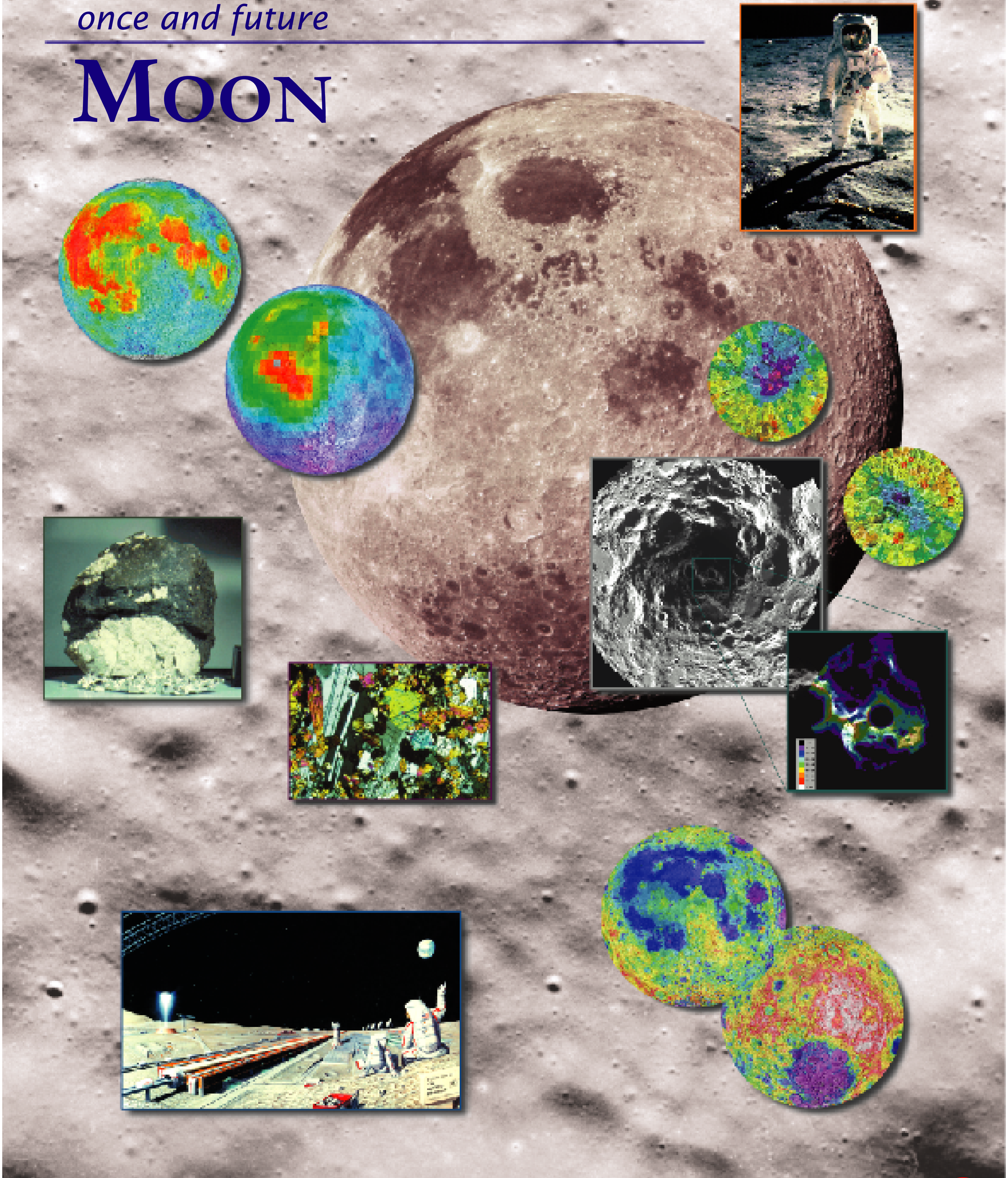
once and future

Moon



National Aeronautics and Space Administration / Lunar and Planetary Institute

WHAT DID WE LEARN ABOUT THE MOON FROM THE APOLLO PROGRAM?

* Not primordial — it is an evolved terrestrial planet.
* Ancient — it still preserves an early history (the first billion years), which must be common to all terrestrial planets.
* Shows evidence for wholesale primordial melting, formation of outer “magma ocean”-large-scale chemical separations within Moon; traces still remain in lunar rocks.
* Dark lunar maria (“seas”) and light-colored highlands made of chemically and mineralogically different rocks.
* Maria made of dark volcanic lavas (basalts) poured out in huge volcanic eruptions 3–4 billion years ago.
* Lifeless — no life, no fossils, no organic chemicals.
* Chemically similar to Earth, but significantly different in details: It has no indigenous water, is poor in volatile elements (readily vaporized).
* Preserves effects of catastrophic early meteorite bombardment — common to all terrestrial planets, including Earth, but traces no longer preserved on active planets like Earth.
* Not uniform throughout; is divided (like Earth) into outer crust, inner mantle, (possible?) small metal core.
* Globally asymmetric (slightly egg-shaped); thicker crust on farside, most maria deposits (lava flows) on nearside.
* Has no magnetic field, little or no metallic core like Earth’s, but “fossil” magnetism is preserved in lunar rocks; this is still a mystery.
* Large-scale (100–1000 kilometers) unexplained magnetic anomalies preserved on lunar surface.
* Lunar surface covered by powdery layer (“lunar soil” or regolith), produced by shattering of bedrock by prolonged meteorite bombardment.
* History of Sun and cosmic rays determined from actual atoms of Sun and stars trapped in lunar rocks and soil.
* Unexplained concentrations of nitrogen isotopes detected in ancient solar wind trapped in lunar regolith.
* Pre-Apollo hypotheses about lunar origins shown to be inadequate.

Scientists now believe that the Moon formed as a result of a collision between early Earth and a Mars-sized planet. This smaller planet was destroyed in the collision, which took place about 4.5 billion years ago. The giant impact sprayed vaporized material into a disk that orbited Earth. This vapor later cooled into droplets that coalesced into the Moon.

TOP TEN SCIENTIFIC DISCOVERIES MADE DURING APOLLO EXPLORATION OF THE MOON

1. **The Moon is not a primordial object; it is an evolved terrestrial planet with internal zoning similar to that of Earth.**

   Before Apollo, the state of the Moon was a subject of almost unlimited speculation. We now know that the Moon is made of rocky material that has been variously melted, erupted through volcanos, and crushed by meteorite impacts. The Moon possesses a thick crust (60 km), a fairly uniform rigid lithosphere (60–1000 km), and a partly liquid, plastic asthenosphere (1000–1740 km); a small iron core at the bottom of the asthenosphere is possible but unconfirmed. Some rocks give hints for ancient magnetic fields although no planetary field exists today.

2. **The Moon is ancient and still preserves an early history (the first billion years) that must be common to all terrestrial planets.**

   The extensive record of meteorite craters on the Moon, when calibrated using absolute ages of rock samples, provides a key for unraveling timescales for the geologic evolution of Mercury, Venus, and Mars based on their individual crater records. Photogeologic interpretation of other planets is based largely on lessons learned from the Moon. Before Apollo, however, the origin of lunar impact craters was not fully understood and the origin of similar craters on Earth was highly debated.

3. **The youngest Moon rocks are virtually as old as the oldest Earth rocks. The earliest processes and events that probably affected both planetary bodies can now only be found on the Moon.**

   Moon rock ages range from about 3.2 billion years in the maria (dark, low basins) to about 4.5 billion years in the terrae (light, rugged highlands). Active geologic forces, including plate tectonics and erosion, continuously repave the oldest surfaces on Earth, whereas old surfaces persist with little disturbance on the Moon.

4. **The Moon and Earth are genetically related and formed from different proportions of a common reservoir of materials.**

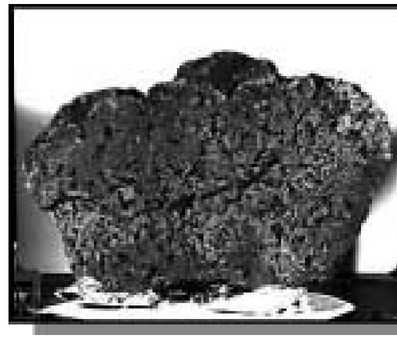
   Oxygen isotope compositions of Moon rocks and Earth rocks clearly show common ancestry. Relative to Earth, however, the Moon was highly depleted in iron and in volatile elements that are needed to form atmospheric gases and water.

5. **The Moon is lifeless; it contains no living organisms, fossils, or native organic compounds.**

   Extensive testing revealed no evidence for life, past or present, among the lunar samples. Even non-biological organic compounds are amazingly absent; traces can be attributed to contamination by meteorites.

6. **All Moon rocks originated through high-temperature processes with little or no involvement with water. They are roughly divisible into three types: basalts, anorthosites, and breccias.**

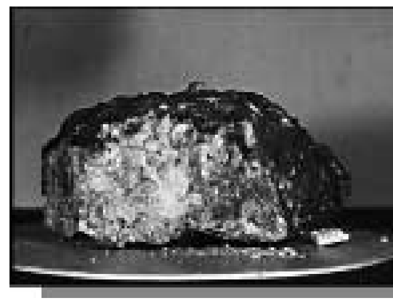
Basalts are dark lava rocks that fill mare basins; they generally resemble, but are much older than, lavas that comprise the oceanic crust of Earth. Anorthosites are light rocks that form the ancient highlands; they generally resemble, but are much older than, the most ancient rocks on Earth. Breccias are composite rocks formed from all other rock types through crushing, mixing, and melting during meteorite impacts. The Moon has no sandstones, shales, or limestones such as testify to the importance of water-borne processes on Earth.



Lunar sample 70035

7. **Early in its history, the Moon was melted to great depths to form a "magma ocean." The lunar highlands contain the remnants of early, low density rocks that floated to the surface of the magma ocean.**

The lunar highlands were formed about 4.4–4.5 billion years ago by flotation of an early, feldspar-rich crust on a magma ocean that covered the Moon to a depth of many tens of kilometers or more. Innumerable meteorite impacts through geologic time reduced much of the ancient crust to curved mountain ranges between basins.



Lunar sample 15415

8. **The lunar magma ocean was followed by a series of huge asteroid impacts that created basins that were later filled by lava flows.**

The large, dark basins such as Mare Imbrium are gigantic impact craters, formed early in lunar history, that were later filled by lava flows about 3.2–3.9 billion years ago. Lunar volcanism occurred mostly as lava floods that spread horizontally; volcanic fire fountains produced deposits of orange and emerald-green glass beads.

9. **The Moon is slightly asymmetrical in bulk form, possibly as a consequence of its evolution under Earth's gravitational influence. Its crust is thicker on the farside, while most volcanic basins — and unusual mass concentrations — occur on the nearside.**

Mass is not distributed uniformly inside the Moon. Large mass concentrations ("mascons") lie beneath the surface of many large lunar basins and probably represent thick accumulations of dense lava. Relative to its geometric center, the Moon's center of mass is displaced toward Earth by several kilometers.

10. **The surface of the Moon is covered by a rubble pile of rock fragments and dust, called the lunar regolith, that contains a unique radiation history of the Sun, which is of importance to understanding climate changes on Earth.**

The regolith was produced by innumerable meteorite impacts through geologic time. Surface rocks and mineral grains are distinctively enriched in chemical elements and isotopes implanted by solar radiation. As such, the Moon has recorded 4 billion years of the Sun's history to a degree of completeness that we are unlikely to find elsewhere.

ACTIVITY 1: GEOLOGIC MAPPING AND THE GEOLOGY OF THE MOON

A regional map showing important geologic features like faults, folds, and channels is called a *geologic map*. Geologic maps also show *surface geologic units*, or groups of rocks with the same definite characteristics that you can see, feel, smell, or measure. A geologic unit is shown on a geologic map with a particular color. The boundary between different geologic units, shown on a geologic map as a thin, solid line, is called a *contact*.

The basic history of how the geologic units in an area were formed and what happened to them over time is called its geologic history. Decoding the geologic history of an area from an overhead photograph or a geologic map requires you to use two simple rules:

Principle of superposition — This deals with a geologic unit that formed without disturbing the features around it (for instance, lava flows or sediment deposits). This rule simply states that whatever unit lies on top of (or *superposes*) other units is the youngest unit. In other words, the bottom unit had to be there first in order for a younger unit to form on top of it.

Principle of cross-cutting relations — This deals with the special situation of structures that disrupt geologic units, such as faults and channels. The structures are younger than the units they disrupt (or *cross-cut*).

GEOLOGY OF THE MOON

Figure 1 shows a photograph of the northwest (upper left) part of the nearside of the Moon. Note the dark-colored, circular feature that fills most of the photograph. Apollo 15 landed in the extreme southeast corner of this feature in 1971.

Fig. 1.

Apollo missions landed at only six different sites on the Moon. For this reason, you might think that very little is known about the Moon's geology. But this isn't true! The pictures of the Moon returned by spacecraft, and even taken through telescopes, contain a great deal of information about the Moon's geology. Studying geology using pictures is called *photogeology*. It is different from studying geology on the ground, because all the observations you make about a surface come from looking at it from a distance.

There are many kinds of surface features in Fig. 1, but they can be lumped into two big classes. *Brightness features* are regions that stand out from their surroundings because of a brighter or darker color, generally caused by a difference in the amounts of light-colored and dark-colored minerals in rocks on the surface. Differences in brightness can also be caused by shadows, so you have to be careful in recognizing brightness features. The most common landforms on the Moon are called *impact craters*. These are circular, raised-rimmed depressions formed by explosions that occur when comets and asteroids collide with the Moon at high velocity (about 12 miles per second). These impact craters provide an important tool for determining the relative ages of different deposits: For a given area, older deposits have more impact craters on them, and younger deposits have fewer impact craters. The number of craters in an area of specified size is called *crater density*; thus, older deposits have a higher crater density than younger deposits.

We recognize geologic units on the Moon using properties we can observe or measure from pictures, including brightness, smoothness or hilliness, and crater density. The nearside of the Moon contains two very basic geologic units. Look carefully at Fig. 1 to see two distinct units. List the characteristics of the units. When you're finished, give each unit a name that you feel is appropriate based on its characteristics.

The two basic units that you just identified have been known since Galileo first looked at the Moon through a very low-power telescope in 1609. He called the light-colored, hilly, heavily cratered unit *terra*, which is Latin for "land." The dark, smooth, less-cratered plains are called *maria* (singular *mare*), which is Latin for "seas," because their smoothness led some early astronomers to think they were the surfaces of lunar oceans.

You identified the mare and terra units photogeologically. That is, you have defined and mapped units based on what you can see in a black-and-white photograph. From what you have done so far, can you say what types of rock the units are made of? Why or why not?

Figure 2 shows an enlarged, high-resolution photograph of part of the region shown in Fig. 1. Cover it with clear plastic. This region is immediately around the Apollo 15 landing site, and has the same two major units you identified previously. On the plastic overlay, trace the units' contact. There are a number of indicators of whether one unit is superposed on another unit. One of these indicators is called an *embayment relation*. This occurs when a unit is deposited in fluid form, for instance, as lava flows or as sediment that settles out of water. In this case, the younger unit embays the older unit; in other words, it fills in low spots of the older unit at the contact. When one feature embays another it often looks like the water of a bay flowing around land features, and this is where the term *embay* comes from. Look carefully at the contact between the mare and terra for an embayment relation. On this basis, which unit (mare or terra) is younger? Why?

Now look at the number of craters on each of the two units. Do the crater densities show the same relative ages of the mare and terra as you just determined? If not, can you think of a possible reason why?

Fig. 2.

The major structure in this photograph is the curvy trough, called Rima Hadley (or in English, Hadley Rille). Trace it on the plastic overlay. What would you call this structure?

What are the relative ages of the mare and Rima Hadley? What principle did you use to recognize this age relation?

Look at the large, round impact crater alongside Rima Hadley. This is Hadley Crater. What are the relative ages of Hadley Crater and Rima Hadley? Why?

Now, reconstruct the geologic history of the area surrounding Rima Hadley by numbering the units and structures in the order in which they formed: ___ Hadley Crater, ___Mare, ___Terra, ___Rima Hadley.

Based on everything you've learned about the mare, what kind of rock do you think it might be (lava flows, sediments, coal, etc.)? What is necessary for you to know for sure?

Look at the slightly brighter region of mare away from the contact with the terra. This region contains an abundance of very small craters with noncircular shapes. Compare and contrast their appearance (size, shape, and relief) with that of Hadley Crater by listing their similarities and differences. Are these unusual craters older or younger than the mare? Why?

How might the origin of the unusual craters have differed from the origin of Hadley Crater? Can you think of a process that could have formed them?

Activity 2: Impact Cratering And Rainy Day Cratering

Impact Craters

When meteorites strike the Moon's surface, they leave impact craters. During a meteorite impact, rocks from deep inside are gouged up and thrown onto the surface, so impact craters can be used to show us rocks from underground. Also, the abundance of impact craters on a surface shows its age — the more craters on a surface, the older it must be.

Start with a flat sand surface. A playground sandbox is ideal, but any unbreakable box with a surface bigger than about 2 feet by 2 feet will do. Smooth the sand surface, and cover the sand with a layer of fine, contrasting powder: different sand, tempera paint powder, or colored sugar work well. Cover this layer with about a few millimeters of sand. Then throw marbles or gravel into the sand, and see if your craters excavate the contrasting layer. *How deep is your crater? How far was the contrasting powder thrown by the impact?* This experiment can be expanded and quantified by experiments with different types of sand, different depths of burial, marbles of different sizes and weights, and different heights and angles of impact. Using a slingshot to shoot the marble will permit higher velocity impacts and bigger craters, but careful supervision is required. **Be sure to wear eye protection.**

Rainy Day Cratering

This activity allows students to learn how planetary surfaces are modified by multiple impacts over time and how surfaces can be dated by the analysis of craters. As the number of impact craters increases on a surface, the appearance of the surface changes. After a period of time, equilibrium is reached, in which old craters are destroyed as quickly as new craters form. This is what has happened on the Moon.

Place a piece of duct tape over the end of a watering can. Using a 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 four pie pans with fine sand. Place one pan on the floor on top of a drop cloth or newspaper. Pour the water from the can very slowly through a mesh screen onto the sand. The mesh screen will break up the drops into smaller drops. Move the screen around so the water hits dry screen as much as possible. Rain on the pan for about 5 seconds until several craters have formed. *How do the crater sizes vary? Are they clustered together? Do they overlap?* Make a crater with your finger in the second dish. Place this dish in the rain for 30 seconds. *What does this surface look like? What happened to the large crater you formed? Are there more overlapping craters than in the first pan?* Make another finger crater in each of the other two pans and rain on each of them for two and four minutes respectively, remembering to pour the water slowly. *What happend to the large crater you formed in the last two pans? Is there a marked difference between the two pans, allowing you to tell which pan spent the most time in the rain?*

WHAT DID WE LEARN ABOUT THE MOON FROM CLEMENTINE AND LUNAR PROSPECTOR?

* Work to understand the data returned from two recent unmanned missions (Clementine, 1994; Lunar Prospector, 1998) is ongoing. However, we do have new knowledge about the Moon and some first-order conclusions from these two missions.

The Global Surface Composition of the Moon

* Crust is highly enriched in aluminum on a global basis, supporting its origin by early global melting (the magma ocean).
* Incompatible trace elements (i.e., those that do not go easily into rock-forming minerals) are concentrated within an elliptical zone on the western nearside (the Imbrium-Procellarum region).
* Magnesium- and iron-rich zones are found within the lunar highlands; these zones are usually associated with large impact basins.
* Mare basalts rich in titanium (returned in abundance by the Apollo 11 and 17 missions) are rare in the global mare lava inventory.

The Topography of the Moon

* The Moon displays an enormous range of global relief (16 kilometers), as big a range as the more active and diverse Earth.
* The dominant cause of high relief on the Moon is the presence of large, multi-ring impact basins.
* Lunar multi-ring basins appear to preserve their original topography for most of geological time.
* The South Pole-Aitken Basin on the farside of the Moon is the largest (2600 kilometers diameter) and deepest (over 12 kilometers) impact basin known in the solar system.

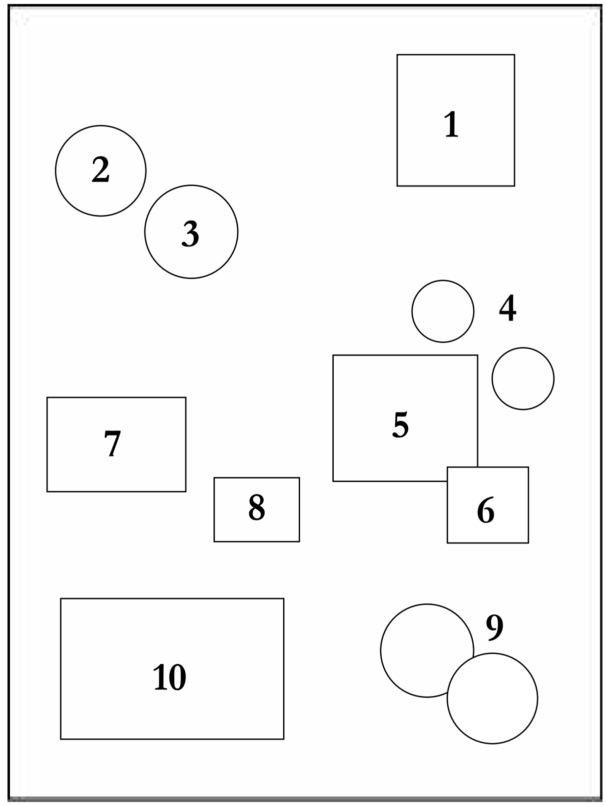
The Internal Structure of the Moon

* The Moon shows many areas of subsurface mass concentrations (mascons) that cause the gravity field of the Moon to be very "lumpy," requiring constant adjustments for orbiting spacecraft.
    * The mascons are always found beneath the floors of large impact basins and probably represent plugs of dense, uplifted rocks from the lunar mantle.

The Poles of the Moon

* Areas are found near the lunar poles that are in permanent darkness; some areas may be in permanent sunlight.
* The south pole appears to have more dark area than the north pole, mostly as a result of its location just inside the rim crest of South Pole-Aitken Basin.
* Water ice, derived from impacting comets, is found in the dark areas near both poles.

POSTER IMAGE CAPTIONS



1. Apollo 11 Lunar Module Pilot Edwin "Buzz" Aldrin stands on the Moon during the first lunar landing mission, July 20, 1969. AS11-40-5903.

2. Map of the iron (Fe) content of the nearside of the Moon, derived from Clementine color data. Reds and yellows are areas having high Fe content (associated with the dark, Fe-rich mare basalts), while blues and purples are zones of low Fe content (associated with the light, rugged highlands).

3. Map of the concentration of the element thorium (Th) on the nearside of the Moon derived from Lunar Prospector gamma-ray data. Thorium is a trace element that tracks the component *KREEP* [for potassium (K), rare-earth elements (REE), and phosphorus (P)], a remnant of the early formation of the lunar crust and mantle. The Lunar Prospector data show that Th (and therefore KREEP) is highly concentrated in the Oceanus Procellarum region of the western nearside (shown by the red and yellow areas). The origin of this unusual material is under study by lunar scientists.

4. Maps of the flux of "mid-energy" neutrons (blue = low, red = high) over the north (left) and south (right) poles of the Moon from Lunar Prospector. Depressions in the number of these neutrons emitted are indicative of large amounts of hydrogen in the lunar soil. These maps show that such areas are confined to small regions near the poles of the Moon, where crater floors are in permanent shadow and it is very cold (–220°C, or only about 50°C above absolute zero). These areas contain deposits of water ice, derived from impacting comets and water-bearing meteorites onto the Moon for the last few billion years.

5. Mosaic of about 650 Clementine images of the south pole of the Moon, from 80°S to the pole (center). The nearside of the Moon Moon is the top half of the image; the bottom half is the farside. Mountainous areas at top center are the remnants of the rim of the enormous South Pole-Aitkin Basin, an impact crater 2500 km in diameter. Large parts of this area (about 15,000 km^2) are permanently shadowed, and both radar data from Clementine and neutron spectrometer data from Lunar Prospector indicate that they contain deposits of water ice.

6. Close-up mosaic of high-resolution images from the Clementine mission showing the illumination conditions near the south pole of the Moon. Because the spin axis of the Moon is perpendicular to the plane of the Moon's orbit around the Sun, portions of the polar regions are in permanent darkness while others are in near-constant illumination. In this image, the colors indicate the fraction of the lunar day (708 hours) a given area is in sunlight. Note that a small region on the left rim crest of the crater Shackleton (at center) is illuminated for between 70% and 80% of the lunar day. This site has many advantages for the future habitation of the Moon.

7. Lunar sample 15455, an impact breccia collected by the Apollo 15 mission in 1971. This rock is a mixture of several rock types, created in a large impact, probably the one forming the Imbrium Basin on the Moon. The black portion consists of melt rock made by the large shock wave of the impact while the white portions are bits of ancient lunar crust picked up during the basin formation. This rock formed about 3.85 billion years ago.

8. Lunar sample 15535, a mare basalt collected by the Apollo 15 mission in 1971. This rock is a piece of an ancient lava flow, erupted onto the lunar surface over 3.3 billion years ago. In this microscopic view, the brightly colored minerals are pyroxene, a magnesium-rich mineral, and the large, gray, lath-shaped crystal is the mineral plagioclase, rich in aluminum and calcium. The black grains are ilmenite, an iron-titanium oxide. Such samples indicate that the Moon has been volcanically active in the distant past.

9. Maps of the topography of the Moon, derived from both laser ranging and stereo photography of the poles from the Clementine mission. The nearside (left) and farside (right) maps are color-coded, with red being high elevation and purple being low. The nearside is relatively smooth, with a range of relief of only a few kilometers, but the farside shows the complete dynamic range of lunar topography, from –8 km on the floor of South Pole-Aitkin Basin to +8 km on the rim crest of that basin.

10. An imagined future on the Moon, showing some of the activities we might undertake there. The long, linear feature is a mass driver, a method of using magnetic levitation and propulsion to launch materials off the Moon's surface without rockets. In this case, oxygen produced from lunar materials is shipped into space for use in orbital refueling stations. The array of dish antennas at right remind us that the surface of the Moon is an excellent place to observe the universe around us. Here, a radio telescope interferometer (an instrument used to integrate data from two or more telescopes) yields high-resolution maps of the radio sky. At bottom right, a young explorer shares the vista of the settlement on the New World with a parent. Artwork by Pat Rawlings.

MOON FACTS

Earth's Moon

Mass	7.35×10^{22} kg (1% mass of Earth)
Radius	1738 km (27% radius of Earth)
Surface area	3.79×10^{7} km^2 (7% area of Earth)
Density	3340 kg/m^3 (3.34 g/cm^3)
Gravity	1.62 m/s^2 (0.17 gravity of Earth)
Escape velocity	2.38 km/s
Orbital velocity	1.68 km/s
Inclination of spin axis (to Sun)	1.6°
Inclination of orbital plane (to Sun)	5.9°
Distance from Earth	closest: 356,410 km; farthest: 406,697 km
Orbital eccentricity	0.055
Albedo (fraction of light reflected)	0.07–0.24 (average terrae: 0.11–0.18; average maria: 0.07–0.10)
Rotation period (noon-to-noon; average)	29.53 Earth days (709 hours)
Revolution period (around Earth)	27.3 Earth days (656 hours)
Average surface temperature	107°C (day); –153°C (night)
Surface temperature in polar areas	–30° to –50°C (in light); –230°C (in shadows)

ADDITIONAL RESOURCES

Books and Articles

Cernan E. and Davis D. (1999) *The Last Man on the Moon.* St. Martin's Press, New York.

Chaikin A. (1994) *A Man on the Moon*. Viking Press, New York. 670 pp.

Harland D. M. (1999) *Exploring the Moon: The Apollo Expeditions.* Springer, New York.

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Light M. (1999) *Full Moon.* Alfred A. Knopf, New York.

Spudis P. D. (1996) *The Once and Future Moon.* Smithsonian Institution Press, Washington, DC.

Wilhelms D. E. (1993) *To a Rocky Moon: A Geologist's History of Lunar Exploration.* University of Arizona Press, Tucson. 477 pp.

Web Sites

Contact Light; A Personal Retrospective of Project Apollo — **http://www.retroweb.com/apollo.html**

Exploring the Moon (LPI) — **http://cass.jsc.nasa.gov/moon.html**

Hawai'i Space Grant Consortium Moon Activities On-line — **http://www.soest.hawaii.edu/SPACEGRANT/class_acts/**

Lunar Bases and Space Activities of the 21st Century (Online Edition) — **http://adsbit.harvard.edu/books/lbsa/**

Lunar Explorers Digest Book List (JSC) — **http://ilewg.jsc.nasa.gov/ILEWG/led.html**

Lunar Sample Information (JSC) — **http://www-curator.jsc.nasa.gov/curator/lunar/lunar.htm**

NASA Educator Guide, Exploring the Moon — **http://spacelink.nasa.gov/products/Exploring.the.Moon/**

NASA Education Program — **http://education.nasa.gov/**

Office of Space Science (OSS) — **http://spacescience.nasa.gov**

Origin of the Moon (Online Edition) — **http://adsbit.harvard.edu/books/ormo/**

Romance to Reality: Moon & Mars Expedition & Settlement Plans — **http://members.aol.com/dsfportree/explore.htm**

The Apollo Lunar Surface Journal (NASA) — **http://www.hq.nasa.gov/office/pao/History/alsj/**

The Lunar Almanac (Reston) — **http://www.reston.com/astro/lunar/almanac.html**

Please take a moment to evaluate this product at http://ehb2.gsfc.nasa.gov/edcats/educational_wallsheet. Your evaluation and suggestions are vital to continually improving NASA educational materials. Thank you.

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