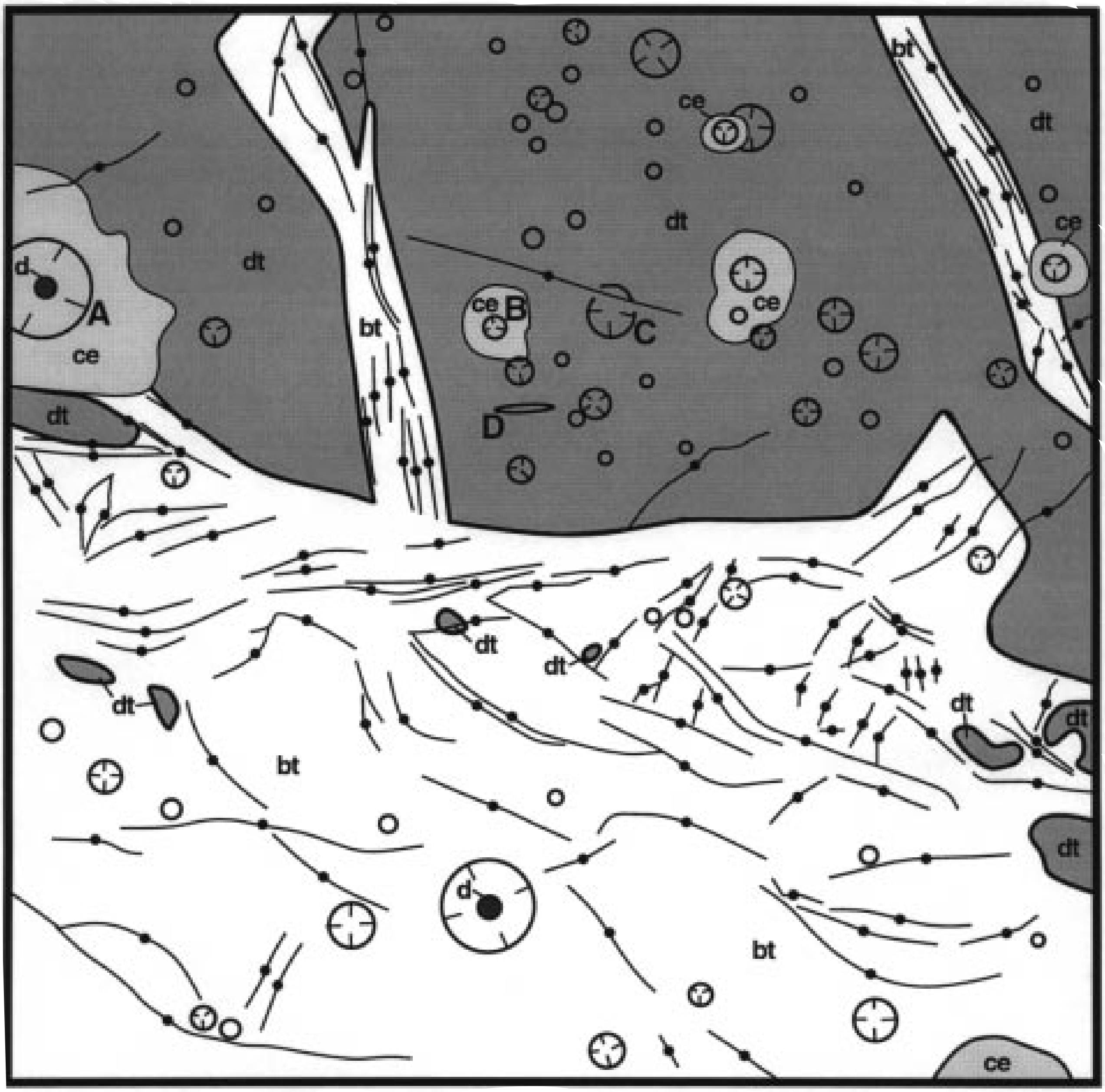


Figure 13.1.b. *Geological sketch map corresponding to Figure 13.1a.*

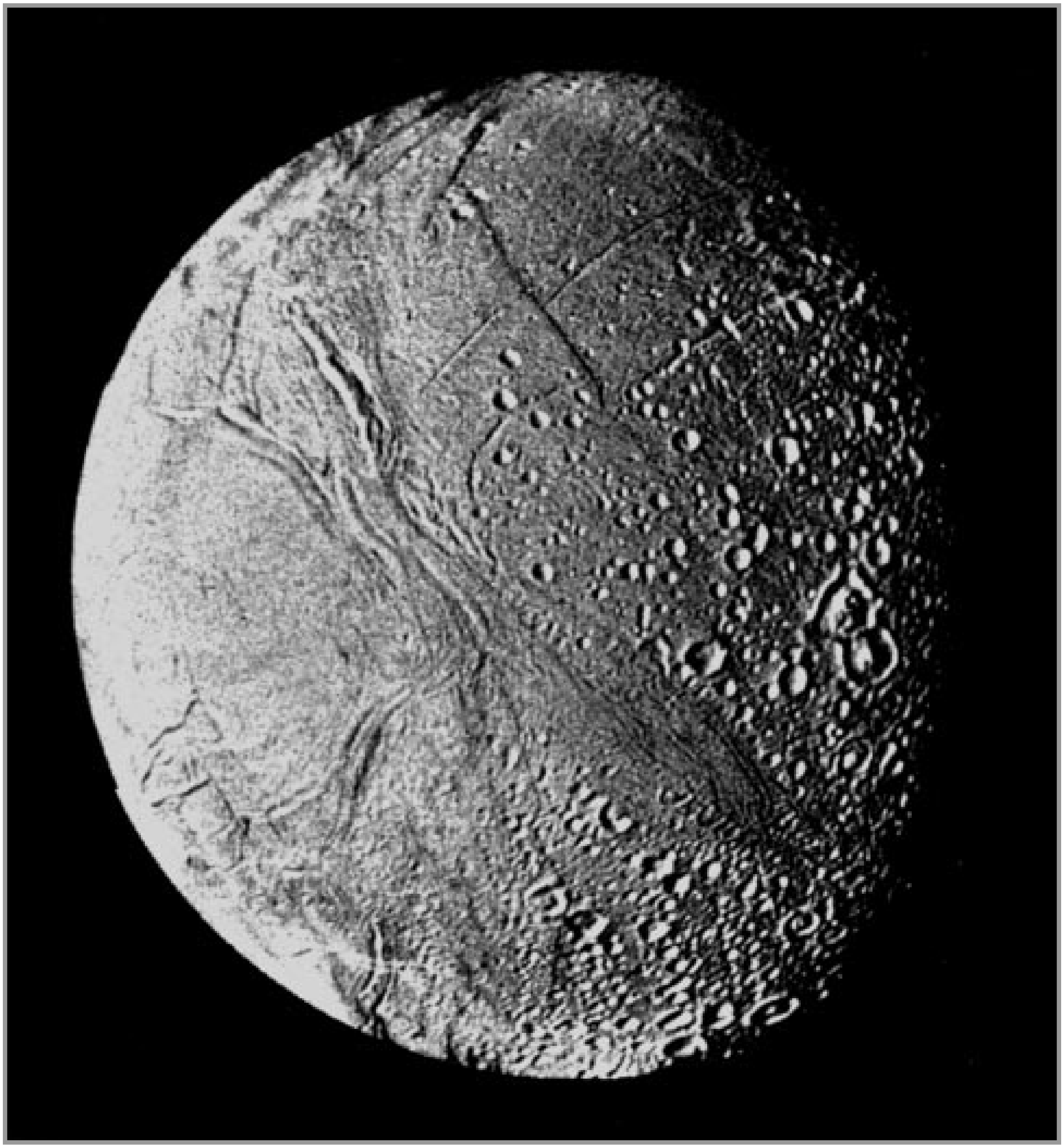


***Figure 13.2.** Photomosaic of Enceladus constructed from Voyager 2 images with resolutions of about 2 km/pixel. The satellite has a diameter of approximately 500 km. (Jet Propulsion Laboratory photomosaic P-23956 BW).*

Figure 13.3. *The surface of Rhea, seen by Voyager 1 at 700 m/pixel (FDS 34952.59).*

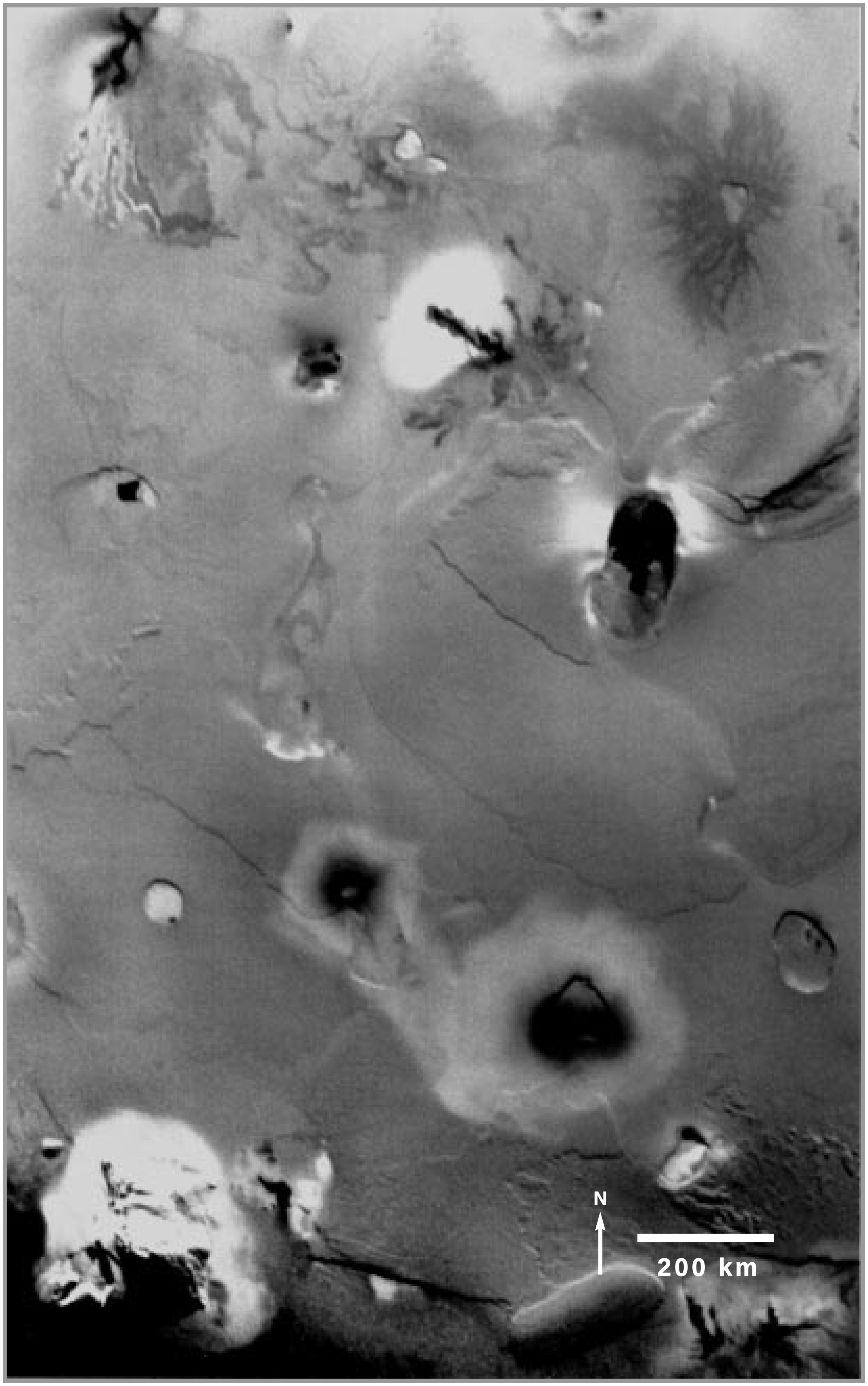


Figure 13.4. *The surface of Io seen in a mosaic of Voyager images FDS 16392.43, .39, and .41. Resolution is 2.1 km/pixel. (United States Geological Survey mosaic V0357/1).*

Exercises Two, Three, Ten, Eleven, Twelve, and Thirteen are suggested as introductory exercises.

■ ★ 2.0 hours

Planets in Stereo

Instructor Notes

Suggested Correlation of Topics

Comparative planetology, impact craters, stereoscopic photography

Purpose

The objective of this exercise is to apply the techniques of stereoscopic photograph analysis to the interpretation of the geology and history of planetary bodies.

Materials

For each student group: Stereoscope

Background

Unit One introduced students to the four geologic processes: volcanism, tectonism, gradation, and impact cratering. In Exercise Three, stereoscopic photographs were used to acquaint students with the three dimensional shapes of some terrestrial landforms created by these processes. Here, these themes are extended to other planets and planetary bodies.

This exercise builds upon previous ones. It would be useful to review the four geologic processes of Unit One before proceeding. The procedure for using stereoscopic photographs is briefly reviewed in the student section of this exercise, but for more detail, refer to Exercise Three: Geologic Processes Seen on Stereoscopic Photos.

This exercise promotes comparisons among the planetary bodies examined, including the Moon, Mars, Venus, and several outer planet satellites. It is useful for the student to have completed previous exercises (10 through 13) which introduce the geology of these bodies, although this exercise can be worked independently.

This exercise has many parts. If time does not permit completion of the entire exercise by all students, then groups of students might be assigned the different parts. Class discussion could then be used to share and synthesize what has been learned.

Science Standards

■ Earth and Space Science

- Origin and evolution of the Earth system

Answer Key

1. a. The contact is sharp and abrupt. The plains appear to lap up against the hills.

   b. The indication is that the plains are younger, having filled low-lying regions.

2. The plains consist of volcanic lava flows. Hadley Rille transported some of these lavas.

3. **a.** Hadley is a bowl shaped crater. Its rim is upraised above the surroundings.

   b. These characteristics suggest an impact origin.

4. Hadley Rille is older, as the crater's ejecta appears to cover part of the rille.

5. The rim is raised and slopes continuously upward from the surrounding plains. Ejecta deposits are superposed on the plains. Moreover, the crater is superimposed on, and thus younger than, Hadley Rille (which probably formed at the same time as the plains).

6. **a.** The crater shows a raised rim, a central peak, terraced walls, and a relatively flat floor.

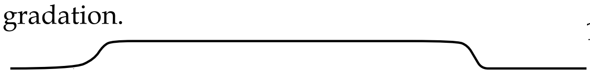
   b. These characteristics suggest an impact origin.

7. The crater forms the rounded edge of the "island." It might have served as a barrier to liquid that flowed around the crater, eroding away material to either side, and leaving an island downstream of the crater. This island might be in a dry river bed. The process is gradation.

8. The material appears to be layered.

9. **a.** Tectonism.

   b. Crater material has slid down a steep slope into the trough below, leaving a rough (radar bright) landslide deposit. This is an example of gradation.

10. a. 

    b. Volcanism.

    c. They are irregular depressions (pits), formed volcanically.

11. **a.** There are many large, irregular depressions. Some smaller depressions are linear or aligned in chains. Some depressions are long and sinuous.

    b. The similarity in shape suggests that the sinuous depressions on Venus may have formed as lava channels and collapsed tubes similar to Hadley Rille on the Moon.

    c. Volcanism.

12. Ida is irregularly shaped rather than spherical. Its outline consists of concavities (some of which are large craters) and ridge-shaped features between them.

13. Cratering; the concavities, ridges, and irregular shape probably resulted from the shattering of a larger parent asteroid and repeated impact bombardment.

14. Cratering.

15. Craters on Rhea have irregular outlines, and they overlap one another. Dione's craters are more circular, and there are fewer craters on Dione, so there is less overlapping. Both satellites show some central peak craters.

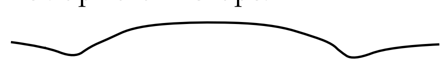
16. **a.** Rhea's surface is older, as it is much more heavily cratered.

    b. Dione may have been volcanically resurfaced in the past. This would have obliterated its older craters. The craters we see have all formed since this event.

17. **a.** A large rift cuts across Titania. It shows curved fault segments and a jagged overall trace.

    b. Tectonism.

18. **a.** The material is smooth appearing and is convex-upward in shape.

    b. 

    c. Tectonism and volcanism.

19. **a.** The coronae show ridges and troughs. This is different from the cratered terrain, which shows few scarps. The cratered terrain is more heavily cratered.

    b. Tectonism, and probably volcanism. Tectonism produced the ridges, grooves, and scarps. Volcanism may be responsible for light and dark patches within the coronae.

Name ____________________

Planets in Stereo

Purpose

To apply techniques of stereoscopic photograph analysis to the interpretation of the geology and history of planetary bodies.

Materials

For each student group: stereoscope

Introduction

Geologists are concerned with rock formations and landforms as three dimensional units. An understanding of the geometry of a geologic formation is important to the interpretation of its origin and history. Topographic information can be obtained in a variety of ways. The most simple and reliable is by means of stereoscopic photographs.

We see in three dimensions and are able to judge the distances to objects because our eyes are spaced about 65 mm apart. We see the same scene from two different angles, and the brain is able to interpret this information to give us a perception of depth. The same principle is used to view a pair of stereoscopic photographs taken from spacecraft.

A stereoscopic pair is made by taking two images of the same scene from slightly different angles. This can be done by a spacecraft as it moves above the surface of a planetary body. For example, the metric mapping cameras of the Apollo orbiter took sequential pictures that overlap by 78%. That is similar to the overlap that our two eyes provide for the same scene.

To observe the three-dimensional stereoscopic effect, each photograph of the stereo pair must be viewed by a separate eye. This can be accomplished by viewing through a stereoscope. Center the stereoscope on the seam between the photographs of a stereo pair, relax your eyes, and let the photos merge together into one image in order to observe the stereo effect. Try placing your index fingers on the same object within each photo of the stereo pair, and then focus until your fingers appear to overlap. When you remove your fingers, the stereo effect should become apparent. Some people cannot see stereo at all; for most others, it simply takes patience and practice.

In analyzing the stereo photographs of this exercise, recall the four geologic processes: **volcanism**, **tectonism**, **gradation**, and **impact cratering**. You will be asked to recognize the processes that have shaped planetary surfaces based on the three-dimensional appearances of the visible **landforms**.

Questions

Part A. Moon.

Examine Figure 14.1, which shows the area of Hadley **Rille**, landing site of Apollo 15. Hadley Rille, the sinuous trough winding across the region, is an ancient lava channel that carried active flows into the dark plains (maria). Hadley crater is the prominent crater beside the rille.

1. Study the **contact** (boundary where two different types of materials meet) between the bright, rough hills and the smooth, dark plains.

   a. Describe this contact. What is the character of the boundary?

b. What conclusions can you draw about the age relationship between the hills and plains?

2. How might the plains have formed?

3. Examine the appearance of Hadley crater.

   a. Describe the crater's shape and characteristics, including its rim and interior.

   b. These characteristics suggest what kind of origin for Hadley crater?

4. Which is older, Hadley Rille or Hadley crater? How can you tell?

5. What evidence is there that Hadley crater is younger than the plains lavas, instead of the plains lavas having flowed around an old pre-existing crater?

Part B. Mars.

Examine Figure 14.2, which shows part of Ares Vallis on Mars.

6. Notice the prominent 7 km crater.

   a. Describe the shape and characteristics of the crater, including its rim and interior.

   b. Based on these characteristics, what geologic process formed this crater?

7. What is the relationship between the crater and the teardrop shaped "island"? How might the teardrop feature have formed? What is the geologic process?

8. Look carefully at the sides of the teardrop "island," and also at the steep cliff near the top of the photo. What can you say about the material near the surface of Mars, as revealed by the cross sections exposed in the cliffs?

Part C. Venus.

The surface of Venus is hidden from direct view by its thick clouds. To penetrate the clouds, **radar** has been used to map the surface of Venus. In general, rough areas appear bright in these radar images, and smooth areas appear dark. (For an introduction to the interpretation of radar images and the geology of Venus, see Exercise Twelve: Geologic Features of Venus.)

9. Examine the stereo images of Figure 14.3, showing the region surrounding crater Geopert-Meyer.

   a. Which of the four geologic processes has most affected this region of Venus?

   b. Notice the rough (radar bright) material aside crater Geopert-Meyer, and its relationship to the prominent trough. What has happened here?

10. Figure 14.4 shows the Eistla region of Venus.

   a. Sketch a cross-section of the shape of the broad domes as they might appear from the surface of Venus. Use the sketch area below.

Sketch area

   b. Which geologic process could have created these domes?

   c. Notice the small depressions on the crests of the broad domes. What is their shape, and what process likely created them?

11. Examine the topographic depressions in Aphrodite Terra seen in Figure 14.5.

   a. Describe the shapes of the topographic depressions that you see.

   b. Compare this image of Aphrodite Terra to the Hadley Rille area of the Moon (Figure 14.1). What does the comparison suggest as to the possible origin of the sinuous depressions on Venus?

   c. Which of the geologic process was most important in shaping this region?

Part D. Asteroid Ida.

A stereoscopic view of asteroid 243 Ida is shown in Figure 14.6.

12. Compare the overall shape of Ida to that of other planetary bodies you have studied. What is unusual about the asteroid's shape?

13. What geological process has affected the surface of Ida? How might this process account for the asteroid's overall shape?

Part E. Outer Planet Satellites.

The following figures show stereoscopic images of some of the **satellites** of Saturn and Uranus. Only five satellites are shown, a sampling of the dozens of moons of the outer planets. All of the moons shown have ice-rich surfaces, and none have atmospheres. Figures 14.7 and 14.8 show Rhea and Dione, respectively. These are two of Saturn's icy satellites.

14. What geologic process has most shaped the surface of Rhea?

15. Compare the appearance of craters on Dione to those on Rhea. Include both similarities and differences in their **morphologies**.

16. **a.** Which satellite appears to have an older surface, Rhea or Dione? How can you tell?

    b. What does this say about whether these satellites might have been resurfaced by volcanism at some time in the past?

Figures 14.9, 14.10, and 14.11 show Titania, Ariel, and Miranda, respectively. These are icy satellites of planet Uranus.

17. Notice the prominent feature that stretches across the surface of Titania (Figure 14.9).

    a. Describe this feature.

    b. What process is responsible for its formation?

18. Several valleys cross the surface of Ariel , especially near the **terminator** (the day/night line), visible on the right side of the stereo image (Figure 14.10).

    a. What is unusual about the appearance of the material in these valleys?

b. Sketch what a profile across a typical one of these valleys might look like in the sketch area below.

Sketch area

c. What two processes probably acted together to form these features?

19. The surface of Miranda (Figure 14.11) consists of cratered terrain and several regions termed **"coronae"** (singular: corona). In contrast to the cratered terrain, the coronae consist of light and dark materials.

    a. Describe the topography and character of the coronae as compared to the cratered terrain which surrounds them.

    b. What process(es) have likely shaped the coronae of Miranda?

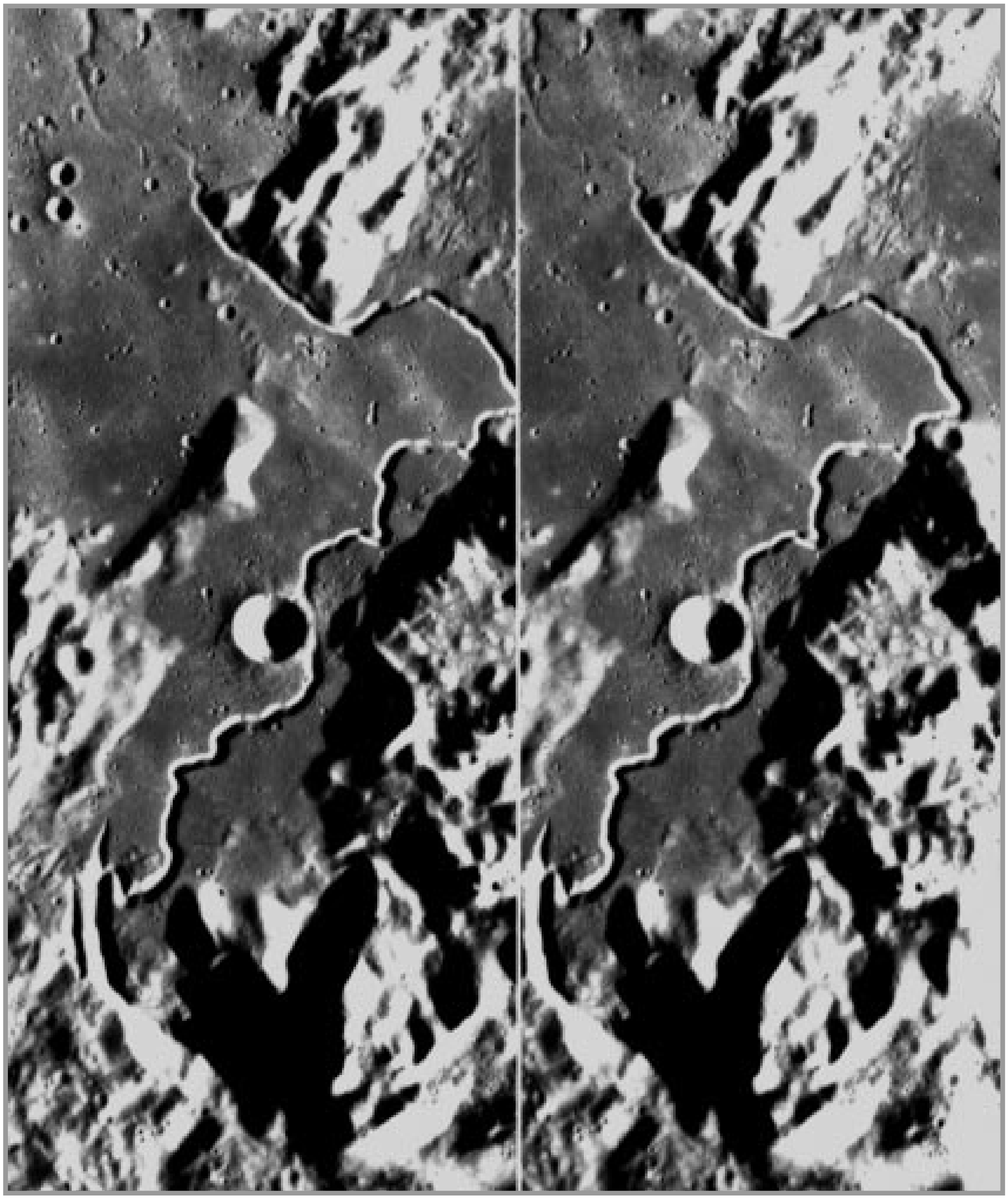


Figure 14.1. *Stereoscopic photographs of the Hadley Rille area of the Moon, landing site of Apollo 15. The sinuous trough (Hadley Rille) is about 300 m deep. The prominent crater, Hadley, is 5.7 km in diameter. North is toward the top. (Left half is part of AS15-0586, right half, AS15-0585. Spacecraft motion was from left to right parallel to the bottom edges of the photos).*

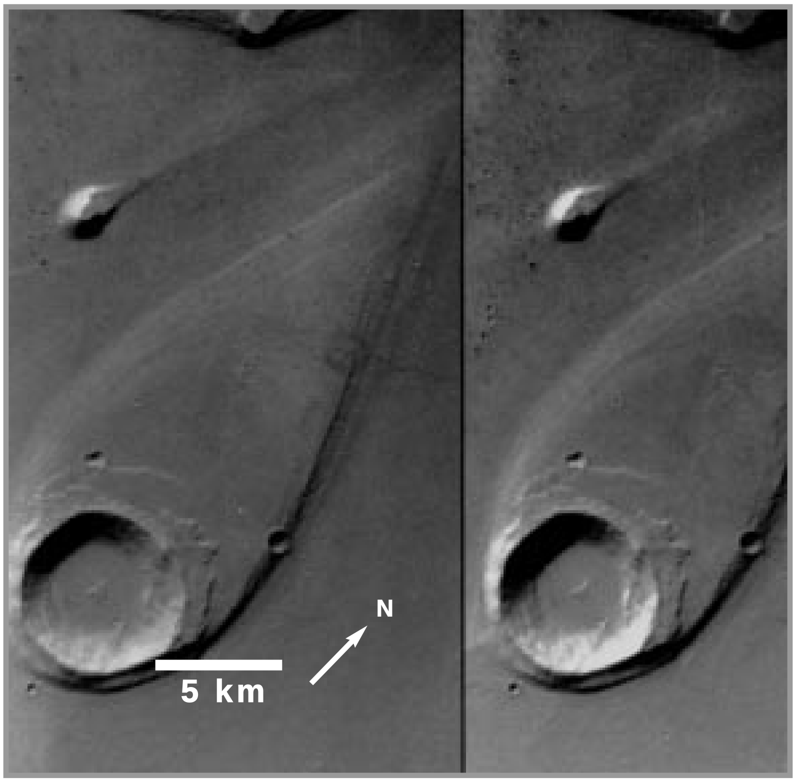


Figure 14.2. *Stereoscopic photographs of the Ares Vallis region of Mars, constructed from Viking orbiter images. North is toward the upper right. The prominent crater is about 7 km across. The Viking 1 Lander site is about 800 km to the west. (Viking Orbiter 004A52, left, and 004A93, right).*

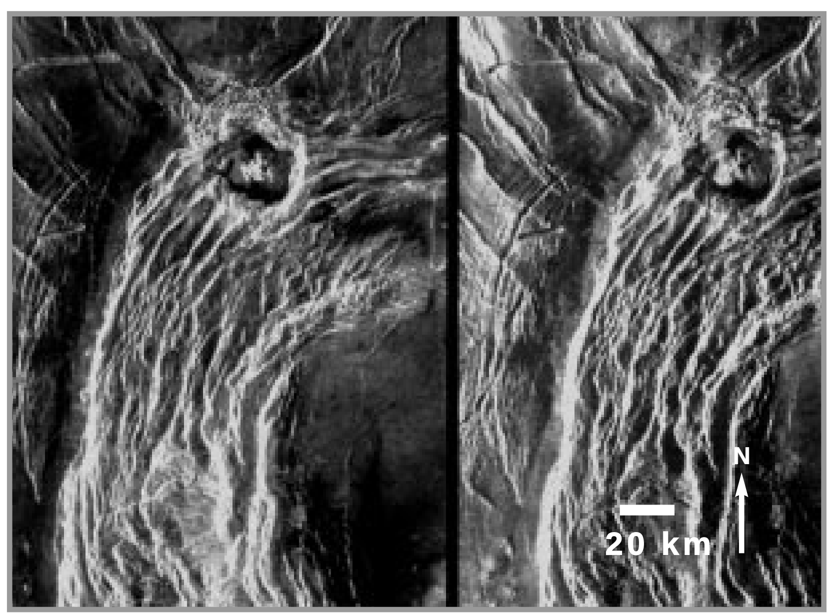


Figure 14.3. *Crater Geopert-Meyer and surrounding features on Venus. The prominent trough is about 1 km deep, and the scene is about 154 km across. North is toward the top (NASA P-42612).*

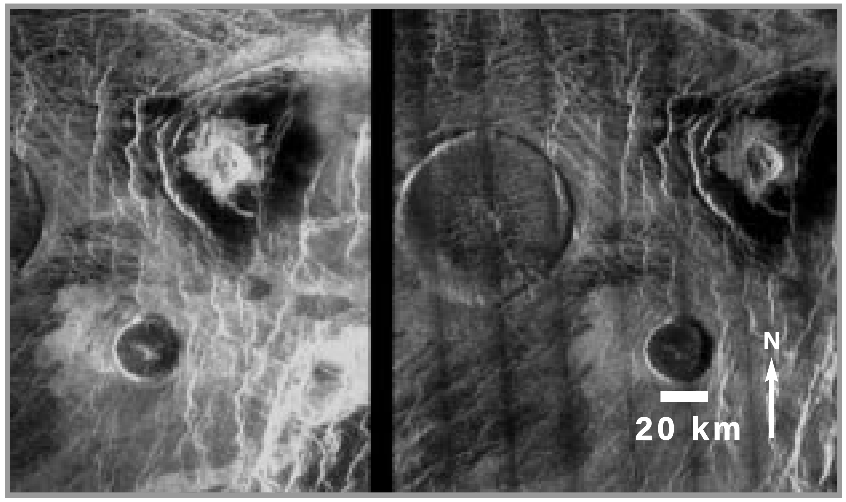


Figure 14.4. *Domes in the Eistla region of Venus. The largest is about 65 km across but less than 1 km in height. North is toward the top (NASA P-42684).*

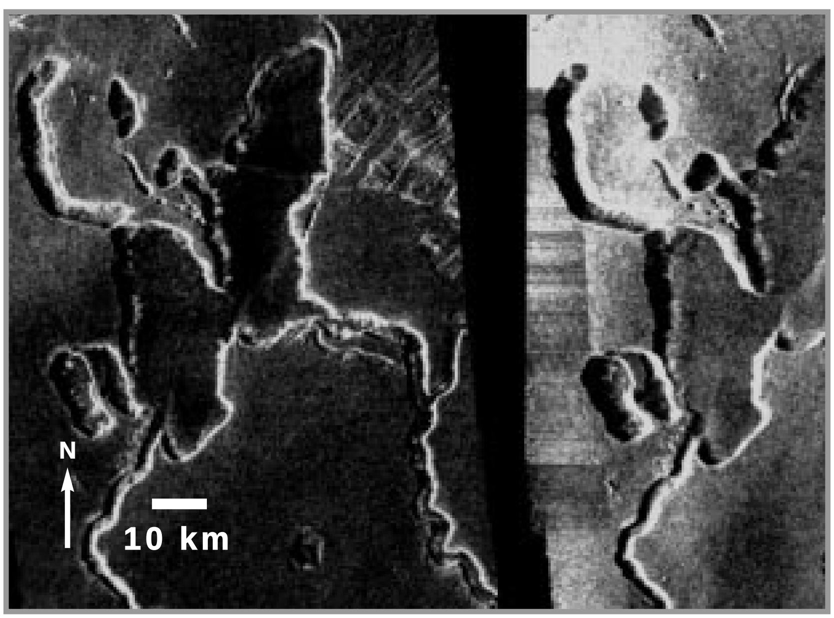


Figure 14.5. *Part of the Aphrodite Terra highlands, Venus. Depths here are as great as 1 km. The image is 73 km wide, and north is toward the top (NASA P-42611).*

Figure 14.6. *Stereoscopic view of asteroid 243 Ida. The asteroid is about 60 km long and 18 km wide. Resolution is 60 m/pixel. (Stereo image courtesy Peter Thomas, Cornell University; from Galileo spacecraft images s0202561945 [left] and s0202562000 [right]).*

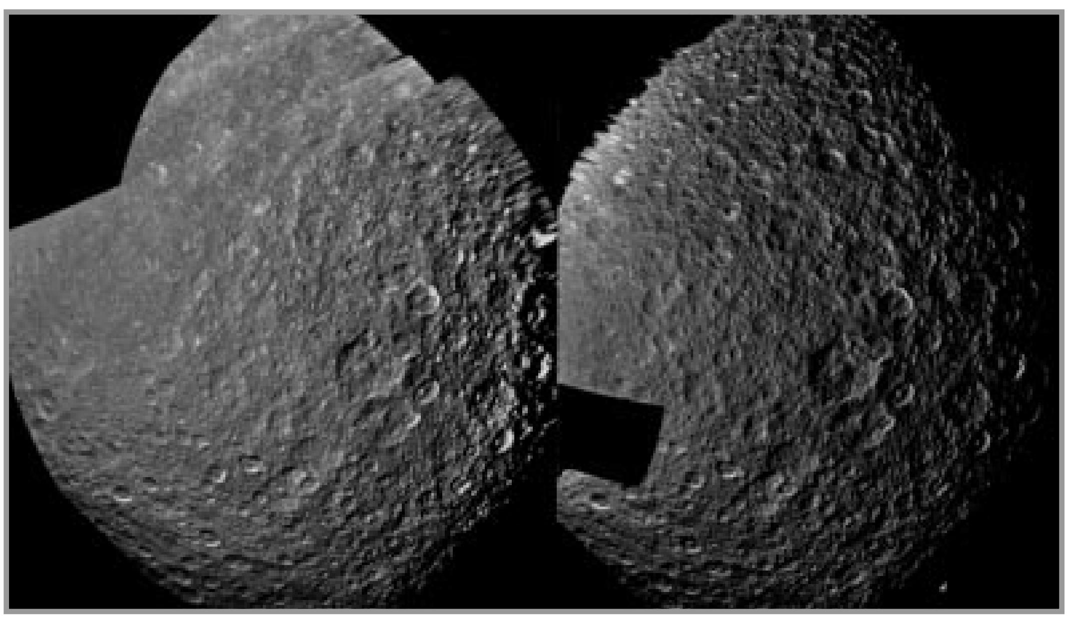


Figure 14.7. *Saturn's icy satellite Rhea is seen in this stereo pair. (Image courtesy Paul Schenk, Lunar and Planetary Laboratory, Houston; reprojected mosaics of Voyager frames FDS 34950.29, .35, .41, .47, and .53 [left] and 34952.53, .55, .57, .59, 34953.01, .03, and .07 [right]).*

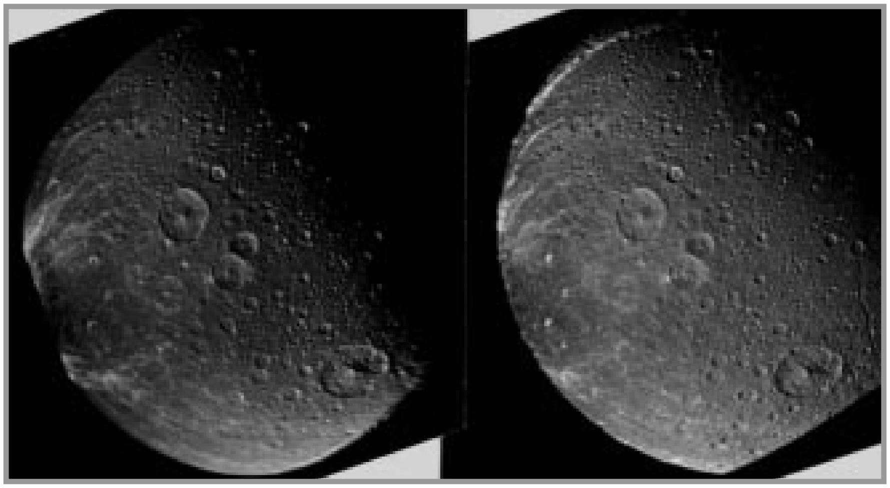


Figure 14.8. *Dione, an icy satellite of Saturn. (Image courtesy Paul Schenk, Lunar and Planetary Laboratory, Houston; reprojected Voyager frames FDS 34944.58 [left] and 34948.28 [right]).*

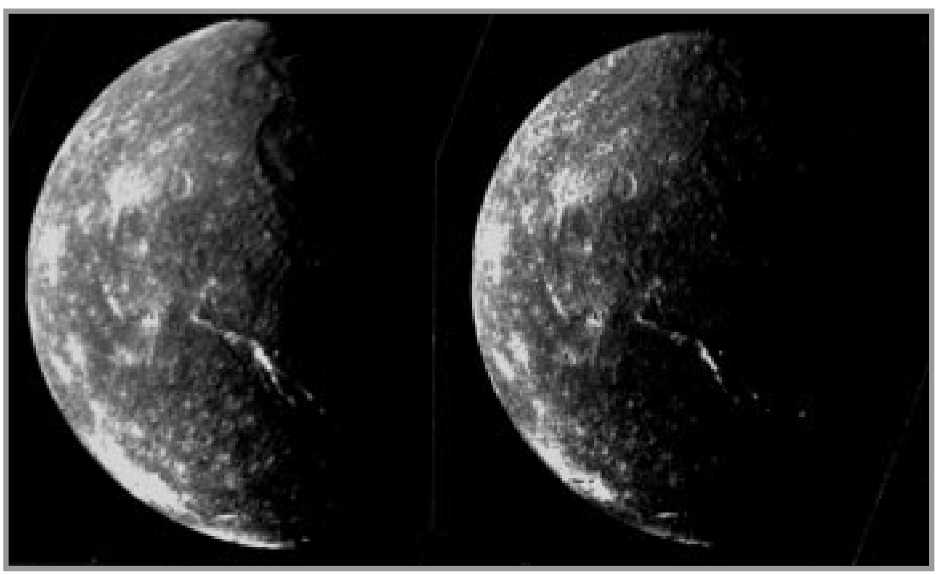


Figure 14.9. *The icy satellite Titania, a moon of Uranus. (Stereo image courtesy Paul Schenk, Lunar and Planetary Laboratory, Houston; reprojected Voyager frames FDS 26836.55 [left] and 26843.13 [right]).*

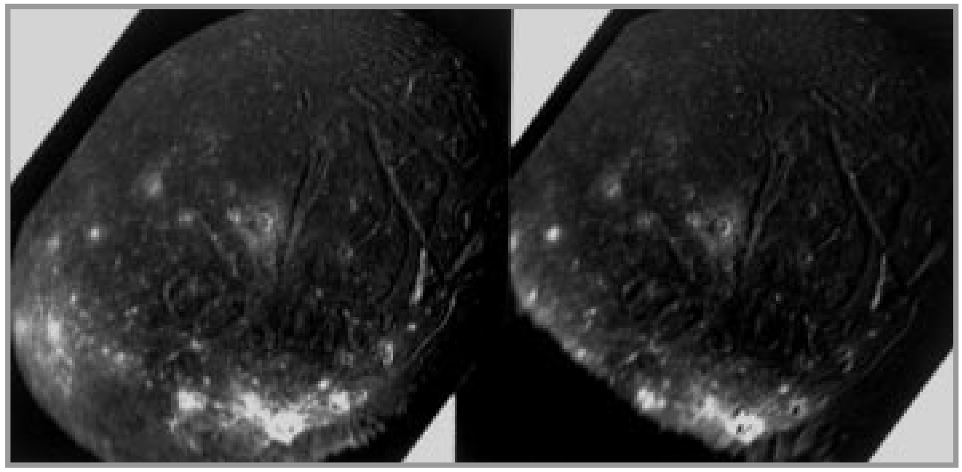


Figure 14.10. *The icy uranian satellite Ariel is seen in this stereo pair. (Image courtesy Paul Schenk, Lunar and Planetary Laboratory, Houston; reprojected Voyager frame FDS 26843.40 [left] and reprojected mosaic of frames 26845.33, .35, .37, and .39 [right]).*

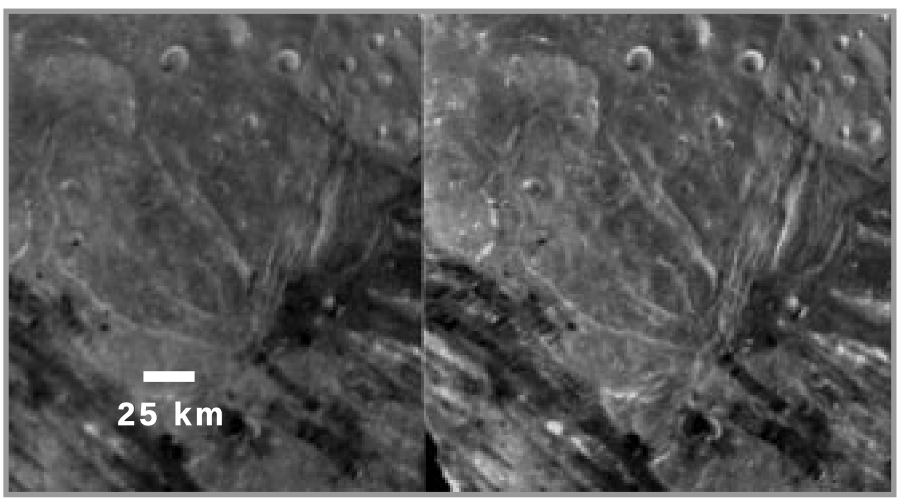


Figure 14.11. *Miranda, the innermost of the five major icy moons of Uranus, seen in stereo. (Image courtesy Paul Schenk, Lunar and Planetary Laboratory, Houston; a reprojected mosaic of Voyager frames FDS 26846.11 and .14 [left] and reprojected frame 26846.26 [right]).*

Introduction to Planetary Geologic Mapping

Maps have been used since the dawn of communication, when early hunters scratched simple maps in dirt with sticks. Through the years maps have evolved to show a wide variety of cultural and political subdivisions, historical events, and natural features. Maps figure prominently in exploration, including solar system exploration.

Geologic maps show the distribution of rocks and structures (such as faults) exposed on planetary surfaces. Geologic maps on Earth are usually derived from field work in which the geologist can examine rock exposures, called outcrops, up close. Geologists also use aerial photographs and other remote sensing data to construct geologic maps of Earth.

Except for the six Apollo landing sites on the Moon, direct field observations are not available for making planetary geologic maps. Consequently, most geologic maps of planets and satellites are derived from photographs and other remote sensing data, using the same geologic principles used on Earth. Planetary geologic maps are similar to preliminary maps constructed for Earth prior to field work.

This unit includes three exercises. The first introduces students to the principles of planetary geologic mapping using photographs, the next two enable the student to put those principles into practice by mapping parts of the Moon and Mars.

Exercise Two is suggested as an introductory exercise.

■ ★ 1.0 hours

Introduction to Photogeologic Mapping

Instructor Notes

Suggested Correlation of Topics

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

Purpose

The objective of this exercise is to demonstrate how observations of a planet can be used to produce geologic maps. This includes the identification of rock units and placement of units in a time sequence.

Materials

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

Substitutions: tracing paper and pencil

Background

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

All additional information for completing this exercise is contained in the student’s introduction. Student maps can be overlaid for comparison. Variation will occur based on the characteristics chosen to delineate each unit. Have the students discuss with each other the reasoning behind their unit selection.

Science Standards

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

Answer Key

1. Answers will vary. At a minimum students should list the following: Terrain One: dark plains—smooth (low relief), dark (low albedo), sparsely cratered, topographically low areas; Terrain Two: bright highlands—rough (high relief), light (high albedo), heavily cratered, topographically high areas. Possible additional terrains include: large young craters with rayed ejecta and moderate albedo highlands.

2. Answers will vary given terrains selected. For the terrains listed in question 1, the highlands are the oldest, the smooth plains are younger, and rayed craters are the youngest. Students should see that the rayed craters are superposed (on top) of the other terrains, and that the smooth plains cover (embay) the highlands.

Unit Descriptions

Unit Name	Observation	Interpretation
Smooth Plains	Smooth plains, few craters (mostly small), low albedo	Volcanic flow
Highlands	Rugged, numerous craters are various sizes, high albedo, topographically high	Old, heavily modified surface, possibly of volcanic origin

3. The graben is younger than the unit that contains it (the highlands).

4. The smooth plains are younger than the highlands. The highlands contain more craters, larger craters, and more eroded craters. In addition, the graben ends at the contact. It is overlain by the volcanic smooth plains.

5. The ridge is younger.

6. The crater is younger.

Stratigraphic Column

	Geologic Unit	Structural Features
Youngest		Crater on Ridge Ridge
	Smooth Plains	
		Graben
Oldest	Highlands	

Geologic History: This region was initially covered by a unit, possibly of volcanic origin, which was heavily cratered and modified by continued cratering. After formation of the highlands, tectonism occurred, as evidenced by the graben. Volcanic flows were emplaced in map area, represented by the smooth plains unit. No source area for the flows is identifiable within the mapped area. Cratering continued after the emplacement of the smooth plains unit. There has been a continuation (or reactivation) of tectonic activity in this area, indicated by the ridge. Finally, cratering has continued—represented by the crater on the ridge.

Name ______________________________

Introduction to Photogeologic Mapping

Purpose

The objective of this exercise is to demonstrate how careful observations of a planet can be used to construct geologic maps. This includes the identification of rock units and placement of units in a time sequence.

Materials

Clear acetate or overhead transparency, overhead projector markers, tape (or tracing paper and pencil)

Introduction

More than three decades of planetary exploration show that the surfaces of the solid planets and satellites have been subjected to the same geologic processes: **volcanism, tectonism** (e.g., earthquakes), **gradation** (erosion, etc.), and **impact cratering.** The relative importance of each process differs from planet to planet, depending upon the local environment. For example, a planet not having running water, such as the Moon, will experience erosion of a different style and intensity in contrast to a planet having abundant running water such as Earth.

Prior to the space program, the importance of impact cratering as a geologic process was not fully appreciated. It is now known that all of the planets were subjected to intense impact cratering in the early history of the solar system. Indeed, most of the craters on the Moon are of impact origin. On some planets, such as the Moon and Mercury, evidence of the impact process is preserved; on other planets, such as Earth, impact cratering is less evident. On the Moon, craters range in size from tiny micro craters of sub-millimeter size to the giant impact basins such as the 1300 km-diameter Imbrium basin.

A geologic map is a graphic portrayal of the distribution and sequence of rock types, structural features such as folds and faults, and other geologic information. Such a map allows geologists to represent observations in a form that can be understood by others and links the observations made at different localities into a unified form. In many respects, a geologic map is like a graph to a physicist; it allows one to understand many observations in a comprehensive form.

The **unit** is the basic component of geologic maps. By definition, it is a three-dimensional body of rock of essentially uniform composition formed during some specified interval of time and that is large enough to be shown on a conventional map. Thus, the making of geologic maps involves subdividing surface and near-surface rocks into different units according to their type and age. On Earth, geologic mapping involves a combination of field work, laboratory studies, and analyses of aerial photographs. In planetary geology, geologic mapping is done primarily by remote sensing methods--commonly interpretation of photographs. Field work is rather costly and not always possible. Mapping units are identified on photographs from **morphology** (the shape of the landforms), **albedo** characteristics (the range of "tone" from light to dark), color, state of surface preservation (degree of erosion), and other properties. Remote sensing of chemical compositions permits refinements of photogeologic units. Once units are identified, interpretations of how the unit was formed are made. In planetary geologic mapping the observation and interpretation parts of a unit description are separated (see figure 15.1).

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

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

Figure 15.1 shows a sample geologic map, including its unit descriptions and stratigraphic column. The relative ages were determined in the following manner: The cratered terrain has more (and larger) craters than the smooth plains unit -- indicating that the cratered terrain unit is older. In addition, fault 1 cuts across the cratered terrain, but does not continue across the smooth plains. Faulting occurred after the formation of the cratered terrain and prior to the formation of the smooth plains -- indicating that the smooth plains unit is younger than the cratered terrain and fault 1. The crater and its ejecta unit occurs on top of the smooth plains unit, and thus is younger. Finally, fault 2 cuts across all the units, including the crater and its ejecta unit, and is thus the youngest event in the region. The geologic history that could be derived from this map would be similar to the following:

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

Questions

The Near Side of the Moon

Examine Figure 15.2, an observatory photograph of the near side of the Moon and answer the following questions:

1. Visually separate the different areas of the Moon into terrains (for example, continents and oceans on Earth). List the characteristics of each terrain.

2. Which terrain do you think is the oldest? the youngest? Explain why.

This figure shows that the surface of the Moon is not the same everywhere. The terrains, however, are not units in the strictest sense. Rather, each terrain is made up of many different units; close inspection of Figure 15.2 shows small areas having distinctive characteristics and that, when observed on high resolution photographs or on the ground, are seen to be distinct rock units.

Examine Figure 15.3. This photo shows in greater detail the boundary between two of the terrains you identified previously. Tape a piece of acetate or tracing paper over the photo. Mark the four corners as reference points in case the sheet shifts while you are working on it and also to allow for overlaying with other maps for comparison. Draw the contact between the rough highlands and the smooth plains. Note the feature indicated by the A on the photo. This is a graben caused by tectonic activity. The feature marked B on the photo is a ridge caused by tectonic activity. Trace these features on your map. Fill in the unit descriptions in the space provided below. Label the units on your map.

Unit Name	Observation	Interpretation

3. What is the age relation between the graben and the highlands? (Is the graben older or younger than the highlands?)

4. What is the age relation between the highlands and the smooth plains? What observations did you use to decide?

5. What is the age relation between the ridge and the smooth plains?

6. What is the age relation between the ridge and the large crater on it?

Place the geologic units and structural features identified above in their correct sequence in the stratigraphic chart below. List the oldest at the bottom and the youngest at the top.

	Geologic Unit	Structural Features
Youngest		
Oldest		

Using your unit descriptions and stratigraphic chart, write a short geologic history for the area you have mapped.

Geologic History:

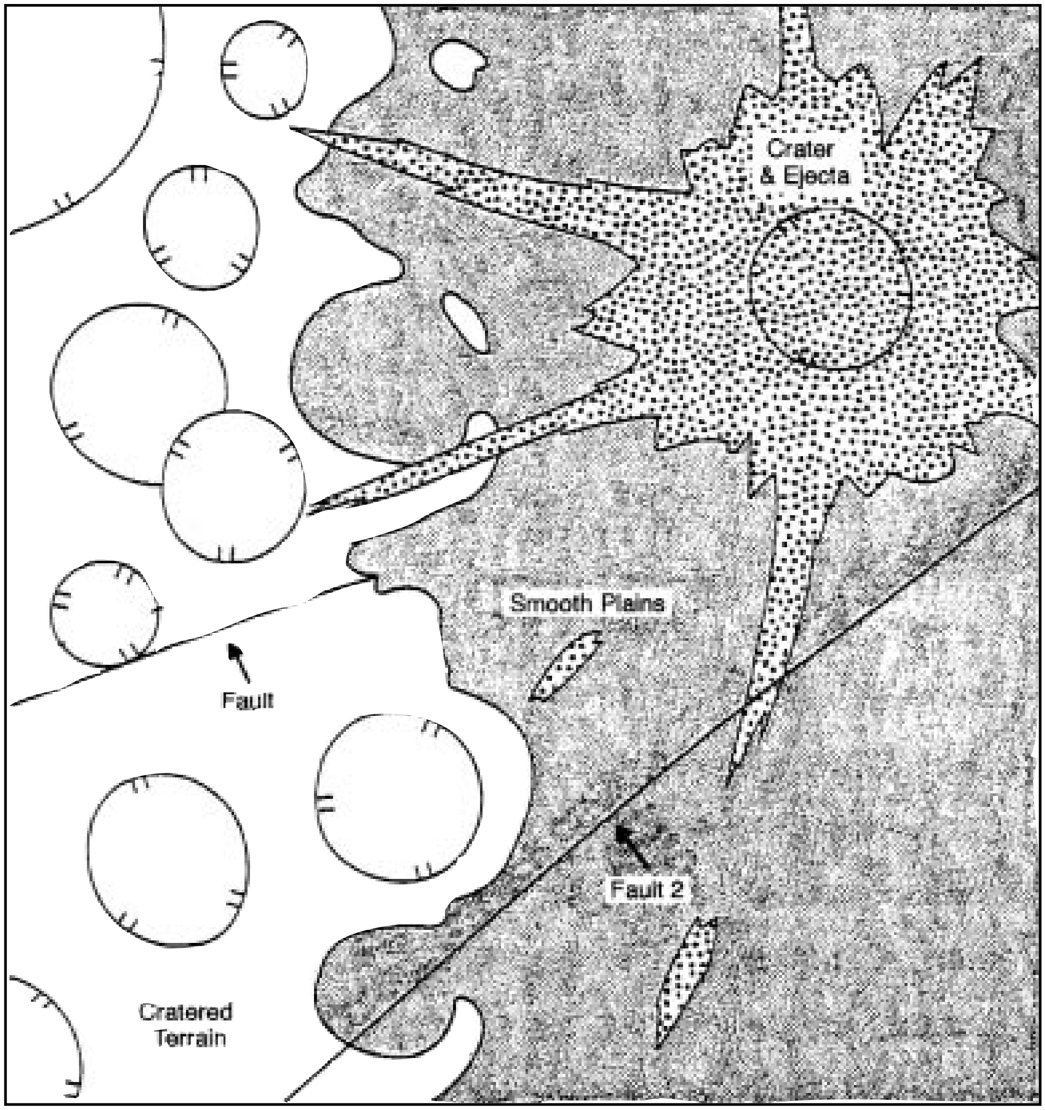


Figure 15.1. *Sample geologic map and derived stratigraphic column.*

Stratographic Column

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

Unit Descriptions

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

Figure 15.2. *Near Side of the Moon. North is to the top. Photo courtesy of Ewen A. Whitaker, Unviersity of Arizona.*

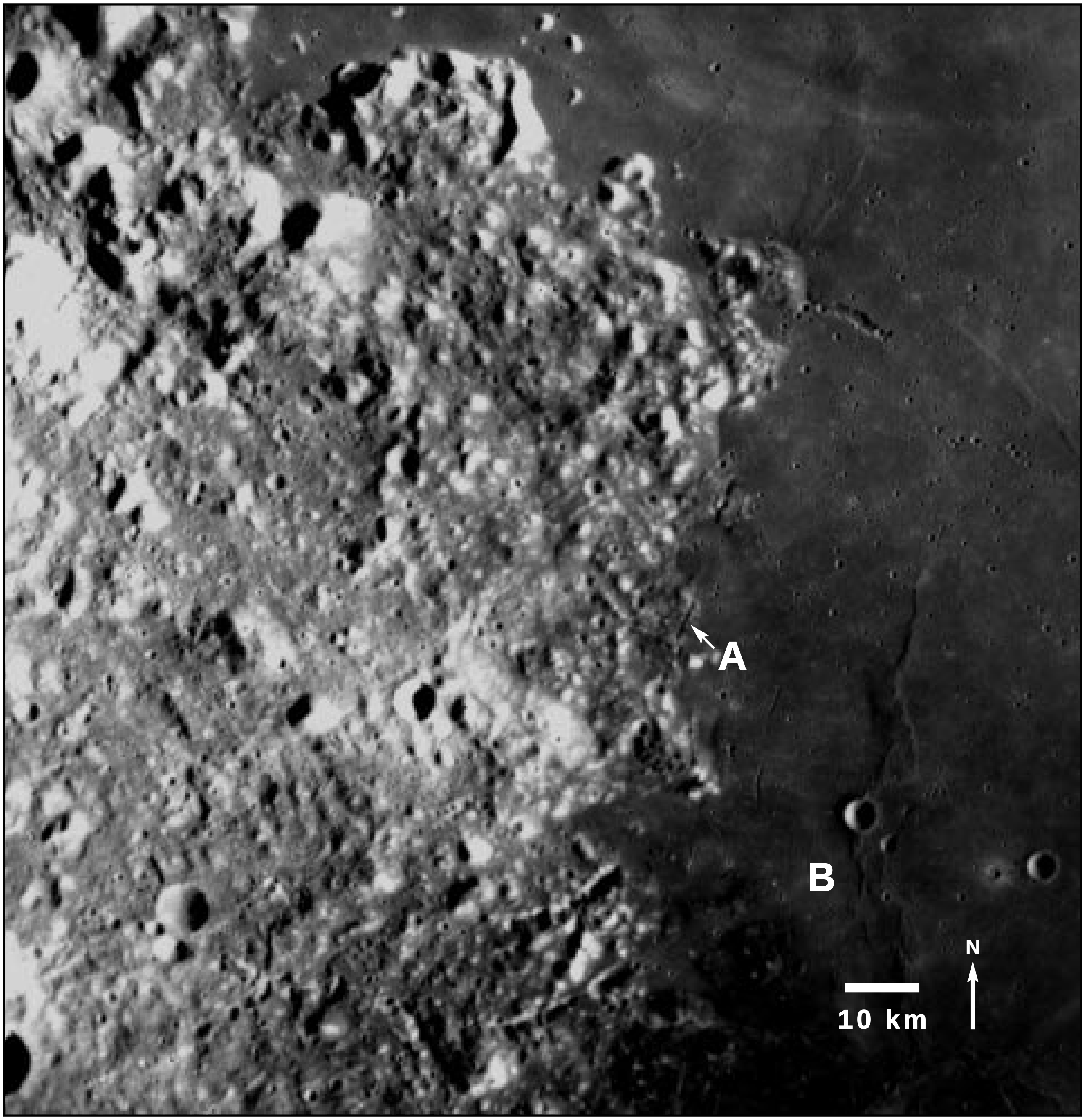


Figure 15.3. *Apollo 15 photograph of the moon. North is to the top. The small crater above the letter B is 3.8 kilometers in diameter. Apollo metric AS15 0583.*

Exercises Two and Fifteen are suggested as introductory exercises.

■ ★ 3.0 hours

Photogeologic Mapping of the Moon

Instructor Notes

Suggested Correlation of Topics

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

Purpose

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

Materials

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

Substitutions: tracing paper, colored pencils

Background

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

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

Science Standards

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

Answer Key

Part A

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

Answer Key, continued

Part B

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

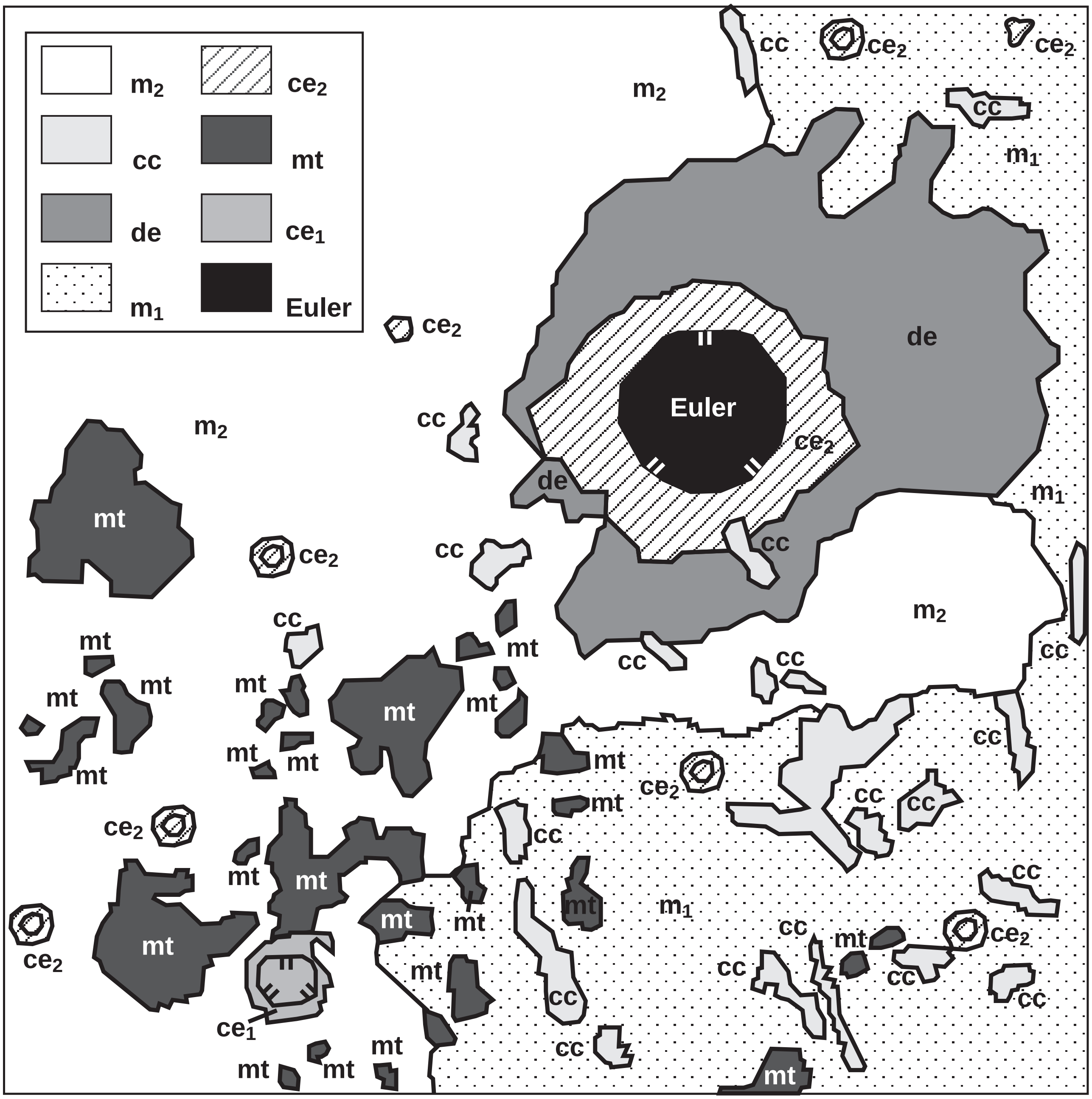
Answer Key, continued

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

Geologic History

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

Answer Key, continued



Name ______________________________

Photogeologic Mapping of the Moon

Purpose

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

Materials

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

Introduction

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

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

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

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

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

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

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

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

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

Procedure and Questions

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

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

Part A

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Part B

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

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

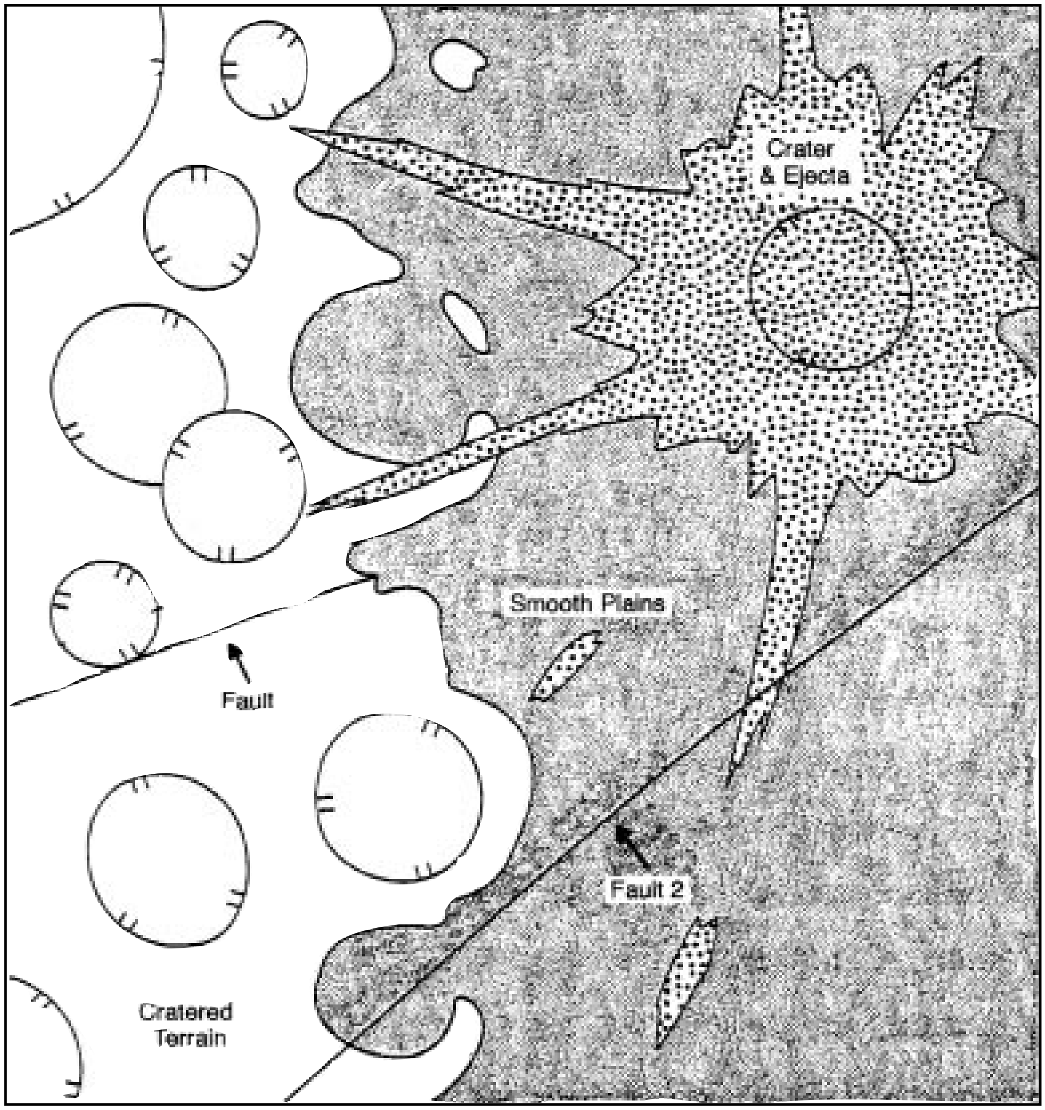


Figure 16.1. *Sample geologic map and derived stratigraphic column.*

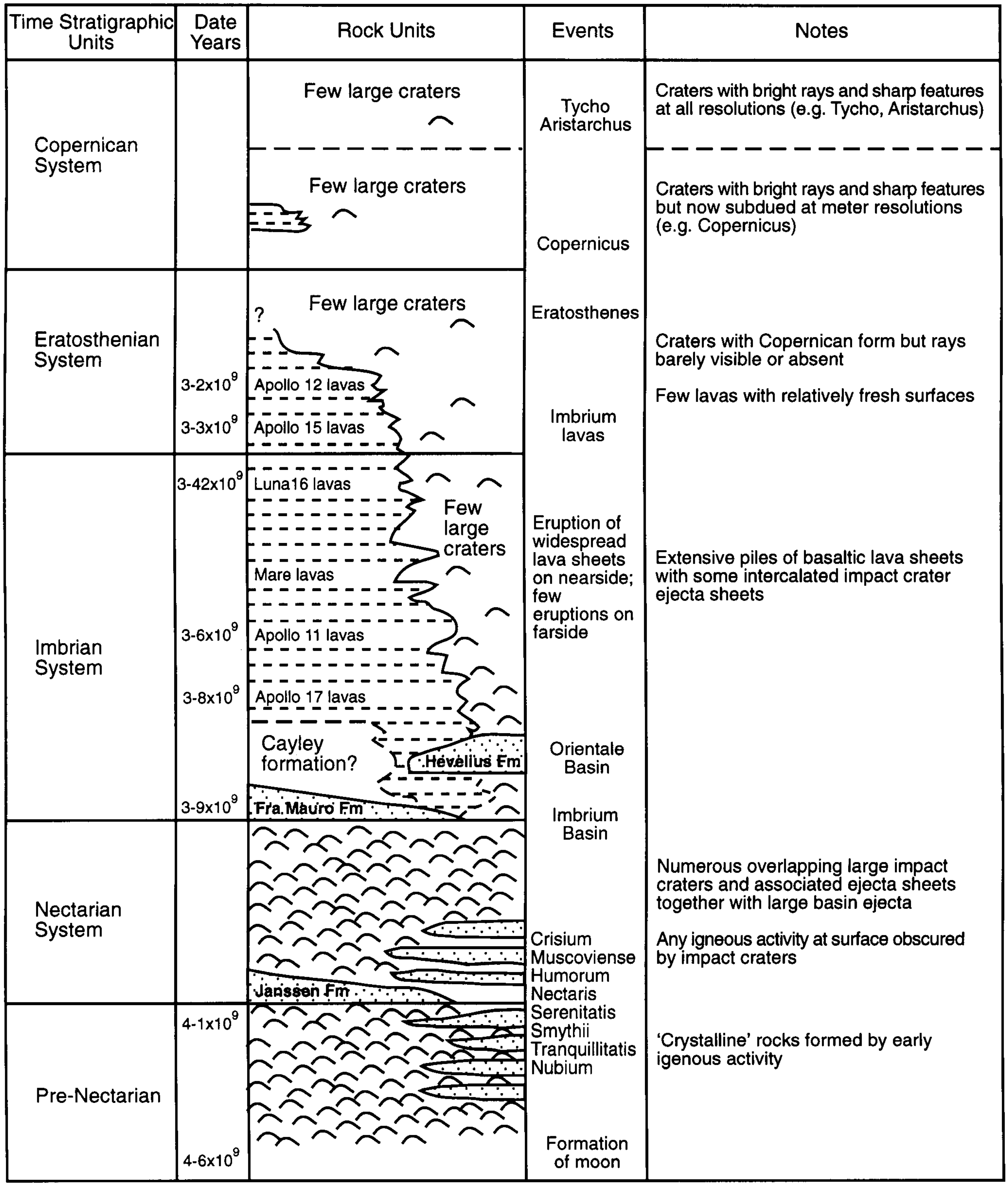
Stratographic Column

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

Unit Descriptions

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

Lunar Geologic Time Scale



(after Guest and Greely, 1977)

Figure 16.2.

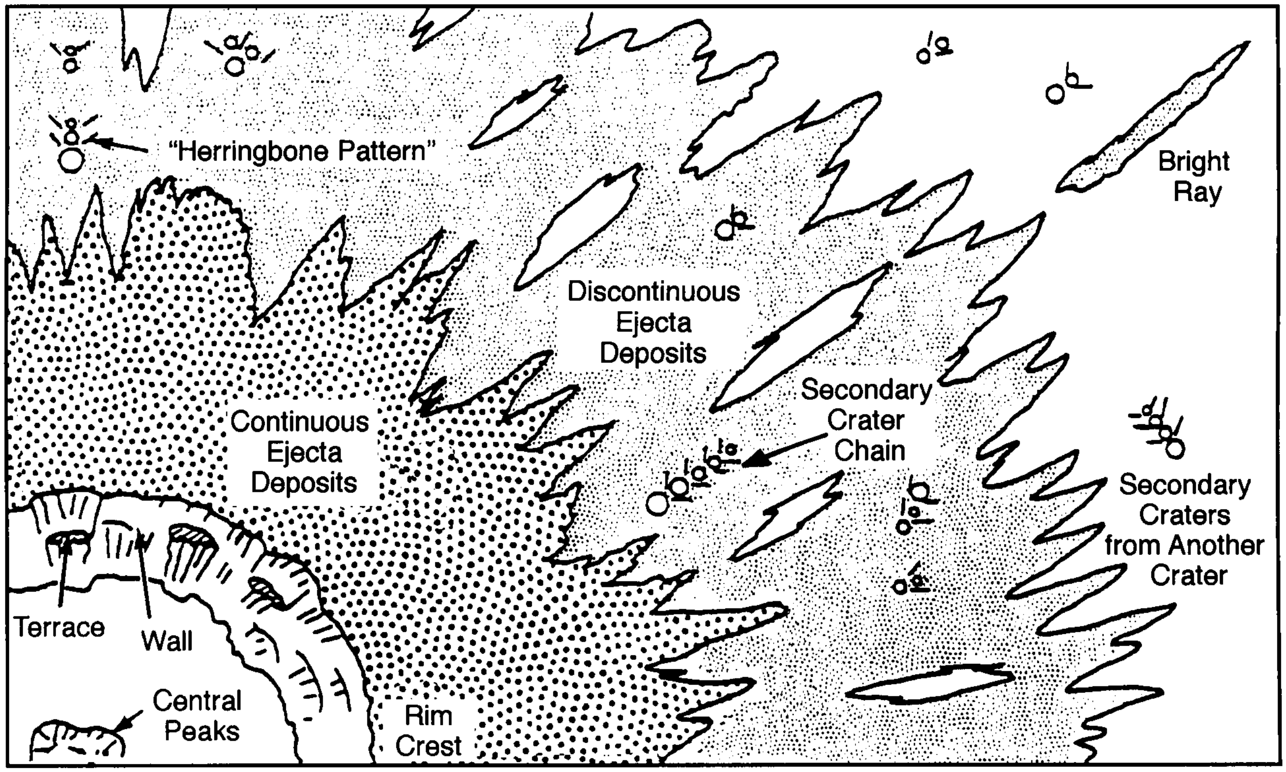


Figure 16.3. *Diagram of typical impact crater deposits.*

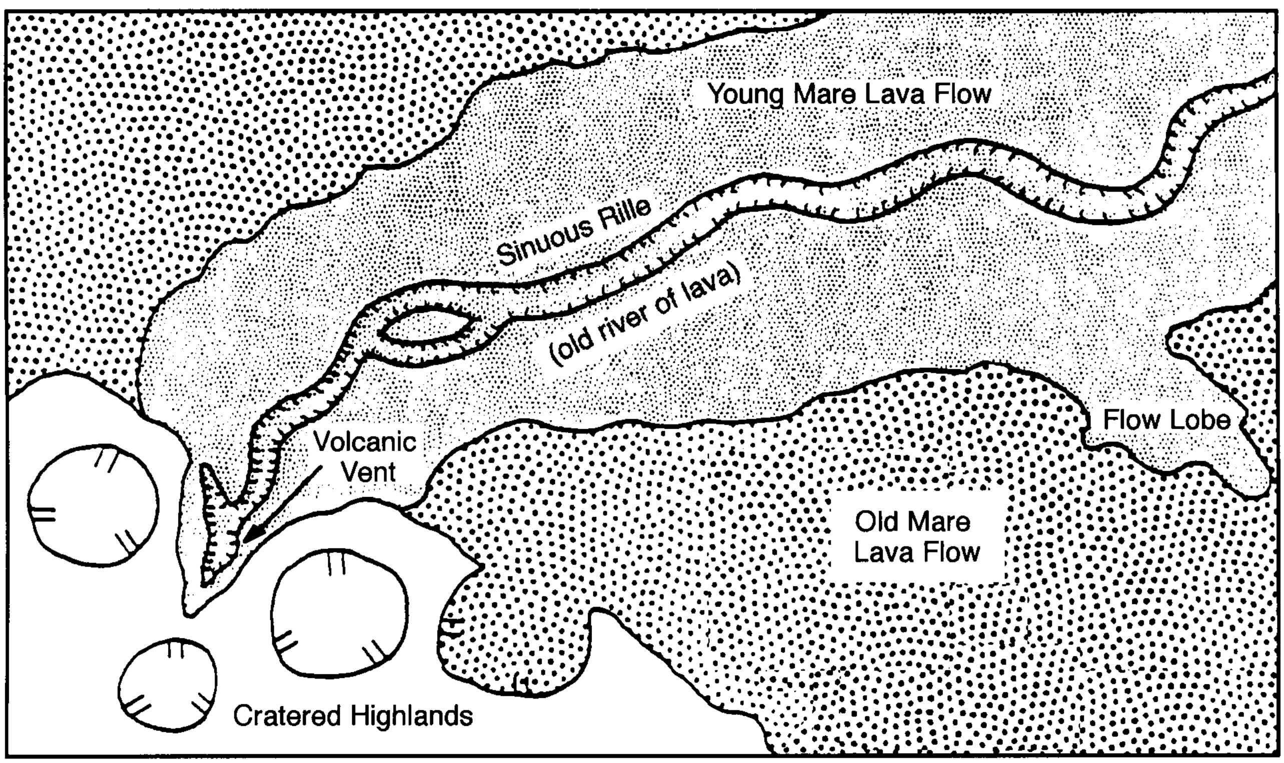


Figure 16.4. *Diagram of a typical sinuous rille.*

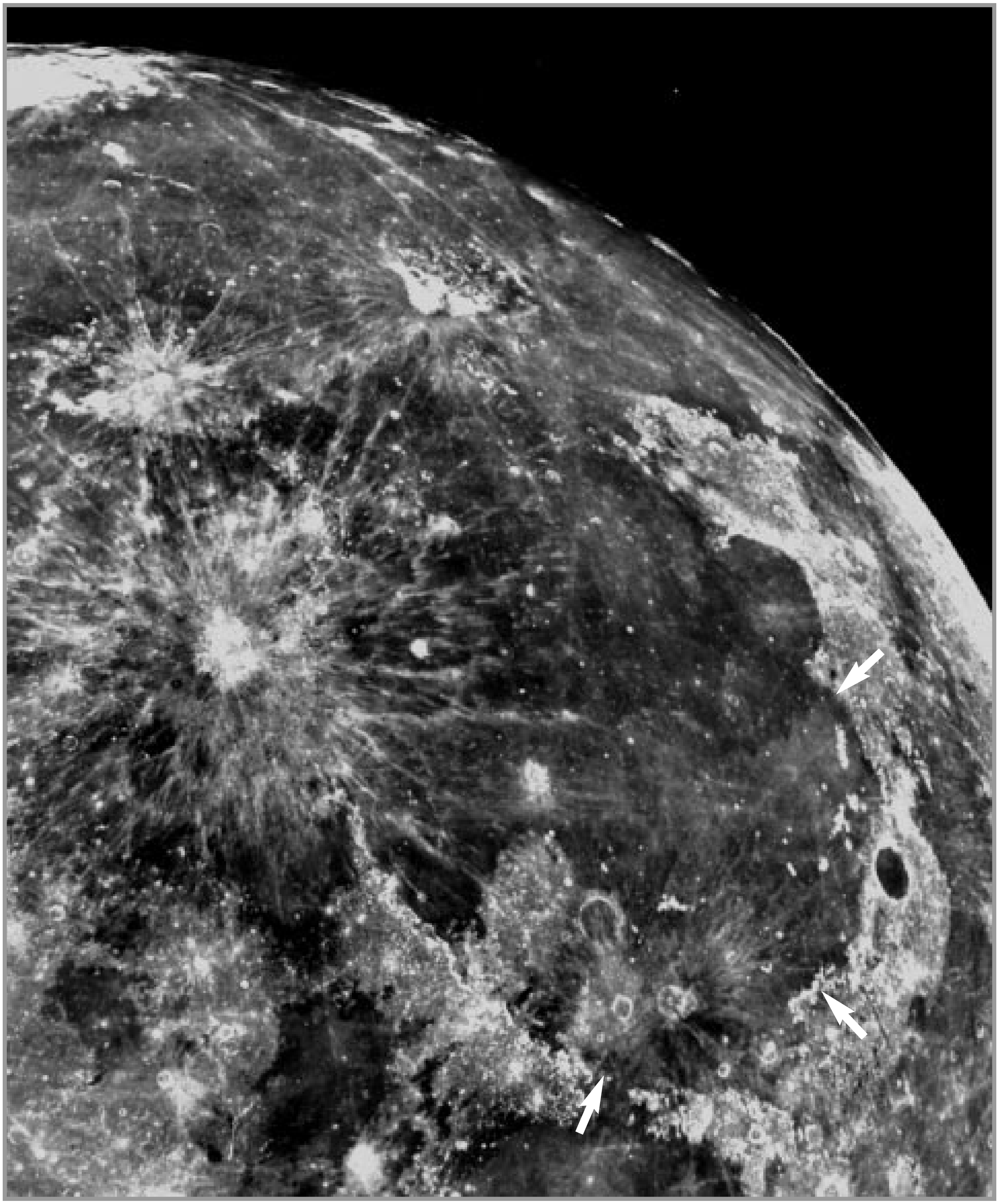


Figure 16.5. *Photograph of the near side of the moon, showing the Imbrium Basin (indicated by arrows). North is to the top. (courtesy of Ewen A. Whitaker, Univ. of Arizona)*

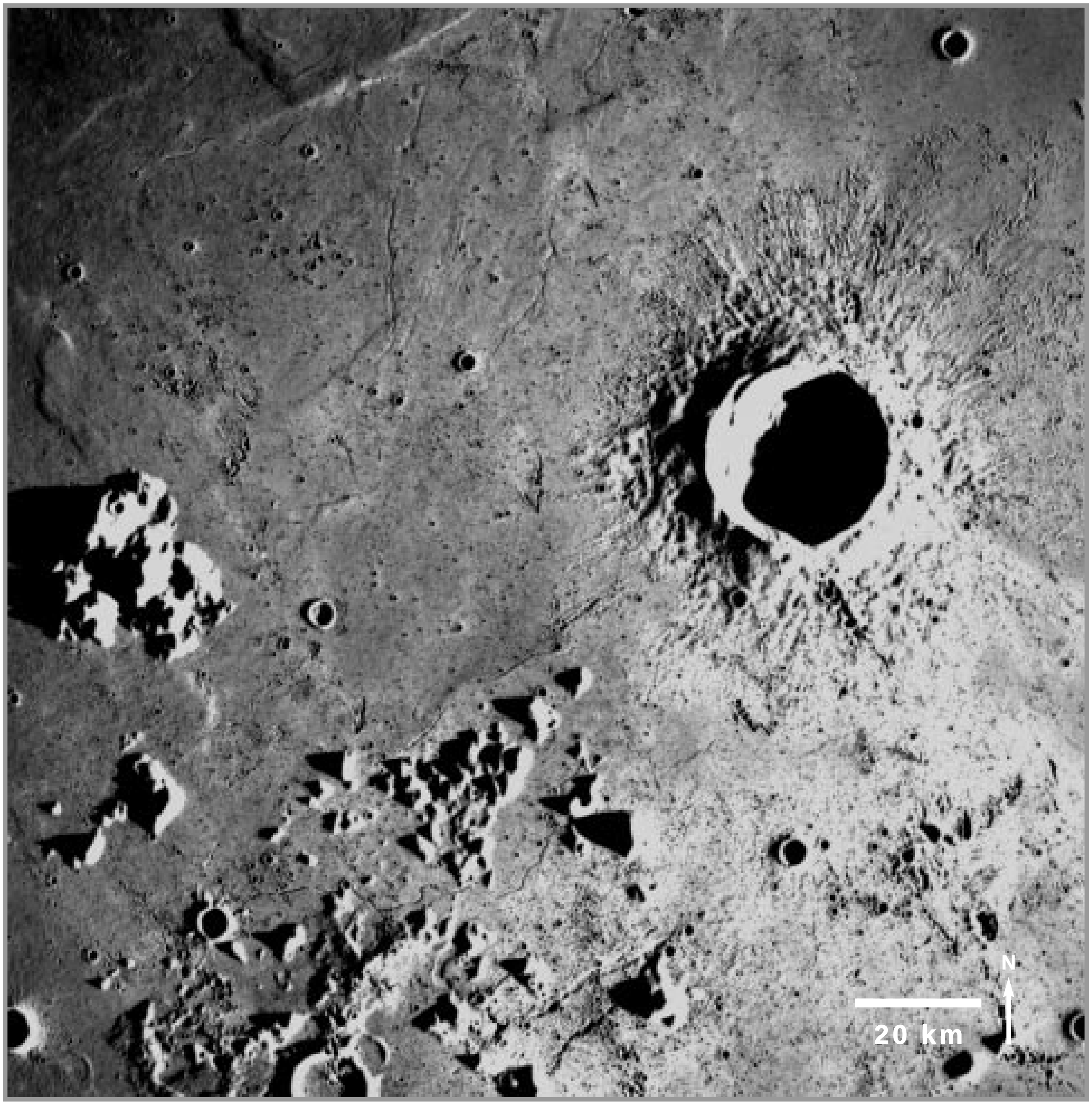


Figure 16.6. *Photograph of the Euler crater region on the near side of the moon. North is to the top. Euler crater (the large one) is 27 kilometers in diameter. Apollo 17 metric photo AS17 2730.*

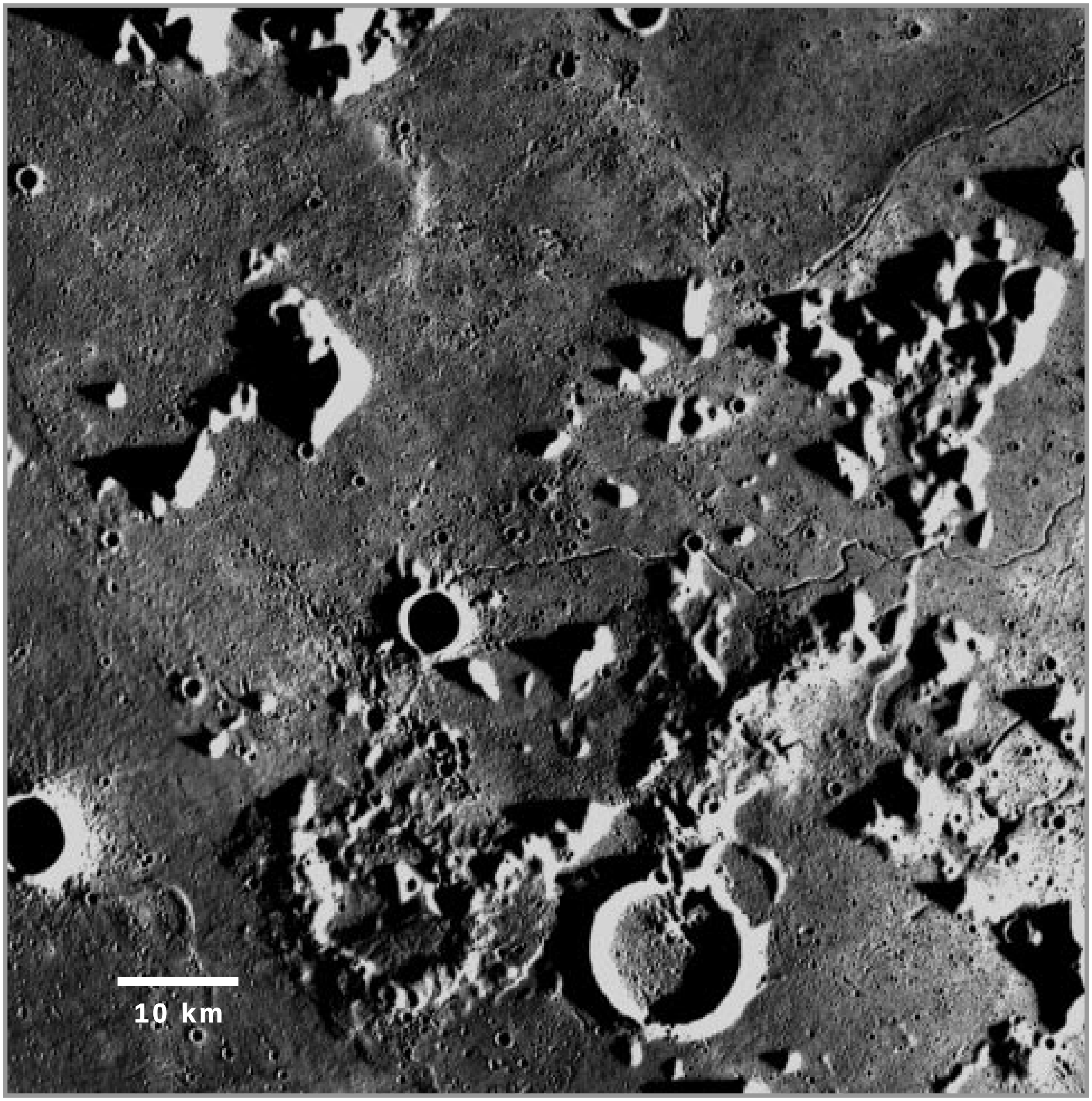


Figure 16.7. *Southwest quadrant of Euler region photo. North is to the top. Apollo 17 metric photo AS17 2730.*

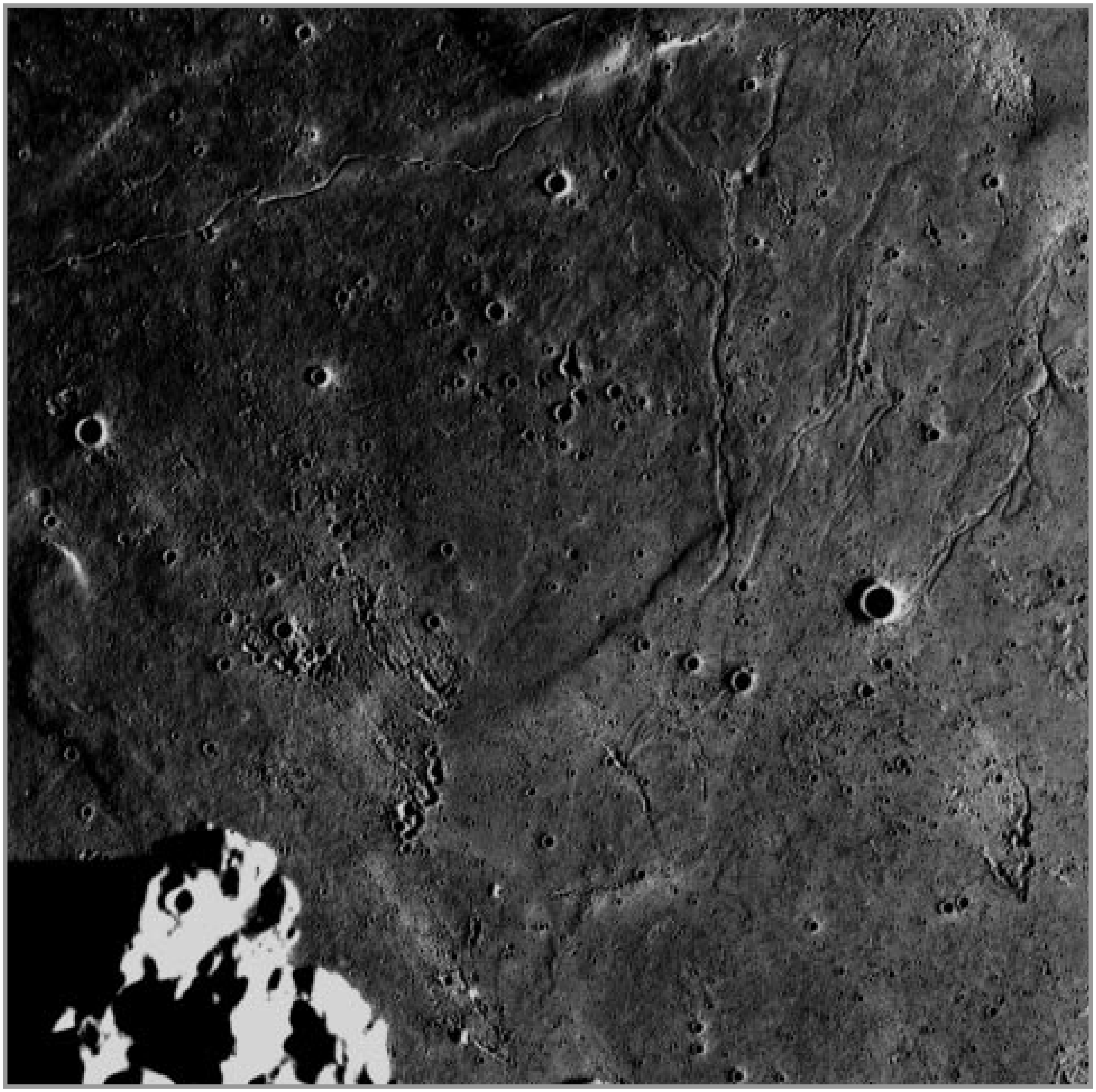


Figure 16.8. *Northwest quadrant of Euler region photo. North is to the top. Scale is the same as for Figure 16.7. Apollo 17 metric photo AS17 2730.*

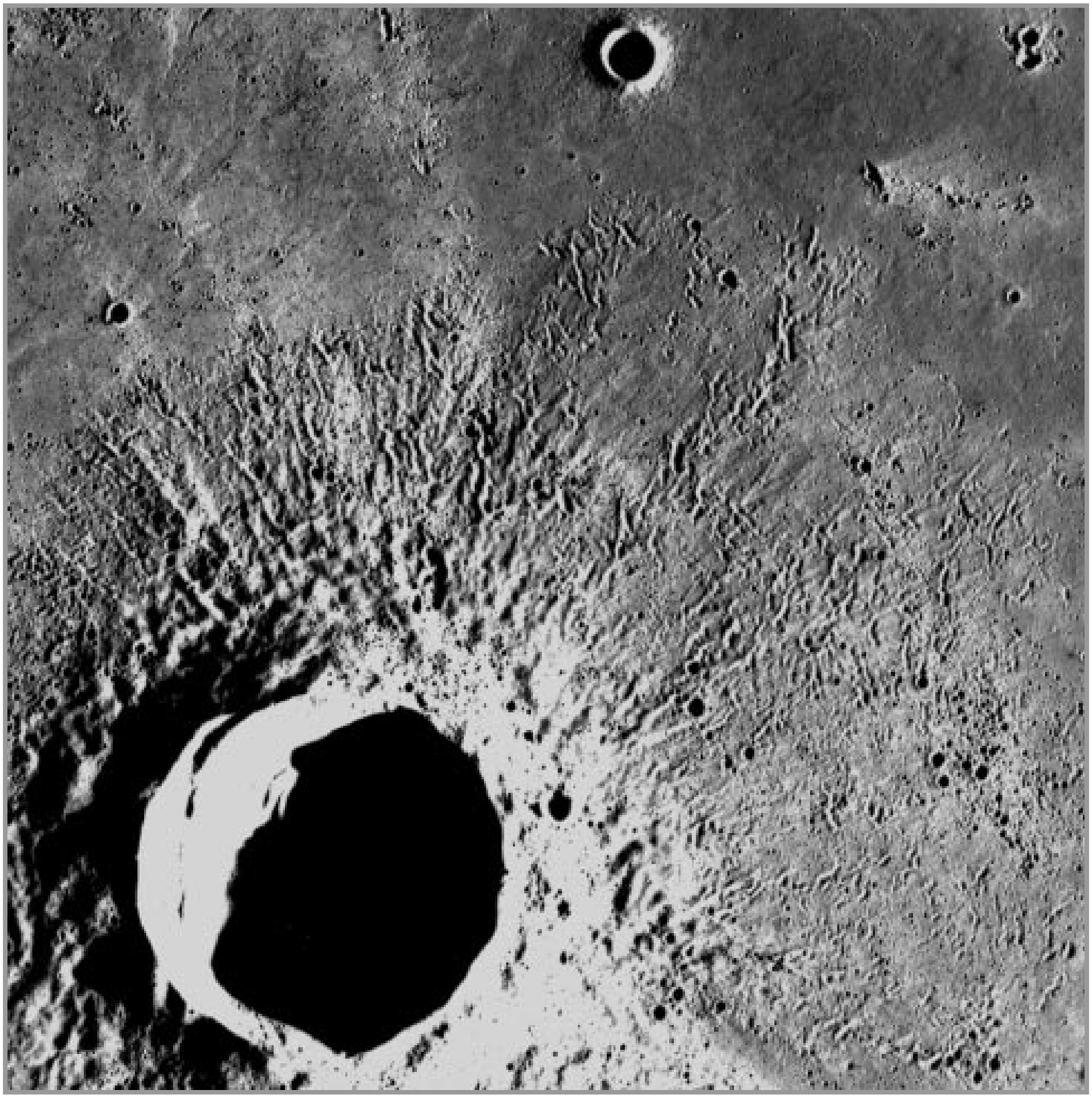


Figure 16.9. *Northeast quadrant of Euler region photo. North is to the top. Scale is the same as for Figure 16.7. Apollo 17 metric photo AS17 2730.*

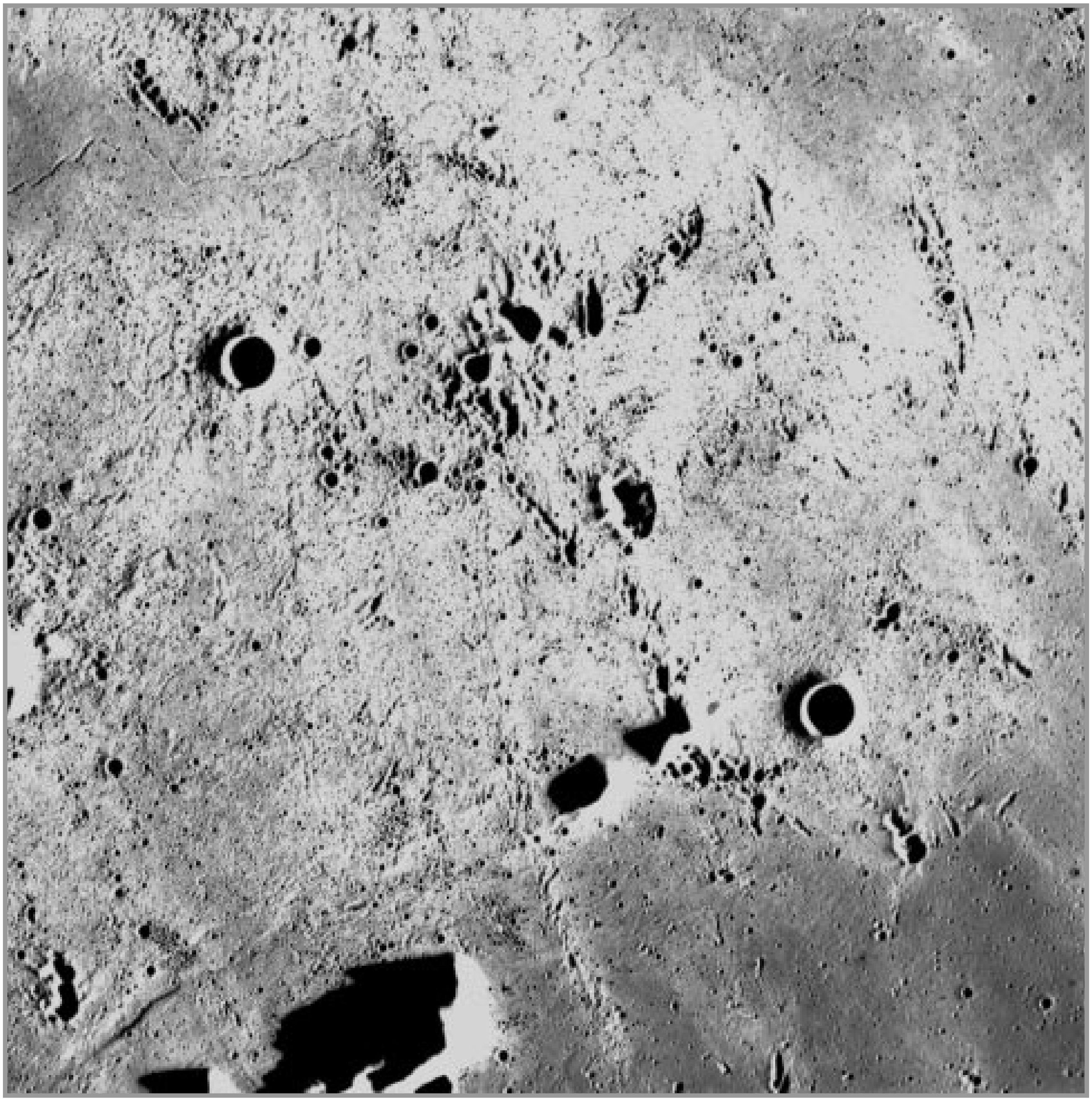


Figure 16.10. *Southeast quadrant of Euler region photo. North is to the top. Scale is the same as for Figure 16.7. Apollo 17 metric photo AS17 2730.*

Unit Name	Observation	Interpretation

Figure 16.11. *Unit descriptions.*

	Geologic Unit	Structural Event	Age
Youngest			
Oldest			

Figure 16.12. *Stratigraphic column.*

Geologic History:

Exercise Two and Fifteen are suggested as introductory exercises.

■ ★ 2.0 hours

Photogeologic Mapping of Mars

Instructor Notes

Suggested Correlation of Topics

Deductive reasoning, geologic time, geometric relations, geomorphology, maps, remote sensing, satellite observations, stratigraphy, superposition

Purpose

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

Materials

Suggested: Photomosaic MC-16 (SE) of Mars (U.S. Geological Survey Map I-1187)*, clear acetate or overhead transparency, overhead projector markers, tape

Substitutions: tracing paper, set of colored pencils

*This can be ordered from: Western Distribution Branch, U.S. Geological Survey, Box 25286, Federal Center, Denver, CO 80225.

Background

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

Science Standards

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

Answer Key

Map after 1) Scott et al., 1981, Map Showing Lava Flows in the Southeast Part of the Memnonia Quadrangle of Mars, USGS Map I-1271 and 2) Craddock and Greeley, 1994, Geologic Map of the MTM - 20147 Quadrangle, Mangala Valles Region of Mars, USGS Map I-2310.

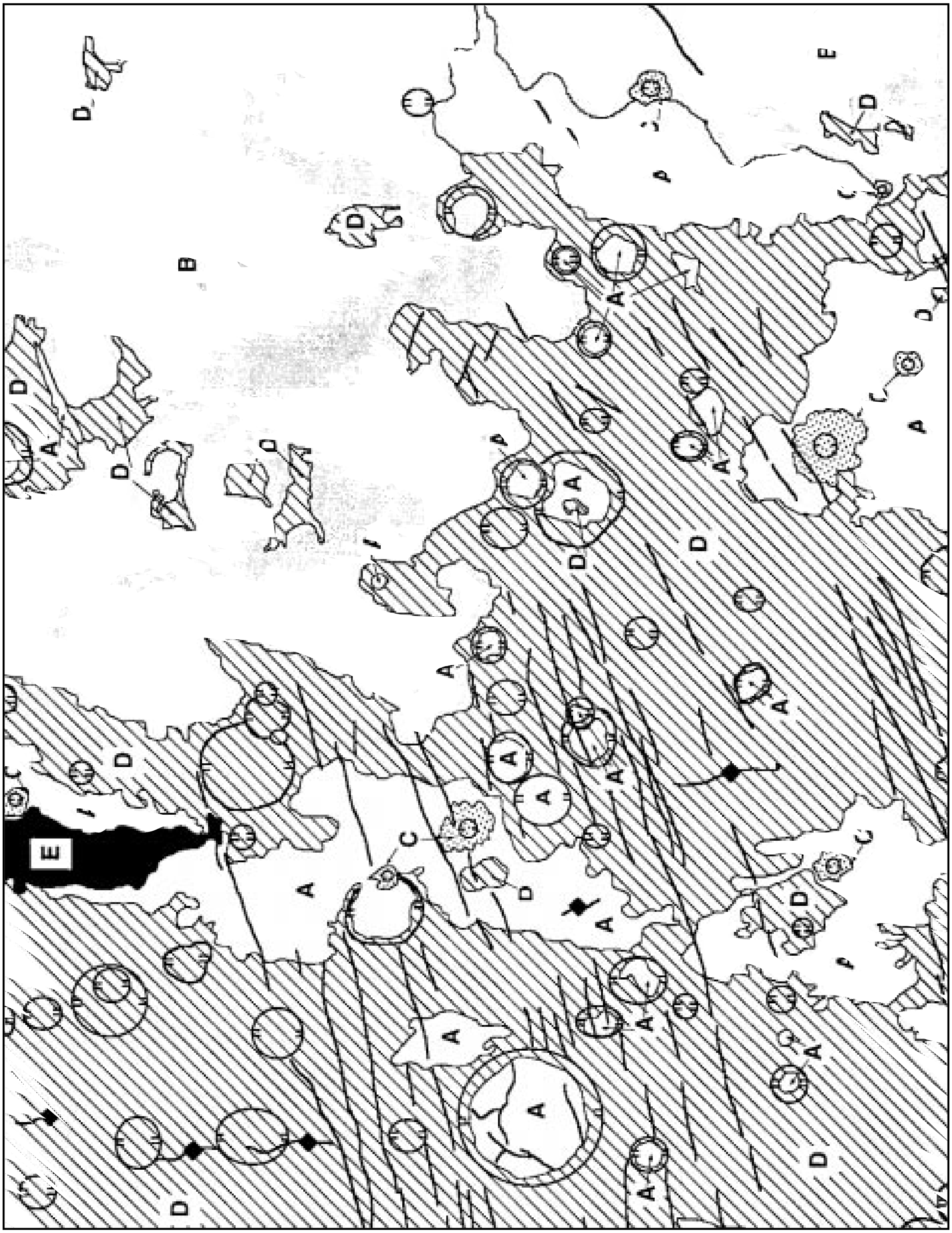
Unit Name	Observation	Interpretation
A	flat, generally featureless plains, uniform albedo, contains faults (graben) and ridges in some areas	probable volcanic flows, may be mantled by wind deposited materials
B	mottled albedo, flow appearance, lobate margins, some channels evident, forms broad lobes and sheets, embays older terrain	volcanic flows, no source visible in area
C	fresh craters with complete rims and identifiable ejecta deposits	impact craters
D	rugged plains, relatively heavily cratered, topographically higher than surroundings, contains faults (graben) and ridges, embayed by younger units	old terrain of unknown origin, possibly volcanic, has undergone extensive cratering
E	streamlined channel deposits	water eroded topography and fluvial deposits

	Geologic Unit	Structural Event
Youngest	C	Graben?
	A	Graben?
	B/E	Ridges?
Oldest	D	Tectonics?

Geologic History

The history of this area begins with the formation of the rugged plains (Unit D). This unit has been extensively cratered. Tectonic events may have initiated at this time. Graben in the area trend ENE, while ridges trend NS. Tectonic activity may have been intermittent or somewhat continuous over time, as graben and a few ridges are found on all units, but are most common on Unit D. Volcanic plains (Unit B) were emplaced in the eastern section of the mapped area; the source of these flows is not contained within the map area, but most likely is to the east. Fluvial activity, perhaps concurrent with volcanic flow emplacement, cut topographic features and deposited materials (Unit E) in the north-central section of the map. The age relation between units B and E is unknown. Large craters and low land areas were filled by Unit A, probably consisting of volcanic flows and a mantling dust/sand deposit. Finally, impacts occurred forming the young craters and their ejecta blankets.

Sample Photogeologic Map for the Memnoia Region, Mars



Name ____________________

Photogeologic Mapping of Mars

Purpose

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

Materials

Photomosaic MC-16 (SE) of Mars, clear acetate or overhead transparency, tape, overhead projector markers (or use tracing paper and colored pencils)

Introduction

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

Three decades of planetary exploration have shown that the surfaces of rocky and icy planets and satellites have all been subjected to the same basic geologic processes: **volcanism, tectonism, gradation,** and **impact cratering.** The relative importance of each process in shaping the surface differs from body to body, depending on the local environment (presence of an atmosphere, running water, etc.). All four of the processes listed above have worked to shape the surface of Mars. In addition to volcanism, seen in the form of large volcanoes and extensive lava flows, and impact cratering, Mars has undergone tectonism. This process is indicated by the presence of faults, fractures, and graben. Gradation has occurred on Mars through the work of running water (in the past), wind, **periglacial** processes, and landslides. All these processes have produced landforms and rock units that can be recognized and mapped. An important part of preparing a geologic map, once the units have been identified, is interpreting what geologic process(es) was responsible for the formation of each map unit. When preparing a planetary photogeologic map, unit descriptions are divided into two parts: the observation (what you see) and the interpretation (how you think it formed).

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

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

Figure 17.1 shows a sample geologic map, including its unit descriptions and stratigraphic column. The relative ages were determined in the following manner: The cratered terrain has more (and larger) craters than the smooth plains unit—indicating that the cratered terrain unit is older. In addition, fault 1 cuts across the cratered terrain, but does not continue across the smooth plains. Faulting occurred after the formation of the cratered terrain and prior to the formation of the smooth plains—indicating that the smooth plains unit is younger than the cratered terrain and fault 1. The crater and its ejecta unit occurs on top of the smooth plains unit and thus is younger. Finally, fault 2 cuts across all the units, including the crater and its ejecta unit, and is thus the youngest event in the region. The geologic history that could be derived from this map would be similar to the following:

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

Procedure and Questions

Part A: The Geologic Map

The area you will be mapping is the Memnonia region (SE), which lies between 135° to 157.5° west longitude and 15° to 30° south latitude. In this area, the volcanic units of the Tharsis region flow onto the southern cratered highlands. All four of the principal geologic processes described above have left their imprint on this region and the rock units resulting from these processes can be mapped.

Examine the photomosaic in detail and identify the geologic units based on surface morphology (hilly, flat, etc.), albedo (light, dark), crater density, and other appropriate characteristics. There are at least 4 major geologic units in the region. Place the acetate (or tracing paper) over the photomosaic and tape it to the photo. If using tracing paper, tape at the top only so that it can be lifted up to see the image beneath. Mark the four corners of the photomosaic to use as reference points if the acetate (or paper) shifts, and also for overlaying with other maps for comparison. Draw preliminary contacts around the units—DO NOT WRITE ON THE PHOTOMOSAIC. Label the units by name, or letters symbols within each unit. Areas of a unit need not be laterally continuous on the surface. Use symbols for features such as faults, grabens, fractures, and crater rims (see symbols sheet, Figure 17.2). Tabulate the units on Figure 17.3 and describe their main characteristics. Names are of your choice, such as "mountain unit, " "smooth plains". If you are using tracing paper, color the map, using a different color for each unit.

Key to Map Symbols

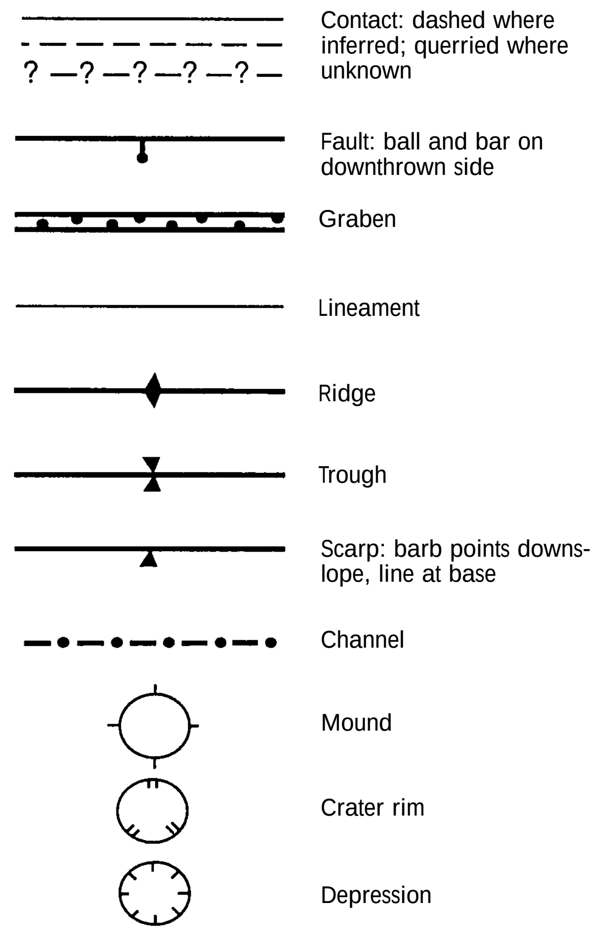


Figure 17.1.

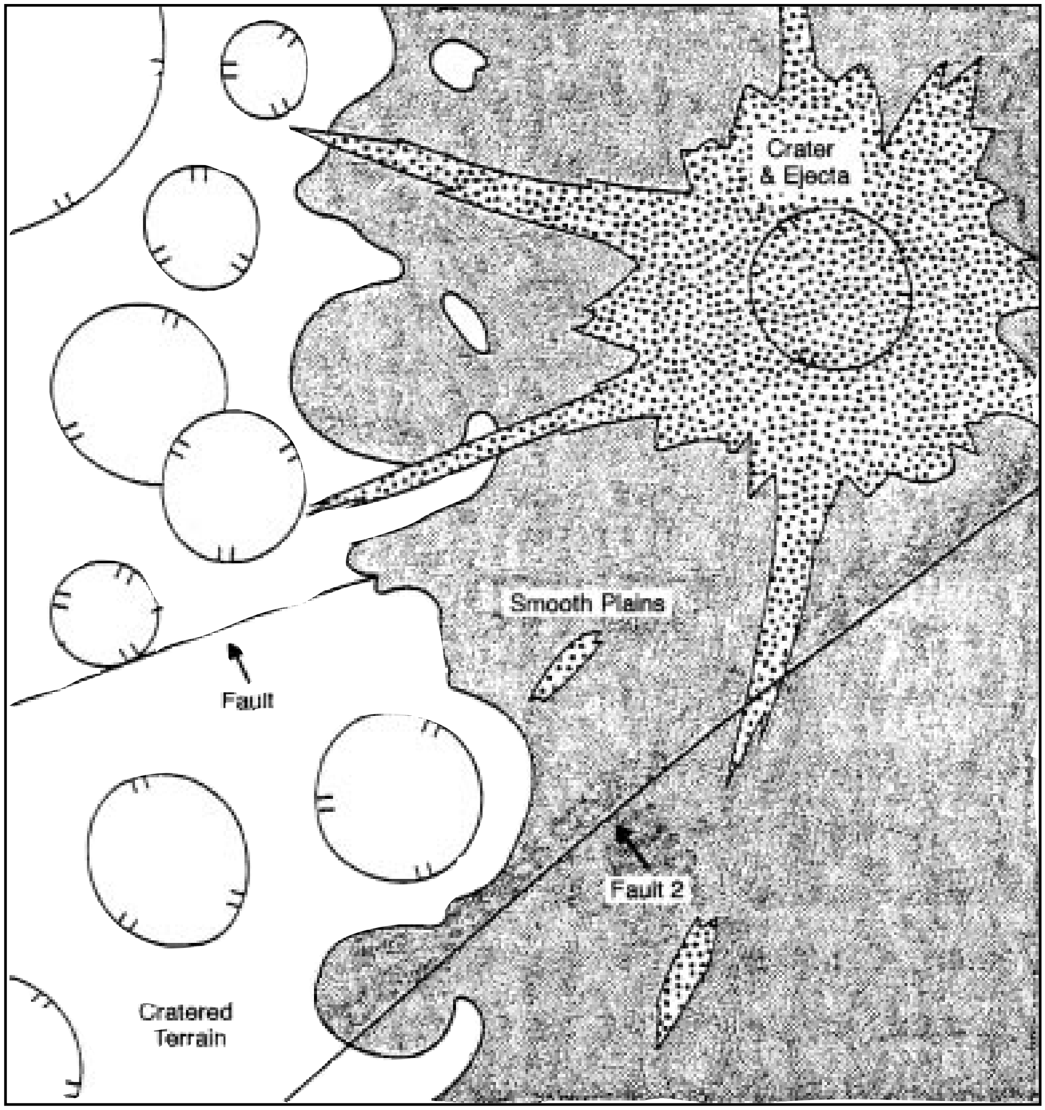


Figure 17.2. *Sample geologic map and derived stratigraphic column.*

Stratographic Column

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

Unit Descriptions

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

Unit Name	Observation	Interpretation

Figure 17.3. *Unit descriptions*

Part B: Regional Geologic History

Based on your observations, determine the stratigraphy of your units (the relative order of units from youngest to oldest). List the units in the column “Geologic Unit” in Figure 17.4 in order from youngest at the top to oldest at the bottom. Place an structural information in the column “Structural Events”. Using the stratigraphic relations and interpretations based on your examination of the photomosaic, derive a geologic history for the Memnonia region.

	Geologic Unit	Structural Event
Youngest		
Oldest		

Figure 17.4. *Stratigraphic column*

Geologic History:

Aeolian: Pertaining to wind.

Albedo: The ratio of the radiation reflected by a body to the amount incident upon it, often expressed as a percentage, as, the albedo of the Earth is 34%.

Angle of illumination: The angle that a ray of electromagnetic energy makes with the plane of a surface (light from directly overhead is at 90°).

Atmosphere: The body of gases surrounding or comprising any planet or other celestial body, held there by gravity.

Caldera: Large, circular to subcircular depression associated with a volcanic vent. Calderas result from collapse, explosion, or erosion.

Cinder cone: A volcanic, conical hill formed by the accumulation of cinders and other pyroclastic materials; slopes are usually greater than 10°.

Contact: A plane or irregular surface between two types or ages of rock.

Coriolis effect: The acceleration which a body in motion experiences when observed in a rotating frame. This force acts at right angles to the direction of the angular velocity.

Corona: Elliptical, tectonically deformed terrains found on Venus and Miranda.

Crater: Circular depression on a surface.

Cyclonic storm: Atmospheric disturbance with circulation of winds in a counterclockwise direction in the northern hemisphere and in a clockwise direction in the southern hemisphere.

Datum plane: A surface of widespread extent used as a reference for stratigraphic determinations.

Density: Measure of the concentration of matter in a substance; mass per unit volume.

Deposition: The accumulation of material by physical or chemical sedimentation.

Dip: The angle that a surface makes with the horizontal (measured perpendicular to the strike of the surface).

Dune: Mound of fine-grained material formed by wind or water

Eddy: A temporary current, usually formed at a point at which a current passes some obstruction, or between two adjacent currents flowing in opposite directions, or at the edge of a permanent current.

Ejecta: The deposit surrounding an impact crater composed of material (rock fragments, glass) thrown from the crater during its formation.

Electromagnetic spectrum: Energy in the form of radiation, all sharing the same speed of propagation (c - speed of light) but varying in frequency and wavelength.

Embayment: A low area containing rocks that extend into the terrain of other rocks (lap over or up against other rock units).

Equilibrium (cratered surface): A state of "balance", in which craters of a given size are formed and obliterated at the same rate.

Erosion: Process whereby materials are loosened, dissolved, or worn away, and moved from one place to another by natural agencies. Includes weathering, solution, corrosion, and transportation.

Fault: A fracture or zone of fractures along which the sides are displaced relative to one another.

Fault, normal: Fault in which the rocks have been shifted vertically by extensional forces.

Fault, reverse: Fault in which the rocks have been shifted vertically by compressional forces.

Fault, strike-slip: Fault in which the rocks have been shifted horizontally past each other along the strike of the fault.

Force: That which tends to put a stationary body in motion or to change the direction or speed of a moving body.

Fracture: General term for any break in a rock or rock unit due to mechanical failure by stress (includes cracks and joints).

Front (storm): The contact at a planet's surface between two different air masses, commonly cold and warm.

Geologic map: A graphic record of the distribution, nature, and age relations of rock units and structural features (such as faults) in an area.

Geomorphic: Pertaining to the surface morphology (landforms) of a planet.

Graben: An elongate crustal depression bounded by normal faults on its long sides.

Gradation: Geological process involving the weathering, erosion, transportation, and deposition of planetary materials by the agents of wind, water, ice, and gravity.

Hadley cell: A thermally driven unit of atmospheric circulation that extends in both directions from the equator. Air rises at the equator, flows poleward, descends, and then flows back toward the equator.

Ice: Solid formed of volatile materials, particularly water, methane, ammonia, and nitrogen.

Impact: In planetology, the collision of objects ranging in size from tiny micrometeoroids to planetesimals.

Impact cratering: Process involving impact of objects with a planetary surface.

Kinetic energy: Energy of motion; $KE = 1/2\ (\text{mass})\ (\text{velocity})^2$

Landform: Any feature of a surface having a distinct shape and origin.

Lava: Magma (molten rock or liquid material) that reaches the surface of a planet or satellite.

Leeward: The side located away from the wind; the sheltered side.

Limb: The edge of the apparent disk of a planetary body.

Linea: Elongate markings on a planetary surface.

Lithosphere: The stiff upper layer of a planetary body; the solid outer part of a planet; on Earth, it includes the crust and the upper part of the mantle and is about 100 km thick.

Macula: A dark spot.

Magma: Melted or fluid rock material.

Mare (pl., maria): An area on the moon that appears darker and smoother than its surroundings; composed primarily of basaltic lava flows.

Mass wasting: The movement of rock and soil downslope caused by gravity.

Meteor: A "shooting star"—the streak of light in the sky produced by the transit of a meteoroid through the Earth's atmosphere; also the glowing meteoroid itself. The term "fireball" is sometimes used for a very bright meteor.

Meteorite: Extraterrestrial material which survives to a planetary surface as a recoverable object.

Meteoroid: A small particle in space.

Morphology: The external structure, form, and arrangement of rocks and solid materials in relation to the development of landforms.

Periglacial: Processes, areas, and climates at the immediate margins of former and existing glaciers and ice sheets, and influenced by the cold temperature of the ice.

Pit crater: An impact crater containing a central depression.

Plate tectonics: The theory of planetary dynamics in which the lithosphere is broken into individual plates that are moved by convection of the upper mantle.

Radar: (1) A method, system, or technique of using beamed, reflected, and timed radio waves for detecting, locating, or tracking objects (such as rockets) , for measuring altitude, etc., in any of various activities, such as air traffic control or guidance. (2) The electronic equipment or apparatus used to generate, transmit, receive, and , usually, to display radio scanning or locating waves; a radar set.

Rays: Long, thin deposits of ejecta thrown out radial to young impact craters.

Regio: A large area on a planetary surface having distinctive albedo markings.

Rift zone: A belt of strike-slip or normal faults in close proximity to each other.

Rille: Trench or crack-like valleys, up to several hundred kilometers long and 1 to 2 kilometers wide. May be sinuous in form.

Rotation: Turning of a body about an internal axis, as a rotation of Earth.

Saltation: A mode of sediment transport in which the particles are moved progressively forward in a series of short intermittent leaps, jumps, hops, or bounces.

Satellite: An attendant body that revolves about another body, the primary.

Scarp: Cliff produced by tectonic, impact, or erosion processes.

Secondary crater: Crater formed by ejecta thrown from a “primary” crater.

Shield volcano: A volcanic mountain in the shape of a broad, flattened dome.

Sinuous rille: see *Rille*

Slip face: The steeply sloping surface on the lee side of a dune, standing at or near the angle of repose of loose sand, and advancing downwind by a succession of slides wherever that angle is exceeded.

Strata: layers of rock (singular = stratum)

Stratigraphic column: Diagram that shows the relative ages of units within an area (oldest at the bottom, youngest at the top)

Stratigraphic relations: see *Stratigraphy*

Stratigraphy: Science of rock strata; concerned with the original succession and age relations of rock strata as well as their form, distribution and composition.

Strike: The azimuth or trend taken by a rock layer or structural surface.

Superposition (principle of): The principle that, in a series of strata that has not been overturned, the oldest rocks are at the bottom and the youngest are at the top.

Suspension: A mode of sediment transport in which the upward currents in eddies of turbulent flow are capable of supporting the weight of sediment particles and keeping them indefinitely held in the surrounding fluid (air or water).

Tectonic: Refers to deformation of planetary materials, as in faulting of Earth’s crust.

Tectonism: Process involving movement of the lithosphere.

Terminator: The line of sunrise or sunset on a planet or satellite.

Terrain: A region of a surface sharing common characteristics (as in "mountainous terrain").

Terrestrial: Of or pertaining to Earth or earthlike.

Tidal heating: The process of frictional heating of a planetary object by the alternate growth and decay of a tide in its lithosphere.

Topography: The general configuration of a surface, including its relief and the position of features.

Traction: A mode of sediment transport in which the particles are swept along, on, near, or immediately above and parallel to a bottom surface by rolling, sliding, pushing, or impact of saltating grains.

Unit: Three-dimensional body of rock with uniform characteristics and formed within a specific period of time.

Vertical exaggeration: The apparent increase in relief as seen in a stereoscopic image.

Volcanism: The process by which magma and its associated gases rise into the crust, and are extruded onto the surface and into the atmosphere.

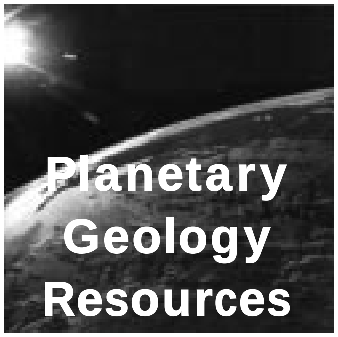
Vortices: Revolving motions within fluid flow.

Wavelength: The distance between successive wavecrests, or other equivalent points, in a series of harmonic waves.

Weathering: Chemical and physical alteration of materials exposed to the environment on or near the surface of a planetary object.

Wind streak: Zone where sediments have been preferentially deposited, eroded, or protected from wind erosion. Often form "tails" on the lee side of obstacles.

Windward: The side located toward the direction form which the wind is blowing; facing the wind.



1.1 Undergraduate geology textbooks.

There are dozens of college freshman textbooks that introduce geology. Most are similarly organized and cover the same basic material. Any college or university which teaches geology or earth science will carry one or more of these in their bookstore.

1.2 Planetary science textbooks.

These publications cover general planetary science and typically include chapters on each planet and planetary system. Most of these books assume a fundamental background in the sciences.

Beatty, J. K., and Chaikin, A., eds. (1990). *The New Solar System,* Cambridge, MA: Sky Publishing Corp. and Cambridge University Press, 326 pp.

Carr, M.H., Saunders, R.S., Strom, R.G., and Wilhelms, D.E. (1984). *The Geology of the Terrestrial Planets,* Washington, DC: National Aeronautics and Space Administration, 317 pp.

Christiansen, E.H. and Hamblin, W.K. (1995). *Exploring the Planets*. Englewood Cliffs, New Jersey: Prentice Hall, 500 pp.

Francis, Peter (1981). *The Planets,* New York: Penguin Books, 411 pp.

Greeley, Ronald (1994). *Planetary Landscapes,* New York: Chapman and Hall, 286 pp.

Guest, J.E. (1979). *Planetary Geology,* London: David and Charles (Publ.) , 208 pp.

Hamblin, W.K., and Christiansen, E.H. (1990). *Exploring the Planets,* New York: Macmillan Publishing Co., 451 pp.

Hartmann, William K. (1983). *Moons and Planets,* 2nd ed., Belmont, CA: Wadsworth Publishing Co., 509 pp.

Morrison, D., and Owen, T. (1988). *The Planetary System,* Reading, MA: Addison-Wesley Publishing Co., 519 pp.

Murray, B., Malin, M.C., and Greeley, R. (1981). *Earthlike Planets: Surfaces of Mercury, Venus, Earth, Moon, Mars,* San Francisco, CA: W.H. Freeman and Co., 387 pp.

1.3 Reference books.

These publications are collections of review papers or deal with focused topics. They serve as research resources at a professional level. Some can be used in advanced classes.

Atreya, S.K., Pollack, J.B., and Matthews, M.S., (1989). *Origin and Evolution of Planetary and Satellite Atmospheres,* Tucson, AZ: The University of Arizona Press, 881 pp.

Barnes, C. W. (1980). *Earth, Time, and Life – An Introduction to Geology,* New York, NY: John Wiley & Sons, Inc., 583 pp.

Barsukov, V.L., et al., eds. (1992). *Venus Geology, Geochemistry, and Geophysics: Research Results from the Soviet Union,* Tucson, AZ: The University of Arizona Press, 421 pp.

Bergstralh, J. T., Miner, E. D. and Matthews, M. S., eds. (1991). *Uranus,* Tucson, AZ: The University of Arizona Press, 1076 pp.

Binzel, R. P., Gehrels, T., and Matthews, M. S., eds. (1990). *Asteroids II,* Tucson, AZ: The University of Arizona Press, 1258 pp.

Bullard, F. M. (1976). *Volcanoes of the Earth,* Austin, TX: University of Texas Press, 579 pp.

Burns, J. W., ed. (1977). *Planetary Satellites,* Tucson, AZ: The University of Arizona Press, 598 pp.

Burns, J. A., and Matthews, M. S., eds. (1986). *Satellites,* Tucson: University of Arizona Press, 1021 pp.

Carr, M. H. (1981). *The Surface of Mars,* New Haven, CT: Yale University, 232 pp.

Cattermole, P. (1992). *Mars: The Story of the Red Planet*. London: Chapman and Hall, 224 pp.

Cattermole, P. (1994). *Venus: The Geological Story.* Baltimore: The Johns Hopkins University Press, 250 pp.

Christianson, N. B. (1989). *Earth Has a Cold Heart,* Glendale, AZ: Ne-do Press, 202 pp.

Cox, A.N., Livingston, W.C. and Matthews, M.S., eds. (1992). *Solar Interior and Atmosphere,* Tucson, AZ: The University of Arizona Press, 1416 pp.

Frazier, K. (1985). *Solar System: Planet Earth,* Alexandria, VA: Time-Life Books, 176 pp.

Gallant, R. (1964). *Bombarded Earth,* London, England: John Bkaer Publishers, Ltd., 256 pp.

Gehrels, T., and Matthews, M. S., eds. (1984). *Saturn,* Tucson, AZ: The University of Arizona Press, 968 pp.

Gehrels, T., ed. (1976). *Jupiter,* Tucson, AZ: The University of Arizona Press, 1254 pp.

Greeley, R., and Batson, R. (1997). *The NASA Atlas of the Solar System.* Cambridge, England: Cambridge University Press, 369 pp.

Greenberg, R., Brahic, W., eds. (1984). *Planetary Rings,* Tucson, AZ: The University of Arizona Press, 784 pp.

Glass, B.P. (1982). *Introduction to Planetary Geology,* New York, NY: Press Syndicate of the University of Cambridge, 469 pp.

Hamblin, W. K. (1975). *The Earth's Dynamic Systems,* Minneapolis, MN: Burgess Publishing Company, 578 pp.

Hartmann, W. K., (1983). *Moons and Planets,* Belmont, CA: Wadsworth Publishing Company, 509 pp.

Hunten, D.M., Colin, L., Donahue, T.M., and Moroz, V.I., eds.(1991). *Venus,* Tucson, AZ: The University of Arizona Press, 1143 pp.

Kieffer, H.H., Jakosky, B.M., Snyder, C.W., and Matthews, M.S., eds. (1992). *Mars,* Tucson, AZ: The University of Arizona Press, 1498 pp.

Mark, K., ed. (1987). *Meteorite Craters,* Tucson, AZ: The University of Arizona Press, 288 pp.

Miller, P., Beer, D., Brown, A. H. (1985). *Atlas of North America,* Washington, DC: National Geographic Society, 264 pp.

Miller, V. C., Miller, C. F. (1961). *Photogeology,* New York, NY: McGraw-Hill Book Company, Inc., 243 pp.

Morrison, D., ed. (1982). *Satellites of Jupiter,* Tucson, AZ: The University of Arizona Press, 972 pp.

Newsom, H. E., Jones, J. H. (1990). *Origin of the Earth,* New York, NY: Oxford University Press, 378 pp.

Palmer, A. R. (1992). *The Geology of North America Series,* Boulder, CO: The Geological Society of America.

Péwé, T. L., ed. (1981). *Desert Dust: Origin, Characteristics, and Effect on Man,* Boulder, CO: The Geological Society of America, Inc., 303 pp.

Roberts, J. L. (1982). *Introduction to Geological Maps and Structures,* Elmsford, NY: Pergamon Press, Ltd., 332 pp.

Roddy, D. J., Pepin, R. O., Merrill, R. B., eds. (1976). *Impact and Explosion Cratering: Planetary and Terrestrial Implications,* Elmsford, NY: Pergamon Press, 1301 pp.

Rothery, D.A., (1992). *Satellites of the Outer Planets: Worlds in their Own Right,* Oxford, England: Clarendon, 208 pp.

Scientific American (1983). *The Planets,* San Francisco, CA: W. H. Freeman and Company, 132 pp.

Shupe, J. F., et al., (1992). *Atlas of the World: Revised Sixth Edition,* Washington, DC: National Geographic Society, 136 pp.

Sonett, C.P., Giampapa, M.S. and Matthews, M.S., eds. (1992). *The Sun in Time,* Tucson: University of Arizona Press, 990 pp.

Walls, J. (1980). *Land, Man, and Sand,* New York, NY: MacMillan Publishing Co., Inc., 336 pp.

Tilling, R. I., ed. (1988). *How Volcanoes Work,* Washington, DC: American Geophysical Union, 14,880 pp.

Vilas, F., Chapman, C.R., Matthews, M.S., eds. (1988). *Mercury,* Tucson, AZ: The University of Arizona Press, 794 pp.

Walls, J. (1980). *Land, Man, and Sand,* New York, NY: MacMillan Publishing Co., Inc., 336 pp.

Wilhelms, D.E. (1987). *The Geologic History of the Moon,* U.S. Geological Survey Professional Paper 1348, Washington, DC: U.S. Govt. Printing Office, 328 pp.

1.4 NASA publications.

NASA publishes a wide variety of books dealing with missions, mission results, and planetary exploration, as well as planetary map atlases. Although many of these are no longer available, copies are usually contained in libraries which carry U.S. Government publications.

Object	Year	Serial	Title	Notes
Earth	1980	SP-403	*Volcanic Features of Hawaii: A Basis for Comparison with Mars*	
Moon	1964	SP-61	*Ranger VII photograph of the Moon,* Part I, Camera A series	
Moon	1965	SP-62	*Ranger VII photographs of the Moon,* Camera B series	Photographic collection
Moon	1965	SP-63	*Ranger VII photographs of the Moon,* Camera P series	Photographic collection
Moon	1966	SP-111	*Ranger VIII photographs of the Moon,* Cameras A, B, P	Photographic collection
Moon	1966	SP-112	*Ranger IX photographs of the Moon*	Photographic collections
Moon	1966	SP-126	*Surveyor I: a preliminary report*	
Moon	1966	JPL-TR 32-800	*Ranger VIII and IX experimenters' analysis and interpretations*	Mission description and science results
Moon	1969	SP-184	*Surveyor: program results*	
Moon	1969	SP-214	*Apollo 11 preliminary science report*	Mission description with photographs; includes descriptions and results from various experiments on board the command module and/or lander spacecraft
Moon	1969	SP-201	*Apollo 8, photography and visual observations*	
Moon	1970	SP-242	*Guide to Lunar orbiter photographs*	Explains camera system and gives footprints
Moon	1970	SP-200	*The Moon as viewed by Lunar orbiter*	Mission description and photographs; includes descriptions and results from various experiments on board the command module and/or lander spacecraft

Object	Year	Serial	Title	Notes
Moon	1971	SP-241	*Atlas and gazeteer of the near side of the Moon*	Lunar orbiter photographs with place names
Moon	1971	SP-206	*Lunar orbiter photographic atlas of the Moon*	Photographic collection
Moon	1971	SP-232	*Apollo 10, photography and visual observations*	Mission description with photographs; includes descriptions and results from various experiments on board the command module and/or lander spacecraft
Moon	1971	SP-238	*Apollo 11 mission report*	
Moon	1971	SP-272	*Apollo 14 preliminary science report*	
Moon	1971	SP-246	*Lunar photographs from Apollo 8, 10, 11*	
Moon	1972	SP-315	*Apollo 16 preliminary science report*	
Moon	1972	SP-289	*Apollo 15 preliminary science report*	
Moon	1972	SP-284	*Analysis of Surveyor 3 material and photographs returned by Apollo 12*	
Moon	1972	SP-306	*Compositions of major and minor minerals in five Apollo 12 crystalline rocks*	Description of samples
Moon	1973	SP-330	*Apollo 17 preliminary science report*	Mission description with photographs; includes descriptions and results from various experiments on board the command module and/or lander spacecraft
Moon	1974	EP-100	*Apollo*	Public information booklet
Moon	1973	SP-341	*Atlas of Surveyor 5 television data*	Photographs with short captions
Moon	1975	SP-350	*Apollo expedition to the Moon*	Mission description with photographs; general public
Moon	1978	SP-362	*Apollo over the Moon*	Summary of Apollo missions to the Moon; color photographs and science discussions

Object	Year	Serial	Title	Notes
Mars	1968	SP-179	*The book of Mars*	
Mars	1971	SP-263	*The Mariner 6 and 7 missions to Mars*	Mission description and photographic collection
Mars	1974	SP-334	*The Viking mission to Mars*	
Mars	1974	SP-329	*Mars as viewed by Mariner 9*	Photographs with science
Mars	1974	SP-337	*The new Mars, the discovery of Mariner 9*	Photographs with science
Mars	1975	SP-425	*The Martian landscape*	Mission description and photographs for Viking
Mars	1979	SP-438	*Atlas of Mars, the 1:5000000 map series*	Map and photomosaic collection
Mars	1980	SP-444	*Images of Mars – the Viking extended mission*	Photograph collection
Mars	1980	SP-441	*Viking orbiter views of Mars*	Photograph collection with science
Mars	1980	CR-3326	*The mosaics of Mars as seen by the Viking lander cameras*	Photomosaics based on Mars charts; gives frame locations
Mars	1981	SP-429	*Viking site selection and certification*	
Mars	1982	CR-3568	*Viking lander atlas of Mars*	Lander photographs and maps
Mars	1983	RP-1093	*A catalog of selected Viking orbiter images*	Photomosaics based on Mars charts; gives frame locations
Mars	1984	SP-4212	*On Mars, exploration of the red planet 1958–1978*	History of missions and explorations
Mercury	1978	SP-423	*Atlas of Mercury*	Synopsis of Mariner 10 results; collection of photographs and USGS charts
Mercury	1978	SP-424	*The voyage of Mariner 10*	Mission description
Venus	1975	SP-382	*The atmosphere of Venus*	
Venus	1983	SP-461	*Pioneer Venus*	Popularized account of mission with discussion of science results

Object	Year	Serial	Title	Notes
Jupiter	1971	SP-268	*The Pioneer mission to Jupiter*	
Jupiter	1974	SP-349	*Pioneer Odyssey – encounter with a giant*	Mission description and photographic collection
Jupiter	1980	SP-439	*Voyage to Jupiter*	Popularized account of mission with discussion
Jupiter	1989	SP-494	*Time-variable phenomena in the jovian system*	
Jupiter/ Saturn	1977	SP-420	*Voyager to Jupiter and Saturn*	
Jupiter/ Saturn	1980	SP-446	*Pioneer: first to Jupiter, Saturn, and beyond*	
Saturn	1974	SP-340	*The atmosphere of Titan*	
Saturn	1974	SP-343	*The rings of Saturn*	
Saturn	1980	JPL-400-100	*Voyager I encounters with Saturn*	Public information booklet
Saturn	1982	SP-451	*Voyages to Saturn*	Popularized account of mission with discussion of science results
Saturn	1984	SP-474	*Voyager I and II atlas of six saturnian satellites*	
Saturn	1978	CP-2068	*The Saturn System*	Conference proceedings
general	1971	SP-267	*Physical studies of the minor planets*	
general	1976	SP-345	*Evolution of the Solar System*	
general	1981	EP-177	*A meeting with the universe*	Popularized account of Solar System exploration
general	1984	SP-469	*The geology of the terrestrial planets*	An introduction to Mercury, Venus, Earth, Moon, and Mars, and a chapter on asteroids, comets, and planet formation
general	1997		*The NASA atlas of the Solar System*	Cambridge Univerity Press

Planet	Mission	Journal
Mercury	Mariner 10	*Science,* 1974, **185,** no. 4146
Mercury	Mariner 10	*J. Geophys. Res.,* 1975, **80,** no. 17
Mercury	Mariner 10	*Phys. Earth Planet. Int.,* 1977, **15,** nos. 2 and 3
Mercury	Mariner 10	*Icarus,* 1976, **28,** no. 4
Venus	Mariner 10	*Science,* 1974, **183,** no. 4131
Venus	Pioneer	*Science,* 1979, **203,** no. 4382
Venus	Pioneer	*Science,* 1979, **205,** no. 4401
Venus	Pioneer	*J. Geophys. Res.,* 1980, **85,** no. A13
Venus	general	*Icarus,* 1982, **51,** no. 2
Venus	general	Icarus, 1982, **52,** no. 2
Venus	Vega	***Science,*** 1986, **231,** no. 4744
Venus	Magellan	*Science,* 1991, **252,** no. 5003
Venus	Magellan	*J. Geophys. Res.,* 1992, **97**, nos. E8 and E9
Moon	Apollo II	*Science,* 1970, **167,** no. 3918
Moon	Apollo	*The Moon,* 1974, **9**
Moon	general	*Rev. Geophys. Space Phys.,* 1974, **12,** no. 1
Moon	general	*The Moon,* 1975, **13,** nos. 1,2 and 3
Moon	Galileo	*Science,* 1992, **255,** no. 5044
Mars	Mariner 6 and 7	*J. Geophys. Res.,* 1971, **76,** no. 2
Mars	Mariner 9	*Icarus,* 1972, **17,** no. 2
Mars	Mariner 9	*Icarus,* 1973, **18,** no. 1
Mars	Mariner 9	*J. Geophys. Res.,* 1973, **78,** no. 20
Mars	Mariner 9	*Icarus,* 1974, **22,** no. 3
Mars	Viking 1	*Science,* 1976, **193,** no. 4255
Mars	Viking 1 and 2	*Science,* 1976, **194,** no. 4260
Mars	Viking	*J. Geophys. Res.,* 1977, **82,** no. 28
Mars	Viking	*Icarus,* 1978, **34,** no. 3
Mars	general	*J. Geophys. Res.,* 1979, **84,** no. B14
Mars	general	*Icarus,* 1981, **45,** nos. 1 and 2
Mars	general	*Icarus,* 1982, **50,** nos. 2 and 3
Mars	general	*J. Geophys. Res.,* 1982, **87,** no. B12
Mars	general	*J. Geophys. Res.,* 1990, **95,** no. B9
Jupiter	Pioneer 11	*Science,* 1975, **188,** no. 4187
Jupiter	Voyager 1	*Nature,* 1979, **280,** no. 5725
Jupiter	Voyager 1	*Science,* 1979, **204,** no. 4396
Jupiter	Voyager 2	*Science,* 1979, **206,** no. 4421
Jupiter	Voyager	*J. Geophys. Res.,* 1981, **86,** no. A10
Saturn	Pioneer 11	*Science,* 1980, **207,** no. 4429
Saturn	Voyager 1	*Nature,* 1981, **292,** no. 5825
Saturn	Voyager 1	*Science,* 1981, **212,** no. 4491
Saturn	Voyager 2	*Science,* 1982, **215,** no. 4532
Saturn	Voyager	*Icarus,* 1983, **53,** no. 2
Uranus	Voyager 2	*Science,* 1986, **233,** no. 4739
Neptune	Voyager 2	*Science,* 1989, **246,** no. 4936
Neptune	Voyager 2	*J. Geophys. Res.,* 1991, **96,** supplement
Neptune-Triton	Voyager 2	*Science,* 1990, **250,** no. 4979
Comet Halley	5 missions	*Nature,* 1986

1.6 Regional Planetary Image Facilities.

In a quarter century of solar system exploration, nearly a million images have been obtained of the planets and their satellites. Some 17 facilities exist worldwide which contain archives of planetary images. These facilities are open to the public for aid in finding specific images. They do not, however, provide copies of photographs (see Section 1.8).

Arizona State University, SPL, Department of Geology, Box 871404, Tempe, AZ 85287-1404

University of Arizona, RPIF, Lunar and Planetary Lab, Tucson, AZ 85721

Brown University, RPIF, Box 1846, Department of Geological Sciences, Providence, RI 02912

Cornell University, SPIF, 317 Space Sciences Building, Ithaca, NY 14885

Deutsche Forschungsanstalt fuer Luftund Raumfahrt e.V. (DLR) , Regional Planetary Image Facility, Institute for Planetary Exploration, Rudower Chaussee 5, 0-1199 Berlin, Germany

University of Hawaii, RPIF, Hawaii Institute of Geophysics, Planetary Geoscience Division, Honolulu, HI 96822

Institute of Space and Astronomical Sciences, Regional Planetary Image Facility, 3-1-1 Yoshinodai, Sagamihara-shi, Kanagawa 229, Japan

Israeli Regional Planetary Image Facility, Ben-Gurion University of the Negev, P.O. Box 653, Beer-Sheva, 84105, Israel.

Jet Propulsion Laboratory, RPIF, MS 202-101, 4800 Oak Grove Drive, Pasadena, CA 91109

University of London Observatory, Regional Planetary Image Facility, 33/35 Daws Lane, Observatory Annexe, London, NW7 4SD, England

Lunar and Planetary Institute, Center for Information Research Services, 3600 Bay Area Blvd., Houston, TX 77058

University of Paris-Sud, Phototheque Plantaire de'Orsay, Laboratoire de Geologie Dynamique de la Terre et des Plantes, Department des Sciences de la Terre, Batiment 509, F-91, 405 Orsay Cedex, France

University of Oulu, Regional Planetary Image Facility, Department of Astronomy, 90570 Oulu, Finland

Southern Europe Regional Planetary Image Facility, CNR Institutio Astrofisica Spaziale, Reparto di Planetologia, Viale Dell' Universita, 11, 00185 Roma, Italy

Smithsonian Institution, RPIF, Room 3773, National Air and Space Museum, Washington, DC 20560

U.S. Geological Survey, RPIF, Branch of Astrogeologic Studies, 2255 N. Gemini Drive, Flagstaff, AZ 86001

Washington University, RPIF, Box 1169, Department of Earth and Planetary Sciences, One Brookings Drive, St. Louis, MO 63130-4899

1.7 Videos

The following sources have video and/or films on planetary science topics. Most will provide catalogs or lists on request.

1. Instructional Video
   P.O. Box 21
   Maumee, Ohio 43537

2. The Planetary Society
   65 North Catalina Ave
   Pasadena, CA 91106
   (818) 793-5100

3. Michigan Technological University
   Video Marketing
   1400 Townsend Drive
   Houghton, MI 49931-1295
   (906) 487-2585

4. Gould Media, Inc.
   44 Parkway West
   Mt. Vernon, NY 10552-1194
   (914) 664-3285
   FAX (914) 664-0312

5. Finley-Holiday Film Corp.
   12607 E. Philadelphia St.
   P.O. Box 619
   Whittier, CA 90601
   (310) 945-3325

6. NASA CORE
   Lorain County Joint Vocational School
   15181 Route 58 South
   Oberlin, OH 44074
   (440) 774-1051 ext. 293/249

7. National Air and Space Museum
   Smithsonian Institution
   Educational Resource Center, MRC 305
   Washington, DC 20560
   (202) 786-2109

8. Films for the Humanities & Sciences
P. O. Box 2053
Princeton, NJ 08543-2053

9. Astronomical Society of the Pacific
390 Ashton Avenue
San Francisco, CA 94112
(800) 335-2624

10. Instructional Video
P. O. Box 21
Maumee, OH 43537
(419) 865-7670
FAX (419) 867-3813

11. JLM Visuals
1208 Bridge Street
Grafton, WI 53024-1946
(414) 377-7775

12. Sky Publishing Corporation
P. O. Box 9111
Belmont, MA 02178-9111
(800) 253-9245

13. Crystal Productions
Box 2159
Glenview, IL 60025
(800) 255-8629
FAX (708) 657-8149

1.8 CD-ROMs

1. Hopkins Technology
421 Hazel Lane
Suite 700
Hopkins, Minnesota 55343-7116

2. National Space Science Data Center
Code 633
Goddard Space Flight Center
Greenbelt, MD 20771
(301) 286-6695

3. Astronomical Society of the Pacific
390 Ashton Avenue
San Francisco, CA 94112
(800) 335-2624

4. Sky Publishing Corporation
P. O. Box 9111
Belmont, MA 02178-9111
(800) 253-9245

5. Crystal Productions
Box 2159
Glenview, IL 60025
(800) 255-8629
FAX (708) 657-8149

1.9 Slide sets

1. Astronomical Society of the Pacific
390 Ashton Ave
San Francisco, CA 94112
(800) 335-2624

2. Finley-Holiday Film Corp.
12607 E. Philadelphia St.
P.O. Box 619
Whittier, CA 90601
(310) 945-3325

3. Lunar and Planetary Institute
3600 Bay Area Blvd.
Houston, TX 77058
(713) 486-2100

4. Gould Media, Inc.
44 Parkway West
Mt. Vernon, NY 10552-1194
(914) 664-3285
FAX (914) 664-0312

5. American Geophysical Union
2000 Florida Avenue, N.W.
Washington, DC 20009
(800) 966-2481 (North America only)
(202) 462-6900

6. NESTA/MESTA Publications
c/o Lisa Bouda
28815 Ironwood
Warren, MI 48093

7. National Association of Geology Teachers
P. O. Box 5443
Bellingham, WA 98227-5443

8. Sky Publishing Corporation
P. O. Box 9111
Belmont, MA 02178-9111
(800) 253-9245

9. Crystal Productions
Box 2159
Glenview, IL 60025
(800) 255-8629
FAX (708) 657-8149

1.10Maps

1. Earth Science Information Center
U. S. Geological Survey
507 National Center
Reston, VA 22092
(703) 860-6045

2. Map Link
   25 Eat Mason
   Santa Barbara, CA 93101
   (805) 965-4402

3. National Space Science Data Center (NSSDC)
   Code 633
   Goddard Space Flight Center
   Greenbelt, MD 20771
   (301) 286-6695

4. U. S. Geological Survey
   Distribution Branch
   Box 25286 Federal Center
   Denver, CO 80225
   (303) 234-3832

1.11 Miscellaneous Products (globes, posters, equipment)

1. Crystal Productions
   Box 2159
   Glenview, IL 60025
   (800) 255-8629
   FAX (708) 657-8149

2. Sky Publishing Corporation
   P. O. Box 9111
   Belmont, MA 02178-9111
   (800) 253-9245

3. Astronomical Society of the Pacific
   390 Ashton Ave
   San Francisco, CA 94112
   (800) 335-2624

4. The Planetary Society
   65 North Catalina Ave
   Pasadena, CA 91106
   (818) 793-5100

5. Lunar Sample Curator (Apollo lunar samples for Colleges/Universities only)
   SN2 NASA/Johnson Space Center
   Houston, TX 77058-3698
   FAX (713) 483-2911

A Note About Photographs

An essential part of Planetary Geology is the use of spacecraft photographs. Ideally each student-team should have access to glossy photographic prints for use during the laboratory exercises. Photocopies of the pictures in this book (such as Xerox copies) generally lack sufficient detail to be useful. Offset printing is slightly better, but again this process is at least three generations removed from the original product.

Glossy prints or copy negatives can be obtained for a nominal cost (in some cases for no charge) from various sources. Each spacecraft photograph caption in this book contains the necessary picture identification numbers to help you in obtaining the photos. Usually the mission name (Apollo, Viking, etc.) and frame number is sufficient identification.

Listed below are sources of space photography. Instructions for ordering photography will be provided upon written request. Be sure to include your name, title, the fact that the photographs will be used at a non-profit educational institution, and specific photograph numbers.

For planetary mission photography:

National Space Science Data Center
Code 633
Goddard Space Flight Center
Greenbelt, MD 20771

For Earth photography:

EROS Data Center
U.S. Geological Survey
Sioux Falls, SD 57198

For photographs indicating Arizona State University as their source, contact:

Arizona State University
Space Photography Laboratory
Department of Geology
Box 871404
Tempe, AZ 85287-1404

Planetary Geology—A Teacher's Guide with Activities in Physical and Earth Sciences

EDUCATOR REPLY CARD

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> **Please take a moment to respond to the statements and questions below. You can submit your response through the Internet or by mail. Send your reply to the following Internet address:**
>
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>
> **You will then be asked to enter your data at the appropriate prompt.**

Otherwise, please return the reply card by mail. Thank you.

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   Number of Teachers/Faculty:

   ______ K-4 ______ Community College
   ______ 5-8 ______ College/University - Undergraduate
   ______ 9-12 ______ College/University - Graduate

   Number of Students:

   ______ K-4 ______ Community College
   ______ 5-8 ______ College/University - Undergraduate
   ______ 9-12 ______ College/University - Graduate

   Number of Others:

   ______ Administrators/Staff ______ Professional Groups
   ______ Parents ______ Civic Groups
   ______ General Public ______ Other ________________________

2. What is your home 5- or 9-digit zip code? __ __ __ __ __ — __ __ __ __

3. How was the quality of this teacher's guide?

   ❏ Excellent ❏ Good ❏ Average ❏ Poor ❏ Very Poor

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   ❏ Demonstrate NASA Materials
   ❏ Group Discussions
   ❏ Integration Into Existing Curricula
   ❏ Lecture
   ❏ Team Activities
   ❏ Critical Thinking Tasks
   ❏ Demonstration
   ❏ Hands-On Activities
   ❏ Interdisciplinary Activity
   ❏ Science and Mathematics Standards Integration
   ❏ Other: Please specify: ________________________

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   ❏ Institution/School System
   ❏ Fellow Educator
   ❏ Workshop/Conference
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   ____
   ____

8. Additional comments:

   ____
   ____
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