BIBLIOGRAPHY

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1. Motion of the Moon and Dynamics of the Earth–Moon Systems; Shape and Gravity Field of the Moon

Ananda, M. P. (Jet Propulsion Lab., Pasadena, CA 91103): 'Lunar Gravity; A Mass Point Model', *J. Geophys. Res.* **82**, 3049–3064. (1977)

A point mass representation of a quasi—global gravity field of the Moon is developed by processing Apollo 15 and 16 subsatellite and Lunar Orbiter 5 Doppler tracking data. The model is generated by reducing the long periodic variations in the mean orbit element rates. The gravity model consists of 117 point masses distributed over the region of ±30° in latitude about the lunar equator. This model resolves all the previously known 'mascons' in the nearside as broad positive gravity regions. The nearside acceleration map evaluated at 100 km above the lunar surface shows good agreement with the line of sight acceleration results. The lunar farside gravity map shows strong broad positive gravity regions for the highland areas. However, all the major ringed basins are resolved as localized negative anomalies in contrast with the nearside basins. This model does not indicate any evidence for the existence of any mascon type feature in the lunar farside. When radial acceleration values are compared with the topographic values obtained from laser altimeter data, there exists a relatively good agreement between the topography and gravity profiles, indicating that the gravity highs and lows correspond to topographic highs and lows for the lunar farside. Also, the 117 masses have been mapped to a twentieth—degree and twentieth—order harmonic coefficient field, and the low—order coefficients show reasonable agreement with other known fields.

Blackshear, W. T. (Environmental and Space Science Div., NASA Langley Research Center, Hampton, VA 23665) and Gapcynski. J. P.: 'An Improved Value of the Lunar Moment of Inertia', J. Geophys. Res. **82**, 1699–1701. (1977)

The lunar gravitational research reported on by Gapcynski *et al.* (1975) has been extended to include an additional 600 days of the time variation of ascending node for the Explorer 49 spacecraft. Analysis of these additional data resulted in an improved value of the second-degree zonal harmonic coefficient $C_{20} = (-2.0219 \pm 0.0091) \times 10^4$. This value of C_{20} used in conjunction with $\beta = (631.27 \pm 0.03) \times 10^6$ and $\gamma = (227.7 \pm 0.7) \times 10^6$ yields a more accurate definition of the lunar moment of inertia ratio of $C/Ma^2 = 0.391 \pm 0.002$.

Burša, M. (Czechoslovak Acad. Sci., Institute of Astronomy, CS–12023 Prague 2, Czechoslovakia): 'Secular motion of the Mean Longitude and Perigee of the Moon due to Perturbations in the Terrestrial and Lunar Gravitational Fields'. Bull. Astron. Inst. Czech. **28**, 173–180. (1977)

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The secular terms in the mean longitude of the Moon and in the argument of the perigee due to the main deviations of the gravitational fields of the Earth, the Moon and the Sun from centrally symmetrical fields are derived. In the distrurbing function the Stokes constants of the following degrees n and orders k are kept: Earth – $n = 2, k = 0; n = 3, k = 0; n = 4, k = 0; n = 2, k = 2; n = 3, k = 1; n = 3, k = 3; n = 4, k = 3$; Moon – $n = 2, k = 0; n = 2, k = 2; n = 3, k = 1$; Sun – $n = 2, k = 0$. Neither the tesseral nor sectorial terms in the terrestrial gravitational field, nor the odd zonal terms effect the purely secular motion; however, this is not the case as regards the lunar gravitational field.

Cappallo, R. J. (Dept. of Earth and Planetary Sciences, M.I.T., Cambridge, MA 02139), Counselman, C. C., III, Shapiro, I. I., and King, R. W.: 'Numerical Model of the Moon's Rotation', *EOS: Trans. Amer. Geophys. Union* **58**, 372. (1977)

The differential equations for the Moon's rotation have been integrated numerically in inertial coordinates, with the initial conditions of the integration, the lunar moment–of–inertia ratios, and the third–degree gravity harmonics being estimated simultaneously with a large set of orbital, geodetic, and other parameters by least–squares fitting to five years of McDonald Observatory lunar laser ranging observations. The rms of the post–fit residuals (observed minus computed ranges) was about 25 cm. Separately, we have adjusted the initial conditions and other parameters of our lunar rotation model to fit the libration angles given by the numerical "LLB–5" model of J. G. Williams and others at JPL. The post–fit rms orientation difference, after removal of a fixed, three–axis rotation, was about 0.03 arcsec (selenocentric). A similar comparison with the semi–analytical "400 series" model of D. H. Eckhardt of AFGL is in progress and the results will be presented.

Cook, A. H. (Cavendish Laboratory, Madingley Road, Cambridge): 'Theories of Lunar Libration', *Phil. Trans. Roy. Soc. London* **A284**, 573–585. (1977)

The measured distance between a point on the Moon and an observatory on the Earth varies with the librational motion of the Moon about her centre of mass. The motion is caused by the varying attraction of the Earth, Sun and planets upon the Moon and obeys highly nonlinear equations of motion. Because of the high precision of measurements with lunar laser ranging systems, the theory of the motion must be worked out in great detail and the absence of adequate developments limits the interpretation of lunar ranging observations. Numerical integration of the equations of motion is carried out at the Jet Propulsion Laboratory and Eckhardt has developed a semi-literal theory in which coefficients of periodic terms are calculated numerically. There is still need, however, for a literal theory. A brief account will be given of a new literal theory, the algebraic manipulations for which are being carried out by the CAMAL machine algebraic program developed in the Computer Laboratory at Cambridge. The third harmonic terms in the gravitational potential of the Moon are included and it is intended to include the effect of the Sun.

Cook, A. H. (Department of Physics, University of Cambridge, Great Britain): 'Towards a New Semi–Literal Theory of the Lunar Librations', *Geophys. J. Roy. Astron. Soc.* **49**, 301. (1977)

A brief account will be given of progress in the development of a new theory of the lunar librations, in which a computer system of algebraic manipulation (CAMAL) is used to develop algebraic expressions.

Ferrari, A. J. (Jet Propulsion Lab., Pasadena, CA 91103): 'Lunar Gravity: A Harmonic Analysis', *J. Geophys. Res.* **82**, 3065–3084.

A sixteenth–degree and sixteenth–order spherical harmonic lunar gravity field has been derived from the long–term Keplerian variations in the orbits of the Apollo subsatellites and Lunar Orbiter 5. This model resolves the major mascon gravity anomalies of the lunar nearside and is in very good agreement with line of sight acceleration results. The farside map shows the major ringed basins to be strong localized negative anomalies located in broad regions of positive gravity which correspond closely to the highlands. The rms pressure levels calculated from equivalent surface height variations show that the Moon and Earth support nearly equal pressures (46 and 57 bars), whereas Mars is appreciably stronger (115 bars). These height variations are equivalent to mean uncompensated loads of 284 kg/cm^2 for the Moon, 58 kg/cm^2 for the Earth, and 308 kg/cm^2 for Mars. The Moon appears to support larger loads than the Earth owing to its weaker central gravity field and perhaps a colder upper lithosphere. Significant differences between the low–degree gravity and topography spectra indicate that the longer–wave–length topographic features are isostatically compensated. The effect of compensation reduces the amplitudes of the low–degree gravity harmonics and is responsible for the slower decay in the Moon's gravity spectrum. A comparison of the gravity effects of topography for the three planets shows that the Moon and Mars support significant topographic features, whereas the Earth is nearly in isostatic equilibrium.

Ferrari, A. J. (Jet Propulsion Lab., Pasadena, CA 91103) and Ananda, M. P.: 'Lunar Gravity: A Long–Term Keplerian Rate Method', *J. Geophys. Res.* **82**, 3085–3097. (1977)

Recent reductions of Apollo subsatellite and Lunar Orbiter 5 data have determined the first plausible models for the farside lunar gravity field. This paper presents a selenodesy method which estimates gravity by fitting to the long–term variations of the Kepler element rates. Raw Doppler tracking data taken over short arcs are reduced to estimate a best set of mean orbital elements for each orbit. A succession of such fits is performed to generate a history of mean elements. The element rates are determined from patched cubic spline fits to the eleements. The rates are adjusted for *n*–body effects and along with the associated elements are used as input to a gravity estimator. This method eliminates certain of the dynamical aspects of long–term selenodesy, and consequently, the gravity inversion is a linear process. Since the rates are generated from a series of patched cubic spline fits, unmodeled spacecraft manoeuvers contaminate at most only several data points, and there is no significant net integrated effect as in conventional long–term methods. Simulations performed demonstrate that farside gravity features can successfully be determined by fitting to mean elements derived from nearside tracking. Arguments are presented which conclude that a long–term gravity method of this type is the most plausible technique which can obtain realistic estimates for farside lunar gravity using the currently available data.

Garlick, G. F. J. (Physics Dept., University of Hull): 'Lunar Surface Movements – The Evidence and the Causes', *Phil. Trans. Roy. Soc. London* **A285**, 325–329. (1977)

A review is made of the various kinds and sources of evidence for motion or disturbance of lunar surface dust. This evidence ranges from the terrestial reporting of transient lunar phenomena to Apollo Mission evidence such as anomalous alpha particle activity over certain areas such as Aristarchus and Grimaldi craters and the occurrence of horizon glow due to dust suspensions at the lunar sunset terminator. Moonquakes of the deep seated kind are relatively unlikely to cause surface dust motion but shallower quakes and those of thermal origin may correlate with dust movement and consequently with terrestrially observed transients, e.g. just after lunar sunrise. Anomalous alpha particle activity and non–equilibrium of daughter product with parent indicate spasmodic gas evolution at sites like Aristarchus where there is evidence of unusual albedo levels also suggestive of surface motion. Future study of transients will be facilitated by monitoring the degree of polarization of moonlight in its variation across the lunar terrain and its marked sensitivity to dust disturbance.

Jones, P. K. (Case Western Reserve University, Cleveland, OH 44106) and Jones, S. L.: 'Lunar Association with Suicide', *Suicide and Life–Threatening Behavior* 7, 31–39. (1977)

Suicides in Cuyahoga County, Ohio, for 1972–1975 are tabulated by year, month of year, day of week, lunar phase, and holiday occurrence. Only lunar phase demonstrates a significant ($p < 0.01$) variation in suicide rate; an increase is observed in this sample with respect to new moon phase but not for full moon phase. Explanations for this finding are considered, but the precise reasons remain unknown.

King, R. W. (Air Force Geophysics Laboratory, Terrestrial Sciences Div., Hanscom Air Force Base, Bedford, MA 01731), Counselman, C. C., III, and Shapiro, I. I.: 'Geodetic Results from Lunar Laser Ranging', *EOS: Trans. Amer. Geophys. Union* 58, 372. (1977)

Lunar laser ranging observations from the McDonald Observatory have been used to estimate simultaneously the coordinates of the lunar retroreflectors and of McDonald, the Moon's physical libration, variations in Universal Time (UT), the constants of the Earth's precession and nutation, the mass of the Earth–Moon system, and parameters describing the orbit of the Moon about the Earth and the Earth–Moon barycenter about the Sun. The root–mean–square (rms) of the postfit range residuals for the 5–year period from October 1970 to November 1075 is 25 cm. The geocentric coordinates of McDonald have been determined with an uncertainty of 1 m. Variations in UT have been determined with an uncertainty of 1 ms. The rms difference between our determinations of UT and those of the Bureau International de l'Heure (BIH) is 2.3 ms with only the mean removed and 1.7 ms with the mean and a 1.5 ms annual term removed.

Kovalevsky, J. (Centre d'Etudes et de Recherches Geodynamiques et Astronomiques, 8 Boulevard Emile–Zola, 06130 Grasse, France): 'Lunar Orbital Theory', *Phil. Trans. Roy. Soc. London* **A284**, 565–571. (1977)

The present and expected accuracies of lunar laser ranging imply that the gravitational theory of the motion of the Moon should be consistent with at least the same precision. It is therefore necessary to aim at internal relative consistencies better than 10^{-11} or 10^{-12}.

Several theories based on numerical integration have been built and are currently being used in reducing the lunar laser ranging data. However, literal or semi-literal analytical theories have several important advantages over purely numerical ephemerides. This is why important programmes of building such theories are now in progress, particularly in the U.S.A. and in France.

Characteristics and the state of advancement of these theories will be reviewed and the possibility of constructing an analytical theory with the above mentioned accuracy discussed.

Kroitzsch, V. (Akademie der Wissenschaften der DDR, Zentralinstitut fur Physik der Erde, DDR–15 Potsdam, Telegrafenberg) Treder, H. -J.: 'Bemerkungen zu Einsteins Berechnung der Periodischen Schwankunger der Tageslange, Welche Durch die Partialfluten des Mondes Verursacht Werden', *Beitrage zur Geophysik* **86**, 97–100. (1977)

A. Einstein (1919) calculated the fluctuations of the inertial momentum and of the rotational velocity ω of the Earth, which are caused by the partial tides of the Moon with periods of 14 days and 18.6 a (Saros). However, Einstein and A. v. Brunn (1919) proved – in Einstein's days – that the calculated amplitudes of these fluctuations are too small as to be verified by observations. Independenctly, H. Jeffreys (1928) made the same calculations of the periodical fluctuations of the Earth's rotation generated by the partial tides of the Moon and Sun, and all the subsequent papers on these problems are based on Jeffreys' work. Today, we are able to verify these periodical fluctuations of the Earth's rotation by atomic clocks.

Lidov, M. L. (Academy of Sciences, Institute of Applied Math., Moscow V–71, USSR): 'One Family of Spatial Periodic Orbits Near Moon and Planets', (In Russian) *Dokl. Akad. Nauk SSSR* **233**, 1068–1071. (1977)

Mulholland, J.D. (McDonald Observatory & Dept. of Astronomy, University of Texas at Austin, Austin, TX 78712): 'Three–Dimensional Determination of the Center of the Watts Datum Relative to the Lunar Center of Mass' *Astron. J.* **82**, 306–308. (1977)

A combination of 2770 photelectric occultations covering the period 1955–1973 and 1787 laser time delays from 1970–1975, have been used to determine the location of the origin of the Watts datum for the marginal zone of the Moon. The resulting selenocentric (i.e., center of mass) vector is $\mathbf{x} = (+\,6.8, -\,2.5, +\,0.06)\,\mathrm{km} \pm (2.4, 0.5, 0.08)$, relative to the reference frame based on the principle axes of inertia.

Sjogren, W. L. (Jet Propulsion Lab., Pasadena, CA 91103): 'Lunar Gravity Determinations and their Implications', *Phil. Trans. Roy. Soc. London* **A285**, 219–226. (1977)

The variations in speed of the orbiting Apollo spacecraft as observed from Earth–based radiometric data have provided a direct measure of the local gravitational field. The gravity data were used to infer mass distributions that relate to topography in varying degrees. The mascons exist as mass excessses in topographic lows in all the near–side ringed basins and are best represented as near surface disks with excess loads of $800\,\mathrm{kg/cm^2}$. Large 100 km size craters like Langrenus, Theophilus, and Copernicus have mass deficits that are consistent with the craters' volumes. Both of these results imply a relatively rigid surface layer that allowed little isostatic adjustment over lunar time. However, the Apennine mountains, presumably formed at the time of the Imbrium impact event, reveal only a small gravitational anomaly compared to their topographic size. This suggests that at this era the Moon was more plastic and isostatically compensated. By using the orbital element history of the subsatellites, the first realistic far–side field has been determined. The far–side ringed basins are mass deficits consistent with the lack of maria filling. The 2 km centre–of–gravity offset from the geometric centre implies a thicker far–side crust that possible prevented far–side maria flooding. The homegeneity parameter (C/MR^2) is near that of a homogeneous sphere having possible a small core with a slight density increase towards its centre.

Szebehely, V. (The University of Texas, Austin, TX 78712) and McKenzie, R. :'Stability of the Sun–Earth–Moon System', *Astron. J.* **82**, 303–305. (1977)

The models of the restricted and general problems of three bodies are used to determine the stability of the Sun–Earth–Moon system by means of surfaces of zero velocity. Hill's result is verified by the model of the restricted problem as long as the ratio $m_{\mathrm{E}}/m_{\mathrm{S}} \geqslant 2.52 \times 10^{-6}$. The model of the general problem, on the other hand, contradicts this result and we show that the eccentricity of the Earth's orbit renders the system unstable by opening the surface of zero velocity. It may be concluded, therefore, that the Moon may escape from the Earth and may become a planet or, in reverse, that the planetary origin and the capture of the Moon by the Earth becomes a strong dynamic possibility.

Weiss, J. R. (College of Engineering & Applied Science, Univ. of Wisconsin, Milwaukee, WI 53201): 'A New Approach to Lunar Librational Stability', *Acta Astronautica* **4**, 271–277. (1977)

The total stability of lunar librational motion is studied in this paper. The analysis is made by extending the concept of Liapunov stability to that of total stability, or stability under constantly acting disturbances, as first introduced by Doubochine.

The equations of librational motion in the absence of disturbing torques are expressed in the first–order vector from $\mathbf{x}'(\tau) = \mathbf{f}(\mathbf{x}, \tau)$, where $\mathbf{x}(\tau)$ represents the motion from the Earth–pointing equilibrium. By adding an expression for external disturbing torques this equation becomes $\mathbf{x}'(\tau) = \mathbf{f}(\mathbf{x}, \tau) + \mathbf{g}(\mathbf{x}, \tau)$. Expressions are found for $\delta_1(\epsilon)$ and $\delta_2(\epsilon)$ such that it $\mathbf{x}(t)$ is a solution to the perturbed equation, if $\|\mathbf{x}(\tau_0)\| < \delta_1(\epsilon)$ and if (in a certain neighborhood of the equilibrium) $\|\mathbf{g}(\mathbf{x}, \tau)\| < \delta_2(\epsilon)$, then $\|\mathbf{x}(\tau)\| < \epsilon$ for all $\tau \geqslant \tau_0$. The expressions for the bounds δ_1 and δ_2 depend on physical parameters of the Moon.

Winters, R. R. (Dept. of Physics & Astronomy, Denison University, Granville, OH 43023) and Malcuit, R. J.: 'The Lunar Capture Hypothesis: Early Post–Capture Lunar Orbital Evolution and Implications for Earth History', *EOS: Trans. Amer. Geophys. Union* 58, 428. (1977)

A great–circle pattern of large circular maria can be interpreted as the signature of an Earth–Moon encounter within the weightlessness limit of the Earth–Moon system. Such an encounter may have resulted in capture if V_∞ were sufficiently small. For this work we assume that the mare–producing encounter was the capture encounter. Love number values sufficient for capture of a lunar–sized body from a near earth–coincident orbit are: Earth: $h = 0.9, k = 0.5$; Moon: $h = 0.45, k = 0.24$. The general scheme of early orbital evolution is that following the capture encounter, each succeeding encounter in geocentric orbit will result in a decrease of eccentricity and increase of Earth–Moon distance at perigee. The energy that must be dissipated in the bodies of the Earth and Moon is about 2×10^{35} ergs for capture within the sphere of influence of Earth (estimated by Öpik, 1976, to be about 270 Earth radii). An additional 4×10^{35} ergs must be dissipated for the Moon's orbit to become nearly circular with radius about 40 Earth radii. The time scale of evolution depends on the assumed love number values for the two bodies and on the geometry of the capture orbit. A series of numerical integrations are being done to estimate this time scale. In general, a large amount of the energy is dissipated within the two bodies during the first few years of orbital evolution. Such energy release would cause widespread melting within the mantles of both bodies. It is suggested that the energy released within the Earth's mantle (about 10^{35} ergs) may have caused mantle homogenation prior to a second stage of mantle–crust differentiation dated by Stacey and Kramers at about 3.7 b.y.

2. Physical Structure of the Moon; Thermal and Stress History of the Moon

Cheng, C. H. (Dept. of Earth and Planetary Sciences, M. I. T., Cambridge, MA 02139) and Toksoz, M. N.: 'Tidal Stresses in the Moon', *EOS: Trans Amer. Geophys. Union* 58, 427. (1977)

Theoretical models of the tidal stresses on a radially heterogeneous Moon are calculated numerically as a function of depth and location within the lunar body. The spatial distribution of the stresses is presented both in terms of global cartesian coordinates and local cartesian coordinates, the latter chosen in such a way that the z–plane is always tangential to the lunar surface. The results show that (1) as a function of depth, all the stress components achieve broad extrema between 500–1000 km depths, and (2) the spatial distribution of the normal stresses is symmetric around the sub–Earth point, changing from, compressive at the center of the luner disc to tensile around the limb. In both coordinate systems the tangential stresses show antisymmetric distributions about the sub–Earth point, with extrema around ±30° longitude and latitude, although the magnitudes and the sharpnesses of these extrema differ from each other. The implications of these results to the locations of moonquake foci and possible fault planes will also be discussed.

Goins, N. R. (Dept. of Earth and Planetary Sciences, M. I. T., Cambridge, MA 02139), Dainty, A. M., Toksoz, M. N., and Shure, L.: 'The Structure of the Lunar interior', *EOS: Trans. Amer. Geophys. Union* 58, 427. (1977)

The lunar interior is studied using the seismic date from a combination of surface events and deep–focus Moonquakes. The surface event data are analyzed using a polarization filter and the resulting record section plots. These analyses imply that the upper mantle seismic velocities are nearly constant to a depth of about 500 km, with average values of 8.0 km/sec and 4.6 km/sec for P and S waves, respectively. The 500 km lower–upper mantle boundary shows up as a distinct reflector. Below 500 km we must use the deep Moonquake data, since surface event shear waves do not return from below this boundary. We have stacked the seismograms at each repeating Moonquake source for signal–to–noise enhancement. The P and S wave arrival times are then inverted using standard and stochastic inversion methods to simultaneously determine the Moonquake locations and structural parameters. The resulting average lower mantle seismic velocities, below 500 km and above the Moonquake depths (about 900 km), are 7.5 ± 0.6 km/sec and 4.1 ± 0.25 km/sec. These low velocities produce a shadow zone agreeing well with the loss of surface event arrivals. we have also used the polarization filter on the stacked Moonquake records, and plotted them as record sections. Besides *P* and *S*, several additional phases are being used to extend the structure below the depth of 1000 km, with particular interest on investigating the existence of a lunar core.

Keihm, S.J. (Lamont–Doherty Geological Obs., Palisades, New York, NY 10964) and Langseth, M. G.: 'The Present Thermal State of the Lunar Interior', *EOS: Trans. Amer. Geophys. Union* **58**, 427. (1977)

Analysis of the geophysical constraints and experimental data on interior temperatures in the Moon indicate that its global heat loss most probably lies in the range 1.4 to $1.8 \mu\mathrm{W\,cm}^{-2}$. These data are also consistent with lunar mantle temperatures very near the solidus at 250–350 km below the surface. The seismic data require subsolidus temperatures, at least to depths of 800 km. These combined conclusions require convection in the lunar interior and a Moon that is presently nearly at steady state, with total uranium abundances between 34–46ppb.

Geochemical evidence indicates that the lunar mantle is depleted in K, U and Th to depths of about 200–400 km, but the present interior temperatures require that below this depth the abundances be close to the global average. Studies of convection of the Moon below a lithosphere of about 300 km have been made. The radial temperature fields produced can be constrained by seismic data and the integrated mass properties of the Moon. These studies indicate that high Rayleigh numbers (greater than 10^5) are required to provide the highly efficient heat transfer necessary for a nearly isothermal lunar interior.

Kopal, Z. (Dept. of Astronomy, University of Manchester): 'Dynamical Arguments which Concern Melting of the Moon', *Phil. Trans. Roy. Soc. London* **A285**, 561–568. (1977)

This paper points out that the observed differences of the moments of inertia of the lunar globe about its principal axes – determined astronomically and verified more recently by laser ranging – are inconsistent with the assumption that the whole Moon was ever covered by a global layer of molten material, extending to a depth of a few hundred kilometres. Moreover, laser determinations of the shape of the Moon (along the tracks overflown by Apollo 15–17 missions) make it quite clear that the Moon's surface did not solidify from a global ocean of lava even 10–20 km deep.

Therefore, any melting which occurred on the Moon (and produced the observed chemical differentiation of the crustal rocks) could have taken place only *locally* – over areas of the size of the lunar maria, but *not* over the Moon as a whole at the same time.

Lammlein, D. R. (Pennzoil Co., P.O. Box 2967, Houston, TX 77001): 'Lunar Seismicity and Tectonics', *Phys. Earth Planet. Interiors* **14**, 224–273. (1977)

Seismic signals from 300–700 deep moonquakes and about four shallow moonquakes are detected by the long-period seismometers of two or more of the Apollo seismic stations annually. Deep-moonquake activity detected by the Apollo seismic network displays tidal periodicities of 0.5 and 1 month, 206-d and 6-a. Repetitive moonquakes from 60 hypocenters produce seismograms characteristic of each. At each hypocenter, moonquakes occure only within an active period of a few days during a characteristic of each. At each hypocenter, moonquakes occur only within an active period of a few days during a characteristic phase of the monthly lunar tidal cycle. An episode of activity may contain up to four quakes from one hypocenter. Nearly equal numbers of hypocenters are active at opposite phases of the monthly cycle, accounting for the 0.5-month periodicity. The 0.5- and 1-month activity peaks occur near times of extreme latitudinal and longitudinal librations and Earth–Moon separation (EMS).

The 206-d and 6-a periodicities in moonquake occurrence and energy release characteristics are associated with the phase variations between the librations and EMS. Because of the exact relationship between tidal phases and the occurrence of deep moonquakes from a particular hypocenter, it is possible to predict not only the occurrence times from month to month, often to within several hours, but also the magnitudes of the moonquakes from that hypocenter. The predicted occurrence of large A_1 moonquakes in 1975, following a 3-a hiatus, confirms the correlation between A_1-moonquake activity and the 6-a lunar tidal cycle and implies a similar resurgence for all of the deep moonquakes. Because no matching shallow moonquake signals have been identified to date, tidal periodicities cannot be identified for the individual sources. However, shallow moonquakes generally occur near the times of extreme librations and EMS and often near the same tidal phase as the closest deep moonquake epicenters. With several possible exceptions, the deep-moonquake foci located to date occur in three narrow belts on the nearside of the Moon. The belts are 100–300 km wide, 1000–2500 km long and 800–1000 km deep and define a global fracture system that intersects in central Oceanus Procellarum. A fourth active, although poorly defined, zone is indicated. The locations of 17 shallow-moonquake foci, although not as accurate as the deep foci show fair agreement with the deep-moonquake belts. Focal depths calculated for the shallow moonquakes range from 0–200 km. Deep-moonquake magnitudes range from 0.5 to 1.3 on the Richter scale with a total energy release estimated to be abount 10^{11} erg annually. The largest shallow moonquakes have magnitudes of 4–5 and release about 10^{15}–10^{18} erg each. Tidal deformation of a rigid lunar lithosphere overlying a reduced-rigidity asthenosphere leads to stress and strain concentrations near the base of the lithosphere at the level of the deep moonquakes. Although tidal strain energy can account for the deep moonquakes in this model, it cannot account for the shallow moonquakes. The tidal stresses within the lunar lithosphere range from about 0.1 to 1 bar and are insufficient to generate moonquakes in unfractured rock, suggesting that lunar tides act as a triggering mechanism. The largest deep moonquakes of each belt usually occur near the same characteristic tidal phases corresponding to near minimum or maximum tidal stress, increasing tidal stress, and alignments of tidal shear stresses that correspond to thrust faulting along planes parallel to the moonquake belts and dipping 30–40°. With few exceptions, the shallow moonquakes occur at times of near minimum tidal stress conditions and increasing tidal stress that also suggest thrust faulting. The secular accumulation of strain energy required for the shallow moonquakes and implied by the uniform polarities of the deep moonquake signals probably results from weak convection. A convective mechanism would explain the close association between moonquake locations and the distribution of filled mare basins and thin lunar crust, the Earth-side topographic bulge, and the ancient lunar magnetic field. The low level of lunar seismic activity and the occurrence of thrust faulting both at shallow and great depths implies that the Moon is presently cooling and contracting at a slow rate.

Lammlein, D. R. (Pennzoil Co., P.O. Box 2967, Houston, TX 77001): 'Lunar Seismicity, Structure, and Tectonics', *Phil. Trans. Roy. Soc. London* **A285**, 451–461. (1977)

Interpretation of lunar seismic data results in a lunar model consisting of at least four and possibly five distinguishable zones: (I) the 50–60 km thick crust characterized by seismic velocities appropriate for plagioclaise rich materials. (II) the 250 km thick upper mantle characterized by seismic velocities consistent with an olivine-pyroxene composition, (III) the 500 km thick middle mantle characterized by a high Poisson's ratio, (IV) the lower mantle characterized by high shear-wave attenuation, and possibly (V) a core of radius between 170 and 360 km characterized by a greatly reduced compressional wave velocity. The Apollo seismic network detects several thousand deep moonquake signals annually. Repetitive signals from 60 deep moonquake hypocentres can be identified. The occurrence characteristics of the moonquakes from the individual moonquake hypocentres are well correlated with lunar tidal phases and display tidal periodicities of 1 month, $7\frac{1}{2}$ months, and 6 years. With several possible exceptions, the deep moonquake foci located to date occure in three narrow belts on the near side of the Moon, and are concentrated at depths of 800–1000 km. The locations of 17 shallow moonquake foci, although not as accurate as those of the deep foci, show fair agreement with the deep moonquake belts. Focal depths calculated for the shallow moonquakes range from

0–300 km. The moonquakes of a particular moonquake belt, or a region within belt, tend to occur near the same tidal phase suggesting similar focal mechanisms. Deep moonquake magnitudes range from about 0.5 to 1.3 on the Richter scale with a total energy release estimated to be about 10^{11} ergs (10^4 J) annually. The largest shallow moonquakes have magnitudes of 4–5 and release about 10^{15}–10^{18} ergs (10^8–10^{11} J) each. Tidal deformation of a rigid lunar lithosphere overlying a reduced-rigidity asthenosphere leads to concentrations of strain energy near the base of the lithosphere. Although tidal strain energy can account for the deep mooquakes in this model, it cannot account for the shallow moonquakes. Tidal stresses within the lunar lithosphere range from about 0.1 to 1 bar (10^4–10^5 Pa). This low level of tidal stresses suggests that tides act as a triggering mechanism. The secular accumulation of strain implied by the uniform polarities of the deep moonquake signals probably results from weak convection. A convective mechanism could explain the distribution of moonquakes, the Earth-side topographic bulge, the distribution of filled mare basins, and the ancient lunar magnetic field.

Meissner, R. (Institut fur Geophysik der Universitat Kiel D–23 Kiel, Neue Universitat, Germany): 'Lunar Viscosity Models', *Phil. Trans. Roy. Soc. London* **A285**, 463–467. (1977)

Viscosity values as estimated from isostatic processes and from temperature and melting point-depth relations show that the Moon's outer layers are much more viscous than any geologic region on Earth. These high η-values are responsible for the survival of the very old lunar landscape. At depths below 500 km η-values increase and permit a limited convection. Moonquakes around 800 km depth seem to be connected with a limited range of viscosity values. A tentative relation between viscosity and seismic Q-values is presented.

Middlehurst, B. M. (Lunar Science Institute, Houston, TX 77058): 'Transient Lunar Phenomena, Deep Moonquakes, and High-Frequency Teleseismic Events: Possible Connections', *Phil. Trans. Roy. Soc. London* **A285**, 485–487. (1977)

The positions of the epicentres of the recently discovered, high-frequency teleseismic (h.f.t.), shallow moonquakes have been compared with those of the surface phenomena known as lunar transient phenomena (l.t.p.). About 300 sites for the latter and about 17 shallow moonquake epicentres have been recorded. Most of the epicentres are within 5° of at least one l.t.p. site and the depths are given by Nakamura *et al.* (1974) as up to 265 km. The present paper considers some of the implications of the correlations between the two classes of sites and between the l.t.p. and the epicentres of the deep moonquakes at levels of about 800–1000 km below the surface. It appears likely that channels produced by the outrush of gases from the interior of the Moon are associated with the sites of the h.f.t. and of the l.t.p. that are almost vertically above them, and that release of gases through poorly consolidated soils at an early stage of the Moon's history may have led to the firmation of at least some of the craters on the Moon.

Nakamura, Y. (Geophysics Lab., Marine Science Institute, University of Texas, Galveston, TX 77550): 'HFT Events: Shallow Moonquakes?', *Phil. Earth Planet. Interiors* **14**, 217–223. (1977)

A few large distant seismic events of distinctly high signal frequency, designed HFT (hight-frequency teleseismic) events, are observed yearly by the Apollo lunar seismic network. Their sources are located on or near the surface of the Moon, leaving a large gap in seismic activity between the zones of HFT sources and deep moonquakes. No strong regularities are found in either their spatial or temporal distributions. Several working hypotheses for the identity of these sources have been advanced, but many characteristics of the events seem to favor a hypothesis that they are shallow moonquakes. Simultaneous observations of other lunar phenomena may eventually enable the determination of their true identity.

Rhodes, J. M. (Lockheed Electronics Corp., Houston, TX 77058): 'Some Compositional Aspects of Lunar Regolith Evolution', *Phil. Trans. Roy. Soc. London* **A285**, 293–301. (1977)

This paper discusses the compositional aspects of the lunar regolith in terms of regolith dynamics. Emphasis is placed on problems concerning lateral movement and mixing of soil components in response to meteoroid bombardment, and on the source of apparently exotic material in mare soils. In particular, it is shown that there are contradictory lines of evidence concerning the efficacy of impact-related lateral transportation of regolith components. Most of the compositional diversity of regolith in the lunar highlands and at the margins of mare basins can be accounted for by comminution and mixing of local rock types with relatively minor lateral transport. In contrast, the mare regolith contains substantial amounts of apparently exotic, highland-derived components in addition to the local basalts, implying efficient lateral transportation. In view of these contradictions, it is suggested that these so-called exotic components may be of local derivation, excavated by meteoroid impact from beneath thin mare basalt layers. A consequence of this model is that the mare basins are filled with impact breccias and melts and covered by a thin beneer of volumetrically insignificant mare basalt.

Tittmann. B. R. (Science Centre, Rockwell International, 1049 Camino Dos Rios, Thousand Oaks, CA 91360): 'Internal Friction Q Factor Measurements in Lunar Rocks, Annual Report, Feb. 1–Dec. 31, 1976', *NASA-CR-151215;* **AR–3**, 5pp. (1977)

To aid in the interpretation of seismic data obtained *below* the lunar surface we report here on measurements under confining pressures with the sample encapsulated under hard vacuum. Since partial crack closure would be expected to occur already at low pressures, as evidenced by the well-known and dramatic increases in velocity with increasing pressure in the 0.5 kbar range, we have been concentrating our Q measurements in this range. In these experiments we have been able to achieve a Q value just under 2000 at 0.5 kbar.

Toksoz, M. N. (Dept. of Earth and Planetary Sciences, M. I. T., Cambridge, MA 02139), Goins, N. R. and Cheng, C. H.: 'Moonquakes: Mechanisms and Relation to Tidal Stresses', *Science* **196**, 979–981. (1977)

Observed features of moonquakes are combined with theoretical calculations of the tidal stresses to interpret the moonquake mechanisms. Tidal stresses, together with a postulated ambient tectonic stress, are sufficient to explain the depth, periodicity, and polarity reversal of moonquakes. Both of these stresses are small (on the order of 1 bar) and consistent with the small magnitudes of moonquakes.

Warren, N. (Institute of Geophysics & Planetary Physics, University of California, Los Angeles, CA 90024) and Trice, R.: 'Structure in the Upper Lunar Crust', *Phil. Trans. Roy. Soc. London* **A285**, 469–473. (1977)

Estimates are made of the degree of lithification and of structure densities which are compatible with lunar *in situ* seismic profiles in the top 30 km of the Moon. Estimates are based on comparison of results of passive and active lunar seismic experiments with the pressure dependence of elastic moduli for various classes of lunar samples. Competent rock, such as igneous rock or recrystallized breccias with crack porosity of not more than about 0.5% are required to satisfy velocity profiles in the depth range 1–30 km. Velocity profiles in the upper 1 km are best satisfied by comminuted material to highly fractured lithic units. These estimates constrain those thermal and shock histories which are compatible with lunar seismic results. After crystallization, or recrystallization, rock below 1 km cannot have been exposed to more than moderate shock levels. In the uppermost 1 km, an unannealed and broken rock layer would imply low thermal conductivity resulting in possible tempertures at 1 km depth of several hundred kelvins.

3. Morphology of the Lunar Surface. Origin and Stratigraphy of Lunar Formations; Mapping of the Moon

Bills, B. G. (Div. of Geological & Planetary Sciences, Calif. Inst. of Tech., Pasadena, CA 91125) and Ferrari, A. J.: 'A Harmonic Analysis of Lunar Topography', *Icarus* **31**, 244–259. (1977)

A global lunar topographic map has been derived from existing Earth-based and orbital observations supplemented in areas without data by a linear autocovariance predictor. Of 2590 bins, each 5° square, 1380 (64.7% by area) contain at least one measurement. A sperical harmonic analysis to degree 12 yields a mean radius of 1737.53 ± 0.03 km (formal standard error) and an offset of the center of figure of 1.98 ± 0.06 km toward (19 ± 2)°S, (194 ± 1)°E. A Bouguer gravity map, derived from a 12-degree free-air gravity model and the present topography data, is presented for an elevation of 100 km above the mean surface. It is confirmed that the low-degree gravity harmonics are determined primarily by surface height variations and only secondarily by lateral density variations.

Dence, M. R. (Earth Physics Branch, Dept. of Energy, Mines and Resources, Ottawa, Canada K1A OY3): 'The Contribution of Major Impact Processes to Lunar Crustal Evolution', *Phil. Trans. Roy. Soc. London* **A285**, 259–265. (1977)

Large terrestrial impact craters provide structural models for the interpretation of lunar craters and basins and petrological data for comparison with complex lunar breccias. The terrestrial examples illustrate the mixing processes operative in the production of impact melts and braccias and the considerable volumes of impact melt rocks in large impact craters. Three forms of craters are found on Earth, Moon, Mars and Mercury: Simple bowl-shaped craters (smallest), central uplift, and ring structures (largest). The variations in form are interpreted as different degrees of gravitational modification which immediately follow the initial excavation. On Earth the transient cavity excavated has diameter/depth (D/d) near 3/1 in non-porous, essentially homogeneous rocks. From Orbiter and Apollo photographic data transient cavities in the most competent lunar materials have D/d of approximately 4/1. Experiments indicate ejecta come from as deep as two-thirds rds the transient cavity depth: disturbed material from greater depths remains as the crater lining. Application to the Imbrium basin indicates a portion of the ejecta at the Apollo 15 site may have come from a deep as 100 km, and from somewhat shallower depths as the Apollo 14 site. Ultramafic green and howarditic glasses are possible candidates for these materials of deep origin. Uplift of upper mantle in the centre of the basin would controbute to the Imbrian mascon.

El-Baz, F. (National Air and Space Museum, Smithsonian Institution, Washington, D.C. 20560): 'Lunar Stratigraphy', *Phil. Trans. Roy. Soc. London* **A285**, 549–553. (1977)

The lunar scene is a continuous panorama of ancient impact physiography. Multi-ringed circular basins and smaller craters scar the Moon's highlands and provide evidence of a violent early history. Basin formation, the major material-transporting mechanism on the Moon, produces a deep inner depression, one or more benches, a basin rim, and radially lineated ejecta. Study of lunar photographs indicates that, on a relative age scale, subdued basin and crater features are older representations of younger, well-preserved forms. Absolute age dating of returned samples makes it feasible to calibrate this relative age scale. All the larger basins were formed during pre-Nectarian, Nectarian and Imbrian times, i.e. 4.6–3.9 Ga ago.

Following this major sculpturing episode, and during the Imbrian and Eratosthenian times, mare volcanism became the most important mode of deposition of lunar surface materials. Basaltic lavas from deep-seated sources flowed to partially fill the impact basins and cover their peripheral troughs and surrounding lowlands between 3.8 and 3.2 Ga ago. This occurred more frequently on the near side than on the far side, probably because the far side crust is thicker. During the past 1 Ga, i.e. Copernican time, only a small number of craters were formed in both highland and mare rocks.

Successes and failures of photogeoligists in studying lunar stratigraphy provide the necessary lessons for understanding the geological history of the terrestrial planets. This is particularly true since both Mars and Mercury display many types of features in common with the Moon.

Fryer, R. J.: 'On a New Unified System of Designation of Objects on the Moon', *Soviet Astron.* **20**, 516–517. (1976)

Some features of systems proposed earlier for the designation of objects on the lunar surface are discussed in the article. An optimum version based on two different systems is presented.

Gold, T. (Center for Radiophysics & Space Research, Cornell University, Ithaca, NY 14853): 'Origin and Evolution of the Lunar Surface: The Major Questions Remaining', *Phil. Trans. Roy. Soc. London* **A285**, 555–559. (1977)

The major factors in the evolution of the lunar surface have not been determined yet. Huge lava flows and lunar differentiation, though commonly assumed, is in discord with much of the evidence. The alternative is for most of the surface to represent the last stages of accretion of the Moon only, with the chemical differentiation having taken place previously in the source material. Radar, seismic, surface exposure, and mascon evidence can then be accounted for. A large-scale surface transport mechanism of soil must then have been present.

Hartmann. W. K. (Planetary Science Institute, 2030 East Speedway, Suite 201, Tucson, AZ 85719): 'Relative Crater Production Rates on Planets', *Icarus* **31**, 260–276. (1977)

Dynamical histories of planetesimals in specified orbits, calculated by Wetherill (1975) and other, have given estimates of relative numbers of impacts on different planets. These impact rates, $\mathcal{F}$, are converted to crater production rates, F, by means of tables developed in this paper. Conversions are dependent on impact velocity and surface gravity. Crater retention ages can then be derived from (crater density)/(crater production rate). Such calculations of impact rates and their histories give the only basis, independent of sample dating, for establishing absolute geologic histories of the planets, contrary to published implications that this can be done by comparison of photos alone. A survey of the results, from orbits of interplanetary objects studied to date, indicates that the terrestrial planets have crater production rates within a factor ten of each other, and that planets' crater retention ages can probably be determined with a factor of ±3. Further calculations of orbital histories of additional interplanetary bodies are suggested to put photogeologic analyses from spacecraft imagery on a firmer basis.

Applications to Mars, as an example, using least-squares fits to crater-count data, suggest an average age of 0.3 to 3 b.y. for two types of channels. The Tharsis volcanics are found to be slightly younger than the channels (strongly confirmed by photomorphology since they are not cut by channels) and Olympus Mons is 2.5 b.y. old and most Martian volcanic provinces older than 3 b.y. Data strongly support the hypothesis that Martian channels formed in a fluvial climate that persisted on Mars until the Tharsis volcanism caused a change in the Martian obliquity state, as outlined by Toon, Ward, and Burns (1977).

Hartung, J. B. (Dept. of Earth & Space Sci., State Univ. of New York at Stony Brook, NY 11794): 'Extrapolation of Gravity Data Suggests Large Impact Structures form Sinking Basins', *EOS: Trans. Amer. Geophys. Union* **58**, 428. (1977)

Gravity anomalies over small (diameter < 4 km), bowl-shaped, impact craters are negative and reflect a mass depletion greatest at the crater center due to ejection of material and brecciation of rocks by the impact. Gravity data over larger (4 km $<$ diameter $<$ 100 km), central-peak craters on the Earth tend to have a concentric pattern consisting of positive anomalies at the crater centers due to stratigraphically uplifted central peak material and surrounding negative anomalies related to ejection, brecciation, and slumping of crater walls. Still larger impact structures, mare basins, on the Moon have positive gravity anomalies caused by stratigraphic uplift of more dense material, the filling of basins with dense basalts, or a combination of these processes. For craters below a certain size the strength of surrounding rocks is sufficient to maintain the gravity anomalies, that is, to withstand for long times the stresses caused by redistribution of material during an impact.

Apparently, the effect of a large impact is to form a topographic low together with a gravity high. Filling of the topographic low by basalt flows or sediments will contribute to a gravity high or mass excess near the crater center. If the impact event is large enough and the time long enough, the structure will begin to sink. The sinking is caused by the inability of the underlying rocks to support an initial mass excess and the increasing mass of material which will fill the topographic low. Sinking will continue until isostatic adjustment has been achieved. Examples of such sunken or sinking impact structures are Mare Imbrium on the Moon and the Hellas Basin on Mars and possible the southern part of the Gulf of St. Lawrence, the south eastern part of Hudson Bay, of the Michigan Basin on the Earth.

Head, J. W. (Dept. of Geological Sciences, Brown University, Providence, Rhode Island 02912): 'Origin of Central Peaks and Peak Rings: Evidence from Peak-Ring Basins on Moon, Mars and Mercury', *EOS: Trans. Amer. Geophys. Union* 58, 424. (1977)

A major question in studies of impact cratering processes has been the identification of factors that govern the formation of central peaks and terraces. Gault *et al.* (1975, J. G. R., 80, 244) have attributed these features to gravitational potential energy as opposed to cratering kinetic energy. Cintala *et al.* (1975, G. R. L., 3, 117) have suggested that factors related to variations in impact velocity and substrate characteristics may be important in explaining observed interplanetary variations in these features. Peak-ring basins a craterform structures in which the normal central peak or peak cluster has expanded to form an inner ring concentric to the basin rim. These basins are transitional between craters and three-ring basins. The relationship between peak ring diameter (Dpr) and basin rim crest diameter (Drc) was investigated for Mercury ($n = 33$) and Mars ($n = 15$) where gravity is approximately the same, and the Moon ($n = 12$), where gravity is about one-half that value. The relationship between these two features was found to be linear and is essentially the same for all three planets, despite the major variation in surface gravity (Moon: Drp = 0.56Drc–17.55; Mars: Dpr = 0.53Drc–7.54; Mercury: Dpr = 0.51Dcr–5.65). The similarity of the relationships for the three planets argues strongly against gravitational potential energy being a major factor in peak ring formation, and by inference in the formation of central peaks. Drc is related to cratering kinetic energy such that Drc $\propto (\mathrm{KE})^x$. Since the relationship between Drc and Dpr is linear, Dpr must be related to KE by approximately the same power. This further supports a kinetic-energy related origin for central peaks (Wood, 1973, Icarus, 20, 503) and peak rings.

McGill, G. E. (Dept. of Geology & Geography, University of Massachusetts, Amherst, MA 01002): 'Craters as "Fossils": The Remote Dating of Planetary Surface Materials', *Geo. Soc. Amer. Bull.* **88**, 1102–1110. (1977)

The need to determine relative ages of materials and surfaces on moons and planets other than the Earth has resulted in the development of dating techniques that are based on the density or the morphology of craters and that supplement the classical techniques of physical stratigraphy. As is the case with the fossil-based relative time scale on Earth, crater-based relative ages can, in principal, be calibrated with radiometric ages of returned samples. Relative ages determined by crater density or crater morphology rest on a small number of basic assumptions concerning the morphology of fresh craters, the randomness of crater-formation processes, and the rates and areal constancy of crater-degradation processes. The validity of these assumptions varies from planet to planet. Despite the problems and controversies that inevitably accompany the development of major new techniques, the basic principles underlaying the use of craters to determine relative ages are well established and logically sound.

Moutsoulas, M. (Lab. of Astronomy, University of Athens, Greece): 'Location Definition of Selenographic Control Points Based on Lunar Craters', *The Moon* **16**, 193–197. (1977)

It is suggested that selenographic positions of circular lunar craters used as reference points should be defined by the position of the center as determined from a best fit to the crater's rim.

Neukum, G. (Max-Planck-Institut fur Kernphysik, Heidelberg, Germany): 'Lunar Cratering', *Phil. Trans. Roy. Soc. London* **A285**, 267–272. (1977)

The form of the lunar impact crater size-frequency distribution is discussed. Latest results on the lunar cratering chronology in the first 1.5 Ga after its formation are reviewed. It is shown that most cratering arguments speak against an extraordinary high flux increase ('cataclysm') at *ca.* 4 Ga ago. From age determination by crater frequency measurements, it is concluded that the dominant process of the formation of light (Cayley) plains is not deposition of basin ejecta but an endogenic one.

Nininger, H. H. (American Meteorite Laboratory, Denver, CO 80201) and Huss, G. I.: 'Was the Formation of Lunar Crater Giordano Bruno Witnesses in 1178? Look Again', *Meteoritics* **12**, 21–25. (1977)

The assumption that five men witnessed the formation of the lunar crater Giordano Bruno on June 18, 1178, is analyzed. The difficulties inherent in this interpretation are discussed. The only tenable solution – that of a meteor passing before the Moon – is presented.

Oberbeck, V. R. (Ames Research Center, NASA, Moffett Field, CA 94035), Quaide, W. L., Arvidson, R. E., and Aggarwal, H. R.: 'Comparative Studies of Lunar, Martian and Mercurian Craters and Plains', *J. Geophys. Res.* **82**, 1681–1698. (1977)

The amount of smooth plains material in craters surrounding the Caloris basin on Mercury depends on the extent these craters have been eroded by Caloris ejecta. Therefore smooth plains surrounding Caloris must have been emplaced at least in part by saturated secondary cratering. Mercurian uplands outside the continuous belt of smooth plains deposits have a crater population which is deficient in craters smaller than 50 km relative to extrapolations of craters larger than 50 km and relative to size frequency distributions of craters $\leqslant$ 50 km on typical lunar upland regions. However, the typical lunar upland regions have been masked by the addition of numerous large basin secondary craters. Only rare areas southwest of Mare Serenitatis appear to be similar to Mercurian terrain at great distances from smooth plains because the areas are relatively free of basin secondaries. Martian uplands also exhibit a crater population which is deficient in craters less than 30–50 km, which was previously interpreted to have been caused by obliteration of some craters less than 30 km by surface processes. The observed crater deficiencies on the Moon, Mars, and Mercury below 30–50 km are mostly a reflection of the primary crater production population; it is characterized by a power function having two different exponents (-2.0 for craters less than 50 km and -3.2 to 3.5 for craters $\geqslant$ 50 km). The hypothesis that the observed deficiency of small lunar craters southwest of Mare Sernitatis resulted from an episode of premare volcanism which obliterated some small craters was evaluated and rejected because highland volcanic rocks are rare in returned samples, and if significant premare upland basaltic volcanism is hypothesized, it would be circumstantial that it occurred only in those areas least affected by basin ejecta. Premare upland volcanic activity would be required also to explain the Mercurian crater counts. However, the Mercurian mapping results indicate that intercrater plains representative of hypothetical volcanic rocks were formed before craters now observed on their surfaces. The most persuasive reason for rejecting the theory of lunar premare volcanism is that reexamination of all available crater count data for lunar uplands shows no evidence for a primary production population characterized by a single power function. Therefore crater counts showing deficiencies relative to a single power function which previously was acceptable evidence for crater obliteration need no longer be considered as evidence for crater obliteration.

Saito, Y.: 'Sinuous Rilles in Western Mare Imbrium', *Contributions from the Kwasan and Hida Observatories, University of Kyoto No. 234,* **1–12.** (1977)

Stratigraphy and morphology of the major 12 sinuous rilles in the western half of Mare Imbrium are analysed on the color contrast photograph, the Lunar Orbiter 4 photographs, and the Apollo photographs. The mare basalts are devided into four layer strata. Stratigraphical analysis leads to the results that 9 of the sinuous rilles are on the oldest 'red' basalts, and that one sinuous rille (Rima Gruithuisen 1) belongs to the next younger strtum. Photogeopogical analysis concludes that some of the sinuous rilles (Rima La Hire and Rima Brayley 2) are the tectonic grabens of origin.

Settle, M. (Air Force Geophysics Lab., Hanscom AFB, MA 01731) and Head, J. W.: 'Radial Variation of Lunar Crater Rim Topography', *Icarus* **31**, 123–135. (1977)

The variation of rim topography as a function of range from the crater rim has been determined for a group of morphologically fresh lunar craters ($D = 10$–140 km) using the recent series of Lunar Topographic Orthophotomaps. The rate at which exterior crater topography converges with the surrounding surface is highly variable along different radial directions at individual craters as well as between different craters. At several craters, oblique impact appears to have contributed to azimuthal elevation/range variations. The topographic expression of a crater above the surrounding surface typically decreases to one-tenth of the estimated rim height at a range of $1.3R$–$1.7R$, well within the rough-textured ejecta deposit surrounding the crater. Comparisons with terrestrial craters suggest that the topographic crater rim is predominantly a structural feature. In most craters large portions of the hummocky facies and virtually all of the radial facies, in spite of their rough appearance and local topographic variations, provide no significant net topographic addition to the preexisting surface. The extreme variability of crater rim topography strongly suggests that ejecta thicknesses are highly variable and that a unique power-law expression cannot truly represent the radial variation of ejecta deposit thickness.

Simonds, C. H. (Lunar Sciences Institute, Houston, TX 77058), Warner, J. L., and Phinney, W. C.: 'Effect of Water on Cratering', *EOS: Trans. Amer. Geophys. Union* **58**, 425. (1977)

The effect of abundant pore water in impact targets is to reduce the amount of impact melt and other thermal effects, and to form a large expanding debris-laden steam cloud. Published studies of the larger terrestrial craters indicate the restriction of melt sheets to craters in crystalline rocks with little or no sedimentary cover relative to the depth of excavation. Lack of melt sheets in larger structures with sedimentary targets and limited subsequent erosion (22 km Gosses Bluff, 25 km Kamenska, 50 km Kara, 24 km Ries and 14 km Wells Ck) contrasts with melt sheet occurences at 3 km Brent, 5 km Lake Mien and the larger, less eroded craters with crystalline targets. Also, craters in thick sedimentary sequences such as the Ries have $< 0.5\%$ melt, while crystalline target craters such as Brent, Mistastin, Manicouagan and W. Clearwater Lake have 1–5% melt.

The behavior of water during cratering depends on its total abundance and whether or not it is bound in silicates. At Manicouagan 2–3% bound water in amphibolite faces metamorphic rocks did not disrupt formation of a melt sheet, but rather dissolved in the melt (shocked to over 600 kb). In contrast, pore water is vaporized by shock waves over 100 kb if overburden pressure is low. Much of the pore water forms a large steam cloud carrying a large amount of debris. The reduced thermal effects in wet targets are a consequence of the heat capacity of steam which gram of gram is equal to silicate melt at over 1700°C. If the Martian crust contains abundant water, Martian impactites should resemble those around sedimentary-target terrestrial craters. Craters in the dry lunar highlands produced abundant impact melts texturally similar to lithologies in and around the crystalline-target terrestrial structures.

Strain, P. L. (National Air Space Museum, Smithsonian Institution, Washington, D.C.) and El-Baz, F.: 'Topography of Sinuous Rilles in the Harbinger Mountains Region of the Moon', *The Moon* **16**, 221–220. (1977)

Five sinuous rilles occur in mare basalts in the Harbinger Mountains region of the Moon. Complete and accurate topographic data, now available for the first time, make possible a detailed topographic study of these rilles. Rille length ranges from 12 to 79 km and width from 0.8 to 4.8 km. Depth varies from 100 to 300 m and the rilles appear to become shallower to the north. The southern ends of the rilles are characterized by circular to elongate depressions that occur on a 30 km in diameter dome of probable volcanic origin. Longitudinal profiles show that the rille floors have a northwardsslope of less than one degree. This slope is consistent with the general slope of the surrounding mare surface. Structural studies indicate that slope rather than the regional structural pattern is the dominant factor controlling rille direction. Topographic data lend support to the theory that the rilles were formed as lava channels or tubes.

Wood, C. A. (Dept. of Geological Sciences, Brown University, Providence, RI 02912): 'Cinder Cones on Earth, Moon and Mars', *EOS: Trans. Amer. Geophys. Union* **58**, 425. (1977)

Interrelationships between heights (H_{co}), basal diameters (W_{co}), and crater diameters (W_{cr}) determined for cinder cones on Mauna Kea, Hawaii, (Porter, *BGSA 83*, 3607; 1972) are typical of many terrestrial cinder cones. Cone-like structures on the Moon and Mars have the same W_{cr}/W_{co} ratios as terrestrial cinder cones, but the lunar cones are only $\frac{1}{4}$ as high (for a given W_{co}) as those on Earth, while the one martian cone is intermediate in height. These observations differ from cinder cone morphologies predicted for the Moon and Mars based on a model developed from eruptions of NE Craters, Mt. Etna (McGetchin *et al. JGR 79,* 3257; 1974). This model predicts that if lunar and martian eruptions occurred under the same conditions as NE Crater, then the resulting cones should have W_{cr}/W_{co} values half that of typical terrestrial cones. Furthermore, the H_{co}/W_{co} values for lunar and martian cones should be ~ 0.02 and ~ 0.08 times those of comparable terrestrial cones, respectively. A possible reason for the discrepancy is that the eruptive conditions observed in NE Crater did not form the lunar and martian cones. The minium velocity required to reach the limit of continuous ejecta for a lunar cinder cone with the same volume and nominal ejection angle (75°) as NE Crater is 25 m/sec, compared to the average value of 50 m/sec measured at NE Crater. For Mars, a velocity of 35 m/sec is required. These figures may indicate that (a) ejection angles on the Moon and Mars are lower than at NE Crater or (b) smaller quantities of volatiles, per unit volume of ejecta, are associated with lunar and martian cinder cone eruptions than with terrestrial eruptions. The latter alternative is consistent with the low volatile content of lunar samples.

4. Chemical Composition of the Moon; Lunar Petrology, Mineralogy and Crystallography

Allegre, C. J. (Institut de Physique du Globe et Department des Sciences de la Terre, Université de Paris 6 et 7, 75230, Paris, France), Shimizu, N., and Treuil, M.: 'Comparative Chemical History of the Earth, the Moon and Parent Body of Achondrite', *Phil. Trans. Roy. Soc. London* **A285**, 55–67. (1977)

Chronological studies on the lunar samples suggest that major chemical fractionation occurred at 4.4 Ga. It is inferred from both whole-rock Rb-Sr isochron and Nd-Sm systematics. It is stressed that any models on the lunar petrogenesis and evolution should reconcile with this early fractionation. A model for chemical evolution of the Moon (extensive fractional crystallization of a molten layer, followed by impact melting and mixing of melts) is dicussed to account for phase relations and r.e.e. abundances. Similar chronological characteristics are observed for achondrite parent body. Achondrite parent body experienced a similar evolutionary history to the Moon starting with a slightly different initial composition (major elements). In the Earth, on the contrary, chemical differentiation has continued (or is still continuing) as indicated by chronological and isotopic evidence.

Anders, E. (Enrico Fermi Institue & Dept. of Chemistry, Univ. of Chicago, Chicago, IL. 60637): 'Chemical Compositions of the Moon, Earth and Eucrite Parent Body', *Phil. Trans. Roy. Soc. London* **A285**, 23–40. (1977)

Model compositions of the Moon and Earth were calculated on the assumption that these planets had experienced the same nebular fractionation processes as the chondrites. The proportions of 7 basic components (early condensate, metal, etc.) were estimated from geochemical constraints, such as K/U, bulk U and Fe abundances, etc., and used to construct abundance tables for 83 elements.

When lunar and terrestrial basalt data are normalized to these model compositions (to cancel differences in bulk composition), the abundance patterns become strikingly similar. This would seem to demonstrate the essential sameness of igneous processes on both planets. The model correctly predicts the abundance ratios of certain volatile/refractory element pairs (e.g. Cd/Ba, Ga/La, Sn/Th, and Pb/U), the density of the Moon, and the major rock types.

The model is also used, in the reverse direction, to reconstruct the composition of the eucrite parent body. It resembles the Moon to a remarkable degree, except for a lower content of refractory elements. Because of this similarity, it is unlikely that the Moon acquired its composition by some unique chance event, such as disintegrative capture. More likely, such compositions represent the natural outcome of nebular fractionation processes, which may have been more extreme in the inner solar system than in the asteroid belt.

All input data required by this model can be obtained by unmanned spacecraft or ground-based observations. Thus, if this model proves viable, it will permit construction of a detailed geochemical profile of a differentiated planet after a single visit by an unmanned spacecraft.

Beckinsale, R. D. (Institute of Geoligical Sciences, 64–78, Grays Inn Road, London WC1X 8NG): 'Hydrogen, Oxygen and Silicon Isotope Systematics in Lunar Material', *Phil. Trans. Roy. Soc. London* **A285**, 417–426. (1977)

In this review the following coclusions are supported:

(1) The bulk of the hydrogen in the lunar soils represents protons implanted from the solar wind and is essentially deuterium free.

(2) Rarely samples of relatively deuterium rich hydrogen are found, probably resulting from *in situ* spallation reactions.

(3) The water found in lunar samples is probably entirely terrestrial contamination (which yields a third component of hydrogen in the lunar samples).

(4) Extreme ^{18}O and ^{30}Si enrichments are found in the surfaces of grains in the lunar soil. These probably result from the condensation of material which was vaporized from the lunar surface by bombardment from micrometeorites, etc., and fractionated in the lunar atmosphere, leaving a heavy isotope enriched fraction to condense. The complimentary fraction enriched in light isotopes escapes and about 1% of the mass of the regolith has been lost in this way.

(5) Oxygen isotope geothermometry on lunar basalts given temperatures in the approximate range 1000–1150°C generally close to experimentally determined liquidus temperatures.

(6) Recent oxygen isotope studies by Clayton and co-workers provide exciting new evidence that the Earth–Moon system has a different origin from the higher temperature codensates in the chondritic meteorites.

Boynton, W. V. (Institute of Geophysics and Planetary Physics, Dept. of Earth and Space Sciences, Los Angeles, CA 90024) and Wasson, J. T.: 'Distribution of 28 Elements in Size Fractions of Lunar Mare and Highlands Soils', *Geochim. Cosmochim. Acta* **41**, 1073–1082. (1977)

Four volatile, six siderophile and 18 generally lithophile elements were determined in six sieve fractions of mare soil 15100 and seven sieve fractions of highland soil 66080; 15100 is a moderately and 66080 a highly mature soil.

Two size fractions of 66080 were subjected to leaching with HCl and etching with HF. Leaching removed *ca.* 25% of the rare earths in both the 500–177 μm and 62–20 μm fractions; the soluble phase, probably a phosphate, is enriched in light rare earths relative to the bulk soil. The leach and etch removed a larger portion of Zn and Cd than expected on the basis of surface concentrations inferred from size distribution data apparently because of selective dissolution of minor volatile-rich phases.

Lithophile concentrations in 66080 are nearly indipendent of grain size. In 15100 decreasing grain size show moderately increasing amounts of KREEP and anorthosite related elements, and decreasing amounts of basalt related elements. In 66080 a maximum in siderophile concentration occurs at *ca.* 150 μm, as previously observed in our studies of 61220, 63500 and 65500. This peaking appears to result from a gradual increase with time in the size of metal grains as a result of welding during micrometeorite impacts. The coarse fraction maximum is not observed in the siderophile data for 15100, probably because of the much smaller fluence of extralunar projectiles at the Apollo 15 site. A modest rise in siderophile concentrations in the smallest size fractions of all soils probably results from recondensation of impact-vaporized materials.

The concentrations of highly volatile Zn and Cd and In in 15100 and 66080 show a marked increase with decreasing size, but the fine coarse ratios are about a factor of two lower than those in soils 61200 and 63500. The lower ratio in 66080 results entirely from higher concentrations in the coarser fractions. It appears that this is a reflection of the higher maturity of 66080, and that the volume-correlated component in lunar soils increases with increasing near-surface residency. The high amount of volume-correlated component in 15100 may be related to the more efficient formation of agglutinates in basalt-rich soils. The observed increase in rare gas and volatile metal concentration with decreasing grain size results from an increasing bias in surface exposure in fine grain sizes, probably as a result of the adhesion of smaller to larger grains.

Brett, R. (U.S. Geological Survey, Reston, VA 22092): 'Equilibration of the Upper Mantle with Sulfide-Rich Liquid During Core Formation, and its Application to the Moon', *EOS: Trans. Amer. Geophys. Union* **58**, 430. (1977)

The proto-core in the proto-upper mantle coalesced with composition within the system Fe–Ni–S–O and probably contained in normative metal, if oxygen fugacities in the pristine upper mantle were slightly above those of the iron-wüstite buffer assemblage. Brett (1971) suggests that upper mantle f_{O_2} is in the above range. The relative oxidation state of the upper mantle and siderophile element abundances are thus reconciled with core formation, contrary to the chemical disequilibrium models and *ad hoc* equilibrium models of workers, including this author. Upper mantel abundances of Ni, Cu, and Co are consistent with partition coefficients between sulfide liquid and silicate under f_{O_2} conditions just above the iron-wüstite buffer curve. For example, the mean of four published laboratory determinations of Ni partitioning between an FeS liquid and solid silicate (olivine and orthopyroxene; $T = 900$–$1270°C$) is 31 ± 27; that calculated for the upper mantle and protocore based on upper mantle abundances and a chondritic Earth (with respect to siderophile elements) is 45. Fe metal-olivine partitioning for Ni in the same temperature range is of the order of 2000.

The proto-core sinking through the middle and lower mantle picked up primordial metallic iron and metal formed by the reaction $3Fe^{2+} = 2Fe^{3+} + Fe^0$ (Mao, 1974). Partitioning of siderophile elements in the lower mantle would therefore involve metal-silicate partitioning. Core-mantle equilibrium is therefore envisaged as equilibrium within a P-T-X gradient.

Sato (1976) and Ringwood and Kesson (1977) suggest that f_{O_2} of the lunar mantle also lies above values in equilibrium with metallic iron. Separation of an oxygen and sulfide-rich liquid in the pristine lunar mantle would therefore occur under conditions similar to that for the Earth, and subsequent partial melts of silicates from both kinds of source regions should therefore contain similar siderophile element abundances. A fission origin (Ringwood and Kesson, 1977) is therefore unnecessary to explain the similarity of abundances of siderophile elements in the lunar and terrestrial mantles.

Brown, G. M. (Dept. of Geological Sci., University of Durham): 'Two-Stage generation of Lunar Mare Basalts', *Phil. Trans. Roy. Soc. London* **A285**, 169–176. (1977)

The Taylor–Jakeš model of two-stage melting for the generation of the mare basalts is reconsidered and expanded. Melting of the outer 1000 km of the Moon early in its history was soon followed by the deposition of a thick series of mafic adcumulates to form a Lower Mantle. Mafic orthocumulates then sank to form the Upper Mantle (60–300 km) while simi-contemporaneous crystallization of feldspar, as a mesh which did not sink and trapped minor mafics, formed the crust. The Rb–Sr model ages of about 4.6 Ga and the Eu anomalies reflect this event. The crystal fractionation gave rise to appreciable enrichment in l.i.l. elements in the pore material of the crustal and Upper Mantle orthocumulates, including a concentration of uranium that is related to the levels at which radioactive heating and second-stage melting occurred, to produce mare basalts from 3.8 to 3.1 Ga. Pore-material melting preserved the 4.6 Ga model ages. The high-Ti and low-Ti basalts and related to shallower and deeper source levels, respectively, in the mafic orthocumulate pile. Convective cells would become numerous as the thickness of the magma shell decreased, to produce complex and variable fractionating systems. Asymmetrical near-surface features such as crustal thicknesses, 'KREEP'-rock distribution, and mare-basalt eruption sites, would be expected from lateral variations in the effectiveness of cumulate fractionation at around 4.6 Ga.

Burnett, D. S. (Div. of Geological & Planetary Sciences, Calif. Inst. of Tech., Pasadena. CA 91125) and Woolum, D. S.: 'Exposure Ages and Erosion Rates For Lunar Rocks', *Physics and Chemistry of the Earth* **10**, 63–101. (1977)

Particle exposure data for lunar rocks are selectively reviewed emphasizing: (a) galactic cosmic ray exposure ages from spallation rare gases as a means of dating lunar impact craters. (b) surface residence times, primarily from galactic ray heavy ion tracks, as a means of determining (1) rock lifetimes against catastrophic impact destruction and (2) microcratering rates. (c) lunar rock erosion rates and mechanisms. Emphasis is placed on explaining the assumptions made in the various age and rate calculations, which may make the results model dependent. Rocks which have had a single stage history of galactic cosmic ray exposure near the lunar surface following excavation from a highly shielded location can be accurately dated and criteria can be given for recognizing such rocks. Thus, accurate ages are known for craters from Apollo 14 (Cone) and Apollo 16 (North and South Ray), although surprisingly few Apollo 16 rocks appear to be primary South Ray ejecta. Despite favorable sampling, a reliable age for Camelot crater (Apollo 17) is not known. The low-K rocks from Apollo 11 have a well-defined age of ~ 110 My, but it is not possible to associate them with any specific crater. Working out multi-stage exposure histories will be necessary to obtain ages for the Apollo 12 craters. Well defined surface residence times for rocks can be obtained provided that the rock has only been exposed in a single orientation on the lunar surface. A necessary criterion for a simple *surface* exposure history is that a steep track profile be observed which agrees with the expected profile for cosmic ray heavy ion attenuation. Surface residence times are usually much less than the total cosmic ray exposure times showing that most rocks have not been directly irradiated on the surface but have been exposed as some shallow (< 3–4 m) depth. When a critical selection of track surface residence time is made, there is no strong evidence from these data for an increase in the contemporary micrometeorite flux compared to the long term average . Lunar rock erosion rates are ~ 1 mm/My which is much higher than estimated for solar wind sputtering but lower than estimated from the present-day micrometeorite fluxes. One possibility is that contemporary fluxes may be higher than the long term average. Erosion rates measured from the flattening of solar flare track gradients were expected to be lower than those obtained from concentration profiles of solar-flare-induced radioactive nuclei but this does not appear to be the case, suggesting that erosional mechanisms are not completely understood.

Chao, E. C. T. (Max-Planck-Institute fur Kernphysik, Heidelberg, Germany): 'Basis for Interpretation Regarding the ages of the Serenitatis, Imbrium and Orientale Events', *Phil. Trans. Roy. Soc. London* **A285**, 115–126. (1977)

One of the most important objectives of lunar study is to relate the lunar sample data to important lunar events. This paper utilizes as the basis of interpretation consideration of the following: (1) Photogeologic data, (2) The choice of a cratering model, (3) Estimates of temperature of impact ejecta and shock-induced heating, (4) Petrologic data of lunar breccias and their thermal and shock history, and (5) Meaningful age measurements. Both the author's interpretations and alternative views are discussed. The age of the Serenitatis event is not yet known. The interpreted age of the Imbrium event is between 3.90 and 3.84 Ga. The age of the Orientale event is 3.84 Ga

Crozaz, G. (McDonnell Center for the Space Sciences, Washington University, St. Louis. MO 63130), Poupeau, G., Walker, R. M., Zinner, E., and Morrison, D. A.: 'The Record of Solar and Galactic Radiations in the Ancient Lunar Regolith and their Implications for the Early History of the Sun and Moon', *Phil. Trans. Roy. Soc. London* **A285**, 587–592. (1977)

A variety of techniques are available for studying past variations of solar wind, solar flares, galactic cosmic rays, and micrometeorites. Lunar rock results which average over the recent past (~ 10 Ma) indicate no major changes in any of these components. At longer times, recent data suggest secular changes in the $^{15}N/^{14}N$ ratio in the solar wind, possible due to enhanced solar flare activity. With the deployment of new techniques, it now appears possible to measure solar wind, solar flare, and micrometeorite records in individual grains removed from different layers of lunar cores. Such grains have been exposed for brief intervals of time (10^3–10^4 a) for times extending at least 10^9 a in the past. Lunar and meteoritic breccias are promising candidates for extending the record back still further, perhaps close to the beginning of the solar system.

Crozaz, G. (McDonnell Center for the Space Sciences & Dept. of Earth & Planetary Sci., Washington University, St. Louis, MO 63130): 'The Irradiation History of the Lunar Soil', *Physics and Chemistry of the Earth* **10**, 197–214. (1977)

Deprived of an atmosphere and a magnetic field to shield her from radiations, the Moon is constantly bombarded by energetic nuclear particles from three sources: solar wind, solar flares and galactic cosmic ray.

Compared to the meteorites which undergo the same type of bombardment, the Moon has two distinct advantages as a detector: (1) its position in space is well-known whereas our knowledge of the meteorite orbits is still limited; (2) meteorites suffer from ablation loss during their passage through the Earth's atmosphere and, consequently, lose the record of the low energy radiation (solar) which was preserved near their original surface.

These radiations to which the Moon has been exposed produce a variety of effects which are used to deduce the temporal changes occurring in the lunar surface. The description of these effects and the conclusions that have been drawn from their study is the object of this article. It should nevertheless be kept in mind that this problem is intimately bound with the past of the different radiations. Implicit in the analysis of many dynamic regolith effects is the assumption that the various radiations have been constant in time. This has been proven directly for cosmic ray and solar flare particles for periods of time up to 10 My by the study of radioactive isotopes (Finkel *et al.*, 1971) and of heavy nuclei particle tracks (Yuhas and Walker, 1973). The following discussion will be limited to the exposure record observed in lunar soils.

Davies, P. A. (Institute of Lunar & Planetary Science, School of Physics, University of Newcastle upon Tyne, Newcastle upon Tyne NE1 7RU) and Stephenson, A.: 'The Ages of the Lunar Maria and the Filling of the Mare Basins', *Phys. Earth Planet. Interiors* **14**, P13–P16. (1977)

The age discrepancy between lunar highlands and mare is examined in terms of a hydrostatic head model incorporating an impact crater being fed continuously from depth with basaltic magma. It is shown that if the age difference is attributed to the filling time of the impact basin, the dimensions of the volcanic feeder conduits are of the order of a few metres.

Dikov, I. P. (Academy Science, Inst. of Ore Deposit Geol, Petrog. Mineral & Geochem., Moscow V-71, USSR), Nemoshkalenko, V. V., Aleshin, V. G., Ivanov, A. V., and Bogatikov, O. A.: 'Reduced Titanium in Lunar Regolith', *Dokl. Akad. Nauk SSSR* **234**, 176–179. (1977)

Dollfus, A. (Observatoire de Paris, Meudon, France) and Geake, J. E. 'Polarimetric and Photometric Studies of Lunar Samples', *Phil. Trans. Roy. Soc. London* **A285**, 398–402. (1977)

The polarization of scattered light has been investigated for lunar samples from six Apollo and two Luna missions. Over a wide range of the phase angle between incidence and observation directions, the light is found to be polarized only either normal (called positive) or parallel (negative) with respect to the incidence/observation plane. The resulting characteristic curves, of degree of polarization vs phase angle, are indicative of surface properties: the maximum value of polarization is inversely proportional to albedo, for dust-covered surfaces, and the slope is inversely proportional to albedo for most surfaces; the width and depth of the negative-going part of the curve indicate the type and complexity of the surface texture, as confirmed by Stereoscan photographs. This information may now be applied to the determination of albedos and surface textures for objects such as asteroids and planetary satellites, for which no samples are available but for which some polarization measurements have been made.

Donaldson, C. H. (Dept. of Geology, University of Manchester), Drever, H. I., and Johnston, R.: 'Supercooling on the Lunar Surface: A Review of Analogue Information', *Phil. Trans. Roy. Soc. London* **A285**, 207–217. (1977)

The crystallization of the principal constituent minerals, olivine, pyroxene and plagioclase, in dendritic or sketetal forms, is much more characteristic of lunar than of terrestrial igneous rocks. This type of crystallization is found in lunar rocks of such varied composition as olivine-normative mare basalt (12009) and spinel troctolite (62295). Olivine and pyroxene often occur as skeletal phenocrysts and the stage at which they crystallized is of crucial significance to interpretations of the genesis and cooling history of the porphyritic lavas. Furthermore, there is a widespread occurrence of glass and of immature, radiate crystallization, particularly of highly zoned pyroxenes and zoned plagioclase. Most of these characteristics are a response to a range of supercooling and rapid crystal-growth conditions that are typically lunar. The research value of controlled cooling-rate experiments, with melts of appropriate composition, is correspondingly enhanced. This need for information on the rapid consolidation of the lavas extruded on the Moon, and of impact liquids, has stimulated investigations of the phase petrology of supercooled melts. The evidence adduced from these analogue approaches is reviewed. Recently published research results based on this evidence have provided new guide-lines to interpreting crystallization on the lunar surface.

Dran, J. C. (Lab. Rene-Bernas – C.S.N.S.M. Orsay 91406, France), Durand, J. P., Klossa, J., Langevin, Y., and Maurette, M.; 'Microprobe Studies of Space Weathering Effects in Extraterrestrial Dust Grains', *Phil. Trans. Roy. Soc. London* **A285**, 433–439. (1977)

A new microprobing procedure is used to characterize both the physical and chemical surface properties of individual grains on a microscale. In this procedure the same sub-micrometre sized area of a given grain is successively analysed with a high voltage electron microscope, an Auger microprobe and a field emission scanning electron microscope. This analytical technique has been applied to study lunar weathering effects and to tentatively infer the irradiation history of a ^{22}Ne-rich fraction of the Orgueil meteorite.

Dreibus, G. (Max-Planck-Institut fur Chemie, Abteilung Kosmochemie, Mainz, Germany), Spettel, B., and Wanke, H.: 'Lithium and Halogens in Lunar Samples', *Phil. Trans. Roy. Soc. London* **A285**, 49–54. (1977)

Lithium and the halogen elements F, Cl, Br and I have been measured in soils, breccias and rock samples from all Apollo missions. With the exception of the anorthosites, the fluorine content of the lunar samples is in the same range as for C1 chondrites. Contrary to fluorine the other halogen concentrations show large variations. The lowest concentrations are found in the mare basalts of Apollo 15 and 17, the highest in some highland breccias.

Lithium correlates well with some of the incompatible elements in both mare basalts and 'KREEP'-containing highland soils and breccias. From the observed ratios it is evident that in the bulk composition of the Moon Li is neither enriched nor depleted; it belongs to the group of non-refractory elements.

From the correlation of Li with some refractory elements (Be, La etc.) a value of 50 : 50 for the refractory to non-refractory portion of the Moon is inferred without any further assumption, thus confirming previous estimates of Wänke *et al.* (1974a, 1975).

Durrani, S. A. (Dept. of Physics, University of Birmingham, Birmingham B15 2TT): 'Charged-Particle Track Analysis, Thermoluminescence and Microcratering Studies of Lunar Samples', *Phil. Trans. Roy. Soc. London* **A285**, 309–317 (1977)

Studies of lunar samples (from both Apollo and Luna missions) have been carried out, using the track analysis and thermoluminescence (t.l.) techniques, with a view to shedding light on the radiation and temperature histories of the Moon. In addition, microcraters in lunar glasses have been studied in order to elucidate the cosmic-dust impact history of the lunar regolith.

In track studies, the topics discussed include the stabilizing effect of the thermal annealing of fossil tracks due to the lunar temperature cycle; the 'radiation annealing' of fresh heavy-ion tracks by large doses of protons (to simulate the effect of lunar radiation-damage on track registration); and correction factors for the anisotropic etching of crystals which are required in reconstructing the exposure history of lunar grains. An abundance ratio of *ca.* $(1.1 + 0.3) = 10^{-3}$ has been obtained, by the differential annealing technique, for the nuclei beyond the iron group to those within that group in the cosmic rays incident on the Moon.

The natural t.l. of lunar samples has been used to estimate their effective storage temperature and mean depth below the surface. A suite of samples from known depths in an artificial trench at the Apollo 17 site have been used to calculate the effective thermal conductivity and thermal wavelength of overlying lunar soil at various depths. The temperatures in the shadow of some Apollo 17 boulders, and the duration of the boulders' presence *in situ,* have also been estimated from samples which have been kept refrigerated since their retrieval from the Moon.

Natural and artificially produced microcraters have been studied with the following two main results: The dust-particle flux appears to have fallen off over a certain period of *ca.* 10^4–10^5 years (if the solar activity is assumed to be constant over that interval). Stones predominate in the large (*ca.* 1.0 μm), in the micrometeorite flux incident of the Moon.

Engelhardt, W. V. (Mineralogical Institute, University of Tubingen, Germany) and Stengelin, R.: 'Chemical Changes at Impact-Induced Phase Transitions on the Lunar Surface', *Phil. Trans. Roy. Soc. London* **A285**, 285–291. (1977)

Impact-induced melting and vaporization on the lunar surface generate products which are different in chemical composition from their parent materials.

By partial shock melting of plagioclase-pyroxene rocks, pure plagioclase melts can be formed because for a given shock pressure, the gain in entropy is higher in plagioclase than in pyroxene. Impact-induced melts of peritectic composition can only be produced if by some mechanism, shock heat is transferred to weakly or non-shocked rocks where partial melting can take place under equilibrium conditions. The formation of large masses of differentiates by partial shock-induced melting on the lunar surface is unlikely.

Distributions of the main chemical components have been determined for 744 lunar rocks and 971 lunar glasses. For glasses, the maxima of alkalies are shifted towards lower, and of aluminium towards higher, concentrations. These differences are attributed to selective vaporization from overheated shock melts.

It is supposed that some of the regular glass bodies and perhaps, also, of the chondrule-like particles in lunar soils and breccias are formed by condensation from shock-produced vapours. In this case they should be richer in magnesium, aluminium and calcium, and poorer in alkalis and silicon as compared with glasses of other origins.

Ford, C. E. (Dept. of Geology, Univ. of Edinburgh, West Mains Road, Edinburgh EH9 3JW), O'Hara, M. J., and Spencer, P. N.: 'The Origin of Lunar Felspathic Liquids', *Phil. Trans. Roy. Soc. London* **A285**, 193–197. (1977)

The critical features of the models which could produce felspathic liquids are discussed. There is no evidence which will support the production of felspathic compositions by dry igneous processes. Indeed, their very existence is the only evidence for their production by dry igneous processes. There is no evidence which will support plagioclase flotation. The cumulus textured troctolites and norites demonstrate that plagioclase sank. There is no evidence against the production of felspathic liquids by wet igneous processes which can account for all of the observed felspathic rocks and leave a residue capable of producing mare basalts.

Fuller, M. D. (Dept. of Geological Sci., University of California, Santa Barbara, CA 93106): 'Review of Effects of Shock (Less than 60 kbar; Less than 6×10^9 Pa) on Magnetism of Lunar Samples', *Phil. Trans. Roy. Soc. London* **A285**, 409–416. (1977)

Experimental shock studies of highland and mare soils in the range of a few to 50 kbar (5×10^9 Pa) have given the following results:

(1) Shock, if less that 20 kbar, does not change the magnetic characteristics of the soil substantially and only weak and unstable shock remanence is generated in a field of 0.5 Oe.

(2) Shock of between 20 and 50 kbar lithifies the soil and gives rise to stable shock remanence. Acquisition is approximately linear in field for a given shock level. At 30 kbar the acquisition parameter for the highland soil was 10^{-5} G cm^3 g^{-1} Oe^{-1}. In this range of 20–50 kbar the products of shock are petrologically and magnetically similar to certain regolith breccias.

(3) Shock demagnetization preferentially demagnetizes the softer part of thermoremanent magnetization (t.r.m.) and hence makes it relatively harder.

The significance of these results is that shock remanence is likely to be the cause of the natural remanent magnetization (n.r.m.) of certain regolith breccias and shock may modify the primary remanence of other samples.

Geake, J. E. (Dept. of Pure and Applied Physics, U.M.I.S.T., Manchester), Walker, G., Telfar, D. J. and Mills, A. A.: 'The Cause and Significance of Luminescence in Lunar Plagioclase', *Phil. Trans. Roy. Soc. London* **A285**, 403–408. (1977)

Most lunar samples luminesce under proton or electron excitation, and most of the emission comes from the plagioclase present. The cause of this luminescence has been found by investigating the emission and excitation spectra of lunar, terrestrial and synthesized plagioclases. Emission spectra show three broad peaks: a weak one around 450 nm which is common to most silicates; a dominant one between 700 and 780 nm for which we conclude the activator to be Fe^{3+} in Al sites. However, this near-infrared peak is usually the dominant one for terrestrial plagioclases; its weakness in lunar samples is attributed to reducing conditions when the lunar surface materials were formed causing more of the iron to be present as Fe^{2+}.

Luminescence photography of lunar rock chips is found to be simple method of surveying plagioclase crystal forms in rough samples.

Geiss, J. (Physikalisches Institut, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland), Eberhardt, P., Grogler, N., Guggisberg, S., Maurer, P., and Stettler, A.: 'Absolute Time Scale of Lunar Mare Formation and Filling', *Phil. Trans. Roy. Soc. London* **A285**, 151–158. (1977)

The high titanium basalts collected in the maria Tranquillitatis and Serenitatis crystallized 3.5–3.9 Ga ago. The ages of the low titanium rocks found in Oceanus Procellarum and on the eastern edge of mare Imbrium are lower, 3.1–3.4 Ga. There is, however, evidence that high-Ti basalts with lower ages and low-Ti basalts with higher ages occur on the Moon. The observed age spread of rocks even in limited areas suggests that lava flow activity in a basin lasted for several 100 Ma. The age variability of Apollo 11 basalts is particularly well documented: there are at least three different times of rock formation, two for the low-K and one for the high-K rocks. The ages of the oldest mare basalts 10003 (high-Ti, low-K rock) and 14053 (an igneous rock with low-Ti, low-K, high-Al mare basalt composition) of 3.91 ± 0.03 Ga and 3.95 ± 0.03 Ga respectively, suggest that mafic basalt flows had already begun to invade the older basins when the last basin-forming impacts occurred.

Gibb, T. C. (Dept. of Inorganic & Structural Chemistry, The University of Leeds, Leeds LS2 9JT), Greatrex, R., and Greenwood, N. N.: 'An Assessment of Results Obtained from Mössbauer Spectra of Lunar Samples', *Phil. Trans. Roy. Soc. London* **A285**, 235–240. (1977)

Most of the minerals on the Moon's surface contain iron as a major constituent, and this enables them to be examined by Mössbauer spectroscopy. The advantages and limitations of this technique for examining lunar samples will be briefly mentioned, before reviewing the results so far obtained on material returned by the Apollo and Luna missions. By far the greatest proportion of iron is present as Fe(II) or Fe(0), and no appreciable concentration of Fe(III) has been observed. The relative amounts of iron-containing minerals at the various lunar sites have been determined and related to the lunar geological features. The more detailed determination of the distribution of iron between the M1 and M2 sites in pyroxene minerals leads to information on the thermal history of the rocks. Likewise the presence of superparamagnetic iron particles within the surface layers of some of the soil particles provides significant evidence concerning their origin and subsequent history.

Gold, T. (Center for Radiophysics and Space Research, Cornell University. Ithaca, NY 14853), Bilson, E., and Baron, R. L.: 'The Relationship of Surface Chemistry and Albedo of Lunar Soil Samples', *Phil. Trans. Roy. Soc. London* **A285**, 427–431. (1977)

A relation between the albedo and the surface iron concentration (determined by Auger electron spectroscopy) of lunar soil samples is described. The effect of solar wind sputtering on the surface chemistry and albedo of the soil is discussed.

Hart, R. K. (Pasat Res. Associates, Inc., 585 Royervista Dr., Atlanta, GA 30342): 'Carbon Distribution Profiles in Lunar Fines Final Report', *NASA-CR-152622*, 31pp. (1977)

Radial distribution profiles of elemental carbon in lunar soils consisting of particles in the size range of 50 to 150 μm were investigated. Initial experiments on specimen preparation and the analysis of prepared specimens by Auger electron spectrometry (AES) and scanning electron microscopy (SEM) are described. Results from splits of samples 61501,84 and 64421,11, which were mounted various ways in several specimen holders, are presented. A low carbon content was observed in AES spectra from soil particles that were subjected to sputter-ion cleaning with 960 eV argon ions for periods of time up to a total exposure of one hour. This ion charge was sufficient to remove approximately 70 nm of material from the surface. All of the physically adsorbed carbon (as well as water vapor, etc.) would normally be removed in the first few minutes, leaving only carbon in the specimen, and metal support structure, to be detected thereafter.

Haskin, L. A. (Dept. of Earth & Planetary Sci, & Dept. of Chemistry, Washington University, St. Louis, MO 63130): 'Composition and Chemical Differentiation of the Moon', *Abstracts of Papers of the American Chemical Society* **173**, 68. (1977)

Chemical analysis of lunar samples has been primarily carried out by the techniques of mass spectrometry, isotope dilution, X-ray fluorescence and neutron activation analysis. Such purely chemical data are considered in combination with general cosmochemical principles and thinking, with measurements of heat flow and of seismic parameters and with phase relationships deduced from synthetic rock. From such data conclusions can be drawn about the bulk composition of the Moon, and about its internal zoning and internal differentiation. Limitations to such inferences will also be discussed.

Hawke, B.R. (Dept. of Geological Sciences, Brown University, Providence, RI 02912): 'Pre-Imbrian Geology of the Apollo 14 Region: Evidence for the Local Origin of KREEP', *EOS: Trans. Amer. Geophys. Union* **58**, 425. (1977)

A major objective of Apollo 14 mission was to sample material comprising the Fra Mauro Formation. Evidence has recently been presented that large amounts of local, pre-Imbrium material were incorporated into the Fra Mauro Formation. I have mapped many pre-Imbrian craters in the region surrounding A14. Several cratering events deposited significant quantities of ejecta at the site. To characterize each ejecta deposit, calculations were performed to determine the thickness, depth of origin, and shock pressures to which the material had been subjected. The major results are: (1) A total ejecta thickness of ~ 1700 m is attributed to the mapped pre-Imbrian craters and basins. (2) The majority (55%) of the ejecta in the pre-Imbrian section of the A14 site was contributed by craters in the vicinity and not basins. The upper 1 km of this section is 92% crater ejecta. (3) Most ejecta contributed by the pre-Imbrian craters was derived from shallow depths within the crust, had been subjected to multiple impact events, and should exhibit a variety of shock features. (4) A14 breccias contain clasts of KREEP basalt and high-Al mare basalt. Farly KREEP volcanic deposits and later high-Al mare basalts may have existed in the target sites of many pre-Imbrian craters and would have been incorporated into their ejecta. Evidence suggesting pre-Imbrian volcanic activity in the region include: (a) the occurrence of spectrally distinct pre-mare material of possible volcanic origin, (b) the existence of regional topographic lows with extensive deposits of pre-mare plains, and (c) the correlation of orbital chemistry data with the drop in elevation around Ptolemaeus, which suggests that early KREEP-volcanism may have occurred preferentially in the topographic lows to the west.

Holmes, H. F. (Chemistry Div., Oak Ridge National Lab., Oak Ridge, TN 37830) and Gammage, R. B.: 'Surface Properties of a North Ray Crater Soil (Apollo 16)', *Earth Planet. Sci. Letters* **35**, 14–18. (1977)

Surface properties of lunar fines sample 67481 have been investigated by measuring the adsorptions of nitrogen (at − 196°C) and water (at 20°C). Characteristics of this sample are similar to those of samples from other locations on the lunar surface and include the more typical alteration reaction with adsorbed water. Although their maturities are markedly different, the surface properties of 67481 are very much like those of the mare mature 63341 from the adjacent station 13. These results indicate that the surface properties of lunar soils attain an equilibrium state faster than other properties used to indicate maturity.

Horn, P. (Museum National d'Histoire Naturelle, Laboratoire de Mineralogie, Paris) and Kirsten, T.: 'Lunar Highland Stratigraphy and Radiometric Dating', *Phil. Trans. Roy. Soc. London* **A285**, 145–150. (1977)

Radiometric age data for lunar highland rocks do not in any simple way reflect the time of excavation of major circular basins from which they are believed to originate. Instead, many rocks are of a more local origin and, in addition, radiometric clocks are not necessarily reset at the occasion of the basin forming impact. The concept of thick hot ejecta blankets far away from the basin cannot be maintained. Arguments supporting this (small) 'crater dominated chronology' are summarized.

Housley, R. M. (Science Center, Rockwell International, Thousand Oaks, CA 91360): 'Solar Wind and Micrometeorite Effects in the Lunar Regolith', *Phil. Trans. Roy. Soc. London* **A285**, 363–367. (1977)

Using available data from the literature, we formulate an outline of the major physical and chemical effects expected during solar wind bombardment of the lunar regolith. In agreement with the results of Auger and e.s.c.a. analyses of the composition of lunar grain surfaces, this outline predicts the solar wind sputtering will tend to clean exposed grain surfaces by ejecting material at velocities exceeding lunar escape velocity. We also discuss results showing that Fe is partially reduced in the outer few 10 nm of grain surfaces and that this reduced Fe forms 10 nm diameter range metal spheres throughout the glass during agglutinate formation by micrometeorite impacts. These metal spheres give the agglutinates their distinctive optical and magnetic properties and are partially responsible for the decreasing albedo of the lunar surface with exposure age.

Hulme, G. (Lunar & Planetary Unit, Dept. of Environmental Sci., University of Lancaster, Lancaster, LA1 4YR) and Fielder, G.: 'Effusion Rates and Rheology of Lunar Lavas', *Phil. Trans. Roy. Soc. London* **A285**, 227–234. (1977)

Flow shapes in Mare Imbrium, Copernicus, Tycho and Aristarchus have been related to lava properties by assuming that lavas have Bingham rheology. A universal formula which expresses flow dimensions in terms of fluid properties, flow rates and slopes has been derived theoretically and tested by means of experimental models and data from terrestrial lava flows. It is now possible to determine flow rates and yield stresses – both of which are related to the composition of lavas – from photographs of flow remnants. Results are presented for the lunar flows under study. Flow rates in Mare Imbrium are found to be very high by terrestrial standards. This is an important clue to the mechanism of formation of lunar sinuous rilles, which may be products of erosion by melting beneath turbulent lava flows.

Jeanloz, R. (Div. of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125), Ahrens, T. J., Lally, J. S., Nord, G. L., Christie, J. M., and Heuer, A. H.: 'Shock-Produced Olivine Glass – 1st Observation', *Science* **197**, 457–459. (1977)

Transmission electron microscope (TEM) observations of an experimentally shock-deformed single crystal of natural peridot, $(Mg_{0.88}Fe_{0.12})_2SiO_4$, recovered from peak pressures of about 56×10^9 *Pa* revealed the presence of amorphous zones located within crystalline regions with a high density of tangled dislocations. This is the first reported observation of olivine glass. The shocked sample exhibits a wide variation in the degree of shock deformation on a small scale, and the glass appears to be intimately associated with the highest density of dislocations. This study suggests that olivine glass may be formed as a result of shock at pressures above about 50 to 55×10^9 *Pa* and that further TEM observations of naturally shocked olivines may demonstrate the presence of glass.

Jovanovic, S. (Chemistry Div., Argonne National Lab., Argonne, IL 60439) and Reed, G. W., Jr.: 'Hg and Os Isotopic Variations in Lunar Breccias', *EOS: Trans. Amer. Geophys. Union* **58**, 431. (1977)

Isotopic compositon data on Hg released from five samples of Apollo 14 breccia 14305 and one sample of 14321 during stepwise heating will be reported. Five to six temperature fractions were collected and in each sample one of these fractions appeared to contain isotopically different Hg. Activation analysis was the technique used. The only isotopes measured by this technique are ^{196}Hg and ^{202}Hg. The isotopic variation appears as an ~ 25% depletion in ^{196}Hg or excess in ^{202}Hg.

Two isotopes of Os, 184 and 190, were measured by the same technique on three Apollo 14 breccia samples. One 14305 sample showed a variation of ~ 16% in the same sense as observed in Hg. A possible small variation is suggested in a Allende meteorite bulk sample.

If the isotopic variations are not due to an unaccounted for experimental effect or to chance then they could be nucleogenetic, although mass fractionation cannot be eliminated. One possible explanation is the addition of extra-solar system material to the breccias. However, the evolution of the Moon is such that this must have occurred at a very late stage of breccia formation.

Kaiser, W. A. (Institut fur Kernchemie, der Universitat Koln, Zupicher Strasse 47, 5000 Koln 41, Germany): 'The Excitation Functions of Ba (p, X) ^{M}Xe (M = 124–136) in the Energy range 38–600 MeV; the Use of 'Cosmogenic' Xenon for Estimating 'Burial' Depth and 'Real' exposure Ages', *Phil. Trans. Roy. Soc. London* **A285**, 337–362. (1977)

Thin target experiments were performed to obtain the excitation functions of the reactions Ba (p, X) ^{M}Xe. The abundances of all stable Xe isotopes and of the radionuclides ^{127}Xe and ^{131}Ba were determined by means of rare gas mass spectroscopy and γ-counting, respectively. The excitation functions show marked characteristics leading to strong variations in the proton-induced Xe-ratios as functions of energy. The ^{131}Xe/^{126}Xe ratio – the special lunar anomaly – was found to vary from 1.14 ± 0.4 (600 MeV) to 248.8 ± 4.0 (75 MeV). The ^{M}Xe production rates and the ^{M}Xe/^{126}Xe ratios as functions of depths were estimated for 2π geometry utilizing the depth dependent galactic-cosmic-ray (g.c.r.) fluxes of Reedy & Arnold (1972). Substantial isotopic variations for all of the proton-induced Xe ratios were found, sufficient to explain most of the cosmogenic Xe ratios (exceptions are ^{130}Xe, and ^{132}Xe) measured yet in lunar samples with proton-induced reactions on Ba at different depths in the Moon. Actual lunar samples are used to check the validity of the results.

Kesson, S. E. (Dept. of Earth & Space Sci., State Univ. of New York, Stony Brook, NY 11794): 'Mare Basalt Petrogenesis', *Phil. Trans. Roy. Soc. London* **A285**, 159–167. (1977)

Melting experiments in vacuum at Fe-saturation for high-Ti basalt compositions 70215 and 15318 Red Glass, and low-Ti basalt composition 15555–15016, have defined equilibrium crystallization sequences and the liquid-line-of-descent, and show that much of the chemical variety in the natural samples is due to near-surface fractionation processes. However, the various groups within the high-Ti suite (Apollo 11 low-K, Apollo 11 high-K and Apollo 17 basalts; Apollo 17 Orange Glass) cannot be interrelated by such processes, nor can the high-Ti suite be a near-surface derivative of a low-Ti parent magma. Likewise, the low-Ti Apollo 12 basalts and Apollo 15 basalts and Green Glass cannot be interrelated by simple fractionation, although much of the chemical variety within each group is explained olivine fractionation.

On the basis of high-pressure studies, low-Ti basalts are beleived to originate as a spectrum of partial melts from a previously differentiated olivine-pyroxenite lunar mantle at depths ranging from approximately 200–500 km. High-Ti basalts are interpreted as hybrid liquids resulting from the assimilation of subcrustal Ti-rich material by a parental magma of low-Ti type.

Kesson, S. E. (Australian National University, Canberra, Australia 2600) and Ringwood, A. E.: 'Siderophile and Volatile Elements in the Moon and in the Earth's Mantle: Implications for Lunar Origin', *EOS: Trans. Amer. Geophys. Union* **58**, 430. (1977)

Abundances of the siderophile elements Ni, Co W, Os, Ir, P, S and Se are generally similar (X2) in terrestrial oceanic tholeiites and in lunar low-Ti mare basalts. This similarity is beleived to extend to their respective ultramafic source regions in the Earth's upper mantle and lunar interior. Abundances of siderophile elements in the Earth's mantle have been determined by the interaction of several complex processes *unique to the Earth*, which relate to core formation and include the effects of very high pressures and temperatures upon distribution of elements between metal and silicate phases. These factors, in particular, the large pressure and temperature effects upon distribution coefficients, could not possibly have operated separately within the Moon. The similarity in siderophile element abundances therefore implies that *the Moon was derived from the Earth's mantle* after the Earth's core was formed.

Abundance patterns of volatile elements in the Moon differ dramatically from those to be expected from condensation of a nebula of solar composition. They are more readily explained by evaporation of the Earth's mantle in a H_2-depleted environment lacking metallic iron, following by selective recondensation, during which the more volatile components were lost. Evaporation of material from the Earth's upper mantle was probably caused by impact of a large planetesimal (cf. Hartman and Davis) on to the rapidly-rotating Earth (period ~ 4 hr) subsequent to core formation when the Earth's surface had been raised to high temperatures by the energy of core-formation. The evaporated matter may have become coupled to the Earth via hydromagnetic torques or turbulent viscosity, and spun out into a disc. The less volatile components of the disc condensed to form a circum-terrestrial ring of planetisimals which then coagulated rapidly to form the Moon.

King, E. A., Jr. (Dept. of Geology, University of Houston, Houston, TX 77004): 'The Lunar Regolith: Physical Characteristics and Dynamics', *Phil. Trans. Roy. Soc. London* **A285**, 273–278. (1977)

The fine size fraction of the lunar regolith (less than 1 mm mean particle diameter) is composed mostly of particles that owe their origins either directly or indirectly to the impacts of meteoroids on the lunar surface. Comminution of pre-existing rocks and particles is the dominant process effecting the characteristics of the regolith. However, agglutination of pre-existing particles by the glassy, molten spatter and ejecta from small meteoroid impacts is a competing constructive process of low efficiency. Grain size frequency distributions of the less than 1 mm fraction of the regolith tend to be slightly bimodal, with a broad mode in the $1-4\phi$ size range ($500-62.5\,\mu$m) due mostly to agglutination and another mode at approximately 5ϕ ($31.3\,\mu$m) and finer that appears to be caused by the ballistic influx of fine particles from older (finer) regolith. In general, the size frequency distribution curves are nearly symmetrical and indicate poor to very poor sorting. There is a strong correlation of sample mean grain size (and other size parameters) with the length of time that the regolith has had to accumulate at each landing site. The greater the total length of regolith accumulation time, the greater the comminution by meteoroids, and hence the finer the sample mean grain size and the greater the total agglutinate content. These properties also correlate positively with solar wind implanted carbon and nitrogen contents. Thus, sample mean size, agglutinate content, solar wind nitrogen and carbon, as well as solar particle track densities, can all be used as measures of regolith 'maturity'. Local sample collection site geology, such as proximity to boulders or recent craters, strongly influences sample modal particle type populations and grain size characteristics. Lunar chondrules of several types have been identified in the regolith and rock samples. Many of these chondrules have textures that are identical with many meteoritic chondrules. The chondrules in lunar surface materials appear to result from lunar impact processes. It may be that chondrules have originated in many meteorites by some of the same processes. If true, this occurrence has important implications for the origin and history of chondritic meteorites.

Kirsten, T. (Max-Planck-Institut fur Kernphysik, Heidelberg, Germany): 'Rare Gases Implanted in Lunar Fines', *Phil. Trans. Roy. Soc. London* **A285**, 391–395. (1977)

Rare gases implanted into lunar fines can be used to study processes in the lunar regolith as well as solar abundances. A short outline of some basic results about the distribution of solar rare gases in lunar soils is given and illustrated by two case studies: (1) Evidence for local endogenic activity near Shorty Crater is inferred from rare gas fractionations in soil 74241. (2) Rare gas concentration profiles measured with a new technique in single lunar soil particles underline the importance of radiation damage as governing factor of migration and promise future possibilities to determine ancient solar abundances free of secondary bias.

Kratschmer, W. (Max-Planck-Institute fur Kernphysik, Heidelberg, Germany) and Gentner, W.: 'A Long Term Change in the Cosmic Ray Composition?: Studies on Fossil Cosmic Ray Tracks in Lunar Samples', *Phil. Trans. Roy. Soc. London* **A285**, 593–599. (1977)

The etching techniques for the identification of very heavy cosmic ray ions from their etchable tracks in mineral track detectors are described and the results so far obtained for the ancient galactic cosmic ray Cr group (V + Cr + Mn) to Fe abundance ratio are presented. It was found that the etchable radiation damage of fossil cosmic ray tracks has probably only been slightly affected by annealing processes. The track data obtained on pyroxenes of different lunar rocks and on pyroxenes and feldspars, i.e. detectors of different track retaining characteristics, yielded consistent results. From this measurements, an ancient Cr group to Fe ratio of approximately 0.7–0.8 was deduced. In comparison with the present day galactic cosmic ray composition, this ratio is enhanced by a factor of about two. From the track data obtained in different lunar soil samples it was concluded that a variation in the Cr group to Fe ratio between 0.4–0.8 exists. Both results indicate, that either a long term change in the cosmic ray composition has taken place or the interpretation of track data is much more complicated than assumed.

Krupenio, N. N.: 'Density of Lunar Soil from Data Obtained by Direct and Indirect Measurements', *Kosm. Issled.* **15**, 135–143. (1977)

Results are reviewed for measurements of lunar-soil density conducted in terrestrial laboratories, on the Moon, and by lunar-orbiting spacecraft. Determinations of the density of the lunar surface layer in various regions by different methods are compared. It is shown that the surface layer of the Moon corresponds best to a depth variation of density with a surface density of 1.2 g/cu cm, substratum densities of 3.2 g/cu cm for mare regions and 2.9 g/cu cm for other regions, and a mean regolith depth of 5 m. Data obtained in different areas on the Moon indicate that the surface density varies from 0.6 to 3.0 cu cm while the regolith depth ranges from 0.4 to 40 m.

Lal, D. (Physical Research Lab., Ahmedabad-380009, India): 'Irradiation and Accretion of Solids in Space Based on Observations of Lunar Rocks and Grains', *Phil. Trans. Roy. Soc. London* **A285**, 69–95. (1977)

Clues to a wide range of questions relating to the origin and evolution of the solar system and dynamic physical and electromagnetic processes occurring concurrently and in the past in our galaxy have been provided by a study of the lunar samples. This information is deduced from a variety of complementary physical and chemical evidence. In this presentation, greatest emphasis is laid on information based on the cosmogenic effects, i.e. those arising from interactions of low energy cosmic rays with lunar surface materials. This information is generally not obtainable from examinations of meteorite samples, except in the case of certain types termed gas-rich meteorites, due to loss of there surface regions by atmospheric ablation. The present discussions will concern the nature of experimental data to date and implications thereof to the charged particle environment of the Moon, ancient magnetic fields and the nature of, time scales involved in the irradiation and accretion of solids in space, based on lunar regolith dynamics.

It becomes clear that there does not yet exist any consensus on the absolute values of charged particle or the meteorite fluxes, and also about the details of the evolution of the lunar regolith. This would be expected also considering that one is dealing with phenomena which range in size/energy scales over many orders of magnitude and that the techniques used for the studies were only recently developed in many cases. The complex history of evolution of lunar material is slowly being understood and it is a hope that a great deal of quantitative information will soon be available which will in turn allow discussion of evolution of solid bodies in the solar system.

Lambert, G. (Centre des Faibles Radioactivites, Lab. mixte C.N.R.S.-C.E.A., 91190-Gif-sur-Yvette, France). 'Accumulation and Circulation of Gaseous Radon between Lunar Fines', *Phil. Trans. Roy. Soc. London* **A285**, 331–336. (1977)

During the lunar night, the temperature of the regolith upper layer is lower than the radon freezing point. Thus radon atoms coming from the interior can be trapped at the surface of the cold lunar fines. The ^{222}Rn daughter products, ^{210}Pb and ^{210}Po, are embedded in a very thin layer at the surface of the grains.

It is therefore possible, by spectrometry, to distinguish between the continuum due to uranium, thorium (and decay products) homogeneously distributed and the narrow peak at 5.3 MeV, due to an excess of ^{210}Po. We have determined a mean day-and-night concentration of about 3.5×10^3 atoms of intergranular ^{222}Rn per gram of superficial fines, corresponding to a continuous flow of 3 atoms $\text{min}^{-1}\text{cm}^{-2}$ of soil. To account for such a flow of radon atoms moving in a random way from a 6 m source depth, the pore size of the regolith should be $60\,\mu$m. On the other hand, the involved changes in the isotopic composition of the radiogenic lead remain less than 1%.

Martin, P. M. (Dept. of Geology & Astronomy, The University, Leicester, UK) and Mills, A. A.: 'Does the Lunar Regolith Follow Rosin's Law?', *The Moon* **16**, 215–129. (1977)

Results from particle-size distribution analyses of the lunar regolith (less than 1 mm) as sampled by Apollo 11, 12, 14, 15 and 16 have been tested to see if they conform to Rosin's law, which has been found to describe crushed products of many kinds and sizes. In all the lunar examples the law appears to be followed closely. It is concluded that the lunar regolith is probably the result of crushing forces, most likely impacts on the lunar surface.

McGee, J. J. (Dept. of Earth and Space Sci., State Univ. of New York, Stony Brook, NY 11794) and Bence, A. E.: 'Oxide Phase Assemblages in Lunar Breccia 79215; Limitations on T–fO_2 Conditions of Metamorphism', *EOS: Trans. Amer. Geophys. Union* **58**, 430. (1977)

Highlands rock 79215 is an annealed, polymict breccia of gabbroic anorthosite composition. It contains multi-phase oxide complexes surrounded by plagioclase coronas. The following assemblages are observed: (1) Cr-spinel (ranging from Mg–Al–Ti chromite to Cr-pleonaste) + ilmenite ± Fe^0 and FeS; (2) Mg–Al–Ti chromite + armalcolite ± ilmenite, FeS, Fe^0; (3) ilmenite + FeS. The chromites contain from less than 4% to as high as 42% Fe_2TiO_4 component in solid solution. Many also contain exsolved ilmenite lamellae and are zoned in Cr–Al content.

Equilibration temperatures, estimated from a variety of geothermometers indicate temperatures of metamorphism in the range 800–900°C.

The occurrence of Fe^0 with $FeTiO_3$, ilmenite exsolution lamellae in the spinel, and the absence of rutile in our samples place constraints on the T–fO_2 conditions that prevailed. Values of fO_2 for these assemblages then lie between the USP/ILM + Fe^0 and ILM/RUT + Fe^0 buffer curves which fixes the maximum fO_2 range at 10^{-18}–10^{-20} atm. for $T = 800$–$900°C$.

Armalcolite in contact with ilmenite or chromite is significant since conditions well below its stability field are indicated. Pure armalcolite $(Fe_{0.5}Mg_{0.5})Ti_2O_5$ begins to break down to ilmenite + rutile at ~ 1010°C at 1 kbar. 79215 armalcolites contain up to 5.2 mole % $R_2^{3+}TiO_5$. This will stabilize armalcolites at lower T's.

Mokeyeva, V. I. (V. I. Vernadskiy Institute of Geochemistry & Analytical Chemistry, Academy of Sciences USSR, Moscow), Simonov, M. A., Belokoneva, E. L., Makarov, E. S., Ivanov, V. I., and Rannev, N. V.: 'X-Ray Study of Details of Atomic Structure and Distribution of Magnesium and Iron Atoms in Lunar and Terrestrial Olivines', *Geochemistry International* **13**, 50–57. (1977)

New data of precision X-ray analysis of four lunar olivines from the Sea of Plenty are presented. The composition of olivines ranges from 27.0 to 48.0% Fa. Comparison of the structural data on terrestrial and lunar olivines, obtained by us and by other investigators, shows that there are no structural details which would distinguish them. There is a well-defined tendency in olivines towards entry of iron atoms into positions M1. The distribution factor K_D, characterizing distribution of magnesium and iron atoms between positions M1 and M2, deviates by ± 0.10 from the straight line $K_D = 1.10$ for all compositions and, according to our data, the degree of deviation does not depend on the Fe/Fe + Mg ratio in olivines.

Murthy, V. R. (Dept. of Geology & Geophysics, University of Minnesota, Minneapolis, MN 55455): 'Lunar Evolution: Is there a Global Radioactive Crust on the Moon?', *Phil. Trans. Roy. Soc. London* **A285**, 127–136. (1977)

Chemical and isotopic analyses of various grain-size fractions of lunar soils show the presence of an 'exotic component' in practically all lunar soils. The patterns of enrichments in the grain-size fractions and the Sr-isotopic data show that the regolith evolution displays the combined effects comminution of local rock types and addition of the exotic component. The chemical characteristics of this exotic component as deduced from the chemical and isotopic data in soils from Apollo 11, 12, 15 and 16 uniformly point to compositions similar to the material from Fra Mauro region collected in the Apollo 14 mission. There is a strong correlation between the amount of exotic component represents trace element enriched material from the Imbrium-Procellarum region, which was surficially deposited during Imbrium excavation and re-exposed from under the mare-lavas in subsequent cratering events. Surficial transport processes have distributed these materials widely over the lunar surface. There appears no need to invoke a global radioactive crust on the Moon nor of 'hot spots' distributed over the entire surface of the Moon to explain the ubiquitous presence of this component in lunar regolith, nor is there a compelling reason at present to postulate a global melting process for the generation of highly differentiated materials such as 'KREEP' and the exotic component.

Nyquist, L. E. (NASA/Johnson Space Center, Houston, TX 77058): 'Lunar Rb–Sr Chronology', *Physics and Chemistry of the Earth* **10**, 103–142. (1977)

The results of study of the returned lunar samples by the Rb–Sr method are reviewed and a data compilation given. Several important conclusions have emerged as a consequence of these studies. Sr incorporated into the Moon at its formation had an isotopic composition as primitive as that of basaltic achondrites. No significant radiogenic growth of ^{87}Sr could have occurred in the solar nebula between the condensation of the Moon and the condensation of the parent planet for basaltic achondrites. Basaltic rocks returned from the lunar maria have ages between 3.1 and 3.9 AE (1 AE = 10^9 years) establishing this as a period of active lunar magmatism. However, the limited sampling represented by the returned samples does not allow the conclusion that magmatism is limited to this period; photogeoligic studies indicate that lava extrusion may have entended to about 2 AE ago.

Many of the multi-ringed lunar basins are now filled by mare basalts. Irrespective of ambiguities in the ages of the basins it can be concluded that the last lava flows into them occurred long after their formation. Ambiguities in basin age arise from an inability to uniquely define the nature of the events which have resulted in a clustering of the ages of lunar highland rocks in the interval ~ 3.9–4.0 AE. A variety of independent evidence must be brought to bear on this problem. At present the author considers that strong arguments exist for placing the formation of the Imbrium and Serenitatis basins at ~ 3.9 AE and ~ 4.0 AE, respectively. A number of other basin-forming events appear to be bracketed by these two. In any event, highland rock ages appear to be dominated by events occurring ~ 3.9–4.0 AE ago. Older ages reported for a few rocks, principally by the $^{39}Ar/^{40}Ar$ technique, seem to represent as yet undefined early lunar crustal events.

The ~ 4.6 AE age for a dunite sample apparently reflects an early lunar differentiation. This early differentiation is also reflected in variations in initial $^{87}Sr/^{86}Sr$ ratios of basalts from the lunar interior. These variations show that source regions of differing Rb/Sr were established long before the period of magmatism which resulted in lava flows to the lunar surfaces. This same effect is evidenced in the single-stage model ages of many lunar rocks which are in the range of 4.3–4.5 AE. An alternative explanation that the variations in initial Sr conposition and the ~ 4.3–4.5 AE model ages are produced by contamination of basaltic lavas with crustal material seems less probable.

The single stage model ages of lunar rocks need have no direct time significance. Assumption of a two-stage model with initial lunar differentiation at ~ 4.6 AE yields model-dependent conclusions concerning the fractionation in Rb/Sr to be $\lesssim 50\%$. The high-K Apollo 11 basalts are an exception: a fractionation of a factor of five is calculated for them. KREEP (for high K, REE and P) rocks present a special problem in that some and perhaps all of them appear to predate at least the Imbrium basin event and to have had their isotopic systematics reset by this or other major events at ~ 3.9–4.0 AE. For these rocks it is probably not appropriate to use their crystallization ages in the two-stage model calculations. If the calculationi is reversed, and it is assumed that a large fractionation in Rb/Sr occurred at some time of this event to be ~ 4.3 AE ago.

The model ages of lunar soils are similar to those of the rocks comprising them, indicating approximate closed system behavior. It is probable that open system behavior occurs to a small extent due to lunar rogolith processes.

O'Hara, M. J. (Dept. of Geology, West Mains Road, Edinburgh EH9 3JW) and Humphries, D. J.: 'Gravitational Separation of Quenching Crystals: A Cause of Chemical Differentiation in Lunar Basalts', *Phil. Trans. Roy. Soc. London* A285, 177–192. (1977)

The low viscosity of lunar lavas allowed skeletal quenching crystals, which formed during post eruption cooling of flows, to sink and accumulate despite the low gravitational acceleration. The crystals which sank were not in chemical equilibrium with the liquid. Hand specimen bulk compositions are related to each other by differential movement of the materials composing the cores and rims of the skeletal'phenocrysts', and not by any equilibrium chemical process. Crystal sinking must have occurred, and cumulates must have formed. Mafic hand specimens, consisting of skeletal phenocrysts in a more feldspathic groundmass, represent the cumulus enriched material and not the original liquids. The lava compositions were much more feldspathic, and were controlled by fractional crystallization at low pressures. The effects of such fractionation must be considered and, in most cases, restored before valid petrogenetic inferences about the mineralogy and chemistry of the lunar interior can be drawn.

O'Keefe, J. A. (Theoretical Studies Group, Goddard Space Flight Center, Greenbelt, MD 20771) and Urey, H. C.: 'The Deficiency of Siderophile Elements in the Moon', *Phil. Trans. Roy. Soc. London* **A285**, 569–575. (1977)

The deficiency of siderophiles in the crust of the Earth is customarily attributed to leaching by metallic nickel-iron, which eventually sank to form the core. A similar deficiency exists in the Moon, which has, at best, a very much smaller core. Hence it is logical to consider the hypothesis that the Moon formed from the mantle of the Earth, after the siderophiles had been removed.

It is shown that the non-hydrostatic figure of the Moon, and the requirement that mascons must be supported, together with the high heat-flow, imply that the metal of the Moon is collected in the core. It probably amounts to less than 1% of the Moon's mass.

Calculations show that if the core is in chemical equilibrium with the lunar silicates, then the nickel has been removed from the Moon as a whole to an extent which is greater than can be explained by theories of direct formation from a nebula.

The only salvation for the idea of direct formation from a nebula appears to be an efficient process of extraction of the siderophiles by successive passage of small amounts of reduced metal through the silicate portion of the Moon.

Since natural processes do not usually operate with the required efficiency, it can be concluded that the formation of the Moon by fission of the Earth is geochemically plausible.

Palme, H. (Enrico Fermi Inst. and Dept. of Chemistry, Univ. of Chicago, Chicago, IL 60637): 'On the Age of KREEP', *EOS: Trans. Amer. Geophys. Union* **58**, 430. (1977)

Internal Rb–Sr isochrons of lunar highland rocks define, in most cases, ages of around 3.9 to 4.0 AE. Total rock model ages could provide information prior to the remelting stages of these rocks. Measured model ages vary, however, between 4 and 6 AE. Highland rocks enriched in incompatible elements (K, Rb, REE, U, Hf, etc.) have the same relative abundances of these elements. This KREEP pattern of incompatible elements had been preserved through the remelting process. Only alkali elements (K, Rb), being more volatile, have been fractionated relative to the more refractory incompatible elements, causing this spread in model ages. By assuming that all KREEP-containing highland rocks evolved with the same Rb/REE ratio before the remelting occurred, much more uniform model ages are obtained: Apollo 16 KREEP: 4.36 ± 0.02 AE (4.47 ± 0.09 AE, without corrections for Rb fractionation 3.9 AE ago); Apollo 17 KREEP 4.45 ± 0.02 AE (4.48 ± 0.09 AE, without correction for Rb fractionation 4 AE ago); all JSC data. This implies different source regions for Apollo 16 and Apollo 17 KREEP. Apollo 14 KREEP is similar to Apollo 16 KREEP, while Apollo 15 KREEP rocks have very different isotopic characteristics. These chemically similar, but isotopically different, KREEP components have evolved in separate reservoirs prior to their excavation, eventurally by mare forming impacts. There is also a gross correspondence between highland rocks with the same meteoritic component and highland rocks with similar Rb–Sr characteristics. The widespread occurrence of this trace element enriched KREEP component implies that the incompatible elements of a major part of the Moon are now concentrated in this.

Palme, H. (Max-Planck-Institut fur Chemie, Abteilung Kosmochemie, Mainz, Germany) and Wanke, H.: 'Lunar Differentiation Processes as Characterized by Trace Element Abundances', *Phil. Trans. Roy. Soc. London* **A285**, 199–205. (1977)

The pattern of incompatible elements (K, Rb, Ba r.e.e., Hf etc.) is the same for most samples from the lunar highlands. It is suspected that this pattern of incompatible elements is typical for the whole lunar crust. This seems to be a reasonable assumption as one can show from heat flow data that a large part of the Moon's total U (and consequently other incompatible elements) has to be concentrated in a thin crustal layer, which certainly contributes to the sampled higland rock types. It is supposed that a partial melting process of the major part of the Moon has extracted and trace elements from the interior into the crust. The patterns of incompatible elements of mare basalts are those expected if a second partial melting process were applied to the trace-element-depleted interior.

Some consequences of this model are discussed. A relatively constant Sr and Eu distribution through the whole Moon is inferred, implying a position Eu-anomaly in the lunar interior.

Pillinger, C. T. (Univerisity of Bristol, School of Chemistry, Organic Geochemistry Unit, Cantock's Close, Bristol BS8 1TS) and Eglinton, G.: 'The Chemistry of Carbon in the Lunar Regolith', *Phil. Trans. Roy. Soc. London* **A285**, 369–377. (1977)

The current status of knowledge concerning the chemistry of carbon in the lunar regolith is discussed. The respective roles of the solar wind and micrometeorite impact in contributing carbon and providing energy to stimulate chemical reactions and mobilize carbon phases are examined. Most detailed information has been obtained by releasing trapped species and decomposing reactive carbon phases by dissolution of lunar soils in concentrated deuterium labelled acids. The method has substantiated that hydrocarbons deriving from solar wind implanted carbon and hydrogen are present in the silicate. In addition to trapped species, a number of carbon phases chemically bound to the matrix have been recognized. The most important of these are an acid hydrolysable species associated with metallic iron and what appears to be a discrete ionic carbide which liberates acetylene. Although the majority of the solar wind implanted carbon may be released and quantitated by pyrolysis there is little information to identify which elements were bonded to the carbon in the sample, if indeed any bonds were present at all.

Ridley, W. I. (Lamont-Doherty Geoligical Obs., Columbia University, Palisades, NY 10964): 'Some Petrological Aspects of Imbrium Stratigraphy', *Phil Trans. Roy. Soc. London* **A285**, 105–114. (1977)

Petrochemical studies of clasts in breccias from Fra Mauro and Apennine Front provide insights into different structural levels of Pre-Imbrium terra crust. Most of the Fra Mauro breccias and included clasts are 'KREEP' basalts showing both igneous and cataclastic textures and are interpreted as the surface veneer of the terra crust. Similar samples were collected from the Apennine Front near Spur Crater, but thery are mixed in with clasts of coarse, plutonic texture. One clast type is spinel pyroxenite whose mineralogy and petrochemistry are consistent with the original rock type being garnet pyroxenite. Such a mineral assemblage could only be stable at greater than 300 km depth, well within the lunar upper mantle. It is suggested that these clasts represent garnet pyroxenite xenoliths, emplaced within the lunar crust during early volcanism, that underwent a phase transition to spinel pyroxenite. Another clast type is plutonic norite, in which coarsely exsolved inverted pigeonite is associated with anorthitic plagioclase. Similar terrestrial rocks are found in Stillwater-type layered intrusions, and it is suggested that the lunar norites were parts of terra crustal layered complexes developed beneath a veneer of impact bracciated crust. Examples of the latter are illustrated by poikiloblastic-textured gabbroic anorthosite, with inverted pigeonite oikocrysts surrounding grains of plagioclase, augate, pigeonite,orthopyroxene, olivine and ilmenite. Application of mineral geothermometers indicates crystallization of these rocks below 1100°C, temperatures that are well below the liquidus. Hence these textures probably developed largely by solid state recrystallization during impact-metamorphism.

Ringwood, A. E. (Research School of Earth Sciences, Australian National University): 'Mare Basalt Petrogenesis and the Composition of the Lunar Interior', *Phil. Trans. Roy. Soc. London* **A285**, 577–586. (1977)

Mare basalts, which are beleived to form by partial melting at considerable depths in the lunar interior, are capable of providing a wealth of infomation concerning the compositions of their source regions. Conversely, any acceptable estimate of the lunar bulk composition must in principle be able to provide source regions capable of yielding mare basalts. A wide range of lunar bulk compositions has been proposed in the recent literature. These differ principally in the proportions of involatile elements, e.g. Ca, Al, to elements of moderate volatility, e.g. Mg, Si, Fe. A detailed experimental investigation has been made of the capacity of the Taylor–Jakes compositional model (8.2% Al_2O_3) to provide source regions for mare basalts. It is demonstrated that this composition is much too rich in alumina to be acceptable. Other lunar bulk compositions even richer in Al_2O_3 such as those advocated by Ganapathy & Anders, Wänke and co-workers and Anderson can likewise be rejected. In order to produce mare basalts, particularly the least fractionated varieties represented by some apollo 12 and 15 basalts, lunar bulk compositions containing only about 4% of Al_2O_3 appear to be required. This is similar in the Moon and in the Earth's mantle. These relationships point towards a common origin for the Moon and for the Earth's mantle.

Ryder, G. (Center for Astrophysics, Harvard College Observatory & Smithsonian Astrophysical Observatory, Cambridge MA 02138), Stoeser, D. B., and Wood, J. A.: 'Apollo 17 KREEPy Basalt: A Rock Type Intermediate between Mare and KREEP Basalts', *Earth Planet. Sci. Letters* **35**, 1–13. (1977)

The Apollo 17 KREEPy basalt is a unique lunar volcanic rock, observed only as clasts in the light friable breccia matrix (72275) of Boulder 1, Station 2 at Taurus-Littrow. Its status as a volcanic rock is confirmed by the absence of any meteoritic contamination, a lack of cognate inclusions or xenocrystal material, and low Ni contents in metal grains.

The basalt was extruded 4.01 ± 0.04 b.y. ago, approximately contemporaneously with the high-alumina mare basalts at Fra Mauro; Shortly afterwards it was disrupted, probably by the Serenitatis impact, and its fragments emplaced in the South Massif. The basalt, which is quartz-normative and aluminous, is chemically and mineralogically intermediate between the Apollo 15 KREEP basalts and the high-alumina mare basalts in most respects. It consists mainly of plagioclase and pigeonitic pyroxene in approximately equal amounts, and 10–30% of mesostatis. Minor phases outside of the mesostatis are chromite, a silica mineral, Fe-metal, and rare olivine; the mesostatis consists primarily of ilmenits, Fe-metal, troilite, and ferroaugite, set in a glassy or microcrystalline Si-rich base.

Chemical and isotopic data indicate that an origin by partial melting of a distinct source region is more probable than hybridization or contamination of magmas, and is responsible for the transitional composition of the basalt. The Moon did not produce two completely distinct volcanic groups, the KREEP basalts and the mare/mare-like basalts; some intermediate rock types were generated as well. A corresponding spectrum of source regions must exist in the interior of the Moon.

Sato, M. (U.S. Geological Survey, Reston, VA 22092): 'The Driving Mechanism of Lunar Pyroclastic Eruptions Inferred from the Oxygen Fugacity Behavior of Apollo 17 Orange Glass', *EOS: Trans. Amer. Geophys. Union* **58**, 425. (1977)

The log f_{O_2} values of hand-picked orange glass spherules (74220) were reproducible, almost linear against $1/\tau$, and 0.3 (at 1000°C) to 0.1 (at 1130°C) log unit higher than those of iron-wüstite, when not heated above 1140°C. The log f_{O_2}-$(1/\tau)$ plots irreversibly shifted down to the mare basalt range at higher temperature, indicating autoreduction of the sample. The reduction was most likely caused by the reaction of minute graphite flakes, internally trapped and sporadically distributed, with the glass matrix to evolve CO gas, because (1) a similar behavior was observed when a minute quantity of graphite was added to a synthetic basaltic glass, (2) the carbon content in orange glass is extremely variable (5 to 100 ppm; Gibson and Moore, 1973), and (3) the reduction did not start until the temperature was above the solidus temperature (1135°C; Green *et al.*, 1975) so that CO could vesiculate. The f_{O_2} of the graphite-($CO + CO_2$) system increases sharply as gas pressure increases, so the relatively high f_{O_2} values of the orange glass measured below 1140°C probably reflect the state of oxidation of the magma under a relatively high gas pressure. The log f_{O_2} values of the orange glass, extrapolated from the pre-reduction linear segment to the estimated pre-eruption temperature of 1220–1320°C, indicate as much as a few hundred atmosphers of CO gas pressure before the eruption.

On the basis of the above findings and deductions, the following chemical mechanism for driving lunar pyroclastic eruption is proposed. (1) In the source region, redox reactions in the magma were in equilibrium at the prevailing pressure, and the f_{O_2} of the magma was mainly controlled by the graphite-CO_2 reaction. The magma probably contained some Fe^{3+}. (2) As the magma ascended and its confining pressure decreased, sporadic graphite flakes began reacting with Fe^{3+} and CO_2 in the magma. The reaction was limited by diffusion, however. (3) When the magma pooled in a magma chamber, convective movement of the magma and the floating motion of graphite facilitated the reaction and the gas pressure rose rapidly. The CO gas probably visiculated as soon as generated because of its presumably small solubility (similar to that of CO_2) in magma under the low crustal pressure. (4) When the gas pressure overcame the resistance of the vent area, the magma erupted as a fine spray of molten silicate droplets into the high-vacuum lunar atmosphere, being propelled by expanding CO gas. Vesiculation during the flight did not happen as little CO was dissolved in the melt and the gas generation depended on the heterogeneous graphite reaction, in contrast to the rapid exsolution of dissolved H_2O in terrestrial lava fountains.

Scarlett, B. (Dept. of Chemical Engineering, Loughborough University of Technology, Leicestershire), Buxton, R. E., and Faulkner, R. G.: 'Formation of Glass Spheres on the Lunar Surface', *Phil. Trans. Roy. Soc. London* **A285**, 279–284. (1977)

The lunar fines contain an appreciable proportion of spherical glass particles. They are formed by local melting and splash due to mèteorite impact. The observed particle size of the spheres is discussed in relation to the physical processes controlling their formation. Detailed studies of the structure of some larger spheres have been made. Three aspects are reported and discussed, the secondary cratering on the surface, the porosity of the spheres and their chemical homogeneity.

Signer, P. (Swiss Federal Institute of Technology, CH-8006 Zurich, Sonneggstrasse 5, Switzerland), Baur, H., Etique, P., Frick, U., and Funk, H.: 'On the Question of the ^{40}Ar Excess in Lunar Soils', *Phil. Trans. Roy. Soc. London* **A285**, 385–390. (1977)

The retrapping mechanism proposed to explain the excess ^{40}Ar in lunar soil samples is discussed. Questions arise from the following experimental facts. Gas release in linear heating experiments is similar for excess ^{40}Ar and for solar wind ^{36}Ar, the latter having much higher implantation energy. In feldspar and olivine-pyroxene separates from a lunar soil the ^{40}Ar/^{36}Ar ratio of surface correlated argon is different. In feldspar grain size separates, potassium and ^{36}Ar appear linearly correlated. Possible influences of the Moon's ancient magnetic properties for the efficiency of the retrapping mechanism are discussed. Arguments supporting the notion of a second process, the transient K coating, are presented.

The problem remains unsettled and further studies are needed.

Strangway, D. W. (Dept. of Geology, University of Toronto, Toronto, Ontario, Canada) and Olhoeft, G. R.: 'Electrical Properties of Planetary Surfaces', *Phil. Trans. Roy. Soc. London* **A285**, 441–450. (1977)

The electrical properties of the lunar surface are those of very good dielectric insulators. The results of Apollo programme and laboratory studies on lunar samples have confirmed the predictions of Earth-based and spacecraft measurements of the dielectric properties of the lunar surface, and helped to increase the reliability of such studies of the surfaces of other planetary bodies. It appears that the electrical properties of the surfaces of Mercury, Venus and Mars are all very similar to those found for the Moon, Mercury has no atmosphere and in this sense is very similar to the Moon; Mars has a mean atmospheric pressure and temperature at the surface that is far below the triple point of water; while Venus has surface temperatures and pressures that are far above the critical point of water. This means that water is unlikely to contribute to the dielectric properties of either planet.

The dielectric constant of the surface of the Moon is determined largely by the bulk density and is related to the density by the formula $k = (1.93 \pm 0.17)^{\rho}$ for dielectric constant, k, at density ρ g/cm^3. Thus, most soils have k about 3, while solid rocks have k about 7.5. Loss tangents appear to be dependent upon density, frequency, temperature, and possible ilmenite content, and thus are more difficult to predict than the dielectric constant. Typical loss tangents are likely about 0.005 for the Moon, Mars and Mercury, and about 0.01 to 0.2 for Venus.

Thorpe, A. N. (Howard University, Washington, D.C. 20001), Minkin, J. A., Senftle, F. E., Alexander, C., Briggs, C., Evans, H. T., Jr., and Nord, G. L., Jr.: 'Cell Dimensions and Antiferromagnetism of Lunar and Terrestrial Ilmenite Single Crystals', *J. Phys. Chem. Solids* 38, 115–123. (1977)

X-Ray diffraction and anisotropic magnetic measurements have been made on single crystals of lunar ilmenite and on terrestrial ilmenite from Bancroft, Ontario, Canada and the Ilmen Mountains, U.S.S.R. The elongated *c*-axis of lunar ilmenite, previously reported, is confirmed by new measurements. The shorter *c*-axis found in terrestrial specimens is ascribed to Fe^{3+} substitution for Ti^{4+} in the titanium layer. Magnetic measurements on the same specimens show that, in agreement with the Ishikawa–Shirane *et al.* model, the initial shortening of the *c*-axis by the above substitution of small amounts of Fe^{3+} ($< 8\%$) causes an increase in Fe^{2+}–Fe^{2+} exchange coupling through Fe^{3+} in the titanium layer that lowers the Néel transition temperature. The Weiss temperatures and other magnetic parameters confirm this model proposed by Ishikawa and Shirane *et al.*

Additional transitions found in one of the terrestrial specimens (Bancroft) have been ascribed to a small amount of an exsolved spinel phase, possibly a solid solution phase of magnetite-ülvospinel. The spinel phase is localized in hematite-rich blebs which exsolved from the host ilmenite-rich phase.

Tittmann, B. R. (Science Center, Rockwell International, Thousand Oaks, CA 91360): 'Lunar Rock *Q* in 3000–5000 Range Achieved in Laboratory', *Phil. Trans. Roy. Soc. London* **A285**, 475–479. (1977)

Q measurements carried out by the vibrating bar technique on lunar sample 70215,85 have yielded *Q* values as high as 4800 at room temperature. The strong outgassing procedures necessary to raise the *Q* to these high vales from $Q \approx 60$ (when received) and studies of the effect on *Q* by a variety of different gases shows that the removal of thin layers of absorbed H_2O are responsible for the dramatic increase in *Q*. Experiments carried out with a low frequency apparatus on a terrestrial analogue at 50 Hz suggest similar increases in *Q* with outgassing, thus providing evidence that dramatic effects on *Q* can be expected to occur down to seismic frequencies. These results, in part, explain the contrast between seismic data in the lunar and terrestrial crust in terms of the absence and presence respectively of adsorbed H_2O.

Turner, G. (Dept. of Physics, University of Sheffield, Sheffield, S3 7RH, England): 'Potassium–Argon Chronology of the Moon, *Physics and Chemistry of the Earth* **10**, 145–195. (1977)

A knowledge of both the relative and absolute time scale of evolution of a planet is fundamental to a full understanding of that evolution. In the case of the Moon a relative time scale for the development of the surface features had been worked out before Apollo but, in spite of much prior speculation, the determination of an absolute time scale had to await the return of lunar samples.

The preliminary K–Ar analysis of samples at the Lunar Receiving Laboratory provided the first clear indication that even the youngest parts of the Moon, the mare regions, were very ancient in terrestrial terms, (3.0 ± 0.7) Gy. Subsequently more refined analysis, using the ^{40}Ar–^{39}Ar, Rb–Sr and U–Pb methods, have provided a detailed time scale accurate to 1% or so. The three main features of this time scale are: (i) an early chemical differentiation of the lunar crust which began at least 4.5 Gy ago; (ii) an intense asteroidal bombardment of the surface, ending rather abruptly around 3.9 Gy ago, and providing the densely cratered features of the lunar highlands; (iii) extrusion of the mare basalts into the giant basins formed by the bombardment, between 3.9 and 3.2 Gy ago. In addition to the major history of lunar development the rates of various surface processes such as regolith formation, micrometeorite impact erosion and recent small cratering events have been determined, making use of a number of cosmic ray exposure effects.

In this article that part of lunar history which has emerged from the use of K–Ar dating methods will be reviewed. This review is set out in six main sections. In the following section the ^{40}Ar–^{39}Ar dating technique will be described. This is a form of K–Ar dating which has proved particularly applicable to lunar sample dating providing ages in many cases where conventional K–Ar techniques would have failed. However, to appreciate fully the implications of the ages obtained it is necessary to understand clearly the limitations as well as strength of the technique. The third and fourth sections review the age information obtained from mare basalts and highland samples, respectively, while section 5 considers a number of special cases which do not conveniently fall into either of these headings. Section 6 provides a summary of the main points together with a brief look at possible future developments.

Vaughan, D. J. (Dept. of Geological Sci., The University of Aston, Birmingham B4 7ET) and Burns, R. G.: 'Electronic Absorption Spectra of Lunar Minerals', *Phil. Trans. Roy. Soc. London* **A285**, 249–258. (1977)

Transition metals play an important role in the lunar rock-forming silicates, occurring particularly in pigeonite, augite, olivine and pyroxferroite. Measurements of the absorption spectra of lunar silicates can provide information on the oxidation states and co-ordinations of the transition metal ions. Such measurements lead us to conclude that Ti^{3+} as well as Fe^{2+} and Ti^{4+} ions are present in lunar silicates. Fe^{3+} ions do not occur in concentrations greater than a few parts per million, and the spectral evidence for Cr^{2+} ions in olivines requires further substantiation – whereas occurrence of Cr^{3+} is very likely. The occurrence of low oxidation states in the transition elements of the lunar rocks suggests that low oxygen fugacities prevailed during the formation of the lunar crust. However, other reduction mechanisms postulated include release of solar-wind gas, and pressure-induced reduction on meteorite impact or during magma genesis at depth.

Correlations of laboratory measurements with remote telescopic measurements confirm that major features in remote reflectance profiles arise from absorption by pyroxenes, enabling average pyroxene compositions to be determined for areas of the lunar surface. Intense absorption towards the ultraviolet-blue end of the spectrum corresponds to high titanium contents, as confirmed by molecular orbital calculations which support the use of remote spectral measurements to map titanium-rich areas of the Moon.

Vickers, D. G. (Dept. of Physics, Queen Mary College, University of London, Mile End Road, London E1 4NS) and Bastin, J. A.:. 'The Interaction of Lunar Rock and Far-Infrared Radiation', *Phil. Trans. Roy. Soc. London* **A285**, 319–324. (1977)

It is the purpose of this paper to review first those measurements which can be made of the interaction of far-infrared radiation with the lunar rock and then to dicuss the significance of the measurements. The measurements themselves may be made either by observing the radiation mostly thermal, which comes from the lunar surface or subsurface layers; or by laboratory observations of the effect of the interaction of a beam of far-infrared radiation with various lunar samples. The interpretations of the measurements can also be subdivided depending on whether they have direct significance for the Moon or more generally for astronomical science.

Wanke, H. (Max-Planck-Institut fur Chemie, Abteilung Kosmochemie, Mainz, Germany), Palme, H., Baddenhausen, H., Dreibus, G., Kruse, H., and Spettel, B.: 'Element Correlations and the Bulk Composition of the Moon', *Phil. Trans. Roy. Soc. London* **A285**, 41–48. (1977)

A great number of element correlations have been observed in lunar samples. It is known from theoretical and experimental studies that in the solar nebula the elements condensed in groups according to their condensation temperatures and chemical affinities. One of these groups – the refractory elements – is represented by the early condensates or high temperature condensates (h.t.c.). From element correlations and group relations we estimate the bulk Moon to contain about 50% of h.t.c.; the other 50%, the non-refractory portion, consists mainly of (Mg, Fe)-silicates and minor phases of about chondritic composition.

Recently we have found strong evidence that most of the lunar highland samples represent mechanical mixtures of a differentiated (feldspathic) lunar component and a primary component from the last accretion stage of the Moon. The contribution of the h.t.c. in this primary material is estimated to 21%. Hence, an inhomogeneous accretion of the Moon is indicated. After the formation of a highly refractory core relatively more and more non-refractory material was added until the Moon reached its final mass. The composition of the primary matter observed in the lunar highlands gives us an important clue to the composition of the non-refractory portion of the Moon and thus leads to a more reliable estimation of the lunar bulk composition.

Warner, J. L. (NASA/Johnson Space Center, Houston, TX 77058), Phinney, W. C., and Simonds, C. H.: 'Crystallization History of Apollo 14 Impactites', *EOS: Trans. Amer. Geophys. Union* 58, 425. (1977)

Crystalline-matrix polymict breccias from Apollo 14 have been systematically investigated utilizing SEM and optical petrography. Our SEM technique allows detailed examination of the matrix of these impactites even though grain-sizes are in the order of micrometers. These data, combined with out two-component thermal model for impactites suggests concepts for the origin of these rocks that are different that we previously suggested (Warner, 1972).

Clast population data demonstrates that vitric-matrix breccias are *not* precursors of the crystalline-matrix breccias. This is demonstrated by the observation that crystalline-matrix breccias contain 10–20% mineral clasts whereas the vitric-matric breccias contain less than 6%. To derive the former from the latter requires the creation of new mineral clasts of inferred plutonic origin. This does not appear to be possible.

The matrix texture in various samples define a sequence that ranges from igneous (interlocking pyroxene and tabular plagioclase) to mosaic (equant, anhedral pyroxene and plagioclas). The igneous texture is explained by our thermal model cited above. The mosaic texture cannot be developed from the igneous texture by progressive annealing because the lithic clasts do not reflect such a thermal event. The mosaic texture may be understood as a case of extreme subsolidus crystallization of glass with an abundance of existing nuclei – a physical situation consistent with our thermal model. Such a highly viscious system (with low diffusion rates compared to a liquid system) would crystallize rapidly using the fragments as nuclei. Crystallization would commence about each nucleus and continue until each crystallization node interferred with its neighbors.

Warner, R. D. (Dept. of Geology & Institute of Meteoritics, Univ. fo New Mexico, Albuquerque, NM 87131), Nehru, C. E., and Keil, K.: 'Opaque Mineral Crystallization in High Titanium Mare Basalts', *EOS: Trans. Amer. Geophys. Union* 58, 430. (1977)

Three major groups of high titanium mare basalts are recognized: (1) Apollo 17 very high-Ti basalts, (2) Apollo 11 high-K basalts. Characteristic opaque mineral assemblages and their range of Fe/(Fe + Mg) are : (1) chromian ulvöspinel (0.72–0.97) and ulvöspinel (0.97–1.00) + armalcolite (0.47–0.72) + ilmanite (0.68–0.99); (2) chromian ulvöspinel (0.72–0.87) or ulvöspinel (0.99) + ilmenite (0.74–0.99); (3) armalcolite (0.48–0.67) + ilmenite (0.79–0.99). Bulk composition of melt, cooling rate and oxygen fugacity are some factors in affecting order of crystallization and stability of opaque oxides. Armalcolite crystallizes from melts with $TiO_2 > 10$–11 wt.% and ceases when Fe/(Fe + Mg) of melt reach ~ 0.70. Amount of Cr_2O_3 in melt controls chromian ulvöspinel crystallization. Ilmenite is first opaque oxide to crystallize only when TiO_2 is too low for armalcolite precipitation and Cr_2O_3 is too low (< 0.25 wt.%) for chromian ulvöspinel crystallization. Slower cooling enhances armalcolite reaction with melt and decreases modal abundance of armalcolite. Modal abundance of chromian ulvöspinel also decreases with slower cooling because of increased Cr substitution in pyroxene and earlier plagioclase nucleation. Early crystallization of one, two or all three above opaque phases depletes melt both in TiO_2 and Cr_2O_3 but has minimal effect on changing MgO wt.%. Olivine and pyroxene crystallization is mainly responsible for continually increasing Fe/(Fe + Mg) in melt.

5. Electromagnetic Properties of the Moon

Berdichevskey, M. N., and Krass, M. S.: 'Calculation of a variable Electromagnetic Field of the Moon', *Akad. Nauk SSSR. Izvestiya. Physics of the Solid Earth* **12**, 666–671. (1977)

This article deals with numerical calculations of an induced variable magnetic field on the Moon's surface and in the shadow cavity. Some aspects of the electromagnetic sounding of the Moon are discussed.

Collinson, D. W. (Institute of Lunar & Planetary Sci., School of Physics, Univ. of Newcastle upon Tyne, Newcastle upon Tyne, NE1 7RU), Stephenson, A., and Runcorn, S. K.: 'Intensity and Origin of the Ancient Lunar Magnetic Field', *Phil. Trans. Roy. Soc. London* **A285**, 241–247. (1977)

There is now strong evidence that the Moon possessed a magnetic field between 4000 and 3200 Ma ago. The evidence for the origin of this field are discussed, and determinations of its intensity described. It is tentatively concluded that the field decreased from an initial intensity of about 1 G (10^{-4}T) during the above time interval, and the implications of the initial intensity and its decay for the origin of the field are discussed.

Fisher, R. M. (U.S. Steel Corp., Research Lab., Monroevill, PA 15146), Huffman, G. P., Nagata, T., and Schwerer, F. C.: 'Electrical Conductivity and the Thermocline of the Moon', *Phil. Trans. Roy. Soc. London* **A285**, 517–521. (1977)

Knowledge of electrical conductivity of lunar materials is required in order to understand various lunar surface and interior phenomena including deduction of lunar temperature profiles. Studies by several investigations of electrical conductivity in controlled environments and at elevated temperature of Apollo lunar rocks, terrestrial pyroxenes and olivines, and synthetic glasses have shown that conductivity values are dependent primarily on concentration, distribution and oxidation state of iron and only secondarily on silicate crystal structure (e.g. olivine, pyroxene or glass). This general observation provides a reasonable basis for using laboratory conductivity data to deduce lunar interior temperatures from conductivity profiles determined by studies of the interaction of solar wind and Moon. Furthermore, correlation of conductivity with iron content provides a basis for the existence of lunar surface conductivity inhomogeneities. In this presentation, salient laboratory measurements of electrical properties by several investigators are discussed in the context of lunar observations from space missions and compared with appropriate lunar evolutionary models.

Fuller, M. (Dept. of Geological Sciences, University of California, Santa Barbara, CA 93106): 'Paleomagnetic Determinations of Ancient Lunar Magnetic Field Intensities', *EOS: Trans. Amer. Geophys. Union* **58**, 383. (1977)

It has proved very difficult to obtain reliable intensity estimates from the paleomagnetism of returned lunar samples, due primarily to the nature of the carriers, which has precluded successful completion of standard intensity determination. In the absence of such determinations it is particularly difficult to isolate the different processes of magnetization and demagnetization to which the samples may have been subjected subsequent to their formation.

Two partially successful Thellier–Thellier determinations were completed several years ago. One, on a highland crystalline rock, gave a field of 1.2 Oe. The second, on a breccia, indicated a field of the order of thousands of gammas. Subsequent work has cast some doubt on even these determinations.

In the face of these difficulties which have their root cause in the irreversible effects of heating, several techniques have been developed which eliminate, or reduce, the heating. The simplest technique is normalization by saturation isothermal remanence (IRM). Normalization by anhysteretic remanence (ARM) is in principle better, because ARM is more like TRM than is IRM_s. There is however an unspecified relation between TRM and ARM, so that an independent heating experiment is needed. Another possibility is to use ARM to monitor the effect of heating. This method reduces the amount of time the sample spends at elevated temperature. Another possible method of mitigating the effects of heating is to use RF heating which is preferably confined to the magnetic carriers which happen to be strongly conducting compared to the rest of the lunar rocks.

Results of all of these methods will be discussed and it will be pointed out that there are indications that some of the older lunar samples were magnetized in fields of at least several tenths of an oersted.

Goldstein, B. E. (Jet Propulsion Lab., Pasadena, CA 91130): 'Compression of Induced Lunar Dipole Field', *EOS: Trans. Amer. Geophys. Union* 58, 427. (1977)

Ferromagnetic iron in the lunar crust or a metallic lunar core would both result in an induced lunar dipole magnetic field due to the external magnetospheric tail field. Measurements of this induced field have been used to estimate the size of a possible lunar core. Low energy particle events (anti-solar plasma flows) at subalfvenic speeds would partially compress the induced field toward the lunar surface. Assuming a cold plasma, and that the plasma flow is aligned with the tail field, the magnetic field in the plasma is described by the same equation as for a vacuum, but with a scaling along the flow direction proportional to the square root of $(1 - V^2/C_A^2)$, where V is the plasma velocity and C_A is the Alfven speed. By matching boundary conditions between plasma and non-plasma (Moon and wake) regions, numerical solutions is terms of spherical harmonics for the compressed field can be found. Implications for very low frequency sounding of the lunar interior will be discussed.

King, J. H. (Goddard Space Flight Center, Greenbelt, MD 20771) and Ness, N. F.: 'Lunar Magnetic Permeability Studies and Magnetometer Sensitivity', *Geophys. Res. Lett.* 4, 129–132. (1977)

A regression of quiet magnetic field components simultaneously measured by the two Explorer 35 magnetometers reveals uncertainties in effective sensitivity factors of up to a few per cent in one or both of these instruments. Given this, the validity of previous lunar permeability studies based on Explorer 35/ALSEP regressions, wherein inferences are drawn from regression line slopes differing from unity by the order of one per cent, is called into question. We emphasize the need to critically address the question of small deviations in magnetometer sensitivity factors from nominal values as a part of any two-magnetometer lunar permeability study.

Runcorn, S. K. (Institute of Lunar and Planetary Sciences, School of Physics, University of Newcastle upon Tyne): 'Interpretation of Lunar Potential Fields', *Phil. Trans. Roy, Soc. London* **A285**, 507–516. (1977)

Understanding of the internal dynamics of the Moon must start from the interpretation of the gravitational and magnetic fields, both present and past.

It has been long known from the study of Cassini's laws and its librations that the Moon substantially departs from hydrostatic equilibrium. This is confirmed by the second harmonic of the gravitational field determined by the tracking of orbiting satellites which also reveals anomalies (the mascons) clearly associated with the processes by which the circular mare formed. The mascons must be retained by the finite strength of the lithosphere, although there is evidence that they may have subsided by about 1 km by slippage along cylindrical fault systems around these mare, and these processes may be important in discussing moonquakes and the lunar transient phenomena. The analyses of the present figure of the Moon by the geometrical librations and by the lunar laser altimeter of Apollo 15 and 16 and other space determintaions now seem essentially in agreement. The data gives evidence of the figure of the Moon prior to the filling of the mare, i.e. before about 3300 Ma and it can be concluded that the present non-hydrostatic low harmonics of the gravity field were not then present. Comparison between the present figure of the Moon and its gravity field show that there is a low harmonic variation in density in the deep interior. Both these conclusions point to thermal convection described by second degree harmonics as being the cause of the present non-hydrostatic shape of the Moon.

The present lunar dipole magnetic field has been shown by successive analyses to be negligible, the most recent value being 0.05 nT at the surface. Yet magnetic anomalies near the surface of the Moon have been discovered: 1 nT at heights of 100 km and 10–30 nT with length scales of 10 km at the surface. These anomalies must arise from the magnetization of the crustal rocks as discovered in the returned samples. These various data conclusively show that the Moon between 4000 and 3200 Ma possessed a field of internal origin, probably dipolar, with an intensity which seemed to have diminished from over 1 G at 4000 Ma to a few thousand nT at 3200 Ma. Whether this field arose by dynamo processes in a small iron core of about 300 km radius, which was inferred from the convection theory and is compatible with the now known value of the moment of inertia factor, or whether it was a permanent magnetization of deep interior produced by a primeval solar system magnetic field must await further understanding of the early thermal history of the Moon. Thermal convection is seen as an essential basis for understanding the thermal history of the Moon, the traces of tectonic evidence in the lithospheric shell and the history of the magnetic field.

Russell, C. T. (Institue of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024) and Goldstein, B. E.: 'On the Apparent Permeability of the Moon: Further Evidence for a Lunar Core', *EOS: Trans. Amer. Geophys. Union* 58, 427. (1977)

Previous analysis of the Apollo subsatellite magnetometer data in the geomagnetic tail lobes has shown that the volume below the altitude of the subsatellites acts as if it were diamagnetic, i.e. the induced moment of the Moon opposes the external field. This behavior would be expected if the Moon possessed a highly conducting core whose Cowling diffusion time exceeded the time for typical passage of the Moon through the geomagnetic tail. Analysis of the surface magnetometer data together with Explorer 35 data is in disagreement with this result.

In order to increase the accuracy of the subsatellite measurements, we have used simultaneous measurements by the lunar surface magnetometers to separate temporal fluctuations from spatial changes in the analysis of the induced lunar moment. These measurements although fewer in number are much improved in accuracy yielding an induced moment of $(-4.2 + 0.6) \times 10^{22}$ Gauss-cm^3 per Gauss of applied field in agreement with our previous analyses. In the terminology of our previous work this moment corresponds to a G factor of -0.0080 ± 0.0011. Examination of the individual measurements as the Moon approaches the plasma sheet shows that only a small amount of energetic plasma surrounding the Moon can cause the apparent induced moment to become strongly positive. The calculation of the moment is so sensitive to the presence of plasma, we suggest that it is the incomplete removal of these plasma effects that has led to previous reports of positive induced moments.

6. Radiation of the Moon; Optical and Thermal Properties of the Lunar Surface

Benson, J. (Dept. of Space Physics & Astronomy, Rice University, Houston, TX 77001), Freeman, J. W., and Schneider, H. E.: 'Observations of Suprathermal Ions during the Lunar Nighttime', *EOS: Trans. Amer. Geophys. Union* **58**, 485. (1977)

The Suprathermal Ion Detector Experiments (SIDE's) deployed at the Apollo 12, 14 and 15 sites, often observe bursts of positive ions during the lunar nighttime. The energies of these ions range from ~ 250 eV/q to 1000 eV/q. Schneider and Freeman have shown that the frequency of occurrence of these nighttime ion events (NIE's) as observed by the Apollo 14 and 15 instruments is greatest near the local *sunrise* terminator. In the analysis done for the present paper, it was found that the frequency of occurence of the NIE's in the Apollo 12 data is greatest shortly after local *sunset*. These enhancements in the frequency of occurrence correspond to the times when each instrument is best situated to observe nightime ions which are accelerated into the detector by the solar wind $\mathbf{V} \times \mathbf{B}$ electric field. The source of these ions is most likely the lunar hydrogen-helium corona. H, H_2 and He that is ionized in sunlight on the dayside and above the terminators can be driven to the nightside by the $\mathbf{V} \times \mathbf{B}$ electric field. The nightside lunar surface potential, which has been observed to be at least 100 volts negative, can then further accelerate these ions into the detector. This surface electric field may account for the observations of the NIE's while the detector is looking in the anti-sunward direction.

Cameron, W. S. (NASA/Goddard Space Flight Center, Greenbelt, MD 20771): 'Lunar Transient Phenomena (LTP): Manifestations, Site Distribution, Correlations and Possible Causes', *Phys. Earth Planet. Interiors* **14**, 194–216. (1977)

The author has been compiling a catalog of LTP reports (temporary changes observed on the Moon). More than 1400 of these observations, of which 1353 have ancillary data, were analyzed in an attempt to determine the possible causes of LTP. There were 201 sites reported at least once; about $\frac{1}{2}$ had two or more reports. One dozen sites contain 70% of all observations, and one site, Aristarchus, provides 30%. Of the dozen most reported sites, $\frac{1}{2}$ are rayed and $\frac{1}{2}$ are dark flat-floored craters. The distribution of sites strongly favors the borders of both the terra and marial sides of the maria. Many are within the maria, and a very few are inland; yet most of these are associated with dark flat areas.

The phenomena manifest themselves in five categories, viz., Brightenings, or Darkenings, or as Gaseous, Reddish and Bluish events. Among the hypotheses proposed for their causes are tidal, low-illumination/thermoluminescence, magnetic-tail and solar-flare effects. Analyses were conducted to see if different phenomena had different causes. There is some suggestion that they do. As concerns the tidal effect, the strongest peaks are at 0.5 (apogee) for Gaseous and Darkenings phenomena, 0.6 for Reddish events, and 0.7 for Brightenings. Reddish LTP have the strongest correlation with sunrise; while Aristarchus, Plato, Ross D area, and Bluish penomena have the strongest correlations with solar-flare activity that produced magnetic storms on earth. "All" observations, the ones labeled "Best" (probable true anomalies), and Aristarchus, showed minima in the first half and maxima in the last half of the anomalistic (tidal) period. Histograms of several individual sites, including neighboring ones, behave differently, e.g. Aristarchus and Herodutus. When observed data are compared with expected observations (assumed to be evenly distributed) there were various correlations. For the Best data, 12 and 10% of the LTP fall close to perigee and apogee, respectively, and 10 % would be expected for each. Seventeen per cent occur within one day after sunrise when 3% would be expected; 20% occur while the Moon is in the Earth's magnetopause where 14% would be expected, and 12% occurred the same day the Earth had a magnetic storm where 3% would be expected.

Charts of albedo vs age of several points for ten features were constructed. From these the normal behavior of the features throughout a lunation period was obtained. Measures that depart 2 or more full steps in Elger's albedo scale, are considered to be anomalies. Several cases of anomalous measures show up; e.g. for points in the south wall of Eimmart an albedo of 3.5 was reported once at age 10 days while for age 9 days the average albedo was 8, as it was afterward at age 11 days. The 3.5 may have been an anomalous darkening but unnoticed by the observer. Most of the features remained stable. A few exceptions were found, with Dawes showing the most anomalies. These amounted to 12% by nights or 2% by individual measures. Thus, monitoring the Moon may yield an LTP once in ten nights, or 50 observations.

All hypotheses show correlations with some categories and some features. Sunrise correlation is the most frequent correlation. Few correlations imvolve as many as 50% of the observations. The distribution of all LTP sites is different from the unique compared with deep- and shallow-focus moonquake epicenters. Routine albedo measures reveal unobserved variations which amount to about 10% in the nights of obsurvation by 2% of individual albedo measures.

Carter, W. E. (Hawaii Institute for Astronomy, University of Hawaii, Honolulu, HI 96822), Berg, E., and Laurila, S.: 'The University of Hawaii Lunar Ranging Experiment Geodetic-Geophysics Support Programme', *Phil. Trans. Roy. Soc. London* **A285**, 451–456. (1977)

Secular changes in the geocentric positions of lunar laser ranging stations will include components due to local and regional crustal deformations and tectonic plane movements.

Terrestrial geodetic and geophysical methods appear to be the most timely and economical approach to determining local and regional effects.

The University of Hawaii expects to implement a comprehensive geodetic-geophysical programme in support of its lunar ranging programme in mid-1976. Measurements will include (a) repeated geodetic surveys between the observatory and selected points on the island of Maui and neighbouring islands, (b) repeated level surveys on the island tied to ocean tide gauges, (c) tilt meter monitoring of changes in the local vertical, (d) gravimetric Earth tidal measurements, and (e) seismic monitoring of crustal activity.

A similar programme is also being undertaken by the University of Texas in support of their MacDonald Observatory lunar ranging programme.

Durrani, S. A. (Department of Physics, University of Birmingham, Great Britain): 'Determination of the Temperature and Duration of some Apollo 17 Boulder Shadows using Thermoluminescence Methods', *Geophys. J. Roy. Astron. Soc.* **49**, 301. (1977)

The natural thermoluminescence (TL) retained by soil samples collected from the shadows of certain Apollo 17 boulders has been compared with that of a nearby sunlit ample. The shaded samples have been kept continuously refrigerated, since soon after their retrieval, to preserve their natural TL. By experimentally determining the various TL parameters of the relevant trapping levels, we have attempted to calculate the temperature (T_1) in the shade and duration (t_1) of the shadow cast on the samples. We obtain the values $T_1 = 256$K and $t_1 \sim 4.0 \times 10^4 - 5.7 = 10^4$ yr, based on a dose-rate of 10 rad yr^{-1} in the shade. On applying various corrections for the fading of the natural TL over the intervening ~ 3 yr, a value of $t_1 \sim 6.5 \times 10^4$ yr is obtained. These values of the storage time in the shade confirm the relatively recent arrival of the boulder concerned at its present location, as was indicated by the freshness of its tracks.

Eve, W. D. (Dept. of Physics, Queen Mary College, Mile End Road, London E1 4NS, England), Sollner, T. C. L. G., and Robson, E. I.: 'Submillimetre Lunar Emission', *Astron. Astrophys.* **59**, 209–213. (1977)

We present a map of lunar thermal emission obtained through the 350 μm atmospheric window. A brief description of the photometer and data collection is given. Previous observational work concerning lunar roughness is discussed. Several empirical expressions are fitted to measurements made from the contour map, the expressions providing the best fit involving a term dependent on the Earth's zenith angle at the point under observation. A theoretical map is also compared with the observational data and found to disagree markedly due to the absence of any roughness considerations.

Evsyukov, N.N.: 'Experiment in Remote Optical Analysis of the Chemical Composition of the Lunar Surface', *Astr. Vestnik* **10**, 177–189. (1977)

The methods of the calculation of the average chemical composition of the lunar regions by means of their albedo and colour-index are given. The connection of the optical and chemical division into Moon's districts is shown. A special attention is made on the complexity of the distantional determination of the chemical composition of the ground in regions with albedo $\rho > 0.18$ and with high colour-index.

Evsyukov, N. N.: 'Chemical-Composition Test of the Lunar Surface By Long-Range Optical Analysis', *Solar System Research* **10**, 143–151. (1977)

We present a method for calculating the chemical composition of lunar features according to albedo and color index. The optical features of the Moon are related to the chemical properties of these regions on the lunar surface. The long-range determination of the chemical composition is difficult for regions with albedo $\rho > 0.18$ and also for regions having high color index.

Friesen, L. J. (502 South Austin, Webster, TX 77598): 'A Hypothesis on the Locations of Lunar Gas Venting', *Phys. Earth Planet. Interiors* **14**, 274–275. (1977)

Both lunar transient phenomena and ^{222}Rn/^{210}Po anomalies observed by Apollo 15 and 16 orbital alpha spectrometers display preferences for certain kinds of locations: rims of circular maria and craters with central peaks and/or dark floors. If these classes of observations are due to lunar gas venting, why are these types of locations preferred? The hypothesis offered is that these are locations at which cracks or channels exist extending deep enough into the Moon to tap lunar volatile reservoirs. Possible channels include circumferential cracks around circular maria, old lava tubes for dark-floor and volcanic central peak craters, and shattered subsurface rock structure for impact central peak craters.

Geake, J. E. (Dept. of Pure & Appliced Physics, The University of Manchester Inst. of Science & Tech., Manchester, Great Britain) and Mills, A. A.: 'Possible Physical Processes Causing Transient Lunar Events', *Phys. Earth Planet. Interiors* **14**, 299–320. (1977)

Transient lunar events appear to involve two main effects: the obscuration of surface detail, and changes in brightness and/or colour which could be caused either by modification of the way in which incident sunlight is scattered, or by the emission of additional light. We find it difficult to explain the obscurations in any other way than to assume that clouds of fine surface dust are raised either by bursts of gas emission from surface fissures, or by impacts; the possible duration and density of such clouds are considered.

Modification of the albedo of a dust surface by agitation has been demonstrated in laboratory experiments: under certain conditions the albedo may increase, but the change appears to be permanent at atmospheric pressure; it may be reversible under lunar vacuum conditions. The most likely lunar process of this type again seems to be the agitation of surface dust by gas emitted from fissures; also, the scattering of sunlight by dust clouds could, under some conditions, result in weak colour effects. Processes that could result in the emission of light include incandescence, luminescence or thermoluminescence, glow discharge in gas clouds (possibly enhanced by the presence of charged dust grains), and lightning-type discharge in dust clouds. We conclude that the lightning-type discharge is the process most likely to be bright enough to be visible from Earth, against the sunlit Moon.

We therefore conclude that transient lunar events of the different types that have been reported could be explained by various processes that may occur in gas-borne dust clouds.

Gorenstein, P. (Center for Astrophysics, Harvard College Observatory/Smithsonian Astrophysical Observatory, Cambridge, MA 02138) and Bjorkholm, P. J.: 'Radon Emanation as an Indicator of Current Acitivity of the Moon', *Phys. Earth Planet. Interiors* 14, 289–292. (1977)

An interpretation of previously reported measurements of the Apollo 15/16 alpha-particle spectrometer on the distribution of ^{222}Rn and ^{210}Po across the lunar surface suggests that continuation of these measurements is a method of monitoring current activity on the Moon. Since the two isotopes are relatively short-lived with effective half-lives of 3 days and 21 years, respectively, the activity detected has had to have been released during this current epoch. Changes in the rate of lunar emanation can be measured on three different time scales: (1) of a few days or less by detecting ^{222}Rn at discrete sites such as the crater Aristarchus; (2) of a month by measing ^{222}Rn activity at the sunrise terminator; (3) of a few years by measuring ^{210}Po activity at various locations. These observations could be carried out very effectively from a lunar polar orbiting satellite.

Herbert, F. (Lunar & Planetary Lab., University of Arizona, Tucson AZ 85721), Sonett, C. P., and Wiskerchen, M. J.: 'Model 'Zero-Age' Lunar Thermal Profiles Resulting from Electrical Induction', *J. Geophys Res.* **82**, 2054–2060. (1977)

Thermal profiles for the Moon are calculated under the assumption that a pre-main-sequence T-Tauri-like solar wind excites both transverse magnetic and transverse electric induction while the Moon is accreting. A substantial initial temperature rise occurs, possibly of sufficient magnitude to cause subsequent early extensive melting throughout the Moon in conjunction with normal long-lived radioactives. In these models, accretion is an unimportant direct source of thermal energy but is important because even small temperature rises from accretion cause significant changes in bulk electrical conductivity. Induction depends upon the radius of the Moon, which we take to be accumulating while it is being heated electrically. The 'zero-age' profiles calculated in this paper are proposed as initial conditions for long-term thermal evolution of the Moon.

Middlehurst, B. M. (2 Portofino, Nassau Bay, Houston, TX 77058): 'A Survey of Lunar Transient Phenomena', *Phys. Earth Planet. Interiors* 14, 185–193. (1977)

Periodic and morphological characteristics of lunar transient phenomena (LTP) are described. Some early historical records are reviewed. Most sites of LTP's show evidence of internal disturbance either initiated from within or by volcanic modification of impact formations. Some individual crater sites are described. The probability of the reliability of at least some, and probably most, reports has been increased by the later discovery of the periodic nature of the deep-focus and shallow moonquakes; spurious reports would not have produced the periodicity of LTP's, but random errors would increase the noise level.

The conclusion to be drawn from the inadequancy of external energy sources is that some energy must be injected from within the Moon, probably in the excitation of gases, but this must remain speculation until better data is obtained, The underlying problem now is still the difficulty of obtaining permanent instrumental records; only twenty heterogeneous reports are at present known.

N.B.
The final part of this Bibliography will appear in *The Moon and the Planets* Volume 18, No. 2.