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; Lunar Astronautics

Griffith, J. S.: 'On Some Approximations in Brown's Lunar Theory', *Celes. Mech.* **4**, 54–9.

A re-evaluation of Brown's Lunar Theory has long been awaited. While working on the 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.

Kaula, W. M.: 'Dynamical Aspects of Lunar Origin', *Rev. Geophys. Space Phys.* **9** (1971), 217–38.

According to tidal friction calculations in which estimates of the current dissipation factor are used, the Moon was close to the Earth less than two billion years ago. The most plausible solution to this 'time scale' problem appears to be a much lesser extent of shallow seas in the past; a coupling of the Moon's orbit with Venus is also a possibility. The same calculations indicate that the Moon had an inclination of at least 10° to the equator, and that the Earth's rotation period was five hours. Fission hypotheses, of which the most carefully developed is by O'Keefe, have not yet dealt successfully with these constraints. Fission theories are also unsatisfyingly episodic: matter must first lose angular momentum to fall into the Earth, and then regain it to separate. All capture hypotheses are inherently improbable, particularly if the Moon came from a different enough part of the solar system to account for the Moon's density difference. The least implausible capture hypothesis, by Urey and MacDonald, entails collision with a pre-existing Earth satellite at 30–40 Earth-radii, but the reasoning behind it is not compelling. Most compatible with the idea that formation of the Moon is closely connected to the formation of the Earth are hypotheses that the Moon formed out of a geocentric swarm of matter to which matter from heliocentric orbit was continually added. The theory of Ruskol seems to incorporate most of the dynamical essentials.

Kaula, W. M.: 'Dynamical Aspects of Lunar Origin', *EOS* **52** (1971), 266

Tidal evolution calculations obtain that the Moon had an inclination of at least 10° to the equator, and the Earth a rotation period of 5 hours. Fission hypotheses have not met these constraints, and are also unsatisfying in that matter must first lose angular momentum to fall into the Earth, and then regain it to separate. All capture hypotheses are inherently improbable, particularly if the Moon came from a different enough part of the solar system to account for its density difference from the Earth. Most compatible with the idea of a lunar formation closely connected to the Earth's are hypotheses that the Moon formed from a geocentric swarm of matter to which matter from heliocentric orbit was continually added. Such models need to be developed further to include gas drag and other effects of the severe heating associated with Earth-Moon chemical fractionation, as well as to account for the lunar orbit inclination. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

3. Shape and Gravitational Field of the Moon

Kaula, W. M.: 'Prospects for Planetary Geodesy', *EOS* **52** (1971), 181.

A better overall determination of the Moon's shape is needed, as well as a farside gravitational field. The former will be partly obtained by the Apollo altimeter. The latter can be achieved by satellite-to-

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satellite tracking or gravity gradiometry, neither of which is expected to be done soon. Orbiters around Mars and Venus will interesting detail on their gravitational fields. Radar will obtain further data on the topographic variations of these planets. For the more distant planets only improvements in masses and radii are anticipated. (Abstract of a paper presented at the April 1971 meeting of the American Geophisical Union.)

Murphy, J. P., Felsentreger, T. L., and Wagner, C. A.: 'Lunar Gravity Models from Lunar Satellite Orbital Element Histories', *EOS* **52** (1971), 479.

Several lunar gravity models have been derived from an analysis of orbital element evolutions for the Lunar Orbiter satellites and the Apollo 8, 10, 11 and 12 Command Modules. At least one of these models, designed ML1.1, shows promise for good orbit prediction in future Apollo missions. The ML1.1 model consists of the current Apollo operational field (the L1 model) plus the following values for the (4, 1) spherical harmonic coefficients (unnormalized): $C_{41} = -0.1284 \times 10^{-4}$, $S_{41} = 0.1590 \times 10^{-4}$. It was determined from Apollo 8, 10, 11 and 12 data only. The main benefit to be derived from this model lies in its capability to predict the Apollo inclinations better than the L1 model by a factor of 3–4 (to within 0.03 deg), and the faster-moving Apollo nodes better than the L1 model by an everage factor of about 10 (to within approximately a degree). In addition, the ML1.1 model performs as well or better than the L1 field in predicting trajectories for Lunar Orbiter as well as Apollo spacecraft. For instance, over a 40-day span of Lunar Orbiter 3 data, the ML1.1 model predicts the inclination to within 0.5 deg, while the L1 model gives results consistently off by a degree or more. Also, fits to short arc Apollo tracking data using the L1 and ML1.1 models are quite comparable. (Abstract of a paper presented at the December 1970 meeting of the American Geophysical Union.)

4. Internal Structure of the Moon

Chapman, W. B. and Middlehurst, B. M.: 'Directional Tides in Moonquake Triggering', *EOS* **52** (1971), 267.

Moonquakes that correlate with each period of minimum Earth-Moon distance (perigee) have been reported. A tentatively identified epicenter is in the area of crater Fra Mauro where calculated tidal gravity, an expression of vertical tidal stress, undergoes a minimum value at every perigee. This vertical correlation can lead to an explanation by means of a fluid dependent mechanism, which, if supported by data from Apollo 14 experiments, would reinforce sparce information about a partially understood lunar geological instability. The significance of tidal stress action in a different direction is also examined here through calculation of horizontal tidal accelerations. In these compared at selected azimuths, the NE tidal acceleration undergoes a maximum value at every perigee, but it is too much like the vertical to offer a separate correlation. In contrast, at the N 30°W azimuth, which is normal to linear rille trends in Fra Mauro and Parry, the tidal acceleration changes most rapidly from NW to SE at every perigee. This maximum rate of change in a directional tidal acceleration is suggested as an improved index of the stress/strain relationship in the triggering of moonquakes. This suggestion, through its application at an azimuth for one set of moonquakes, will tend to be verified if the times of occurrence develop a shift in phase that closely matches the systematic shift from perigee of the N 30°W tidal calculation. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Danes, Z. F. and McNeely, D. R.: 'Mascons and Lunar Isostasy', *EOS* **52** (1971), 435.

Combining data on isostatic compensation of lunar craters (shape of crater versus age) with the gravity anomalies revealed by the perturbations of lunar satellites reveals that the Moon may have at least three layers: a 'crust' of viscosity comparable of terrestrial basalts (10^{24} P) and thickness of a few km; an 'asthenosphere' of viscosity comparable to that necessary for the Fennoscandian uplift and Lake Bonneville adjustment (10^{21}–10^{22} P) and thickness of the order of 100 km; and a 'core' of viscosity of 10^{25} P. (Abstract of a paper presented at the Pacific Northwest Regional Meeting October 1970.)

Duennebier, F. K.: 'Short-Period Seismic Events from Apollo XI', *EOS* **52** (1971), 267

Several hundred events were detected by the Apollo 11 short-period seismometer. Of these events, two sets, T-type and I-type events, are interesting in that all events of each set are nearly identical. In this way they are similar to the moonquakes detected by the Apollo 12 long-period seismometers. The I- and T-type events differ from the Apollo 12 moonquakes in that they are more frequent, shorter in duration, and higher in frequency content. Evidence suggests that the I-type events are generated by seismic energy originating at the Apollo 11 descent stage. Since the I- and T-type events have different signatures, they probably originate at different sources. It is suggested that T-type events are moonquakes. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Thapar, M. R.: 'Further Experimental Investigation of the Nature of the Lunar Seismic Signals' *EOS* **52** (1971), 267.

Several different models of the Moon have been proposed by various workers in order to explain the unexpected nature of the lunar seismic signals received during the Apollo 12 and Apollo 13 Moon missions. While Gold and Soter proposed a layer of powder all around the Moon, Nakamura, Latham, Ewing and Dorman attempted to explain the nature of the lunar seismic signals by assuming intense scattering of surface waves due to the heterogeneity in the upper few kilometers of the Moon. Thapar showed experimentally that an impact on a homogeneous steel sphere gives rise to a signal similar to the lunar signal (decaying slowly with time). This experimental study has been further extended to show the phenomenon of dispersion with distance on a steel sphere. These laboratory experiments have demonstrated that the signal is mainly due to the surface wave energy in a homogeneous sphere and that the effect of scattering due to a dent in the sphere reduces the amplitude of the signal. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

5. Thermal and Stress History of the Moon

Green, D. H.: 'Experimental Petrology and Petrogenesis of Apollo 12 Basalts', *EOS* **52** (1971), 272.

Experimental studies at 1 bar and up to 30 kbar establish the crystallization sequences for basalts 12021, 12065, 12022, 12009, and 12040. Olivine is the liquidus phase at low pressures, with minor chromium spinel and pigeonitic clinopyroxene joining the olivine at lower temperatures or accompanying the olivine in the less magnesian basalts (12021, 12065). At higher pressures, sub-calcic clinopyroxene becomes the liquides phasu except in the most magnesian basalt (12040) where orthopyroxene joins the olivine and becomes the liquidus phase at pressures of 25kbar. The Apollo 12 basalts provide clear evidence for the genesis of olivine-rich basalts in the lunar interior and for the nature of the source rocks as a pyroxenite or olivine-bearing pyroxenite in which orthopyroxene is probably the major phase with lesser sub-calcic or pigeonitic clinopyroxene. The 100Mg/Mg + Fe ratio of the source region in the deep lunar interior is 75–80. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Hafner, S. S., Virgo, D., Warburton, D., Fernandez-Moran, H., Ohtsuki, M., and Hibino, A.: 'Subsolidus Cooling History of Coarse-Grained Lunar Basalt from Oceanus Procellarum', *Nature* **231** (1971), 79–80.

Investigations of the chemical and structural relationships in clinopyroxene crystals reveal information on the crystallization temperatures of the lunar magmas and subsequent cooling rates. The authors studied lunar basalt 12021. The groundmass of this basalt consists predominantly of extremely inhomogeneous brown clinopyroxene, calcium rich plagioclase, and ilmenite. It was found that the natural Mg^{2+}, Fe^{2+} distribution in the clinopyroxene corresponds to an equilibrium temperature of approximately 570°C. Also, the extensive exsolution is evidence for slow cooling rates, or possibly

annealing, at temperatures in the subsolidus range. The textural relationships and the exceedingly slow cooling rate, or possible annealing, between approximately 1000 and 480°C are consistent with the suggestion that basalt number 12021 is part of the slowly cooled interior of a lava flow or lake on the lunar surface.

Heiken, G. and Lofgren, G.: 'Terrestrial Glass Spheres', *Geol. Soc. Am. Bull.* **82** (1971), 1045–50.

Terrestrial glass spheres similar to the glass spheres found in the lunar soil samples have been produced by the eruption of low-viscosity basaltic magmas and by a TNT surface explosion on alluvium. The vocanic spheres range in diameter from 2μ to several millimeters and have smooth surfaces. The explosion-produced spheres are of similar size but have surfaces covered with smaller spheres and angular particles. Both the volcanic and the explosion-produced spheres have analogs in the lunar materials.

Hollister, L. S., Hargraves, R. B., and Trzcienski, W. E., Jr.: 'Role of Pigeonite Phenocrysts in the Interpretation of Magnetic Processes on the Moon', *EOS* **52** (1971), 270.

Understanding the crystallization history of the pigeonite (and olivine) phenocrysts of the porphyritic basalts is crucial to the interpretation of magmatic processes on the Moon. It has been proposed (1) that the phenocrysts are the result of growth during an initial slow cooling state, possibly in the lunar interior, followed by a rapid cooling stage on the lunar surface and (2) that they are the first crystals to have grown when superheated melts, compositionally the same as the bulk rocks, were supercooled on the lunar surface. The first alternative implies processes common to terrestrial basalts: partial melting and/or differentiation. The second alternative implies a magma generation process which results in highly mafic liquids; and it suggests that metastable nucleation and growth of phases may play an important role in the development of the observed diversity of mineral assemblages. The authors suggest that there is sufficient evidence for serious consideration of the second alternative. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

James, O. B.: 'Origin of Lunar Microbreccia 12013', *EOS* **52** (1971), 272.

Petrographic and microprobe studies indicate that 12013 is a thermally metamorphosed microbreccia. The sample is heterogeneous, with three dominant lithologies: (1) gray fragment aggregate; (2) dark gray fragment aggregate; and (3) light gray felsite. Mineralogically, lithologies (1) and (2) consist dominantly of pyroxene and plagioclase where lithology (3) is composed almost entirely of potassium feldspar and quartz. Lithologies (1) and (2) contain different fragment suites and different types of matrices indicating that they initially represented two different fragmental rocks. Most of 12013 is a mottled mixture of lithologies (1) and (3); lithology (2) occurs as large patches within this mottles rock. The textures and gross structures of the rock and comparisons with unmetamorphosed lunar breccias suggest the following interpretation of the origin of the sample. Gray aggregate (1) consists largely of fallout impact debris; it represents the 'groundmass' material of the breccia. Dark gray aggregate (2) was included in this breccia as aggregates of fragments bound together by a molten or glassy matrix. Felsite (3) was incorporated as fragments of glass of irregular droplets of melt. Heating during or after aggregation produced metamorphic mineral reactions and textures. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Papanastassiou, D. A., Turner, G., and Wasserburg, G. J.: 'Beginnings of a Lunar Chronology', *EOS* **52** (1971), 265.

A sequence of magnetic events on the Moon was revealed through Rb-Sr and ^{40}Ar-^{39}Ar dating. Chronologies are in close agreement apart from minor differences and indicate: (a) 4.6 AE, large-scale differentiation, concentration of K, Rb, Th, U at the surface; (b) 4.0 AE, remelting of granite and injection into 'basaltic' breccia; (c) 3.65 AE, basaltic flows on the Sea of Tranquillity; (d) 3.25 AE,

basaltic flows on the Ocean of Storms. Initial Sr *isotopic* compositions show Moon accreted from non-chondritic material, highly fractionated with respect to solar abundances. Similarity of rock 13 granitic phase with granitic quintessence isolated from basaltic rocks shows that granite (and certainly rhyolite flows) were formed during each magmatic event including the earliest differentiation at 4.6 AE. Granite formation may involve filter pressing and liquid immiscibility on a large scale as well as fractionation processes operative on Earth. The outer part of the Moon may reflect an original accretional layering (modified by shallow differentiation) or may be the result of differentiation of the deep interior. Most lunar rocks and soil magic component are consistent with closed evolution for 4.6 AE and may reflect only limited subsequent activity in a shallow crust. Differentiation processes over the first ~ 1.5 AE may occur on other lunar-size planets (Mars and Galilean satellites) in contrast to either a continuously rejuvenated Earth or fossil asteroids. (Abstracts of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Papanastassiou, D. A. and Wasserburg, G. J.: 'Lunar Chronology and Evolution from Rb-Sr Studies of Apollo 11 and 12 Samples', *Earth Planetary Sci. Letters* **11** (1971), 37–62.

Rb-Sr internal isochrons for a total of eight Apollo 12 crystalline rocks yield ages of 3.36 to 3.16 AE. The initial Sr compositions (1) are relatively primitive and range from 0.699 18 to 0.699 57 as compared to BABI = 0.698 98 ± 3. No clear groupings in I are observed, however, the wide range indicates that at least four different rock bodies were sampled. An Apollo 11 basalt (10024) yielded an age of 3.61 ± 0.07 AE and $I = 0.69935 \mp 8$ in agreement with previous results on other Apollo 11 high K rocks. Several Apollo 12 soil samples yield model ages which range from 4.4 to 4.6 AE and indicate that the special nature and older 'age' of the lunar soil determined at the Apollo 11 site is a widespread phenomenon. Initial Sr compositions from Apollo 11 and Apollo 12 support our previous conclusions that the Moon as a whole has a Rb/Sr much lower (Rb/Sr ~ 0.008) than found in chondrites. The authors summarize the current status of Rb-Sr lunar chronology and some implications regarding the melting and differentiation history of the Moon.

Romey, W. D.: 'Lunar "Anorthosite"?', *Science* **172** (1971), 292–3.

The author is unconvinced that lunar 'anorthosite' is anorthosite at all, because it does not resemble anorthosite, kenningite, or any other widely distributed terrestrial rock that he knows of. The lunar 'anorthosite' is very fine grained, and the anorthite content of its plagioclase is mainly 96 to 98%. Terrestrial anorthosite, on the other hand, is generally a coarse-grained, plutonic rock in which individual plagioclase crystals generally exceed the size of the complete lunar rock fragments. The anorthite content of terrestrial anorthosite ranges from about 30% to between 85 and 90% averaging between 45 and 70%.

Sun, J. M. S.: 'Cometary Impact Origin of Some Glasses on the Moon', *EOS* **52** (1971), 274.

The Apollo-11 samples from the Moon contain abundant glasses which occur in the forms of spheres, droplets, glazes, splashes, and coatings. Some samples contain as much as 50% of glasses by volume. According to a prevailing hypothesis, these glasses were formed by shock wave compression caused by meteoritic impacts. Evidences of meteoritic impacts and explosion cratering experiments on Earth would indicate that only a small amount of glasses, not including glazed glasses, could be formed by meteoritic impacts. Evidences of the midair cometary explosion over Tunguzka, and the above-ground Trinity atomic explosion near Alamogordo, New Mexico would lead to an alternative hypothesis that the lunar glasses were formed by the heating of above-ground fireballs of cometary impact explosions. Thetomorphic glasses may also be formed by shock wave compression of a cometary explosion. Large amount of glasses were formed by the Trinity atomic fireball. Meteorites would penetrate deep into the ground and then explode, whereas a snowball comet could explode above the ground. Some theoretical consideration and examination of cratering phenomenology would substantiate this hypothesis of cometary impact origin of the lunar glasses. Further studies of the glasses would help to understand better the nature of the comet, and throw more light to the origin of the solar system. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Takeda, H. and Reid, A. M.: 1971, 'Euhedral Clinopyroxenes in a Vug from an Apollo 12 Rock', *EOS* **52** (1971), 271.

Prismatic crystals with {110} and {010} in a vug from rock 12052 have been studied by single-crystal X-ray diffraction and electron probe microanalysis. Honey yellow core pigeonites $Wo_9En_{63}Fs_{28}$ (rarely $Wo_{22}En_{51}Fs_{27}$ core) are overgrown, with approximately (100) in common, by dark brown augites $Wo_{33}En_{43}FS_{24}$ which exsolve very small amounts of pigeonites on (001). Zoning is much less than in the phenocrysts (Bence *et al.*, 1970), and the boundaries between pigeonite and augite are sharp. The lack of high Fe increase at the margins can be correlated with the formation of vugs. The beta angles (pig. 108.40°, aug. 106.82°) are close to those of crystals quenched from the temperatures near the solubility gap. The crystal structure and the cation distribution of an augite ($Ca_{0.59}$ $Fe_{0.43}$ $Mg_{0.78}$ $Ti_{0.07}$ $Cr_{0.03}$ $Al_{0.06}$) ($Si_{1.79}$ $Al_{0.21}$)O_6, *a* 9.726(2) *b* 8.909(3) *c* 5.269(1) Å, beta 106.82°(2), *C*2/c, separated from the rim, has been refined by least squares technique using 625 reflections to $R = 0.06$. The M2 polyhedra, containing considerable Mg and Fe, are characterized by shorter M2-01,02 distances (av. 2.252 Å) and longer M2-03 (av. 2.717 Å) than those of a diopside and of Kakanui augite. This deformation is compatibled with the above thermal history and suggests very rapid post-crystallization cooling on or near the lunar surface. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Hsui, A., Turcotte, D. L., and Torrance, K. E.: 'Thermal Convection Within a Fluid Sphere and Its Application to the Moon', *EOS* **52** (1971), 267.

Evidence that the Moon has been hot during some portion of its evolution is overwhelming. In bodies of planetary size it is expected that heat transfer by solid-state convection will be dominant at temperatures above 1000°C. Within the Moon the pressure is sufficiently small so that the pressure influence on solid-state viscosity can be neglected. A series of numerical calculations has been carried out to obtain the structure of convection cells within a self-gravitating fluid sphere with uniform heat release. From the critical Rayleigh number ($Ra = \alpha\varphi H\ G\ R^6/k\chi\ \nu$, α coefficient of thermal expansion, φ density, H heat release per unit mass, G universal constant of gravitation, R radius, k thermal conductivity, χ thermal diffusivity, ν kinematic viscosity) of 5758 up to 5×10^5 steady flows were obtained. However as the Rayleigh number increased the number of cells also increased. In the range $5758 < Ra < 3 \times 10^4$ a single convection cell was found, for $2 \times 10^4 < Ra < 5 \times 10^5$ double cell convection was observed, and at $Ra = 5 \times 10^5$ four cells developed. Flow fields, temperature distributions, and the variation of the surface heat flux have been obtained. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Urey, H. C.: 'Was the Moon Originally Cold?', *Science* **172** (1971), 403–5.

Defending the idea of a cold or cool origin of the Moon, which was first definitely stated by the author, he explains the origin and purpose of the suggestion and his present ideas in regard to the problem. He and his co-workers assumed the formation of the Moon from a limited number of objects in a low-temperature condition. Some of the early ideas in regard to lunar structure had to be modfied when the mascons were discovered and the surface regions proved to be highly differentiated. A model of a melted surface layer and a cool interior for the early structure was adopted. The author now disagrees with many things that he once advanced. However, he feels that those who attempt to understand the arguments will recognize that he was more right than wrong.

Wakita, H. and Schmitt, R. A.: 'Lunar Anorthosites: Plagioclase Crystallization', *Science* **172** (1971), 184.

The authors admit a misunderstanding of a reference cited and a resulting false conclusion in a report published in *Science* **170** (1970), 969.

Walter, L. S.: 'Late-Stage Emplacement of Iron in Lunar Samples', *EOS* **52** (1971), 271.

Metallic iron occurs in two Apollo 12 samples, forming textures strongly suggestive of latestage emplacement after crystallization of the rocks. In thin section 12021.142, about 50 parallel needles of metallic iron occur within a large pyroxene crystal in an area about 200 μm in diameter. Individual needles have rhombic cross-sections about 10 μm on edge, with edges parallel to the cleavage traces of the host pyroxene. The iron needles contain about 1.5 wt. percent Co and 0.5 wt. percent Ni. There are no significant compositional gradients in the pyroxene adjacent to the needles. In section 12040.47, metallic Fe (containing about 4 wt. percent Ni and 1.5 wt. percent Co) fills irregular cracks in both pyroxene and chrome spinel. In both specimens, the metal phase is not associated with sulfide and has the same composition as other interstitial metal particles in the specimen. The textures, combined with the higher melting point of the metal relative to its host minerals, indicate emplacement of the metal from a late-stage vapor phase after crystallization of the rock. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

6. Chemical Composition of the Moon

Adams, J. A. S., Barretto, P. M., Clark, R. B., and Duval, J. S., Jr.: 'Radon-222 Emanation and the High Apparent Lead Isotope Ages in Lunar Dust', *Nature* **231** (1971) 174–5.

Uranium-lead and thorium-lead ages for Apollo 11 and Apollo 12 lunar samples do not match and, furthermore, the dust samples seem to be older than the rocks. These experimental observations are generally thought to require some source of parentless lead. The authors propose that the escape of ^{222}Rn, ^{219}Rn and ^{220}Rn produced in the ^{238}U, ^{235}U and ^{232}Th decay chains may be a significant mechanism for a partial redistribution of the post-radon lead daughters.

Barber, G. F. and Schaeffer, O. A.: 'Exposure Ages of Lunar Rocks', *EOS* **52** (1971), 273.

Cosmic ray exposure age estimations of rock 10057 based on ^{38}Ar-^{39}Ar measurements are as much as a factor of two greater than exposure ages estimated from ^{3}He-^{3}H measurements. To investigate the possibility of incorrectly estimated production cross section for ^{38}Ar used in the exposure age calculation, thick targets of calcium floride and potassium chloride were bombarded with 600 MeV protons and counted prior to a mass spectrometric analysis of all chain yield rare gas isotopes. Preparation for analysis consisted of segmenting the targets, vacuum melting the calcium targets at 1500°C and the *K* targets at 1200°C, gettering the active components with hot titanium, and separating the rare gases into two fractions with charcoal at liquid nitrogen temperatures. The analysis resulted in ^{38}Ar production cross-sections of 64.6 ± 6.5 mb for potassium and 41.0 ± 4.1 mb for calcium, each about 30% greater than estimated values. The larger cross-sections applied to rock 10057 results in an exposure age of 86 million yr approximately 25% lower than the previously estimated values of 110 million yr. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Bown, M. G. and Gay, P.: 'Lunar Antiperthites', *Earth Planetary Sci. Letters* **11** (1971), 23–7.

Antiperthitic intergrowths have been recognized during single-crystal X-ray studies of some plagioclases from lunar rock 12013.10. Host plagioclase crystals can be in the labradorite-bytownite rangle contrasting with the less calcium-rich feldspars normally associated with such textures in terrestrial rocks. The nature of the included phase has not finally been established but it is certainly a potash feldspar of some kind. The occurrence of such intergrowths implies that some plagioclase crystallized at high temperature in a potassium-rich environment.

Brown, G. E., Prewitt, C. T., and Papike, J. J.: 'Structural Studies of Intergrown Lunar Pyroxenes', *EOS* **52** (1971), 270.

Because the compositions of intimate intergrowths of lunar pyroxenes cannot be resolved using the electron microprobe or microscopic techniques, several schemes for estimating these compositions using X-ray cell data have evolved. Because these schemes give only rough estimates of composition, the authors have attempted to refine both structure and composition for crystals of intergrown pigeonite and (001) augite from rock 12021.20. Single-crystal diffraction data consisting of 1300 pigeonite and 500 augite reflections were obtained from a crystal of $Wo_{10}En_{60}Fs_{30}$. The effects of overlap of pigeonite and augite reflections were minimized by careful data selection. Preliminary least-squares refinement resulted in *R*-factors of 0.06 and 0.10 for pigeonite and augite, respectively, and the following site populations for pigeonite: M1 (0.87 Mg + 0.13 Fe); M2 0.10 Ca + 0.43 Mg + + 0.47 Fe). Analysis of peak half-widths of the C-centered (*a* reflections) and primitive (*b* reflections) data for this plus one other pyroxene ($Wo_{27}En_{30}Es_{43}$) indicate a slower cooling history in comparison with the Mull pigeonite/augite and an Apollo 11 pigeonite/augite. Heating experiments up to the $P_{21}/c \rightarrow C_2/c$ transitions on a 4-circle diffractometer showed no significant changes in peak half-widths of the *b* reflections. These experiments provide no evidence for small domains of clino-hypersthene and diopside. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Butler, P., Jr.: 'Characterization of Lunar Magmas by Olivine Compositions', *EOS* **52** (1971), 270–1.

Olivine, as one of the first minerals to crystallize, provides evidence of the early compositions of the liquids from which lunar rocks formed. Analyses of 38 olivine phenocrysts from three basalts (12004, 12009, 12022), each of different texture, show similarities in the patterns of elemental variation from grain to grain within each rock. Over the olivine compositional ranges (about 22–30 wt.% FeO in each rock) represented by the unzoned interiors Ti, Mn, and Ca vary directly and Cr inversely with Fe. These variations seem to depend more on changes in distribution coefficients with the Fe content of olivine than on liquid depletion effects produced by crystallization. Differences in the Ti and Cr contents of the more primitive olivines (low Fe content) among the rocks show that 12022 could not have been derived from the same magma as either 12004 or 12009, which themselves may have been derived from different magmas. Analyses of 4 olivines from a vitrophyric basalt (12008) show that it solidified from a magma more closely related to 12022 (holocrystalline) than to the texturally identical rock 12009. Olivine in 12035 (microgabbro) and in an orthopyroxene-plagioclase fragment show distinctive compositional characteristics. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Cadogan, P. H., Eglinton, G., Maxwell, J. R. and Pillinger, C. T.: 'Carbon Chemistry of the Lunar Surface', *Nature* **231** (1971), 29–31.

Indigenous CH_4 and the electrical reaction product CD_4 released by deuterated acid etch of Apollo 11 and 12 lunar samples have been examined by gas chromatography. Possible origins for the CH_4 include solar wind synthesis and a small primordial contribution. The CD_4 probably arises from carbide or 'carbide-like' materials contributed by meteorite impact and solar wind implantation.

Clark, J. R., Ross, M., and Appleman, D. E.: 'Crystal Chemistry of a Lunar Pigeonite', *Amer. Mineral.* **56** (1971), 888–908.

A lunar pigeonite crystal from rock 10003.38 has broadened class (b) reflections ($h + k = 2n + 1$), similar to those observed by Morimoto and Tokonami for a pigeonite from Isle of Mull Scotland. The broadening suggests the presence of a domain structure with domains about 100 Å in size. Least-squares refinement of the class (b) diffraction data reveals that the structure of the principal domains in the lunar pigeonite is close to that of a clinohypersthene with composition approximately $Mg_{0.54}$ $Fe_{0.46}SiO_3$; the M2 site is six-coordinated, and the domains are assumed to have very little Ca (0.04

atom per given formula unit, at most). The boundary regions between the domains are assumed to be Ca-rich, as suggested by Morimoto and Tokonami. Least-squares refinement of all the data or of the class (a) data alone ($h+k=2n$) produces a 'statistical' structure, similar to that described by Morimoto and Güven for the Mull pigeonite. The 'statistical' structure is considered to be an artifact produced by using normal data handling procedures in an abnormal situation. The most plausible explanation for its appearance is the presence of the 'antiphase' domains postulated by Morimoto and Tokonami.

Cliff, R. A., Lee-Hu, C., and Wetherill, G. W.: 'Rb-Sr and U, Th-Pb Measurements on Lunar Samples', *EOS* **52** (1971), 265.

Crystalline rocks from both the Apollo 11 and 12 sites consist almost entirely of basaltic rocks which have been shown by several laboratories to be 3.6 and 3.3 b.y. of age respectively. The fine 'soil' material contains additional components, and is different at the two sites. Apollo 11 soil is characterized by concordant U, Th-Pb ages of 4.6 b.y., as well as falling on a 4.6 b.y. Rb-Sr isochron. Apollo 12 soil has dicordant, U, Th-Pb ages, suggesting that a 4.6 b.y system has been involved in relatively recent Pb loss. The soil is greatly enriched in Rb relative to the basaltic rocks, resulting in highly radiogenic Sr, concentrated in plagioclase-orthopyroxene and associated glass. Possible explanations of these differences will be discussed. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Cohen, A. J.: 'Origin of Trace Fe^{3+} and Ti^{3+} in Apollo 11 and 12 Crystalline Rocks', *EOS* **52** (1971), 272.

Trace Fe^{3+} and Ti^{3+} have been found in the pyroxene minerals of pristine lunar rocks 10017, 10022, and 12018, cut from interior samples, by spectrophotometric analysis. Thirty micron thich polished sections were used in this work. Heating experiments at 140°, 150°, 170° and 198°C for periods of 1.5 to 2 hr. produced no optical changes. At 200–225°C onset of the following reaction takes place in all samples (in air): $Fe^{3+}+Ti^{3+}\rightarrow Fe^{2+}+Ti^{4+}$. X-irradiation causes the reverse reaction. Cr^{3+} follows Fe3+ in all reactions studied as follows: $Cr^{3+}\rightarrow Cr^{2+}$. UV light produces the same effects as heating. It is suggested that a portion or all of the Fe^{3+} and Ti^{3+} were absent in the original melt but have been produced subsequently by secondary ionization processes following cosmic ray bombardment. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Drake, M. J. and Weill, D. F.: 'Petrology of 10071.33, an Unusual Igneous Rock Sample from the Sea of Tranquillity', *EOS* **52** (1971), 271.

Apollo 11 sample 10071.33 is composed of two texturally distinct parts. The texture of the larger part (hereafter the *coarse grained* basalt) is typical of Apollo 11 basalts, while the smaller part (hereafter the *fine grained* basalt) is made up largely of sheaf-like aggregates of acicular plagioclase feldspar and clinopyroxene crystals. Electron probe analyses of the 'bulk rock' of each part and of the individual phases in each part confirm that the two parts of 10071 are chemically distinct. The fine grained basalt is interpreted as having crystallized rapidly from a melt which was produced by fractional crystallization of a more basic lunar basalt, and emplaced in a crack or fissure in the already solidified *coarse grained* basalt. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Dybwad, J. P.: 'Radiation Effects on Silicates (5-keV H^+, D^+, He^+, N_2^+', *Geophys. Res.* **76** (1971), 4023–9.

Selected silicates were exposed to 5-keV, 10 μA cm^{-2} ion irradiation, and their mid-infrared spectra were monitored during the exposure. Irradiation with H^+, D^+, He^+, and N_2^+ did not significantly alter the spectral signature of the minerals. A slight shift of the 10μ Si-O band to longer wavelength was

observed, however, in reflection spectra of single crystals when they were irradiated with any of the three smaller ions. The bandshift reached its maximum after exposure to about 10^{19} ions cm^{-2}. It is shown that the maximum represents a steady state of ion penetration and surface sputtering, and it is concluded, from comparison of irradiations with different ions, that the 10μ bandshift is caused by gas retention within the samples rather than by lattice breakdown or chemical reactions. Implications for the lunar surface are that changes within silicates exposed to the low-energy solar wind remain small and will not increase after exposure of about 100000 yr. No darkening was observed on these surfaces as a result of ion irradiation. Sputtered deposits on recipient NaCl surfaces appear to be composed of silicate glass.

Gibb, F. G. F. and Zussman, J.: 'Zoned Olivines in Four Apollo 12 Samples'; *Earth Planetary Sci. Letters* **11** (1971), 161–7.

The distributions of Fe, Mg, Si, Ca, Mn, and Cr in selected olivine crystals from 12040, 12052, 12075 and 12076 have been determined by electron probe analysis. The results indicate that all crystals are continuously zoned, almost certainly as a result of fractional crystallization. 12040 contains two populations of olivine crystals, one of which could have been introduced by crystal settling. 12052, 12075 and 12076 have olivine and chrome spinel as the first crystalline phases and all three rocks could have crystallized from a single (or chemically similar) magma(s). The olivines in 12040 exhibit features inconsistent with an origin by simple olivine accumulation from a magma similar to the others and must have crystallized from a chemically different liquid.

Marvin, U. B.: 'Lunar Niobian Rutile', *Earth Planetary Sc. Letters* **11** (1971), 7–9.

A grain of rutile containing 6.4% Nb_2O_5, 3.3% Cr_2O_3, and less than 1% each of Ta_2O_5, V_2O_3, Ce_2O_3, and La_2O_3 has been found associated with ilmenite in a microbreccia fragment from Apollo 12 sample 12070.35. The composition is unique among lunar and terrestrial rutiles: $(Nb, Ta)_{0.04}$ (Cr, V, Ce, $La)_{0.04}$ $Ti_{0.92}O_2$. This is the first niobium-enriched mineral to be identified in the lunar rocks and soils most of which contain sparing amounts of 5–50 ppm Nb. Rare-earth elements are concentrated in several other lunar minerals but have not been reported in rutiles from any source.

Marvin, U. B.: 'Two Unique Lunar Microbreccias', *EOS* **52** (1971), 272.

A closely-packed aggregate of dark red nearly opaque glass spherules and shards, from Apollo 12 Sample 12033, has a uniform composition characterized by a high content of titanium (17% TiO_2–31% normative ilmenite) together with 54% normative olivine + pyroxene and 15% normative plagioclase. This microbreccia, which is markedly more Ti-rich than the average basalts of Tranquillity Base, clearly derives from a type of source rock that has not yet been discovered among the crystalline lithologies in the lunar samples. The chemical composition suggests an ilmenite-rich cumulate and the texture reflects melting, fragmentation, and accumulation with little or no admixture of extraneous materials. A microbreccia of similar texture from Apollo 11 Sample 10084 consists mainly of bright orange and yellow glass spherules. This fragment also has a bulk composition differing from that of any analyzed lunar crystalline rock. Speculations will be offered on the possible parent rocks and modes of formation of these microbreccias. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Murthy, V. R., Evensen, N. M., and Hall, H. T.: 'Consequences of Fe-S Liquid Segregation in the Early History of the Moon', *EOS* **52** (1971), 267–8.

The authors suggested earlier that a first chemical differentiation in the Earth resulted from Fe-S liquid segregation. A similar process for the Moon can not only account for the depletion of chalcophile and siderophile elements in the lunar surface but also the depletion of K, Rb and Cs which can be shown to be chalcophilic under some conditions. A consequence of this model is the establishment

of the low K/U, Rb/Sr and high U/Pb ratios in the source regions of mare basalts early in the history of the Moon, as is required by the existing geochemical data. An Fe-S liquid segregation will result in a separation of K from U, Th, and will have significant implications for thermal models of the Moon, irrespective of assumed initial radioactivities. The authors tentatively identify the high electrical conductivity material at ~ 200 km depth as an FeS layer containing reasonable amounts of early segregated K^{40}. Such a layer would cause extensive melting in the surface regions of the Moon, ~ 1 b.y. after its formation as indicated by the basalt age data, and may also account for the remanent magnetism in the basalts. The formation and distribution of FeS liquid masses in the early history of the Moon may also be related to the origin of 'mascons'. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Podosek, F. A., Huneke, J. C., Burnett, D. S., and Wasserburg, G. J.: 'Xe and Kr in Lunar Soil and the Solar Wind', *EOS* **52** (1971), 273.

Measurements were made of amounts and isotopic compositions of heavy noble gases in bulk and grain-size fractions of lunar soil from Apollo 11 and 12. The isotopic compositions of surface-correlated (SUCOR) Xe and Kr are derived by assuming uniform irradiation histories of the various samples at each site, with account taken for variations in spallation target element abundances. The isotopic composition of SUCOR Xe is the same at both sites and lighter than terrestrial Xe 3–4%/mass. Fractionation alone is insufficient to account for details in the comparison between SUCOR and terrestrial Xe. Data indicate that SUCOR Kr at the Apollo 12 site is identical to terrestrial Kr, but that SUCOR Kr at the Apollo 11 site is heavier by 0.7%/mass with no departures from a linear fractionation pattern. The spallation ratio $(Kr/Xe)_{sp} \times (Ba/Sr)$ is similar at both sites. Thermal release experiments show that the compositions of surface-correlated Xe and Kr vary with degassing temperature and that the SUCOR gas is a mixture of at least two components. The extent to which the calculated SUCOR compositions represent the solar wind compositions is thus uncertain, and these compositions may reflect fractionation processes and reimplantation of gases from the lunar atmosphere or some other lunar surface process. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Reid, J. B., Jr.: 'The Petrology of Basaltic Particles in Apollo 12 Soils', *EOS* **52** (1971), 271.

Texturally, the 200 basaltic fragments from the author's Apollo 12 soils fit a smoothly continuous sequence from pyroxene vitrophyres through variolitic and subophitic basalts to coarse cumulate gabbros. Major element data from the olivines, pyroxenes, and simpels are consistent with the textural suggestion that the vitrophyres and fine basalts are suffase and near-surface layers of flows that differentiated by crystal settling. Pyroxenes from all rocks fall on the same trend on plots of Cr_2O_3 (wt. %) vs Fe/(Fe + Mn + Mg), as do olivines, with vitrophyre phenocrysts being most Cr-, Mg-rich. Crystal settling depletes all but the rapidly quenched vitrophyres of their earliest most Cr-, Mg-rich phenocrysts. Spinels with intermediate Fe/Mg from fine basalts fall into two groups of Ti contents, suggesting the likelihood of at least two discrete magma generations. On plots of Ti/(Cr + Al + 2Ti) vs Fe/(Fe + Mn + Mg), spinels from the coarse cumulate gabbro 12035 fall on a trend which diverges from the trend for the fine grained basalts at compositions rich in Mg and Cr, consistent with the formation of rock 12035 as a cumulate early in the crystallization of its flow or lava pool. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Trzcienski, W. E., Jr. and Hollister, L.S.: 'Barium and Potassium Phases and Plagioclase from Apollo 12 Sample 12063', *EOS* **52** (1971), 271.

Electron microprobe analysis of late stage residua in Apollo 12 sample 12063 show the coexistence of a high Ba and a high K phase. These phases are asssociated with fayalite and cristobalite in a fine grained intergrowth texture. The potassium phase is high in silica (70-80 wt. percent SiO_2) and contains seven to nine weight percent K_2O. The barium phase, containing approximately 12 weight percent BaO and 7 weight percent K_2O, has a composition indicative of the hyalophane-celsian solid solution series. The plagioclase (An_{92}-An_{80}) commonly occurs as crystals with hollow sectors which are filled predominantly with late pyroxene. The highest An-content occurs one-third to one-half the distance between the exterior and interior rims of 'hollow' crystals and decreases towards both rims. On the other hand, potassium ($Or_{0.03}$ to Or_{11}), barium (0.00 to 0.04 wt. percent BaO), and iron (0.63 to 1.12 wt. percent FeO) increase markedly only towards the exterior rim. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

7. Lunar Exosphere

Freeman, J. W., Jr.: 'Suprathermal Ions on the Night Side of the Moon', *EOS* **52** (1971), 340–1.

Recurrent 'clouds' of positive ions are a persistent feature of the data from the Apollo 12 ALSEP Suprathermal Ion Detector. Most remarkable is the occasional occurrence of these 'clouds' when the ALSEP is deep in the lunar night. This paper reports one such series of 'clouds' seen during December 1969 approximately 4.5 days before sunrise at the ALSEP site. The bursts of suprathermal ions that represent these 'clouds' have durations of the order of ten minutes and recur with a highly variable frequency averaging one every several hours. The ions have differential energy spectra with broad peaks ranging in maximum energy from 50 to 500 eV. They can be seen when the narrow field of view of the detectors looks as close as 17° from the antisolar direction. Average integral fluxes are of the order of 5×10^4 ions/cm^2 s ster. Mass per unit charge spectra from similar, more intense clouds near sunrise are suggestive of periodic gas venting from the lunar surface. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Manka, R. H. and Michel, F. C.: 'Detection of Lunar Atmosphere in Lunar Samples', *EOS* **52** (1971), 266.

The possibility that lunar atmosphere gases, in addition to Ar^{40}, have already been detected in lunar samples is discussed. The characteristics expected for solar wind gases, which are retrapped from the atmosphere, are presented. A mass fractionation in the retrapped isotopes is possible and in some cases, an enhancement of the lighter isotopes in the sample is expected. Numerical results are presented for several elements for the enhancement of isotopic ratios due to a consistent mass effect in the trapping of atmospheric ions. These calculations are compared to the enhanced ratios obtained in initial releases from stepwise heated samples, and the possibility that these initial gases can be attributed to trapped lunar atmosphere, in addition to diffusive effects, is discussed. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Michel, F. C. and Manka, R. H.: 'Characteristics of the Lunar Atmosphere', *EOS* **52** (1971), 266.

Some characteristics are presented for the lunar atmosphere, and Ar^{40} in particular, which are relevant to measurements by lunar surface ion detectors and sample analysis. Ions formed in the atmosphere are accelerated along the interplanetary electric field, have directions correlated to the interplanetary magnetic field, and impact the Moon with energies of tens of electron volts up to a few keV; and in some cases the surface magnetic and electric fields can have significant effects. Using these trajectories, the ratio of solar Ar^{36} to lunar atmosphere Ar^{40} found in lunar surface samples, and the efficiency for trapping Ar^{40} from the atmosphere a number density for neutral Ar^{40} in the lunar atmosphere is estimated to be about 10^3 cm^{-3}. The flux of ions to the surface from this neutral atmosphere is given and comparisons are made between the predicted directions and energies of ions and results obtained by surface ion detectors. Evidences for the detection of other species are discussed. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Plieninger, T. and Kratschmer, W.: 'Comparison of Particle Tracks Produced by Artificially Accelerated Iron and Calcium Ions with Fossil Tracks in Meteorites and Lunar Samples', *EOS* **52** (1971), 268.

Silicate minerals abundant in meteorites, lunar material and terrestrial rocks were exposed to Fe and Ca ions accelerated by a Tandem van de Graaff. Energies in the range of 0.2 to 1.5 MeV/nucleon were applied. The shapes of the etched tracks were studied with a Scanning Electron Microscope applying the replica technique. Lengths in the range of 0.5 to 7 μm were measured with an accuracy of ± 0.2 μm. The observed track length was found to be a linear function of incident particle velocity. The registration thresholds for various minerals are estimated. A comparison with track length data obtained from fossil tracks in minerals exposed to the cosmic radiation is made. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Thompson, S. O. and Maxwell, D. E.: 'Cross Sections for Proton-induced Spallation Reactions in Terrestrial Rocks Simulating Lunar Soil Composition', *EOS* **52** (1971), 272.

The absolute production cross-section of radio-nuclides induced in pure metal foils and in rock samples whose mineralogical and chemical composition simulated lunar soil were determined by bombarding these materials with beams of protons and alpha particles available at the Brookhaven National Laboratory facilities. The energy range of the particles was selected to simulate that of solar flares. Cross-section determinations for the following target elements were made: magnesium, aluminum, silicon, titanium, calcium, iron, nickel, chromium. Mineral targets of ilmenite, pigeonite, olivine, anorthite, and basalt were irradiated. These studies were undertaken to estimate the effect of the solar flare contribution to the total radio activity in the lunar soils. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

8. Lunar Coordinates and Mapping of the Moon

Lipskii, Y. N. and Chikmachev, V. I.: 'A Catalog of Reference Points in the Western Libration Zone and the Eastern Sector of the Moon's far Side', *Sov. Astron. – AJ* **14**, 1023–9.

A catalog has been compiled from a reduction of the original television pictures transmitted by normal telemetry from the Soviet space probe Zond 3 in 1965. Rectified images of 14 frames have furnished a tie-in of the coordinates. The positions of the catalog objects relative to the basis points on the visible side of the Moon are in error by no more than 15′.

10. Origin and Stratigraphy of Lunar Formations

Greeley, R.: 'Origin of the Lunar Hadley Rille', *EOS* **52** (1971), 274.

Hadley Rille, situated in a valley of the Apennine Mts., east of Mare Imbrium, has been selected as the Apollo 15 landing site. The Rille belongs to a class of sinuous rilles which characteristically: (1) originate in apparently endogenetic craters or depressions, (2) trend generally downslope, (3) have discontinuous channels and cut-off branches, (4) taper toward the apparent terminus, (5) form topographic highs along parts of the rille axis, and (6) are restricted to mare surfaces and appear to be controlled by pre-mare topography. Qualitative and quantitative geomorphology, comparisons with possible terrestrial analogs, and consideration of laboratory studies on the viscosity and thermal conductivity by Murase and McBirney (1970) indicate that the Hadley Rille is a lava channel, parts of which were roofed to form lava tubes. The lava channel/tube system developed in lavas emitted from concentric fissure-fractures of the Imbrium Basin. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Greeley, R.: 'Lunar Hadley Rille: Considerations of Its Origin', *Science* **172** (1971), 722–5.

Geomorphology, topographic configuration, comparisons with terrestrial analogs, and considerations of the chemical and physical characteristics of mare lavas indicate that the Hadley Rille is a lava channel. Some of the structure was roofed to form a lava tube, parts of which have subsequently collapsed.

Ronca, L. B.: 'The Geomorphology of Lunar Stratigraphic Units', *EOS* **52** (1971), 274.

The geomorphic index of lunar surfaces is obtained by solving a function which relates the number density of craters (excluding ghost craters) to the number of uneroded craters. The geomorphic indices of the surfaces of the different stratigraphic units, as indicated by the USGS geological maps, were measured. For Procellarum and pre-Procellarum units, the lower the stratigraphic position, the higher is the index, with relatively little scattering. For post-Procellarum units, the higher the stratigraphic position, the higher the index, with considerable scattering. This is explained by proposing the existence of two geomorphic processes operating on the lunar surface, i.e. the continuous degradation sequence, due mainly to micrometeoritic erosion, and the discontinuing degradation, due to the ejecta of near-by large impacts. In addition, the results show that the indices can be used diagnostically to determine the stratigraphic position of a unit. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Ronca, L. B.: 'Ages of Lunar Mare Surfaces', *Geol. Soc. Am. Bull.* **82** (1971), 1743–8.

Each near-side lunar mare displays a range of geomorphic indices on its surface. This is interpreted to be due to the presence of effusions of different ages on the surface of each mare. This interpretation contradicts the theory that mare surfaces were formed contemporaneously. The landing sites of Apollo 11 and 12 have geomorphic indices of 10.3 and 8.4, respectively; the radiometric ages of the rocks are approximately 3.6×10^9 and 3.4×10^9 yr. Geomorphic indices on mare surfaces range from less than 5 to more than 14, indicating that the two landing sites were formed approximately in the middle of the time span required for mare surface formation. Using four possible relationships between geomorphic index and age, the length of time between the beginning and end of mare effusion is inferred to be at least 1×10^9 yr, and possible twice as much. Some evidence is presented that effusive activity may have reached two maxima.

11. Physical Structure of the Lunar Surface

Cherkasov, I. I., Schwarev, V. V., Steinberg, G. S., Baitursunova, N., and Drugininskaya, V. I.: 'The Physical and Mechanical properties of Modern Deposits of Kamchatka Volcanoes and Their Comparison with Lunar Soils', *Mod. Geol.* **2** (1971), 159–72.

The results of the first comprehensive investigation of the friable volcanic deposits of Kamchatka is presented. Physical properties were measured in the laboratory and on the field, by using a special apparatus attached to the chassis of a helicopter. The properties are compared with those of the lunar soil, as determined by the Luna and Surveyor stations and the analyses of Apollo specimens. Conclusions are summarized in tables.

Hu, T. and Watkins, J. S.: 'The Crater Ejecta Component in the Lunar Regolith', *EOS* **52** (1971), 273.

A model of the lunar regolith assumed to be a result of the accumulation of overlapping ejecta layers spread out from meteorite craters has been investigated. The thickness of the regolith at the Apollo 11 and 12 sites calculated on the basis of size and distance of craters within 1000 km agree well with thicknesses inferred from other data. At the Apollo 12 landing site, a stratigraphic column is set up from ejecta calculations and geologic mapping of the nearby lunarsurface. Both thickness of ekjecta and sequential order of ejecta of the calculated stratigraphic column are in good agreement with the observable units present in the core-sample. The results of the investigation suggest that it may be possible to (1) establish a Moon-wide stratigraphic sequence, (2) study rocks from diverse areas on the Moon from a selected suite of cores of regolith and (3) study the history of igneous activity on the lunar surface by dating the crystalline rocks in the different ejecta layers. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Quaide, W.: 'Distribution of Non-Local Components in an Inhomogeneous Lunar Regolith', *EOS* **52** (1971), 273.

Lunar sample studies and theoretical considerations indicate that the degree of reworking and the percentage of non-local components in the regolith are directly proportional to initial bed thickness and rate of deposition. Regolith growth takes place primarily by addition of discrete layers of ejecta. If layers are of sufficient thickness, they survive as strata with small percentages of non-local components. Since the rate of supply of additional layers decreases with time, the extent of reworking and the proportion of debris of non-local origin increases toward the surface. Differences in composition between surface or near surface samples of fine debris and rocks indicates the presence of foreign components. Estimates of proportions of the foreign fraction have been made, but do not constitute meaningful average values because (1) the proportions of non-local components increase toward the surface, (2) the regolith is composed of both fine debris and rocks is as yet unknown proportions, and (3) surface rocks may not provide a valid sample of the average composition of local bedrock. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Russ, G. P., Huneke, J. C., Podosek, F. A., Burnett, D. S., and Wasserburg, G. J.: 'The Irradiation History of Lunar Samples Inferred from Gd and Rare Gas Isotopic Measurements', *EOS* **52** (1971), 273.

Neutron exposures for various Apollo 11 and 12 soil samples are the same to within 10%. The regoliths at different mare sites appear to be well-mixed seas from the point of view of nuclear bombardment. Using new theoretical calculations of the neutron flux gradient by Lingenfelter *et al.*, the measured neutron exposures for soil samples yield regolith mixing depths of 10–20 m, assuming total mixing. This is distinctly higher than regolith thicknesses estimated from crater depths. For the same model, mixing depths of ~ 10 m are obtained from spallation Xe^{126} in soil samples. The alternative case of a continuous accumulation model will also be presented. The Apollo 12 double core shows only a small, but significant, gradient in neutron exposure ($\sim 10\%$ larger at the bottom). The observed stratification is thus comparatively recent (within the last 50 m.y.). Spallation Xe^{126} measurements are compatible with this conclusion. Limits on deposition times can be set for various layering models. Apollo 11 and 12 rocks have similar neutron exposures. No variations in neutron exposures are observed for samples from different depths in 12002, implying a surface exposure time on a given orientation of less than 200 m.y. From the measured ratio of the neutron dosage to spallation ^{126}Xe, irradiation depths for lunar rocks can be estimated. (Abstract of a paper presented at the April 1971 meeting of the America Geophysical Union.)

Thompson, T. W., Mazursky, H., Shorthill, R. W., Tyler, G. L., and Zisk, S. H.: 'Infrared, Radar, and Geologic Characteristics of Lunar Craters', *EOS* **52** (1971), 274.

Fifty-two prominent infrared and radar anomalies are consistent with impact craters. The youngest craters are pronounced infrared and radar anomalies, presumably arising from rocks in the ejecta. Older craters are weaker anomalies with the radar enhancements a longer wavelengths being the last anomaly to disappear. This presumably results from the depletion of surface and near-surface rocks by meteoritic bombardment. Also, large strewn fields of centimeter-sized rock fragments have been identified by comparing infrared and radar maps. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

12. Photometry of the Moon

Dollfus, A. and Bowell, E.: 'Polarimetric properties of the Lunar Surface and its Interpretation – Part I. Telescopic Observations', *Astron. Astrophys.* **10** (1971), 29–53.

Two new photoelectric polarimeters, one for the infrared and one for the ultraviolet, have been developed at Meudon Observatory. These instruments are capable of measuring the degree of polarization to an accruracy of 0.001, and may be used to isolate regions on the lunar surface as small as a few arc-seconds diameter. Using telescopes at Meudon and Pic-du-Midi, a detailed study of the polarimetric properties of the lunar surface has been undertaken. The present Part I of this publication reports about these observations. Subsequent Parts II and III will describe the laboratory measurements on terrestrial and lunar samples, and conclusions about the interpretation of the polarimetric measurements on the Moon. The lunar observations are divided into two parts: firstly polarization curves as complete as possible have been obtained for 14 lunar regions of 65″ diameter, in 8 colours covering the wavelength range 0.327μ to 1.05μ. The relation between the maximum degree of polarization P_m, and the normal albedo A, has been investigated. It is found that a close relation exists, and that an expression of the form $\log A = -0.724 \log P_m - 1.81$ holds for all lunar terrains. The spectral variation of the maximum polarization, P_m, and normal albedo, A, of the Moon is also discussed; these quantities change with wavelength, λ, according to the formula $\bar{P}_m = \bar{A}/3.5 \times \lambda^2$. The invariance of the negative branch of lunar polarization curves is discussed, and a dependence of the inversion angle on the wavelength of observation has been observed. The phase angle at which maximum polarization occurs is shown to be dependent only upon the maximum degree of polarization for all types of lunar terrain within the range of wavelengths of our observations. The second series of observations is concerned with the determination of the maximum degree of polarization, in orange light, of 142 regions mostly of less than 5″ diameter, with a view to further investigate the relation given above between the maximum degree of polarization, P_m, and the normal albedo, A, of small lunar regions. A discussion of the errors inherent in the measurement of P_m and A reveals that this relation is probably strictly true of all lunar terrains. The authors conclude that the surface microstructure of the entire Moon has been weathered to an extremely uniform texture. This inference is also drawn from the invariance of the form of the negative branches of lunar polarization curves. An Appendix describes the determination of a new lunar normal albedo scale based on measurements provided from nine sources. A catalogue of normal albedoes for 67 small lunar regions is presented.

Dollfus, R., Bowell, E., and Titulaer, C.: 'Polarimetric Properties of the Lunar Surface and Its Interpretation – Part II. Terrestrial Samples in Orange Light', *Astron. Astrophys.* **10** (1971), 450–66.

For the interpretation of lunar polarization measurements, described in Part I of this work, samples were measured in the laboratory, using orange light of wavelength 6000 Å. In all 61 rocks were used, including a wide variety of meteorites, volcanic ashes, basalts and other rocks. 31 samples were sieved into 4 grain size groups, with average grain sizes ranging from 160μ to 26μ. Both the maximum degree of polarization and the normal albedo are dependent on the grain size. The lunar data indicate a linear correlation between the log of the normal albedo and the log of the maximum degree of polarization. Most of the meteorites and the terrestrial samples are different, but some chondrites and the fine-grained basalts provide the best fit of the lunar properties. It is shown that several physical processes (upwelling, proton darkening, diminution of grain size and surface compaction) have a bearing upon the normal albedo and degree of polarization, and may improve the agreement between basalts and lunar measures, thus possibly enabling to determine the importance of certain physical processes on the Moon's surface.

Dollfus, A. and Titulaer, C.: 'Polarimetric Properties of the Lunar Surface and Its Interpretation – Part III: Volcanic Samples in Several Wavelengths', *Astron. Astrophys.* **12** (1971), 199–209.

The wavelength dependences of the albedo A (measured at $V = 5°$) and of the maximum degree of polarization P_m have been measured and reported for 38 terrestrial volcanic pulverized samples.

These results are compared in a log A — log P_m diagram with the similar telescopic lunar determinations and the Apollo 11 and 12 lunar sample measurements. The linear relation obtained between log A and log P_m is explained. A correction is indicated for the absolute photometric scale of telescopic measurements. The best fit with the lunar values is given by finely pulverized lava flow basalts. A sample of Pahoehoe lava from Hawaii with grain size 25μ, matches exactly the optical properties of the lunar surface.

Goetz, A. F. H. and Head, J. W., III: 'Lunar Surface Compositional Variation from Orbital Multispectral Photography', *EOS* **52** (1971), 274.

A study was made of Apollo 12 orbital multispectral photography which had been computer processed to enhance subtle differences in spectral reflectivity, independent of albedo. Photography covered the Central Highlands and several mare-highland boundaries. Differences were detected in the Descartes region which can be attributed to exposed crystalline rock in the ejecta blanket of Dollond E. No color difference was detected across the mare-upland boundary at Fra Mauro. With few exceptions, the uplands are extremely uniform and the variation is spectral reflectivity seen in any frame is less than that found in the Apollo 12 core samples. The uniformity transcends mapped age and morphological boundaries. Possible reasons for the uniformity and their implications are discussed. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Morozhenko, A. V. and Yanovitskii, É. G.: 'Optical Properties of the Lunar Surface Layer', *Sov. Astron.* **15** (1971), 134–43.

A discussion is given of the problem of diffuse light reflection by a plane layer of a medium of infinite optical depth. Allowance is made for the 'shadow effect'. An equation is obtained representing the exact solution of the problem for singly scattered light. This reflection law is applied to establish the optical properties and relative density of the lunar surface layer. Higher-order scattering is taken approximately into account. The wavelength dependence of the albedo for the particles comprising the lunar surface layer and the scattering indicatrix are derived from observational data. The parameter g, which describes the relative density of the surface layer, is found to have an average value of 0.25 for the Moon. The porosity of the uppermost layer of the lunar surface (less than 1 mm thick) is accordingly 0.95, in good agreement with the direct measurements by the Surveyor probes. A comparison of the observed brightness distribution along the equator of intensity with the theoretical distribution also shows good agreement.

13. Thermal Emission of the Lunar Surface

Buhl, D.: 'Lunar Rocks and Thermal Anomalies', *J. Geophys. Res.* **76** (1971), 3384–90.

Recent microwave and infrared spectral observations of several of the large bright-rayed craters on the Moon suggest that the thermal anomalies in these craters are produced by large rocks, boulders, and exposed rock strata. The data for the crater Tycho can be simulated by a surface consisting of 16% loose rocks of 1-m size and 4% exposed rock strata.

14. Electromagnetic Properties of the Moon

Cassen, P., Barnes, A., Mihalov, J. D., and Eviatar, A.: 'Lunar Surface Magnetism and the Solar Wind', *EOS* **52** (1971), 480.

Magnetic compressions intermittently observed outside the lunar wake in the solar wind may be limb shocks caused by the presence of local regions of permanent magnetism ('magcons') on the lunar

limb. Observable compression would be due to magcons of length scale $\gtrsim$ several tens km and field strength $\gtrsim$ 10 γ. Thousands of such regions might exist on the lunar surface. The steady magnetic field measured at the Apollo 12 site probably has length scale $\lesssim$ 2 km, and probably does not produce an observable limb shock. (Abstract of a paper presented at the December 1970 meeting of the American Geophysical Union.)

Collinson, D. W., O'Reilly, W., Runcorn, S. K., and Stephenson, A.: 'The Origin of the NRM of Apollo Lunar Samples and the Internal Dynamics of the Moon', *EOS* **52** (1971), 265.

The magnetic properties of the Apollo 11 and 12 samples is reviewed. The properties of the various types of remnant magnetization which can be acquired by the samples will be discussed. The natural remnant magnetization (NRM) of the crystalline rocks, (5–10) 10^{-6} emu gm^{-1}, is considered to have been acquired while the rocks were on the Moon, a conclusion supported by the Apollo 12 magnetometer experiment. It is thought that the NRM was acquired during or soon after the cooling of the lava 3700 m.y. ago. Various possible causes of the field from which the NRM was acquired will be considered but it is concluded to be a lunar field of internal origin. This is held to support the existence of a small iron core in the Moon, an idea previously inferred from the nature of the convection currents postulated to explain the discrepancy between the dynamical ellipticity of the Moon and its external figure. Other evidence for the existence of thermal convection within the Moon will be reviewed. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Criswell, D. R.: 'Electric Fields and Motion of Lunar Fines', *EOS* **52** (1971), 266.

A fraction (h) of the photoelectrons ejected from sunlit lunar areas accrete in adjacent dark areas producing stable positive and negative surface charge ($\pm\sigma$) distributions. The $\pm\sigma$ potential difference (U) is determined by the balancing of the photoelectron accretion current induced by the integral flux of solar photons with energy $\geqslant eU$ against the $\pm\sigma$ conduction current through the lunar soil ($k \sim$ conductivity). The stable electric fields between $\pm\sigma$ areas are much more intense than electric fields extending from the sunlit surface to photoelectron layers above the surface. For $k \simeq 10^{-16}$ mhos/m, $h = 1$, and quit-time solar conditions the value $U \simeq 10^3$ V is reasonable. Assuming a uniform $-\sigma$ distribution and utilizing the measured differential diameter distribution (0.1 to 1000 μm) of maria material one finds that electric fields induced between $\pm\sigma$ areas separated by 1 cm can levitate 10 μm diameter lunar fines. Forward diffraction of sunlight by such levitated fines can explain the post sunset glow photographed on the western lunar horizon by Surveyors 6 and 7. Transport of fines appears to start after sunset at the soil surface. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Lindeman, R. A., Freeman, J. W., Jr., and Hills, H. K.: 'Recurring Ion Clouds at the Lunar Surface', *EOS* **52** (1971), 340.

The Suprathermal Ion Detector Experiment (SIDE) placed on the lunar surface (November 19, 1969) by the Apollo 12 astronauts consists of two detectors: the Mass Analyzer which measured the mass/unit charge of low energy ions (0.2–48.6 eV), and the Total Ion Detector which measures the energy/unit charge of ions in twenty narrow energy steps (10–3500 eV). After 14 months of data, a recurrence of ion clouds at certain positions in the Moon's orbit has become apparent. These clouds fall into 3 classes: (a) at sunset, ion clouds with energies of 100–750 eV are observed with less frequent events of 2000–3500 eV; (b) a few days prior to sunrise, ion clouds are observed with energies of 50–750 eV; (c) at sunrise, ion clouds are observed containing all energies. The higher energy ions in class (a) are believed to be ions ejected from the earth's bow shock and propagating upstream in the solar wind. It is possible that one or more of these classes of clouds results from ionization of temporary gas bursts from the lunar surface. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Pearce, G. W., Strangway, D. W., and Larson, E. E.: 'Magnetic Studies on Lunar Samples', *EOS* **52** (1971), 267.

Studies of lunar samples from Apollo 11 and 12 have shown that all the igneous rocks have a weak remanent magnetism. This magnetism consists of two distinct fractions. One is fairly unstable and is carried by native iron. The second component is much more stable to AF demagnetization and is believed to be carried by antiferromagnetic troilite. Since both fractions have the same direction the authors consider that they are both of lunar origin and both are thermoremanent magnetism. A variety of magnetic tests will be presented to support this view and which suggest that the moon had a magnetic field of a few thousand gammas, 3.6 billion years ago. It is believed that this field is due to the presence of a liquid core at that time. (Abstract of a paper presented at the April 1971 meeting of the American Geophysical Union.)

Schwerer, F. C., Nagata, T., Fisher, R. M., Fuller, M. D., Wasilewski, P. J., and Conroy, J. W.: 'Electrical Conductivity of Lunar Surface Rocks', *Earth Planetary Sci. Letters* **11** (1971), 127–9.

The authors have measured the electrical conductivity of four lunar samples returned by Apollo 11 and 12. These measurements were carried out in a vacuum furnace over a range of temperatures. The results of these measurements will help to determine the electromagnetic interaction between the Moon and the solar wind.

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** (1971), 359–62.

The authors report the first measurements of the bulk electrical conductivity profile of the Moon. These results confirm the strong electrical induction which occurs when the Moon is affected by the interplanetary magnetic field. The authors show evidence, based on the harmonic response, for a layer at a depth of about 250 km which has a spectacular and anomalously high value of electrical conductivity. The authors' conclusions suggest that the Moon is radially stratified, with a core of radius 1400 km, in composition representative of an ultramafic substrate such as an olivine, or olivine-pyroxene; a lower mantle composed of a material transitional between the substrate and the upper mantle and ranging in radius from 1400–1500 km, followed by an upper mantle with the electrical properties of an Apollo basalt.

Sonett, C. P., Dyal, P., Parkin, C. W., Colburn, D. S., Mihalov, J. D., and Smith, B. F.: 'Whole Body Response of the Moon to Electromagnetic Induction by the Solar Wind', *Science* **172** (1971), 256–8.

A comparison has been made of the interplanetary magnetic field as measured both by Apollo 12 on the lunar surface and by Explorer 35 in orbit around the Moon. Two examples are given, one of a step change in the field vector and another of a sinusoidally varying field. A large response measured on the surface is attributed to confinement of the induced field lines between the streaming solar plasma and the high-conductivity interior. A steep bulk electrical conductivity gradient in the lunar crust is implied, with a confining layer roughly 100 km deep.

Wright, D. A.: 'Electrical Conductivity of Lunar Rock', *Nature* **231** (1971), 169–70.

The object of this communication is to advance a simpler explanation of the varying conductivity along the radius of the Moon which does not call for radial variation of bulk rock composition. The author's suggestion is that the loss of oxygen inevitably resulting from a prolonged existence in high vacuum with temperature cycles at least up to 150 °C at the surface has led to the formation of oxygen-deficient materials in the outer layers. If the rock forms a predominantly *n*-type semi-conductor, there will be an increasing concentration of donor centres, and the electrical conductivity σ_0 – the value at 300 K – will correspondingly increase outwards along a radius. The combined effect of the variation of temperature and σ_0 will lead to a variation in conductivity σ with radius of the type reported by Sonett *et al.*

15. Exploration of the Moon by Spacecraft

Hinners, N. W.: 'The New Moon: A View', *Rev. Geophys. Space Phys.* **9**, 447–522.

A review of Apollo 11, 12, and 14 and Luna 16 data shows that a genuine step-function increase has occurred in our understanding of the Moon. This results largely from the ability to conduct detailed analyses, most of which cannot be done by remote means, on returned sample. Geophysical data from Apollo-emplaced science stations is a valuable complement to the new sample knowledge. It is evident that the great store of data previously gathered from Earth-based telescopic observations and unmanned spacecraft and the interpretations of it are enabling us to construct much better lunar models than otherwise possible. Without this pre-existing framework, the lunar samples acquired would be of diminished value. The lunar 'sum total experience' will reach beyond the Moon and should be particularly valuable in interpreting remotely sensed data from Mars and other planets.

It appears that the Moon originated about 4.6 b.y. ago, as did the Earth and meteorites, thus at the beginning of the solar system. It seems to have suffered most of its internal thermal spasms in the first 1 or 2 b.y. of life and has been slowly dying since, in contrast to the Earth, which today may be as active as ever. The lunar surface was exposed to a large but rapidly decreasing flux of infalling objects in its first $1\frac{1}{2}$ b.y., some of which might have been part of the accretionary population that evidently formed the Moon. That activity has been at a greatly diminished level for the past 3 b.y. and may now be comparable to the action of solar and galactic atomic particles in effecting surface modifications.

The igneous processes that resulted in flooding of the mare basins with basaltic lavas are now reasonably well understood, as are the effects of meteoroids in generating the shallow (meter scale) surficial soil or regolith. Processes responsible for modification of the near-surface layer (micron scale), which gives rise to the remotely sensed spectra, are not wholly clear. Evidence exists that the lunar near-surface highlands are compositionally heterogeneous, but neither the mare basalts nor Imbrium ejecta (Fra Mauro) can be representative of the lunar deep-interior composition. However, a good model of the 'primordial' or existing interior composition does not yet exist, although geochemical and geophysical evidence indicates that the deep interior may represent accreted material that has never been above the melting point. On the other hand, the outer regions have undergone severe chemical modification. These outer regions are, and probably always have been, depleted in volatile elements and enriched in refractories, an observation constraining models of lunar origin.

All basic models of lunar origin (capture, dual-planet, Earth-fission) are alive, although the idea of direct fission from Earth is quite sick. Sicker yet, and essentially dead, are tektites- and meteorites-from-the-Moon hypotheses. The meteorite evidence does indicate, though, that processes similar to those forming lunar-mare basalts occurred at other places in the early solar system.

Questions relating to the origin of life must await future planetary explanation, for no life forms have been found, nor have organic molecules been unambiguously identified as being indigeneous to the Moon. The virtually complete lack of water and the 4+ b.y. of exposure to a harsh space environment make eventual detection of lunar life unlikely.