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The Surveyor Lunar Landings

Landed spacecraft have returned much information about the surfaces of lunar maria and highlands.

Leonard D. Jaffe

Five Surveyor spacecraft have landed intact (soft landed) on the surface of the moon (Fig. 1) and returned large quantities of scientific information. The more important findings are: (i) The surface of both maria and highlands is covered with a layer of particulate material, with a particle size predominantly of the order of 10 micrometers. A variety of rocks and clods are scattered on and in this layer; rocks are more common around crater rims. (ii) The depth of the layer is a few meters in the maria and appears to vary from a few centimeters to tens of meters in the highlands. Density and other properties of the particulate layer vary strongly with depth, at least near the surface. (iii) The particulate material has cohesion: about 0.05 newton per square centimeter at a few centimeters depth. Its bearing capacity is about 0.1 newton per square centimeter for the top millimeter and increases about 1 newton per square centimeter per centimeter of depth, to at least a 5-centimeter depth; this is for bearing widths 1 to 10 times the depth. (iv) The fine material moves gradually downhill. (v) Freshly exposed fine material from below the surface is darker than previously exposed surface material. (vi) The density of a surface rock was found to be 2.8 ± 0.4 grams per cubic centimeter. (vii) The composition of surface material is approximately that of a basalt. The mare material has an elemental composition corresponding to that of a high-iron basalt; the highland material has that of a low-iron basalt, at the one site examined. Not more than one-quarter volume percent of metallic iron is present. (viii) The lunar surface material has gone through extensive melting and chemical differentiation.

This paper is a brief summary of procedures and results; more detailed accounts are available elsewhere (*1*, *2*).

The Surveyor spacecraft have provided data about lunar maria and highlands through a television camera, spacecraft leg strain gages, a soil mechanics surface sampler, an alpha-particle back-scattering instrument, magnets, thermal sensors, movable shadowing elements, radar system, rocket engines and gas jets, gyros and accelerometers, and a radio doppler transponder. The information returned included: surface structure, topography, and geology; chemical composition of surface and near-surface material and content of magnetic particles; cohesion, bearing and shear strengths, internal friction and density of surface material as functions of depth; strength and density of individual rocks; elastic velocity of near-surface material; permeability to gases, adhesion, and response to gas erosion; surface temperatures, thermal inertia, and directional infrared emission; radar reflectivity; surface photometry, polarization, and color; and shape and motion of the moon. They also returned information about the earth—optical polarization, photometry and color; optical and microwave transmission by the atmosphere; and cloud patterns—and about the extent, photometry, and polarization of the solar corona.

Spacecraft and Instrumentation

There were some variations from spacecraft to spacecraft but the configuration of the Surveyor 7 spacecraft after landing is illustrative (Fig. 2). The spaceframe structure was of tubular aluminum; hinged to the spaceframe were three landing legs, each with a shock absorber and a hinged footpad. These footpads and the landing blocks, which were attached under the spaceframe near each leg hinge, were constructed of crushable, energy-absorbing aluminum honeycomb to reduce landing shock. Two thermally controlled compartments housed the electronic equipment. A vertical mast carried the movable solar-cell panel and planar array communications antenna (high-gain). Two omnidirectional antennas (low-gain) were also available for communication; the communication equipment included a transponder which would return a signal in fixed ratio of frequency to that received from the earth.

The main engine for braking (retro engine) of the spacecraft utilized solid propellant. Each of the three liquid-fueled vernier engines were throttleable from about 460- to 120-newton thrust. Nitrogen gas jets provided attitude control when the engines were off. For attitude reference during flights, the spacecraft carried sun and Canopus sensors and gyroscopes. A radar altimeter furnished an altitude mark to initiate main retro engine firing during descent to the lunar surface. Another radar, providing measurements of velocity and altitude, was used with the vernier engines, in a closed loop under

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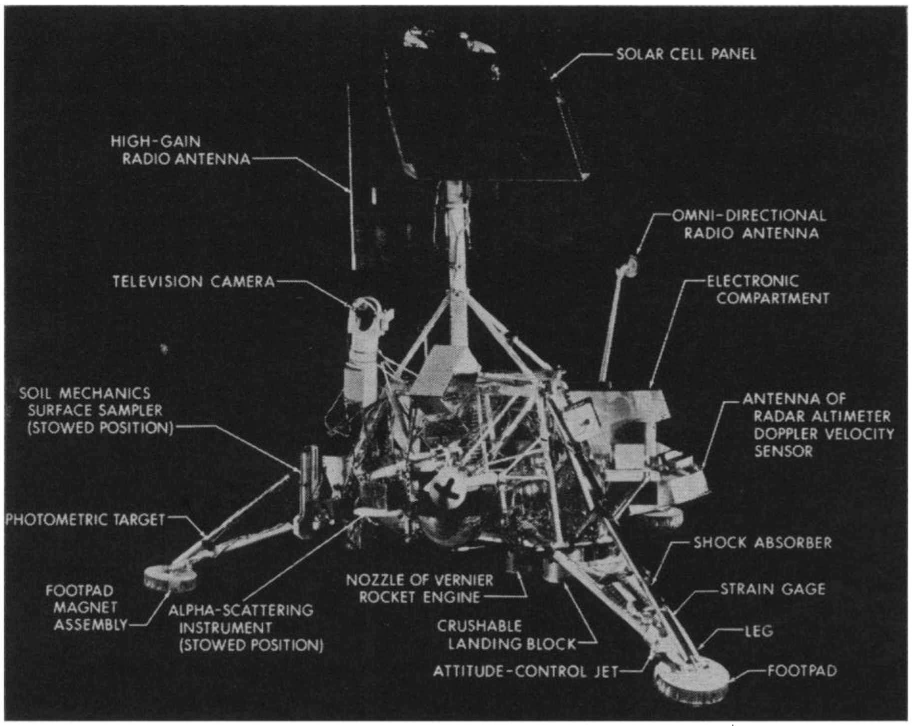


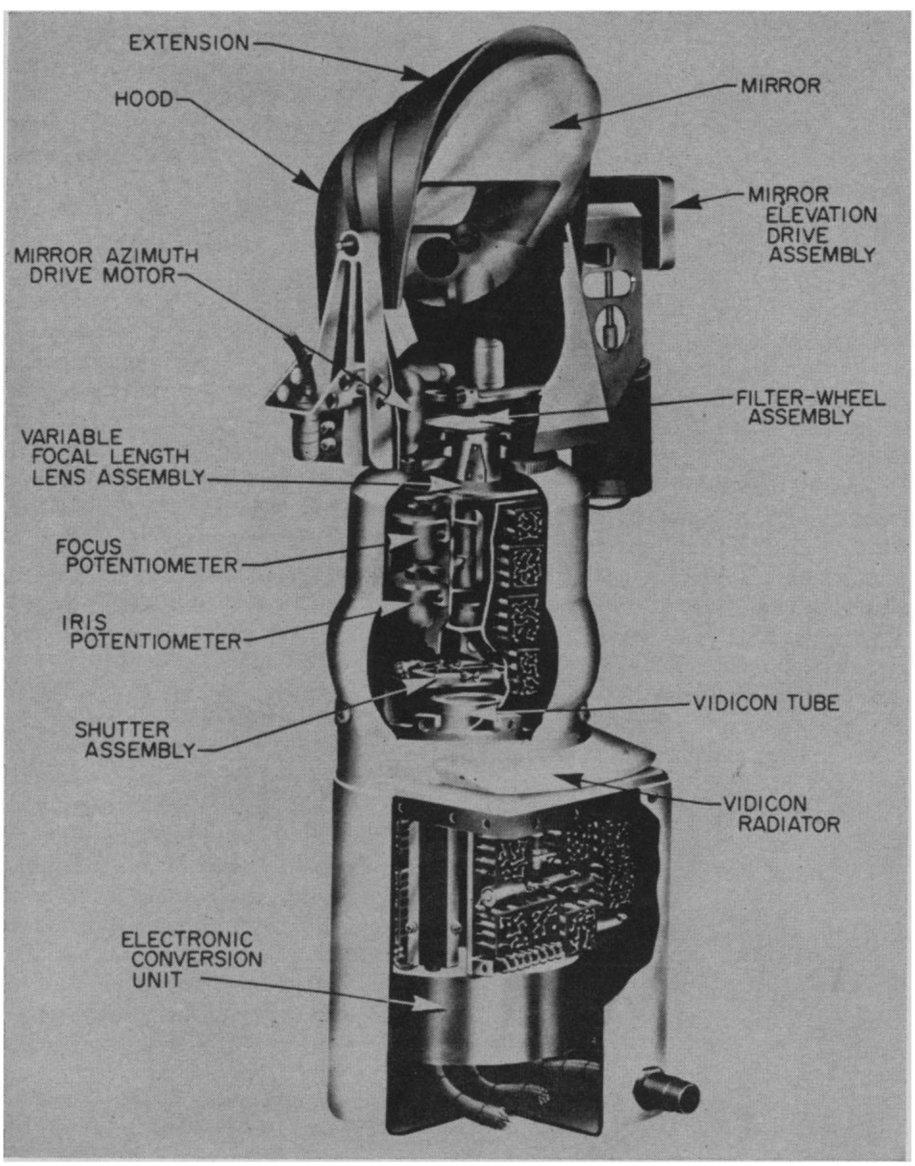


Fig. 2 (top left). Surveyor 7 spacecraft in landed configuration (model).

Fig. 3 (bottom left). Surveyor 1 television camera.

control of a computer on board, for the final phases of the descent.

The primary instruments carried by Surveyors were the television camera, the soil mechanics surface sampler, and the alpha-particle back-scattering instrument.

In the television camera, the vidicon tube, lenses, shutter, filter, and iris were mounted along an optical axis inclined approximately 16 degrees to the central axis of the spacecraft; they were topped by a mirror that could be turned in azimuth and elevation to provide a view in the desired direction (Fig. 3). The azimuth, elevation, focal length, focus, exposure, iris, and filter were adjusted as needed by commands from earth. Focal length adjustment provided either a narrow-angle (6.4-degree) or a wide-angle (25-degree) field of view. Color filters were carried on some spacecraft, polarizing filters on others. The vidicon could be scanned to provide either a 200- or 600-line picture. The 200-line pictures could be transmitted over either the omnidirectional antenna or the planar array antenna; the planar array antenna was used for all 600-line pictures. The observed resolution for 600-line pictures was 0.5 to 1 millimeter at 1.6 meters from the camera.

The soil surface sampler consisted primarily of a scoop, approximately 12 by 5 centimeters, with a motor-operated door. The scoop was mounted on a pantograph arm that could be extended about 1.5 meters or retracted close to the spacecraft by a motor drive (Fig. 4). The arm could also be moved in azimuth or elevation by motor drives, or dropped onto the lunar surface under force provided by gravity and a spring. The surface sampler could manipulate the lunar surface material in a number of ways, and the results could be observed by the television camera.

The alpha-scattering instrument was designed to analyze the lunar surface chemically by irradiating it with alpha particles from curium-242 sources and measuring the spectrum of alpha particles scattered back. It also provided spectral data on protons produced by (α, p) reactions with the atoms of the lunar surface. These spectra could be interpreted in terms of the kind and quantity of elements present in the surface. Physically, the instrument consisted of a sensor head (Fig. 5), a cube about 15 centimeters on a side, which could be lowered to the lunar surface by a nylon cord, and an alpha-scattering electronics compartment located on the spaceframe (*3*).

Some of the Surveyors carried magnets and nonmagnetic control bars on footpads and the surface sampler scoop to indicate the presence of lunar surface material with high magnetic susceptibility. These magnets could be observed with the television camera. A variety of auxiliary mirrors was also carried, to improve visibility of areas below the spacecraft, provide stereoscopic viewing, and indicate adhesion of dust. In addition, there were over 100 engineering sensors, such as resistance thermometers, voltage sensors, strain gages, accelerometers, and position indicators for movable spacecraft parts; some of these could provide information of scientific interest.

Spacecraft Operations

Surveyor spacecraft were launched from Cape Kennedy, Florida, by Atlas–Centaur launch vehicles. After injection on a trajectory intersecting the moon, the spacecraft were separated from the launch vehicles. Midcourse maneuvers, utilizing the vernier engines, brought the spacecraft to the desired landing areas. For the terminal descent, the main retro engine provided most of the braking. After the main engine burned out, nominally at about 10 kilometers altitude, it was jettisoned and the vernier engines continued to slow the spacecraft. To reduce disturbance of the lunar surface by engine exhaust, the vernier engines were turned off (except for Surveyor 3) when the spacecraft altitude was about 4 meters and approach velocity was about 1.5 meters per second. The spacecraft then fell freely to the surface. The velocity components at touchdown were in the range of 3 to 4 meters per second vertically and less than 0.5 meter per second horizontally. The spacecraft masses at injection were 995 to 1040 kilograms, and at touchdown, 294 to 306 kilograms.

The vernier engines on Surveyor 3 did not shut down before initial touchdown, but continued to burn, lifting the spacecraft from the surface. It landed again about 20 meters from the initial position, with engines still on, and lifted off a second time. The engines were then turned off, and the spacecraft touched down again 11 meters from the position of the second touchdown. The vertical velocity component for the three touchdowns was 1 to 2 meters per second, and the horizontal component was 0.3 to 0.9 meter per second.

Operations of the Surveyors continued and some data were received for periods of 2 weeks to 8 months after landing. Operations were not always continuous; for example, the spacecraft were shut down a few hours or days after each local sunset, when temperatures were low, and sometimes near local noon, when temperatures were high. Various operations of the spacecraft have provided scientific information (Table 1).

Landing Sites

Four Surveyor spacecraft landed in the lunar maria, near the equator (Fig. 1). Surveyor 7, the last in the series, landed in the highland region close to the crater Tycho, a site chosen primarily for its scientific interest; it was thought to be a sample of very young highland material which could have originated at considerable depth.

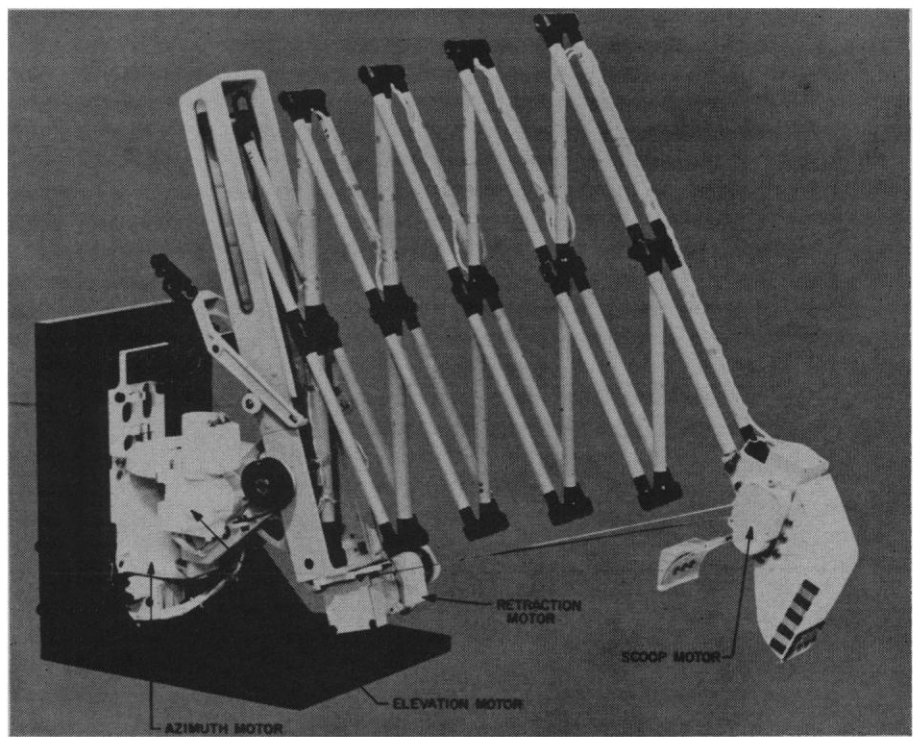


Fig. 4. Surveyor soil mechanics surface sampler.

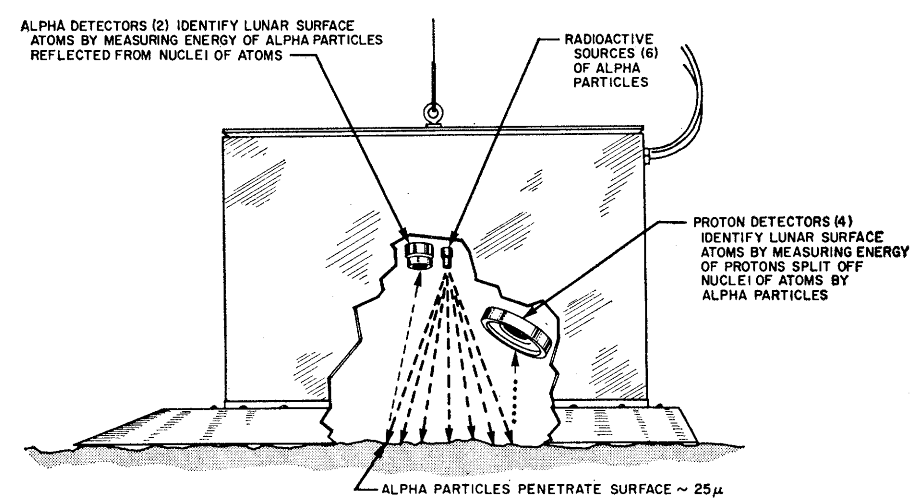
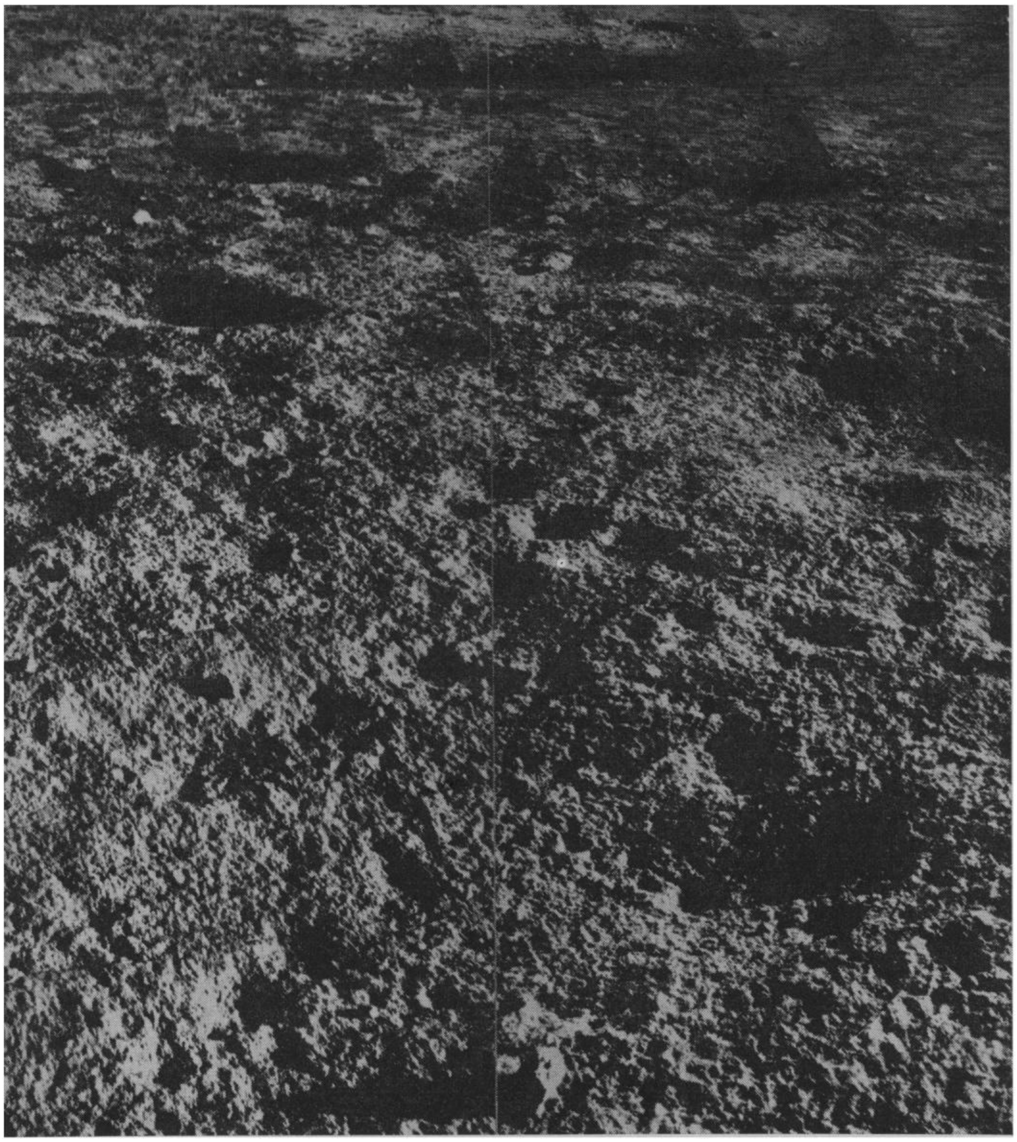


Fig. 5. Surveyor alpha-scattering instrument. View of sensor-head internal configuration. [After Turkevich, Franzgrote, and Patterson (*38*)]



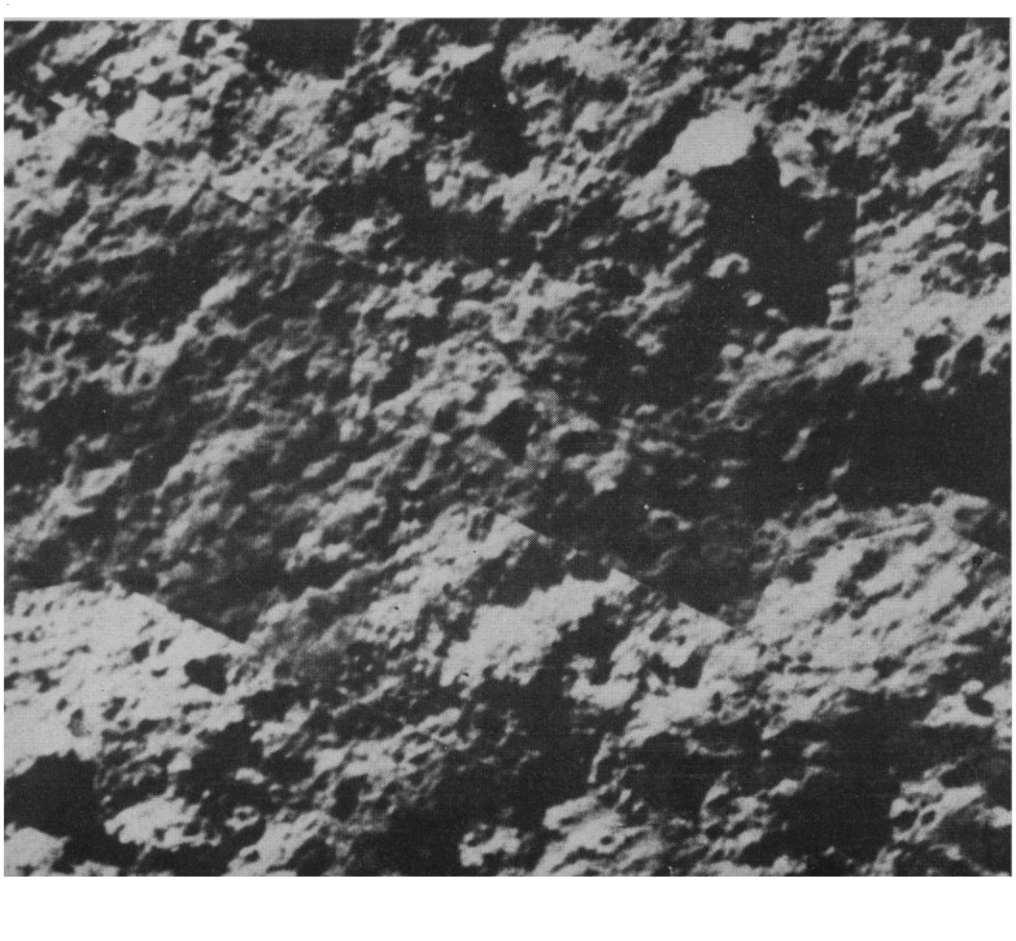


Fig. 6 (top left). General view of mare surface near Surveyor 1. (Mosaic of narrow-angle pictures taken 13 June 1966. Portion of Catalog Nos. 1SE1C and 1SE1D.) Fig. 7 (bottom left). Lunar highland surface close to Surveyor 7. (Mosaic of narrow-angle pictures taken 21 January 1968. Portion of Catalog No. 7-SE-16.)

Surveyors landed on varieties of terrain. Two sets of coordinates are given for each landing site. The first set is based on radio doppler tracking from the earth of the landed spacecraft. This method locates the site in inertial coordinates relative to the center of gravity of the moon. The second set is a listing of selenographic coordinates, in the system used in the *Orthographic Atlas* and in *Lunar Charts* of the Aeronautical Chart and Information Center (*4*). Selenographic coordinates were obtained by matching features shown in Surveyor pictures with corresponding features in Lunar Orbiter photographs (*5–8*). The Lunar Orbiter photographs were, in turn, related to *Orthographic Atlas* coordinates by matching large features, visible from the earth. Differences between the inertial and the selenographic coordinates arise in part from uncertainties in the selenographic grid and from differences between the center of figure and the center of gravity of the moon. Surveyor 1 was photographed on the lunar surface by Lunar Orbiters 1 and 3. The Lunar Orbiter photographs of the other Surveyor landing sites were made before the Surveyors landed.

The Lunar Surface

The pictures and other data from the Surveyors show that the lunar surface consists primarily of a matrix of fine, somewhat cohesive, particles less than 1 millimeter in diameter, with larger agglomerates and rocks scattered in and on the matrix. Small-scale surface features of maria and highlands are similar (Figs. 6 and 7). Craters in sizes down to a few centimeters in diameter are common; the great majority of the smaller craters appear to be due to impact of primary or secondary meteoroids (Figs. 8 and 9). Crater size-frequency distributions have been measured.

The depth of the weakly cohesive granular material varies from 1 to 20 meters in the mare areas observed, as indicated by the presence or absence of blocky throwout around secondary craters of various depths (*5, 6, 9*). In the highland area immediately adjacent to Surveyor 7, the surface sampler showed that the depth of the weak granular material varied from 1 to 20 centimeters or more, but did not exceed 1 meter; on other areas of highland terrain viewed by Surveyor 7 the character of crater throwout suggests depths ranging from 2 to over 20 meters (*7, 10*). Below these depths, the lunar material is stronger, more cohesive, and probably denser. It may, however, be particulate or porous to considerably greater depths; the ejecta or flows from Tycho and the upper portion of the maria filling may be fragmental or vesiculated.

Similarity of lunar surface material at all sites examined includes small-scale topographic features, structure of the surface layer, mechanical properties, optical, thermal, and radar properties, chemical composition, and the content of magnetic particles. As might be expected, the four maria sites more closely resemble each other than they resemble the highland site on the rim of Tycho, but, even for the Tycho site, the resemblances to the maria are far more evident than the differences.

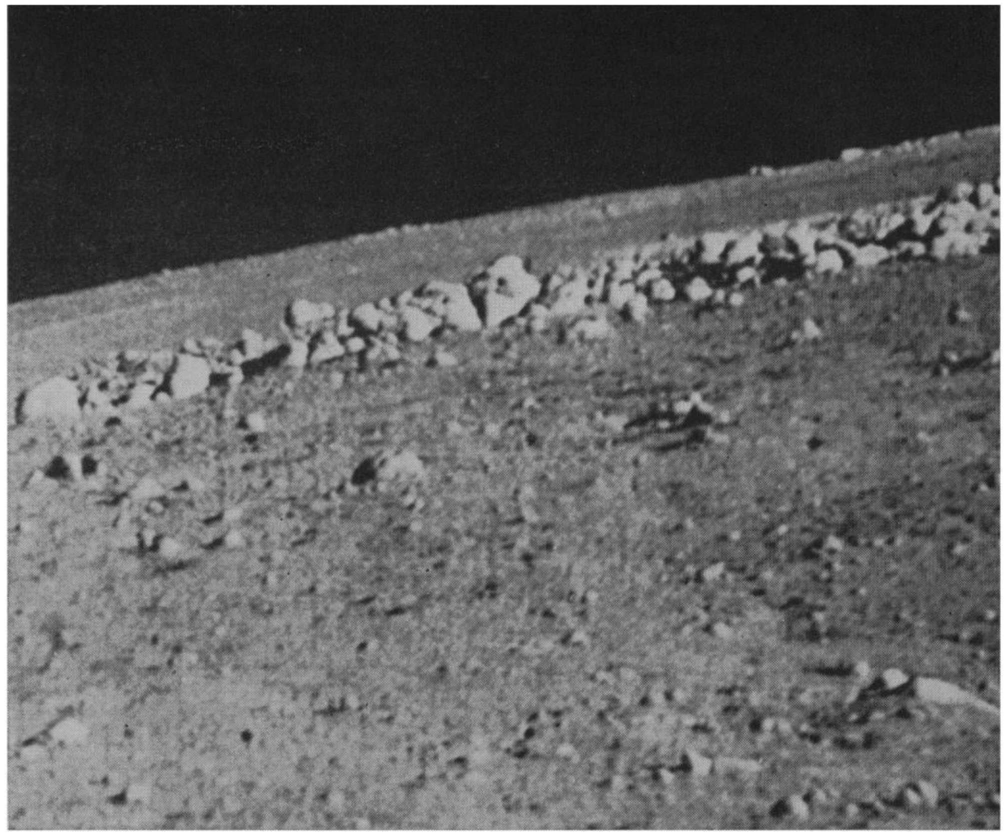
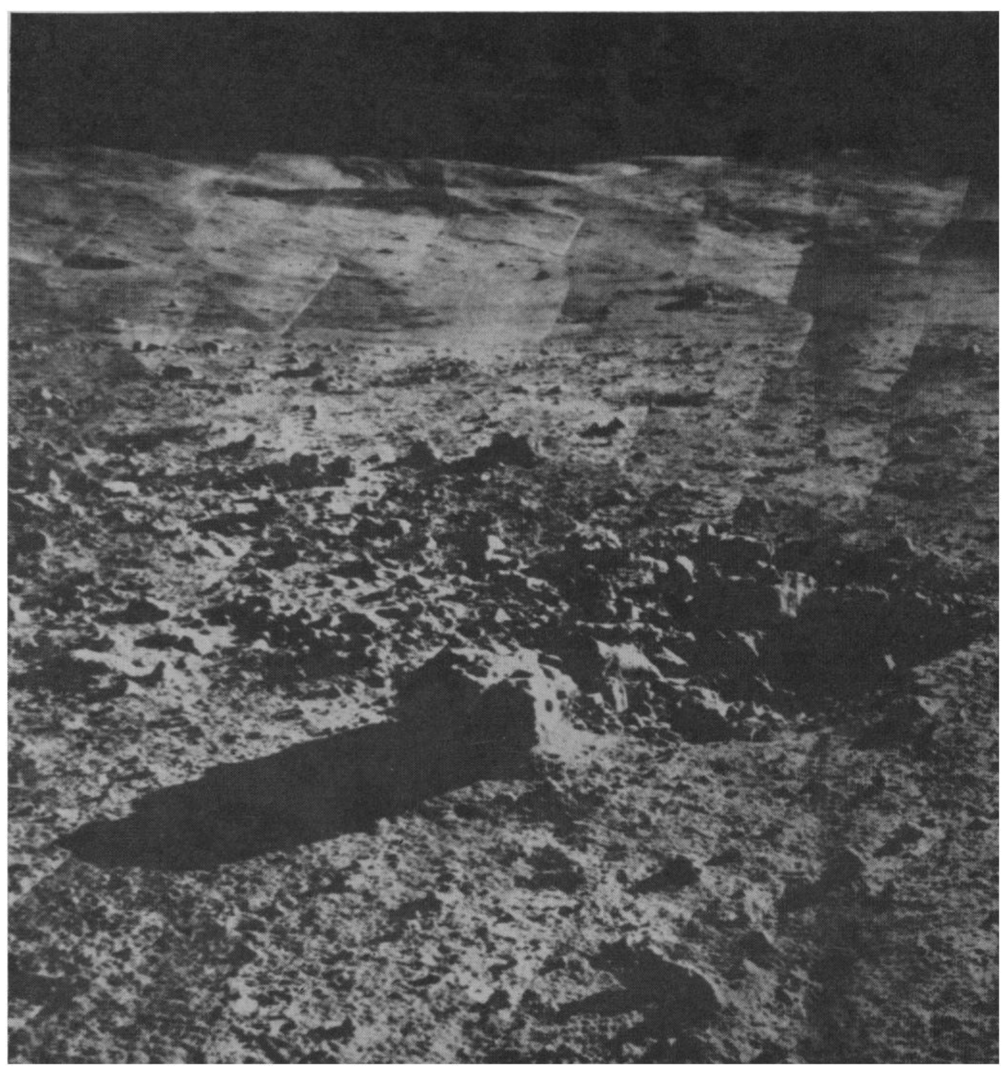


Fig. 8 (above). Rocks along rim of crater 170 meters in diameter. (Surveyor 1 narrow-angle picture taken 13 June 1966, 19:47:18 U.T. Digital computer-processed.) Fig. 9 (below). Crater about 3 meters in diameter and associated rock field near Surveyor 7, with highland landscape. Horizon ridge at right center is about 20 kilometers distant. (Mosaic of narrow-angle pictures taken 10 January 1968. Portion of Catalog No. 7-SE-31-M.)



Density and Mechanical Properties of the Fine Matrix

Density of fine matrix material was determined from its response to mechanical loading. At depths of about 5 centimeters the deformation characteristics (Fig. 10) and the variation of bearing capacity with bearing diameter point to a bulk density near 1.5 grams per cubic centimeter, corresponding to 40 to 50 percent porosity (*11*). At depths of a few millimeters, a density near 1 gram per cubic centimeter seems to fit the observations best; this would correspond to about 70 percent porosity (*6, 9, 12–14*). The increase of density with depth apparently continues beyond 5 centimeters.

The static bearing capacity of the lunar surface determined by measuring depth of penetration of a number of components, vertical loads they imposed on the soil, and the corresponding bearing area. These components include: lunar particles, millimeters to a few centimeters in diameter, which were disturbed by the spacecraft (Fig. 11); the spacecraft footpads and crushable landing blocks (Fig. 12); the alpha-scattering sensor head (Fig. 13); and the surface sampler scoop (Fig. 10).

Table 1. Surveyor operations that have provided scientific information.

Device	Operations	Scientific information obtained*
Television camera	Taking 87,674 pictures from lunar surface (five sites), including lunar surface, 1.5 to 30 meters from camera; undisturbed and disturbed by spacecraft; at sun angles of 0 to 90 degrees and in earthlight. Earth, at various phases and time intervals. Earth eclipsing sun. Lasers on earth, at 1-watt transmitted power. Solar corona, inner and outer, to 50 solar radii. Planets Mercury, Venus, and Jupiter. Stars, to sixth magnitude. Spacecraft, showing effects of lunar material upon it.	Lunar topography, surface structure and geology; lunar photometry, polarization, and color; cohesion of lunar surface material; terrestrial photometry, polarization, and color; terrestrial atmospheric transmission, color, and cloud patterns; solar corona extent, photometry, and polarization; ability to point lasers from earth to lunar locations.
Alpha-scattering instrument	Obtaining alpha and proton spectra from six samples of lunar surface irradiated with alpha particles (three sites). Obtaining background rates.	Chemical composition of lunar surface and near surface; radiation level on lunar surface.
Soil mechanics surface sampler	Static bearing, impact, and trenching tests on lunar surface (two sites). Manipulation of rocks and fine material. Rock weighing. Mechanical manipulation of alpha-scattering instrument to overcome a malfunction, and moving alpha-scattering instrument to additional lunar samples.	Bearing and shear strengths of lunar surface and near-surface material; cohesion, internal friction, and density of lunar surface material; surface rock strength and density.
Spacecraft leg strain gages, landing radar system, flight control gyros and accelerometers	Measurements of radar return from lunar surface during descent. Measurements of spacecraft leg loads during landing. Measurements of spacecraft motion during these operations (five sites).	Bearing strength, cohesion, internal friction of lunar surface material; radar reflectivity and dielectric constant of lunar surface material; density and elastic velocity of lunar surface material.
Spacecraft resistance thermometers, solar panels, sun sensors, and directional antenna	Temperature measurements on spacecraft components, radiatively coupled to the lunar surface during day and night (five sites) and eclipse (two sites). Measurements of sun direction. Controlled shading.	Lunar surface temperatures, thermal inertia, and directional infrared emission.
Magnets	Placing magnets in contact with fine and coarse lunar surface particles (three sites). Blowing on them.	Content of magnetic particles in lunar surface material.
Spacecraft vernier propulsion system and attitude control jet system	Firing against lunar surface (four sites). Launching Surveyor 6 from the lunar surface 8 days after initial landing, and landing again 2.4 meters from original position (maximum altitude 3.5 meters).	Lunar surface permeability to gases, cohesion, adhesion, response to gas erosion.
Spacecraft radio transponder	Doppler frequency measurements from earth (five lunar sites).	Position of landing sites; shape and motion of moon; microwave transmission by terrestrial atmosphere.

* Much scientific information was provided through the combined operations of several devices, but is listed under only one.

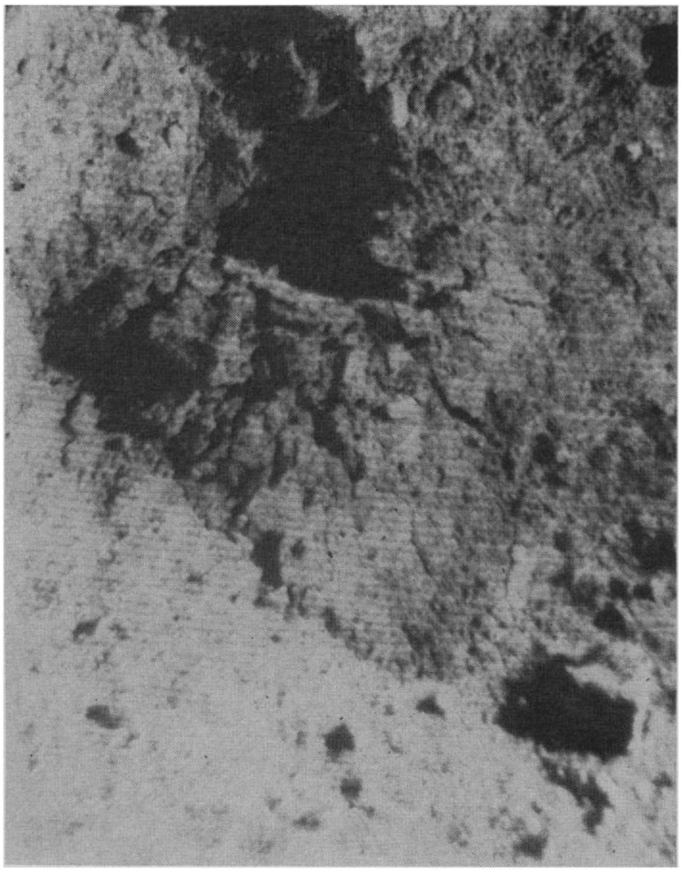
The static bearing capacity is about 0.1 newton per square centimeter at 1 millimeter and 5 newtons per square centimeter at 5 centimeters deep; the increase with depth over this range is near linear at the rate of 1 newton per cubic centimeter (Fig. 14). Static-bearing load was measured as a function of penetration near Tycho for the surface sampler bearing width of 2.5 centimeters; the first centimeter was penetrated at rather low loads; beyond this the rate of increase of bearing pressure with depth was 0.7 to 1.0 newton per cubic centimeter, to a depth of 3 centimeters (*10*). The strength increased with depth to the 18 centimeters reached by the Surveyor 3 surface sampler (*11*).

The cohesion of the matrix material was determined by observations of the effects of firing vernier engines and attitude-control jets against it and of disturbing it with the surface sampler, as well as by the bearing capacity measurements (*10–12, 15*). Cohesion is approximately 0.05 newton per square centimeter at a depth of a few centimeters; the top millimeter has slightly lower cohesion. Increase in cohesion with depth may continue downward. Fine material tends to cohere into clods (weak aggregates); clods were more common in material pushed out by the spacecraft than on the undisturbed surface. In the maria (Surveyor 3 site), clods did not recohere to the original extent when once broken apart (*10*). Clods flattened by compression held together (*16*). Trenches excavated 15 to 18 centimeters deep retained vertical walls (Fig. 15).

Surface bulging, extending about 10 centimeters from surface sampler imprints, pointed to an internal friction angle of 35 to 40 degrees, at a depth of about 5 centimeters (Fig. 10) (*10, 11*).

The oscillation frequency of the spacecraft, elastically coupled to the surface during the few seconds following touchdown, gave preliminary values for the soil shear wave velocity of 15 to 30 meters per second and for the soil compressional wave velocity of 30 to 90 meters per second at a depth of about 10 centimeters (*12, 17*).

In general, the lunar surface material did not adhere to spacecraft surfaces (metal, paint, glass) on contact; thus, its adhesion was less than its cohesion (0.03 newton per square centimeter for the top millimeter). Lunar surface material did, on occasion, adhere when thrown against painted or metal sur-



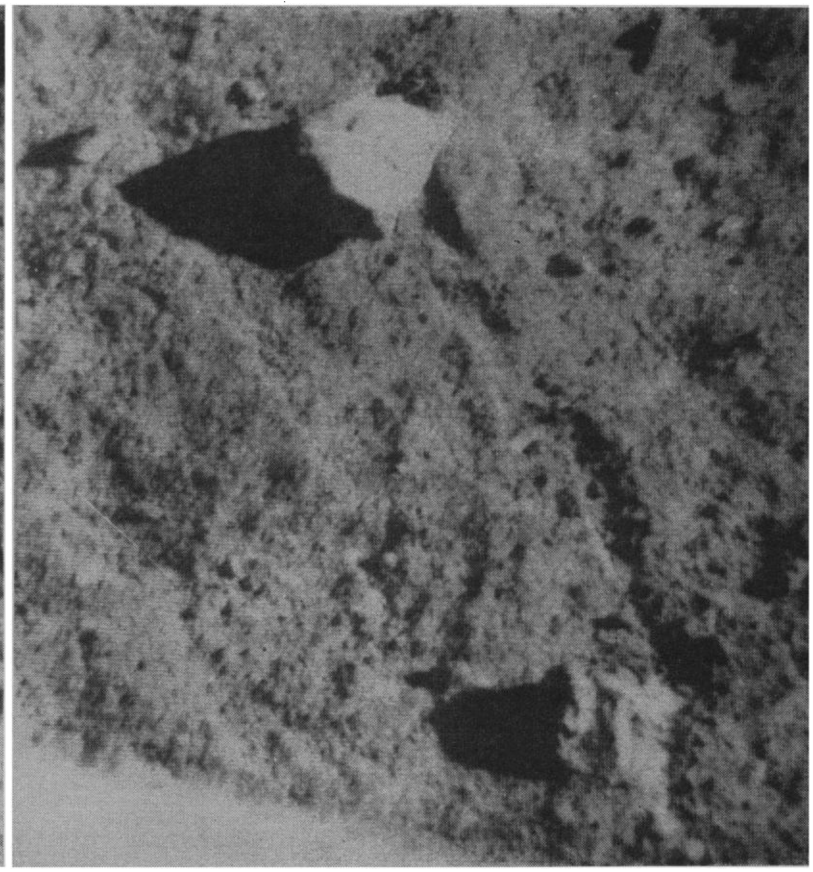
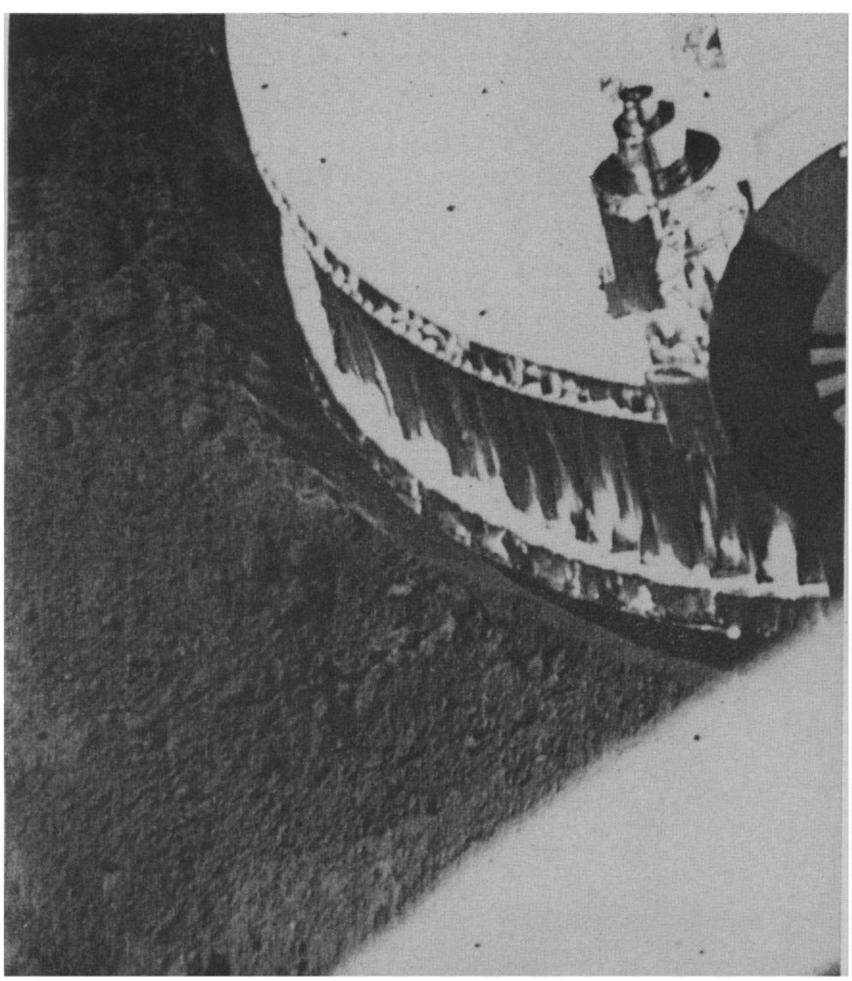
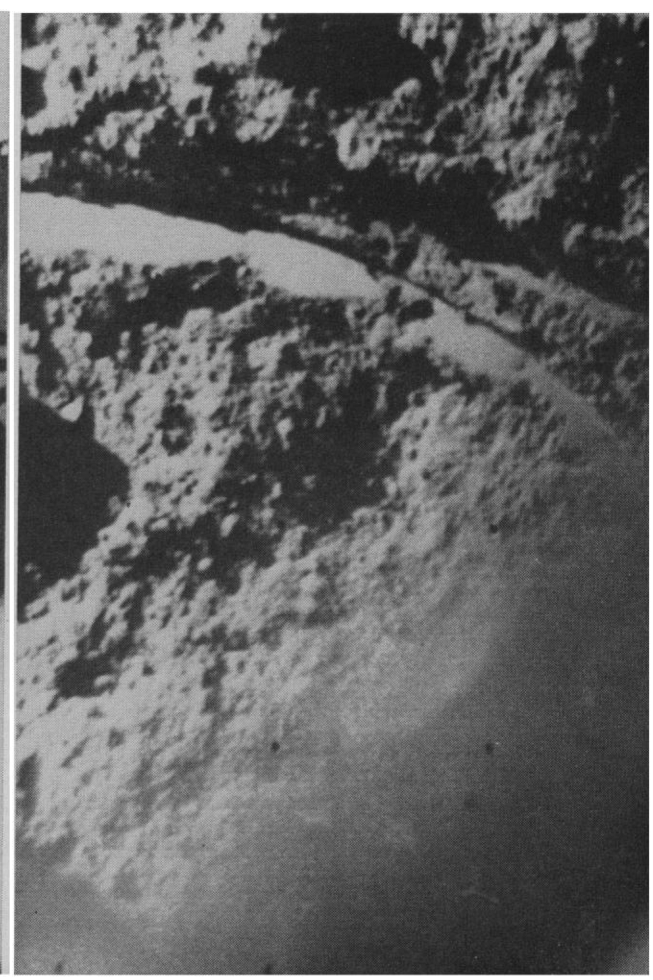
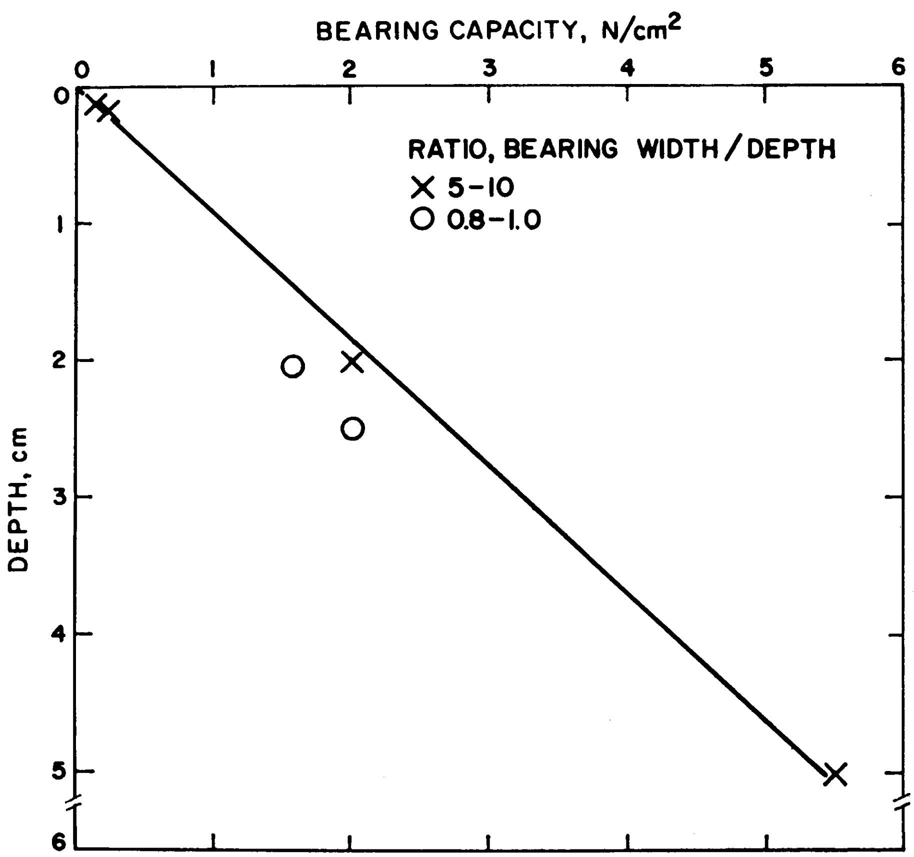


Fig. 10 (above left). Imprint on lunar surface made by soil mechanics surface sampler bearing test. (Surveyor 7 narrow-angle picture taken 12 January 1968, 00:30:0 U.T. Fig. 11 (above right). Track on lunar surface made by small particle of surface material dislodged by spacecraft landing. (Surveyor 5 narrow-angle picture taken 12 September 1967, 06:07:26 U.T.) Fig. 12 (below left). Imprint of spacecraft footpad on lunar surface. (Surveyor 1 narrow-angle picture taken 4 June 1968, 06:55:26 U.T. Digital computer-processed.) Fig. 13 (below right). Imprint on lunar surface of alpha-scattering instrument sensor head. (Surveyor 7 narrow-angle picture taken 12 January 1968, 1:53:37 U.T.)







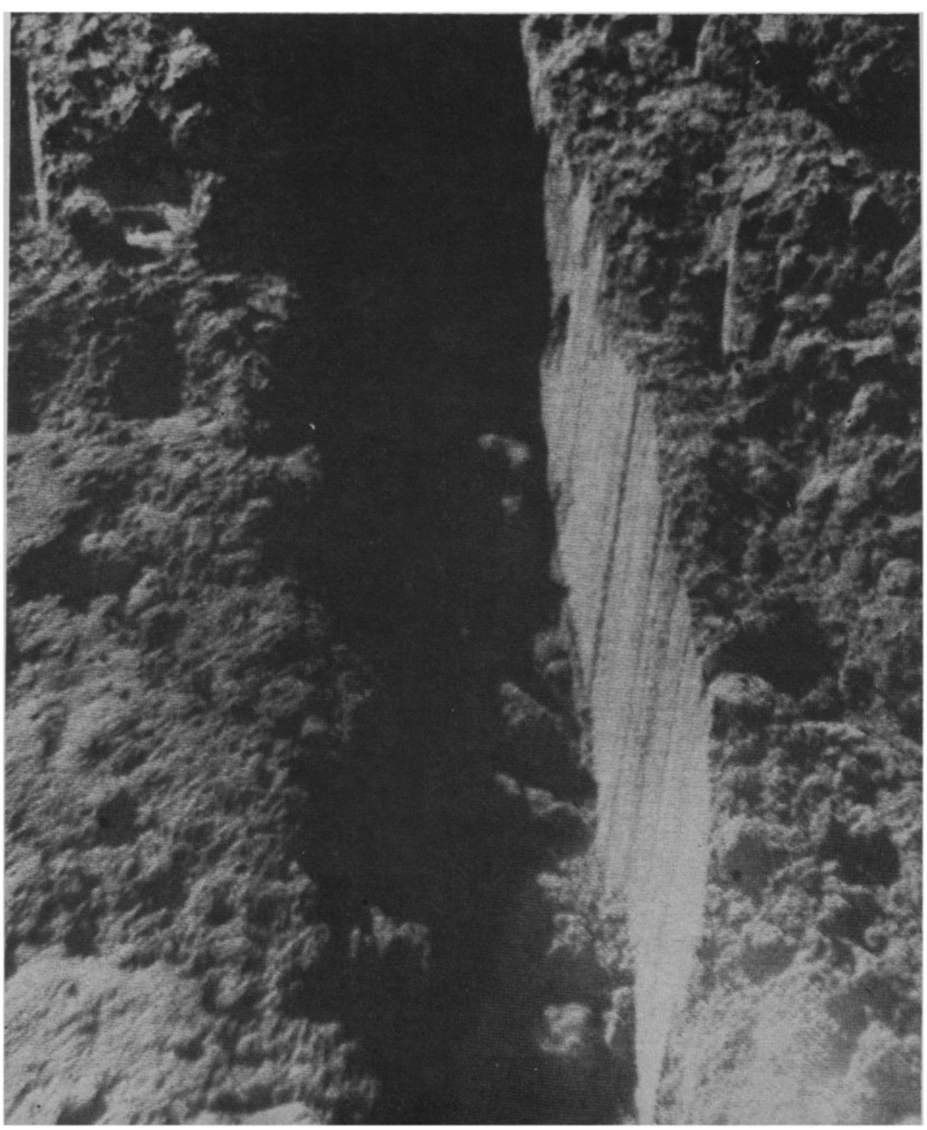


Fig. 14 (top left). Static bearing capacity of lunar soil as a function of depth (*10, 11, 16, 20*). Fig. 15 (bottom left). Short section of trench dug in lunar surface by surface sampler. Depth about 15 centimeters, width 5 centimeters. (Surveyor 7 narrow-angle picture taken 20 January 1968, 09:51:50 U.T.)

faces or when strongly pressed or repeatedly rubbed against them (*5, 10–12, 15, 16, 18, 19*). Some material (Fig. 16) stayed in place despite shear loads greater than 0.005 newton per square centimeter. Adhesion between lunar surface material and silicone-base paint, under Surveyor conditions, is, then, about 10^{-2} newton per square centimeter.

To a depth of a few centimeters lunar soil mechanical characteristics correspond roughly to those of terrestrial garden soils.

Optical Behavior of Fine Matrix

Optical properties of fine surface material are generally similar to those of the lunar disk as seen from the earth. The normal luminance factor (normal albedo) of undisturbed matrix in maria is about 8 percent; at the Surveyor 7 highland site about 13 percent. Subsurface matrix material, even within a millimeter of the surface, is noticeably darker; so was material thrown out or pushed up by the footpads and surface sampler. Such material has about 6 percent normal luminance factor in the maria and about 10 percent at the highland site (Fig. 17). The transition from the brighter surface material to the darker subsurface material occurs within 1 millimeter of the surface; thus, there is a relatively bright (higher albedo) surface layer not over one millimeter thick. Portions of the surface matrix that were compressed by spacecraft footpads or other components changed in photometric function; they are brighter than undisturbed material at phase angles away from 0 degree, and they are more like a Lambertian reflector; this points to a breakdown of the surface granular structure in compression, resulting in a less porous material (*5–7, 11, 12, 15, 17, 18, 20, 21*).

The polarization of sunlight reflected from the surface matrix varies with phase angle in the same general manner as for the lunar disk seen from the earth. The color of the matrix appears to be uniformly gray (*5–7, 21*).

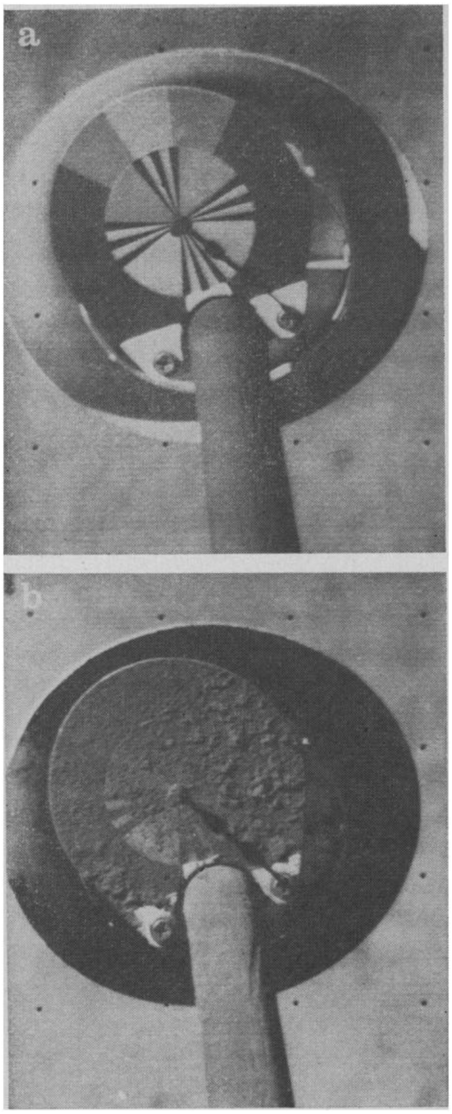


Fig. 16. Lunar material adhering to spacecraft. Photometric target on Surveyor 6 omnidirectional antenna boom (a) before, and (b) after hop. Clod of lunar material was thrown against target by vernier engine exhaust and adhered through landing acceleration of at least 45 m/sec^2. Thickness of adhering material is at least 0.9 millimeter. (Narrow-angle pictures taken 17 November 1967, 09:37:05 and 12:30:00 U.T.)

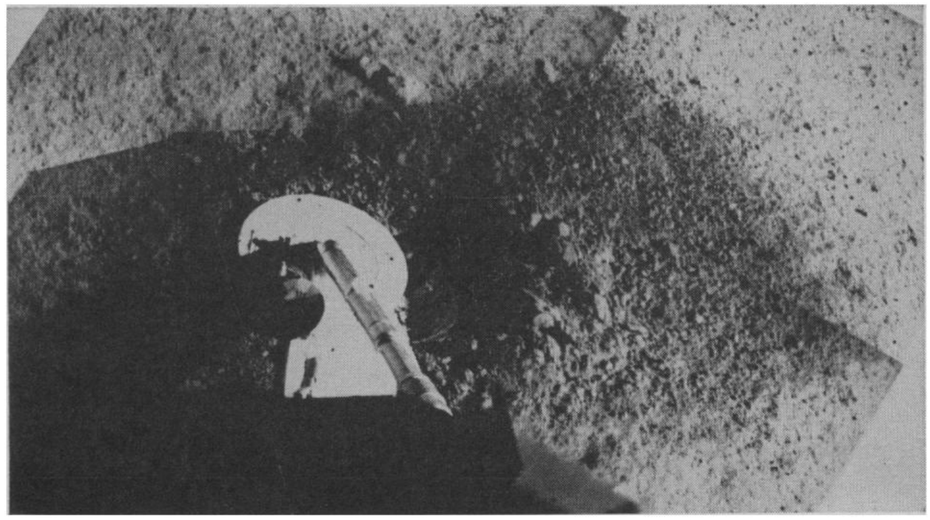


Fig. 17. Dark throwout of lunar soil around spacecraft footpad. (Surveyor 6 wide-angle mosaic, Catalog No. 6-SE-20, taken 22 November 1967.)

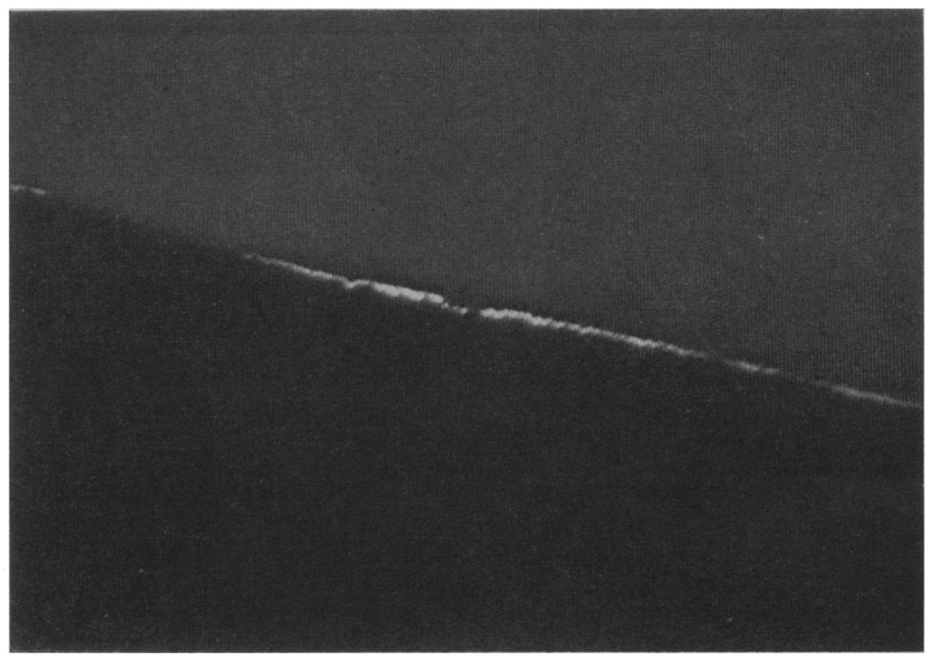


Fig. 18. Brightness along western horizon 90 minutes after upper limb of the sun had set. Exposure 1.2 seconds at $f/10$. (Portion of Surveyor 7 narrow-angle picture, width 6.4 degrees, taken 23 January 1968, 07:32:49 U.T.)

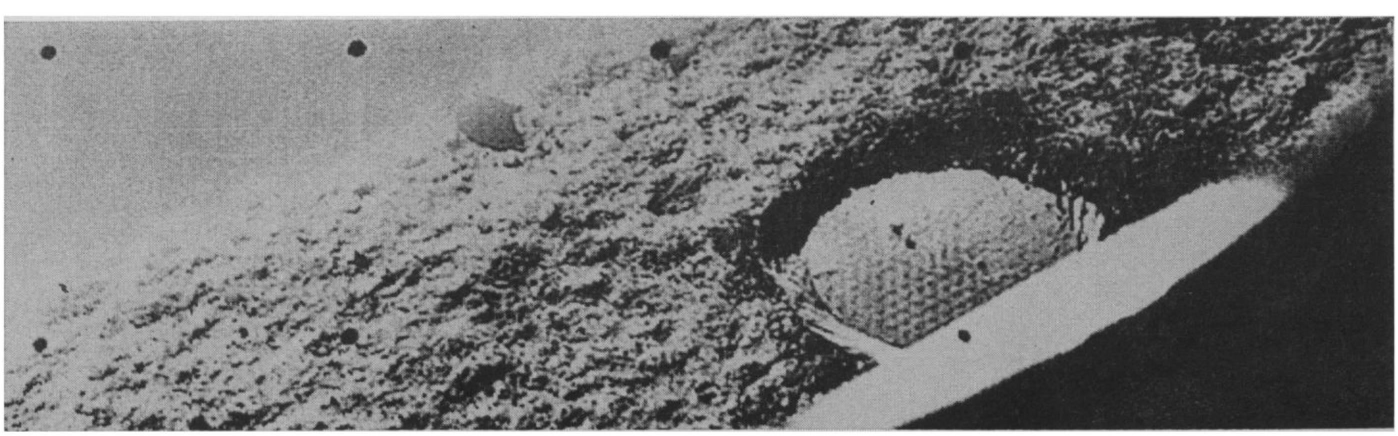


Fig. 19. Imprint on lunar surface of spacecraft footpad. Note replica of waffle pattern on bottom of footpad which had ridges about 60 microns high. (Portion of Surveyor 3 narrow-angle picture taken 21 April 1967, 08:24:20 U.T. Digital computer-processed.)

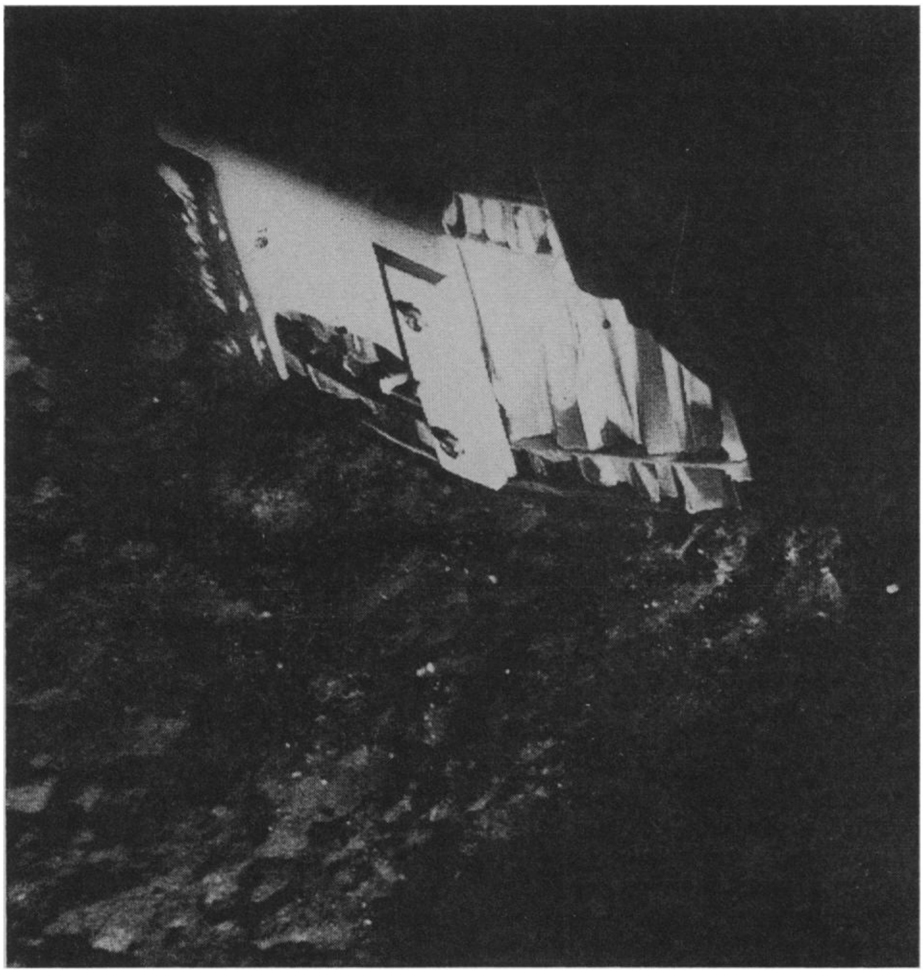


Fig. 20. Fine, dark, lunar particles adhering to magnet on Surveyor footpad (left bar). Nonmagnetic control bar (at right) is essentially free of lunar particles. (Surveyor 5 narrow-angle picture taken 23 September 1967, 09:54:20 U.T. Digital computer-processed.)

Fig. 21. Lunar surface close to Surveyor 1, with rock about 0.5 meter long. Narrow-angle picture taken 12 July 1966, 10:41:48 U.T. Digital computer-processed.)

After local sunset, when the center of the sun was about 1 degree below the horizon, a bright band was visible very close to the horizon near the sunset azimuth, extending up to 5 degrees horizontally (Fig. 18). The light from this band is apparently not polarized. The effect is presumably due to diffraction, refraction, or scattering by the surface material (*6, 7, 22–24*).

Size and Movement of Fine Particles

The permeability of the lunar soil to flow of gases is in the range 1×10^{-8} to 7×10^{-8} square centimeter, at depths less than 25 centimeters. This was determined by comparison of the size of the crater produced by firing Surveyor vernier engines against the lunar surface with the calculated size of crater that would be produced by firing against soils of various permeabilities under conditions such that the crater is formed primarily by eruption of diffused gas at engine shutdown (*15*).

The fine matrix material took excellent imprints of ridges only 50 to 70 micrometers high on the bottom of a footpad (Fig. 19) (*17*). This implies that much of the material is finer than 60 microns. The permeability to gas flow, mentioned above, corresponds, for earth soils, to grain sizes of 6 to 16 microns (*15*). Other evidence on particle size of the unresolved matrix is provided by sharp edges of spacecraft shadows cast on the lunar surface, photometric properties before and after compression, the cohesion, and angular spread of the horizon brightness after sunset (*13, 18*). These observations indicate that the particle size of the bulk of the material is in the range of 2 to 60 micrometers, with the midpoint of the mass distribution probably near 10 micrometers.

The fine material in general contacts the larger rocks along an almost horizontal plane, with a small fillet at the line of contact. For rocks on a slope, however, there is a noticeably larger fillet of the fine material piled against the uphill side of the rocks. This suggests gradual movement of fine material downhill; the motion may be induced partly by thermal or seismic disturbances, but is probably in large measure due to ejection of fine secondary or tertiary particles by meteoritic impacts, with the particles tending to accumulate preferentially downhill (*7, 18, 24*).

Composition of Surface Matrix

The chemical composition of matrix material was measured with the alpha-scattering instrument at three sites (Table 2). On the lunar surface, as on the earth, the most common elements are oxygen, silicon, and aluminum, in that order. The composition corresponds to that of a basalt, with relatively high iron content at the two mare sites and relatively low iron content at the site near Tycho (*2, 24–26*).

Fine matrix material adhered to the magnets when they were brought in contact with the surface (Fig. 20). Laboratory calibration tests indicated that the amount of lunar material adhering is consistent with a basalt and not with an acidic or ultrabasic rock, and that the content of free iron is less than ¼ percent by volume (*27, 28*).

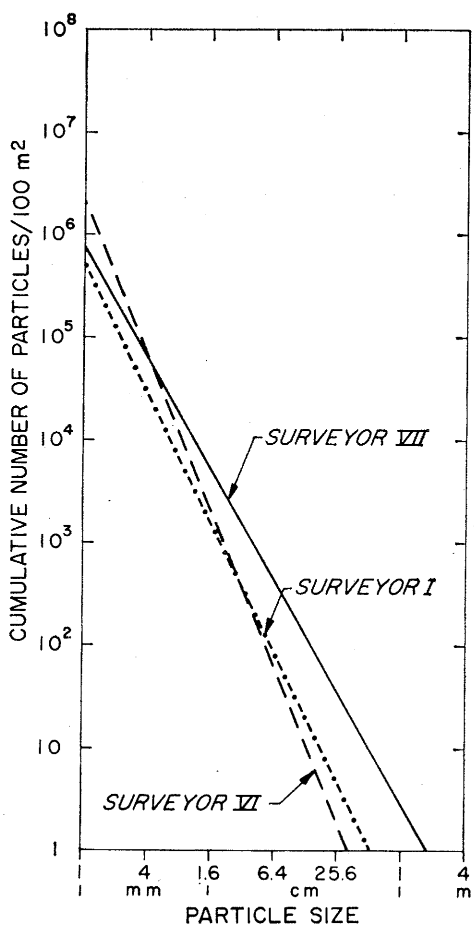
That the lunar surface material is basaltic in composition implies that it has undergone chemical differentiation in a melt, and therefore that the moon has probably undergone large-scale melting. The difference in iron content between mare and highland samples, if generally valid, may provide an explanation of the albedo difference between maria and highland (*2, 23–25, 29*).

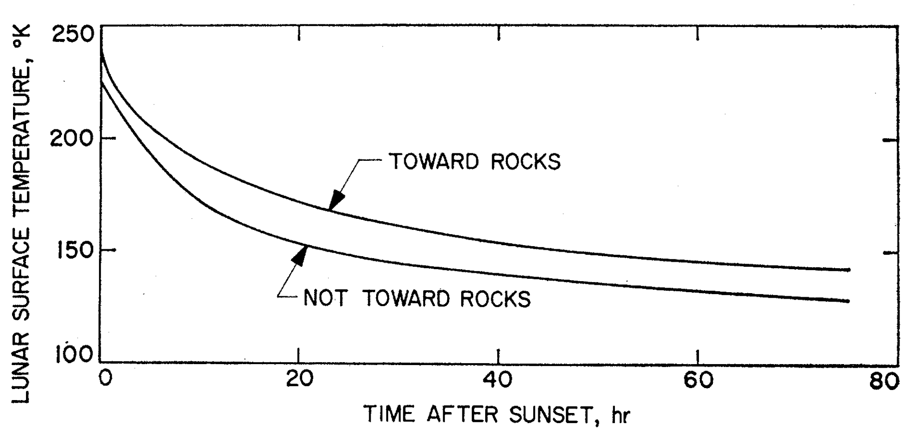
Rock Properties and Distribution

Lunar rocks show a wide variety of shapes and surface characteristics (Fig. 21). Some are roughly spherical, others flat; some surfaces appear fractured, others vesiculated, others pitted or eroded. Many of the rocks appear to be lying on the fine matrix, others seem to extend slightly below the matrix surface, others are almost completely buried. Many of the blocks up to a few centimeters in diameter appear to be clods—weakly cohesive aggregates of fine particles. Other blocks are aggregates of rock chips and finer particles (*5–7, 9, 18, 21, 24*).

The rocks are gray, like the matrix. Most, but not all of them, are brighter than the fine material, with albedo of 14 to 22 percent; a few are quite dark, some are mottled; portions of some seem to be coated with fine particles, especially in crevices. Light reflected from some rocks showed polarization up to 30 percent at phase angles near 120 degrees (*5, 7, 9, 21, 24*).

The density of one rock, a few centimeters across, was determined by weighing it with the Surveyor 7 surface sampler and measuring its volume by stereoscopic television. The result was 2.8 ± 0.4 grams per cubic centimeter, with a probable value of 2.8 to 2.9





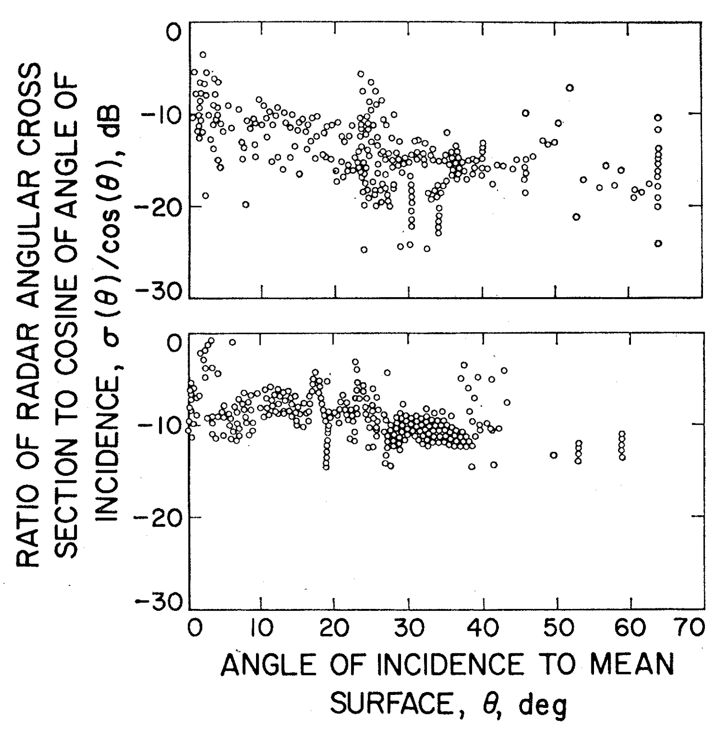


Fig. 22 (above). Cumulative size-frequency distribution of lunar rocks. [After Shoemaker *et al.* (*7*)] Fig. 23 (top right). Lunar surface temperatures after sunset in two areas near Surveyor 7. [After Vitkus *et al.* (*30*)] Fig. 24 (bottom right). Ratio of lunar radar cross section to cosine of angle of incidence. Top: Surveyor 5, in Sinus Medii. Bottom: Surveyor 7, near Tycho. [After Muhleman *et al.* (*32*)]

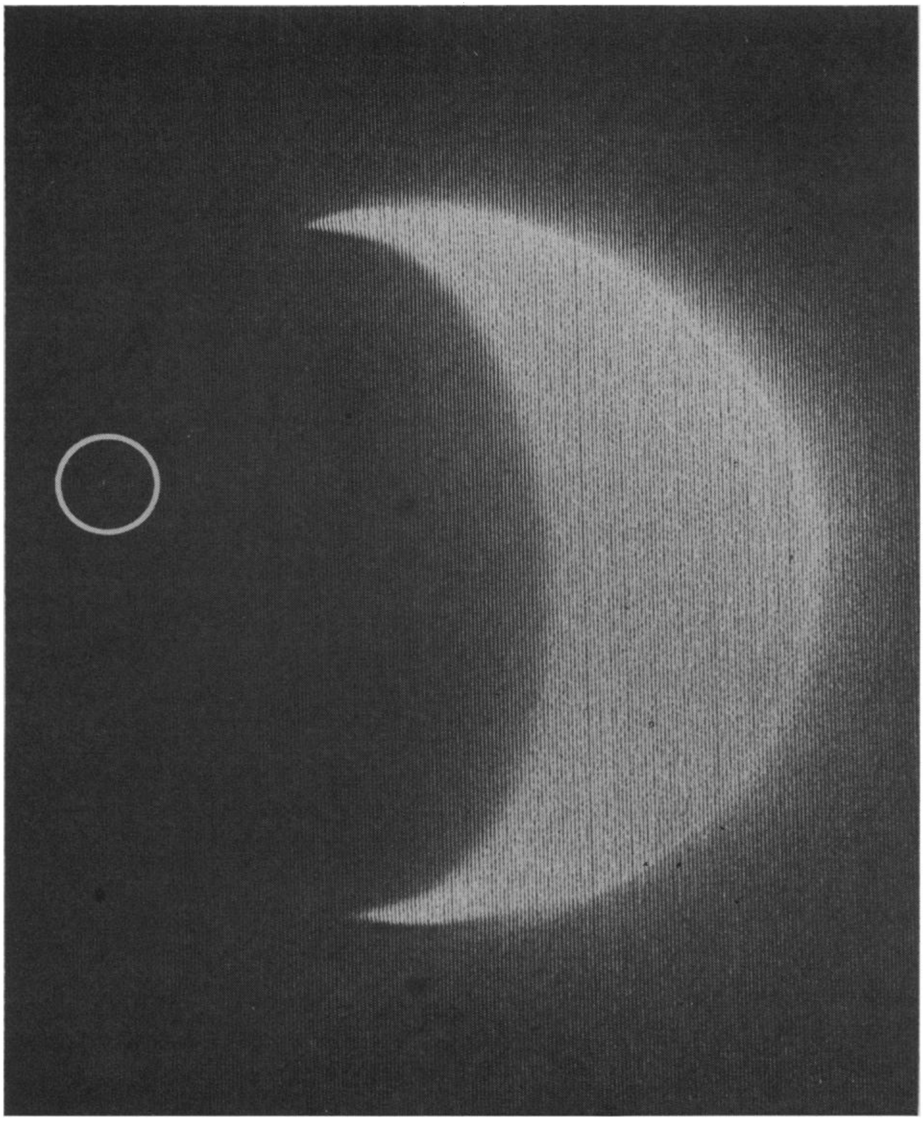


Fig. 25. Lasers on earth, pointed to Surveyor on moon. Two bright spots in circle are lasers at Table Mountain, California, and Kitt Peak, Arizona. Image of crescent earth is spread by deliberate overexposure. (Portion of Surveyor 7 narrow-angle picture taken 20 January 1968, 09:12:58 U.T. Exposure 1.2 seconds at $f/4$.)

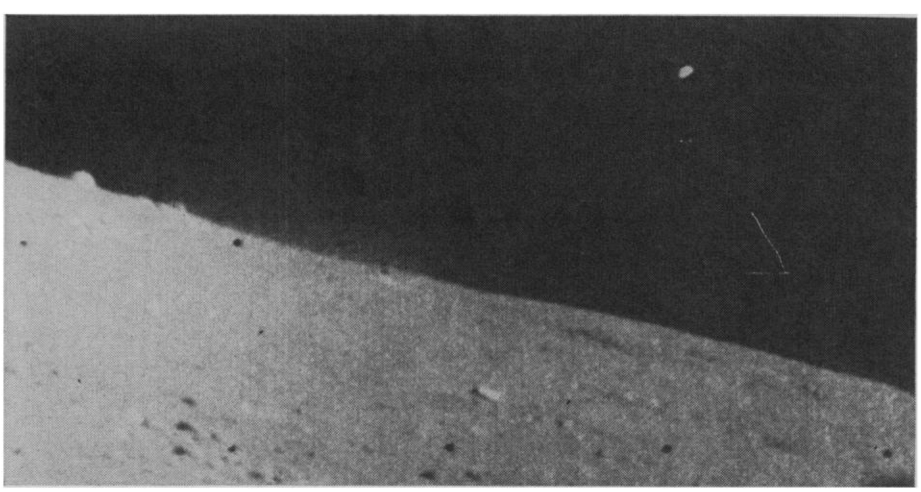


Fig. 26. Outer solar corona showing above lunar horizon about 15 hours after sunset. Lunar surface illuminated by earthshine. Planet Mercury shows as disk, elongated by lunar rotation during exposure. (Surveyor 7 wide-angle picture; 30-minute exposure at $f/4$, ending 23 January 1968, 20:46:55 U.T. Polarized filter.)

grams per cubic centimeter (*10*). Calculations of theoretical solid densities for reasonable rock compositions consistent with the compositions mentioned above gave 3.0 grams per cubic centimeter for the highland site and 3.2 for the maria. Thus, the highland rock may be less dense than the maria and there may be some degree of isostasy (*2, 24*).

One rock was broken by dropping the surface sampler on it, with the sharp edge of the scoop exposed, and one was apparently broken by squeezing it between the scoop door and body. The calculated stress applied along the scoop edge for the latter rock was 200 newtons per square centimeter (*11, 12, 17*).

A somewhat rounded object about a centimeter in diameter was picked up at the Surveyor 7 site by magnets attached to the surface sampler. It was evidently ferromagnetic or ferrimagnetic, and may have been magnetite or meteoritic nickel-iron (*28*).

The frequency of exposed resolvable blocks of various sizes in some areas of the observed lunar surface is given in Fig. 22. It is not clear whether the resolved rocks and the unresolved fine particles of the matrix represent coarser and finer portions of the same population or whether they represent two separate populations.

The rocks are by no means randomly distributed across the surface. There is a strong tendency for the larger rocks, in particular, to be concentrated in fields around rims of some craters, extending out about one crater radius, and to some extent within the craters (Figs. 8 and 9). Presumably these craters were produced by primary or secondary meteoritic impact, and were sufficiently deep for the impact to affect the strongly cohesive material underlying the weaker surface layer and throw out the rocks. The rocks are, in turn, apparently gradually worn away by repeated impacts of micrometeorites (*21*).

Large-Scale Lunar Behavior

Data on lunar surface temperature over areas 10 to 20 meters on a side are now being reduced for lunar day, sunset, and eclipse periods. Preliminary indications are that peak daytime temperatures for these areas are not very different from those averaged over the surrounding areas 18 kilometers on a

Table 2. Chemical composition of the lunar surface (*2*); A.W., atomic weight.

<table>
<tr><th rowspan="2">Element</th><th colspan="3">Amount (atom percent)</th></tr>
<tr><th>Surveyor 5*</th><th>Surveyor 6†</th><th>Surveyor 7†</th></tr>
<tr><td>O</td><td>57 ± 5</td><td>57 ± 5</td><td>58 ± 5</td></tr>
<tr><td>Si</td><td>19 ± 3</td><td>22 ± 4</td><td>18 ± 4</td></tr>
<tr><td>Al</td><td>6.5 ± 2</td><td>6.5 ± 2</td><td>9 ± 3</td></tr>
<tr><td>Ca group A.W. 30 to 47</td><td rowspan="2">13 ± 3</td><td>6 ± 2</td><td>6 ± 2</td></tr>
<tr><td>Fe group A.W. 47 to 65</td><td>5 ± 2</td><td>2 ± 1</td></tr>
<tr><td>Mg</td><td>3 ± 3</td><td>3 ± 3</td><td>4 ± 3</td></tr>
<tr><td>Na</td><td>< 2</td><td>< 2</td><td>< 3</td></tr>
<tr><td>C</td><td>< 3</td><td>< 2</td><td>< 2</td></tr>
</table>

* A few millimeters below undisturbed surface. † Undisturbed surface.

side as indicated by earth-based measurements, and that the thermal parameter, $\gamma = (k\rho c)^{-1/2}$ (where k = thermal conductivity, ρ = density, and c = specific heat), may be somewhat lower for the Surveyor measurements. The value of γ at the site on the Tycho rim deposit was about half that for the maria sites, presumably because there are more large rocks at this site. For Surveyor 7, a significantly lower γ was found in the direction of a nearby rock pile than in a direction more typical of the nearby surface (Fig. 23) (*30, 31*).

Reduction of the radar data (Fig. 24) in the conventional way indicates that the mare surface reflectivity, at 2- to 3-centimeter wavelength, is 0.04 ± 0.01 and the dielectric constant 2.2 ± 0.2. Near the Surveyor 7 site, the reflectivity is about 0.08 and dielectric constant about 3.3. The local radar return was noticeably increased by some identified lunar features, particularly craters of the order of 100 meters in diameter (*32, 33*).

The extensive periods of two-way radio doppler tracking of landed Surveyors have permitted verification of an improved lunar ephemeris and provided lunar inertial coordinates for points on the surface which can be compared with selenographic coordinates. This may provide information on the shape of the lunar surface and the relative positions of the center of figure and the center of gravity.

Observations of Earth and Sun

Surveyor pictures, through color filters, of the earth eclipsing the sun have provided quantitative data on the transmission of light through the earth's atmosphere as a function of altitude, angle of refraction, and atmospheric conditions. Clouds at the limb of the earth occulted the refracted sunlight, producing a "bead" pattern.

Pictures of illuminated portions of the earth, through color and polarizing filters, provided the first color pictures of the entire disk of the earth and maps of polarization of sunlight reflected by the earth. Significant polarization was observed, which appeared to arise from specular reflection, principally off the oceans (*7*).

To evaluate techniques for illuminating a selected point on the moon with laser beams from the earth, television pictures were obtained from the moon by Surveyor 7 which show argon-ion lasers transmitting continuous 1-watt beams at about 5000 angstroms from two earth stations (Fig. 25) (*34*).

Radio doppler tracking of landed Surveyors provided accurate information on the position in terrestrial inertial coordinates of points on the earth (the ground tracking stations) and on effects of the earth's atmosphere on transmissions at 2200 megahertz.

A number of pictures of the solar K-corona and F-corona were obtained after local sunset, when the lunar horizon served to occult the solar disk; many of these were taken through polarizing filters (Fig. 26). Radiance was visible over the entire angular range out to 40 or 50 solar radii, filling the previous gap between coronal and zodiacal light observations. Analyses should provide information on the distribution and particle size of the interplanetary dust within the orbit of Mercury (*35*).

Availability of Data

Interested scientists may obtain copies of Surveyor television pictures and other Surveyor data through the National Space Science Data Center, Goddard Space Flight Center, Greenbelt, Maryland. Individual pictures can best be identified by the spacecraft number, day of year, and time (U.T.) at which they were taken. Mosaics can best be identified by catalog number.

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Non-Darwinian Evolution

Most evolutionary change in proteins may be due to neutral mutations and genetic drift.

Jack Lester King and Thomas H. Jukes

Darwinism is so well established that it is difficult to think of evolution except in terms of selection for desirable characteristics and advantageous genes. New technical developments and new knowledge, such as the sequential analysis of proteins and the deciphering of the genetic code, have made a much closer examination of evolutionary processes possible, and therefore necessary. Patterns of evolutionary change that have been observed at the phenotypic level do not necessarily apply at the genotypic and molecular levels. We need new rules in order to understand the patterns and dynamics of molecular evolution.

Evolutionary change at the morphological, functional, and behavioral levels results from the process of natural selection, operating through adaptive changes in DNA. It does not necessarily follow that all, or most, evolutionary change in DNA is due to the action of Darwinian natural selection. There appears to be considerable latitude at the molecular level for random genetic changes that have no effect upon the fitness of the organism. Selectively neutral mutations, if they occur, become passively fixed as evolutionary changes through the action of random genetic drift.

The idea of selectively neutral change at the molecular level has not been readily accepted by many classical evolutionists, perhaps because of the pervasiveness of Darwinian thought. Change in DNA and protein, when it is thought of at all, is thought to be limited to a response to activities at a higher level. For example, Simpson (*1*) quotes Weiss (*2*) as stating that there is a cellular control of molecular activities, and Simpson adds that there is also an organismal control of cellular activities and a populational control of organismal activities, and concludes (*1*):

> The consensus is that completely neutral genes or alleles must be very rare if they exist at all. To an evolutionary biologist, it therefore seems highly improbable that proteins, supposedly fully determined by genes, should have nonfunctional parts, that dormant genes should exist over periods of generations, or that molecules should change in a regular but nonadaptive way . . . [natural selection] is the composer of the genetic message, and DNA, RNA, enzymes, and other molecules in the system are successively its messengers.

We cannot agree with Simpson that DNA is a passive carrier of the evolutionary message. Evolutionary change is not imposed upon DNA from without; it arises from within. Natural selection is the editor, rather than the composer, of the genetic message. One thing the editor does *not* do is to remove changes which it is unable to perceive.

The view that mutations cannot be selectively neutral is not confined to organismal evolutionists. Smith (*3*) states:

> One of the objectives of protein chemistry is to have a full and comprehensive understanding of all the possible roles that the 20 amino acids can play in function and conformation. Each of these amino acids must have a unique survival value in the phenotype of the organism—the phenotype being manifested in the structures of the proteins. This is as true for a single protein as for the whole organism.

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