BIBLIOGRAPHY

Edited by Z. Kopal, M. Moutsoulas, and J. W. Salisbury

1. Motion of the Moon in Space, and Dynamics of the Earth-Moon System

Griffith, J. S.: 'On Some Approximations in Brown's Lunar Theory', *Celest. Mech.* **4**, 54–59.

A re-evaluation of Brown's Lunar Theory has long been awaited. While working on this problem a number of questions about the adequacy of Brown's approach have arisen, and some of these questions including that of the need for a literal solution of the main problem are discussed in this paper.

Jeffries, A. J.: 'An Investigation of the Lunar Ejecta Theory of the Cause of the Gegenschein', *Planetary Space Sci.* **19**, 841–850.

A theoretical investigation has been carried out into the lunar ejecta theory of the cause of the Gegenschein. This theory proposes that the Gegenschein, the enhancement in the brightness of the zodiacal light observed in the antisolar region, is caused by the ejection of dust particles from the Moon by the impact of meteorites, the particles being pushed in the antisolar direction by solar radiation pressure to form a dust-tail seen visually as the Gegenschein. An IBM 360 computer has been used to calculate the trajectories of particles ejected from various positions on the Moon and for different positions of the Moon in its orbit, the particles being subject to the gravitational forces of the Earth, Sun and Moon, solar radiation pressure and the Coriolis force of the rotating heliocentric co-ordinate system. From an analysis of the final positions of the particles it is concluded that the lunar ejecta theory explains the principal observational features of the Gegenschein.

3. Shape and Gravitational Field of the Moon

Booker, J. R. and Kovach, R. L.: 'Mascons and the Moon's Gravity Field', *Phys. Earth Planetary Int.* **4**, 180.

The apparent surface mass M of the mascon in a lunar ringed mare is approximately proportional to the area A of the deep mare material in the basin: $M \propto A^{\sigma}$, where σ lies between 0.85 and 1.20 with a most probable value of 1.02. This relationship can be interpreted in terms of thin plates of dense rock whose thickness is the same for all ringed maria. This characteristic thickness may be associated with the depth to a lunar 'Moho'. For a crust-mare density contrast of 0.5 g/cm^3, the thickness of the plates would be 8.32 km. The mass-area relationship predicts mascons in Maria Orientale and Smythii on the west and east limbs of the Moon which are consistent with Lunar Orbiter Doppler data. If the mascons are embedded at the same distance from the centre of an otherwise homogeneous Moon, the predicted dynamical asymmetry $(B-A)/(C-A)$ is 0.39 ± 0.09 in good agreement with the astronomically derived value 0.37. However, if the mascons are at the lunar surface, the differences in moments of inertia, $(B-A)$ and $(C-A)$, are both ten times smaller than the values derived from harmonic analyses of the lunar gravitational field. To reconcile this difference while preserving the peak acceleration on a satellite 100 km above the lunar surface requires mascons ten times more massive than the authors propose buried deeper than 250 km. This depth seems unlikely and suggests that the prediction of the dynamical asymmetry by the mascons may be accidental. The degree variances of harmonic analyses of the lunar gravity field show a gentle peak near degree ten. Such a peak is predicted by the mascon distribution and is essentially a result of the spacing between the two largest mascons, Imbrium and Serenitatis. However, the observed peak is ten times larger than the predicted peak. This large amplification of all the higher degree variances seems likely to be an artifact of the lack of constraint on the spherical harmonic models by the real gravity field on the lunar farside. (Abstract only).

The Moon **4** (1972) 250–268. *All Rights Reserved*

Jeffreys, H.: 'Dynamics of the Moon', *Phys. Earth Planetary Int.* **4**, 153–155.

The author critically reviews the recent literature on the dynamics of the lunar interior and evaluates the acceptability of various theories.

Kaula, W. M.: 'Interpretation of the Lunar Gravitational Field', *Phys. Earth Planetary Int.* **4**, 185–192.

The most significant inference from the gravitational field is that the isostatic compensation of the highlands requires a thorough fractionation of at least one-third of the Moon's mass. The Apollo samples and other recent data make creation of the mascons by surface transfer processes much less plausible, leave their creation by infalling denser bodies speculative, and make more acceptable to disciples of William of Occam their creation by processes internal to the Moon. A Moon which experienced drastic fractionation of its outer parts and then a billion years later has volcanism is certainly one which would have a thermal history where the outer parts cooled relative to the inner. The interpretation of magnetometry near and on the Moon is still sufficiently unsure that broad variations in the gravitational field could be caused by convection in the Moon's core. The orientation of the maria toward the Earth might be caused by tidal effects when the Moon was a few Earth radii from the Earth, but the mechanism of such effects depends upon how the Moon's orbit was modified by infalling bodies from outside the Earth-Moon system.

Latham, G., Ewing, M., Dorman, J., Lammlein, D., Press, F., Toksöz, N., Sutton, G., Duennebier, F., and Nakamura, Y.: 'Moonquakes', *Science* **174**, 687–692.

Although the average rate of seismic energy release within the Moon appears to be far below that of the Earth, over 100 events believed to be Moonquakes have been recorded by the two seismic stations installed on the lunar surface during Apollo missions 12 and 14. With few exceptions, the Moonquakes occur at monthly intervals near times of perigee and apogee and show correlations with the longer-term (7-month) lunar gravity variations. The repeating Moonquakes are believed to occur at not less than 10 different locations. However, a single focal zone accounts for 80% of the total seismic energy detected. This active zone appears to be 600 km south-southwest of the Apollo 12 and 14 sites and deep within the Moon. Each focal zone must be small (less than 10 km in linear dimension) and fixed in location over a 14-month period. Cumulative strain at each location is inferred. Thus, the Moonquakes appear to be releasing internal strain of unknown origin, the release being triggered by tidal stresses.

Liu, A. S. and Laing, P. A.: 'Lunar Gravity Analysis from Long-Term Effects', *Science* **173**, 1017–1020.

The global lunar gravity field was determined from a weighted least-squares analysis of the averaged classical element of the five Lunar Orbiters. The observed-minus-computed residuals have been reduced by a factor of 10 from a previously derived gravity field. The values of the second-degree zonal and sectorial harmonics are compatible with those derived from libration data.

Nance, R. L.: 'Gravity Measured at the Apollo 12 Landing Site', *Phys. Earth Planetary Int.* **4**, 193–196.

The gravity at the landing site of the second lunar landing mission has been determined from data telemetered to Earth from the lunar module on the lunar surface. The measurement was used to compute the gravity anomaly and the lunar radius at the landing site. The gravity was predicted for the site by the use of a simple model of the lunar mass distribution. Comparisons between the results from Apollo 11 and Apollo 12 were made of the observed gravity, the predicted gravity, the radius from tracking data, the radius from gravity data and the gravity anomaly.

Nance, R. L.: 'Gravity Measured at the Apollo 14 Landing Site', *Science* **174**, 1022–1023.

The gravity at the Apollo 14 landing site has been determined from the accelerometer data that were telemetered from the lunar module. The values for the lunar gravity measured at the Apollo 11, 12, and 14 sites were reduced to a common elevation and were then compared between sites. A theoretical gravity, based on the assumption of a spherical Moon, was computed for each landing site and compared with the observed value. The observed gravity was also used to compute the lunar radius at each landing site.

Sjogren, W. L.: 'Lunar Gravity Estimate: Independent Confirmation', *J. Geophys. Res.* **76**, 23.

Reduction of $2\frac{1}{2}$ days of Lunar Orbiter 4 radio tracking data has provided an independent estimate of the low-degree spherical harmonic coefficients in the lunar potential model. The estimate is in good agreement with previous results and confirms that the Moon is essentially homogeneous. These Doppler data, never incorporated in other gravity estimates, were obtained at relatively high spacecraft altitudes (2700–6000 km). This high-altitude data allowed the model to fit to the noise level of 1 mm/s, unlike previous results, where systematic residuals of tens of millimeters per second occurred, owing to local gravity anomalies detectable at low spacecraft altitudes ($\approx$ 100 km).

Sjogren, W. L., Gottlieb, P., Muller, P. M., and Wollenhaupt, W.R.: 'Lunar Gravity via Apollo 14 Doppler Radio Tracking', *Science* **175**, 165–168.

Gravity measurements at high resolution were obtained over a 100 km band from $+70°$ to $-70°$ of longitude during the orbits of low periapsis altitude (approximately 16 km). The line-of-sight accelerations are plotted on Aeronautical Chart and Information Center mercator charts (scale 1:1, 000, 000) as contours at 10 mgal intervals. Direct correlations between gravity variations and surface features are easily determined. Theophilus, Hipparchus, and Ptolemaeus are negative features, whereas Mare Nectaris is a large positive region. The acceleration profiles over Mare Nectaris are suggestive of a broad disk near the surface rather than a deeply buried spherical body. These data are in good agreement with the short arc of Apollo 12 lunar module descent data.

Wollenhaupt, W. R. and Ransford, G. A.: 'Lunar Radii Values from Apollo Missions', *Bull. Am Astron. Soc.* **3**, 272.

Optical position measurements of seventeen relatively small lunar features were made by crew members from the orbiting spacecraft during the first four Apollo lunar missions. The measurements, which covered about 65% of the lunar equator, were made in a near equatorial band from 31 °W across the near side in an eastward direction to approximately 158 °W on the far side. The selenographic positions of the observed features were derived from sets of angular measurements made from the orbiting spacecraft to the specified feature. The radii for the eleven near side features ranged in value from 1732.99 to 1737.98 km. This latter value was obtained for a crater in the highland region located at 15.5°E longitude, 8.9°S latitude. It was the only value which came near the generally accepted mean lunar radius value of 1738.09 km. All others were at least one km below this. Where comparison points were available, the Apollo values agreed well with those obtained from the Ranger, Surveyor, and Lunar Orbiter spaceflight projects. All values appeared to be systematically lower than the values obtained from earth-based photography which are considered to be center of figure measurements. The three lowest values (1735.4, 1735.2, and 1733 km) were obtained for craters located in Mare Tranquillitatis, Spumans, and Smythii, respectively. Of the six Apollo far side features, four had radii values from 1739.0 to 1742.2 km. The remaining two had radius values of 1737.2 and 1735.2 km. This latter value was obtained for a crater located in a highland region approximately 8.6° east and 11.8° south of the crater in Smythii. In general the Apollo near side data do not indicate the presence of an equatorial bulge toward the Earth. Although the number of far side points are very limited, they do provide further indication of a displacement between the Moon's center of figure and center of mass. (Abstract of a paper presented at the meeting of the American Astronomical Society, December 1970).

Wong, L., Buechler, G., Downs, W., Sjogren, W., Muller, P., and Gottlieb, P.: 'A Surface-Layer Representation of the Lunar Gravitational Field', *J. Geophys. Res.* **76**, 6220–6236.

A surface-layer representation of the lunar gravitational field has been derived dynamically from the analysis of Doppler observations on both polar and equatorial lunar orbiters. The force model contained 600 discrete masses located on the mean lunar surface between the approximate boundaries of ±60° latitude and ±95° longitude. The derived major mascons were generally in agreement with a model based on polar orbits alone. A technique for combining the discrete mass gravitational field for the front side with a spherical harmonics expansion for the back side is described. Harmonic analysis of the resultant field shows that the higher end of the power spectrum roughly follows the decay rule predicted by W. M. Kaula.

4. Internal Structure of the Moon

Watkins, J. S. and Kovach, R. L.: 'Preliminary Interpretation of Apollo 14 Active Seismic Experiment Data', *EOS* **52**, 534.

Thumper refraction arrival times indicate that the lunar near-surface at the Apollo 14 site consists of a 7.5 m thick layer with a compressional wave velocity of 104 mps. This layer is underlain by a layer with a velocity of 298 mps. Thickness of the 298 mps layer is estimated to be 15 m from Passive Seismic Experiment data (G. V. Latham, pers. comm.). The 104 mps layer is interpreted to be the lunar regolith, and probably contains the Fra Mauro Formation (Mare Imbrium ejecta blanket). The 298 mps layer is thought to be volcanic in origin but data are also consistent with the interpretation that this layer is the Fra Mauro Formation. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union).

5. Thermal and Stress History of the Moon

Baldwin, R. B.: 'The Question of Isostasy on the Moon', *Phys. Earth Planetary Int.* **4**, 167–179.

It is well known on Earth that Bouguer gravity anomalies are generally strongly negative in mountainous regions and are still more positive over the oceans. These observations are explained only if it is assumed that the average mass density is less under mountains and larger under oceans than it is under lowlands. Then the effect of mountains and oceans on the gravity anomalies is at least partially compensated by the mass distribution of the Earth's crust. Isostatic equilibrium means that at some distances below sea level the pressure of the superimposed load is everywhere the same, regardless of whether the surface units are under mountains, lowlands or oceans. This depth at which isostatic equilibrium prevails is called the 'depth of compensation'. Changes in surface loading result in isostatic changes in elevation. In this paper the author discusses vertical motions on the Moon which resulted from stress differences and which, in all cases, caused the Moon to approach the condition of 'isostatic equilibrium' as closely as the threshold strength of the lunar materials permit. The Orbiter vehicles clearly showed (Muller and Sjogren, 1968) that the Moon is nearly in isostatic equilibrium. Any gross distortion of the surface of the Moon will cause a flow of viscous materials as gravitational forces act. The distortion of the surface produces a deviation from isostatic equilibrium and this deviation will die down and it will approach a condition of isostasy as closely as the threshold strength of the affected materials will permit.

Bastin, J. A.: 'The Diffusion of Lunar Seismic Energy', *Phys. Earth Planetary Int.* **4**, 218–221.

At the time of the Apollo 12 seismic experiment no explanation was forthcoming for the continued 'ringing' of the seismometer situated 75 km from the impact site of the discarded ascent stage of the lunar module. Since then, a number of authors (Bastin, 1969, 1970; Latham *et al.*, 1970; Klemens and Stegg, 1970) have favoured similar diffusion-like models in which the lunar seismic energy is localized relatively close to the explosion site by discontinuities in the bulk or surface structure of the Moon. The author describes various aspects of the diffusion explanation, and considers also other hypotheses of a different kind which have been proposed to account for the observations. Although the exact nature of the scattering or reflecting centres or surfaces is still uncertain, there are good reasons for discounting any of the alternative hypotheses which have been suggested, and the diffusion hypothesis in its general form seems virtually confirmed as the only tenable hypothesis to account for the observations.

Bell, P. R.: 'An Origin of the Moon Compatible with its Present Condition', *Phys. Earth Planetary Int.* **4**, 215–217.

Old igneous rocks plus evidence for a cool interior suggest cold accumulation and fusion of a thin surface layer by the early 'superluminous' phase of the Sun. This melted layer, estimated from crater slumping to be 5–6 km thick, filled collision craters to form 'mascons'. Fusion of the surface and accumulating material explains the scarcity of volatile elements.

O'Hara, M. J., Biggar, G. M., Richardson, S. W., Ford, C. E., and Jamieson. B. G.: 'The Nature of Seas, Mascons and the Lunar Interior in the Light of Experimental Studies, II', *Phys. Earth Planetary Int.* **4**, 181–184.

After a brief review of previously published views, the flotation of anorthosite crust, the fractional crystallization process in lunar seas and some aspects of genesis of mascons are specifically discussed in the light of experimental data and the petrogenetic scheme which they support.

Ronca, L. B.: 'The Ages of the Lunar Seas (Apollo Data/Geomorphic Indices)', *Proc. Natl. Acad. Sci.* **68**, 1188–1189.

Two ages are attributed to each circular lunar sea, the age of formation of the circular basin, probably by impact, and the age of the filling of the basin by lava-like effusions. Each lunar-sea surface displays a range of geomorphic indices. This is interpreted as being due to the presence of effusions of different ages on the surface of each sea. The landing sites of Apollo 11 and 12 have geomorphic indices of value 10.3 and 8.4. The radiometric ages of the rocks are, respectively, approximately 3.65×10^9 and 3.36×10^9 yr. The range of geomorphic indices on sea surfaces is from less than 5 to more than 14, which indicates that the two Apollo crafts landed on surfaces formed about in the middle of the total span of time of sea-surface formation. Using four possible relationships between geomorphic index and age, the author concludes that the age of the youngest effusions is less than 3×10^9 yr and the age of the oldest effusions is more than 4×10^9 yr. The results of the analyses of the Russian Luna 16 samples, although preliminary, fit in this interpretation.

Sutter, J. F., Husain, L., and Schaeffer, O. A.: '^{40}Ar–^{39}Ar Ages from Fra Mauro', *Earth Planetary Sci. Letters* **11**, 249–253.

High temperature ^{40}Ar–^{39}Ar ages have been determined for four rock fragments selected from coarse fines returned from Fra Mauro. Three are fragmental rocks in varying stages of recrystallization and the fourth is crystalline with a gabbro mineralogy, relatively devoid of shock features. All of the fragments have a common age of $3.75 \pm 0.15 \times 10^9$ yr. The ages suggest intense activity, possibly the Imbrium event, at 3.75×10^9 yr ago which has precluded the identification of more primitive material.

Turner, G.: '^{40}Ar–^{39}Ar Ages from the Lunar Maria'; *Earth Planetary Sci. Letters* **11**, 169–191.

Neutron activation and stepwise heating experiments have been used to measure argon retention ages of crystalline rocks 12002, 12051 and 12065 from Oceanus Procellarum. The effects of appreciable argon loss are observed for all rocks. Ages based on the release of argon from retentive sites are, within the errors of measurement, identical and are respectively 3.24 ± 0.05, 3.27 ± 0.05 and 3.24 ± ± 0.05 aeons. These ages are distinctly lower than ^{40}Ar–^{39}Ar ages determined for Apollo 11 rocks. A high K lithic fragment from an Apollo 11 breccia yields an age of 3.53 ± 0.12 AE in good agreement with previous measurements of Apollo 11 high K crystalline rocks. The ^{40}Ar–^{39}Ar dating technique has been applied to three fragments of lunar rock 12013, with widely differing K concentrations. The samples analyzed show no effects of either argon loss or excess argon and an age of (4.03 ± 0.07) AE indicates a time at which the major potassium-bearing components were essentially devoid of radiogenic argon. A study of the release of neutron produced ^{39}Ar as a function of temperature indicates that the radiogenic ^{40}Ar loss which occurs on the lunar surface is consistent with a heat source which is relatively uniform for all the samples and may, in fact, be solar heating. The multicomponent mixing systematics for argon extracted from neutron-irradiated rocks are considered in detail in an attempt to evaluate the effects of cosmogenic and trapped ^{40}Ar on ^{40}Ar–^{39}Ar ages. The effects are shown to be small in the crystalline rocks so far analyzed, but may be significant if younger rocks are returned from future missions. An ^{40}Ar/^{38}Ar ratio of 0.7 ± 0.3 has been determined for cosmogenic argon in lunar basalts.

Turner, G., Huneke, J. C., Podosek, F. A., and Wasserburg, G. J.: '^{40}Ar–^{39}Ar Ages and Cosmic Ray Exposure Ages of Apollo 14 Samples', *Earth Planetary Sci. Letters* **12**, 19–35.

The authors have used the ^{40}Ar–^{39}Ar dating technique on eight samples of Apollo 14 rocks (14053, 14310), breccia fragments (14321), and soil fragments (14001, 14167). The large basalt fragments give reasonable ^{40}Ar–^{39}Ar release patterns and yield well defined crystallization ages between 3.89–3.95 aeons. Correlation of the ^{40}Ar–^{39}Ar release patterns with ^{39}Ar–^{37}Ar patterns showed that the low temperature fractions with high radiogenic argon loss came from K-rich phases. A highly shocked sample and fragments included in the breccia yield complex release patterns with a low temperature peak. The total argon age of these fragments is 3.95 AE. Cosmic ray exposure ages on these samples are obtained from the ratio of spallogenic ^{38}Ar to reactor induced ^{37}Ar and show a distinct grouping of low exposure ages of ~ 26 my correlated with Cone crater. Other samples have exposure ages of more than 260 my and identify material with a more complex integrated cosmic age exposure history.

Wasson, J. T.: 'Volatile Elements on the Earth and the Moon', *Earth Planetary Sci. Letters* **11**, 219–225.

A comparison of the concentrations of volatile elements in terrestrial and lunar rocks shows that those elements with the highest terrestrial/lunar concentration ratios are the same ones showing high abundance in Cl chondrites relative to ordinary chondrites. The terrestrial/lunar concentration ratio pattern is inconsistent with partial volatilization or condensation processes, but in agreement with explanations involving the accretion of a volatile-rich component to the Earth in amounts greatly exceeding those accreted to the Moon. It is proposed that the bulk of the Earth and Moon formed from materials having low contents of volatile elements, and that the volatiles were added during a final stage in which the main source of accreted matter was comets. If the Earth had an atmosphere at this time, it would have retained nearly all of the accreting material, whereas an atmosphereless Moon may have retained as little as 0.003 of it, as is necessary to explain the lower content of volatile elements.

Watkins, J. S.: 'Seismic Velocity Models of the Lunar near Surface and Their Implications', *J. Geophys. Res.* **76**, 6246–6252.

Models of the lunar near-surface seismic velocity distribution are derived that represent hypothetical moons in which the near-surface character is due to (1) cold accretion of particles from space and (2) steady-state impact. Comparison of model travel times with observed travel times favors the cold-accretion model.

Wood, B. J. and Strens, R. G. J.: 'The Crystallization of Lunar Basalts', *Phys. Earth Planetary Int.* **4**, 222–225.

The crystallization of olivine (O) and silica (S) normative varieties of Apollo 11 crystalline rocks has been followed at 1 atm. The sequence of phases precipitating is (S): spinel, olivine, ilmenite, clinopyroxene plus plagioclase; and (O): spinel, olivine, ilmenite plus plagioclase, clinopyroxene. The last 50% (O) to 75% (S) of the liquid crystallizes as a pyroxene-plagioclase-ilmenite cotectic over a narrow temperature range, approximately 1095 to 1125 °C, leaving a small silica-rich residue. Analyses of the important magnetic minerals shows i.a. that iron crystallizes as 10 μm octahedra, which take up any nickel present in the melt. Spinel has MCr_2O_4:MAl_2O_4:$M_2TiO_4 \approx 1:1:3$, with $M = Fe + Mg$ ranging from 66 to 79% Fe. Ilmenite contains approximately 1% Al_2O_3, 1% Cr_2O_3 and a few mole percent Ti_2O_3, and has $M = Fe + Mg$ ranging from 63 to 82% Fe. Partial analyses were made of the important silicate phases. Lunar basalts have viscosities from one to two orders of magnitude less than terrestrial basalts, and this permits faster flow, more crystal fractionation within individual flows, and (in intrusions) rapid crystal sinking and convection, and extreme rhythmic layering. The analytical data have been used to calculate the probable composition of the source region of the lunar basalts. The lunar mantle is thought to consist of major ortho- and clinopyroxenes, with minor spinel, ilmenite, metal, sulphides, olivine, plagioclase and liquid, plus rutile and garnet at depth. The europium fractionation found in the authors' experiments is consistent with the idea that the lunar highlands are anorthositic.

6. Chemical Composition of the Moon

Anderson, A. T., Jr.: 'Exotic Armalcolite and the Origin of Apollo 11 Ilmenite Basalts', *Geochim. Cosmochim. Acta* **35**, 969–973.

Armalcolite is probably partly exotic in lunar basalt 10022 as suggested by K_2O, SiO_2-rich devitrified glass included within it. Assimilation of armalcolite (and possibly ilmenite) and addition of a K_2O, SiO_2 rich liquid probably helped produce the high TiO_2 content and variable alkali contents of Apollo 11 ilmenite basalts.

Brunfelt, A. O., Heier, K. S., Steinnes, E., and Sundvoll, B.: 'Determination of 36 Elements in Apollo 14 Bulk Fines 14163 by Activation Analysis', *Earth Planetary Sci. Letters* **11**, 351–353.

36 elements were determined in Apollo 14 bulk fines 14163. A one gram bulk sample was split from the 4.960 g received of sample 14163, 154 and analysed according to the method described by Brunfelt and Steinnes with some slight modifications.

Compston, W., Vernon, M. J., Berry, H., and Rudowski, R.: 'The Age of the Fra Mauro Formation: A Radiometric Older Limit; *Earth Planetary Sci. Letters* **12**, 55–58.

The internal Rb-Sr age of a 0.17 g basaltic clast from an Apollo 14 breccia is 4.15 ± 0.10 by. This limits the Imbrium event to not older than 4.25 AE on current interpretations of lunar stratigraphy.

Eberhardt, P., Geiss, J., Grogler, N., Krahenbuhl, U., Morgeli, M., and Stettler, A.: Potassium-Argon Age of Apollo 11 Rock 10003; *Earth Planetary Sci. Letters* **11**, 245–247.

The K-Ar ages of a whole rock sample and a feldspar concentrate from lunar rock 10003 were determined as $(3.74 \pm 0.06) \times 10^9$ yr and $(3.82 \pm 0.05) \times 10^9$ yr respectively. The K-Ar age of the feldspar concentrate is in essential agreement with the high temperature K-Ar age of $(3.92 \pm 0.07 \times \times 10^9$ yr obtained by Turner with the ^{40}Ar–^{39}Ar dating technique. These results thus confirm the relatively high age of the low-K Apollo 11 rock 10003.

Gancarz, A. J., Albee, A. L., and Chodos, A. A.: 'Petrologic and Mineralogic Investigation of Some Crystalline Rocks Returned by the Apollo 14 Mission, *Earth Planetary Sci. Letters* **12**, 1–18.

Apollo 14 crystalline rocks (14053 and 14310) and crystalline rock fragments (14001, 7, 1; 14001, 7, 3; 14073; 14167, 8, 1 and 14321, 191, X-1) on which Rb/Sr, ^{40}Ar–^{39}Ar, or cosmic ray exposure ages have been determined by the authors' colleagues were studied with the electron microprobe and the petrographic microscope. Rock samples 14053 and 14310 are mineralogically and petrologically distinct from each other. On the basis of mineralogic and petrologic characteristics all of the fragments, except 14001,7,1, are correlative with rock 14310. Sample 14073 is an orthopyroxene basalt with chemical and mineralogic affinities to 'KREEP', the 'magic' and 'cryptic' components. Fragment 14001,7,1 is very similar to Luny Rock I.

Herzenberg, C. L. and Riley, D. L.: 'Analysis of Returned Lunar Samples by Techniques Based on Mossbauer Spectrometry', *Phys. Earth Planetary Int.* **4**, 204–214.

Standard techniques of spectral analysis, including least squares fitting of the spectra, have been used for the quantitative interpretation of the spectra. The authors found only small variations in spectra between different soil samples from the Apollo 11 return. In a typical soil or fines sample from Tranquillity Base, about 3/4 of the iron is Fe^{2+} in the silicate phase, about 1/5 of the iron is in ilmenite and about 1/20 of the iron is free metallic iron. Only about 1% of the iron in the soil is in troilite. The authors find no evidence of any significant amount of ferric iron. By a comparison of the total resonant absorption produced by a lunar sample with the total resonant absorption produced by a standard absorber measured under similar conditions, they are able to estimate the total iron content of the lunar sample. While these estimates are only approximate, they found an average of about 12% iron in the Apollo 11 fines, in good agreement with the 12.4% originally reported for type D fines. Preliminary results have just recently been obtained for the first few Apollo 12 samples allocated to this research. Comparison of these spectra with spectra of Apollo 11 soil and rock samples show that this Apollo 12 rock and soil contain a considerably lower abundance of ilmenite and a greater abundance of olivine than the Apollo 11 material; similar conclusions appear to apply to other Apollo 12 samples currently under investigation. It appears from these measurements that lunar material from the Ocean of Storms is distinctively different from lunar material from the Sea of Tranquillity, and that Mossbauer spectrometry can contribute directly to the characterization of regional differences in lunar materials as well as to their general analysis.

Heymann, D. and Yaniv, A.: 'Distribution of Radon-222 on the Surface of the Moon', *Nature* **233**, 37–39.

In this communication the authors examine the effects that may be expected in the α emission rate from ^{222}Rn near the terminator.

Husain, L., Sutter, J. F., and Schaeffer, O. A.: 'Ages of Crystalline Rocks from Fra Mauro', *Science* **173**, 1235–1236.

Crystallization ages for six rocks from Fra Mauro have been measured by the argon-40-argon-39 method. All six rocks give an age of $3.77 \pm 0.15 \times 10^9$ yr, which is the same as for fragmental rocks from this site. It is concluded that the Imbrium event and the crystallization of a significant portion of the pre-Imbrian basalts were essentially contemporaneous.

Lindstrom, R. M., Evans, J. C., Jr., Finkel, R. C., and Arnold, J. R.: 'Radon Emanation from the Lunar Surface', *Earth Planetary Sci. Letters* **11**, 254–256.

The radon daughter ^{210}Pb in surface samples of lunar soil and rock is in equilibrium with its parent uranium to within five percent. The lack of a surface excess in these samples, if real, implies an effective diffusion coefficient for radon of less than 10^{-6} that observed in terrestrial soils.

Nagy, B., Modzeleski, J. E., Modzeleski, V. E., Mohammad, M. A. J., Nagy, L. A., Scott, W. M., Drew, C. M., Thomas, J. E., Ward, R., Hamilton, P. B., and Urey, H. C.: 'Carbon Compounds in Apollo 12 Lunar Samples', *Nature* **232**, 94–98.

Analysis of surface fines and core samples obtained on the Apollo 12 mission reveals small quantities of carbon compounds. The results from pyrolysis, mass spectrometry, ion exchange chromatography, and both optical and electron microscopy may shed some light on the origin and history of these organic molecules.

Papanastassiou, D. A. and Wasserburg, C. J.: 'Rb-Sr Ages of Igneous Rocks from the Apollo 14 Mission and the Age of the Fra Mauro Formation', *Earth Planetary Sci. Letters* **12**, 36–48.

Internal Rb-Sr isochrons were determined on four basaltic rocks and on a basaltic clast from a breccia from the Fra Mauro landing site. Rocks 14310, 14073 and 14001,7,3 yield essentially identical ages $T = 3.88 \pm 0.04$ AE and identical high initial $^{87}Sr/^{86}Sr$, $I = 0.70035 \pm 4$. Rock 14053 and the clast from breccia 14321 both yield a higher age $T = 3.95 \pm 0.04$ AE and a distinctly lower $I = 0.69945 \pm 4$. Model ages relative to BABI for these rocks range from 4.3 to 4.6 AE. Model ages were determined for soil samples 14141, 14149, 14163, 14259 yielding T_{BABI} of 4.4, 4.5, 4.5 and 4.7 AE respectively. An internal isochron was determined for 12004 and yielded (3.29 ± 0.07 AE, 0.69948 ± 5) in agreement with the authors' previous results for basaltic rocks from the Apollo 12 site. The crystallization ages for Apollo 14 basalts are only 0.2 to 0.3 AE older than were found for mare basalts from the Sea of Tranquillity. Assuming these leucocratic igneous rocks to be representative of the Fra Mauro site, it follows that there were major igneous processes active in these regions, and presumably throughout the highlands, at times only slightly preceding the periods at which the maria were last flooded. If the breccias represent the Fra Mauro formation and if this is the result of excavation of the Imbrium Basin, the authors conclude that a major bombardment of the Earth-Moon system continued to take place at least as late as 3.9 AE or about 0.7 AE after the formation of the solar system. Such a late major bombardment could remove the need for internal heat sources to explain some mare lava flows. Some of the lunar differentiation processes could possibly represent the result of collisional melting of a thin outer layer. This late bombardment requires that planetary objects ~ 100 km in size must be stored in unstable orbits with lifetimes of 10^8 yr or more.

Reed, G. W., Jovanovic, S., and Fuchs, L. H.: 'Fluorine and Other Trace Elements in Lunar Plagioclase Concentrates, *Earth Planetary Sci. Letters* **11**, 354–358.

The F contents of plagioclase concentrates from Apollo 11 fines and an anorthosite inclusion from an Apollo 12 breccia are of the order of 100 ppm. This is very much lower than the ~ 2500 ppm F found by Surveyor VII in soil of anorthositic composition at the crater Tycho. Thus it appears that there is a negligible admixture of this type of terra material at the Tranquillitatis and Procellarum landing sites. Apollo 14 soils from Fra Mauro are rich in plagioclase but contain no more F than the mare soils. In addition to F the contents of Br, Ba, U, Ru and Os were measured in the Apollo 11 and 12 plagioclase concentrates and in rock 12040 and core sample 10004.

Ringwood, A. E. and Green, D. H.: 'The Gabbro to Eclogite Transformation in Terrestrial and Lunar Basalts', *EOS* **52**, 535–536.

The subsolidus mineralogies of olivine-rich lunar basalts 12009 and 12040 have been determined experimentally in the pressure range up to 40 kb. The low pressure gabbroic assemblage ($\varrho \simeq 3.38$) transforms through a transitional pyroxenite assemblage lacking feldspar ($\varrho \simeq 3.53$) ultimately to eclogite mineralogy ($\varrho \simeq 3.65$). The data are applied to demonstrate that the mean internal composition of the Moon must differ from any of the sampled basalts and that the basalts are derived from a more primitive source material with higher $Mg/Mg + Fe$ ratio. The work on lunar basalt compositions can be integrated with the authors' previous studies on terrestrial basalts and enhances understanding of the component mineral reactions involved in the gabbro to eclogite transformation. It is shown that recent work of Ito and Kennedy provides excellent confirmation of our earlier studies although it is in conflict with earlier work by the same authors. A synthesis of experimental data confirms the authors' previous conclusions that the gabbro-eclogite transformation cannot explain the *M*-discontinuity in normal continental or oceanic regions, but may be important in orogenic areas. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union).

Schnetzler, C. C. and Nava, D. F.: 'Chemical Composition of Apollo 14 Soils 14163 and 14259', *Earth Planetary Sci. Letters* **11**, 345–350.

Major and minor element concentrations have been determined by atomic absorption spectrophotometry and isotope dilution in Apollo 14 soils 14163 and 14259. The two soils have quite similar compositions. These soils have higher Si, Al, K, rare earths, Ba, Li, Rb, Zr and Hf, and lower Fe, Ti, Mn, and Cr concentrations than soils from the mare areas sampled by Apollo 11, Apollo 12 and Luna 16. They most closely resemble in chemical composition the exotic fragments, such as KREEP or norite, found in Apollo 11 and 12 soils, or the dark portion of rock 12013. Similarities between chemical characteristics of Apollo 12 soils and breccias, rock 12013 and the two Apollo 14 soils suggest that extensive quantities of Fra Mauro material have been transferred to the Apollo 12 mare site. The data are consistent with the hypotheses that the pre-mare crust of the Moon is the result of extreme differentiation or the Moon accumulated inhomogeneously.

Silver, L. T.: 'U-Th-Pb Isotope Systems in Apollo 11 and 12 Regolithic Materials and a Possible Age for the Copernicus Impact Event', *EOS* **52**, 534.

The U-Th-Pb isotope systems in the surficial debris layers of the mare sampled by Apollo 11 and 12 expeditions (and Luna 16) apparently are comprised of different mixtures of components. Experimental attempts to isolate these components reveal significant differences in major contributions to the isotope systems at each site. At Tranquillity, the local rocks dominate the U and Th contributions; a small exotic rock population is also present. The local lead isotope composition and concentration is strongly influenced by a parentless lead of high Pb^{207}/Pb^{206} ratio and probably also by older rock debris derived from the nearby highlands. Apollo 12 soils are dominated in all three elements by significant quantities of exotic debris with very high U, Th, Pb concentrations. They also contain a significant fraction of old parentless leads. The local rocks contribute much less than 15% of the observed U, Th and Pb. Luna 16 soil (Vinogradov, 1971) is markedly lower in U and Th than Apollo samples. The isotope systematics of exotic radioactive debris in the Apollo 12 soils, when isolated from the contributions of the older parentless leads, shows an impressively consistant discordance pattern. This pattern seems to be the end product of isotopic disturbance of older generations of rocks (with apparent composite ages of 4.4 by) during an important thermal episode less than 1.0 by ago. Interpretation of available geological studies, local stratigraphy, and the isotope data suggests that this episode (ca. 0.85 ± 0.1 by) was the Copernicus impact and associated ray ejection. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union).

Taylor, S. R., Muir, P., and Kaye, M.: 'Trace Element Chemistry of Apollo 14 Lunar Soil from Fra Mauro', *Geochim. Cosmochim. Acta* **35**, 975–981.

Analytical data are presented for Apollo 14 fines (<1 mm) sample 14163,136 for 31 trace elements. The heavy REE are enriched monotonically by factors of 105 ± 10 over chondrites. Eu shows a large depletion (30 × chondrites) and the light REE show a smooth progressive enrichment with a slight fall at La, Ba, Cs, Th, U, Nb, Zr and Hf are strongly enriched, relative to chondritic abundances. Thus the outer portions of the moon sampled by the Imbrium event, and now represented by the Fra Mauro Formation, possessed high concentrations (100–200 × chondrites) for many elements, prior to the excavation of the mare basins. A correlation may exist between Gd/Eu and Zr/Hf ratios in lunar materials.

Wood, J. A., Marvin, U. B., Reid, J. B., Jr., Taylor, G. J., Bower, J. F., Powell, B. N., and Dickey, J. S., Jr.: 'Mineralogy and Petrology of the Apollo 12 Lunar Sample', Smithsonian Astrophysical Observatory Special Report 333, 272 pp.

The authors sectioned, examined, and classified 499 coarse (> 0.6 mm) particles from five of the Apollo 12 soil samples: 12070, collected on the rim of Surveyor Crater; 12032 and 12037, from the rim of Bench Crater; 12033, from a light-colored layer in a trench dug in the rim of Head Crater; and 12001, collected between craters. Samples 12070 and 12001 appear to be well-gardened soils, random mixtures of debris fragments, most of which derive from bedrock near at hand. The particles consist largely of mare basalts or degradation products thereof (microbreccia, cindery glasses of composition equivalent to the bulk soil), samples of the volcanic flows of Eratosthenian age that cover this portion of Oceanus Procellarum. Textures and mineral compositions of virtually all the basalt fragments they examined point to their formation in one or more relatively thin (~ 10 m) lava flows. All the soils contain about 10% of particles that are noritic in composition (low-Ca pyroxenes and calcic plagioclase in nearly equal amounts), but most of these have the textures of thermally recrystallized microbreccias. Many of the Apollo 11 anorthosites (a type that was not found in the Apollo 12 soil) have similar textures; the authors suggest that primary igneous anorthosites and norites were brecciated and recrystallized in an early, hot regolith. Soils 12032 and 12033 contain major amounts of a component alien to the local soil (as represented by 12070 and 12001) in the form of twisted, ropy particles of brownish glass. These are noritic in composition, but apparently derive from a different source than the crystalline norities in the soil. They believe the latter came from small terra exposures in the vicinity of the Apollo 12 site and from beneath the local mare basalt, while the ropy glasses are ejecta from the Crater Copernicus, samples of a Copernican ray that crosses the Apollo 12 site. Petrological characteristics of the lunar rocks and geophysical (gravity, topography) properties of the lunar surface are consistent with a structural model in which Oceanus Procellarum and the non-mascon maria are underlain by ~ 25 km of norite (with a thin covering of basalt), the mascon maria by lunar mantle material (covered by > 1 km of basalt), and the highlands by ~ 25 km of anorthosite. Most of this structure appears to have developed during crystallization and differentiation of an early lunar surface magma system; the mare basalts were erupted in a later episode of igneous activity, probably owing to decay of long-lived radioactivity at depth in the Moon. Several unusual particles were found: a rhyolite or micrographic granite rich in K and Fe; an agglomeration of glassy spherules of composition unmatched by any other known lunar material (high in normative ilmenite and mafics, low in plagioclase); and a meteorite, more similar to Type II carbonaceous chondrites than to any other known meteorite class.

10. Origin and Stratigraphy of Lunar Formations

DeHon, R. A.: 'Cauldron Subsidence in Lunar Craters Ritter and Sabine', *J. Geophys. Res.* **76**, 5712–5718.

Ritter and Sabine, on the southwestern edge of the Sea of Tranquillity, form a contiguous pair of post-mare craters almost identical in size (30–32 km in diameter). In contrast to craters presumably of impact origin, Ritter and Sabine are characterized by low depth-to-diameter ratios, relatively smooth dark rims, and an absence of secondary craters. The fundamentally different morphological aspects of these craters compared with eumorphic craters of the same age suggest a different mode of origin. The best analogies for Ritter and Sabine are found in terrestrial caldera such as Valles, New Mexico. Ritter and Sabine exhibit a wide variety of internal features similar to those of cauldrons of subsidence, including subsidence along ring faults, postsubsidence volcanism controlled by ring fractures, and probable resurgence of magma with accompanying uplift of the caldera floor. The floor of Ritter has collapsed along multiple ring fractures and stepped crescent wedges. The central floor is uplifted along inner ring faults, creating an elevated central plateau. Domes of probable volcanic origin are located over ring fractures and on the central floor. Sabine displays a prominent arcuate ridge of coalescing domes on the periphery of the western floor, as well as a large dome that straddles the southern rim crest and a well-developed flank ridge. Such structures are unexplained by an impact hypothesis, but they are compatible with a volcanic hypothesis.

Ganapathy, R., Laul, J. C., Morgan, J. W., and Anders, E.: 'Moon: Possible Nature of the Body that Produced the Imbrian Basin, from the Composition of Apollo 14 Samples', *Science* **175**, 55–59.

Soils from the Apollo 14 site contain nearly three times as much meteoritic material as soils from the Apollo 11, Apollo 12, and Luna 16 sites. Part of this material consists of the ubiquitous micrometeorite component, of primitive (carbonaceous-chondrite-like) composition. The remainder, seen most conspicuously in coarse glass and norite fragments, has a decidedly fractionated composition, with volatile elements less than one-tenth as abundant as siderophiles. This material seems to be debris of the Cyprus-sized planetesimal that produced the Imbrian basin. Compositionally this planetesimal has no exact counterpart among known meteorite classes, though group IVA irons come close. It also resembles the initial composition of the Earth as postulated by the two-component model. Apparently, the Imbrian planetesimal was an Earth satellite swept up by the Moon during tidal recession or capture, or an asteroid deflected by Mars into terrestrial space.

Neukum, G. and Dietzel, H.: 'On the Development of the Crater Population on the Moon with Time Under Meteoroid and Solar Wind Bombardment', *Earth Planetary Sci. Letters* **12**, 59–66.

In this paper a theory is evaluated to describe the development of the lunar crater population with time under the bombardment by meteoroids and solar wind. Starting from a general mass distribution law a differential equation has been established and solved separately for meteoroid impact and solar wind bombardment. The theory permits the calculation of absolute formation ages of the lunar surface as well as the particle flux, supposing the crater distributions on the moon have been measured. As an important result it includes a D^{-2} equilibrium crater distribution law (D = crater diameter), actually measured in Mare Tranquillitatis and Oceanus Procellarum. Additionally, the exponential decrease of particle flux with time is confirmed.

Rahn, P. H.: 'Lunar Wrinkle Ridges Indicative of Strike-Slip Faulting: Discussion', *Geol. Soc. Am. Bull.* **82**, 2365–2366.

The paper by H. D. Tjia (1970) offers an interesting possibility for the origin of mare ridges on the Moon. Based on inspection of Lunar Orbiter IV photographs of selected areas of lunar mare, Tjia noted that most lunar ridges contain smaller elongated bulges arranged en echelon relative to the larger containing ridge. Tjia suggests that these features are either (a) tension gashes, possibly filled with dikes, produced by north-south compression; or (b) more likely, drag folds produced by east-west compression. In either case, the implication is that these features are produced by tectonic forces orginating within the moon, giving rise to strike-slip faults. A more plausible hypothesis would be that the lunar wrinkle ranges are in ancient volcanic flows, or more likely debris flows, which move down-slope toward the centers of the maria under the influence of the Moon's, Earth's, and Sun's gravity.

In a reply, the author agrees with Rahn that some wrinkle ridges and ranges, especially those near the mare margins, may be of nondiastrophic character, but the majority of wrinkle ranges suggest a tectonic origin. Distinctly nonrandom azimuths of highland as well as mare lineaments, such as crater chains, straight rills, and short to extremely long fractures have been demonstrated. Rahn's other arguments against the existence of tectonism on the Moon are not wholly valid. Rahn's observations on the absence of isostasy and large moonquakes may be valid for the Moon's present state, but they can hardly apply to lunar conditions in the past. Similarly, the argument against volcanism on the Moon appears to be valid only for its present state.

Short, N. M. and Forman, M. L.: 'Thickness of Impact Crater Ejecta on the Lunar Surface', *Modern Geol.* **3**, 69–91.

Calculations based on improved models for impact cratering indicate an average thickness (if spread uniformly) of ejecta from craters and basins between 3.5 and 500 km diameters on the visible face of the Moon that ranges from 0.74 to 8.00 km (best estimate values between 1.36–2.39 km), depending on combinations of critical parameters utilized. These parameters include: (1) initial effective diameters of craters of excavation, (2) depth/diameter ratios between 0.05 and 0.35, (3) fractional enlargement of diameters by slimping from zero to 50%, (4) efficiency of ejection, (5) frequency distribution of craters in the size range used, and (6) appropriate selection of circular structures as impact-generated. Chief uncertainty is the identification of those large basins definitely caused by impact; where mare-filled, the proper choice of diameter becomes critical. Contributions from mascon-related basins versus all roughly circular basins are treated separately. The general thinness of rubble cover (1–20 m) on some mare surfaces implies that most major craters were formed early in lunar history. An anorthositic lunar highlands (indicated by Apollo 11 results) should be covered to varying depths with ejecta derived largely from impact basins cut into a pre-mare crust (anorthosite?) that was continuous around the lunar sphere. Ejecta from earlier (now covered or destroyed) craters plus unknown amounts of volcanic ash would add to the average thickness that can be calculated from observable impact craters.

Smith, E. I.: 'Determination of Origin of Small Lunar and Terrestrial Craters by Depth Diameter Ratio', *J. Geophys. Res.* **76**, 5683–5689.

One hundred small (< 3.5-km diameter) terrestrial meteorite-impact and volcanic-explosion craters on a depth-diameter plot show consistent differentiation into two fields, i.e., a low depth/diameter field of impact craters and a high depth/diameter field of volcanic craters. Lunar craters show the same relationship. Randomly scattered, well-preserved bowl craters with raised rims and associated ejecta and small ray craters plot in the field of terrestrial meteorite-impact craters, whereas craters on the summit of domes and cones lie in the field of terrestrial volcanic-explosion and summit craters. Collapse craters in terrestrial basalt lie in the impact field but may be distinguished from impact craters by absence of rim, rays, and ejecta. By these criteria, many small craters in the maria are formed by meteorite impact or collapse. Lunar volcanic-explosion craters are generally associated with domes, cones, and rills.

11. Physical Structure of the Lunar Surface

Cross, C. A.: 'Formation of Glass Spheres on the Moon', *Nature* **233**, 185–186.

Attention is drawn to a remarkable morphological similarity between lunar glass spheres and the glass shot which is formed during the manufacture of mineral wool. These results establish the remarkable overall similarities between these two kinds of glass shot. They suggest strong similarities in their mechanisms of formation. Both may have been formed by the atomization of a mineral melt in a high speed gas stream. The comparison of lunar spheres and mineral wool shot lends additional support to the views that the lunar shot is produced by high speed primary meteorite impacts, presumably as the intensely hot plasma expands through the surrounding solid particles, causing both melting and atomization. The fact that mineral wool and lunar shot morphologies are so similar should at least inhibit suggestions that the lunar processes must necessarily have taken place at low ambient pressure and great dilution. Mineral wool is made at one atmosphere in a very intensive process, but the shot so formed does not contain either 'grape clusters' or changes in shape obviously attributable to the surrounding gas.

Fanale, F. P., Nash, D. B., and Cannon, W. A.: 'Lunar Fines and Terrestrial Rock Powders: Relative Surface Areas and Heats of Adsorption', *J. Geophys. Res.* **76**, 6459–6461.

Surface area measurements by Kr adsorption (BET method) indicate that Apollo 11 lunar fines and ground terrestrial mafic rock powders have similar effective surface areas that are a factor of 10–100 higher than their geometrical or surficial surface areas. There is no evidence that a significant increase in surface roughness for lunar fines has resulted from their peculiar history of exposure on the Moon's surface. Low apparent heats of adsorption for Kr adsorption on lunar fine material are consistent with the presence of glassy or glass-coated particles.

Gutkin, A. M., Markov, M. S., Raitburd, Ts. M., and Slonimskaya, M. V.: 'On Possible Mechanisms of Gas Accumulation in the Surface Layer of the Moon', *The Moon* **3**, 214–220.

It was supposed before that the porous layer of the ground covering the surface of the Moon plays an active part in the gas balance. Indeed, even with low stationary atmospheric density observed at present on the Moon, there is a gas flow directed towards its surface. Despite the insignificant value of this flow, a considerable amount of gas can accumulate in the surface layer during the geological time. Such accumulation requires a mechanism that would promote the movement of gases adsorbed by the outer surface of the porous layer into its depths. This movement may be accounted for by: (1) presence of a temperature gradient; (2) concentration gradient of molecules adsorbed by the surface of the pores in the uppermost layer.

Hörz, F., Morrison, D. A., and Hartung, J. B.: 'The Surface Orientation of Some Apollo 14 Rocks', *Modern Geol.* **3**, 93–104.

Detailed stereomicroscopic studies of the distribution of microcraters, soil covers, and glass coatings were performed to reconstruct the most recent surface orientations of selected Apollo 14 rocks. Surface orientations could be established for rocks 14053, 14073, 14301, 14303, 14307, 14310, and 14311 (which includes rock 14308). A tentative orientation of rock 14055 is suggested, and comments concerning the surface history of rocks 14302, 14305, and 14318 are presented. The examination of rocks 14066, 14306, and 14321 indicates that these specimens have complicated surface histories that prevent reconstruction of their orientation by the criteria that were established in these stereomicroscopic studies.

Jones, R. H.: 'Lunar Surface Mechanical Properties from Surveyor Data', *J. Geophys. Res.* **76**, 7833-7843.

During the Surveyor program spacecraft were successfully landed at five widely separated lunar locations. Recent computer simulations of each landing have provided more comprehensive data on the mechanical properties of the lunar surface than have been obtained previously by this method of analysis. Results show that the variations in surface bearing pressure observed at the various lunar sites are probably due to surface slope effects and do not necessarily indicate differences in soil properties at these sites. Estimates of cohesion at two sites give almost identical results and further support the conclusion that the soil properties at all sites are probably very similar. Surface pressures that resist horizontal (plowing) motion are largely due to cohesion, and density and gravitational contributions are small. It is concluded that the lunar surface bearing strength is essentially zero at the surface and, for zero surface slope, increases with penetration depth at a rate of 1.87 ± 0.33 N/cm^3. The cohesion of the lunar soil is estimated to be between 0.11 and 0.17 N/cm^2.

Lofgren, G.: 'Spherulitic Textures in Glassy and Crystalline Rocks', *J. Geophys. Res.* **76**, 5635–5648.

Spherulites are clusters of confocally radiating crystals that, contrary to the implication of their name, are not commonly spherical but usually resemble sheaves of wheat tied at the center. The variation of morphology from the wheat sheaf to the spherical spherulite and the transition of growth conditions from the spherulite to the single dendrite and then to the more equant polyhedral crystal is well explained by a theory of spherulite growth developed and experimentally verified for high polymers. The stability of dendrites or spherulites during growth depends on the accumulation of a lower temperature component than the growing phase (impurity) at the interface of that growing crystal. The presence and dimensions of this layer are functions of the diffusion rate of the impuriy and the growth rate of the crystal; spherulite- and dendrite-forming melts must have the proper ratio of these two variables. To stabilize multicrystalline spherulites, the impurity layer must be sufficiently small. As the width of this layer increases or as the diffusion rate more closely approaches the growth rate, the transition to dendritic or fibrous single-crystal growth, and ultimately to the growth of more equant polyhedral crystals, is observed. The presence of spherulites or dendrites in crystalline or glassy material therefore indicates that a given silicate melt or glass has existed in the range of physical conditions that, for a particular composition, is suitable for the growth of these fibrous crystal forms. A single-rock specimen, lunar sample 12009, contains all growth forms, equant phenocrysts, phenocrysts with dendritic projections, feathery dendritic single crystals, and spherulites. The presence of these crystal forms does not uniquely define the mode of formation of the original material, for example, as formed by shock-melting processes.

McKay, D. S. and Morrison, D. A.: 'Lunar Breccias', *J. Geophys. Res.* **76**, 5658–69.

Four primary types of breccia have been described thus far from the Apollo samples. These are (1) welded or sintered breccias, (2) glassy breccias in which glass is the dominant component and which contain xenocrysts and xenoliths in various stages of disruption, (3) breccias having the characteristics of 'instant rock' described by N. M. Short and E. C. T. Chao *et al.*, and (4) recrystallized breccias in which matrix and clasts have undergone partial to complete thermal recrystallization. The welded or sintered breccias are the dominant breccia type in the hand-specimen-size breccia samples from the Apollo 11 site. Welded breccias are a mixture of rock fragments, crystal fragments, and glasses variable in both composition and form and sintered to varying degrees of induration. There is little or no evidence of displacement of components relative to each other after incorporation into the breccia. Porosity varies but is generally high, and the degree of induration and cohesion is variable. Accretionary lapilli are common. The chemistry of these breccias, although similar to that of the returned soil at the Apollo 11 site, is distinct and varies between samples in a systematic way. The available evidence indicates that the welded lunar breccias were formed by sintering of impact-generated debris and are not the result of shock lithification of lunar soil.

Reedy, R. C. and Arnold, J. R.: 'Interaction of Solar and Galactic Cosmic-Ray Particles with the Moon', *J. Geophys. Res.* **77**, 537–555.

The rates of formation of radionuclides as a function of depth in the Moon are calculated for bombardments by galactic-cosmic-ray particles and by solar protons. The fluxes and spectra of galactic-cosmic-ray particles and of solar protons as a function of depth in the Moon are first determined semiempirically. For galactic cosmic rays, the model emphasises the production of secondary particles and the attenuation of particles by nuclear interactions. Solar proton calculations cover a range of observed spectral parameters. Here only ionization energy losses need be considered. The excitation functions for the nuclear reactions used in these calculations are presented. The calculated production rates are given for a range of depths in the Moon and are compared with experimental results and with earlier calculations. The model can also be applied to other effects of particle bombardment.

Stephenson, A.: 'Single Domain Grain Distributions – II. The Distribution of Single Domain Iron Grains in Apollo 11 Lunar Dust', *Phys. Earth Planetary Int.* **4**, 361–369.

A quantitative analysis of some of the magnetic properties of an Apollo 11 lunar dust sample is given. The measurements involved are the acquisition of isothermal and viscous remanence, the thermal demagnetization of isothermal and thermoremanence, and the temperature and frequency dependence of the initial susceptibility. It is shown that the experimental results are in good agreement with those predicted from single domain theory and can be explained on the basis of an assembly of single domain iron grains distributed such that the number of grains within a given volume range is inversely proportional to the square of the volume.

Swann, G. A., Trask, N. J., Hait, M. H., and Sutton, R. L.: 'Geologic Setting of the Apollo 14 Samples', *Science* **173**, 716–719.

The Apollo 14 lunar module landed in a region of the lunar highlands that is part of a widespread blanket of ejecta surrounding the Mare Imbrium basin. Samples were collected from the regolith developed on a nearly level plain, a ridge 100 m high, and a blocky ejecta deposit around a young crater. Large boulders in the vicinity of the landing site are coherent fragmental rocks as are some of the returned samples.

Tyler, G. L. and Ingalls, D. H. H.: 'Functional Dependences of Bistatic-Radar Frequency Spectra and Cross Sections on Surface Scattering Laws', *J. Geophys. Res.* **76**, 4775–4785.

A technique for computing bistatic-radar echo characteristics from arbitrary scattering functions is developed and applied to several well-known laws. For a Gaussian scattering law, the bandwidth of the echo spectrum is nearly proportional to surface slopes, whereas the total received power is only weakly dependent on slopes. The contribution to radar cross section of a diffuse scattering law under oblique bistatic geometries can be markedly less than for monostatic geometry at large ranges. Numerically obtained dependences of bistatic cross section on mean square surface slopes support previous inferences from Explorer 35 data that lunar highlands are less reflective than the seas.

12. Photometry of the Moon

Armstrong, T. W.: 'Calculation of the Lunar Photon Albedo from Galactic and Solar Proton Bombardment', *J. Geophys. Res.* **77**, 524–536.

The lunar photon albedo due to cosmogenic and primordial photon sources has been calculated. The individual photon leakage spectra from prompt photons produced by galactic cosmic ray (GCR) and solar cosmic ray (SCR) induced nuclear interactions, from the decay of GCR- and SCR-induced radionuclides, and from the decay of naturally occurring radionuclides are given. An approximate estimate of the leakage from the photon-electron cascade initiated by the decay of neutral pions is also given. Monte Carlo methods have been used to determine the nucleonmeson cascade, and discrete-ordinates methods were used for the photon and low-energy neutron transport.

Hoyt, H. P., Jr., Miyajima, M., and Walker, R. M.: 'Brief Review of Thermoluminescence Studies in Lunar Samples', *Modern Geol.* **2**, 263–264.

Samples of rock and soil from both Apollos 11 and 12 exhibit a weak thermoluminescence due primarily to plagioclase feldspar. The TL increases with depth below the surface for about 10 cm and then becomes relatively flat. This depth dependence can be used to prove that the core tubes have not been mixed in transit and to derive average depths for bulk soil samples. The effect also establishes the penetration of the diurnal temperature wave. Some TL stratigraphy in the cores may be present. Although the surface rocks show evidence of thermal draining, preliminary results indicate considerable differences between surface and interior samples. Quantitative studies of this effect may make it possible to measure solar flare particle spectra averaged over the last 10^4 yr. The efficiency of TL production in these samples is too low to account for any Earth-based observation of transient optical effects on the Moon.

Kemp, J. C., Wolstencroft, R. D., and Swedlund, J. B.: 'Circular Polarization: Jupiter and Other Planets', *Nature* **232**, 165–168.

Circular polarization of scattered light from Jupiter has now been studied during a recent opposition of the planet, showing changes in the sign of the north and south polar values indicative of a non-magnetic origin for the polarization. Preliminary observations on Mars, Venus, Mercury and the Moon demonstrate the generality of this effect and its potential usefulness.

McCord, T. B., Charette, M., Johnson, T. V., Lebofsky, L. A., and Pieters, C.: 'Lunar Spectral Types', *Bull. Am. Astron. Soc.* **3**, 280.

Distinct classes of spectral reflectivity curves exist for various regions of the lunar surface and these classes are directly correlated with surface morphology (i.e. maria, uplands, bright craters) (McCord, 1969; *J. Geophys. Res.* **74**, 3131). Also, a weak absorption band appears at 0.95 μ in the lunar reflection spectrum (McCord and Johnson, *ibid.* 4395; 1970, *Science* **169**, 855). More extensive telescope observations of lunar areas on the scale of 10–20 km in the extended spectral region 0.30–1.10 μ reveal that: (1) there is a spectral feature in the reflection spectrum in the UV spectral region which further characterizes the spectral curve types found earlier; (2) a continuous series of spectral curves exists with fresh, bright crater curves as one end-member and background upland or background maria curves as the other extreme of the series, implying a relation between age and optical properties; (3) within the maria a curve-series exists, extending from curves for very dark, less red mare areas to curves for brighter, redder mare regions; (4) an absorption band exists in nearly all reflection spectra measured and the band always occurs at 0.95 ± 0.01 μ regardless of the lunar area observed, implying little variation in the average *mafic* mineral composition over the entire lunar surface. (Abstract of a paper presented at the February 1971 meeting of the American Astronomical Society).

14. Electromagnetic Properties of the Moon

Jackson, J. S.: 'Diurnal Variation of the Geomagnetic Field. 2. The Lunar Variation', *J. Geophys. Res.* **76**, 6909–6914.

The dynamo theory of the lunar magnetic variations is developed as a three-dimensional problem. The finite thickness of the ionospheric-current layer and the anistropy of the conductivity are considered. The currents responsible for the lunar magnetic variations are assumed to flow in the same layer of the ionosphere as those responsible for the solar magnetic variations, i.e. from 100 to 120 km above the Earth's surface. The pattern of the results is similar to that for the solar variation, especially the magnetic-field results. The horizontal magnetic field is greatest in the middle of the current layer and at that height it is about 7 times as great as that at the ground. The pressure variation in the lower half of the layer is about 180° out of phase with that at the ground.

Jiracek, G. R. and Ward, S. H.: 'Oblique Electromagnetic Reflection from Layered Lunar Models Based on Data from Apollo 11 and Apollo 12', *J. Geophys. Res.* **76**, 6237–6245.

Specular reflection of an arbitrarily polarized plane electromagnetic wave incident on lunar models that consist of discrete plane layers is completely determined by two orthogonal complex reflection coefficients. These measurable quantities permit estimates of the electrical properties and vertical extents of near-surface plane homogeneous layers and may be diagnostic of pore moisture in any layer. Substitution of a gradational lunar regolith for a homogeneous one does not alter the above comments, but at high frequencies the reflection coefficients pertain only to the properties of the very top of the debris. Reflection from layers that have magnetic properties similar to those measured in the Apollo 11 and Apollo 12 lunar samples yields fictitious estimates of dielectric constant values, significantly lower than actual, if the permeability is ignored in the interpretation process. Theoretical bistatic radar results presented at 136.11 MHz clearly show that large changes in reflectivity may be the result of very small changes in debris thickness. When lateral variations exist within the reflecting area, interpretations based on laterally homogeneous layering must be modified.

Kuckes, A. F.: 'Lunar Electrical Conductivity Profile', *Nature*, **232**, 249–251.

Recent measurements and analysis of magnetic field fluctuations on the surface of the Moon have led Sonett *et al.* to conclude that the Moon is stratified into an upper mantle, a lower mantle and a core. Using an eight-layer model, their computer analysis of magnetic field fluctuation data led to the conclusion that there is a highly conducting shell about 100 km thick, located about 220 km below the lunar surface. In this article their experimental data are re-analyzed in terms of a simple two layer model. The author concludes that the field fluctuation spectrum observed accurately follows from a Moon with an inner core which has a uniform conductivity of 6×10^{-4} mho m^{-1} and an insulating mantle about 160 km thick. These results coincide more closely with the preliminary conclusions of Sonnett *et al.* than their more refined calculations which indicate a very non-uniform and non-monotonic conductivity profile.

Ness, N. F.: 'Interaction of the Solar Wind with the Moon', *Phys. Earth Planetary Int.* **4**, 197–198.

During its orbit about the Earth, the Moon is located in the interplanetary medium or the geomagnetosheath-geomagnetotail formed by the solar wind interaction with Earth. In the tail no evidence is found for a lunar magnetic field limiting the magnetic moment to 10^{20} G cm^3 ($< 10^{-6}$ of that of the Earth). In the interplanetary medium, no evidence exists for a bow shock or a trailing shock although a well defined plasma wake region is observed in the anti-solar wind direction. The Moon absorbs the solar wind plasma which strikes its surface and creates a void region or cavity in the flow. Small perturbations of the interplanetary magnetic field magnitude ($\lesssim 30\%$) and direction ($\lesssim 20°$) are observed to be correlated with the location of the solar wind plasma umbra and penumbra. Characteristic perturbations in magnitude are $+ - + - +$ as a satellite traverses the wake region. The magnitude of the anomalies is correlated principally with the diamagnetic properties of the solar wind, as measured by β, and less with the direction of the interplanetary magnetic field. The observed lunar Mach cone gives evidence for the anisotropic propagation of waves in the magnetized collisionless warm solar wind plasma. Neither the Gold-Tozer-Wilson mechanism of accretion of field lines or the Sonett-Colburn-Hollweg mechanism of unipolar induction is significant in the interaction. The transmission of microstructural discontinuities in the interplanetary medium past the Moon show little distortion, indicating a low effective electrical conductivity ($< 10^{-4}\ \Omega^{-1}\ \mathrm{m}^{-1}$) which implies a relatively cool interior ($\lesssim 10^3$K) of the lunar body. Fluctuations of the interplanetary magnetic field upstream from the plasma wake are stimulated by the disturbed conditions in that region. The Moon behaves like a cold, nonmagnetic fully absorbing dielectric sphere in the solar wind flow. (Abstract only).

Schubert, G. and Colburn, D. S.: 'Thin Highly Conducting Layer in the Moon: Consistent Interpretation of Dayside and Nightside Electromagnetic Responses', *J. Geophys. Res.* **76**, 8174–8180.

The vacuum transient response of the Moon to a time-varying spatially uniform magnetic field is determined for a lunar electrical conductivity model that was based on the harmonic analysis of Apollo 12 and Explorer 35 dayside magnetometer data. The transient response of the model is found to provide a plausible explanation of the behaviour of the local vertical-surface magnetic field for an Apollo 12 magnetometer darkside transient event. A model containing a conducting core and a highly conducting thin subsurface layer is presented, and its transient behavior is discussed.

Sonett, C. P., Colburn, D. S., Dyal, P., Parkin, C. W., Smith, B. F., Schubert, G., and Schwartz, K.: 'Lunar Electrical Conductivity Profile', *Nature* **230**, 359–362.

Measurements of electrical conductivity profile provide information about the mantle-core stratification, near surface thermal gradient, heat flux and composition of the Moon.

Sonett, C. P. and Mihalov, J. D.: 'Lunar Fossil Magnetism and Perturbations of the Solar Wind' *J. Geophys. Res.* **77**, 588–603.

Perturbations of the solar wind downstream of the Moon and lying outside of the rare faction wave that defines the diamagnetic cavity are used to define possible source regions comprised of intrinsically magnetized areas of the Moon. A map of the Moon is constructed showing that a model in which the sources are exposed to the grazing solar wind during the lunation yields a selenographically invarient set of regions strongly favoring the lunar highlands over the maria. An alternative model with the source due to electromagnetic induction is explored. The ages of the field sources should be consistent with those based on the basalt ages and possibly far older if the sources are connected with the formation of the highland rocks themselves. The perturbations are tentatively identified as weak shock waves, and a Mach angle in accord with nominal values for the solar wind is found.

Tsay, F. D., Chan, S. I., and Manatt, S. L.: 'Ferromagnetic Resonance of Lunar Samples', *Geochim. Cosmochim. Acta* **35**, 865–875.

Evidence is presented to support that the electron spin resonance (ESR) spectra observed for a selection of Apollo 11 lunar samples (10087-10, 11; 10046-29, 30; 10062-26, 27; 10017-35, 36) arise from the ferromagnetic centers consisting of metallic Fe. A model study to simulate the polycrystalline spectra has been carried out, from which it was possible to ascertain with some degree of certainty the size and shape of the ferromagnetic centers as well as the metallic iron content. Some variations in the metallic Fe content have been noted in these samples, for example, between rocks and fine soil.

15. Exploration of the Moon by Spacecraft

The Lunar Sample Preliminary Examination Team: 'Preliminary Examination of Lunar Samples from Apollo 14', *Science* **173**, 681–693.

The major findings of the preliminary physical, chemical, mineralogical, and biological analysis of 43 kg of lunar rocks and fines are that only a small portion of the larger rocks has basaltic textures. The samples consist largely of fragmental rocks containing clasts of diverse lithologies and histories. The rocks contain orthopyroxene and more plagioclase than earlier lunar samples. They differ chemically from earlier lunar rocks and from their closest meteorite and terrestrial analogs. The chemical composition of the soil closely resembles that of the rocks. Rocks display impact microcraters, rounding of the surface, and shock effects, and no evidence of exposure to water or to an environment with high oxygen activity. The concentration of solar wind – implanted material is large in the soil, but ranging from approximately that of the soil to essentially zero in the fragmental rocks. Carbon contents lie within the range of those for earlier Apollo samples. Four fragmental rocks show much shorter exposure times than Apollo 11 and 12 rocks. A much broader range of soil mechanics properties was encountered at the Apollo 14 landing site than at former landing sites, f.i. lesser cohesion, coarser grain size and greater resistance to penetration. The soils are more poorly sorted, but the range of grain size is similar to those of the earlier Apollo soils. No evidence of biological material has been found.

Reasoner, D. L. and O'Brien, B. J.: 'Measurement of Plasma Clouds Produced by the Apollo 14 Lunar Module Impact', *EOS* **52**, 535.

The Apollo 14 Lunar Module ascent stage impacted on the lunar surface on 7 February 1971 at 00 hr, 45 min, 24 s GMT. Shortly after the impact the Charged Particle Lunar Environment Experiment (CPLEE) detected fluxes of low energy ions and negative particles, with intensities a factor of 10 greater than ambient fluxes. The ion and negative particle enhancements exhibited near-perfect temporal simultaneity, and thus the authors refer to these events as plasma clouds. They report a preliminary study of these plasma clouds. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union).

Watts, R. N., Jr.: 'Apollo 14's Moon Mission', *Sky Telesc.* **41**, 200–208.

A popular description of the mission accompanied by photographs of lunar rocks in situ.

Watts, R. N., Jr.: 'Apollo 15 Television from the Moon', *Sky Telesc.* **42**, 136–138.

A selection of Apollo 15 television photographs is presented with notes on the mission.