Atomic substitution. The theoretical formula for montmorillonite without structural substitutions is $(OH)_4Si_8Al_4O_{20} \cdot nH_2O$ (interlayer). However, montmorillonite always differs from the above theoretical formula because of structural substitution. In the tetrahedral sheet, aluminum and possibly phosphorus substitute for silicon, whereas ions such as magnesium, iron, and lithium substitute for aluminum in octahedral coordination. Total replacement of aluminum by magnesium yields the mineral saponite; replacement of aluminum by iron yields nontronite. If all octahedral positions are filled by ions, the mineral is trioctahedral; if only two-thirds are occupied, the mineral is dioctahedral.

The montmorillonite structure is always unbalanced by the substitutions noted above. The resulting positive net charge deficiency is balanced by exchangeable cations adsorbed between the unit layers and around their edges. The cation-exchange capacity of montmorillonite is normally quite high (100 ± milliequivalents per 100 g) and is not appreciably affected by particle size. Substitutions within the structure cause about 80% of the total exchange capacity, and broken bonds are responsible for the remainder.

Other properties. Montmorillonite particles are extremely small and may further disperse in water to units approaching single-cell-layer dimensions. Most montmorillonite units are equidimensional flakes. However, nontronite tends to occur in elongate lath-shaped units, and hectorite, the fluorine-bearing magnesium-rich montmorillonite, is found in thin laths.

There is general agreement that the adsorbed interlayer water between the silicate layers has some sort of definite configuration, but the precise nature of this configuration is not agreed upon. The extent and nature of the orientation of the adsorbed water varies with identity of the adsorbed cations.

When montmorillonite is dehydrated, the interlayer water is lost at a relatively low temperature (212–390°F or 100–200°C). The loss of structural (OH) water begins gradually at about 840–930°F (450–500°C), ending at 1110–1290°F (600–750°C). These temperatures vary with the type and amount of structural substitution. The structure of montmorillonite usually persists to temperatures of the order of 1470–1650°F (800–900°C). On further heating montmorillonite, a variety of phases form, such as mullite, cristobalite, and cordierite, depending on the composition and structure prior to fusion at 1830–2700°F (1000–1500°C).

Organic ionic compounds enter into cation-exchange reactions with montmorillonite. Polar organic compounds, like glycerol, react by replacing the interlayer water, causing a shift in the *c*-axis spacing of the montmorillonite units. Thus, the identification of montmorillonite by x-ray diffraction is greatly simplified by preliminary treatment with certain organic reagents. The reaction of montmorillonite and organic material is the base of considerable economic use of montmorillonite clays.

Occurrence. Members of the montmorillonite group of clay minerals vary greatly in modes of formation. Alkaline conditions and the presence of magnesium particularly favor the formation of these minerals. Montmorillonites are stable over a wide temperature range and have formed by low-temperature hydrothermal processes, as well as by weathering processes. Several important modes of occurrence are in soils, in bentonites, in mineral veins, in marine shales, and as alteration products of other minerals. Recent sediments have a fairly high montmorillonite content. *SEE BENTONITE; CLAY MINERALS; MARINE SEDIMENTS.*

Floyd M. Wahl; Ralph E. Grim

Monzonite

A phaneritic (visibly crystalline) plutonic rock composed chiefly of sodic plagioclase (oligoclase or andesine) and alkali feldspar (microcline orthoclase, usually perthitic), with subordinate amounts of dark-colored (mafic) minerals (biotite, amphibole, or pyroxene). Monzonite is more or less intermediate between syenite and diorite. Plagioclase is dominant over alkali feldspar in monzonite but is subordinate to alkali feldspar in syenite. Diorite contains little, or no alkali feldspar. *SEE SYENITE.*

Carleton A. Chapman

Moon

The Earth's natural satellite. United States and Soviet spacecraft have obtained lunar data and samples, and Americans have orbited, landed, and roved upon the Moon (**Fig. 1**). Though the first wave of exploration has passed, it left a store of information whose meanings are still being deciphered. Many of the Moon's properties are now well understood, but its origin and relations to other planets remain obscure. Theories of its origin include: independent condensation and then capture by the Earth; formation in the same cloud of preplanetary matter with the Earth; fission from the Earth; and formation after the impact of a Mars-sized body on the proto-Earth. Because many of the Moon's geologic processes stopped long ago, its surface preserves a record of very ancient events. However, because the Moon's rocks and soils were reworked by geochemical and impact processes, their origins are partly obscured, so that working out the Moon's early history remains a fascinating puzzle. Major characteristics of the Moon are listed in **Table** 1.

The apparent motions of the Moon, its waxing and waning, and the visible markings on its face (Fig. 1), are reflected in stories and legends from every early civilization. At the beginning of recorded history on the Earth, it was already known that time could be reckoned by observing the position and phases of the Moon. Attempts to reconcile the repetitive but incommensurate motions of the Moon and Sun led to the construction of calendars in ancient Chinese and Mesopotamian societies and also, a thousand years later, by the Maya. By about 300 B.C., the Babylonian astronomer-priests had accumulated long spans of observational data and so were able to predict eclipses. Major events in the subsequent development of human knowledge of the Moon are summarized in Table 2.

Space flight experiments have now confirmed and vastly extended understanding of the Moon; however, they have also opened many new questions for future lunar explorers.

Motions. The Earth and Moon now make one revolution about their barycenter, or common center of mass (a point about 2900 mi or 4670 km from the Earth's center), in $27^d 7^h 43^m 11.6^s$. This sidereal period is slowly lengthening, and the distance (now about 60.27 earth radii) between centers of mass is increasing, because of tidal friction in the oceans of

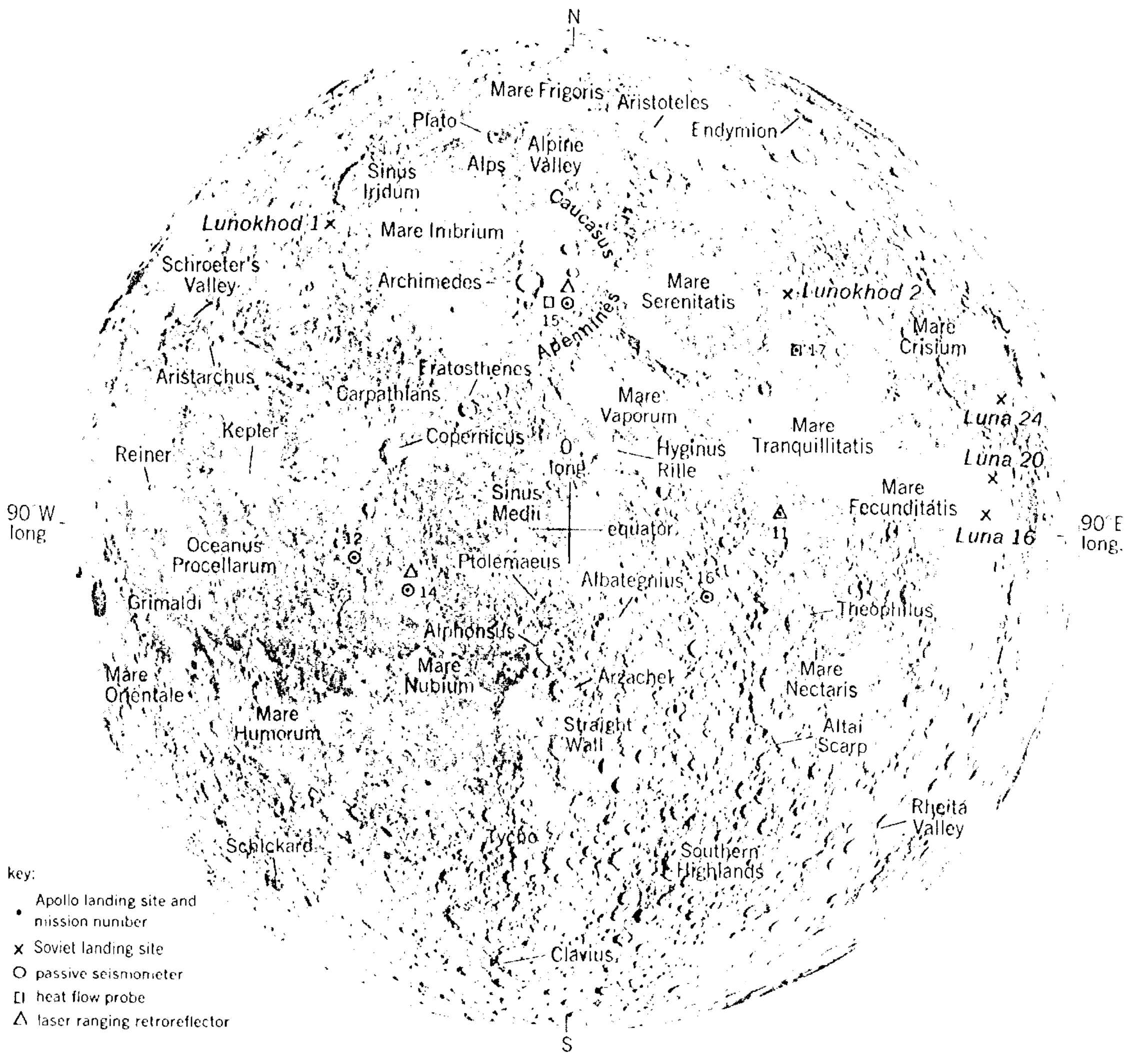

Fig. 1. Map of near side of Moon, showing principal features and American and Soviet landing sites,

Table 1. Characteristics of the Moon

Characteristics	Values and remarks
Diameter (approximate)	2160 mi (3476 km)
Mass	1/81,301 Earth's mass, or 1.62 x 10''³lb (7348 x 10²² f(g)
Mean density	0.604 Earth's, or 209 lb/ft³ (3.34 g/cm³)
Mean surface gravity	0.165 Earth's, or 5,3 ft/s² (162 cm/s')
surface escape velocity	0.213 Earth's, or 1.48 mi/s (2.38 km/s)
Atmosphere	Surface pressure 10-12 torr (1.3 x 10'10 Pa); hints of some charged dust particles and occasional venting of volatiles
Magnetic field	Dipole field loss than -0.5 x 10'5 Earth's; remanent magnetism in rocks shows past field was much stronger
Dielectric properties	Surface material has apparent dielectric constant of 2.8 or less; bulk apparent conductivity y is 10"5 mho/m or loss
Natural radioactivity	Mainly duo to solar- and cosmic-ray-induced background (shout 1 milliroentgen par hour for quiet Sun)
Seismic activity	Much lower than Earth's; doop moonquakes occur more frequently when the Moon is near perigee; subsurface layer evident
Heat flow	3 x 10⁻² W/m* (Ape/h 75 site)
Surface composition and properties	Basic silicates, three sites (Table 4); some magnetic material present; soil grain size is 2.60 μm and 50% isloss than 10 μm; soil-bearing strength 15 lb/in.² (1kg/cm²) at, depth of 1-2' in. (a few centimeters)
Rocks	All sizes up to tens of meters present, concentrated in strewn fields; rock samples from Mare Tranquillitatis include fine- and medium-grained igneous and breccia
Surface temperature range	At equator 260°F (400 K) at noon; 315 to - 280°F (80- 100 K) night minimum; 3 ft (1 m) below surface, -45 °F (230 K); at poles - 280°F (~100 K)

the Earth. The tidal bulges raised by the Moon are dragged eastward by the Earth's daily rotation. The displaced water masses exert a gravitational force on the Moon, with a component along its direction of motion, causing the Moon to spiral slowly outward. The Moon, through this same tidal friction, acts to slow the Earth's rotation, lengthening the day. Tidal effects on the Moon itself have caused its rotation to become synchronous with its orbital period, so that it always turns the same face toward the Earth.

Tracing lunar motions backward in time is very difficult, because small errors in the recent data propagate through the lengthy calculations, and because the Earth's own moment of inertia may not have been constant over geologic time. Nevertheless, the attempt is being made by using diverse data sources, such as the old Babylonian eclipse records and the growth rings of fossil shellfish. At its present rate of departure, the Moon would have been quite close to the Earth about 4.6×10^9 years ago, a time which other evidence suggests as the approximate epoch of formation of the Earth.

The Moon's present orbit (**Fig.** 2) is inclined about $5°$ to the plane of the ecliptic. **Table 3** gives the di-

table 2. Growth of human understanding of the Moon

Prehistory	Markings and phases observed, legends created connecting Moon with silver, dark markings with rabbit (shape of maria) or with mud.
~300 B.C.	Apparent lunar motions recorded and forecast by Babylonians and Chaldeans.
~150 B.C.	Phases and eclipses correctly explained, distance to Moon and Sun measured by Hipparchus.
~A.D. 150	Ancient observations compiled and extended by C. Ptolemy.
~700	Ephemeris refined by Arabs.
~1600	Empirical laws of planetary motion derived by J. Kepler.
1609	Lunar craters observed with telescopes by T. Harriet and Galileo.
1650	Moon mapped by J. Hevelius and G. Riccioli; features named by thorn in system still in use.
1667	Experiments by R. Hooke simulating cratering through impact and vulcanism.
1687	Moon's motion ascribed to gravity by I. Newton.
1692	Empirical laws of lunar motion stated by J. D. Cassini.
1700-1800	Lunar Vibrations measured, lunar ephemeris computed using perturbation theory by T. Mayer, Secular changes computed by J. L. Lagrange and P. S. de Laplace. Theory of planetary evolution propounded by I. Kant and Laplace. Many lunar surface features described by J. H. Schroeter and other observers.
1800-1920	Lunar motion theory and observations further refined, leading to understanding of tidal interaction and irregularities in Earth's rotation rate. Photography, photometry, and bolometry applied to description of lunar surface and environment. Lunar atmosphere proved absent New disciplines of geology and evolution applied to Moon, providing impetus to theories of its origin,
1924	Polarization measured by B. F. Lyot, showing surface to be composed of small particles.
1927-1930	Lunar day, night, and eclipse temperatures measured by E. Pettit and S B. Nicholson.
1946	First radar return from Moon.
1950-1957	New photographic lunar atlases and geologic reasoning; renewed interest in theories of lunar origin by G. P. Kuiper, H. C. Urey, and E. M. Shoemaker. New methods (for example, isotope dating) applied to meteorites, concepts extended to planetology of Moon. Low subsurface temperatures confirmed by Earth-based microwave radiometry.
1959	Absence of lunar magnetic field (on sunlit side) shown by *Luna* 2.
1960	Eastern far side photographed by *Luna 3.* Slower cooling of Tycho detected during lunar eclipse.
1961	United States commitment to crewed lunar flight.
1962	Earth-Moon mass ratio measured by *Mariner 2.*
1964	High-resolution pictures sent by *Ranger* 7. Surface temperatures during eclipse measured by Earth-based infrared scan.
1965	Western far side photographed by *Zond 3.*
1966	Surface pictures produced by *Luna 9* and *Surveyor 7.* Radiation dose at surface measured by *Luna 9.* Gamma radioactively measured by *Luna 10.* High-resolution, broad-area photographs taken by *Lunar Orbiter 1.* Surface strength and density measurements ma do by *Luna 13.*
1967	Mare soil properties and chemistry measured by *Surveyor 3, 5,* and *6*. Wholo front face mapped by *Lunar Orbiter 4,* sites of special scientific interest examined by *Lunar Orbiter* 5. Particle-and-field environment in lunar orbit measured by *Explorer 35,*
1968	Highland soil and rock properties and chemistry measured by Surveyor 7. Mass concentrations at circular maria discovered.
1968	Astronauts orbit Moon, return with photographs,
1969	Astronauts land and emplace instruments on Moon, return with lunar samples and photographs.
1969 1972	Lunar seismic and laser retroreflector networks established. Heat flow measured at two sites. Remanent magnetism discolored in lunar rocks, Geologic traverses accomplished. Orbital surveys of natural gamma radioactivity, x-ray fluorescence, gravity, magnetic field, surface elevation, and subsurface electromagnetic properties made at low latitudes. Metric mapping photos obtained. Samples returned by both piloted (United States) and automated (Soviet) missions; sample analyses confirmed early heating and chemical differentiation of Moon, with surface rocks enriched in refractory elements and depleted In volatiles. Age dating of lunar rocks and soils showed that most of tho Moon's activity (meteoritic, tectonic, volcanic) occurred more than 3 x 10^9 years ago,
1975	Giant-impact hypothesis for lunar origin advanced by W. K. Hartmann and D. R. Davis,
1982	Earth.based spectrometry reveals mineral variations over Moon's near side; central peaks of crater Copernicus found to be rich in olivine.
1983	Antarctic meteorite, ALHA 81005, proved to have come from the Moon.

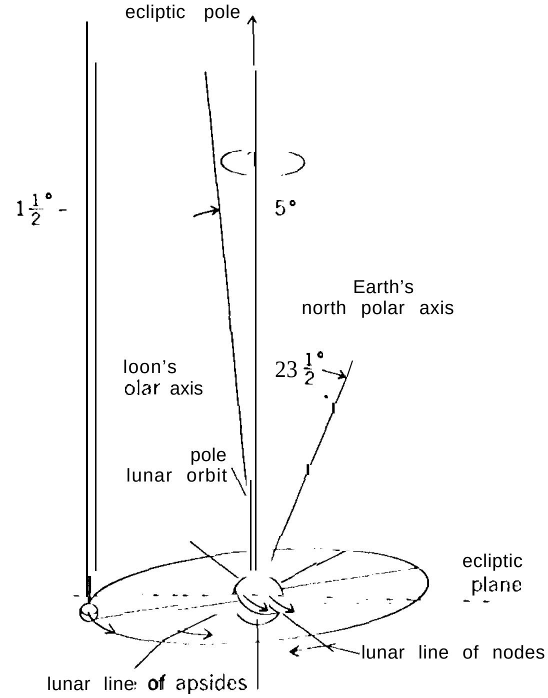

Fig. 2. Sketch of Moon's orbit.

mensions of the orbit (in conventional coordinates with origin at the center of the Earth, rather than the Earth-Moon barycenter). As a result of differential attraction by the Sun on the Earth-Moon system, the Moon's orbital plane rotates slowly relative to the ecliptic (the line of nodes regresses in an average period of 18.60 years) and the Moon's apogee and perigee rotate slowly in the plane of the or-bit (the line of apsides advances in a period of 8.850 years). Looking dow non the system from the north, the Moon moves counterclockwise. It travels along its orbit at an average speed of nearly 0.6 mi/s (1 km/s) or about 1 lunar diameter per hour; as seen from Earth, its mean motion eastward among the stars is 13°11' per day.

As a result of the Earth's annual motion around the Sun, the direction of solar illumination changes about 1° pcr day, so the lunar phases do not repeat in the sidereal period given above but in the synodic period, which averages 29^{d}12^{h}44"' and varies some 13 h because of the eccentricity of the Moon's orbit. *See Earth rotation and orbital motion; Orbital motion.*

When the lunar line of nodes (Fig. 2) coincides with the direction to the Sun. and the Moon happens to be near a node, eclipses can occur. Because of the 18.6-year regression of the nodes, groups of eclipses recur wilh this period. When it passes through the Earth's shadow in a lunar eclipse, the Moon remains dimly visible because of the reddish light scattered through the atmosphere around the limbs of the Earth. When the Moon passes between the Earth and Sun, the solar eclipse may be total or annular. As seen from Earth, the angular diameter of the Moon (31') is almost the same as that of the Sun, but both apparent diameters vary because of the eccentricities of the orbits of Moon and Earth. Eclipses are annular when the Moon is near apogee and the Earth is near perihelion at the time of eclipse. A partial solar eclipse is seen from places on Earth that arc not directly along the track of the Moon's shadow. *See Eclipse.*

The Moon's polar axis is inclined slightly to the pole of the lunar orbit (Fig. 2) and rotates with the same 18.6-year period about the ecliptic pole. The rotation of the. Moon about its polar axis is nearly uniform, but its orbital motion is not, owing to the. finite eccentricity and Kepler's law of equal areas, so that the face of the Moon appears to swing cast and west about 8° from its central position every month. This is the apparent libration in longitude. The Moon dots rock to and fro in a very small oscillation about its mean rotation rate; this is called the physical libration. There is also a libration in latitude because of the inclination of the Moon's polar axis. The librations make it possible to see. about 59% of the Moon's surface from the Earth.

The lunar ephemeris, derived from precise astronomical observations and refined through lengthy computations of the effects perturbing the movements of the Moon, has now reached a high degree of accuracy in forecasting lunar motions and events such as eclipses. Laser ranging to retroreflectors landed on the Moon, aided by radio ringing to spacecraft, provides measurements of Earth-Moon distances to a precision of the order of meters. *See Perturbation (astronomy).*

Selenodesy. The problem of determining the Moon's true size and shape and its gravitational and inertial properties has been under attack by various methods for centuries (Tables 1 and 2). However, results from space flights have invalidated some of the

Table 3. Dimensions of Moon's orbit

Characteristics	Values
Sidereal period (true period of rotation and revolution)	(27.32166140 + 0.000000167) ephemeris days, where T is in centuries from 1900
Synodic period (new Moon to new Moon)	(29.5305882 + 0.000000167) ephemeris days
Apogee	252,700 mi or 406,700 km (largest); 251,971 mi or 405,508 km (mean)
Perigee	221,500 mi or 356,400 km (smallest); 225,744 mi or 363,300 km (mean)
Period of rotation of perigee	8.8503 years direct ("direct" meaning that the motion of perigee is in tha direction of Moon's motion about the Earth)
Period of regression of nodas	18.5995 years
Eccentricity of orbit	0.054900489 (mean)
Inclination of orbit to ecliptic	5°8'43" (oscillating ± 9' with period of 173 days)
Inclination of orbit to Earth's equator	Maximum 26035', minimum 18°21'
Inclination of lunar equator	
to ecliptic	1°32'40"
to orbit	6°41'

premises on which the earlier methods were based, and have revealed discrepancies in the older data. The relation between the Moon's shape and its mass distribution is very important to theories of lunar origin and the history of the Earth-Moon system. Radio-tracking data from Lunar Orbiters indicate that the Moon's gravitational field is ellipsoidal, with the. short axis being the polar onc (as expected for any rotating body), and with the equatorial section being an ellipse possibly slightly elongated in the Earth-Moon direction. But the Earth-based radar measurements and tracking data from Rangers and Surveyors showed that the Moon's actual surface at the points of landing is about 1.2 mi (2 km) farther from tbc Earth than expected. Further evidence of an anomalous relationship between mass and shape for the Moon is provided by the mass concentrations in circular maria, discovered through analysis of short-term variations in the Lunar Orbiter tracking data and then mapped in detail by Apollo tracking (see Fig. 3). By radio altimetry, Apollo confirmed that the Moon's surface on the far side is higher on the average than the near side; that is, the center of mass is offset from the center of figure. The offset is about 1.2 mi (2 km) toward the Earth. These observations suggest that the Moon's crust is thicker on the far side than on the near side, as shown (not to scale) in **Fig. 4.** *SEE SPACE PROBE*

Body properties. The Moon's small size and low mean density (Table 1) result in surface gravity too low to hold a permanent atmosphere, and therefore it was to be expected that lunar surface characteristics would be very different from those of Barth. However, the bulk properties of the Moon are also quite different--the density alone is evidence of that—and the unraveling of the Moon's internal history and constitution is a great challenge to planetologists. *SEE EARTH.*

The Earth, with its dense metallic fluid core, convective mantle, strong and variable magnetic field with trapped radiation belts, widespread seismic tremors, volcanoes and folded mountain ranges, moving lithospheric plates, and highly differentiated radioactive rocks, is plainly a planet seething with inner activity. Is the Moon also an active, evolving world or is it something very different? The answer lies in a group of related experiments: seismic investigations, heat-flow measurements, surface magnetic and gravity profiles, determination of abundances and ages of the radioactive isotopes in 'lunar material, and comparison of the latter with those found in the Earth and meteorites. Present theories and experimental data yield the following clues to the problem.

1. The Moon is too small to have compressed its silicates into a metallic phase by gravity; therefore, if it has a dense core at all, the core should be of nickel-iron. But the low mass of the whole Moon does not permit a large core unless the outer layers are of very light material; available data suggest that the Moon's iron core may have a diameter of at most a few hundred kilometers.

2. The Moon has no radiation belts, and behaves as a nonconductor in the presence of the interplanetary field. Moon rocks are magnetized, but the source of the magnetism remains a mystery as there is now little or no general lunar magnetic field.

3. The Moon's natural radioactivity from long-lived isotopes of potassium, thorium, and uranium, expected to provide internal heat sufficient for partial melting, was roughly measured from orbit by *Luna* 10, and the component above the cosmic-ray-induced background radiation was found to be at most that of basic or ultrabasic earthly rock, rather than that of more highly radioactive, differentiated rocks such as granites. *Apollo 11* and 12 rock samples confirmed this result; *Apollo* 15, 16, and 17 mapped lunar composition and radioactivity from orbit (Fig. 3). X-ray experiments showed higher aluminum-silicon concentration ratios over highland areas and lower values over maria (**Fig. 5**), while magnesium-silicon ratios showed a converse relationship higher values over maria and lower values over highlands.

4. The Moon is seismically much quieter than the Earth. Moonquakes are small, many of them originate deep in the interior (Fig. 4), and activity is correlated with tidal stress: more quakes occur when the Moon is near perigee.

When all of the Apollo observations are taken together, it is evident that the Moon was melted to an unknown depth and chemically differentiated about 4.5 X 109 years ago, leaving the highlands relatively rich in aluminum and an underlying mantle relatively rich in iron and magnesium, with all known lunar materials depleted in volatiles. The subsequent history of impacts and lava flooding includes further episodes of partial melting until about 3.9 x 10^9 years ago, with

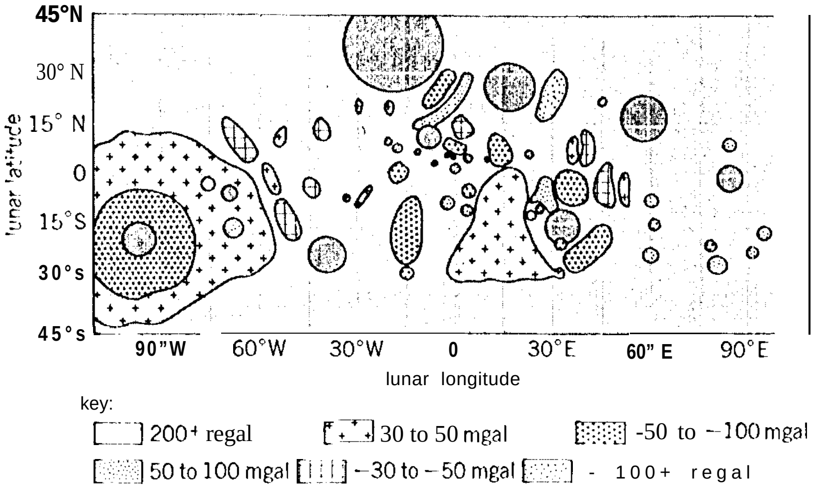

Fig. 3. Gravity anomalies on the lunar naar side and limb regions. 1 mGal = gravitational **acceleration** of 10^{-5} **m/s²** = 3.3 x 10⁻⁵ **ft/s. Circular** areas correspond to mass concentrations in circular **maria.** (W. *L.* ***Sjogren,*** *Jet* ***Propulsion*** *Laboratory, NASA)*

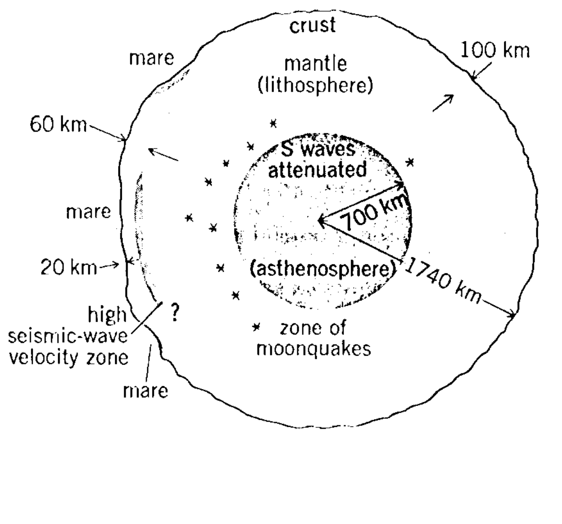

Fig. 4. **Schematic** diagram of lunar **structure. The** near aide of the **Moon** la to the left of the figure. 1 km = 0.6 **mi.** (After S. ***R.*** *Taylor,* ***Lunar Science: A Post-Apollo View, Pergamon Press, 1975)***

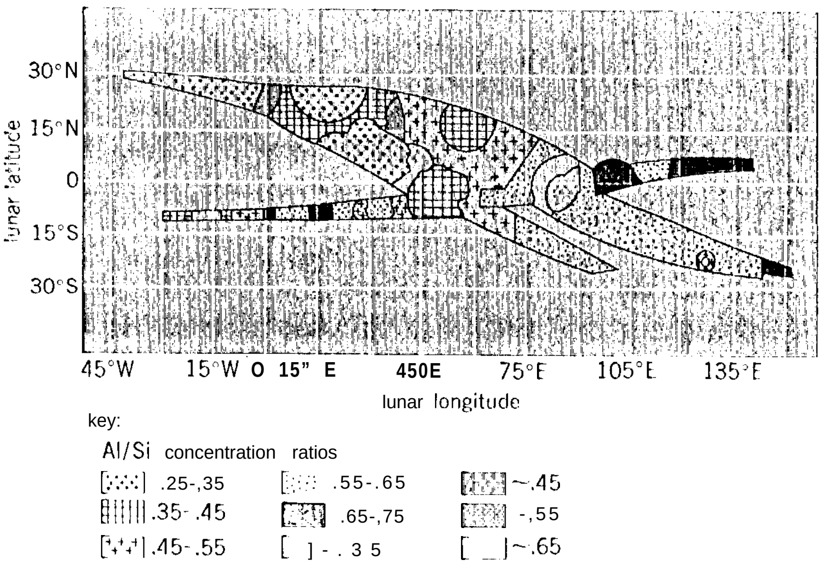

Fig. 5 Aluminum-silicon concentration ratios as detected **bv x-rav** experiments on *Apollo* 75 and 16. (/. Adler, ***University*** *of* Maryland)

the fins] result being a thick, rigid crust with only minor evidence of recent basaltic extrusions. The temperature profile and physical properties of the Moon's deep interioi arc, despite the Apollo seismic and heat-flow data, under active debate. Figure 4 shows a rough sketch of the Moon as revealed by the data.

Large-scale surface features. As can bc seem from tbc Earth with tbc unaided eye, tbc Moon has two major types of surface: the dark, smooth maria and the lighter, rougher highlands (Fig. 1 and **Fig.** 6). Photography by spacecraft shows that, for some unknown reason, the Moon's far side consists mainly of highlands (**Fig.** 7). Both maria and highlands are covered with craters of all sizes. Craters are more numerous in the highlands than in the maria, except on the steeper slopes, where downhill movement of material apparently tends to obliterate them. Numerous different types of craters can bc recognized. Some of them appear very similar to tbc craters made by explosions on the Earth; they have raised rims, sometimes have central peaks, and are surrounded by fields of hummocky, blocky ejecta. Others are rimless and tend to occur in lines along cracks in the lunar surface. Some of the rimless craters, particularly those with dark halos, may be gas vents; others may bc just the result of surface material funneling down into subsurface voids. Most prominent at full moon are tbc bright ray craters (Fig. 1) whose grayish ejecta appear to have traveled for hundreds of kilometer-s across the lunar surface. Observers have long recognized that some erosive process has been and rosy still bc active on the Moon. For example, when craters overlap so that their relative ages are evident, tbc younger ones are seen to have sharper outlines than the older ones. Bombardment of the airless Moon by meteoritic mat-

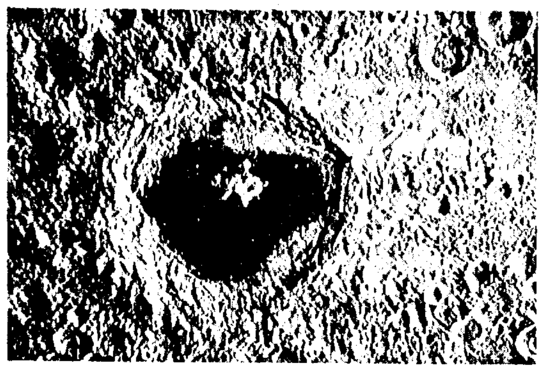

Fig. 7. Mare **Tsiolkovski** on far side of Moon. Crater, partly flooded by dark mare **material,** Is about 120 ml (200 km) across. (Langley *Research Center, NASA)*

tcr and solar particles, and extreme temperature cycling, are now considered the most likely erosive agents, but local internal activity is also a possibility. Rocks returned by the Apollo astronauts are covered with tiny glass-lined pits, confirming erosion by small bigb-speed particles.

'l'he lunar mountains, though very high (26,000 ft or 8000 m or more), are not extremely steep, and lunar explorers see rolling rather than jagged scenery (**Fig.** 8). 'l'here are steep slopes (30 40°) on the inside walls and central peaks of recent craters, where tbc lunar material appears to be resting at its maximum angle of repose, and rocks can bc seen to have rolled down to the crater bottoms.

Though widespread networks of cracks are visible, there is no evidence on the Moon of the great mountain-building processes seen on the Earth. 'l'here arc some low domes suggestive of volcanic activity, bLrt the higher mountains arc all part of the gently rolling highlands or the vast circular structures surrounding major basins, **Figure** 9 shows one of these, the Mare Orientale, as revealed by *Lunar Orbiter* 4. "l'his large concentric structure is almost invisible from Earth because it lies just past the Moon's western limb; at

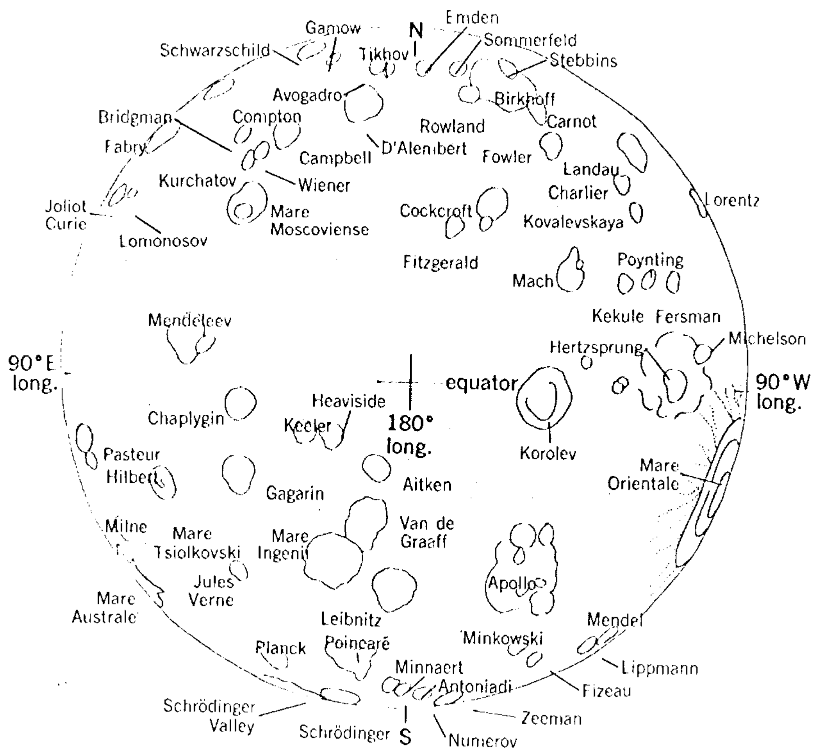

Fig. 6. Map of far side of Moon.

favorable libations parts of its basin and mountain ramparts can be seen. The great region of radial sculpture surrounding the Orientale basin strongly suggests a catastrophic origin, with huge masses of matter [brown outward from the center. Note, however, the gentle appearance of the flooding by the dark mare material, which seems to lie only in the lowest parts of the concentric rings. Other basins, namely, Imbrium, Serenitatis, and Crisium, appear more fully flooded (Fig. 1). These maria were created by giant impacts, followed by subsidence of the ejecta and (probably much later) upwelling of lava from inside the Moon. Examination of small variations in Lunar Orbiter motions has revealed that each of the great circular maria is the site of a positive gravity anomaly (excess mass), shown in Fig. 3. The old argument about impact versus volcanism as the primary agent in forming the lunar relief, reflected in lunar literature over the past 100 years, appear. to be entering a new, more complicated phase with the confirmation of extensive flooding of impact craters by lava on the Moon's near side, while on the far side, where the crust is thicker, the great basins remain mostly empty.

Fig. 8. The **crater** Copernicus, showing the central peaks, slump terraces, patterned crater walls, and (background) , slopes of the **Carpathian** Mountains. *(Langley Research* ***Center,*** *NASA)*

in some of the Moon's mountainous regions bordering, on tbc maria arc found sinuous rilles (**Fig. 10**).. These winding valleys, some of them known since the eighteenth century, were shown in Lunar Orbiter pictures to have an exquisite fineness of detail. Sonic of them originate in small circular pits and then wriggle delicately across the Moon's gentle slopes for hundreds of kilometers, detouring around even slight obstacles, before vanishing 011 the plains, Though their resemblance to meandering rivers is strong, the sinuous rilles have no tributaries or deltas. No explanation for them yet offered (for example, dust flows, lava channels, or subsurface ducts made by water eroding ice) has proved entirely convincing,.

Other strange large-scale features, observed by telescope anti then revealed in more detail by spacecraft cameras, are the ghost craters, circular structures protruding slightly from the maria, and the low, ropy wrinkle ridges that stretch for hundreds of kilometers around some mare borders.

Small-scale surface features. Careful observations, some of them made decades before the beginning of space flight, revealed much about tile fine-

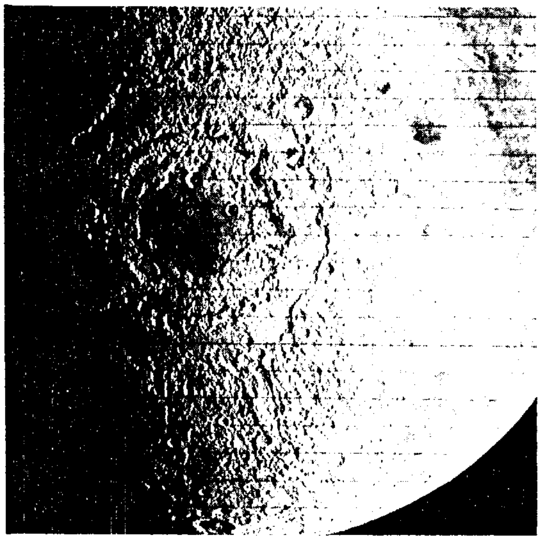

Fig. 9. Mare Orientale. (***Langley*** *Research* Center, *NASA)*

scale nature of the lunar surface. Since the smallest lunar feature telescopically observable from the Earth is some hundreds of meters in extent, methods other than direct visual observation had to be used. Photometry, polarimetry, and later radiometry and radar probing gave the early fine-scaic data. Some results of these investigations suggested bizarre characteristics for the Moon. Nevertheless, many of their findings have now been confirmed by spacecraft: The

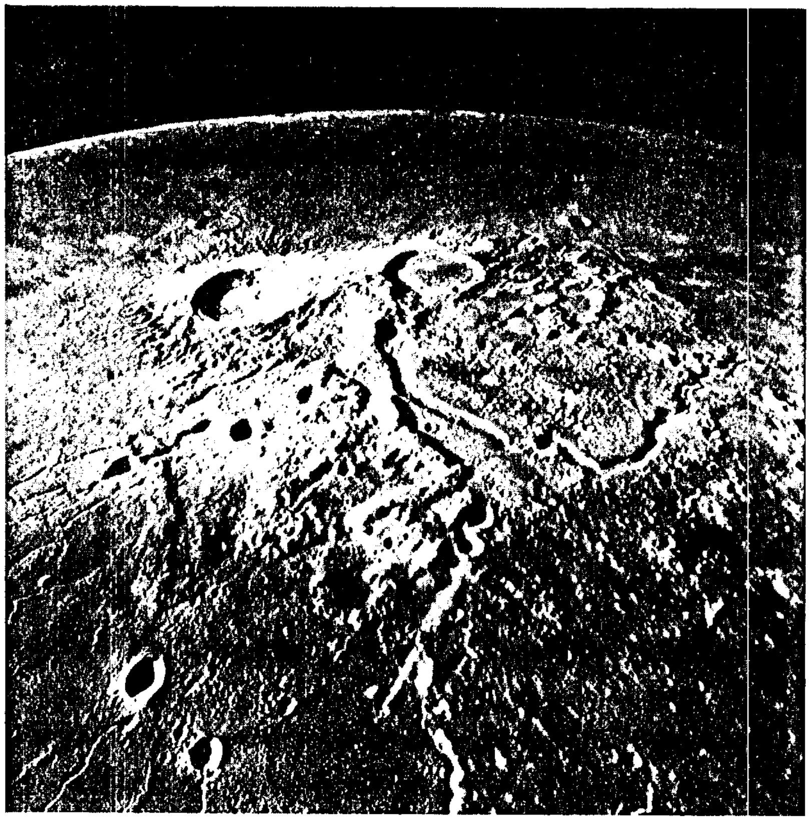

Fig. 10. Aristarchus-Harbinger region of the Moon, photographed from the ***Apollo*** 15 spacecraft in lunar orbit, with the craters **Aristarchus** and **Herodotus** and **Schroeter's** Valley, **the** largest sinuous **rille** on the Moon. The Impact crater **Aristarchus**, about 25 ml (40 km) in diameter and more than 2.5 ml (4 km) deep, lies at the edge of a mountainous region that shows evidence of volcanic activity. *(NASA)*

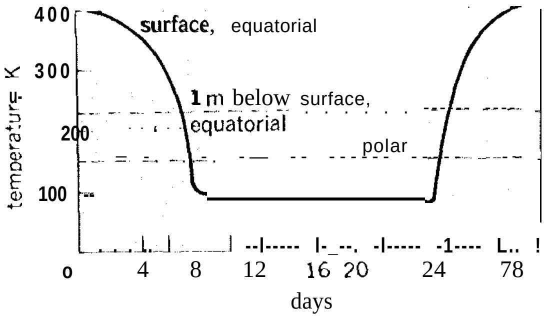

Fig. 11. Lunar surface and **subsurface temperatures.**

Moon seems to be totally covered, to a depth of at least tens of meters, by a layer of rubble and soil with very peculiar optical and thermal properties. This layer is called the regolith. The observed optical and radio properties are as follows. *See Photometry; Polarized light, "Radar; Radiometry.*

1. The Moon reflects only a small portion of the light incident on it (the average albedo of the maria is only 7%, darker than any familiar object except things like soot or black velvet).

2. The full moon is more than 10 times as bright as the half moon.

3. At full moon, the disk is almost equally bright all the way to the edge; that is, there is no "limb darkening" such as is observed for ordinary spheres, whether they be specular or diffuse reflectors.

4. Color variations are slight; the Moon is a uniform dark gray with a small yellowish cast. Some of the maria are a little redder, some a little bluer, and these differences do correlate with large-scale. surface morphology, but the visible color differences are so slight that they arc detectable only with special filters. (Infrared spectral differences are more pronounced and have provided a method for snapping variations in the Moon's surface composition.)

5. The Moon's polarization properties are those of a surface covered completely by small, opaque grains in the size range of a few micrometers.

6. The material at the lunar surface is an extremely good thermal insulator, better than the most porous terrestrial rocks. The cooling rate as measured by infrared observations during a lunar eclipse is strongly variable; the bright ray craters cool more slowly than their surroundings.

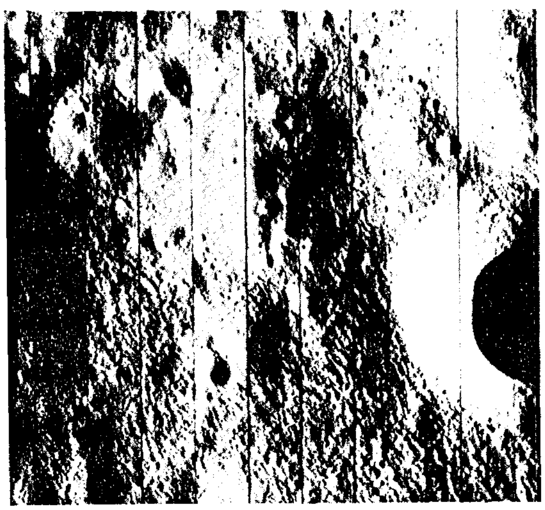

Fig. 12. Lunar patterned ground, a common feature on moderate slopes. (Langley *Research Center, NASA)*

7. The Moon emits thermal radiation in the radio wavelength rang, c; interpretations of this and the infrared data yield estimates of surface and shallow subsurface temperatures as shown in **Fig. 11.**

8. At wavelength.s in tbc meter range, the Moon appears smooth to radar, with a dielectric constant lower than that of most dry terrestrial rocks. To centimeter waves, the Moon appears rather rough, and at visible light wavelengths it is extremely rough (a conclusion from observations 1-5 above).

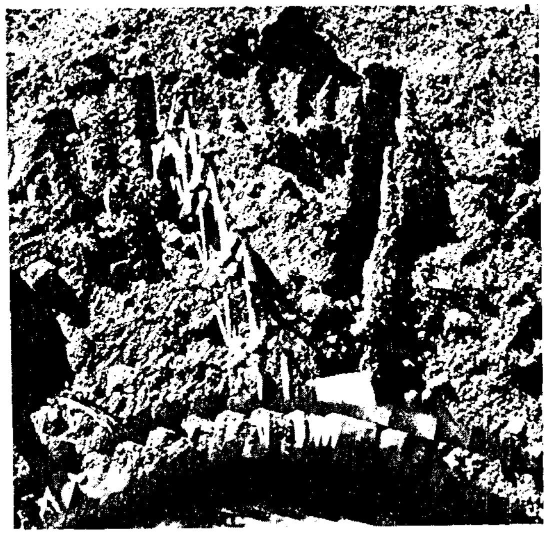

Fig. 13. Lunar soil and rocks, and the trenches made by Surveyor 7. (*Jet Propulsion* Laboratory, NASA)

Fig. 14. Crater showing appearance of upwelling on its floor. (Langley Research Center, *NASA)*

These observations all point to a highly porous or underdense structure for at least the top few millimeters of the lunar surface material. The so-called backscatter peak in the photometric function, which describes the sudden brightening near full Moon, is characteristic of surfaces with deep holes or with other roughness elements that arc shadowed when the lighting is oblique.

The Ranger, Luna, Surveyor, and Lunar Orbiter missions made it clear that these strange electromagnetic properties arc generic characteristics of the dark-gray, fine soil that appears to mantle the entire Moon, softening most surface contours and covering everything except occasional fields of rocks (**Figs. 12** and **13**). This soil, with a slightly cohesive character like that of damp sand and a chemical composition similar 10 that of some basic silicates on the Earth, is a product of the radiation, meteoroid, and thermal environment al the lunar surface. Figure 12 shows a surface texture, called patterned ground, that is common on the moderate slopes of the Moon, This widespread phenomenon is unexplained, though there arc some similar sur faces developed on the Earth when unconsolidated rock, lava, or glacial ice moves downhill beneath an overburden. At many places on the Mocrn, there is unmistakable evidence of downward sliding or slumping of material and rolling rocks. I'here are also a few instances of apparent upwelling (Fig. **14**), **as** well as numerous "lakes" where material has collected in depressions. **Figures 15, 16,** and **17** show, at different scales, the landing site of *Surveyor* 7 near the great ray crater Tycho (Fig. 1). *Surveyor* 7 found the soil of the highlands near Tycho to be rockier

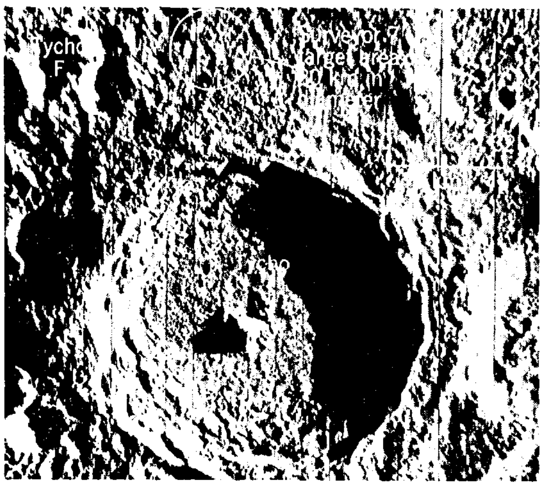

Fig. 15. Region near tha crater Tycho, including Surveyor 7 landing site. 20 km = 12 ml. *(Langley Research Center, NASA)*

than, anti slightly different in chemical composition from, the mare materials sampled by earlier Surveyors. Figure 13 shows trenches made in the lunar soil during soil mechanics experiments on *Surveyor* 7. Magnets on the Surveyors collected magnetic particles from the soii, demonstrating the presence of either meteoritic or native iron minerals at the sites examined. Meteoroid experiments on the Lunar Orbiters showed about the same flux of small particles as is observed at the Earth, so that the lunar soil would be expected to contain a representative sample of meteoritic and possibly aiso cometary matter. Apollo results confirmed anti extended the Surveyor data and also indicated that glassy particles are abundant in and on the soil. Evidence of micrometeoroid bombardment is seen in tbc many glass-lined microcraters found on lunar rocks (**Fig. 18**). *SEE COMET; METEOR*.

Chemical, mineral, and isotopic analyses of minerals from the *Apollo 11* site showed that mare rocks there are indeed of the basic igneous class and are very ancient (3- 4 x 10^9 years). The *Apollo 12* samples arc significantly younger, suggesting that blare

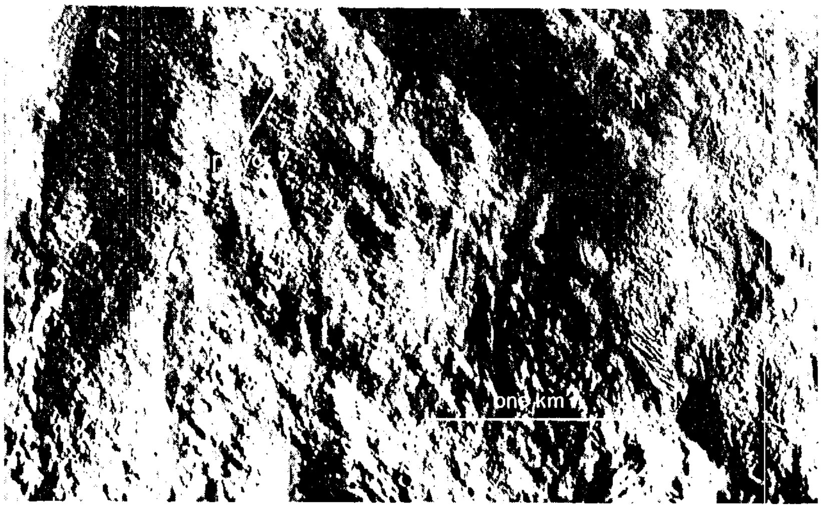

Fig. **16.** ***Orbiter* photograph of** *Surveyor* **7 site. (Langley** *Research* **Center, NASA)**

Tranquillitatis anti Oceanus Procellarum were formed during a long and complex lunar history. The *Apollo* 12 astronauts visited *Surveyor 3* and brought back parts of that spacecraft to permit analysis of the effects of its 2 ½-year exposure on the surface of the Moon. The lunar rock and soil samples returned by the Apollo and Luna missions have yielded much ncw information cm the composition and history of the Moon, Among tbc dominant characteristics of these rocks are enrichment in refractories, depletion in volatiles, much evidence of repeated breaking up and rewelding into breccias, and ages since solidification extending back from the mare flows of 3- 4 x 10^9 years ago into the period of highland formation more than 4 X 10^9 years ago, but not as yet including the time of the. Moon's original accretion, Sonic characteristics of the lunar samples are summarized in **'1'able 4.**

In 1983 an Antarctic meteorite was found to resemble some of the lunar samples, and it was determined by analysis to have come from the Moon (**Fig.** 19). *SEE METEORITE*

As the Apollo missions progressed, each new landing site was selected with the aim of elucidating more of the Moon's history. A main objective was to sam-

Fig. 17, Surface view at Surveyor 7 site. *(Jet **Propulsion*** Laboratory)

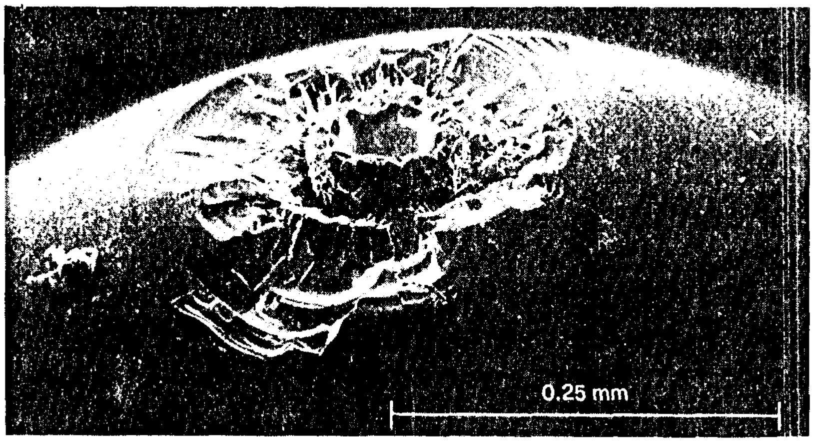

Fig. 18. Example of microcratering, caused by hypervelocity Impact of tiny particles, on a dark-brown glass sphere. The diameter of the sphere is approximately 0.75 mm, and tho diameter of the Inner crater, inside the raised rim, Is about 50 μm. This photograph was taken through a scanning electron microscope.

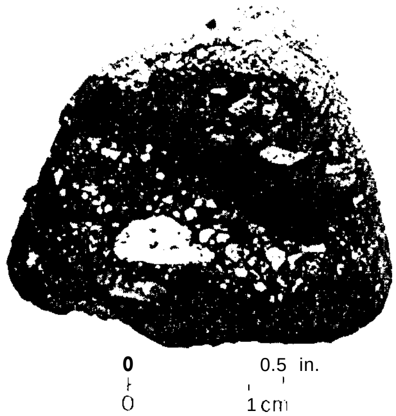

Fig. 19. Meteorite collected In Antarctica In 1982, designated ALHA 81005, proved by **analysls** to be a lunar rock. (NASA)

ple each of the geologic units mapped by remote observation, either by landing on it or by collecting materials naturally transported from it to the landing site. Although this process did result in collection of both mare and highland materials with a wide range of ages and chemical compositions, it did not result in a complete unraveling of the history of the Moon. Apparently, the great impacts of 3- 4 x 10^9 years ago erased much of the previous record, resetting radioactive clocks and scrambling minerals of diverse origins into [he complicated soils and breccias found today. *Si f SPACE FI /[if/I.*

Atmosphere. '1'bough the Moon may at one time have contained appreciable quantities of the volatile elements and compounds (for example, hydrogen, helium, argon, water, sulfur, and carbon compounds) **found** in meteorites anti on the Earth, its high daytime surface temperature and low gravity would cause rapid escape of the lighter elements. Solar ultraviolet and x-ray irradiation would tend to break down volatile compounds at the surface, and solar charged-particle bombardment would ionize and sweep away even the heavier gas species. Observations from the Earth, looking for a twilight glow of the lunar atmosphere just past the terminator on the Moon, and watching radio-star occultations have all been negative, setting an upper limit of 10" ^{12} times the Earth's sea-level atmospheric density for any lunar gas envelope. Therefore, either the lunar volatile compounds have vanished into space or they are trapped beneath the surface. The samples returned by Apollo are enriched in refractory elements,. depleted in volatiles, and impregnated with rare gases from the solar wind, No water appears to have ever been present at any Apollo site, and carbonaceous materials were present, if at all, only in very small amounts.

Occasional luminescent events reported by reliable **observers** suggest **that** some volcanic gases are vented from time to time on the Moon, particularly in the regions of the craters Aristarchus and Alphonsus. A slight, transient atmosphere dots exist on the night side of [he Moon as a result of the trapping and re-

Table 4. Some selected data from Apollo and Luna mlssions

Mission	Main sample properties	Other data
Apollo 71,	Mare basalts, differentiated from melt at depth 3,7 x 10^9 years ago. Somo crystalline highland fragments in soils, Unexpected abundance of glass Much evidence of impact shock and microcratering. No water or organic materials.	Study of seismic properties showed low background, much scattering, and tow attenuation.
Apollo 12	Basalts 3.2 x 10^9 years old. One sample 4,0 x 10^9 years old includes granitic component. Some samples wirb high potassium, rare-earth elements, and phosphorus (KREE P) may be Copernicus crater ejects	Surveyor parts returned showed effects of solar and cosmic bombardment.
Apollo 13	Spacecraft failure- no samples.	Despito emergency, some lunar photos returned.
Luna 16'	Basalt 3.4 x 10^9 years old, relatively high **Al** content.	
Ape//o 74	Shocked highland basalts, probably Imbrium ejecta, 3,95 x 10^9 years old, higher Al and lower Fe than mare materials.	Deep moonquakes.
Ape//o 75	Highland anorthosites including one samplo 4.1 x 10^9 years old, mare basalts similar to *Ape//o 71* samples.	Orbital remote sensing began mapping of surface compositions,
Lena 20	Possibly Crisium ejects, 3.9 x 10^9 years old,	
Apollo 76	Highland anorthosite breccias 3.9 4 x 10^9 years old, also possibly Imbrium ejecta.	Seismic network began recording locations of impacts and deep moonquakes; orbital compositional mapping extended,
Ape//o 77	Variety of basalts and anorthosites 3,7-4 x 10^9 years old, possibly volcanic glass, few dunite fragments 4,48 x 10' years old, possibly surviving from before the great highland bombardment.	Orbital mapping, and study of seismic, particle and-held, and subsurface electrical properties yielded comprehensive (but still unexplained) picture of **Moon**
L urra 24	Very tow titanium basalt from Mare Crisium. Sample includes rock 3.3 x 10^9 years old.	

lease of gas molecules at the very low temperatures prevailing there; also frozen liquids or gases could exist in permanently shadowed crater bottoms near the lunar poles. No experiment to detect such accumulations of volatiles has been made. *Lunokhod* 2, a Soviet roving spacecraft, measured a slight glow attributed 10 a very thin cloud of small particles near the sur face, which could explain the Surveyor observations of a slight horizon 'glow after sunset, Also, the ALSEP (Apollo lunar surface experiments packages) experiments landed by Apollo have occasionally detected small gas emanations, including water, from unknown sources.

Lunar resources. Enough is known about the Moon to show that it is a huge storehouse of metals, oxygen (bound into silicates), and other materials potentially available for future human use in space. Because of the Moon's weak gravity, lunar materials could be placed into orbit at less than one-twentieth of the energy cost for delivering them from Earth. At the sites so far explored, no water exists, and the only available hydrogen is the small amount implanted in soil by the solar wind. It will be a task for future explorations to find the polar ices if they exist, to discover concentrations of meteoritic or cometary materials, and to investigate atypical geologic phenomena such as the seemingly volcanic regions. Any of these sites might yield additional treasures, but it is already known that the Moon could be an important resource for humanity in space.

Jams D. Burke

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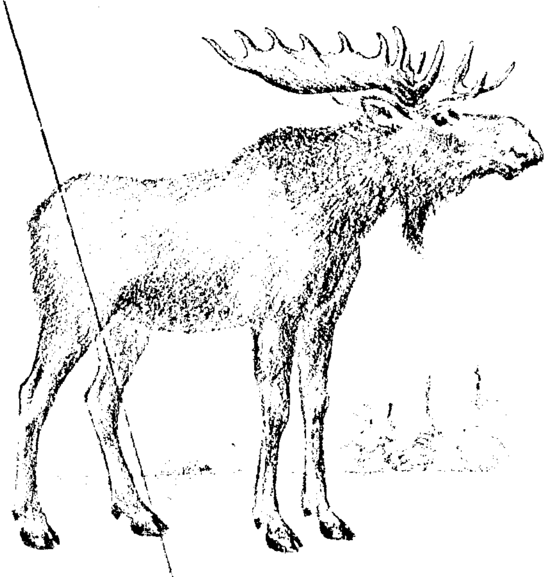
Moose

An even-toed ungulate (Artiodactyla) which is a member of the deer family, Cervidae. *Alces alces* is the largest member of the family and ranges in the boreal forested areas throughout North America and in northern Eurasia. The moose is known as the elk in Europe and is believed by some authorities to be a race of the American moose (*A. americana*). The adult male is 6 ft (1.8 m) high, weighs over 1200 lb (550 kg), and has spatulate antlers which may be over 6 ft (1.8 m) in width (see **illus.**). The legs are long, making the animal well-adapted for its feeding habits



The male moose, distinguished by his "Roman" nose, overhanging upper lip, beard, end spatulate antlers.

of wading for aquatic plants and browsing, on trees and bushes. The moost live in small groups during the summer but tend to form larger groups for defense during the winter, since they are susceptible to predation from wolves and even wolverines During the rutting season in the early fall, the male gathers a number of cows together, and mating takes place. After a gestation period of about 37 weeks, one or two calves are born. The moose is a big-game animal, but hunting restrictions have helped to maintain its numbers; it is abundant in Canada and the northern United States. SEE ARTIODACTYLA.

Charles B. Curtin

Moraine

An accumulation of glacial debris, usually till, with distinct surface expression related to some former ice front position. End moraine, the most common form, is an uneven ridge of till built in front of or around the terminus of a glacier margin), and reflects some degree of equilibrium between rate of ice motion, supply of rock debris at the ice front, temperature of the glacier base, and shape and resistance of underlying bedrock (see **illus.**).

If an end moraine represents the farthest forward position a glacier ever moved, it is a terminal moraine. It demonstrates a steady-state condit ion for a per iod of time within the ice body where constant forward motion is balanced by frontal melting; and a continual supply of debris, as on an endless conveyor belt, is brought forward to the glacier terminus. If the ice front then melts farther back than it moves forward, till is spread unevenly over the land as ground moraine. If a retreatal position of steady-state equilibrium is maintained again, a recessional moraine may be constructed.

A variety of moraines transverse to the ice-flow direction are known. If it can be proved that a series of small recessional moraines are yearly deposits, they are called annual moraines. Ice may override previously deposited ground moraine and push till into ridges, Some moraines may be ridges of till stacked up on top of each other. A zone of stagnant ice around a glacier margin may produce a series of mo-