ABSTRACTS OF PAPERS SUBMITTED TO THE FIFTH LUNAR SCIENCE CONFERENCE, HOUSTON, 1974

12. Characteristics and Movement of Materials in the Lunar Regolith: III

Evensen, N. M., Rama Murthy, V., and Coscio, M. R., Jr.: 'Episodic Lunacy – V: Origin of the Exotic Component'.

We have previously reported on trace element and isotopic analyses of grain size fractions of regolith samples from Apollo missions 11, 14, 15 and 17. These investigations have been directed primarily toward characterizing the 'exotic' component present ubiquitously in the lunar soils. The exotic component is required to account for differences in trace element concentrations and isotopic systematics between coexisting rocks and soils at various sampled sites. It is inferred to be enriched with respect to major basalt and anorthosite rock types in a number of trace elements, including K and Rb, and to have a Rb–Sr model age of the order of 4.5 AE. This material is thus probably very similar chemically and isotopically to KREEP; however KREEP has been defined petrologically and chemically by examination of distinguishable rock fragments, while the characteristics of the exotic component have been inferred only indirectly from studies on mixtures of exotic component and locally derived soil, too fine grained to permit identification of specific mineralogic and petrologic components. We therefore tentatively retain the distinction.

Where large proportions ($\geqslant 10\%$) of exotic components are present, they can readily be demonstrated by direct comparison of rock and soil compositions. Measurements of K, Rb, Sr and Ba concentrations in various soil size fractions from 4 to 1000 μ at such sites (e.g., Apollo 15 soil 15531) show progressive increase in trace element content, particularly K and Rb, with decreasing grain size. Also, progressively finer size fractions plotted on a Sr evolution diagram deviate increasingly from the typical local rock isochron, in a direction indicating addition of material with high Rb/Sr and ~ 4.5 AE model age. Similar, though less marked trends are seen in soils differing less noticably from local rock compositions and therefore presumably containing a lower proportion of exotic component (e.g., Apollo 17 soils 71501, 75081). We conclude that the exotic component tends to be finer grained than the locally derived soil, and hypothesize that this difference is a consequence of transport of exotic component from a distant source, resulting in increased mechanical breakup of material. It is of interest to note that plagioclase separates obtained from individual size fractions of soil 10084 tend to mirror the trend of increasing trace element content with decreasing grain size, while ilmenite concentrates from the same fractions show no tendency to increase. Plagioclase is a common lunar mineral and could well be partially exotic in origin, while the ilmenite is probably almost entirely derived from the local very ilmenite-rich Apollo 11 rocks.

The orbital gamma ray spectrometry experiments have shown that high K, U, Th concentrations are present at several areas in the Mare Imbrium region. One of these, Fra Mauro, has been directly sampled by Apollo 14 and contains material chemically and isotopically similar to the inferred exotic component. If the Imbrium area were the sole source of such material on the lunar surface, a strong correlation between distance from the source and proportion of exotic component should be seen. Using comparison of rock and soil compositions to estimate the percentage of exotic component, and taking Fra Mauro as a hypothetical source area, such a correlation appears to exist, ranging from $\sim 35\%$ exotic component at the Apollo 12 site, 300 km from Fra Mauro, to $\sim 1\%$ exotic component at the Luna 16 and 20 sites, > 2000 km from Fra Mauro. Of course the actual source would be a more diffuse area, but this does not strongly affect the correlation, especially for more distant sites. Apollo 14 soils 14149 and 14259 show none of the grain size effects which we have attributed to transport and are therefore consistent with this model.

The regolith at Fra Mauro, and presumably the other high K, U, Th material in the Imbrium region, is believed to be derived from the excavation of the Imbrium basin at $\gtrsim 4$ AE ago. Since Imbrium has the largest and deepest of the circular mare basins, its excavation may have brought up

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material from deeper in the lunar interior than is accessible from any other source. Such material would initially be found as ejecta surrounding the Imbrium basin, but over the subsequent 4 AE would diffuse outward into surrounding regolith at a rate controlled by the nature of lunar transport processes. Such processes are reasonably effective at, for example, transporting anorthosite and other exotic fragments into mare regions, and would presumably transport proportionately more fine grained material. Imbrium ejecta which landed on younger mare basins would be covered over by subsequent mare filling.

In view of the chemical and isotopic similarities between KREEP and the exotic component, as well as the general correlation between abundance of exotic component and the proportion of identifiable KREEP fragments in the soil, it is tempting to speculate that KREEP has a history similar to that hypothesized above, particularly since no evidence of localized reservoirs of KREEP-like material has been found. The lunar regolith would then be pictured as locally derived material dominated by the mare basalt-highland anorthosite bimodal tendency, overprinted with distance dependent KREEP-exotic component, with additional vertical and lateral mixing provided by lunar gardening and transport processes. If the major portion of trace element enriched lunar material were derived from the deep lunar interior by an essentially unique event, considerable implications regarding the Moon's differentiation history and present structure would arise. Although such a hypothesis must remain tentative at best in the present state of our knowledge, some of these implications might be of interest to explore further.

Philpotts, J. A., Schuhmann, S., Kouns, C. W., and Lum, R. K. L.: 'Lithophile Trace Elements in Apollo 17 Soils'.

Li, K, Rb, Sr, Ba, rare-earth and Zr abundances in Apollo 17 soil samples (twenty), soil breccia, KREEP-breccia and mare-basalts (four) have been determined by mass-spectrometric isotope dilution. Abundances of Rb and Yb, two of the more informative trace elements, are plotted. Most of the soils approximate two component mixtures with (high Yb) mare basalt, similar to trace-element depleted Apollo 11 basalt (e.g. 10062), as one end member. The 'dark-mantle' soils 70181 and 71501 are highest in this component. The other component which shows some similarities to Apollo 16 soil, may have been introduced as an ejecta blanket. The 'white-mantle' soils (72501, 73121 and 73141) may represent mixtures of KREEP and this component. It, or 'white-mantle', may also be present in the relatively pure orange (74220) and black (74001) soils from Station 4. Other Station 4 soils approximate mixtures of 'whitemantle' and local basalt. Variations of soil composition with depth appear relatively limited in the Station 4 drive tube, and the Station 2a and 8 trenches. Major element data are consistent with these observations.

McCallister, R. H. and Meyer, H. O. A.: 'Apollo 16: Core 60004 – Analysis of <1 mm Fines'.

Core 60004 is part of the drill core string which penetrated approximately 2 m of the regolith at Station 10, Apollo 16. The section 60004 constitutes that portion between 70 cm and 110 cm depth. Twelve samples of less than 1 mm fines, randomly spaced throughout this length, have been analyzed for particle size, particle type, mineral content and chemical composition of constituent grains. The aim of the study being to uniquely characterize the various horizons in the core in order to understand better the physical conditions leading to formation of the lunar regolith. These conditions include how surface material is distributed and from whence it came, the destructive and constructive processes operating at the regolith surface, and the variation in exposure time at the lunar surface for the various horizons within the core.

Initially the samples were dry sieved using mesh sizes between 500 μ and 40 μ ($\varnothing$, 1–4.64). No data were included for material greater than 1 mm which had been removed at the Curatorial facility during dissection of the cores. A marked bimodal distribution in grain size occurred for all samples throughout the core, with the major percentage of material being less than 64 μ ($\varnothing$, 3.98) in size. In all cases the minimum in the distribution fell in the 125–86 μ ($\varnothing$, 3–3.5) fraction with broad modes occurring between 500–125 μ ($\varnothing$, 1–2) and below 86 μ ($\varnothing$, 3.5). Bimodal distribution of <1 mm fines from Apollo 16 surface soils has been noted previously (1.). Cumulative size frequency distribution plots for each sample are fairly similar. This region is also within that observed for other Apollo 16 fines in this size range.

Qualitative examination indicates variation of agglutinate content as a function of depth. If agglutinate content is proportional to exposure age then this would indicate a non-uniform rate for soil accretion. There is also a variation of agglutinate content for different size fractions of the same sample. For example, in sample 60004, 355 (approximately 38 cm depth in the core) the 250–125 μ fraction consists of almost 50% agglutinates, whereas the fraction below 64 μ contain a much lower percentage.

Besides agglutinates there are present glasses (green, yellow, brown, colorless), crystalline mineral fragments (plagioclase, pyroxene, olivine, spinel), rock fragments (predominantly anorthositic types, both shocked and unshocked), breccias and some opaque particles (metals and opaque oxides). At this time there is insufficient data to attempt comparison and correlation between these samples from 70 to 110 cm depth and those obtained from the lunar surface. However, it appears that the soil samples, less than 1 mm size, examined from core 60004, form part of a heterogenous regolith.

Basford, J. R., Coscio, M. R., Jr., Dragon, J. C., Murthy, V. R., and Pepin, R. O.: 'K–Ar Ages and Depositional Chronologies of Apollo 15 Drill Core Fines'.

Rare gas isotopic compositions and abundances, and concentrations of K, Rb, Sr and Ba were measured in suites of four grain-sized fractions of 25 mg soil samples taken from the base of each of the six Apollo 15 drill stem sections. K–Ar ages were determined from correlations of $^{40}Ar/^{36}Ar$ vs $K/^{36}Ar$ over grain-sized separates of each sample. Isotopic compositions of surface-correlated rare gases, and concentrations of spallogenic isotopes, were deduced from intercepts and slopes of ordinate intercept correlations, corrected for spallation target element variations where data were available. We limit this report to discussion of Ar data.

The distribution of K–Ar age with depth in the drill core is presented. The data are consistent with (a) a roughly uniform age of 2.9 ± 0.2 AE for the section between 65 gm cm^{-2} and 340 gm cm^{-2}, with the deep sample 15001 older at $\simeq 3.3$ AE; or (b) progressively older material at increasing depth, with the age increasing by ~ 450 m.y. down the lower 350 gm cm^{-2} of the core. Although the data are not sufficiently precise to rule convincingly between these alternatives, one central conclusion seems evident: the soils comprising the regolith penetrated by the drill string were outgassed in a major thermal event ~ 2.9 AE ago, or in a series of such events spanning a few hundred million years around 2.9 AE. Among the comparatively few soils studied by the K–Ar isochron method or by similar techniques, there is now evidence from five of the eight sampled lunar sites for large-scale thermal energy input into regolith materials during the period 2.5–3 AE ago.

Measurements of isotopic variations in Gd and Sm with depth in the Apollo 15 drill core fines have revealed smoothly varying neutron fluences which are in quantitative accord with a depositional history consisting of rapid deposition of pre-irradiated regolith, *in situ* irradiation of the section for the past ~ 450 m.y., and recent addition of a surface layer of thickness ~ 35 g cm^{-2}. We have examined the concentrations of spallationproduced ^{38}Ar as a function of depth for additional clues to the depositional chronology. $^{38}Ar_{sp}$ varies smoothly down the section. The depth dependence differs from that of the neutron fluence data. The shallower peak is entirely consistent with production by higher energy galactic-cosmic-ray secondary particles than the <0.18 eV neutrons to which Gd is sensitive, as expected.

In calculating the integrated $^{38}Ar_{sp}$ production profiles expected for various depositional models, we have assumed that the production rate of $^{38}Ar_{sp}$ vs depth is the same as that recently calculated for ^{37}Ar, to within a constant scaling factor. For the 'instantaneous deposition' model, profiles were calculated as functions of TP_s^{38} (the product of post-accumulation *in situ* irradiation time T and the $^{38}Ar_{sp}$ *surface* production rate P_s^{38}), N_0 (the concentration of $^{38}Ar_{sp}$ produced by pre-accumulation irradiation of these regolith materials, assumed constant throughout the section), and t_s (thickness of a possible surface slab of regolith deposited very recently at the drill core site). Calculated porfiles converge strongly to the measured profile for $TP_s^{38} \rightarrow 28 \times 10^{-8}$ ccSTP g^{-1}, $N_0 \rightarrow 15 \times 10^{-8}$ ccSTP g^{-1}, and $t_s \rightarrow 45$ g cm^{-2}. There are no fits for the cases $N_0 = 0$ and/or $t_s = 0$. P_s^{38} was estimated by assuming that a typical sampled lunar soil has been irradiated at or above a regolith depth of ~ 1 m; the average $^{38}Ar_{sp}$ production rate $\langle P^{38} \rangle$ is then $\cong 1.93 P_s^{38}$, deduced by integration over the ^{37}Ar production rate profile to this depth. The calculation is insensitive, within comparatively wide limits, to the choice of maximum irradiation depth: $\langle P^{38} \rangle$ is within 10% of $1.93 P_s^{38}$ for depths ranging from 30–150 cm. $\langle P^{38} \rangle$ was taken equal to 1.69×10^{-8} ccSTP g^{-1} (Ca)-m.y., the average measured production rate in ~ 50 Apollo 11 and 12 soils. P_s^{38} is then 8.8×10^{-9} ccSTP g^{-1} (Ca) $-$m.y. $= 6.25 \times 10^{-10}$ ccSTP g^{-1} $-$m.y. for the drill core samples. With this choice, the *in situ* irradiation time for the lower ~ 370 g cm^{-2} of the drill core is $T = 450 \pm 25$ m.y., where the error reflects the convergence of the calculated and measured profiles it does not include uncertainty in P_s^{38}, which may be larger.

Other depositional models are in agreement with measured $^{38}Ar_{sp}$ profile. One we have considered in detail involves steady accretion of initially unirradiated regolith at a rate ϱ g cm^{-2}-m.y. to a depth ~ 40 g cm^{-2} below the present surface, followed by *in situ* irradiation of the accreted section for time T, and recent deposit of the final surface layer. Here, the best fit of calculated and measured profiles yields $\varrho = 2.7$ g cm^{-2}-m.y. ($T_{accretion}$ ~ 150 m.y.) and $T = 520$ m.y. Similar (but not identical) models have been shown to satisfy the neutron fluence data as well.

For instantaneous deposition, the detailed histories of the Apollo 15 drill core fines as separately described by model fits to measured neutron fluence and Ar spallation profiles are in impressive agreement. An important element in these coherent chronological descriptions is the fact that the depth dependencies of the two measured profiles are sufficiently different that no reasonable probability remains that either profile results from the fortuitous juxtaposition of variably pre-irradiated depositional layers in the core section. It seems clear that the lower 370 g cm^{-2} of the core material has experienced no significant vertical mixing for $\geqslant 450$ m.y.

Lindsay, J. F.: 'Depositional Processes on the Lunar Surface'.

Introduction: Surface and shallow core samples returned by the Apollo missions suggest that the lunar soil is not a static deposit but is a continually evolving sedimentary body. In the following paper a series of samples from the Apollo 15 deep drill is examined in an attempt to understand the transporting mechanism and its effect on the nature of the lunar soil. Grain size data from Apollo 17 samples are also compared with data from earlier missions in order to determine the nature of erosional processes on the Moon's surface.

Stratigraphic Layers: The thickness-frequency distribution of the 42 stratigraphic layers in the Apollo 15 deep core is bimodal with the strongest mode at 1.0 to 1.5 cm and a second weaker mode at 4.5 to 5.0 cm. This implies that: first the impact events which constantly rework the lunar soil are, for the most part, small. Second, the major mode at 1.0 to 1.5 cm suggests that thinner morphologic units are destroyed by continuous micrometeorite reworking of the surface layers. Finally, unless there are observational errors, the meteorite energy frequency distribution may be bimodal.

Grain Size: Both normal and reverse grading were observed in some stratigraphic layers during dissection. The layers studied here are not regularly graded but there are enough similarities in the grain size data to suggest that the grain size distribution is being modified in a regular manner by a process or processes. For example, Units 002-VI and 002-X are similar in thickness and in both cases a major inflection is present in the curves of their grain size parameters at between 2 and 3 cm below their upper boundaries. Likewise weaker inflections appear in the curves for unit 002-IVE.

Evidence of base surges is abundant in the textures of the soil breccias and some Apollo 16 soils. Particles transported in a base surge are fluidized by the upward flow of escaping gases. The settling velocity (under Stokes Law) of the particles is determined by their size or more precisely their radii squared and to some extent their shape. Thus larger more spherical particles tend to move towards the base of the flowing mass of debris and produce normally graded deposits. The supply of fluidizing gases is not necessarily in any direct proportion to the momentum of the base surge with the result that one of two things may occur. If the gas supply is abundant fluidization will continue until the base surge comes to rest and a normally graded depositional unit will result. If, on the other hand, the gas supply is limited the base surge may collapse rapidly before the flow has completely come to rest. In this situation fluidization will cease and inertial grain flow will dominate. Bagnold has shows that at a given shear stress the dispersive pressure in inertial grain flow is a direct function of the square of the diameter of the particles and that larger particles will tend to migrate to regions of least shear strain. That is, they will tend to migrate towards the top of the flow and produce reverse graded depositional units. The three units studied appear to have undergone some inertial grain flow just prior to coming to rest with the result that concentrations of larger particles occur in the middle of the unit.

Uniformity of Sedimentary Processes: Grain size data have been gathered using standard methods for Apollo 15, 16 and 17 soil samples. This allows the soils from three sites to be compared directly. A Students *t*-test (5% level of significance) indicates that there is no significant difference between pairs of sites for the man, standard deviation and skewness. The soils are all poorly sorted and coarse skewed. Kurtosis values for the Apollo 15 and 17 missions are from the same populations, however, the Apollo 16 soils have kurtosis values which are significantly smaller than for the other two sites.

A strong linear relationship exists between the mean and standard deviation of soils from both the Apollo 15 and 16 sites. The two regression lines parallel each other but the intercept of the Apollo 16 regression line is somewhat smaller. The displacement of the regression lines may be connected with the fact that the Apollo 16 soils are generally from older surfaces. The constant slope of the regression lines suggest that uniform depositional processes were active at the sites. Apollo 17 data are not complete enough to establish a regression line, however, the points fall close to the Apollo 15 and 16 regression lines indicating that a similar relationship exists. Overall the data from the three widely spaced sites are consistent with there being a very uniform set of erosional processes active on the lunar surface. This suggests that if vulcanism ever played a significant role in soil formation the randomness of its effects has since been obliterated by the long term homogenizing effects of meteorite impact.

Gold, T., Bilson, E., and Baron, R. L.: 'Optical Properties of the Apollo 15 Deep Core Samples'.

The albedo of 17 powder samples from the Apollo 15 deep core tube was determined. The position of these samples ranged from 15 cm to 108 cm depth from the top of the core.

Due to the minute quantities of core samples available, the reflectivity measurements were made with very small (4 mm in diam) sample surfaces. In order to increase accuracy, every measurement was repeated with 3 different sample orientations and the data points represent the arithmetic average of these measurements. The upper and lower limits are also shown. The different curves connect data points obtained with different sample preparation methods. The albedo at 0 cm depth is that of a typical Apollo 15 surface sample, the top of the core sample not being available.

If we take the results obtained with the loosely compacted sample, (perhaps the closest to the actual lunar situation) we find the albedo varies between 9.3% (at 15 cm depth) and 15.2% (at 63 cm depth) and that this variation is a seemingly random function of depth.

It is also remarkable how sharply the albedo changes with a small change in depth. At 63 cm depth, for example, the albedo is 15% whereas at 63.5 cm it is 12.7%. This again, as we pointed out earlier, indicates the existance of a surface transportation mechanism which is capable of depositing a very thin layer of soil without mixing it with the underlying layer.

The minimum cosmic ray track density counts (according to Fleischer and Hart) in samples of one core tube section, along with our albedo results, was plotted. These curves indicate a rather striking positive correlation between track density and albedo, suggesting that different layers had suffered a different history of surface exposure related to the darkening process. Comparisons of different regional samples had also suggested a relationship, but of the opposite sign. This is not necessarily in conflict, since many situations can be envisioned where such a correlation, if it exists, can be of either sign. It is clear that a further study of this relationship would be most interesting both with surface and core samples.

Arnold, J. R., Finkel, R. C., Honda, M., Imamura, M., Kocimski, S. M., Kohl, C. P., and Nishiizumi, K.: 'Cosmic Ray Produced Mn and Be Radionuclides in the Lunar Regolith'.

Once the depth profiles for the various effects produced by high energy particle bombardment of the undisturbed lunar surface are measured and understood, they can be used as probes for the rates of surface processes, in particular of the mixing of the lunar regolith. The long-lived radio-nuclides are especially useful because of their well-established timescales.

Mn^{53} ($t_{1/2} = 3.7 \times 10^6$ yr) is the most important of these. It is measured using a sensitive neutron activation technique which allows us to obtain activities using fairly small samples. The fact that it is produced mainly from Fe eliminates complicating effects due to variations in the chemical composition of different samples. Measurements have been made on a series of samples taken from the ends of sections of the Apollo 16 drill stem. These measurements agree very well with our earlier data for the Apollo 15 long core and like our Apollo 15 measurements are in good agreement with the theoretical activity profile calculated using the model of Reedy and Arnold. Thus it appears that the lunar regolith at the sites of both the Apollo 15 and 16 long cores has been undisturbed on a meter scale for the past five million years. According to a Monte Carlo model of mixing by meteoritic impact, being developed by one of us (J.R.A.), mixing of the lunar surface in times comparable to the Mn^{53} half-life (using present-day bombardment fluxes) has usually been confined to a depth of the order of centimeters. The Mn^{53} data are consistent with expectations on this model and also with evidence from other properties, such as Gd isotope anomalies. One section (60005) of the Apollo 16 drill stem was not completely full when returned from the Moon. It was not known if material had been lost from this section or if the drill stem had not been completely filled and some of the material had slid up creating a gap. The Mn^{53} activities we measured give a better fit with the previous profile if $\sim$ 180 g of material is assumed to have been lost from section 60005.

Mn^{53} was also measured in soil sample 63321, a 'permanently shadowed' soil. The high activity of Mn^{53} indicates that it was not shielded from cosmic-ray bombardment to an appreciable extent.

Various cosmogenic radionuclides were measured in Apollo 17 trench soils 78481 (0–1 cm depth) and 78421 (10–25 cm depth). Included were Fe^{55}, Al^{26}, Na^{22} and Be^7. These nuclides have high activities in the surface sample reflecting the intense solar flare of August 4, 1972 and decrease to the expected values for GCR bombardment in the deep sample.

The ratio of the production rates of the radioactive Be isotopes (Be^{10}, 1.5×10^6 yr; Be^7, 53 days) is of interest for lunar studies and also for broader reasons. For example, it enters into the question of the mean lifetime of 'galactic' cosmic rays. Because the production rates depend similarly on the energy of the bombarding particle, and because the GCR flux appears to have been constant, the observed activity ratio should be close to the production rate ratio. The direct measurements of the French group suggest a ratio close to 0.08. Radiochemical measurements have given a much higher value. Correction for the new Be^{10} half-life reduces the radiochemical ratio to about 0.15. Our measurements of the ratio in an Apollo 17 trench soil 78421 (10–25 cm depth), and also in the chondrite Canon City, give values close to 0.14. It appears that either the radiochemical measurements are more accurate, or the assumptions are violated. Dependence on the nature of the bombarding particle (proton or neutron) may be important.

Fireman, E. L.: 'History of the Lunar Regolith from Neutrons'.

A statistical model for regolith development based on calculated neutron capture rates and Sm and Gd isotope measurements is used to: (1) obtain soil mixing and deposition rates from measurements of the Sm and Gd isotopes in the Apolla 16 and 15 drill stems, (2) relate parameters of meteor-impact calculations to those of neutron capture calculations, and (3) answer the question of whether the moon is gaining or losing mass by meteor impacts.

It is conceivable that the lunar regolith cannot be treated statistically for any period of time; then the Sm and Gd measurements are essentially useless. All data could be fit by the deposition of properly preirradiated lunar material without any restriction on the deposition times. On the other hand, if it is possible to define a time of statistical applicability, then the data can be made very meaningful. This time can be set by two quantities: (1) the ratio of the capture rate in Sm^{149} to that in Gd^{157} and (2) the Gd^{158} enrichment at one depth. If the ratio of the calculated capture rates, $\langle Sm^{149}/Gd^{157}\rangle$, is the same as the ratio of captures that have occurred, then the calculated capture rates can be used back to when the initial Sm and Gd isotopic abundances were primordial. If, however, the ratio of capture rates differs from the ratio of captures that have occurred, then the calculated capture rates apply only for a shorter time.

The number of neutron captures, $C(x_0)$, occurring in an isotope currently at depth, x_0, is related to the capture rate, R, by the equation

$$C(x_0) = \int_0^D R(x)\, t(x, x_0)\, \mathrm{d}x, \qquad (1)$$

where $t(x, x_0)\,dx$ is the time that the material currently at x_0 spends between x and $x+dx$, and D is the soil thickness. The irradiation time, T, is related to $t(x, x_0)$ by

$$T = \int_{0}^{D} t(x, x_0)\,dx. \tag{2}$$

If no soil deposition occurs, then T is independent of x_0, otherwise, generally not. The present (Gd^{158}/Gd^{157}) ratio is related to the initial ratio, $(Gd^{158}/Gd^{157})_i$, by

$$(Gd^{158}/Gd^{157}) = \frac{(Gd^{158}/Gd^{157})_i + \int_0^D R(x)\,t(x, x_0)\,dx}{1 - \int_0^D R(x)\,t(x, x_0)\,dx}. \tag{3}$$

The expression for $t(x, x_0)$ and the boundary conditions necessary to determine (Gd^{158}/Gd^{157}) as a function of depth in (3) can be supplied by a model of soil development. Conversely, some of the parameters in this model can be determined by use of (Gd^{158}/Gd^{157}) measurements in Equation (3).

The deepest samples recovered in the Apollo 15 and 16 drill stems were at 230-cm depth. We therefore chose the bottom boundary in our model of soil motion to be slightly larger, i.e., 250 cm. In our model, soil currently at x_0 spends approximately equal times at depths between $250-Y(x_0)$ and 250 cm. The time distribution, $t(x, x_0)$, is a square wave; essentially identical results are obtained when $t(x, x_0)$ is a gaussian with width, $Y(x_0)$. With the square waveform for $t(x, x_0)$,

$$T(x_0) = \frac{[(Gd^{158}/Gd^{157})_{Meas} - (Gd^{158}/Gd^{157})_i]\,Y(x_0)}{[1 + (Gd^{158}/Gd^{157})_{Meas}]\int_{250-Y(x_0)}^{250} R\,dx}. \tag{4}$$

The irradiation time, $T(230)$, is assumed to be the minimum time for the occurrence of the deposition of a thick soil blanket (>250 cm). This minimum time occurs when $Y(230) = 150$ cm. Since h is defined to be the median depth that has turned over once, $h = x_0/2$ when $Y(x_0) = 250$ cm. The irradiation times at shallow depths are affected by the net balance of irradiated and unirradiated material that leaves and enters the surface. By use of mass balance requirements, the mixing, deposition, and escape rates are determined. The average escape rate of 80 g cm^{-2} aeon can replace the condition of constant soil thickness at the sites to obtain the second approximation to the average mass escape rate from the moon in an iterative approach. If estimates of meteor mass influx rates based on soil composition are used, then the moon is losing rather than gaining mass.

Woolum, D. S. and Burnett, D. S.: 'Lunar Neutron Capture Rates and Surface Mixing of the Regolith'.

The Apollo 17 Lunar Neutron Probe Experiment (LNEP) was performed in order to provide *in situ* lunar surface data on (a) the absolute rates of low energy neutron capture as measured in ^{235}U and ^{10}B targets, (b) the depth dependence of these rates down to 2 m and (c) the neutron energy spectrum by measuring Cd absorption and by measuring the amounts of $^{80,82}Kr$ produced by neutron capture on $^{79,81}Br$ (data to be reported by Marti and co-workers). All of the above objectives were accomplished. Although we are in the last phases of data processing, the results on ^{10}B capture given here should be regarded as preliminary. However, the ^{235}U fission data have been completely analyzed.

Fission track densities from mica detectors at 8 different depths have been converted, using laboratory calibration data, into ^{235}U fission rates. For comparison the theoretical fission rate profile of Lingenfelter *et al.*, (LCH) multiplied by a factor of 0.89, is given. No adjustment of the depth scale of the theoretical profile has been made. The LCH curve has been corrected for the difference in galactic cosmic ray intensity between the Apollo 17 mission and the average of the last solar cycle. The error bars on the data points indicate relative errors only. The uncertainty in the absolute fission rate scale is about ±10% (standard deviation); consequently, there is good agreement between the depth dependence of the theoretically predicted and experimentally obtained fission rate profiles.

The depth dependence of track densities in TN cellulose triacetate plastic which was exposed to the

^{10}B targets is calculated. No corrections have been applied to the data as yet and the errors are one standard deviation calculated purely from counting statistics. In this case, we have normalized the theoretical capture rate profile to the data point at 140 g cm^{-2}, near the peak in the profile. The shape of the theoretical profile is a reasonable description of the trend of the data points. There is more scatter in the data than was the case for the ^{235}U. Some of the scatter may represent variations in the efficiencies of individual detector positions, for which corrections have not yet been applied, but it also in part reflects difficulties in long term counting reproducibility of the short, low density tracks in the plastic detectors. Nevertheless, the correspondence of the shapes of the experimental and theoretical profile indicates that the depth variation of lunar neutron capture rates is relatively well known for the purpose of interpreting lunar sample data.

Based on calibration data, the absolute ^{10}B capture rate is about 2/3 of that calculated by LCH. Additional data processing will be carried out to check this preliminary result but the difference in the experimental and theoretical rates, although not large, appears to be significant. Our final accuracy in the measured ^{10}B capture rate should be significantly better than $\pm 15\%$ (standard deviation). For comparison, the ^{235}U fission rate at the same depth is 0.89 ± 0.11 of the theoretical value and the ^{60}Co activity reported by Wahlen *et al.*, corresponds to 0.67 ± 0.24 of the theoretical value. The uncertainty in the absolute normalization of the theoretical calculations was estimated as $\pm 30\%$ by LCH so the overall agreement in all experimental capture rates is good although at this stage the data suggest that capture rates which are slightly ($\sim 20\%$) lower than the theoretical values should be adopted.

The LNPE contained cylinders of Cd surrounding ^{10}B – TN detectors at 180 and 370 g cm^{-2}. Cd strongly absorbs neutrons below about 0.5 eV; thus, a decrease in track density (ϱ) is observed underneath the Cd compared to the track density (ϱ_0) outside. The equivalent attenuation measured for a well-thermalized neutron flux is shown for comparison. The attenuation is much smaller for the lunar data, graphically illustrating the expected non-thermal shape of the low energy lunar neutron spectrum which is due to the significant abundances of low energy neutron absorbers in the lunar materials (Fe, Ti, REE, etc.). The lunar (ϱ/ϱ_0) ratio can be used to calculate a 'Cd ratio' of the total density (n/cc) of neutrons (for energies from 0 to $\sim$ 10 eV) to the density above 0.5 eV. Cd ratios of 2.1 ± 0.2 and 2.7 ± 0.4 at 180 and 370 g cm^{-2}, respectively are obtained, which can be compared to the theoretical values of 2.7 and 2.9 at similar depths. Although the experimental ratios require further confirmation, it appears that: (a) the LCH spectrum has an excess of low evergy neutrons, as also inferred from the relative capture rates of ^{149}Sm and ^{157}Gd in lunar samples, and (b) the increase in the fraction of neutrons below 0.5 eV with increasing depth may be somewhat larger than predicted theoretically.

The overall good agreement between the LNPE results and the LCH calculations shows that lunar neutron capture processes are relatively well understood and that previous interpretations of the neutron capture data obtained from lunar samples should be reliable. Because of differences in the actual and theoretical energy spectra, additional consideration must be given to the uncertainties in the critical ^{157}Gd capture rate which is quite sensitive to the shape of the spectrum below 0.2 eV. It is still possible that the LCH capture rate for ^{157}Gd may be high by as much as 40%, although even a change of this amount would not drastically alter previous conclusions.

As discussed previously neutron fluences calculated for surface soils from Gd isotopic data are low compared to those expected for a well-mixed regolith using regolith depths reported from field observations or active seismic data. Our results show that this 'neutron deficit' cannot be due to inaccuracies in the theoretical capture rate profiles used previously. Either (a) the regolith has not been uniformly mixed over a 10^9 yr time scale and progressively more irradiated material is located at the base of the regolith than at the surface, (b) the average cosmic ray flux striking the lunar surface was less in the past 10^9 yr than at present by a factor of 2–3, or (c) the regolith depths inferred from field or seismic data are low by factors of 2–3. Alternative (a) is reasonable if most of the Gd found in surface soils is the result of a relatively recent (within $\sim 10^9$ yr) deposition of previously unirradiated (preferably Gd-rich) material and has only been mixed through the upper few meters. The similarity of the required properties of the deposit to those of Apollo 12 KREEP make this model attractive for this site, but it is then puzzling why the fluences are similar for surface soils from all missions. This similarity can be explained if the depth through which the Gd-rich surface deposit has been mixed by subsequent small scale impacts is correlated with the time of deposition, i.e., older deposits have been mixed deeper. A ratio of depth of mixing to deposition time (i.e., a surface mixing rate') of $\sim$ 1 m 300 m.y.$^{-1}$ can account for the observed fluences.

Arrhenius, G. and Asunmaa, S. K.: 'Adhesion and Clustering of Dielectric Particles in the Space Environment. 1. Electric Dipole Character of Lunar Soil Grains'.

Introduction. Exposure to space environment causes the lunar soil surface particles to adhere to each other forming grain clusters with low bulk density. This phenomenon is likely to be of general improtance for aggregation of grains in space now and in the preplanetary history of the solar system. Our previous investigations have shown the adhesion forces to be electrostatic and due to persistent internal polarization.

The purpose of the present research is to clarify experimentally the detailed nature of this phenomenon, to measure the magnitude of the attractive force between individual grains and to interpret the results in terms of particle behavior on the Moon. During exposure to corpuscular radiation primarily from the Sun, the grains have been subjected to structural disordering and charge along the tracks of penetrating ions and to deposition of mass impurities and charge at the end of the paths of implanted ions. Local charge accumulations so obtained are likely to become polarized even in low intensity fields such as the Moon's sunlit side.

Comparison of the electrostatic adhesion in top and bottom strata of the Apollo 12 double core where the age relationships are approximately known show that the adhesion although perceptibly decayed, still persists after burial times estimated to be of the order of 10^7 yr.

Objectives and achievements. The primary objectives of the present investigation have been:

(1) to determine magnitude of dipole moments of individual grains.

(2) to compare the dipole characteristics before and after removal of mobile surface charges in order to distinguish between surface polarization and internal dipole.

(3) to establish dependence of dipole strength on parameters such as mass, composition and structure of the grains.

(4) to examine changes in dipole strength induced by stepwise removal of the surface layer of irradiated grains.

Techniques have been developed for two independent approaches for measurement of dipole moments. First, using a dynamic technique, grains in free fall in vacuum were subjected to electrostatic attraction in an axisymmetric field. In the other technique, the volume polarization of the lunar dust was examined under static conditions. The dielectric constant of powder samples is being determined in a paraffin matrix under two conditions (a) grains in random orientation; (b) the grains electrically aligned with respect to field lines in an homogeneous electric field. New experimental devices have been constructed for both techniques.

Two independent techniques have also been used for elimination of surface charges. In one approach thermally stimulated discharging by infrared heating was employed. As a complementary technique, the most heavily irradiated surface layer was removed by treatment with dielectric solvents. The effect on the dipole strength of the removal of a 500–1000 Å layer was examined in individual grains as well as in bulk powder samples.

The axisymmetric electric field for measurement of dipole moments. The principal components of the device for examination of grain behavior in free fall in a non-homogeneous electric field are a central wire electrode (10 μm diam) at potentials up to 2000 V and a field limiting brass cylinder at ground potential. The potential distribution in the field is shown. The grains are introduced into the field through an aperture at a distance of 0.3 cm from the field axis. The device is operated in a vacuum of 10^{-5} Torr with external contacts for the high voltage and a vibrator in contact with the grain supply funnel. Optical and scanning electron microscope techniques were employed for identification and measurement of grain dimensions and locations on the wire electrode at sites of contact where the grains remain adhered.

The behavior of Apollo 17 soil grains in the electric field was compared with that of terrestrial augite of similar particle size.

Dipole moments of lunar grains in Apollo 17 soil. The logarithmic correlation between dipole moment and grain mass in sample 78501.14 is shown. The dipole moments range from 10^9 to 10^{13} D (1 D $= 10^{-18}$ esu). Similar distributions are found for samples 75081.63, 72501.14 and 75810.53.

The scatter of dipole moments around the least square average curve *AB* is probably due to differences in grain composition, structure, irradiation history and geometry. The estimated experimental errors are small compared to this scatter. The experimental data are discussed in a companion paper.

13. Characterization and Evolution of the Mare Basins: III

Eggleton, R. E., Pike, R. J., and Schaber, G. G.: 'Photogeologic Detection of Surfaces Buried by Mare Basalts'.

Lunar main-sequence craters are sufficiently abundant and geometrically systematic so that most of the geometric characteristics of an individual crater can be predicted fairly accurately from very limited observations of its geometry, e.g., a rim-crest diameter. The predictions are based on statistical studies of crater morphology. An important application of this is the detection of surfaces covered by mare basalts. A surface exposed to the flux of interplanetary debris for a significant interval collects a substantial population of craters. For a given exposure interval there is a range of subsequently covering basalt thicknesses which will partially obscure the larger craters on the covered surface and completely obscure the smaller ones.

For example, in a 160000 km^2 area of northern Oceanus Procellarum, Eggleton and Smith mapped about 50 craters 1 to 20 km in diam partly obscured by mare basalt. Schaber (1969) mapped 14 similar craters in northwestern Mare Imbrium. The most thoroughly obscured craters on a covered surface, which are still detectable, are completely covered by basalt but produce a low raised ring on the mare surface apparently formed by differential subsidence of the mare surface. The diameter of the crest of the raised ring can be measured and from it the height of the covered crater rim can be estimated from the morphologic statistics on non-covered craters. The rim heights are the order of 1/20 of the crater diameter or about 50 to 75 m for the small, barely covered craters in northern Oceanus Procellarum and 75 to 100 m in northwestern Mare Imbrium. The basalt covering the crater rim crest represents an uncertainty in the estimate of the total thickness of basalt covering the crater. The cover over the rim crest is probably only a few meters thick or about 5% or 10% of the total thickness. The relief on the telltale ridge on the mare surface is also of this order so that the thickness of basalt cover in intercrater areas is probably within one or a few percent of the original rim heights of the barely covered craters.

Two other types of covering, in slightly larger craters, also indicate intercrater depths of cover closely comparable to the rim height of the partly obscured craters. Craters that are barely larger than those described above have their rims entirely covered but their interiors only partially filled in with basalt; for example, to 1/3 to 2/3 their original depths. The flooding of the interiors probably took place locally at one or more low places in the rim crest, perhaps only during a flood stage of the flow of lava, and ceased before filling of the interior was completed. Slightly larger craters show no apparent filling by basalt but also lack any rim that remains uncovered.

All larger craters have some fraction of their rim height covered. Statistical knowledge of the radial crater-rim profiles permits estimation of thickness of covering basalt in these cases.

Probably the simplest model for interpretation of the data is that in a local region such as a mare basin, Serenitatis, for example, the partly obscured craters were all formed on the same surface and then were rapidly covered to some higher level so that few craters (or none) which formed at intervening levels will be detected. Areally systematic patterns of thickness variation may then be expected. More than one buried, long-exposed surface in an area may be searched for. Buried surfaces of mare basalt and terra plains rubble and/or breccia deposits will be fairly flat and level, but ultimately the essentially plane-layered sequences will lie on an irregular, rough, highly cratered terra 'basement' surface.

Where there is sufficient data for the estimation of the crater population on the buried surface, the thickness of the associated regolith may also be estimated. Simple populations of individual lunar craters may be interpreted as composed of impact craters possessing a range of large sizes dominated by primary impact craters, an intermediate size range dominated by dispersed secondary impact craters, and a range of small sizes in a steady state in which craters are destroyed at the same rate at which they are produced. In the large and intermediate ranges, the population density increases with time. An observation of part of the population in the large or intermediate size range, for instance in a population of mare-flooded craters, permits the estimation of the completely buried remainder of the population. Furthermore the characteristics of the associated regolith may be estimated – in particular the thickness, which is especially significant for the development of models of stratigraphic sequences.

Young, R. A., Brennan, W. J., and Nichols, D. J.: 'Stratigraphic Variations Beneath Lunar Mare Surfaces as Indicated by Ejecta Characteristics of 0.5 to 2 km Craters'.

The increasing evidence for the complex volcanic history of the lunar maria and of the rapid decrease in impact flux prior to and during mare flooding suggests the following: (1) the maria were almost certainly filled by a series of volcanic flows of different thicknesses and dimensions, (2) during this time interval some of the circular maria must have been undergoing tectonic adjustments and may at first have looked much like Mare Orientale, and (3) the rapidly decreasing impact flux probably formed variable thicknesses of regolith and ejecta deposits on each new extrusive sequence. The gradual filling of the lunar maria would have proceeded so that: (1) the lowest depressions within the maria were probably filled first, producing larger, more level, uniform surfaces for younger deposits, and (2) the later stages of filling were characterized, in part, by more extensive, thinner flows which could have covered increasingly wider regions. The filling of initially uneven areas over different time intervals by flows of varying thicknesses and areal dimensions would give rise to basically different stratigraphic sequences in different regions (within or between individual maria). Each mare region must therefore be underlain by a different sequence consisting of layered flows, ejecta from large impacts, and regolith zones formed between episodes of volcanism.

Postmare impacts which penetrated these different regional stratigraphic sequences should have produced exposures of layering in crater walls and ejecta deposits characteristic of each subsurface stratigraphic section. It appears that for craters larger than a few kilometers in diameter, the effect of the impact process on the 'typical' mare stratigraphic sequence has been to homogenize the ejected debris to the extent that differences between crater ejecta blankets are not always obvious. In addition, the fractured nature of the crater wall materials makes tracing of individual layers for extended distances difficult. The uniformity of the ejecta deposits may be the result of impact penetration through many layers which are thin in comparison with the crater dimensions.

Recent Apollo panoramic photography (with resolution approaching 10 m) provides the first extensive lunar coverage which permits uniform, detailed regional comparisons of crater ejecta characteristics for craters in the 0.5 to 2 km diam size range. Since these small craters represent penetrations of a smaller number of subsurface stratigraphic units, their ejecta deposits would be more likely to show differences resulting from excavation of only a few, possibly dissimilar near-surface units.

Evidence supporting this hypothesis can be seen in the consistent differences among the ejecta deposits of small craters across Mare Imbrium and Mare Serenitatis. Generally speaking, small craters are conspicuously more blocky in southeastern Serenitatis than in southern Imbrium. Terrestrial explosion studies suggest that blockiness may be greater either where impacts penetrate through surface flows and the energy produced is directed laterally into less coherent subsurface layers, or where surface flows are more conspicuously jointed.

Another conclusion resulting from these observations is that conspicuous blockiness is not always produced by impacts in lava flows at or near the lunar surface. For example: craters in the Imbrium flows northeast of Lambert or near rilles such as Hadley and others (presumed to be collapsed lava tubes or channels which would indicate flows near the surface) are not as blocky as the craters on the older (more densely cratered) surface of southern Serenitatis. Portions of Serenitatis exhibit a greater blockiness for 0.5 to 2 km diam craters in all stages of degradation.

Therefore, it appears that blockiness by itself is not a reliable criterion for crater age, for speculations on depth to rock, or for determining the volcanic vs impact origins of small craters. Crater parameters are more likely to be a function of stratigraphic differences on a local or regional scale where impact penetration of 2 or more different units has occurred.

The comparison of crater characteristics in the 0.5 to 2 km size range may be a useful tool for delineating major near-surface stratigraphic variations across mare surfaces, which are not apparent from crater density distributions, or which might be masked by surface color changes related to minor surface events. Exposure of blocky (crystalline) material in the craters should provide suitable targets for Earth-based, near-infrared spectral reflectance studies of subsurface mineralogical variations in the lunar maria.

Boyce, J. M., Dial, A. L., and Soderblom, L. A.: 'Relative Ages of Lunar Nearside Plains'.

A study was conducted to map the distribution of mare and light plains units of uniform age over the entire lunar frontside. The technique used is that described by Soderblom and Lebofsky and Boyce and Dial which involves a quantitative determination of the 'softness' of craters. 'Softness' is quantitatively defined as a maximum slope of the interior wall. The softness of all craters of a particular diameter is expressed as a ratio of craters with unshadowed interiors to those without. An erosion model developed by Soderblom is used to reduce this information to estimate the total areal accumulation of small impacts which have eroded these craters. The erosion is caused by both primaries and background secondaries, the latter being the more predominant. The smoothing is effected by craters much smaller than the eroded craters. Hence, the eroding craters are so abundant that they have saturated the surface several times over and statistical error produced by secondary swarms are averaged out. This is not true for most cratercounting techniques. Boyce and Dial developed a procedure for using this technique as a mapping tool and applied it to a limited set of Apollo 17 metric photographs. The results presented in this study are based on all available photographs and provide a preliminary distribution and sequence of emplacement of volcanic units throughout the lunar frontside.

The results indicate that the light plains deposits (i.e., Cayley Formation) pre-dates the emplacement of the maria. In general, the mare basalts decrease in age westward. This probably accounts for the uniformity in antiquity of the Apollo basalts as Apollo tended to land in the eastern frontside. The oldest lunar maria sampled is Mare Tranquillitatis. The large ring-mare (Mare Serenitatis, Mare Imbrium and Mare Humorum) were next filled with lavas like the Apollo 15 basalts during the period between 3.3 to 3.5 b.y. ago. Finally, a series of young flows invaded the western maria (Oceanus Procellarum); a few patches were superimposed on southwestern Mare Imbrium, northern Mare Humorum, and northwestern Mare Serenitatis. These young units may have crystallization ages as 2.0 b.y. based on current knowledge of the lunar flux history.

Stettler, A., Eberhardt, P., Geiss, J., Grögler, N., and Maurer, P.: 'Sequence of Terra Rock Formation and Basaltic Lava Flows on the Moon'.

A general time-scale of lunar rock formation has been established by radiometric dating. In broad terms there are two immediate problems concerning this time-scale which are still largely unresolved:

(a) Does the clustering of terra rock ages reflect a lunar cataclysm in the sense that a substantial fraction of the maria was excaved in a relatively short time interval ~ 3.95 AE ago, or is the clustering observed because the last 2 large impacts (by the Oriental and Imbrian projectiles) have obliterated the record of earlier events at the lunar surface near the Apollo landing sites, leaving only very few traces of older rock formation?

(b) Was the filling of a mare basin accomplished within a relatively short period, or did the filling by successive lava flows last over times comparable to the interval between excavation and filling.

This paper is meant as a contribution to answering these two questions.

All highland rocks investigated in the past in our laboratory have yielder Ar^{39}–Ar^{40} ages near 3.95 AE, whenever a high or intermediate temperature plateau was found. Encouraged by the report of higher ages of small rock fragments from the neighbourhood of the Apollo 16 North Ray Crater (3) we have begun a study of rock fragments in the 2–4 mm size range collected at station 13, about 800 m from the rim of this crater. The data were corrected for trapped Ar^{40} which was determined from Ar^{40}/Ar^{36}– Ar^{39}/Ar^{36} plots. A small piece of each fragment was set a side for petrologic classification. The ages of 3 fragments lie between 3.95 and 4.00 AE, but one gives an age of 4.19 ± 0.06 AE. This age is based on a well defined plateau, and therefore it is not simply some relict from the early history of this rock, but should represent a definite period of rock formation or at least a severe metamorphic event. The exposure age of 55 m.y. for this fragment indicates a North Ray Crater origin. This crater may have excavated older material from below the Cayley layer. Age determinations on additional fragments from station 13 are in progress.

The exposure age of 1.8 m.y. of rock 65315, a B_2 breccia with anorthositic composition, indicates excavation from South Ray Crater. Taken at face value the Ar^{40}/Ar^{39} release curve implies a 2-stage metamorphism in the history of this rock. This would be in agreement with the postulate that the B_2 rocks have been brecciated and rebrecciated. The low temperature part of the release curve (~ 2 AE) would then correspond to the rebrecciation caused during formation of older craters, whereas the primary brecciation took place between 3 and 4 AE. If we assume that this event was accompanied by a very high Ar loss, then the apparent age of the last temperature step of 4.30 ± 0.26 AE could be an indication of anorthosite formation early in the history of the Moon.

Turner found a systematic difference between the Ar^{39}–Ar^{40} ages of the low-K and high-K Apollo 11 basalts. Our data confirm this. It is not clear yet whether there is a quasi continuous sequence of ages or whether there are three age groups. In either case the age pattern implies that the lava flows in Mare Tranquillitatis lasted at least 400 m. Models of Apollo 11 rock stratigraphy have been deduced from the exposure age distribution and the contents of slow neutron products. In one model the high-K basalts overlie the low-K rocks. This would fit the Ar^{39}–Ar^{40} age relation. The highest age (3.92 ± 0.03 AE, rock 10003) is very well established by measurements on whole rock and separated feldspar samples. Considering the large spread of Apollo 11 basalt ages, the fact that a rock of such a high age was found near the surface of the lava filled Tranquillity basin suggests that the latter was excavated appreciably earlier than the cataclysmic period mentioned above.

De Hon, R. A.: 'Thickness of Mare Material in the Tranquillitatis and Nectaris Basins'.

The thickness of mare filling materials in the irregular mare basins and the shelf areas of circular mare basins is estimated from partially buried craters similar to the studies of the Lansberg region by Marshall. The present analysis of the eastern maria uses improved crater diameter and rim height parameters to obtain average depth of fill in the vicinity of partially buried craters. Thickness estimates in the Tranquillitatis and Nectaris basins provide a basis for isopachus and structural contouring within the basins.

Within Mare Tranquillitatis the average thickness of mare fill is 500 to 600 m. Maximum accumulation in excess of 1200 m lies along a broad arc from Lamont, trending northeast to near the crater Jansen. Elsewhere the basin is relatively shallow throughout. The mare fill thickens from the periphery to near 900 m within the basin with local lenses greater than 900 m thick within craters. The total volume of materials filling the Tranquillitatis basin is estimated to be 262000 km^3.

The Nectaris basin is an incompletely filled multi-ringed basin. The flooded inner basin is filled with at least 1200 m of material. The maximum thickness in the center of the basin is undetermined but may not exceed 1500 to 1800 m. Between Mare Tranquillitatis and Mare Nectaris the data reveal a well-defined, deep, narrow trough. This depression is filled with material in excess of 900 m and attains a maximum thickness of over 1500 m in the region of the crater Torricelli. The volume of fill within the Nectaris basin and northern trough is approximately 85000 km^3.

Sub-basin contours retain much of the form of the surface topography, which suggests that surface elevation errors on the LAC base maps exceed the thickness of fill within the basins. As surface elevation data are improved, reliable subsurface maps will be possible. In general, the data suggest that the irregular maria are flooded by a relatively thin layer of materials. The data provide useful limits to mare fill thickness, and models of mare basalts within the irregular basins which involve thicknesses in excess of 1500 m should be considered with caution.

Adams, G. F., Brown, W. E., Jr., Eggleton, R. E., Jackson, P. L., Jordan, R., Peeples, W. J., Phillips, R. J., Porcello, L. J., Schaber, G. G., Sill, W. R., Thompson, T. W., Ward, S. H., and Zelenka, J. S.: 'The Apollo 17 Lunar Sounder Experiment: A Progress Report'.

During the past year we have been engaged in radar profile data reduction, imagery interpretation, and computer software development for production processing of subsurface data.

The elevation profiles of the Moon taken by the HF1 (5 MHz) radar during revolutions 16, 17, and 18 have been extracted from the data. The sample points along track are spaced every 50 m and have a footprint of about 2000 m each. The data are plotted with respect to the center of mass, center of figure, and with respect to a great circle fitted to the major maria.

A comparison of the laser altimeter and the radar data show good agreement over the maria. The uncertainty of the elevation profiles is approximately 100 m over the maria for the global profiles. A supplemental Doppler profiling technique has been developed that provides a relative uncertainty of less than 10 m.

The along track variation of echo strength has also been recovered and the effective dielectric constant inferred.

The high resolution VHF (150 MHz) profile-imagery has been studied in detail in the Serenitatis and Crisium basins with an aim toward interpretation of both the subtle local patterns and the general regional patterns in terms of basin deformation.

The sounder data is undergoing production computer processing for subsurface features. We have an interactive capability to select the dip angle and integration length during the subsurface data processing. During digitalto-film playback we can interactively select black and white tonal distributions for the photographic displays. We have completed processing (zero dip, 10 km integration) for the prime HF1 passes over Mare Serenitatis, Mare Crisium, and Oceanus Procellarum. There are numerous apparent or real subsurface reflections in the output data. The key issue is to distinguish real subsurface reflections from surface reflections arising from the linear surface features, principally mare scarps and ridges. For the first time we are able to look at our various data in a regional context; i.e., multiple complete passes across a mare. In particular, the availability of multiple passes aids in a geometrical separation of pervasive subsurface features from linear surface features.

During the first quarter of 1974 we have begun an intensive study correlating subsurface results with high resolution photography. The aim is to distinguish the signatures of surface and subsurface features and place the results in a geologic framework.

Kunze, A. W. G.: 'Lunar Crustal Density Profile from an Analysis of Doppler Gravity Data'.

Line-of-sight gravity residuals obtained from Doppler radio tracking data of various Apollo missions over lunar highland terrain correlate unmistakeably with major lunar topographic features. If local lunar gravity anomalies over a given region are indeed caused entirely by topographic inequalities, then these anomalies should reflect crustal densities and density gradients sampled by crustal topography. The present study investigates the usefulness of planetary gravity anomalies as a remote sensing tool for the determination of crustal density gradients.

Line-of-sight gravity observations are valid estimators of radial (vertical) gravity components only near the center of the lunar disk. Consequently, in this study, available line-of-sight gravity data were converted to radial gravity components over selected lunar highland regions utilizing a method similar to the equivalent source technique used in geoexploration. The resulting equispaced radial gravity net was normalized to an altitude of 20 km above the lunar surface. As expected, the larger lunar craters are clearly associated with pronounced negative gravity anomalies. However, highpass filtering of the gravity data revealed almost no additional anomalies that could be correlated with smaller craters. Smaller features are apparently beyond resolution due to noise either present in the data or introduced by conversion and filtering operations.

The gravity anomaly produced by a crater shaped mass (or mass deficit) of radius R is similar to that of a disk shape of the same radius and of thickness t, where t is one half of the crater depth, and is given approximately by

$$\Delta g = 2\pi \cdot G\bar{\varrho} \cdot t \cdot (1 - H/\sqrt{H^2 + R^2}).$$

G is the gravitational constant, $\bar{\varrho}$ is the mean density of the disturbing mass, and H is the height of observation. Solving for $\bar{\varrho}$ yields

$$\bar{\varrho} = \Delta g \cdot \sqrt{H^2 + R^2} / 2\pi G t \cdot (\sqrt{H^2 + R^2} - H).$$

This expression indicates the mean crustal density corresponding to a given negative anomaly for a given crater geometry.

Sjogren, W. L., Wimberly, R. N., and Wollenhaupt, W. R.: 'Apollo 17 Gravity Results'.

Reduced radio tracking data from the Command and Service Module (CSM) during ten orbits just prior to the Lunar Module descent (20 km periapsis altitude) reveal gravity information for Grimaldi, Copernicus, Mare Procellarum, the Appenines, Mare Serenitatis, Littrow and Mare Crisium. These line-of-sight velocity data, produce a band of gravity contours approximately 60 km wide from 70° W long to 70° E long. The areas of redundant coverage with the Apollo 14, 15 and 16 missions agree to 10 mgals or better.

Various models were tested to match the gravity profile for Grimaldi, Copernicus and Mare Serenitatis.

The gravity anomaly for Copernicus is just the opposite of Grimaldi in that it is negative and consistent with some twenty other crater anomalies. Again various solution results are shown in comparison with the real gravity profile. Notice that the point mass estimate (0.3 km radius) could not produce gradients steep enough to match the real data. A fairly good match was obtained when three masses were estimated. One mass was placed in the optical center of Copernicus while the others were placed in the rim deposits where the trajectory crossed over them. The mass deficiency is 3.24×10^{16} kg. If one uses Baldwin's dimensions of Copernicus and computes a volume for the crater, a density of 3.57 g cm^{-3} is obtained. To reduce the density to 3.00 g cm^{-3}, there must be a 550 m increase in crater depth, a 0.6×10^{16} kg error in the mass, or a combination. The first two inferences and possibly the third seem to be outside known error bounds. This implies that the lunar crust to a depth of 3 km has a density near the average lunar density of 3.34 g cm^{-3}, say closer to 3.10 g cm^{-3} than 2.90 g cm^{-3}.

A prediction for the Apollo 17 Mare Serenitatis anomaly was made from the best Apollo 15 model. The prediction was 40% too small. This inconsistency was resolved when gravity contours were obtained from the Apollo 15 subsatellite data that revealed two peaks in the Serenitatis anomaly. The Apollo 17 gravity profile was fit very well with a 221 km radius surface disk located at 22.9°N and 18.6°E, consistent with the lower peak. The mass solution yielded the same loading per unit area as the Apollo 15 data. The Mare Crisium gravity profiles from Apollo missions 15 and 17 agreed very well for their trajectories passed over essentially the same area of the basin.

The Apollo 17 landing site at Littrow was gravity sampled by a surface gravimeter which read $162{,}695 \pm 5$ mgals. The absolute gravity at the landing site (1734.8 km from center of gravity) for a completely homogeneous sphere would be $162{,}908 \pm 6$ mgals. This implies a -213 ± 8 mgal anomaly. The results from the orbital data show a -205 ± 10 mgals anomaly – very consistent with the surface gravimeter. Sources other than those in the data itself which can contribute 20–40 mgal variations are the absolute elevation (19 mgals/100 m), local topography, and downward continuation from the 20 km spacecraft altitude. This large negative anomaly is not due solely to the large positive anomaly in Mare Serenitatis. Simulations with surface slabs the size of the Mare Serenitatis mascon produce only -50 mgal edge effects for these trajectories. The implication is that this area has a real mass deficiency probably at depths of 10–50 km. Possibly in the Littrow area some of the denser material at depth was transported to the Serenitatis basin and lower density material took its place.

Phillips, R. J. and Saunders, R. S.: 'Interpretation of Gravity Anomalies in the Irregular Maria'.

We have argued that the anomalous masses giving rise to the so-called mascons are most likely thin plate-like distributions of volcanic fill. Such masses are superisostatic; i.e., they represent material added after a circular basin has achieved isostatic equilibrium. Such equilibrium is initially achieved by an undetermined combination of mantle rebound and basin flooding. Many of the structural features of the circular basins can be explained by isostatic adjustment of the excess masses, but compensation is far from complete. We postulated that a simple hydrostatic mechanism gave rise to the excess masses and we showed that the amount of excess mass, and hence the gravity anomaly, is linearly proportional to the basin depth *after* initial compensation. If the circular basins were deeper than the irregular maria prior to superisostatic filling, then the gross gravitational difference between these two mare types is explainable.

We postulate that the last flooding in the circular basins, giving rise to the mascons, occured at a time when the lunar crust had cooled to a state too rigid to allow complete isostatic compensation. If the above scenario is correct, then volcanic accumulations in the irregular maria, and most certainly those younger than the last circular mare fill, ought to give rise to positive gravity anomalies.

The general pattern of gravity in the irregular maria is one of a general backround of approximately zero gravity, indicating regional isostatic compensation, upon which are superimposed numerous and not insignificant positive and negative gravity anomalies. The correlation of volcanic 'centers' with positive gravity anomalies has been previously noted and we are now attempting to test in detail this correlation. Independent determination of accumulation thickness can lead to quantitative statements on the degree of isostatic adjustment. Of particular interest is the striking correlation between the positive gravity anomaly in southwestern Mare Tranquillitatis and the anomalously thick accumulation of volcanics mapped by R. A. DeHon (personal communication). These volcanics predate what is probably the mascon forming material and in fact belong to the oldest (3.7 aeons) of three basic mare units mapped by Soderblom. The implication is that the lunar crust was cold and rigid *prior* to any of the observable volcanic flooding. Such information can impart an important constraint on the thermal evolution of the crust. Further, if the amount of (incomplete) compensation can be correlated with the ages of the three units, then the amount and rate of deformation are also determined. Adaptation of a temperature-viscosity relationship will then lead to a thermal history of the crust during the time of mareflooding.

If the seismic velocity interpretation of 20 km of basalt in (at least) eastern Oceanus Procellarum is correct, then much of this accumulation must represent an early (eruptive?) phase that was isostatically compensated prior to the deposition of the three mare units.

Scott, D. H.: 'The Geologic Significance of Some Lunar Gravity Anomalies'.

Close correlations between observed negative anomalies associated with unfilled craters and theoretical estimates of gravity determined from crater geometry show that little, if any, isostatic adjustment has occurred on the Moon for a long period of time. Recent calculations made by the writer using the latest gravity and topographic control suggest that the Cayley fill within the crater Ptolemaeus has the same density as the adjacent highlands or about 3 gms cm^{-3}. Thus it is probably not necessary to assume that the Cayley Formation is composed of relatively low density material as proposed by Zisk. More likely, it is made up of breccias similar to those of the highlands.

Many new positive gravity anomalies or small mascons have been found on the Moon's nearside. Some are nearly circular and probably represent unrecognized basins or subbasins. Two lie nearly along a line connecting the Serenitatis and Nectaris mascons; one is centered over the crater Lamont and the other is near the old crater Torricelli north of Theophilus. The Lamont anomaly may result from a system of shallow intrusive bodies expressed at the surface as a network of radial and concentric ridges around the 75 km diam crater Lamont. More probably, the apparent buried rimcrest of Lamont is only the innermost ring of a much larger structure within southwestern Mare Tranquillitatis. This subbasin is more deeply filled with basalt than other parts of the region and may have been the source of the flows which formed Mare Tranquillitatis. A re-examination of lunar photographs covering the Torricelli anomaly indicates that this crater also, like Lamont, may represent the inner ring of an unrecognized basin.

Apollo 17 and Apollo 15 gravity results over part of Mare Serenitatis revealed certain inconsistencies when the data were optimized to a single disk gravitational model. The resolution of this problem seems to require an additional disk or mascon north of the basin center. This solution by Sjogren and his fellow workers would substantiate a previous geologic observation that the northwest part of the Serenitatis basin was formed by separate impact and has its own ring structure.

Some of the latest gravity results from Apollo 16 and 17, and Apollo 15 and 16 subsatellites show numerous isolated anomalies throughout central and southern Oceanus Procellarum. When these anomalies, together with those disclosed by previous missions, are plotted and studied in a regional context they clearly show a positive gravity axis extending for about 1000 km along Oceanus Procellarum. The positive axis may be associated with Procellarum intrusive ridge systems, a series of individual basins arranged more or less linearly like those between Serenitatis and Nectaris, or represent a tectonic trough deeply filled with mare material.

Bryan, W. B. and Adams, M.-L.: 'Volcanic and Tectonic Features of Crater Aitken'.

Crater Aitken on the Lunar far side resembles the more familiar crater Tsiolkovsky although it is smaller, measuring about 140 km in diam. However, Aitken and some of the adjacent craters also show unique landforms which appear to be of both constructional volcanic and compressional tectonic origin. These landforms have been studied in both metric and panoramic photography from the Apollo 17 mission.

The general morphology of Aitken suggests an impact origin. There is a central peak, and a highly fractured, chaotic floor resembling that of Aristarchus is exposed on the north side of the crater. There is a large secondary crater, probably of impact origin, on the north rim. Most of the floor is covered by a dark, mare-like fill. In this fill there are a number of low crater rings 8–10 km in diam which enclose clusters of bulbous, bun-like domes. Several of these craters show internal 'high lava marks'. There are also several indistinct drowned craters which may have enclosed dome-like structures. Between these craters the dark fill is essentially featureless, except for numerous small impact craters. Locally, there are short rille-like depressions, marginal scarps, and wrinkle-ridges. The latter may be traced into the crater wall where they merge with slumps and thrust faults. Similar rille-like features and wrinkle-ridges appear in Tsiolkovsky.

A crater northeast of Aitken shows a remarkable pattern of slumps and faults, part of a sinuous set of faults which can be traced for at least 150 km and which may continue beyond the northern limit of photography. The fault slices show a lobate, flow-like form which could easily be mistaken for lava flows or fronts of ejecta blankets. This feature may be the equivalent of a 'wrinkle-ridge' developed in deep regolith of the far side highlands.

A second crater west of Aitken is about 25 km in diam and encloses a raised, fractured, plug-like mass with a subhorizontal undulating surface. Several craters are centered on the annular depression between the plug and the crater walls. The plug and its enclosing crater appear to be related to north-south and east-west trending lines of pit craters in the adjacent highlands.

The origin of many of these landforms cannot be unequivocally demonstrated. The Aitken dark fill is almost certainly mare-type basalt lava. The internal craters with enclosed domes and 'high lava marks' are interpreted as vents from which most of the mare fill issued and into which there was some final drain-back. The domes may be latestage viscous extrusions, or simply fractured mare fill, caught in the vent during drainback and modified by impact erosion. Wrinkle-ridges are not concentric with the central fill and are not restricted to it, so cannot be the result of isostatic subsidence, as suggested for some mare ridges nor can they be flow fronts as suggested by El Baz. These ridges, and reverse faulting which crosses the highlands northeast of Aitken may be attributed to regional east-west compression. The tholoid-like central fill in the crater west of Aitken is most readily interpreted as a viscous extrusion, possibly a largescale equivalent of the dome complexes within Aitken.

Muehlberger, W. R.: 'Structural History of Southeastern Mare Serenitatis and Adjacent Highlands'.

Successive deformations of southeastern Mare Serenitatis and adjacent highlands can be traced through time by identifying bent and fractured surfaces that are assumed to have been horizontal when formed. The decreasing magnitude of successive deformations and associated subsidence of the Mare Serenitatis basin shows that the lunar crust became progressively stronger through time. The earliest recognized folding deforms the ca. 3.8 b.y. basalt of the Taurus-Littrow valley (Apollo 17 landing site): older highlands plains had not been tilted prior to this event. The second basalt sequence (ca. 3.5 b.y.) is gently tilted toward the Serenitatis basin. The third and youngest (ca. 3.2 b.y.) basalt sequence, the main filling of Mare Serenitatis, is barely tilted southeast showing that the lunar crust was strong enough by that time to maintain this load out of isostatic equilibrium to present (the mascon mass). Since ca. 3.2 b.y., contraction by cooling of the Moon has put the outer shell into a compressional regime as demonstrated by the systematic patterns of wrinkle ridges tormed by crumpling of the compressed plate of mare basalt. Wrinkle ridges are localized by either stratigraphic and structural discontinuities in the mare sequence or where large craters have penetrated the mare sequence. Asymmetric scarps of the Taurus-Littrow Mountains are also young compressional features. Wrinkle ridges began forming prior to the termination of ca. 2.5 b.y. old basalt eruptions in Mare Imbrium. The localization of wrinkle ridges by large fresh craters and deformation of small craters, as well as similar evidence of youth on the scarps in the highlands indicates that deformation is still going on.

Stage 1 Deformation: *Post-Taurus-Littrow Basalts*: The Taurus-Littrow basalts have been folded into a broad north-trending anticline whose crest lies west of the Apollo 17 landing site. The present day structural relief, 700 m, is only partial because the present surface dips west to an unknown depth beneath the Mare Serenitatis basalt. The older highlands light plains east and north of the landing valley, including the floor of the crater Littrow, have dips equal to those of the basalt; thus no tilting occurred in the time interval between the deposition of these units. East of 32° long., the highlands plains are horizontal. The boundary of the east flank of the anticline is along one of the Serenitatis basin rings. The southern boundary of the anticline lies along the north base of Mons Argaeus, a structure radial to the Serenitatis basin.

Grabens (linear rilles) on the basalt-covered annulus of the Serenitatis basin indicate strong downwarping of the basin during this interval. Their prominent development around the southern and eastern quadrants suggests an asymmetrical warping that reaches a maximum in the southeastern sector. North of the landing site, the main graben (Rima Littrow I) trends obliquely across the anticline and continues into the highlands at a slight angle to the present margin of the mare basin. The lack of parallelism of Rima Littrow I to the presumed circular shape of Mare Serenitatis suggests that this is only an approximation to the shape of the older sagged surface. Other small grabens that trend parallel to the anticlinal crest are probably contemporaneous with both Rima Littrow I and formation of the anticline.

Other basalts along the southern and southwestern rim of Mare Serenitatis presumably contemporaneous with those of Taurus-Littrow, have also been broken by graben. Whether this region has been folded into a ring anticline similar to that of the Taurus-Littrow region is not known (topographic maps are not available). Stereoscopic study of photographs shows that the old basalts dip strongly toward the Serenitatis basin.

Stage 2 Deformation: *Post-Basalt Near Dawes*: Southwest of Mons Argaeus is a basalt unit that buries the older folded and faulted basalt. A sinuous rille from a line of cones radial to Mare Serenitatis shows that the lava flowed toward Mare Serenitatis. Spectral data suggest that these basalts are titanium-rich; they were probably extremely fluid. The presentday slopes are such that the basalt should have run rapidly down the slope and not have spread laterally across the 30 km wide outcrop band, hence, the present day dip is interpreted to be greater than the initial dip.

Two other areas along the eastern and southwestern parts of the outer annulus of Mare Serenitatis also contain basalt of the second sequence of eruption. These basalts are also gently deformed and cover the earlier graben. Spectral analysis suggests these are low titanium basalts (Serenitatis type of Soderblom, and thus they may be younger than Soderblom's Tranquillity type (high-titanium) basalt near Dawes.

Deformation of these basalts has been limited to tilting. If sharp folding and/or faulting occurred after eruption of the second sequence, it must have been in the area now covered by the third basalt sequence that fills Mare Serenitatis.

Stage 3 Deformation: *Post-Mare Serenitatis Basalt*: The brownish gray basalt that fills Mare Serenitatis has a cratering age roughly equal to the Apollo 12 and 15 basalts: about 3.2 b.y. The deformation of this unit is minor as compared to that of the older basalts. This decrease in amplitude of deformation through time can be ascribed to an increase in lithospheric strength sufficient by at least 3.2 b.y. ago for the Mare Serenitatis basalt to be supported out of isostatic equilibrium as a mascon.

The deformation of Mare Serenitatis since ca. 3.2 b.y. ago consists of a slight tilt to the southeast as shown by Apollo laser altimetry and the formation of wrinkle ridges on the mare surface. The laser altimeter data also show that breaks in regional mare slope coincide with wrinkle ridges.

The mare wrinkle ridges of central and eastern Mare Serenitatis are north-trending elongate anticlinal zones, 5–15 km across, with sharp narrow asymmetrical upwards about 1 km across, parallel to the main ridges. The amplitudes are generally less than 200 m. The shapes are consistent with a compressional origin with the axis of horizontal shortening being perpendicular to the fold axis. The main anticline represents the folding of the entire sequence of basalt flows and the tight narrow wrinkles represent the disharmonic folding of the upper layer (layers?). The location of the concentric wrinkle ridges is probably controlled by scarps along the buried basin margin. The change in strike of the wrinkle ridges at the crater Bessel in south-central Mare Serenitatis suggests that these wrinkle ridges resulted from deformation by stress concentration around a hole in compressed mare basalt. The location of some wrinkle ridges on other mare also appear to be directly related to prominent fresh craters. (eg: Lambert, C. Hershel; Mare Imbrium).

The wrinkle ridges of southwestern Mare Serenitatis differ in that the anticlinal ridges are offset by faults whose northwest strike lies at 60° to the strike of the fold axis. This consistent fault offset of the fold axis produces a strong asymmetry to the wrinkle ridge. The fault trend is nearly parallel to Imbrium sculpture in the adjacent highlands, a structure that probably underlies the mare at shallow depths in the marginal zone and which thus influenced the shape of the wrinkle ridge system.

The youth of the wrinkle ridges is shown by the fact that they deform young craters (eg: Littrow BB) and have unfilled cracks parallel to their crests.

Along the southeastern edge of Mare Serenitatis where wrinkle ridges extend into the annulus of older basalts, the amplitude of the ridge decreases sharply, a result of folding a different package of basalt flows. Those that extend into the Taurus-Littrow basalt west of the Apollo 17 landing site displace graben (Rima Littrow I-IV) and continue southeastward as asymmetrical ridges and scarps in both highland and mare surfaces to the crater Vitruvius. One of these, the east-facing scarp traversed by the Apollo 17 crew averages 80 m in height across most of the valley of Taurus-Littrow before it apparently dies out southward near the South Massif. It extends northward along the lower slopes of North Massif, continues for nearly 40 km along the western edge of the Taurus-Littrow highlands to crater Littrow B. The smooth appearance of the North Massif below the scarp as compared with the rest of the slope, and the smooth areas west of the scarp between Family Mountain and South Massif that also has open cracks that extend onto the avalanche deposit from South Massif, may be the result of recent movement along this fault. Seismic shaking is assumed to be the cause of the smooth appearance of the cratered surface of a moving thrust sheet. This continuing regional compression seems most likely to result from contraction of the moon during cooling since the termination of mare volcanism.

14. Constraints on Structure and Composition of the Lunar Interior: II

Arkani-Hamed, J.: 'Density and Stress Differences in the Moon'.

Because of the strong abnormal behavior of the coefficients of the 13th degree spherical harmonics of the lunar gravitational potential presented by Michael and Blackshear, these coefficients were excluded in the computation of the density distribution inside the Earth. Recently Michael and Blackshear corrected their coefficients (C13.10; S13,10). The new values make the correlation of the tow different expressions of the lunar gravitional potential to be reasonable, which justifies the enclusion of the 13th degree harmonics in the density calculation. In the present paper a new model is presented for the lateral variations of the density inside the Moon. The stress differences associated with the variations of density indicate that the upper 600 km of the lunar interior has been quite strong within the last 3 b.y., and they support the mascon formation model proposed by the auther.

Colburn, D. S., Schubert, G., Schwartz, K., Smith, B. F., and Sonett, C. P.: 'Mare Imbrium: A Regional Site of Anomalous Electrical Conductivity'.

The Apollo 15 Lunar Surface Magnetometer has observed magnetic field oscillations which, at frequencies above about 5 mHz, and in the plane tangent to the lunar surface, are predominantly fluctuations in a northwest-southeast direction. With the Apollo 15 site located on the southeast margin of Mare Imbrium, this direction is roughly toward the center of the Imbrium basin. The Apollo 15 polarization phenomenon, and a similar but weaker one at the Apollo 12 site far to the south of Mare Imbrium, have been interpreted as a possible regional influence of the Imbrium structure on lunar magnetic induction. We present preliminary model calculations which show that induction in an electrical conductivity anomaly associated with the Imbrium basin can qualitatively explain the observed directional character of magnetic fluctuations at both the Apollo 15 and 12 sites.

The Imbrium electrical conductivity anomaly is modelled by a spherical cap current layer of arbitrary size, electrical conductivity – thickness product $\sigma\delta$, and depth $(a-b)$ beneath the lunar surface. External magnetic fields uniform in space and oscillatory in time with circular frequency ω induce eddy currents in the cap. The external fields can be either parallel or perpendicular to the cap at its center. Induced magnetic fields are confined to the lunar volume which is assumed nonconducting except for the cap. The major result of these model induction calculations is that the tangential lunar surface magnetic field component which points to the cap center can be anomalously large over the edge of the cap if the external driving field has the parallel orientation. This magnetic field anomaly can be attributed to a concentration of circumferential eddy currents toward the outer margin of the cap.

This component of surface magnetic field normalized with respect to the corresponding component of the external driving field, i.e. the magnitude of the transfer function $|A|$ as a function of angular distance from above the cap center $180° - \theta$ for various cap depths below the surface and for a cap of half-angle 25° with $\omega\mu\sigma\delta a = 6.87$ (μ is the magnetic permeability and a is the lunar radius). The magnetic field anomaly over the cap edge is narrower and larger, the nearer the cap to the surface. The magnitude of the magnetic field anomaly increases with $\omega\mu\sigma\delta a$ for a given cap depth below the surface.

The Imbrium structure could be a site of electrical conductivity in excess of the global lunar conductivity or it could be a hole in an otherwise conducting Moon. Either type of conductivity anomaly would produce induced magnetic fields with the observed directional character. Although we have not yet attempted to quantitatively model the observations it seems as though the conductivity anomaly must be deep, i.e. at a depth of about 100 km, if the regional induction is to be felt at the Apollo 12 site. A more conducting structure at the Imbrium location might be associated with magma production at depth subsequent to the Imbrium impact event and the rise of such magma to fill the basin perhaps preferentially beneath the basin margins. A less conducting Imbrium site could be the result of the violent fracturing of a large region around the impact, leaving, to this day, circumferential cracks at great depth. Whatever the physical nature of the Mare Imbrium conductivity anomaly, it is certain from the observations that eddy currents flow preferentially in a direction which is circumferential to Imbrium at the Apollo 15 site.

Dyal, P., Parkin, C. W., and Daily, W. D.: 'Global Lunar Properties from Magnetometer Measurements'.

Magnetometers have been deployed at four Apollo sites on the Moon to measure remanent and induced lunar magnetic fields. Measurements from this network of instruments have been used to calculate the electrical conductivity, temperature, magnetic permeability, and iron abundance of the lunar interior. Global lunar fields due to eddy currents, induced in the lunar interior by magnetic transients, have been anlyzed to calculate an electrical conductivity profile for the Moon. From nightside magnetometer data in the solar wind it has been found that deeper than 170 km into the Moon the conductivity rises from 3×10^{-4} mhos m^{-1} to 10^{-2} mhos m^{-1} at 1000 km depth. Recent analysis of data obtained in the geomagnetic tail, in regions free of complicating plasma effects, yields results which are slightly lower than nightside values. Conductivity profiles calculated from data obtained in the geotail region will be presented. The conductivity profile is used to calculate the temperature for an assumed lunar material of olivine. In an outer layer ($\sim$ 170 km thick) the temperature rises to 1100 °C, after which it gradually increases to 1500 °C at a depth of $\sim$ 1000 km. Whole-Moon hysteresis curves are plotted using Apollo 12 lunar surface magnetometer data with simultaneous lunar orbiting Explorer 35 data. From these curves a new global relative permeability $\mu/\mu_0 = 1.012 \pm 0.006$ is calculated. From the magnetic data the free iron abundance is calculated to be 2.5 wt %. The remanent fields range from 3 γ as minimum at the Apollo 15 site to 327 γ maximum at Apollo 16. Simultaneous magnetic field and solar plasma pressure measurements show that the remanent fields at the Apollo 12 and 16 sites interact with, and are compressed by, the solar wind. Remanent fields at Apollo 12 and 16 sites are increased 16 γ and 32 γ, respectively, by a solar plasma bulk pressure increase of 1.5×10^{-7} day cm^{-2}.

Russell, C, T., Coleman, P. J., Jr., Lichtenstein, B. R., and Schubert, G.: 'The Permanent and Induced Magnetic Dipole Moment of the Moon'.

Data obtained with the fluxgate magnetometer on the Apollo 15 subsatellite have been used to measure separately the permanent and induced magnetic dipole moments of the Moon. To measure the permanent dipole moment the fields were referenced to the 0° selenographic meridian, while to measure the induced moment the fields were referenced to the projection of the field in the orbit plane. The moments deduced for each tail lobe were then combined giving each equal weight and thus minimizing the contribution of the induced dipole to the measure of the permanent dipole moment and vice versa. Nearly complete orbits of data from 19 quiet passes in the north lobe and 10 from the south lobe of the geomagnetic tail were used in this study.

The magnitude of the permanent dipole moment in the orbit plane of the subsatellite is found to be less than our estimate of the noise level of 3×10^{18} Γ-cm^3 in accord with earlier estimates. Thus, we conclude that if the moon ever possessed a dipole magnetic field, either from an internal dynamo or due to natural remanent magnetization, capable of magnetizing the lunar surface material to the extent observed, this field has effectively disappeared.

The ionosphere would shield the lunar surface from the full external field of the geomagnetic tail. Therefore, the whole body permeability estimates must be raised to compensate for the ionospheric effects. For example, assuming the ionospheric plasma fills the region between the subsatellite and the Moon, an ionospheric permeability of 0.6 μ_0 and a whole Moon permeability of 1.05 μ_0 would be consistent with the subsatellite data. However, ionospheric shielding would reduce the apparent permeability reduced from surface measurements to 1.02 μ_0. We conclude that while magnetic measurements can provide important constraints on lunar thermal and compositional models, these measurements must go hand in hand with an accurate measurement of the lunar plasma environment.

Anderson, K. A., Chase, L. M., Howe, H. C., Lin, R. P., McCoy, J. E., and McGuire, R. E.: 'Observation of Energetic Electron Mirroring'.

The plasma and energetic particle experiment on the Apollo 15 Subsatellite included a curved plate electrostatic analyzer to measure the pitch angle distribution of 13.6–14.8 keV electrons. Using the magnetic field direction measured by the onboard UCLA magnetometer the flux of electrons in each of four pitch angle sectors (0°–45°, 45°–90°, 90°–135°, 135°–180°; hereafter called sectors I, II, III, IV respectively) was measured every 24 s. On September 3, 1971, the Moon was in the southern lobe of the high latitude magnetotail (solar magnetospheric coordinates $Y_{SM} = 20\ R_E$, $Z_{SM} = -10\ R_E$) and the measured magnetic field was quiet ($B \cong 10\ \gamma$) and directed radially away from the Sun. During the darkside portions of the Subsatellite orbit, sectors III and IV looked away from the Moon and observed particles coming from the distant magnetotail while sectors I and II looked at the lunar surface.

As the Subsatellite traversed the dark side of the Moon, large, steady, and isotropic fluxes of 13.6–14.8 keV electrons were observed in sectors III and IV. These electrons were flowing earthward from an unknown source in the distant magnetotail. These electrons may have come from the inter-planetary medium along open field lines after being produced by an earlier solar flare. Concurrently, measurements in sectors I and II showed weaker, irregular and anisotropic fluxes coming from the lunar surface. These fluxes are interpreted to be electrons from the distant magnetotail which magnetically mirrored near the lunar surface by the remnant lunar magnetic field.

Several factors argue in favor of a mirroring interpretation.

1. Remnant lunar fields over 300 γ have been measured at the lunar surface by the Apollo astronauts. Although the geometry of field reconnection is complicated, when reconnected to the magnetotail field of 10 γ, could mirror a substantial fraction of the observed incoming particles.

2. The measured flux of mirrored electrons with pitch angles between 45° and 90° (sector II) is always larger than the flux between 0° and 45° (sector I). For a given increase in field magnitude along a single field line this is expected because small pitch angle electrons may strike the surface before mirroring.

3. Reflected electrons are never observed in the absence of incident electrons. This argues against the possibility that the electrons are generated at the lunar surface. Backscattering from the lunar surface can contribute no more than 10% of the observed reflected flux.

It is interesting to note that when 0°–45° (sector I) mirrored fluxes are observed the flux in the 45°–90° sector (sector II) is still less than the incident flux. If the field reconnection were smooth over the distant of the electron gyroradius ($\sim$ 40 km), a field strong enough to mirror any 0°–45° electrons should mirror all 45°–90° electrons. That this is not observed indicates that some pitch angle scattering by magnetic irregularities is occurring near the surface. For scattering to occur, the scale size of the irregularities must be of the order of the gyroradii of the mirrored particles. Thus, we may infer that the scale size of the lunar remnant field which gives rise to the irregularities is of the order of 40 km or less.

Huffman, G. P., Nagata, T., and Schwerer, F. C.: 'Electrical Conductivity of Lunar Surface Rocks: Laboratory Measurements and Implications for Lunar Interior Temperatures'.

Laboratory Measurements – The electrical conductivity of six Apollo lunar rocks with Fe^{2+} contents from 4 to 20 wt.% has been measured in the temperature range 20 °C to 1000 °C. Both *d–c* and low frequency *a–c* (nominally 5 Hz) measurements were made using a three-electrode technique. For all samples studied, the electrical conductivity was observed to depend in a complex fashion on the furnace atmosphere and on prior thermochemical treatments; however, reproducible data could be obtained for specified sets of conditions. This dependence was most severe for the more porous or cracked samples and was apparently associated with chemical alteration of sample surface regions. Mossbauer spectroscopy corroborated the expectation that the changes in conductivity were associated with changes in the valence and distribution of iron. The conductivity was lowest for samples measured in reducing atmosphere (He–H_2 mixtures) and after reduction at high temperatures. Furthermore, data obtained under these conditions were very similar to data obtained during the initial heating of samples and are considered to be most representative of pristine lunar samples. These data can be described analytically by one or two exponential terms.

Petrographic analyses of lunar samples indicate that the bulk *d–c* electrical conductivity will be determined by the silicate phases, in particular, by minerals from the pyroxene and feldspar series.

Implications for Lunar Interior Temperatures – The electromagnetic response of the moon as measured by surface and orbiting magnetometers has been analyzed to yield electrical conductivity profiles of the lunar interior. Nightside profile with the conductivity data for lunar samples 15418 and 15058 (7 and 16 wt.% Fe, respectively). Similar analyses of two-shell conductivity profiles produce estimates of temperatures for $0.55 \leqslant R/R_m \leqslant 0.9$ of 1000 to 1200°C when conductivity data for the two samples named above were used and of 900 to 1400°C when data of all samples were used. Except for the lowest part of each band, these temperatures involve extrapolation of measured data and are most consistent with recent 'hot' Moon models.

15. Characteristics and Movement of Materials in the Lunar Regolith: IV

Mason, B., Jacobson, S., Nelen, J. A., Melson, W. G., and Simkin, T.: 'Regolith Compositions from the Apollo 17 Mission'.

We have investigated the following regolith samples:

71501, 71502: from Station la, north flank of Steno Crater; dark mantle, according to the Apollo Field Geology Investigation Team.

72441, 72442: from Station 2, South Massif; on boundary between massif material and bright mantle.

74121, 74122: from LRV 6, 1.1 km northeast of Station 3; bright mantle.

75081, 75082: from Station 5, southwest rim of Camelot Crater; dark mantle.

76501, 76502: from Station 6, North Massif; massif material.

79511, 79512: from Station 9, southwest rim of Van Serg Crater; dark mantle.

Two groups of basalts have been distinguished, one medium to coarse-grained, the other fine-grained to aphanitic, the average grainsize of the latter being less than 0.1 mm; thus at least two different basalts are present at the mare sites, with the medium to coarse-grained being the commoner. Breccias range considerably, from dark brown to black matrix types in mare locations to light to dark gray matrix types in massif and bright mantle areas.

Our samples of highland regolith came from the North Massif (76501–2), the South Massif (72441–2), and the bright mantle believed to be avalanche material from the South Massif (74121–2); the similarity in chemical composition and rock types between the latter two strongly supports the postulate of avalanche origin of the bright mantle. The chemical compositions at all three sites are very similar and correspond to an olivine norite; the relatively high K_2O and P_2O_5 indicate the presence of a KREEP component. The coarse fines from the South Massif and the bright mantle contained no basalt fragments, whereas the coarse fines from the North Massif contained some 15%, evidently because the site of the latter (Station 6) is practically on the mare-highland margin, whereas the other locations are farther removed from mare material. The material from Station 6 (76501–2) is noteworthy for its content of large plagioclase fragments, which make up 17% of the coarse fines at this site; this indicates the occurrence of a coarsegrained, perhaps unbrecciated anorthositic rock in the North Massif and its absence from the South Massif. The presence in 76501 of a concentration of magnesium-rich olivine (mean composition Fa_{12}), if derived from this rock, indicates that it is a troctolite. The higher percentage of agglutinate in 74122 than in the other coarse fines suggest that the bright mantle may have been exposed to glass-forming impacts for a relatively longer period than the regolith at other sites.

The mare basalt materials (71501–2 and 75081–2) are very similar in composition and are probably representative of the dark mantle. They consist of mare basalt and comminuted material derived therefrom, with minor admixture (10–20%) of the plagioclase-rich material derived from the highlands. The absence of free silica and the presence of minor olivine in the norm indicate that the mare basalts at this site are on average slightly undersaturated.

The material from Station 9 (Van Serg Crater), although mapped as dark mantle like the preceding samples, is clearly distinct. Our samples (79511–2) contain much less basalt and much more breccia than the other mare samples. The composition is also distinctive, being higher in Al_2O_3 and lower in TiO_2 and FeO than the mare basalt sites; this can be seen in the norm as higher anorthite and lower ilmenite contents. The composition indicates a mixture of subequal amounts of highland material and mare basalt; however, few fragments of highland rocks were found in the coarse fines, and the two materials have evidently been thoroughly mixed within the breccias that appear to form the bedrock at this site. How extensive this breccia is cannot be decided from the few samples from a single site that we have examined. It does suggest, however, that it may be a distinct geological formation bordering the North Massif and the Sculptured Hills.

Butler, J. C. and King, E. A., Jr.: 'Analysis of the Grain Size Frequency Distributions of Lunar Fines'.

Grain size frequency distributions of a total of 72 samples (3 Apollo 11, 9 Apollo 12, 8 Apollo 14, 12 Apollo 15, 19 Apollo 16 and 21 Apollo 17) of lunar fines have been completed by sieving with an Allen-Bradley sonic sifter and precision sieves. Relative humidity was controlled in the sieving chamber so as to avoid clumping of the less than 30 μm fraction and the 'thumping action' was minimized to preserve the delicate agglutinates. Weight of sample retained on each of a total of 14 sieves (841, 420, 250, 177, 149, 125, 105, 74, 53, 44, 37, 30, 20, and 10 μm) and the pan was measured to the nearest 0.0001 g. These data were converted to percentage form, a cumulative curve with a probability ordinate was prepared for each sample and the graphic mean grain size, the graphic standard deviation and graphic skewness were calculated and described as suggested by R. L. Folk.

The lunar fines that we have analyzed can be characterized as bimodal, poorly to very poorly sorted and nearly symmetrical. The broad mode in the 1–40 ⌀ (500–62.5 μm) size range is composed primarily of lithic fragments and agglutinates, the 4–5 ⌀ (62.5–31.3 μm) size range is relatively depleted in weight fraction in many of the samples and the greater than 5 ⌀ size range constitutes a second mode composed of mineral grains and glass. Although we have observed a considerable variation in size frequency distribution properties, the cumulative frequency plots are nearly linear and sub parallel such that a log normal distribution model is justified.

There appears to be a positive correlation between graphic mean grain size and total sample weight for those samples for which we have received more than one split. At our request, five gram splits of 76321,10 and 78221,8 were made available by the LRL for the purpose of ascertaining whether or not a larger sample would possess a greater graphic mean grain size as a result of our sieving procedures. Another purpose of requesting the two five gram splits was to investigate systematic differences in grain size results between different laboratories. Each sample was homogenized by rolling on a sheet of powder paper and two quarter sample splits and four eighth sample splits were prepared from each parent sample. A large (approximately 1.4 g) and a small (approximately 0.6 g) split from each parent sample have been sieved in our laboratory. Differences observed by our laboratory between aliquots of these comparison samples are much less than the differences found between sample aliquots distributed by the LRL. Causes of variations between the LRL distributed aliquots are difficult to specify, although it seems probable that they reflect size sorting of particles during preliminary handling and sieving in the LRL and/or during splitting prior to distribution. If the apparent biasing is widespread, then additional problems arise in comparing the results of size analyses performed by different groups of investigators if the same weights of sample were not used.

Several investigators have noted a significant negative correlation between graphic mean grain size and graphic standard deviation (a measure of sorting). For our 72 samples the correlation is positive; that is, our finer grained samples are poorly sorted than our coarser grained samples. Thus, it is presently impossible to develop a model for the genesis of the lunar regolith that make use of all of the grain size information available from all laboratories.

Splits of 76321,10 and 78221,8 were sent to D. McKay at JSC to J. Lindsay at La Trobe University for grain size analysis using the same techniques that they had used in their recent analyses of the lunar regolith. These investigators have been using a Millipore particle measurement computer system for the analysis of the fine fraction and sieving for the coarse fraction. Millipore results are made compatible with the weight percent data from the coarse fraction by graphical integration assuming spherical particles of uniform density. The cumulative frequency distributions for McKay's and Lindsay's data exhibit marked increases in slope at the Ø unit corresponding to the change from sieve data to Millipore data. Because Lindsay changes to the Millipore system at 44 μm, the effect is more pronounced for his data than for McKay's, in which the change was made at 20 μm). Recasting the Millipore data to make it compatible with the weight data apparently forces the cumulative percent to equal 100 at the lower limit of resolution of the device. Grain size distributions obtained using the Millipore system terminate at 8.33 Ø for Lindsay's data and 9 Ø for McKay's data. Grain size frequency distributions for our data do not have a fixed end point. Graphic mean, graphic standard deviation and graphic skewness are computed as functions of $\varnothing_{16}$, $\varnothing_{50}$ and $\varnothing_{84}$ and in the two comparison samples analyzed by all groups, $\varnothing_{84}$ occurs at a greater Ø value than that at which changes in technique were made. Therefore, the value of $\varnothing_{84}$ selected from our plot is considerably larger than that selected from the plots of the other investigators with the result that (if $\varnothing_{16}$ and $\varnothing_{50}$ are the same for all three groups) McKay's and Lindsay's samples would possess lesser graphic mean grain sizes (coarser), lesser graphic standard deviations (better sorted) and a lesser positive (or greater negative) graphic skewness. The effect of change in slope and a fixed end point is most pronounced for those samples that have greater graphic mean grain sizes and it would appear that the coarser samples of McKay and Lindsay must of necessity be poorer sorted than their finer samples. The total effect of mixing together data from two different techniques, however, is quite complex and each sample must be treated independently if comparisons between the size analyses performed by different groups are required.

Q mode factor analysis has been used to examine our weight percent data for relationships between the 72 different samples analyzed. Rotated factor loadings were converted to factor components and plotted on a ternary diagram. Samples 68411,13 from Station 4 on Stone Mountain, 12037,32 from the rim of Bench Crater and 12041,23 from 75 m from the rim of Bench Crater can be considered as the 'end members' for factors 1, II, and III, respectively.

By comparing the grain size frequency distributions of these three samples it is possible to speculate as to the importance of these samples in our lunar grain size data. Sample 12037,32 (II) is strongly bimodal, coarse, poorly sorted, and nearly symmetrical. Closely associated on the plot with 12037,32 are samples from Cone, North Ray, Elbow, Head and Surveyor craters. Sample 12041,23 (III) is poorly sorted, of intermediate size and negatively skewed. This sample contains a pronounced mode in the greater than 5 Ø size range. Sample 68411,13 (I) is very fine, very poorly sorted, nearly symmetrical and only slightly bimodal. We suggest that the regolith associated with impact craters with fresh characteristics will have a large factor II contribution. With time (an increase in I) the mean grain size is reduced through micrometeoroid comminution and the sample becomes more poorly sorted. This evolutionary scheme may be modified at any time by the influx of fine material (increase in III) and/or the creation of a new impact crater (increase in II). In addition to the concept of lithologic maturity it may be useful to define grain size maturity on the factor I content of the sample. Samples taken from ejecta of fresh impact craters at all sites form a distinct cluster with a large content of component II. For the other samples, those from Apollo 11 and 12 have relatively low grain size maturities. Apollo 14 and 15 (Apennine Front) are more mature and samples from Apollo 16 and 17 exhibit a wide range of maturity values because of the complicated local site geology. Nonlinear mapping of the 72 samples also supports the above conclusions. These results are in agreement with our previous conclusions that there are grain size distribution differences within and between the Apollo sites that can be related to local geology and total time of regolith accumulation.

McKay, D. S., Fruland, R. M., and Heiken, G. H.: 'Grain Size Distribution as an Indicator of the Maturity of Lunar Soils'.

Size Parameters. Size parameters of 42 Apollo 17 soils are presented which includes combined coarse fine and submillimeter data. As previously shown this plot serves to separate the samples along a somewhat linear trend in which the coarsest samples are the most poorly sorted and the finest samples are the best sorted.

Soil Maturity. It has been shown that well reworked or mature soils have high agglutinate contents, high track ages, high rare gas contents, and are finer grained and usually better sorted compared to immature soils. Consequently, we have divided the samples into fields representing the state of maturity of the samples; soils coarser than about 120 μm are classified as immature, soils from 80–120 μm are submature, and soils finer than 80 μm are mature. The average agglutinate content of each of the three major groups as determined by petrographic analysis of the 90–150 μm fraction is also shown. As expected, the immature soils contain the fewest agglutinates and the mature soils contain the most. Sample 79221,1 was not included in the averages because it is anomalous in that it contains relatively high agglutinates but possesses immature size characteristics; it is discussed below. In most cases, the maturity state of the samples can be understood in terms of the specific sample locality. For example, immature soils 71041 and 71061 were collected from the blocky rim of a fresh appearing 10 M crater. 75081 was collected from near the rim of Camelot and its submaturity may reflect an intermediate age for Camelot. The most mature samples were collected from undisturbed areas away from blocky craters. The orange and black glass form a separate class and cannot be considered normal soils. They are very immature having low track ages and low agglutinate contents, but are the best sorted and among the finest grained of any lunar material. It has previously been proposed that these samples may represent pyroclastic ejecta.

Histogram Shapes and Soil Evolution Paths. The grain size distribution of lunar soils results from a series of complex interactions in the regolith but it may be possible to understand size distribution in terms of simplified models or soil evolution paths. In path 1, reworking dominates mixing. An initial grain size distribution is created by a single impact into hard rock. This grain size distribution has been determined experimentally for small impacts in basalt and in granite. The size distribution of some of the suevite ejecta from the Ries somewhat resembles this distribution as does the soil from the rim of Cone Crater. If such fresh ejecta is now subjected to reworking and comminution by small meteorites, the coarse material will be broken up, additional fine material will be produced, and, after passing through intermediate stages (immature, submature). This distribution resembles that calculated by the Shoemaker 'bucket model' for the Apollo 11 site and based on prolonged comminution of bedrock and regolith by meteorites. If nearly all of the material less than 16 μm were converted to agglutinates which were then distributed among the size fractions where they are normally most abundant (500–16 μm), the calculated distribution could be made to resemble rather closely the actual size distribution of a mature soil and the agglutinate contents of these size fractions would be on the order of 50% which is about the agglutinate content actually present in these size ranges in a mature soil. At any stage along this evolution path, all of the size fractions have had a common history and a common degree of maturity. This first soil evolution path, dominated by reworking, can be contrasted to a second soil evolution path in which physical mixing of different soils dominates reworking. In evolution path 2, a mature soil can be physically mixed by impact with an immature soil or with fresh ejecta. If for example a soil were formed by mixing half 14141 and 72141, the resultant size distribution would be very similar to an immature soil, but the soil would differ from an immature path 1 soil in that different size fractions have had different histories and represent different degrees of maturity. In the example, the finest size fractions are completely dominated by 72141 and are mature whereas the coarser size fractions are dominated by 14141 and are immature. It then becomes necessary to consider the bulk maturity and the maturity of each size fraction separately and the sample can be considered to have a fractional maturity. In principal it should be possible to tell soils which have followed evolution path 1 from those which followed path 2 by detailed analyses of each size fraction. Possible examples of path 1 may be the North Ray Crater soils at the Apollo 16 site. A possible example of a path 2 soil may be 79221, the anomalous soil noted above. In this soil, the coarser size fractions may be dominated by Van Serg ejecta whereas the finer fractions may be dominated by a more mature pre-existing soil having a high agglutinate content. Apollo 16 South Ray soils may also represent path 2 evolution in which a pre-existing mature soil has had some slight contribution, primarily in the coarsest size fractions, by South Ray ejecta. It is of course possible for a soil to jump back and forth from one evolutionary path to the other. In summary, soil may follow different evolutionary paths, may show fractional maturity, and may require detailed analyses of size fractions to completely characterize maturity.

Goswami, J. N. and Lal, D.: 'Cosmic Ray Irradiation Pattern at the Apollo 17 Site: Implication to Regolith Dynamics'.

Observations of cosmic ray induced fossil tracks provide important clues to lunar regolith dynamics. We have now extended our fossil track observations to the several selenological units sampled at the

Apollo 17 site, using experimental techniques described earlier. These results and some general features of the dynamical processes occurring in the lunar regolith, based on the observed fossil track record of 38 Apollo Scoop samples and 55 Apollo and Luna core samples, are summarised here.

During its existence on the lunar surface, the cosmic ray tracks are stored in the 'fines' in a very depth sensitive manner. We present here data on these 3 parameters for the Apollo 17 and other lunar sites studied.

Borg, J., Comstock, G. M., Langevin, Y., Maurette, M., and Thibaut, C.: 'Lunar Soil Maturation, Part I: Microscopic and Macroscopic Dynamic Processes in the Regolith'.

1. *General Introduction to Parts* 1, 2, 3.

One of the major problems in lunar science concerns the 'maturation' of the lunar regolith with time which results from complex interactions between the lunar surface and its space environment. We present a progress report which is divided into three very distinct parts and concerns the combined effects of such 'Moon-Space' interactions on lunar dust grains. In this paper (Part 1) which is designed for LSI topic 2 we analyse purely 'mechanical' effects due to dynamic processes acting either at a very shallow depth ($< 100\ \mu$) or at great depth (~ 1 m) in the regolith and we try to evaluate various time constants attached to such microscopic and macroscopic processes. In part 2 and 3 specifically designed for LSI topic 6, we treat other classes of effects due to the maturation of the regolith such as the synthesis of new 'products' in the lunar soil (Part 2) and the 'aging' of radiation damage features in lunar dust grains (Part 3).

2. *Microscopic Dynamic Processes on the Top Surface of the Regolith*

2.1. *Lunar wind microgardening.* We already suggested that the expanding gas clouds that constitute the lunar wind can communicate a momentum to the lunar dust grains exposed on the top surface of the regolith. Such an interaction can trigger the individual turn-over of the grains at a rate, ν_{1w} (number of turn-overs per year), computed as a function of the grain size with the following assumptions: the grains are spherical; a turn-over only occurs when the displacement of the grain is greater than its radius, r; the frictional forces acting on the grains are negligible; a 'most probable' grain elevation, h, above the lunar surface is introduced which is estimated from the roughness of the lunar soil on a microscopic scale. Our main results are: (a) the micronsized grains have much higher turn-over rates ($\nu_{1w} \sim 1$ yr^{-1} for $r = 1\ \mu$ and $h \sim 2\ r$) than the coarser ones ($\nu_{1w} \sim 10^{-6}$ yr^{-1}, for $r = 100\ \mu$ and $h \sim 5\ \mu$) and this conclusion is evidenced by our radiation damage studies that show homogeneous amorphous coatings on the micron-sized grains but very inhomogeneous '2-micron' track gradients in the 200 mesh grains; (b) about one time every 1000 yr the finest soil grains ($r \sim 1000$ Å) can be ejected at speeds of $\gtrsim 20$ m s^{-1} during lunar wind 'impact' and this contributes to their collisional sticking on the surface of larger grains (see Chapter II.3).

2.2. *Solar wind sputtering.* We have just completed an extensive set of artificial solar wind type implantations with low energy ions ($0.2 < E < 3$ keV amu^{-1}) ranging from hydrogen up to lead nuclei. A great variety of targets were used, including micron-sized grains either found in the lunar regolith or proposed as plausible models for cosmic dust particles. From high voltage electron microscope (HVEM) observations we first evaluated for each target and each type of ion the critical flux values, ϕ_c, which correspond both to the formation of an amorphous coating of radiation damaged material on the grains and to a severe rounding of their habit due to ion sputtering. Then we directly determined the ion sputtering erosion rate, S, of feldspar grains by using a double irradiation technique where a thick amorphous coating produced by 3 keV amu^{-1} ions is subsequently gradually eroded away with a beam of 0.2 keV amu^{-1} ions. Finally the erosion rates and the lifetime of micron-sized grains in the contemporary solar wind was deduced first by using the ϕ_c scalings for going from feldspars to the other minerals and then by dividing the S values so far obtained for a parallel beam of ions by a 'lunar geometrical factor' of about 10. Our results clearly suggest that solar wind sputtering alone can already contribute to the 'mineralogical-chemical' fractionation effects observed in the finest size fractions of mature soil samples (see paper 2).

2.3. *Microaggregation of lunar dust grains.* There are two extreme examples of dust aggregation products in the lunar regolith that are the lunar breccias and the micron-sized dust aggregates observed in mature soil samples. These microaggregates seem to belong to two distinct types: in type I the secondary particles attached to the central grains have a much smaller radius (~ 1000 Å) than the central grain; in type II the constituant particles in the aggregates have about the same radius ($\sim 1\ \mu$).

Such aggregates could result either from the desaggregation of weakly consolided breccias or from the collisional radiation damage sticking (CRDS) of individual grains already covered with an amorphous coating. Our pellet sintering experiments now conducted both with lunar soil samples and with artificially irradiated grains as well as our HVEM observations of lunar dust grains firmly stuck to the mineral paint of the Surveyor III spacecraft favor a CRDS origin for at least the type I aggregates. From our measured density of micron-sized lunar dust grains on the Surveyor paint ($\sim 0.05/\mu^2$) we deduce a collisional sticking probability of about 0.2 for such grains, if we suppose that they were set in ballistic motion at speeds of about 50–100 m s^{-1} by the Apollo 12 rocket exhaust. If the same sticking coefficient is applied to describe a $\gtrsim 20$ m s^{-1} collision between two lunar dust grains set in motion either via ejecta blankets or by rare but violent lunar wind 'impact' it can be shown that the lunar wind is likely to be the major contributor for triggering the CRDS of the grains. Then the number of secondary particles, N_s, attached to the central grain of a type I aggregate and which increases up to values of about 10 with the various indices of soil maturity, could be used to deduce a maximum integrated residence time of the grains in the lunar wind ($\lesssim 10^4$ yr for $N_s \lesssim 10$), which is compatible with the lifetime of the grains against solar wind sputtering. A similar argument shows that the lunar wind cannot account for the formation of type II aggregate.

3. *Macroscopic Dynamic Processes in the Lunar Regolith as Deciphered from Radiation Damage Stratigraphy in Lunar Core Tube.*

3.1. *Some of the raw data and their statistical analysis.* For each 200 mesh grain we measure the track density at the grain center (ϱ_c), near the edge (3 μ–5 μ) but still in the solar flare particle region (ϱ_b) and when possible still closer to the edge $\lesssim 1\ \mu(\varrho_\mu)$. The ratios $\Gamma = \varrho_b/\varrho_c$ and $\Gamma_\mu = \varrho_\mu/\varrho_b$ then characterize the solar flare and 'suprathermal' particle gradients which may be present in the grains. For each grain, Γ and Γ_μ can be determined from opposite edges to yield information on multiple exposures. Finally ϱ_c, Γ and Γ_μ can be determined for different regimes of track lengths, to yield chronological information based on track aging (see paper III). Our computer program then searches for correlations among these various measurements of ϱ_c, Γ and Γ_μ and analyses their distribution as a function of both maturity indices and depth in core tubes. We thus get general conclusions that are *independent of model assumptions*: 1. nearly all 200 mesh soil grains have at one time resided within 1 mm of the surface, most have resided there in several different orientations and about half have had less than 1 grain radius ($\sim 50\ \mu$) of covering material and hence have been exposed to very low energy ions. Since ejecta layers are typically ~ 1 cm thick our results further show that near-surface gardening processes play an important role in the maturation of the grains; 2. we have identified and characterized at least 2 populations of abundant primary particle tracks (see paper III) that we interpret as being either 'younger' tracks formed when the grains were last near surface (Population I) or 'older', more mature tracks (Population II) that have been severely aged in the regolith. The median density of population I tracks (which is not given by the lowest track densities in a layer) varies widely from layer to layer reflecting the difference in their last surface residence time.

3.2. *Theoretical simulation of irradiation history.* To quantitatively interpret soil maturity and accurately determine surface residence time and core chronology from track Population I and II we are perfecting a series of computer simulation programs which increase step by step the complexity (and maturity) of the irradiation history for artificially generated 'soil grains': 1. the first step determines the track formation rate and track length distributions as a function of depth and investigates the effect on the track gradients of a variable or uneven shielding thickness. Such simple irradiation histories, which have so far been the only ones used by others, explain some of the young Population I track distributions in individual grains *but not their statistical distribution in a given soil layer*; 2. the second step is to simulate the latest irradiation history due to a near-surface (1 μ–1 cm) gardening process. The comparison of the artificially generated track distribution with the Population I track distribution will yield the best values for the latest surface residence time for each layer and therefore a good core chronology can be constructed. It is important that this model be constructed carefully since our experimental results show that the track density in most of the grains has resulted essentially from near-surface exposure of the grains; 3. the 3rd step is intended to predict the characteristics of mature Population II tracks, by combining the effects of several simulated near-surface gardening episodes for random residence times and including the relatively small additional dosage received during burial below ~ 1 cm. The comparison between the artificially generated 'old' tracks and Population II tracks should then tell us how many ejecta blanket episodes are needed and perhaps give some information on impact rates in the past.

Goel, P. S., Shukla, P. N., Kothari, B. K., and Garg, A. N.: 'Solar Wind as Source of Nitrogen in Lunar Fines'.

New data on total nitrogen contents of some fines obtained by neutron activation analysis are presented. Sieve analyses of a number of soils have also been done.

It had been noted earlier that the plots of nitrogen contents versus $1/d$ are linear as expected for a surface correlated nitrogen. More analyses do not give a linear correlation. A large apparent 'volume component' of nitrogen is noted. It is suggested that this is due to agglutination process. Taking the published agglutinate data on Apollo 16 soils we see that total nitrogen contents (2, 3, 6) increase linearly with agglutinate contents. A similar relation is seen for carbon contents also.

The maximum surface concentration of nitrogen in soil grains is found to be about 20×18^{-8} g cm^{-2}. This is more than an order of magnitude lower than the saturation concentration value of 10^{17} atom cm^{-2} suggested for the case of He^4. The solar wind nitrogen (and carbon) is not saturated. Assuming a solar wind nitrogen influx rate of 2×10^4 atoms cm^{-2} s^{-1}, at the Moon as suggested by Banks we calculate the maximum exposure the grains have experienced to be about 2×10^4 yr. The same surface exposure time is obtained from an examination of particle track data and also from the consideration of regolith thickness, its total age and the average soil grain diameter.

Since the soils are almost certainly not saturated with solar wind nitrogen and carbon, it is reasonable to take the C/N ratio in the soils indicative of the solar wind relative abundances. Moreover, most of the nitrogen (and carbon) is accountable from a single source viz. solar wind. The C/N ratio in fines is almost constant (1 to 1.7) and is unlike any meteoritic value, indicating an absence of appreciable meteoritic contribution.

DesMarais, D. J., Hayes, J. M., and Meinschein, W. G.: 'Retention of Solar Wind-Implanted Elements in Lunar Soils'.

Two distinct mechanics of volatile element loss have been resolved: (1) diffusive escape, and (2) eviction during cycling. In addition, we have roughly determined the extent to which each mechanism affects H, N, C, and the rare gases.

Jordan, J. L., Walton, J. R., Heymann, D., and Lakatos, S.: 'The Rim of North Ray Crater: A Relatively Young Regolith'.

Cosmogenic Ne-21 contents of 9 single particles (500–1000 μm) from 67701 range from 1 to 7 Paneth with an average value of 4.0 Paneth. The cosmogenic Ne-21 contents of 6 size fractions from 67701 range from 3.4 to 5.4 Paneth with an average value of 4.2 Paneth. In contrast, the cosmogenic Ne-21 contents of size fractions from 61221 and 61241 show averages of approximately 45 Paneth. From this we conclude that the thin soil cover at Station 11 comes essentially from only one source: N.R. Crater ejecta, with little contamination by materials from elsewhere. The age of N.R. Crater has been reported as about 50 m.y. and as about 30 m.y. The Ne-21 production rate inferred from the first age of 0.08 Paneth per m.y. is at least one-half the expected rate. The second age gives production rates more in line with the expected value. We have considered the following explanations for this paradox:

(a) The age of N.R. Crater is 50 m.y. The regolith at Station 11 contains some debris from this time. However most of the rocks and the soil at Station 11 come from a younger crater (younger than 30 m.y.) nearby,

(b) The survival time of < 1 mm particles in a soil cover of a few cm is substantially less than 50 m.y.,

(c) The low Ne-21 production rate is a 'memory' of shielding in relatively large boulders for millions of years.

The over-all trapping efficiency of the soil cover, assumed 5 cm thick, for solar-wind He-4 is only 0.0003. This implies that the thin cover had been 'saturated' with trapped He-4 on a time-scale of ten thousand years. An alternative interpretation is that the rim of N.R. Crater has always been an active *erosional surface*. An initial soil thickness of several meters, whittled down to a few cm in 50 m.y. would bring the over-all trapping efficiency of solar-wind He-4 more in line with previous estimates and would alleviate the problem.

n-values are given for 67701, 61221, and 61241 together with Ne-21 ages, agglutinate contents and mean grain size. There is no correlation between n and any of the other entities, which shows that n-values cannot be used as an index of maturation of a soil. Comparison of Ne-21 ages, agglutinate contents, and gas-loading (number of trapped gas atoms per cm^2 of surface) are indicative of the residence time of a soil in an upper, active zone of the regolith, perhaps only a few mm thick. The rate of agglutinate production and gas loading decreases rapidly with depth, but Ne-21 production is still substantial at one meter depth.

The n-values are all less than unity. We conclude that this reflects mainly a substantial and continuous production of fresh, unexposed (to solar wind) surfaces. We do not know whether the grain-size distribution of 67701 has reached a steady state, but if it has, then the rate of production of fresh unexposed surfaces, when expressed as $R = kD^{-p}$ (R = rate, k = proportionality constant, D = particle diameter) must be such that p is greater than 1, because the specific surface area is proportional to D. This, in turn, would seem to imply that the mean lifetime against rupture of particles < 1 mm depends strongly on particle size. For a simple model, in which the mean lifetimes are proportional to D^q, we calculate from the n-values that the mean lifetime of particles in 67701, 61221, and 61241 decreases roughly by a factor of 5 for a decrease by a factor of 10 in diam.

The fines from the trench at Station 1: 61221 and 61241 are definitely *not* N.R. Crater ejecta. Their cosmogenic Ne-21 contents show that these fines have been on the surface much longer than 50 m.y. Fines 61221 are unique in at least one respect. Its trapped gas content decreases normally with increasing grain size until about 150 μm, then increases significantly up to 1 mm. These fines seem to contain a relatively gas-rich, coarse-grained component. The origin of this component is still undermined.

Hörz, F. and Schneider, E.: 'Lunar Rock Erosion'.

Two basic processes caused by the bombardment of micrometeoroids contribute to the descruction of lunar rocks i.e., catastrophic breakup: and 'particle abrasion'. The latter process was simulated in the present study via Monte Carlo computer techniques in order to assess the gradual mass wasting of lunar rocks.

Input data: Measured microcrater size frequency distributions from rocks 12054 and 60015 for craters 400–2500 μm spall diameter (D) and an extrapolated microcrater production slope of $N_D = CD^{-3}$ for all larger craters yielded the probability of occurrence for specific crater sizes. The crater volumina (V_c) were calculated using Gault's (1973) experimental data. From these volumina the crater depth (d_c) was derived via the simple relationship $d_c = V_c/\pi(D/2)^2$. The test surface was a grid consisting of 175 × 175 'cells' of fixed x/y coordinates ($x_{1 \ldots 175}/Y_{1 \ldots 175}$) and of 400 μm sidelength each, thus resulting in a total test area of 49 cm^2. However, only a central square of 25 cm^2 was analyzed in order to eliminate 'edge-effects' at the boundary of the test surface. The crater size intervals were chosen such that the surface area of the associated average crater (C_a) was an integer number of 'cells' (Z), i.e., $C_a = uZ$; for the smallest crater $u = 1$; for the largest crater $u = 1965$.

Computer run: Using the above input data, three random number generators determined the X/Y coordinates of the impact point and the crater size produced. The entire output was purposely expressed only in terms of total number of craters produced. Thus the raw data are independent of the actual flux of micrometeoroids and model elapsed times may easily be defined based on best estimates of the flux of micrometeoroids.

Hartung, J. B., Hörz, F., and Storzer, D.: 'Toward a Lunar Microcrater Clock'.

Because microcratering is the dominant erosion mechanism on lunar rocks, a clock based on the accumulation of microcraters measures the time the outer-most surface not affected by those microcraters is exposed. Iron-group solar flare particles penetrate a few hundred microns. Because this penetration is less than the scale for the dominant microcratering events, particle track densities yield comparable exposure time information. Exposure times based on galactic cosmic ray track densities and cosmogenic inert gas concentrations are not comparable because the measurable quantities are produced at depths of millimeters to tens of centimeters and not at the exposed surface.

An exposure time clock requires the measurement of a time-proportional parameter (density of craters or track etch pits) and independent knowledge of a production rate (meteoroid or solar flare particle flux). Production rates for tracks and microcraters are known from analyses of Surveyor 3 mirror glass and satellite-borne meteoroid detection experiments, respectively. Therefore, one type of clock, solar flare track or microcrater, may be used to check or improve the accuracy of the other. The important measurement which provides a basis for the comparison and improvement of the two methods is the ratio of the number of craters to the number of tracks produced in the same sample during the same exposure interval. Our objective is to establish that ratio.

Iron-group solar flare tracks and microcraters have been measured on several surfaces not in equilibrium with respect to cratering. *Average* crater density to track density ratios over about 10^4 to 10^5 yr are obtained in this way for each sample. We have measured the track density in a number of glasses or annealed zones from recently formed, individual, microcrater pits. This approach yields the *variation* of the crater to track density ratio with time. The density of tracks is corrected upward to account for track annealing according to the relationship, $F = -8.9 + 2 \log \delta_{10}$, where F is the correction factor, δ_{10} is the observed solar flare track density (cm^{-2}) at a depth of 10 μ and 8.9 and 2 are constants obtained from a comparison of track densities in glass and pyroxene crystals included within the glass and empirical results of track annealing studies.

We interpret the non-linear behavior of the variation of microcrater density with solar flare track density in terms of a recent increase in meteoroid flux, although a higher solar flare activity in the past or some combination of effects is possible.

The ratio of crater to track densities we obtain for recent times is essentially equivalent to that based on independent meteoroid and solar flare flux measuring experiments, which yield 0.06 meteoroids ($m \geqslant 1.7 \times 10^{-10}$ g)/$cm^2 \cdot yr \cdot 2\pi$ ster and 3×10^4 tracks $cm^{-2} \cdot yr \cdot 2\pi$ ster at a depth of 10 μ, respectively. Absolute values for both rates or fluxes remains dependent upon accurate measurements from present-day, in situ, standardization experiments of either solar flare or meteoroid flux.

Attempts have been made to develop a surface-exposure-time clock based on the areal density of microcraters with pits 0.1 to 1 mm in diameter observed on rock surfaces not clearly in production at these crater sizes. We deny the general validity of this approach basically because the observed crater populations are not necessarily representative of the population of craters formed on a randomly selected exposed surface. Rock surfaces collected from the lunar surface are 'selected' in the sense that only those surviving catastrophic rupture can be picked up; and these are statistically depleted in the large, destruction-producing, cratering events. Output from a Monte Carlo simulation of crater population development illustrates an 'observed' population of microcraters on a *selected* surface, with a characteristic steepening at larger crater sizes, which is not directly related to the actual production of craters on a *random* surface. The magnitude of this selection effect depends on the slope of the microcrater production size distribution and a factor, M, given as follows from probability theory.

$$M = \frac{1}{n} \cdot \frac{\log n}{\log n - \log(n-1)},$$

where M is the selection effect factor and n is the ratio of the number of rocks initially available for destruction to the number surviving at the time of collection. For example, almost 200 rock-destroying impacts are required to destroy 49 out 50 rocks initially present, which corresponds to a selection effect factor of about 4. Populations of rocks exposed recently suffer a negligible selection effect; and only rocks from these populations yield valid microcrater exposure ages.

A correlation between track and 0.1-to-1-mm pit densities may be used as an argument supporting the validity of using craters of this size indiscriminately as a basis for a microcrater clock. Such a correlation is expected and observed on surfaces exposed a short time, less than 10^6 yr, because both parameters are indeed time dependent. However, even after equilibrium with respect to cratering is reached, a correlation between these parameters still may be expected because both track and microcrater densities are dependent upon the rate of erosion or erodability, which may differ from rock to rock.

Prospects for a lunar microcrater clock usable over an exposure time range of about 10^3 to 10^6 yr appear good, although somewhat complicated by a time-varying meteoroid flux.

McDonnell, J. A. M. and Flavill, R. P.: 'Sputter Erosion on the Lunar Surface: Measurements and Features under Simulated Solar He^+ Bombardment'.

In a program to identify features and evaluate the relative importance of microscale erosion on the lunar surface, we have experimentally investigated hypervelocity impact, thermal cycling and solar wind ion sputtering. Results of the hypervelocity impact and thermal erosion experiments have been reported elsewhere. Impact craters are not substantially different from those on terrestrial materials and in subsequent thermal cycling experiments no further degradation was observed. We now report on extended measurements of the sputter experiments:

The source comprised an R.F. excited plasma bottle using analytical grade Helium at an extraction energy of 2.5 kV, commensurate with a solar wind velocity of 400 km s^{-1}. The integrated beam current was 80 μÅ and the maximum current density 240 μÅ cm^{-2}. Measurements were performed on polished sections of sample 14321.148 and on quartz reference surfaces on which hypervelocity impact craters had been formed. Surface charge neutralisation was achieved by a 'flood' of low energy electrons. Both the effective sputter rate (i.e. the erosion required to erase a feature of certain depth) and the absolute sputter rate were measured. From the latter measurement, the ion sputter yield can be deduced. A depth of 20 μ was eroded in total.

Features observed on impact craters under simulated solar wind erosion are

(1) a preferential loss of material from the rim of the primary hypervelocity crater.

(2) preferential etching of spall zone faults

(3) an increase of the crater dimension prior to erasure, and

(4) that an absolute erosion of greater than the crater depth is required for erasure. Preferential etching of the crystalline boundaries of the polished section is also very evident, where *V* shaped notches are formed delineating grains over which uniform sputtering is observed. Under heavier sputtering at a constant incidence angle, clusters of needles were formed indicating in these regions the sputter yield increases with high geometric inclinations to the incident beam. Computer models have also been developed to investigate the modification of surface profiles under sputtering to understand more clearly the variety of observed features. Preliminary results are presented.

The absolute sputter rate on the lunar surface averaged over the lunar cycle deduced from these measurements is 0.043 ± 0.010 Å per annum. The equivalent ion yield ratio is calculated 0.31 atoms per incident ion. These measurements are somewhat higher than our first preliminary experimental sputter results, but still very much lower than the pre-Apollo estimates. They give excellent experimental confirmation of earlier predictions of 0.021 Å yr^{-1}. In terms of the total microscale erosion the magnitude of the sputter mechanism is very much lower than micrometeorite impact erosion, but even this low sputter rate is very significant in determining the lifetime of sub-micron craters. Micrometeorite influx rates deduced from exposed lunar surfaces in sputter equilibrium should be interpreted in the light of this new experimental measurement.

Dollfus, A.: 'Regolith in the Solar System'.

The regolith at the surface of celestial bodies is the superficial layer of finely divided particulate material resulting from the pulverization of the solid surface by meteoritic and micrometeoritic impacts.

A regolithic structure is recognizable at the surface of distant celestial objects from remote telescopic observations. Several criteria in the optical properties of the light are specific:

(a) Retro-reflection of light towards the incident beam's direction is enhanced, as the mutual shadowing between the grains of the complex texture of mutually supporting grains drastically reduces the light returned toward the observer when the observing direction departs from the exact direction of the incident beam. The result is a spike in the photometric curve near 0° phase angle.

(b) Multiple scattering between the surfaces of the opaque grains in a complex structure generate a certain amount of polarized light with an enhanced electric vector parallel to the plane containing the incident and emergent beams (negative polarization) for observation azimuths near the direction of incidence. The result is a very specific and characteristic negative branch in the polarization curve for phase angles smaller than 24°.

(c) The dark glasses generated by impact melting and possible solar wind irradiation processes produce an overall change of colour and darkening of the surface. The result is a low albedo and a specific type of spectrophotometric reflectivity curve; another result is that the opacity of the grains produces an inversely proportional relationship between the geometric Albedo A and the maximum amount of polarization P_{max} for all wavelengths in the optical range.

We shall discuss these optical criteria for a large number of celestial bodies on the basis of lunar results, and with emphasis on the polarization criteria.

For the Moon, the spike effect on the photometric curve at 0° phase angle, the negative branch of polarization, the spectrophotometric curve and the albedo-polarization relationship observed telescopically are fully reproduced on the returned lunar fines samples.

For Mercury, all these criteria are also noted with relevant observational accuracies; the similarity with the Moon is striking in all aspects, the departures being too marginal to deserve physical interpretations. Thus, Mercury must be covered by a regolithic layer of lunar type, impac-generated on a material of approximately the same nature.

For Mars, the negative branch of polarization is of the lunar type and indicates the creation of a layer of finely divided particles, most probably impact-generated. The spike effect is small and the photometric curve is flat, indicating a smoothing out of the micro-texture and small impact craters by wind transportation of the grains. The spectrophotometric reflection curve is characteristic of hydrated ferrous oxides and implies a superficial oxidization of the grains by the atmosphere.

For Jupiter's satellites, *Callisto* has a contrast between its surface markings, a global albedo (0.14) and a spike effect of the lunar type. On the leading hemisphere in its orbital motion, the negative branch of polarization gives a minimum of $-9\ 10^{-3}$ against $-12\ 10^{-3}$ for the Moon indicating a regolithic structure of the lunar type covering most, if not all, of the surface – although perhaps slightly tighter packed. But on the trailing hemisphere, the polarization curve shows a minimum of -6×10^{-3} and a change of the sign of polarization at phase angle 13°. These properties are not characteristic of a regolith at all, but rather of consolidated rocks. This surprising result represents the unique exception among all the Solar System bodies already polarimetrically investigated. Explanations could involve impact mechanisms on orbit around Jupiter, or perhaps the recent disappearance of a frost deposit.

The surface of *Europa* resembles an almost uniform water-frost deposit in all its investigated properties. Observations of *Io* indicate a volatile deposit of a different nature.

Ganymede resembles a lunar or Callisto-type surface partly covered with large areas of water-frost deposits.

The asteroids for which photometric curves have been measured sometimes show spike effects at 0° phase angle. Their albedo measurements are based on infrared observations and on the slopes of polarization curves at the inversion angle. The albedo range covered is very large, and extends from 0.04 to 0.23; this rules out the possibility of a uniform surface caused by irradiation or impact melting; the reason is the very low escape velocity (0.1 km s^{-1} for asteroids of 130 km diam); the powder ejected at impact is lost into space, and the surface is continually rejuvenated by micro-impacting. The range of Albedoes also rules out a mantling of the surface by cosmic slowly accreted at low velocity. It implies, and the variety of spectrophotometric reflection curves confirm, that the asteroids are made from varieties of material of different compositions.

The negative branch of polarization however, already determined for about 20 asteroids always shows inversion angles between 18° and 25°, and minimum polarization between $-6\ 10^{-3}$ and $-15\ 10^{-3}$. This minimum is roughly inversely correlated with the logarithm of albedo, in a way that rules out freshly chipped solid rocks, and suggests textures consistent with regolithic structures. This polarimetric behaviour is also consistent with brecciated surfaces coated with adhesive dust; this last structure may be preferred because of the impossibility of generating pure regolith with such a low escape velocity. The four darkest asteroids measured (1 Ceres, 2 Pallas, 324 Bamberga and 511 Davida) have albedo and negative branches of polarization of the type observed in the laboratory on the Orgueil carbonaceous chondrite.

16. Nature of Impact Processes and Their Effects on Lunar Materials: III

Gault, D. E., Hörz, F., Morrison, R. H., Oberbeck, V. R., and Quaide, W. L.: 'Effects of Formation of Large Craters and Basins on Emplacement of Smooth Plains Materials'.

Formation of laboratory impact craters, laboratory explosion craters and larger N.T.S. explosion craters have been studied to determine the effects of ejection of material from large lunar impact craters on distant terrain. High-speed motion pictures of large explosion craters formed at scaled depths of burst that simulate impact crater formation show that most of the material is ejected from large craters at angles that are similar to those for material ejected from small impact craters. Impact, break-up, and mixture of this material with secondary crater ejecta are responsible for formation of the dust aerosol that produces base surges. Primary crater ejecta and the ejecta of secondary craters mix with the expanding air cloud. Because there is no lunar atmosphere, lunar base surges of this type will not occur. Instead material ejected from large lunar craters produces a combined radial depositional and cratering regime that mixes pre-existing materials with basin or crater ejecta.

Study of the herringbone pattern associated with lunar secondary craters has shown that fragments producing them were ejected from craters like Copernicus at angles less than 30° measured from the horizontal. This knowledge together with knowledge of range of the secondary from the primary crater permits one to estimate the part of the emplaced deposit that is mass ejected from the local terrain relative to the part that is primary crater ejecta. This estimate is obtained both by direct simulation of secondary craters and by computation.

Simulation of secondary crater formation and calculations based on measurements of secondary craters and energy-size scaling relationships for crater formation indicate that the proportion of primary crater ejecta in secondary crater deposits decreases with the distance of the deposit from the primary crater or basin. For example, if secondaries of Orientale basin are present near the Apollo 16 landing site, any deposits associated with the Orientale event would be scattered in a discontinuous manner about the isolated secondaries and the material from Orientale basin would be at most about 12% of the deposit. The remainder is local material. On the other hand, the proportion of primary crater ejecta in that part of the Cayley Formation emplaced by a nearby highland crater can be much higher. These findings support the interpretations that local and regional craters had an important effect on the history and petrology of the Apollo 16 site.

Additional calculations show that the total mass ejected by all secondaries of a primary crater can be a significant fraction or multiple of the total mass ejected from the primary crater. The cratering mechanics analysis predicts large mass wasting deposits produced by formation of secondary craters in or near depressions of the highlands and in intercrater areas that are the sites of intense bombardment material ejected from the primary craters. This material, however, will consist of rather high proportions of ejecta of pre-existing local and regional highland craters. So, in addition to fallback breccia and ejecta blankets of local craters secondaries of local and distant craters have eroded the rims of local craters and the highland materials into depressions to contribute to the Cayley Formation.

Smooth plains materials in a depression northeast of crater Tycho are shown to be adjacent to and downrange from saturated fields of Tycho secondaries on the highlands. The secondaries must have ejected material of the highlands into these smooth plains areas and contributed a significant amount of material of highland composition to this smooth plains unit during Copernican time. Calculations show that approximately 1/2 of the mass emplaced in this smooth plains unit by Tycho is material from the highlands and 1/2 is Tycho ejecta. This smooth plains unit adjacent to a zone of saturated secondary craters suggests that, if larger continuous units of smooth plains are to be related to the formation of a single crater or basin, they must occur near the zone of saturated secondary craters of that primary crater or basin. Secondary craters at greater distances from the source could produce only discontinuous deposits because the secondary craters are separated outside the saturated zone.

The association of saturated secondaries of crater Tycho with adjacent smooth plains is used as a possible explanation of the observed relationships between the lineated pre-Imbrium terrain and the adjacent, much larger patches of smooth plains units in the southern highlands. The lineated terrain has been considered by previous investigators to be a result of either faulting associated with formation of the Imbrium basin or Imbrium secondary cratering. If the lineated terrain is produced by secondaries of Imbrium, these craters could have ejected large quantities of highland material into depressions like Ptolemaeus crater and at the Apollo 16 landing site. If so, the part of the Cayley Formation emplaced by the Imbrium event would be at most about 20% Imbrium ejecta and at least 80% ejecta from the local highlands. Other post Ptolemaeus local highland craters have also eroded the highlands and crater rims and added this material and primary crater ejecta to the Apollo 16 site. The percentage of primary crater ejecta in material contributed by local craters is considerably higher. Some smooth plains units might also consist partially of fallback breccias, impact melts or volcanic deposits.

Applications of the cratering theory to consideration of origin of materials of the Fra Mauro Formation are discussed. It is concluded that much of the material of this formation is also derived from the local terrain and it has been mixed with ejecta from the Imbrium basin. These conclusions are supported by observations of the nature of the basal units of the continuous deposits of the Ries crater. They contain significant deposits of local material that were cratered by Ries ejecta.

Abadian, M., Dence, M. R., Graup, G., and Stöffler, D.: 'Ejecta Formations and Pre-Impact Stratigraphy of Lunar and Terrestrial Craters: Possible Implications for the Ancient Lunar Crust'.

Based on geologic-petrologic data from terrestrial and experimental impact craters and their ejecta formations and on petrographic and chemical data of regolith particles of the Apollo 14, 15, and 16 sites we have checked the relations between ejecta deposits and pre-impact stratigraphy for the crucial cratering events of these sites (Cone, North and South Ray craters) and tentatively also for the Imbrium event.

Dence, M. R., Grieve, R. A. F., and Plant, A. G.: 'Characteristics of Impact Melts in the Lunar Highlands'.

Samples from the Apollo 16 site can be compared more closely with the products of large terrestrial impacts, which formed craters 20–60 km in diam, than those from other missions. As craters in this size range are common in this part of the lunar highlands, detailed comparison is encouraged. Here we concentrate on samples interpreted as impact melts from the highlands.

The suite of impact melt products ranges from glasses to fine and medium grained igneous rocks with sub-ophitic and poikilitic textures. Xenocrysts, some partly digested, recrystallized or overgrown, are generally a conspicuous 10 to 20% of the mode. The range in grain size and textures can be closely matched in samples from craters such as Lake Mistastin, Labrador and Clearwater Lake, Quebec, where the sheets of impact melt on the crater floor reach thicknesses of more than 100 m. Field and laboratory studies at these and other craters demonstrate that extreme thermal metamorphism and partial melting play only a minor role in the formation of impact melts and breccias, and in contrast with other authors we consider that this was also the case at the Descartes site. The principal mechanism in the formation of impact melts is the dynamic mixing of totally melted and locally homogenized materials from close to the point of impact with less strongly shocked rocks. The latter are incorporated into the melt during its movement across the floor of the expanding cavity. During movement, but mainly after coming to rest, assimilation and thermal metamorphism, including local partial melting, of the inclusions by the surrounding hot melt matrix takes place. Lunar examples of partial melting processes have been noted in rocks 64455 and 65075 (3) and in fragments from soil 12070 but appear to be relatively as rare on the moon as they are on earth.

Samples analysed include glasses, lithic fragments of impact melt and small, chondrule-like bodies with a fine granular matrix. The compositional array is roughly fan shaped with anorthositic rock compositions at the apex, and a base ranging from granitic to iron-rich partial melt compositions. A tight cluster of compositions at 26–28% Al_2O_3 is formed by the majority of the glasses, including all glass coatings on other fragments and by few lithic fragments. Most of the latter, the chondrule-like fragments and a number of small glass chips have more varied compositions with less than 24% Al_2O_3. The high alumina cluster corresponds to glass compositions named highland basalt while most of the less aluminous group are in the range of the Low K Fra Mauro basalt composition. A small number of more extreme mafic or siliceous compositions includes a granitic glass notable for having 2.5% Na_2O.

Data from terrestrial analogs indicate that small glassy masses from craters with heterogeneous target rocks show a spread of compositions along various mixing lines, with a tendency to cluster about the mean composition of the country rocks. Larger bodies of impact melt show a smaller spread due to more complete mixing of larger volumes of country rocks, but many still fall on mixing lines between country rocks of diverse compositions. Only in very large ($\geqslant$ 100 km) impact craters are there likely to be bodies of melt sufficiently large for gravitational differentiation to be important.

The spread of analyses in the Apollo 16 samples is remarkable considering the evidence for many large impacts in the history of the lunar highlands. In keeping with the terrestrial observations, the diversity of glass analyses is greater than that of the crystalline impact melts. The extreme glass compositions, by this analogy, probably approach the compositions of primary crustal rocks, while lithic fragment compositions are closer to local or regional averages. It is likely that the tight cluster around the highland basalt composition is a good average composition for the dominant components of the upper lunar highland crust. In this case repeated bombardment has apparently produced a significant homogenization of primary rock types which may be represented by coarser-grained components of some Apollo 16 rocks, anorthosites and less aluminous, more mafic rocks, such as troctolites. The wide compositional scatter, particularly in FeO, MgO and K_2O, of the less aluminous rocks and glasses indicates that in this range convergence towards a homogeneous composition is much less complete. The data are consistent with the view that there are no large bodies of specific Fra Mauro melt composition, and that each melt in this range represents a mix of local rocks of extreme composition, lying near the low-alumina base of the fan-like array, with material from the dominant anorthosite-troctolite suite.

The highland model thus derived is in substantial agreement with some previous suggestions; an upper highland crust approximately 20 km thick of highland basalt composition, differentiated into an anorthositic upper layer with more mafic rocks below, studded with small pockets of rocks of variable residual compositions, including granites and rocks high in Fe-Ti-K. In this model there is no requirement for magmas of Fra Mauro composition to be generated internally. However the model does require a period in early lunar history when igneous differentiation processes dominated over the homogenizing effect of impact. This may place some restraints on the duration of the postulated intense period of bombardment ~ 4 AE.

Phinney, W. C., Simonds, C. H., and Warner, J. L.: 'Impact Induced Fractionation in the Highlands'.

Petrologic processes on the Moon are not necessarily the same as those on Earth. We suggest that total and partial melting during impact events, a process insignificant on Earth, is important in the petrogenesis of the lunar highlands. The following considerations drive us to that conclusion.

(1) Why are about 85% of the non-mare rocks polymict breccias?

(2) Why do the bulk rocks at each landing site display a wide range of compositions whereas the soils show a narrower range?

(3) Why do all breccias have a significant meteorite component?

(4) Why do about half the non-mare breccias have melt-derived matrices?

(5) How can a 'primitive' (old) rock survive multiple impacts?

The answers to these questions have important petrologic implications.

(1) Most non-mare rocks are impact-produced breccias that have undergone multiple impact events, evidenced by common breccia-in-breccia texture. The compositional range of the lithic and mineral clasts is a measure of the amount of mixing that each rock has undergone.

(2) Assuming that rocks represent local bedrock, and that, to a first approximation, soils are derived by crushing of bedrock during impact events, the restricted range of soil compositions at each site reflects the mixing efficiency of impact processes.

(3) Meteorite components are additional evidence that all breccias have been mixed with the regolith (this relies on assumed base level abundances (1)).

(4) Apparently portions of ejecta and fall-back blankets reached melting temperatures, and the large fraction of non-mare breccias involved, suggest that melting processes on the lunar surface are potentially important. Total melting will have the effect of mixing, but partial melting may produce differentiation. Fractional crystallization would also produce differentiation, but rapid cooling and high clast contents make this process unlikely.

(5) A rock with high melting temperature has the best probability to survive. The few identified 'primitive' rocks are high melting-temperature cumulates.

This evidence of mixing and melting leads to the expected conclusion that non-mare rocks have recorded the intense impact history that is evident from photogeology. A straightforward prediction from these concepts is that all breccias within a 'region of mixing' should be of almost constant composition. The 'region of mixing' is defined by the saturation-crater size in the highlands: at least 50 km in diam, yielding a region of 7500 km^2 that is up to 10 km deep. However, in the area of one landing site which is two orders of magnitude smaller than the 'region of mixing', the rocks do not have a constant composition, indicating that the above prediction is wrong.

This apparent paradox may be resolved if the diversity of highland breccia compositions may somehow be ascribed to the same impacts that tend to homogenize compositions. Impact partial melting, accompanied by separation of melt and residue, is such a process. The following points test the geochemical data in the context of impact partial melting. Soils are used as an example of bulk composition of parental material within ejecta and fall-back blankets.

(6) Why do impact melts at each landing site show a definite pattern in composition from KREEP through VHA basalt to Highland basalt, even though the 'average' (soil) composition at each site is different?

(7) Why do all non-mare breccias (including impact melts) have the same slope to their REE distributions, and an inverse correlation between Al_2O_3 and many trace element (e.g., Sm) contents?

(8) Why do most crystallization ages of highland rocks fall between 3.85 and 4.05 AE, with a few as old as 4.25 AE?

(9) Why can the whole rock Rb–Sr data be approximated by a 4.6 AE, $I_{Sr} = 0.6990$ line for low Rb samples, and a 4.26 AE, $I_{Sr} = 0.69925$ line for moderate and high Rb samples?

These questions may be answered with quite reasonable assumptions that suggest the nature of the partial melting.

(6) Phase equilibrium relations show that it is possible to generate: KREEP by small (10–35%) amounts of partial melting of almost any highland soil; VHA basalt by large (ca. 60%) amounts of partial melting of a feldspathic (Apollo 16 type) highland soil, or by small (< 20%) amounts of partial melting of a feldspathic spinel troctolite (phase equilibria cannot distinguish between these two sources for VHA basalt); and Highland basalt (or higher Al_2O_3 compositions such as 68415/416) by nearly total melting of feldspathic (Apollo 16 type) highland soils.

(7) The REE data for highland and mare samples considered together demand that KREEP and VHA basalt are partial melts. Since the REE, derived mainly from accessory phases, are enriched in the first extracts of partial melts, they will be inversely correlated with the amount of partial melting, and phase equilibria relations show that Al_2O_3 from feldspar grains is directly correlated with the amount of partial melting. Hence the REE slope and Al_2O_3 correlation of KREEP and VHA may be generated by partial melting of local soil.

Since a significant meteorite component has been in all analyzed non-mare melt rocks, and most contain shocked clasts, none of them is a pure partial melt from the lunar interior. There are three possible schemes to account for the data: (i) a partial melt from the lunar interior that has been contaminated with regolith on its way to the surface, (ii) a total impact melt of a mixture of volcanic rock plus regolith, and (iii) a partial to total impact melt of regolith or bedrock plus regolith. For schemes (i) and (ii), if the volcanic rocks were young (3.9–4.1 AE), we would expect to find fragments with primary textures (which we don't), and, if the volcanic rocks were old, they would have been obliterated in the mixing of subsequent impacts. Although scheme (iii) requires physical separation of a partial melt within an ejecta or fall-back blanket, the separation distance need be only in the order of meters (the size of the largest known masses of KREEP and VHA basalt), and terrestrial impact melts do separate.

(8) The spectra of crystallization ages and the lack of older dates have been used as evidence of a lunar-wide cataclysm at about 3.9 AE. The data are also consistent with a continuum of smaller impact events of sufficient intensity and frequency to reset the radiometric clocks with a half-life of about 100 m.y. This implies that few highland rocks will age in ejecta for more than 200 m.y. before being remelted. The impacts capable of resetting ages and remelting materials seem to have stopped by 3.85 AE.

(9) These relations do not suggest a unique geologic process. Consider Rb–Sr evolution by partial impact melting starting at 4.6 AE with an average highland composition ($^{87}Rb/^{87}Sr = 0.05$, $I_{Sr} = 0.6990$); at 100 m.y. intervals from 4.6 to 3.9 AE iterate the system by aging, mixing, and partial melting; from 3.9 AE to the present the system is only aged. This model adequately matches the data.

The model accounts for the observed relations. Early in the Moon's history intense cratering continuously crushed and mixed most material on the lunar surface to a depth of at least 10 km while simultaneously generating impact melts in ejecta and fall-back blankets. These events continued from the formation of the Moon to 3.85 AE, with a thermal cycle of 100 to 200 m.y. The observed diversity of highland rock compositions (excluding the 'primitive' cumulates) is largely due to partial melting of surface materials during impact events.

Residue from this partial melting process must meet well-defined chemical criteria: (i) Al_2O_3 and CaO higher than the parent (local soil), (ii) MgO greater than FeO, (iii) TiO_2, K_2O, and REE lower than the parent. Uncertainty about the residue texture of an impact partial melt allows several alternatives: 61016 is a high ^{87}Sr cataclastic anorthosite; 67955 is a light matrix breccia; 61295 is a glassy to melted matrix breccia; and 68815 is a devitrified glass. We favor cataclastic anorthosites as the residue since they are the white material in the migmatitic black and white rocks. Other workers have suggested that there are two series of anorthosites. Perhaps one of these is derived from the Moon's original crust and the other from the residue of impact partial melting.

Crawford, M. L. and Hollister, L. S.: 'Feldspathic Basalt 14310, A Lunar Mantle Derived Magma'.

Despite the increase in the number of lunar samples with the composition of KREEP, its origin has not been established. We have continued our efforts in understanding the crystallization history of feldspathic basalt 14310, A KREEP basalt, in the hopes that we might arrive at an interpretation of its origin and hence the origin of other lunar samples with the composition of KREEP. In addition to our detailed studies of the pyroxenes and feldspars in 14310,21, the interpretation given below is based on the papers on 14310 in the Proceedings of the Third Lunar Science Conference and on the work of James.

In this, as in other lunar rocks, the minor element variations in the pyroxene and feldspar are critical to obtain a complete crystallization history. In 14310, we have recognized two generations of orthopyroxene based on the Al_2O_3 zoning trends. The first, or core, bronzite ($En_{76}Fs_{20}Wo_4$) has a low (less than 2 %) but variable Al_2O_3 content while the second, which surrounds the first, is slightly but uniformly more magnesian ($En_{79}Fs_{18}Wo_3$) and has higher Al_2O_3 (up to 3.6 %) adjacent to the boundary of the core grains. Outward from the boundary, the Al_2O_3 content drops moothly to a level comparable to that of the core bronzite. Minor elements in plagioclase are used to determine the crystallization sequence by assuming that the later plagioclase will have a higher Fe/(Mg + Fe) and K/Na ratio due to concentration of Fe and K in the melt as crystallization proceeds. The correlation of Fe/(Mg + Fe) in plagioclase in 14310 to the progressive decrease in grain size from mm long blocky grains to large, medium and then fine tabular crystals supports the reliance on minor element variation as a guide to the order of crystallizaion.

We propose the following interpretation for the history of sample 14310:

(1) Crystallization of sodic augite together with the first generation bronzite. The sodic augite occurs as blebs enclosed within the core bronzite as described by Hollister, *et al.* The experimental evidence suggests this clinopyroxene may have crystallized at pressures as high as 15 kb. The minute amount of clinopyroxene observed and the absence of spinel, which crystallizes with the clinopyroxene in the experimental charges, suggests the crystallization at high pressure was possibly followed by resorption of early crystals. The earliest plagioclase may accompany the crystallization of the core bronzite, but this cannot be demonstrated; it forms the cores of the large blocky grains, has the lowest Fe/(Mg + Fe) ratio (0.17–0.25) and the highest anorthite content (An_{96}) of any in the rock. The core bronzite and the core of the blocky plagioclase grains are free of inclusions (with the exception of the sodic augite) in contrast to later pyroxene and plagioclase.

(2) Crystallization of orthopyroxene ceased but growth of blocky plagioclase continued. The Fe/(Mg + Fe) ratio of the plagioclase changes from 0.25 to 0.38 and it becomes slightly more sodic (An_{92}). This is interpreted to correspond to continued crystallization of plagioclase during the rise of the magma, outside the field of crystallization of pyroxene + plagioclase (10 to 0 kbars).

(3) Near the outer margins of the blocky plagioclase grains there is a sharp decrease in anorthite content (to An_{86}), with no accompanying change in Fe/(Mg + Fe) ratio. This is interpreted as reflecting the initial exsolution of volatiles from the melt and probably occurs when the magma is very close to or at the surface.

(4) The second generation of orthopyroxene, slightly more magnesian than the first, starts to crystallize at or shortly after the abrupt change in plagioclase content, accompanied by nucleation and growth of the coarsest of the tabular plagioclase grains. Small bronzite needles about 20 mμ long and a few mμ in width are enclosed within the cores of plagioclase of An_{86} on the rims of the blocky grains. The first generation bronzite also served as a nucleation site for this second bronzite and in a number of places tabular plagioclases have nucleated on that boundary and are enclosed in the second bronzite. The initially high Al_2O_3 content of the second bronzite is probably due to rapid growth in a highly aluminous melt. Many of the bronzite grains trapped me.t which later crystallized to plagioclase with a distinctive high K content. As plagioclase continues to nucleate and grow, in large part as radial aggregates of tabular grains, the Al_2O_3 in the bronzite decreases and reaches a level equal to or slightly below that of the core bronzite ($T \approx 1200°$). Individual grains of second generation orthopyroxene, some with cores of first generation orthopyroxene, occur in intergrowths which can best be interpreted as a group of grains growing outward from a common nucleation area.

When these clusters are intersected by the plane of a thin section the intergranular relations can be quite complex.

(5) Due to the rapid initial growth of plagioclase and pyroxene and consequent release of heat of fusion, the rate of temperature decrease is slowed and possibly even reversed locally. This is interpreted to result in complex crystallization trends in the outer zones of the second bronzite. Some continue to crystallize as orthopyroxene, reaching compositions of $En_{60}Fs_{36}Wo_4$. James reports even more iron rich hypersthene. Others zone continuously outward to pigeonite ($En_{59}Fs_{31}Wo_{10}$) followed by augite ($En_{41}Fs_{28}Wo_{31}$). A number of grains which follow the latter trend show evidence of inversion of the earliest pigeonite back to orthopyroxene with accompanying exsolution of augite lamellae parallel to (100), as discussed by James.

(6) The plagioclase crystallization trend splits into two parts as a result of the onset of liquid immiscibility in the remaining melt. One of the liquids is enriched in K, Ba and Na and precipitates plagioclase to $An_{73}Ab_{22}Or_5$ followed by a Ba–K phase. The other liquid, depleted in the above elements, precipitates anorthite ($An_{93}Ab_6Or_1$), high iron pigeonite, and fine grained plagioclase-pyroxene clots. The immiscible liquids reported by Roedder and Weiblen from sample 14310 may represent only the final stages of this immiscibility.

Our data are consistent with a mode. of the 14310 melt being generated at depth (>300 km) in the Moon, partially crystallizing during ascent, and finally quenched at the surface. Based on the systematic, multiple history reflected in the plagioclase and orthopyroxene zoning, the 14310 melt is unlikely to have resulted from a simple quench of an impact produced melt.

Richter, D., Schatz, J., Siegfried, R., and Simmons, G.: 'Estimating Peak Shock Pressures for Lunar Rocks'.

In order to understand the way in which crack distributions are affected by shock waves, and thus determine the peak shock pressures to which the lunar samples have been subjected, we have studied a set of terrestrial rocks shocked to known peak pressure.

A suite of granodiorite samples has been obtained from the vicinity of the Piledriver underground nuclear test in Nevada where the shock pressures were monitored in the ground surrounding the shot point. Our samples were cored after the device was detonated. The maximum shock pressure experienced by our samples was 52 kb.

We have measured static linear compressibility and compressional velocity in two orthogonal directions ($\parallel$ and $\perp$ to the core axis) for the shocked samples and for a virgin sample collected from the area before the explosion. From the strain vs pressure curves for our samples, we have determined a parameter that is related to the crack porosity of the sample due to cracks oriented roughly normal to the direction in which the compressibility was measured. This parameter, $\eta(l)$, is the zero pressure intercept of the linear part of the strain vs pressure curve. For an isotropically cracked rock, it would be equal to 1/3 of the total crack porosity, η_c. Since a typical lunar rock has probably been exposed to shock waves from several events in different locations, the shock induced crack distribution is likely to be isotropic in lunar samples. Therefore, in order to compare our results for terrestrial rocks shocked by one event with lunar samples, we consider an effective crack porosity, $\eta_c(\text{eff}) = 3\text{Max}[\eta_c(l)]$. $\eta_c(\text{eff})$ is the crack porosity that one of our samples might be expected to have if it had been subjected to several shock events arriving in different directions. We use $\eta_c(\text{eff})$ and other information derived from compressibility curves and velocity measurements to characterize the crack distributions in shocked rocks. These crack distributions will then be related to the peak shock pressure to which a sample has been exposed by means of comparison with samples exposed to a known peak shock pressure.

Further study of crack-related properties of shocked rocks may help us to better understand the relations between physical properties and peak shock pressures. In particular, the fact that lunar samples group according to rock type raises such interesting questions as this – do the breccias have a high crack porosity because they have been shocked repeatedly, because they have been shocked strongly, or because of the particular response of breccias as a rock type to shock waves?

Scolar, C. B. and Bauer, J. F.: 'Shock Effects in Lunar Rocks 60015 and 77017'.

Lunar rock 60015 is a white coarse-grained anorthositic rock which is coated with dark-brown vesicular glass. The interior of the anorthositic rock (section 60015,127) consists of highly strained plagioclase set in an intergranular and interstitial matrix of very fine-grained aggregates of plagioclase of the same composition. The intergranular aggregates of plagioclase commonly are arranged in palisade-like structures oriented normal to the margins of contiguous large plagioclase crystals; the interstitial pockets of plagioclase show near-center seams and voids toward which crystallites of plagioclase apparently grew. Although the outer part of the rock appears to be devoid of the fine-grained plagioclase aggregates, a zone of fine-grained plagioclase commonly with palisade structure up to 200 μ in thickness occurs at the contact between the anorthositic rock and the dark glass (section 60015,130). The structure of the fine-grained plagioclase has been interpreted as the result of directional crystallization from a rapidly cooled melt of plagioclase composition. Such melts may have been produced by shock-induced intergranular melting of either pre-existing anorthosite or, more probably, porous anorthositic breccia derived from the regolith of the lunar highlands.

A microscopic study of rock 60015 in reflected light revealed the presence of a minute quantity of metal particles. The metal grains occur solely in the fine-grained plagioclase aggregates in the form of angular interstitial fillings less than 15 μ in size. Electron probe analysis shows that the metal grains are virtually pure iron which contains 0.20 to 0.25 % cobalt and 0.10 to 0.15 % nickel. Cobalt is invariably dominant over nickel. The composition of the metal and its Co/Ni ratio are consistent with the hypothesis that the fine-grained aggregates of plagioclase represent a quenched shock-induced me.t derived from the large plagioclase crystals by intergranular melting. The metal was probably produced by reduction of iron, cobalt, and nickel ions in the shock-produced liquid of plagioclase composition, and apparently crystallized from the plagioclase melt as a relatively late interstitial phase. Shock-induced reduction of iron ions to metallic iron in the lunar environment has been suggested previously to explain the occurrence of metallic iron in Luna 20 plagioclase, subsolidus reduction of ilmenite xenocrysts in shock-produced basaltic glass to iron plus rutile, and the abundance of metallic iron in shock-produced basaltic glass.

Lunar rock 77017 is a coarse-grained anorthositic gabbro which in section 77017,65 is almost completely surrounded by a thin rind of pale-brown vesicular glass. The gabbro contains olivine which occurs as euhedral to subhedral crystals surrounded by single-crystal mantles of pyroxene and as relatively small round grains enclosed in plagioclase. The pyroxene occurs as large poikilitic plates which enclose euhedral to subhedral plagioclase and which are commonly in optical continuity with the pyroxene mantles of the olivine. The pyroxene is pigeonite which contains coarse exsolution lamellae of augite parallel to (001). The rock also contains a relatively large amount of metal (perhaps one or two per cent by weight) which is commonly associated with troilite. The metal occurs as very large irregular grains up to 300 μ in size which form void-free interstitial fillings between the silicate grains. The textural relationships suggest that it is a late-magmatic constituent. The composition of the metal as determined by electron probe analysis is 87–95 % iron, 7–13 % nickel, and 0.5–1.0 % cobalt. The gabbro appears to have been shocked as based on undulatory extinction and mosaicism of the plagioclase and the very intense fracturing of the plagioclase. In addition, the rock contains narrow zones of relatively finegrained crushed material of the same mineral composition as the main body of coarse-grained rock. There is no textural evidence for movement or transport of the comminuted material of the kind which is characteristic of cataclastic tectonites and the crushed zones are considered to be produced by shock. A detailed study of the microstructure of the meta. in this rock is in progress inasmuch as the inferred shock history of the rock should be recorded in the metal.

There are about six reported occurrences of a regular micro-intergrowth of K-feldspar and quartz in the returned lunar samples. One of the largest occurs as a clast about one square mm in diameter in glassy-matrix breccia 12057,22. Such granitic material is of considerable importance in the development of petrogenetic models of lunar evolution. Accordingly, in collaboration with M. Prinz and K. Keil, an electron microprobe study of the phase chemistry of the granitic clast in 12057,22 has been completed, and the petrological implications of the results are under consideration.

Cole, D. M. and Ahrens, T. J.: 'Shock Compression of Lunar Fines Apollo 17'.

A series of samples of 70051 consisting of angular lithic and mineral fragments ($\sim$ 5 to 100 μ) of pyroxene ($\sim$ 60 %), plagioclase ($\sim$ 30 %), brown glass and opaques ($\sim$ 10 %) has been shocked to pressures of 126 kbar. The sample is largely from rocks (70017, 70215, 76055, 77035 and 74035) colected in the BSLSS bag (EVA III) and is probably representative of the gross lithology at the base of the North Massif. Cylindrical samples, 4 mm thick, 16 mm diam having an initial nominal density of 1.80 ± 0.01 g cm^{-3} were prepared by cold compression. Initial densities are calculated from exact sample dimensions and masses. Projectile and shock velocities were obtained by laser obscuration and streak camera techniques. Below 50 kbar, the present data lie close to the extrapolated static compression curve for the lunar fines examined by Stephens and Lilley suggesting that the low pressure irreversible compaction behavior of these two samples is roughly similar. However, the single datum for powdered Vacaville basalt lies at least 25 kbar above the lunar data. In order to separate the effects of mechanical resistance to shock induced compaction and shock heating, we have constructed a theoretical intrinsic mineral Hugoniot from the following chemical and mineral model: SiO_2 (wt %) 40; TiO_2, 9.3; Al_2O_3; 11.2, FeO, 17.3; MgO, 9.7; and CaO, 10.9. Agglutinates (vol %) 32, basalt fragments 19, plagioclase 8.5, pyroxene 21, opaques 5.6, glass spherules, 5.7, metal spherules, 1.5. This model is based on an analysis of soil samples (70161, 70181, 71061, 71501, 75061, and 75081). Assuming Stephens and Lilley compression curve for a material with crustal density of 3.13 gm cm^3 and a Gruneisen's parameter of 0.8, the theoretical Hugoniots for various distensions, $m = \varrho_0/\varrho_{00}$, are calculated. (Here ϱ_{00} and ϱ_0 are the distended and crystal densities.) The present data, corresponding to $m = 1.74$, lie close to the $m = 1.7$ curve. This analysis implies that irreversible shock compaction occurs at ~ 50 kbar and at higher pressure, the Hugoniot is controlled by heating effects. Above 150 kbar this model will be invalid due to phase changes in the silicates. Using the method of Ahrens and O'Keefe the impact velocities required of iron and stoney meteoroids to produce complete post-shock melting of lunar fines is given.

Cisowski, S., Fuller, M., Rose, M. F., and Wasilewski, P. J.: 'Impact Processes and their Effect on Lunar Magnetism'.

The natural remanent magnetization (NRM) of a particular lunar sample is predominantly controlled by three factors; the magnetic characteristics of the carriers of NRM, the mechanism of magnetization and the ambient field in which the magnetization was acquired. Each of these three factors may in certain instances be affected by impact processes. We have undertaken a variety of experimental studies to assess the probable importance of the effect of shock upon the magnetic characteristics of the carriers of lunar NRM and to calibrate field and shock level dependence of the shock remanent magnetization (SRM).

In order to characterize the magnetic carriers of remanence in lunar samples, we have relied primarily upon their saturation magnetization (J_s), saturation remanent magnetization (IRM_s), initial susceptibility (X_0), coercive force (H_c) and remanent coercivity (H_{RC}). In particular we have found that plots of IRM_s/J_s against X_0/J_s reveal a progressive increase of grain size of the ferromagnetic iron from that in the soils and unannealed breccias, through annealed breccias to that in igneous rocks. Thus in assessing the effect of shock upon the magnetic characteristics of the ferromagnetic material, we compare shocked material with its unshocked analogue in terms of these hysteresis parameters. To describe the shock remanent magnetization (SRM) acquired in the experiment, its alternating field (AF) and thermal demagnetization characteristics have been determined.

Three types of material have been used in the study. First, artificially shocked lunar samples were used to provide the calibration of shock effects. Second, individual hand-picked soil particles, which can be compared magnetically with large samples of similar rock type have been used to obtain an estimate of the magnetic effects of the comminution process. Third, samples from the LONAR impact crater have been used to provide naturally shocked and control basaltic material.

1. *Artificial Shock Experiments.* In earlier experiments soil samples were shocked to 50, 75, 100 and 250 kb using a modified flying plate technique and the magnetic characteristics of the sampes were found to be markedly changed. In the 50, 75 and 100 kb samples the coercive force (H_c) and saturation remanence (IRM_s) increased substantially. In the 250 kb sample these parameters did not change but additional fine iron was produced. These experiments were carried out in the earth's field and remanence of 10^{-3} to 10^{-4} gauss cm^3 g^{-1} was generated. This remanence exhibited alternating field (AF stability) similar to partial thermal remanence (pTRM). The shock remanence (SRM) however had more distributed blocking temperatures, suggesting inhomogeneous heating.

Powdered samples prepared from 12053, have now been subjected to 75 kb shock. A spectacular increase in saturation remanence and remanent coercivity was observed when these parameters were compared with those of the starting material. The remanent magnetization acquired is relatively soft and hence unlike that of the pTRM-like shock remanence acquired by the soil. It may be distinctive of an isothermal type of shock remanence. The characteristics exhibited by the powdered rock are not unlike those of a number of lunar samples. The simplest explanation of the difference between the shock remanence of the soil and that of the powdered rock is related to the presence in the former only of near superparamagnetic iron with low blocking temperatures. Thus, it alone acquires pTRM in the low temperatures to which the samples are heated in the shock experiment. These experiments are being continued with solid rock samples. With the use of an air gun they will be extended to calibrate field and stress dependence of shock remanence in the low stress, low field region.

2. *Hand-picked Soil Particles (10086,30)*. The study of individual soil particles permits a direct observation of the magnetic effects of the comminution process or by comparison of igneous soi. particles with their parent type. It also makes available such interesting particles as glassy agglutenets and orange soil glasses for magnetic studies. Individual fine basalt, coarse basalt, breccia, microbreccia, and glassy agglutinate particles varying in mass from 0.0001 to 0.003 g were separated by Dr G. Eglinton and were studied in our laboratory. Critical magnetic characteristics were observed and the NRM of individual particles studied. All particles exhibited strong saturation isothermal remanence and high remanent coercivity (H_{RC} varied from 350 to 900 Oe). Even igneous fragments exhibited remanent coercivities as high as 700 Oe which is far greater than those of the parent rock type. All particles carried NRM. The intensity varied from 10^{-3} to 10^{-6} G cm^3 g^{-1}. The AF stability of NRM was very variable with one microbreccia almost untouched by demagnetization to 900 Oe, while other samples decreased sharply in low fields of 100 Oe, so that demagnetization had to be terminated. Although complete thermal demagnetization remains to be carried out, it is already clear that the remanence is not entirely a low temperature pTRM. It therefore appears that the process of comminution which gives rise to soil profoundly alters the characteristics of the carriers of NRM in the individual particles. It is possible that the process actually generates magnetization since the NRM of igneous fragments in the soil appears to be large compared with those of equivalent igneous rock samples. Such remanence would add another lunar magnetic puzzle, since unless it was generated during the early history of the moon, the origin of the necessary magnetic field is obscure.

3. *Lonar Samples*. Lonar crater is in the Buldana District of Maharashtra India in the Deccan traps. It is 1800 m across and 150 m deep. Samples have been obtained from the crater rim basalts, from drill holes within the crater and from trenches cut in ejecta material within 100 m of the crater rim. Many of the samples were obtained for us by Dr J. Fredriksson. The majority of the rim basalts studied carry stable NRM which appears to be the primary NRM of the lava and unaffected by the impact. They serve as control samples. In contrast, a basalt from drill hole exhibited soft NRM similar to the isothermal-like shock remanence carried by the powdered lunar sample 12053,35. A breccia from the drill hole had a low intensity of NRM which was unstable in direction. Glass from the ejecta exhibited strong and stable NRM. The NRM of the basalts from the trench in the ejecta had rather low NRM compared with the control basalts, although some carried NRM indistinguishable from that of the control samples. The ejecta from this crater carries a wide variety of NRM; some samples such as the glass have NRM which is clearly due to the impact, but the NRM of some basalts is apparently unaffected by the impact. The directions of magnetization within the ejecta are not coherent, but vary from sample to sample. Work is continuing to assess the effect of shock upon the characteristics of the carriers of NRM in these rocks. At this point it is clear that a variety of rocks are available at this site which may throw light on lunar impact processes. An important preliminary indication is that the ejecta material is not coherently magnetized, so that individual large fragments carry a record of earlier history and the ejecta does not give rise to a substantial magnetic anomaly.

These studies reveal that impact related shock can have a profound effect on the magnetic characteristics of carriers of NRM and that in some instances it can generate NRM. In the lunar samples the major effect appears to be an increased capability to carry remanence and hardening of the carriers. The increase of remanent coercivity of the 12053,35 powder on shocking to 75 kb was particularly remarkable, as was the magnitude of SRM it acquired. The AF demagnetizaion of the SRM of the sample is similar to that of a number of lunar samples. Individual soil particles exhibit magnetic characteristics which suggest that the process of comminution involves similar effects to those of the experimental shock. For example, the remanent coercivity (H_{RC}) and saturation remanence (IRM_s) of igneous fragments in the soil is large compared with those of the parent rock types. These samples also appear to have anomalously large NRM. The samples from Lonar crater gave evidence of the softer isothermal type of shock remanence in basalts. Ejecta shows very variable NRM in individual large fragments and is not coherently magnetized. These results suggest that the role of shock in determining the magnetic characteristics and indeed the NRM of certain lunar samples may have been seriously underestimated in the past.

Christie, J. M., Fisher, R. M., Griggs, D. T., Heuer, A. H., Lally, J. S., Nord, G. L., Jr., and Radcliffe, S. V.: 'Electron Petrographic Evidence Concerning the Origin and Lithification of the Lunar Breccias'.

In a previous publication we proposed, from analysis of Apollo 14 and 15 samples by high voltage electron microscopy (HVEM), a simple classification of the lunar breccias based on the presence or absence of recrystallization in the matrix. New observations on Apollo 17 breccias 79035,30 and 73275,33 indicate that the microscopic and submicroscopic structures are similar to those observed in the earlier study.

Sample 79035,30, collected from the ejecta of Van Serg Crater, is a dark, fine-grained, friable, porous breccia with clasts of ilmenite-rich basalt, fragment-laden vesicular glass-bonded breccia, black and orange glass spheres and fragments and a green glass splash on the surface. The basalt fragments exhibit moderate deformation, as shown by undulatory extinction in plagioclase and augite and abundant twinning in ilmenite. The fine-grained matrix was examined by HVEM and found to be rich in glass, which cements both crystalline and pre-existing glassy fragments and spherules. The matrix glass may be homogeneous or 'spotted' and vesicular. The homogeneous glass commonly cements the vesicular glass and is thus of a later origin. The clasts range from undeformed to deformed or partially recrystallized (suggesting that the internal structures are inherited) and in some clasts, particle tracks are well preserved, indicating that the temperature of the cementing glass was never sufficiently high to anneal these features. This is a class *A* breccia resembling 14301.

Sample 73275, collected from the light mantle material at station 3, is a light colored, feldspathic breccia with very low porosity but some irregular 0.1 mm size vesicules. Large clasts of plagioclase (1.0–0.3 mm) and smaller olivine (0.05–0.2 mm) and orthopyroxene (0.1–0.2 mm) are well recovered and have reaction rims with a fine (0.05–0.001 mm) recrystallized matrix, coarser than that observed in 15418. The plagioclase clasts are anorthitic, An_{97-90}, one of which exhibits optically visible exsolution, indicative of a long, high temperature thermal history. The rims of the clasts and the groundmass plagioclase are more albitic, An_{85-90}. In the electron microscope we have observed recovered structures, resorption of twins in plagioclase clasts, and exsolution in the recrystallized matrix plagioclase. This is a class *B* breccia, more extensively recrystallized than 15418 (1).

Electron microscopy of single crystal enstatite En_{85}, shocked to 226 kb and single crystal plagioclase An_{65}, shocked to 100 kb by R. Gibbons showed extensive fracturing but no plastic deformation or vitrification, except for slight glass formation along some cracks in the enstatite. This contrasts markedly with the substructure of lunar dust shocked to comparable stresses.

The optical and electron petrographic evidence from all of the lunar samples that we have examined appears to warrant two important generalizations regarding the formation of the lunar breccias. (a) The absence of plastic deformation and shock vitrification in most of the igneous rocks collected on the Moon and in many of the mineral and rock clasts in the breccias indicates that the basement igneous rocks cratered out by impacts on the lunar surface are in a relatively undeformed condition when they first become part of the regolith. (b) The substructures of all the breccia samples that we have examined are consistent with the hypothesis is that they were simultaneously deformed and consolidated by shock waves from one or more impact events affecting porous regolith material of varied provanance*. The class *A* breccias were cemented by glass, produced by shock ($\leqslant 50$ kb) at clast boundaries and the class *B* breccias were lithified by extreme deformation of the finer grained mineral and glass clasts by stronger shock waves, followed by recovery and recrystallization caused by heating in the same shock event. We cannot exclude the possibility that some recrystallization may be due to pure thermal metamorphism of previously lithified breccias, but our sampling suggests that this process is of minor importance.

17. Characterization and Evolution of the Lunar Crust: III

Chyi, L. and Ehmann, W. D.: 'Implications of Zr and Hf Abundances and their Ratios in Lunar Materials'.

In continuation of our studies of Zr and Hf abundances in lunar materials we have directed our attention to their modest fractionation among various lunar rock types.

The four major rock types which include mare basalt, KREEP basalt, very high aluminum basalt, and anorthosite can be readily distinguished based on Zr and Hf abundances and Zr/Hf ratios. Mare basalts have moderate Zr–Hf contents grouped according to missions from an average of 111 ppm for Apollo 15 up to 534 ppm for Apollo 11, and low Zr/Hf ratios ranging from 38.8 for Apollo 15 down to 33.9 for Apollo 11. KREEP basalts are characterized by very high Zr contents (Zr mean = = 1380 ppm) and high Zr/Hf ratios (mean = 48.2) Very high aluminum (VHA) basalts have an average Zr content of 296 ppm which is much lower than that for the KREEP basalts, but their mean Zr/Hf ratio of 46.8 is very similar to that of KREEP basalts. Hence, our Zr–Hf data do not reveal whether the VHA materials represent an independent magma type, or are related to KREEP basalts. Anorthosites have very low Zr and Hf contents. Owing to the difficulty of measuring the Zr content at this low level, we cannot report a reliable Zr/Hf ratio at the present time. However, if Apollo 16 soils are derived from anorthosite, VHA basalts, and KREEP basalts, the Zr/Hf ratio in typical anorthosites must be lower than 45.5 which is the average ratio for Apollo 16 soils. It is worth noting that Apollo 14 rock 14053 with Al_2O_3, FeO and MgO contents intermediate between those of typical mare basalts and those of VHA basalts has a Zr/Hf ratio also intermediate between the ratios for these two rock types. The orange soil from the Apollo 17 mission has a very low Zr/Hf ratio (32.6) which is lower than for any lunar rock types discovered. This indicates that the orange soil cannot be produced by simple mechanical mixing of any identified rock types for which data are presently available. We have previously suggested that these modest Zr–Hf fractionations may be due to a Zr–Hf charge disparity under extremely reducing conditions, where Zr exists as 3+ while Hf remains as 4+.

Because of the geochemical coherence of Zr and Hf, their improbability of forming volatile complexes in the lunar environment, and their very low abundances in both chondritic and iron meteorites, the Zr/Hf ratios in lunar rocks should be representative of their original magmas, and relatively independent of cooling rates, release of volatiles, and surface processes. Although the Zr contents in ilmenite and ulvöspinel are a function of temperature and may change due to subsolidus redistribution if the magma has been cooled slowly enough, the Zr/Hf ratios as established by bulk chemical analyses should always represent the original ratios at the time the rock was first solidified.

Jakeš, P. and Taylor, S. R.: 'Geochemical Zoning in the Moon'.

The lunar samples returned by the Apollo missions display many unique geochemical features, compared to terrestrial rocks or meteorites. These include (1) depletion of volatile elements (Rb, K, Tl) (2) depletion of siderophile elements, with volatile elements (e.g. Ag) depleted more than refractory ones (e.g. Ir) (3) enrichment of many refractory elements (Ba, Zr, Hf, REE, Th, U) by two orders of magnitude over primitive CCI abundances (4) high abundances of Mg(Cr in aluminous crustal rocks (5) similarity of volatile/involatile element ratios (e.g. Cs/U, K/Zr, K/La) in mare and highland rocks (6) high Cr/Ni ratios (7) Eu anomalies (8) occurrence of several types of mare basalts with varying Mg/Fe, Ti, Ree and Eu depletion.

We attempt here to reconcile the geochemical information with the geophysical constraints and the sequence of geological events. We assume that the Moon accreted from refractory material from which the volatile elements (Rb, Pb, Tl, Bi, Cs etc.) had already been depleted. The volatile siderophile elements (Ag) were depleted, more than refractory ones (Ir) as shown by Re/Ir/Ni/Au/Ag ratios.

The accretion was homogeneous since there is (a) good correlation between volatile/involatile element ratios (e.g. Cs/U, K/Zr) in both highland and mare samples, (b) the element distribution in crustal rocks is governed not by volatility differences, but by ionic radius and valency, indicating crystal-liquid equilibria. If heterogeneous accretion models are excluded, very efficient large scale element fractionation must occur, implying melting of most of the Moon. The heat source is accretionary. Initial cooling takes place by convection. The lunar interior is highly reduced because of lack of volatiles. Large scale melting is consistent with the lack of major seismic discontinuities between 60 and 1000 km.

Two alternative models may account for the deep lunar interior (below 1000 km):

(a) An immiscible Fe–FeS liquid sinks to form a core effectively removing most siderophile and chalcophile elements. The core radius is restricted to < 700 km by the moment of inertia (0.395). Enough sulfur is retained to form FeS. The partially liquid zone below 1000 km is interpreted as due to dispersed FeS in olivine-orthopyroxene matrix. The magnetic field results from a core dynamo.

(b) The meeting did not extend below 1000 km. The center is primitive unfractionated material, now partially molten due to trapped K, U and Th. This model precludes core formation, since, sinking Fe–FeS wi.l drive incompatible elements upwards. This model is a better fit for the P wave velocities. The magnetic field is external. The choice between these depends critically on the amount of the early siderophile and chalcophile element depletion. If the siderophile elements were accreted, a lunar core is required to remove them.

Following accretional melting, the first silicate phase to separate is Mg-rich olivine, which removes Ni^{2+}, and lesser amounts of Cr^{2+} and Co^{2+}. As crystallization proceeds, orthopyroxene precipitates. In the low pressure (<50 kbar) environment, most cations except Mg, Fe, Ni, Co and Cr^{2+} are excluded from the olivine and orthopyroxene lattice sites, and migrate upwards. These include Ca and Al. The high Cr^{3+} values indicate that separation of clinopyroxene below 300 km was minor. A frozen crust quickly developed, although continually broken up by the declining meteoritic bombardment. This frozen surface layer, analogous to a chilled margin retained high concentrations of Mg, Cr etc. in near surface regions. These elements are not derived from chondritic meteorites, which would have contributed high Ni, Ir etc. Because of the refractory nature of the total lunar composition, and the low abundance of volatiles and K, a granitic type residual phase does not form at first, and a Ca-Al rich residuum develops. Increasing crystallization at depth leads to an increasing concentration of these elements, trapped under the frozen surface layer. When the concentration of Al reaches 12–17 % Al_2O_3, An-rich plagioclase precipitates, and concentrates beneath the frozen surface whereas the Mg–Fe phases sink. The Ca–Al rich region incorporates Sr^{2+} and Eu^{2+}, but most other elements are unable to enter the Ca^{2+} sites.

As crystallization proceeds in both top (crustal Ca–Al) and bottom (mantle Fe–Mg) regions, additional fractionation changes the Mg/Fe ratio, produces zones of Fe–Ti oxide accumulation and further removes the siderophile elements. Those elements unable to enter the plagioclase above or the Mg–Fe sites below are trapped between. In this zone, all the remaining elements concentrate. These include K, Ba, Rb, Cs, REE, Th, U, Zr, Nb. Thus following the primordial fractionation, a chemically zoned Moon is produced.

The crustal zonation established at about 4.5 aeons is changed very quickly. The declining stages of the meteoritic bombardment pulverize the chilled zone and larger impacts mix in the underlying anorthosite. The high concentration of heat-producing elements K, U and Th (and Zr, Hf, REE etc.) beneath the plagioclase zone provide the high element abundances for the Fra Mauro or KREEP basalts. Possibly this zone did not solidify but the residual liquids invaded the crust, where impact mixing of the primitive surface, layer, the plagioclase and the residual liquids produced the parent material for the anorthositic gabbro (highland basalt) and the Fra Mauro basalts. The stage continues to 3.9 aeons, culminating in the production of the ringed basisn and the cessation of the intense highland cratering. The high heat flow (0.7 HFu) is due to the near surface concentration of most of the lunar K, U and Th.

Partial melting next occurs in successively deeper layers as the lesser amounts of the heat producing elements induce partial melting, and a succession of 'mare-type' basalts are erupted. The first of these are the aluminous (12–13 % Al_2O_3 basalts (e.g. 14053, 14072) from shallow depths beneath the KREEP source layer. These overlap with the later stages of the bombardment, and predate the Imbrium collision in part, as shown by their presence in Fra Mauro breccias. Next (3.8–3.6 aeons), the Ti-rich Apollo 11 and 17 basalts are erupted from a zone where Fe–Ti oxides accumulated. They have ~ 1 ppm Ni. Later (3.4–3.2 aeons) the Apollo 12 and 15 quartz and olivine normative basalts were extruded. These contain nickel indicating extensive partial melting involving olivine, and show evidence of near surface fractionation. The deepest material erupted is the Apollo 15 emerald green glass (15426) with 180 ppm Ni and primitive REE patterns, low total REE (3-5X chondrites) and no Eu anomaly.

The model is consistent with a total Moon composition, relative to primitive Solar System abundances, highly depleted in volatile and strongly siderophile elements and enriched 2-5X chondrites in the refractory elements.

Birck, J. L. and Allegre, C. J.: 'Constraints Imposed by ^{87}Rb–^{87}Sr on Lunar Processes and on the Composition of the Lunar Mantle''.

Rb–Sr dating of Apollo 16 and 17 rocks has resulted in an age of 3.9 b.y. for the brecciated anorthosites and of 3.83 b.y. for the basaltic igneous rocks. These ages were obtained from internal isochrons.

The initial ($^{87}Sr/^{86}Sr$) ratio of the brecciated anorthosite is rather high, but some of plagioclase in those breccias have conserved a lower initial strontium isotope ratio. These observations may be interpreted as indicating an impact metamorphic event at 3.9 b.y. ago.

The ($^{7}Sr/^{86}Sr$) initial ratio of the basalts is very low, one Apollo 17 basalt has even an initial strontium isotope ratio smaller than BABI. The total rock strontium isotopic composition of all anorthosites and norites from the lunar highlands fall on, or very close to, 4.5 ± 0.2 b.y. isochron. The total rock strontium isotopic compositions of all lunar basalts, except the high K Apollo 11 basalts, plot also in this isochron, notwithstanding that these rocks have widely differing Rb/Sr ratios. A really trivial consequence of this observation is that lunar soils should, and indeed do, plot on or close to, this isochron. Isotopic reequilibration occurring after the 4.5 ± 0.2 b.y. is responsible for the minor deviations shown by the lunar soil points on our isochron plot.

The fact that the total rock strontium isotopic compositions of nearly all lunar rocks fall on this isochron of 4.5 ± 0.2 b.y. implies that no Rb/Sr fractionation has occurred since then. Accepting the petrological estimate that the lunar basalts are the result of a 15 to 25 % partial fusion of the lunar mantle, one may draw one of the following conclusions:

(1) The internal isochron age is the solidification age, which occurred quite soon after partial fusion of the lunar mantle. The basaltic liquid rose to the surface without being contaminated. No fractional crystallization giving rise to different liquids after partial fusion occurred. In this case, the lunar mantle should contain less than 0.2 % plagioclase in order to prevent Rb/Sr fractionation and according to the Apollo 12 and 17 basalts, the lunar mantle should be heterogeneous. Further, one will have some problems in interpreting the initial ($^{87}Sr/^{86}Sr$) ratio as has been pointed out by Wasserburg.

(2) Same as point (1), but during their ascent to the surface, the basaltic liquids were contaminated. To preserve the 4.5 ± 0.2 b.y. age, no Rb/Sr fractionation should occur subsequently. If this interpretation is correct, one should observe a linear mixing relationship for the samples of the same site. Except for the Apollo 14 basalts, no mixing relationships have been observed for the samples of the same site.

(3) Partial melting and genesis of the basalts took place at 4.5 ± 0.2 b.y. The internal isochron ages give the age of remelting and solidification. The remelting is presumably due to an external event such as for example a meteorite impact. This interpretation would mean a very much simpler thermal history than is suggested by points (1) and (2). The Rb–Sr internal isochrons for the basaltic achondrites indicate also the possibility of producing basalt during the early differentiation of a planet.

Mark, R. K., Lee-Hu, C., and Wetherill, G. W.: 'Rb–Sr Measurements on Lunar Igneous Rocks and Breccia Clasts'.

Igneous and microbreccia clasts from Fra Mauro breccias have been dated by Rb-Sr between 3.95 to 4.06×10^9 yr. These ages are all within experimental error and the spread is reduced to 70 m.y. if inter-laboratory biases are corrected by adjusting dates to a common 14310 age. It has been suggested that these ages might be the result of metamorphism in the Imbrium ejecta blanket. We have demonstrated that the Fra Mauro breccia 14321 had not been totally equilibrated in the ejecta blanket and that while the internal isochron ages of a basalt clast and a microbreccia clast were not distinguishable, their initial Sr ratios were distinct. This result did not preclude the possibility of short range ($\lesssim 1$ mm) diffusion of Rb and Sr to reset internal ages. To test this hypotheiss, we examined Rb–Sr systematics for a basalt clast and adjacent ($\lesssim 1$ mm) microbreccia fragments from 14321,578. The data show that neither equilibration nor detectable approach to equilibrium occurred at 4 b.y. on a scale of 1 mm. It is thus unlikely that the measured ages are the result of diffusion in the Imbrium ejecta blanket and more likely that the internal ages measured on the microbreccia clasts and intermediate iron-rich basalts (such as 14053) predate the Imbrium event. As the oldest basin-filling mare basalts postdate the Imbrium impact, it is possible to bracket the age of the impact between 3.8 and 4.0×10^9 years.

A five point isochron for KREEP-rich basalt 14310 yields an age of $3.94 \pm 0.03 \times 10^9$ yr and initial ratio of 0.70041 ± 5. This basalt has now been dated by most of the laboratories measuring Rb–Sr ages of lunar samples and can be a useful tiepoint for interlaboratory comparisons. 14310 is probably the product of impact melting and has an uncertain relationship to the Fra Mauro Formation.

62295 is a mesostasis-rich spinel troctolite, probably produced by shock melting. We have obtained a five point internal isochron of $4.00 \pm 0.06 \times 10^9$ yr and initial ratio of 0.69956 ± 6. If fraction D, which requires a blank correction, is omitted, an isochron of $4.00 \pm 0.07 \times 10^9$ yr and 0.69956 ± 8 results. Possible stratigraphic correlations range from pre basin-forming events to Imbrium ejecta.

A 0.5 g basalt clast from relatively friable breccia 15265 is significantly younger than the above samples. It has an age and initial Sr isotopic ratio consistent with Apollo 15 mare balsats. A similar age has been reported for a basalt clast in breccia 15459.

Stephenson, A. and Collinson, D. W.: 'The Determination of Lunar Magnetic Field Palaeointensities'.

The existence of an ancient field in which the lunar rocks cooled is now well-established because of the hard components of magnetization found in many of the lunar samples. One of the major objectives of lunar magnetic studies is the determination of the intensity of the field and this is now currently under investigation.

The standard method of determining palaeointensities is by the Thellier method by which the natural remanent magnetization (NRM) lost during thermal demagnetization from temperature T_1 to T_2 is compared with the partial thermoremanent magnetizaion (PTRM) induced in a known field between the same temperatures. This method is not however always successful because of chemical changes which can occur when the samples are heated. An alternative method not involving heating is to use anhysteretic remanent magnetization (ARM).

The method used on the lunar samples involves the determinaton of the alternating field demagnetization curve of the NRM and the acquisition of ARM in a fixed direct field as a function of peak alternating field. This direct field was produced by 4 coplanar magnets giving a field of 1.8 Oe and this was constant to within a few percent over a volume of 1 cm^3 which was large enough to enclose the sample. The relationship of TRM to ARM may be expressed by the relation

$$1/h_T \partial I_T/\partial H = f'1/h_A \partial I_A/\partial H,$$

where h_T and h_A are the direct fields involved in producing TRM I_T and ARM I_A respectively. H is the peak value of the alternating field used to demagnetize the samples. f' is a constant greater than unity which has to be determined experimentally.

f' was determined by comparing the AF demagnetization curves of samples which had been given a TRM in a known field, with the acquistion of ARM. A plot of TRM lost against ARM gained then gave a slope from which f' could be evaluated. For a synthetic sample containing iron grains (ex carbonyl), f' was 1.28 and for a lunar basalt sample 10050,33, f' was 1.40. A mean value of 1.34 was therefore used in the calculations.

A test of the method was used on 62235,53 (basalt) on which the Thellier method had been used and which gave a value of 1.2 Oe for the field. The ARM result is shown, where the inset diagram gives a slope corresponding to an ancient field of 1.4 Oe and is thus in good agreement with the Thellier method. The non-linearity below 60 Oe is probably explained by partial demagnetization of the NRM by solar heating of the sample on the lunar surface and this is consistent with the constant direction obtained.

An anorthosite sample (60015,49) had an extremely weak NRM (1.04×10^{-6} G cm^3 g^{-1}) and could only be demagnetized up to 90 Oe at which point the measurement errors became too large for further readings. However, the NRN-ARM plot shows linearity through the origin showing that no demagnetization has taken place at the lunar surface and that there are no secondary components. There were no direction changes on demagnetization which is also consistent with this interpretation.

Other Apollo 16 samples investigated were 68416,23 (gabbroic anorthosite) and 66055,10 (breccia). The former sample yielded a complex curve and from the direction changes which took place on demagnetization clearly contained several components, the hardest of which was isolated above a demagnetizing field of about 150 Oe where the direction remained constant and where the NRM–ARM plot yielded a slope corresponding to a field of about 1.2 Oe. The latter sample yielded a field value of about 0.13 Oe but this must be regarded with caution since large direction changes occurred.

Apollo 11 samples 10050,33 and 10057,7 showed evidence of secondary components both from the NRM–ARM plot and also from the direction changes of the demagnetization curves of the NRM. The field values determined from the curves were 0.38 and 0.14 Oe respectively.

Dated samples are 60015,49 which gave a well determined field of 0.33 Oe and 10057 which gave a field of 0.14 Oe. The crystallization ages for these two samples are 3.58 and 3.63 $\times 10^9$ yr respectively.

It is not yet possible to decide whether the variations in field, have occurred smoothly or more randomly. A surface field of the same order as that of the Earth's would mean that if a lunar core were responsible it would have a higher moment per unit volume than the Earth's core by a factor of more than 15 if its radius were less than 1/5th the radius of the Moon. Permanent magnetism of theMoon however would require an average lunar magnetization higher than typical values of the saturated remanent magnetization of lunar basalts. More information regarding the time variation of the field is clearly required before the mechanism responsible can be positively identified from these and other possibilities.

Banerjee, S. K., Hoffman, K., and Swits, G.: 'Reversed Polarity Remanent Magnetization in a Layered Boulder Near South Massif'.

The Apollo 17 astronauts collected oriented samples representing three distinct layers from Boulder 1 near Station 2 during A-17 EVA. This 2 m-sized breccia boulder is unique because of its layering and its dark clasts which have anorthositic cores. We have made paleomagnetic measurements to determine the average directions and intensities of natural remanent magnetization (NRM) of the matrix of two layers, approximately 1 m apart.

The mutually oriented large (each approx. 3 g in wt) samples studied were 72275,46; 72275,47; 72275,56, and 72255,33 and 72255,36. The first three samples represent a less indurated layer than the non-porous layer which yielded the last two of the above samples. The present study was limited primarily to (a) the search for the average intensities and directions (if any) of NRM as recorded in the matrix of the two layers prior to studying the clasts embedded in them and (b), a secondary set of experiments utilized 100 mg chips to measure the high field saturation magnetization (σ_s), coercive force (H_c) and isothermal remanent magnetization (IRM_{SAT}). Given an understanding of the magnetization process, group (b) experiments provide a quantitative estimate of the iron (Fe°) content and a qualitative idea of their grainsize.

An equatorial projection of the NRM vector directions from three matrix sub-samples of 72275 (46,47 and 56) and two matrix sub-samples of 72255 (33 and 36) is down. Mutual orientation information was available from sample photographs and from page 24 of *The Lunar Sample Information Catalogue – Apollo 17*. The average NRM directions of the two rocks (each representing a different layer from the same boulder) are seen to be antiparallel to each other. It is estimated that orientationt errors can be no larger than $\pm 20°$. Another remarkable fact is that samples, in contrast to most other lunar samples, have unusually homogeneous remanent intensities and coherent NRM directions. We show the values of various magnetic properties of the 3 g and 100 mg sub-samples of 72275 and 72255. Saturation magnetization (σ_s), coercive force (H_c) and saturation isothermal remanent magnetization (IRM_{SAT}) were measured only for the 100 mg ('chip') sub-samples. NRM values of the larger samples indicate 72275 to have an order of magnitude larger intensity than 72255. σ_s values indicate that half of this increase can be attributed to a greater iron content in 7275 ($\sim$1.72%) by wt) than in 72255 (0.36%). This is corroborated by IRM_{SAT} data. The other half of the specific NRM increase in 72275 may be attributed to a larger number of more efficient carriers of NRM.

In a terrestrial situation we would ascribe the antiparallel NRM directions to a reversal of the magnetizing field (field-reversal) or a self-reversal, the latter being due to some type of magnetic interaction between two, or more, magnetic phases. However, before considering such speculation it is necessary to first conduct storage tests and partial alternating field (AF) or thermal demagnetization experiments in order to establish whether the reversed directions were indeed stable. We have thus far only completed a storage test (>40 days in zero field) and, fortunately, unlike many lunar rocks, these samples *do not* show a decay of NRM with time. That is, there is no sign of an unstable Viscous Remanent Magnetization (VRM). Since AF-demagnetization has been shown to impart irregular error signals in some lunar rocks, we are proceeding with thermal demagnetization in a H_2/CO_2 gas buffer system suitable for preventing the oxidation of iron grains while thermal demagnetization is in progress. The data from thermal demagnetization will be presented at this conference. Until then, our tentative conclusion is that the two rocks, 72275 and 72255, were magnetized antiparallel to each other. If we assume that the NRM is a thermoremanent magnetization (TRM) and these divergent directions are not due to self-reversal (a safe assumption when iron is the magnetic carrier), then the two layers must have been magnetized (i.e., cooled from above 770°C) at different times. More specifically, upon the onset of a field-reversal, the terrestrial dynamo (size $\sim 10^3$ km) takes about 5×10^3 yr. to completely reverse its dipolar field. If we assume the ancient lunar magnetizing field to also be due to such a dynamo then, purely by analogy, these two rocks must be that much different in age.

The following scenario emerges for the formation of the South Massif, based on a hypothesis by J. A. Wood. A large cratering event (possibly the Serenitatis basin-forming event) created a base-surge type deposit of mineral debris and clasts. The layers represent different effective thermal conductivities. The passage of the 770°C isotherm (and resultant imprinting of NRM) from the layer containing the 72275 samples to that of the 72255 samples took place during a reversal of the ambient magnetic field. Alternatively, if future non-magnetic data force us to accept a truly *simultaneous* magnetizing events for both the layers, an ambient magnetic field of a most peculiar geometry has to be postulated and can be provided by an irregular source of dc field such as a local dynamo in the shallow part of the crust or in the dusty plasma in the base-surge.

Gose, W. A., Pearce, G. W., and Strangway, D. W.: 'Magnetism of the Apollo 17 Samples'.

A. *Magnetic Properties*

We have performed a variety of magnetic measurements at room temperature on 24 Apollo 17 samples. A summary of these measurements, includes saturation magnetization (J_s), paramagnetic (X_p) and initial (X_0) susceptibilities, ratio of saturation remanence, J_{rs}, to J_s, coercivity (H_c), remanence coercivity (H_{rc}) and three derived quantities – approximate values of wt % Fe° and Fe^{++} and their ratio. The procedures used and the accuracy of these parameters have been previously documented (1).

Some observations are as follows:

(1) The Apollo 17 mare basalts have similar magnetic properties to those returned on previous missions (Apollo 12 and 15) (1). These samples continue to have a fairly low metallic iron content but the values range somewhat higher than we have seen previously. 74275, in particular, is high in metallic iron. Low values of the ratio J_{rs}/J_s imply that the iron is largely multidomained (> 300 Å) again in a manner similar to other mare samples.

(2) The massif rocks – noritic and anorthositic in composition – have high Fe° contents when compared to the mare basalts, but the metallic iron present is also coarse grained (> 300 Å as shown by low J_{rs}/J_s ratios). In this sense the Apollo 17 massif rocks are similar to the highly recrystallized highland rocks collected at Apollo 16 (2). The Apollo 17 rocks in general have less Fe° than those from Apollo 16. Four measurements (3 of matrix, 1 of a clast) of 76315 show however that there is considerable variation in the Fe° content within individual rocks. Such variability is also shown by 72415 and 72435, which are, respectively, an Fe° poor dunite clast and an Fe° rich sample of the matrix from the same boulder sampled on the South Massif. On the basis of grain size of the iron particles and iron content these are by and large highly recrystallized samples.

(3) The soil 75081 (from a mare site) differs from 72321 and 72441 (from a massif site) in the same way that mare and highland soils from previous missions have been found to vary (1). Thus 75081 has a higher J_{rs}/J_s ratio and a more rounded magnetization curve signifying a greater abundance of fine iron metal particles (single domain ($\sim$ 150–300 Å) and superparamagnetic (< 150 Å)) than do the massif soils.

(4) The orange soil 74220 has a very low saturation moment and thus is quite distinct from the ordinary regolith soils. Magnetically, it most closely resembles the green clod 15426 in containing very little or no Fe°. In fact, we have previously reported that this sample appears to contain magnetite rather than iron.

(5) Soil breccia 79135 is similar to breccia 15498 in that it has a high coercive force and a high value of J_{rs}/J_s implying the presence of a large proportion of single domain particles.

(6) The correlation between wt % FeO of some rock samples as measured magnetically and as measured by X-ray fluorescence by LSPET is shown. The agreement is very good for the massif rocks, while for the mare basalts the magnetic measurements tend to be slightly high possibly signifying the presence of paramagnetic ions other than Fe^{++}. The mare soil breccia 79135 shows a very high metallic iron concentration due to the presence of superparamagnetic iron particles which have not been destroyed on heating the sample.

B. *Remanent Magnetization of Samples for Station 2 and Station 6 Boulders.*

Of particular interest among the Apollo 17 rocks are the samples from the boulders. Seven chips from two rock samples (76015, 76315) are very stable against AF demagnetization, both in direction as well as in intensity. By contrast, 3 chips of 72275 decrease to less than 10 % of their NRM intensity upon demagnetization to 100 Oe. This intensity change is accompanied by a very large change in direction along a great circle. No stable direction can be obtained. The different behavior of the two boulders is surprising in that both rocks are magnetically dominated by multidomain iron. Detailed petrographic examination and further magnetic studies are necessary to explain the difference.

Larson, E. E., Reynolds, R. L., and Watson, D. E.: 'Microscopic and Thermomagnetic Analysis of Apollo 17 Breccia and Basalt: Feasibility of Obtaining Meaningful Paleointensities of the Lunar Magnetic Field'.

Two specimens of metabreccia (#73235) and two of basalt (#71055) from the Apollo 17 mission were studied by means of (a) thermomagnetic analysis (J_s vs T) and (b) transmitted- and reflected-light microscopy (at 500 × magnification) in an attempt to identify magnetic carriers and their behavior during thermal experiments, including paleointensity determinations. The heating experiments were conducted in a controlled-oxygen environment ($fO_2 \leqslant 10^{-25}$ atm at 700 °C) to minimize alteration. (1).

In the basalt, nickel-free iron was the only identifiable carrier of natural remanence. The iron occurs as crystals up to 25 μ and is most commonly associated with troilite which occurs in grains up to 40 μ. The troilite-iron grains are in general closely associated with either ilmenite or ülvospinel crystals. The average iron content, estimated from saturation magnetization measurements, is about 0.14 % by weight. The average natural remanent magnetization (NRM) of the two basalt specimens is 2.0×10^{-5} emu gm^{-1}. During thermal cycling up to 800 °C (less than one hour/cycle), some troilite breaks down to produce additional iron. In some cases the content of free iron is increased by as much as 60 % over the initial amount after completion of only two heating cycles.

In the metabreccia, the principal ferromagnetic material is also iron; however, some iron is nickel-free whereas some contains up to 6 % nickel. The latter apparently resulted from incorporation of meteoritic debris. Total free iron averages about 0.31 % by weight which is about 2.2 times greater than that in the basalt specimens. However, the average NRM of the breccia specimens is only about 6×10^{-6} emu gm^{-1}, which is less than one-third the average moment of the basalts. The iron in the breccia is generally more finegrained than that in the basalt; in fact so fine-grained that it is impossible to inhibit its partial oxidation to Fe_3O_4 at temperatures below 550 °C even in an atmosphere in which $fO_2 \approx 10^{-22}$ atm. The iron in the breccia is less commonly associated with troilite than in the basalt and generally occurs as blebs within and marginal to breccia glass fragments. Since free Fe is consistently more abundant in the lunar breccias than in the basalts, it appears that the formation of additional iron is related to the brecciation process. Some of the 'newly formed' iron, as demonstrated by Pearce, and others, probably came from the thermal breakdown of an iron-rich glass under reducing conditions. In addition, some iron undoubtedly formed by the reduction of troilite (FeS) (particularly that of very small grain size) during and shortly after meteorite impact. As a result, short-time thermomagnetic experiments produce little or no additional decomposition of troilite, thereby leading to nearly reversible J_s–T curves.

Transmitted-and reflected-light microscopic observations indicate that the breccia has been heated to temperatures sufficient to cause skeletal crystallization of ilmenite and partial recrystallization of silicate glass. This observation, the fine-grained nature of the iron in the breccia, and the reversible nature of the J_s–T curves for the breccia leads us to conclude that the breccia is more suitable than the basalt for paleointensity experiments. A similar conclusion was reached by Gose and others.

Based on an analysis of the higher temperature iron components for the lunar breccia, a tentative result for the strength of the lunar magnetizing field is 1100. A value about twice this one was obtained by Gose and others.

Aitken, F. K., Powell, B. N., and Weiblen, P. W.: 'Petrogenetic Relationships of Spinel-Troctolites, Troctolites, and Anorthositic-Norites'.

Current interpretations of the growing volume of chemical data on lunar samples of all types reveal that impact processes on the Moon have left intact the chemical signatures of a relatively few sequential large scale magmatic events. Analysis of petrographic data, on the other hand, reveals a bewildering diversity which reflects the local complexity of impact processes. Despite this, the petrographic data have aided in the development of a generally accepted model for the origin of the lunar crust. Plagioclase fractionation is conceded to be the dominant mechanism for the formation of the feldspathic crust. This implies complementary cumulates at depth, the volume and mineral assemblages of which reflect the original bulk composition. Subsequent magnetic events could have produced a variety of rock series by partial melting of different cumulates with or without subsequent differentiation. The fundamental petrologic problem is to recognize the total diversity of rocks and distinguish the early cumulates from younger *derived* rocks.

The current literature on the petrogenetic relationships among highlands rocks is particularly confusing. For example, the suggestion has been made that the spinel-troctolites and anorthositic-norites are all part of a single rock series. However, experimental work suggests that the spinel-troctolites are near-surface melts generated from source rocks which are *not* simply related to the anorthositic-norites. To clarify these relationships we have compiled textural information and applied mass balance methods to mineral compositional data on a variety of relevant lithic fragments to provide constraints on proposed genetic relationships between spinel-troctolites and anorthositic-norites. We have examined the 1–4 mm fraction of several lunar soil samples and report here textural and mineral compositional data on lithic fragments containing either $Sp + Pl + Ol(\pm Opx)$ and $Pl + Ol(\pm Opx)$. Similar data on the polymict breccia 67915 discussed below are presented in a companion abstract [6]. The lithic fragments exhibit textures which reflect a variety of processes including deep-seated and near-surface magmatic crystallization as well as several impact-related processes such as shock, melting, and thermal metamorphism. We consider fragments with basaltic textures to be of particular interest because a common near-surface environment of crystallization can be inferred. In our samples such materials fall into two distinct textural groups: those in which olivine appears to precede plagioclase in the crystallization sequence (Group A) and those in which plagioclase precedes olivine (Group B). In Group A fragments the assemblages $Sp < Ol > Opx < Pl$, $Sp < Ol < Pl$ and $Ol < Pl$ were found. In contrast, Group B fragments contain $Sp < Pl > Ol > Opx$, $Pl > Ol > Opx$, and $Pl > Ol < Opx$.

Unusual features found include subhedral grains of rutile in and interstitial to olivine in a Group A fragment; melt inclusions in spinel and interstitial glasses which texturally suggest two immiscible melts in a Group B fragment. In both groups spinel occurs both *in* and *interstitial to* olivine; but we observe that euhedral spinels are most common in fragments with relatively large amounts of glass, while glass is less abundant in fragments containing resorbed, rounded, or no spinel. Thus preservation of spinel in both groups can be attributed to rapid crystallization. Because of a similar environment of crystallization for both textural types we conclude that the difference in olivine, pyroxene, and mesostasis modal abundances must be related to differences in composition of two distinct parent melts of whatever origin.

An FeO–MgO variation diagram provides a convenient framework in which to summarize and discuss some of the compositional data. There appears to be a continuum of olivine compositions, but Group A olivines fall in the range of the VHA basalts (e.g. 62295) (Fo 94–80) and do not overlap with those from Group B (Fo 80–70). Group B low-Ca pyroxenes and olivines fall in the range of those of poikilitic norites .The most Mg-rich spinels occur in Group A fragments and the most Fe-rich pleonastes are found in Group B fragments. The compositions of olivines in polymict breccia 67915 span those of Groups A and B and extend to more Fe-rich compositions. Low-Ca pyroxene and spinel in the peridotite and sodic ferrogabbro clasts in 67915 are all more Fe-rich than those in Group B fragments. Thus, although the textural data suggest possibly two distinct parent liquids for the fragments studied, the mafic phase chemistry *appears* to be interpretable in terms of a simple differentiation sequence. This continuum and overlap in Fe–Mg data for possible liquid compositions as well as minerals has been illustrated by Steele and Smith.

From the similarity of the phase chemistry of the VHA basalt 62295 to that of Group A fragments and a similar relationship between Group B fragments and poikilitic anorthosite 60315, it appears that our data are pertinent to the question of the relationships between these two feldspathic rock types. Could a *melt* or *cumulates* of the composition of 60315 be generated from a VHA basalt? Mass balance for Si, Al, Ti, Fe, Mg, Ca, Mn, and Na show this to be possible by plagioclase and olivine fractionation. However, such fractionation does *not* produce adequate enrichment of K (62295 contains 0.11 % K_2O c.f. 0.49 % in 60315). (It is interesting to note that the most abundant occurrence of possible high-K mesostasis was found in Group B fragments.) Furthermore, the observed Fe–Mg trends in analyzed melt compositions from 62295 do not show the necessary Fe enrichment. The observed trends are consistent with the early and abundant olivine crystallization in Group A fragments. The concave upward trend for Fe enrichment requires early and abundant plagioclase separation, but this is evidenced only in Group B fragments, in which the olivine compositions are not appropriate. Both of these observations, which argue against a simple fractionation relation between 60315 and 62295 rock compositions, are in agreement with the interpretation of REE and Sr systematics of these samples. Thus our data support the concept that two distinct feldspathic lunar rock series have been sampled. One is inherently low in LIL elements and is exemplified by a variety of troctolites and spinel-troctolites (Group A). The other may include similar rock types (but Group B varieties) but is dominated by anorthositic-norites which contain higher LIL element and Fe contents than the former. Mass balance calculations indicate that the peridotite and sodic ferrogabbro clasts in 67915 could be derived from a 60315 melt but *not* from a 62295 melt. This is due to the high Fe/Mg ratios and K contents of these clasts. The *troctolite* clasts in 67915 on the other hand *could* be derived from a 62295 liquid. Thus we see evidence that polymict breccia 67915 contains clasts which *could* be part of a sequence of possible source rocks which gave rise to the two postulated magma series.

Drake, M. J., Goles, G. G., and Taylor, C. J.: 'Petrology and Geochemistry of Lunar Crustal Rocks'.

The geochemistry of petrologically-characterized lithic fragments from the Apollo 16 landing site is discussed. The data are used to investigate the provenance of the Cayley Formation and the initial REE concentrations in liquids in equilibrium with lunar anorthosites.

Few (if any) of the lithic fragments sampled exhibit primary textures. Most fragments are breccias which have experienced various degrees of recrystallization while a few have been completely remelted. The assumption implicit to the following discussion is that during brecciation and recrystallization or remelting, the bulk compositions of the particles have not been significantly altered. Hence, from a study of these particles, meaningful generalizations may be drawn concerning the composition and evolution of the lunar crust.

Lithic fragments in the size range 2–4 mm from soil samples 60053, 61283, 60503, 68823, and 68843 may be divided petrologically into four groups: the ANT suite; poikiloblastic rocks; (spinel)-troctolites; and K, SiO_2-rich mesostasis-bearing rocks. This fourth category is frequently indistinguishable petrologically from ANT rocks except for the presence of mesostasis: No light-matrix breccias were observed.

REE concentrations in ANT rocks are given. All samples display positive Eu anomalies. For Sm, enrichments relative to chondrites range from 0.2 to ~ 0.5 for essentially pure anorthosites (96–100 % plagioclase) to ~ 10 for an anorthositic norite (68 % plagioclase). REE concentrations in poikiloblastic rocks are given. All samples display negative Eu anomalies and enrichments of Sm relative to chondrites ranging from 50–160. None of the (spinel)-troctolites display a cumulate texture, but rather a variety of textures ranging from recrystallized breccias to diabasic is observed. All are characterized by the presence of plagioclase, olivine, usually (MgAl)-rich spinel, and SiO_2-poor mesostasis. REE concentrations are given. Enrichments in Sm relative to chondrites range from 7 to 115. Most samples display negative Eu anomalies although one sample displays a positive Eu anomaly. REE concentrations in the K, SiO_2-rich mesostasis-bearing rocks are given. All samples except one show negative Eu anomalies and Sm enrichments relative to chondrites of 25–70. The exception displays a positive Eu anomaly and Sm is $10 \times$ chondrites. The REE concentrations in these samples, and also in the poikiloblastic rocks, are directly related to the amount of residual phases (K-rich mesostasis, phosphates etc.).

A census of 1–2 mm lithic fragments in Apollo 16 soil samples suggests that ANT rocks are most abundant in our best sample of the Descartes Highlands while poikiloblastic rocks are most abundant in our best sample of the Cayley Plains. The data suggest intermediate to high LIL-element concentrations for the Cayley Plains materials. Yet the orbital γ-ray experiments indicate very low activity and hence low LIL-element concentrations in the Orientale basin. In view of this it is considered unlikely that the Cayley Plain material is Orientale ejecta and a more local source is implied.

ANT rocks 20, 8, 13, and 7 are essentially pure plagioclase anorthosites. Calculations of REE concentrations in model liquids in equilibrium with these anorthosites may be performed using the experimental Eu distribution coefficient data of Weill and Drake. Assuming these liquids did not have an initial Eu anomaly, initial REE concentrations of 5–8 $\times$ chondrites are indicated.

Taylor, L. A. and Williams, K. L.: 'Formational History of Lunar Rocks: Applications of Experimental Geochemistry of the Opaque Minerals'.

In this paper we present new experimental data bearing directly on the cooling histories of lunar rocks, as well as descriptive mineralogy of certain opaque minerals in the Apollo 17 samples. Results of our earlier Apollo 17 investigations have been reported elsewhere.

Cooling Rates. Taylor and McCallister experimentally determined the partitioning of Zr between ilmenite and ulvöspinel in the Fe–Ti–Zr–O system and showed this partitioning to be strongly a function of temperature.

In an attempt to answer this query, kinetic studies have been initiated to determine the rate at which a Zr partitioning formed at high temperatures will reequilibrate upon cooling. An assemblage of $FeTiO_3 + Fe_2TiO_4 + Fe + ZrO_2$ was equilibrated at 1100°C. Splits of this run were then placed at 900° and 800°C, where the ilmenite and ulvöspinel would be initially supersaturated, and samples were taken after various annealing times. The samples were analyzed by EMP for the Zr contents of the ilmenite and ulvöspinel. Because the Zr content of the ilmenite varies greatly as a function of temperature, it was used as an indicator of the reequilibration process. The Zr content of the ilmenite was 1.1 wt % at the start of the runs (the 1100°C Zr saturation): The 900°C equilibrium Zr content is about 0.49 wt. %.

The 900°C charges reached equilibrium in 30 to 40 days, whereas those at 800°C were less than 1/2 way along towards equilibrium even after 50 days. Based on these data, it would appear that certain of the lunar rocks, which have Zr partitionings indicative of high temperature equilibrium (i.e. $\gg 1000$°C), have *cooled rapidly* to temperatures below 900°C – *times on the order of several days to a few weeks*. This might be expected near the top of a flow or ejecta blanket. In order to check the applicability of these data, further experimentation continues using appropriate lunar samples.

Ti *In Troilite.* Three of the samples, 71502, 75122 and 75035, contain several grains of coexisting troilite (FeS) and ilmenite. The troilite contains traces of Ti, and the partitioning of Ti between these two phases has been experimentally shown to be a function of temperature.

Armalcolites. Armalcolites were observed in samples 71502 and 75122 and are of both the 'ortho- and para-' type as described by Haggerty. Williams and Taylor recently stated that the use of this terminology to distinguish 2 types or varieties of armalcolite does not appear to be valid – a conclusion supported by Smyth and Brett. Instead, we prefer to regard any minor optical and/or chemical variations as continuous and probably resulting from fractional crystallization. It is noteworthy that the 'ortho-' armalcolites which are mantled by ilmenite and presumed to be early in the paragenetic sequence, tend to high MgO and Cr_2O_3 contents. Alternatively, the 'para-' armalcolites, which occur as euhedral crystals or partly mantled by ilmenite, have higher FeO and lower MgO and Cr_2O_3 contents. However, our data show *no consistent differences* between the two 'types', suggesting that crystallization was probably rapid and hence, compositional differences tended to be governed by local inhomogeneities in the parent liquid rather than by a well-defined fractionation. *The terms 'ortho- and para-' simply refer to armalcolites which occurred at two different times in the paragenetic sequence.*

During the present study, numerous armalcolite grains were analyzed by EMP. Most of the compositions fall within the range which we have previously reported, with the exception of 2 grains in 75122 which have low MgO (3.98 and 4.27 wt. %)

The ilmenites associated with the armalcolites were also analyzed in order to discern any possible systematic elemental partitioning between them.

Native Fe. 70017 and 75035 contain Fe metal with Co > Ni, and the compositions are similar to native Fe from Apollo 11 samples. 77017, an anorthositic gabbro, contains numerous FeNi grains with high Ni contents, and most of the compositions are near or in the meteoritic range defined by Goldstein and Yakowitz.

Samples 71502 and 75122 contain Fe grains which are similar – mostly Apollo 11 but also a few meteoritic compositions – 75122 contains some Co-rich Fe grains as well. Based on Co/Ni ratios at least 3 types of vesicular glassy basalt can be distinguished in these soils, and the rock fragments in these soils represent at least 7 types. Notable is the observation that *the rock chips containing armalcolite all have* Fe *grains with* Co > Ni *similar to Apollo 11* Fe *metal grains.*

Spinels. All of the samples examined contain spinels. The compositions of these phases are given. The compositions are diverse. The ulvöspinels in 75035 are rather pure – the only oxides present in amounts > 1 wt. % are FeO, TiO_2 and Al_2O_3, where Al_2O_3 ranges from 2.15 to 4.27 wt. %. Sample

77017 contains only chromite, Mg ilmenite and FeNi metal as opaque phases. A single rock chip in 71502, a peridotite fragment, contains only chromite and FeNi grains as opaques – no ilmenite. The ulvöspinels and ilmenites in all of the Apollo 17 samples contain only small amounts of Zr (usually < 0.1 wt. %) such that the Zr partitioning geothermometer of Taylor and McCallister is not applicable.

McCallum, I. S., Okamura, F. P., Mathez, E. A., and Ghose, S.: 'Pyroxene Relations in Highland Plutonic and High Grade Metamorphic Rocks'.

67075 is an extreme.y friable anorthositic breccia from Station 11, North Ray Crater, composed of over 80 % anorthitic plagioclase, which occurs as isolated fragments and as micro-anorthosites with polygonal grain boundaries. Mafic minerals include pyroxene, showing unusually well developed exsolution lamellae up to 30 μm wide, olivine, Ti-chromite, ilmenite, Fe-Ni, and troilite. Single crystal X-ray precession photographs reveal a very complex pattern of multiple exsolution and inversion in the pyroxene grains. Cell dimensions of the components in two selected crystals are given, and probe analyses are listed. While host and exsolved phases in individual macrocrystals are homogeneous, considerable intergrain variation exists. The Ca contents and K_D (Fe–Mg) values of adjacent host-lamellae pairs indicate extensive subsolidus, 'intracrystalline' reequilibration. Pigeonite has exsolved augite on (001) and (100) planes. Diffuse streaks parallel to a^* connect host pigeonite reflections to corresponding hypersthene reflections, indicating partial inversion. This inversion is isochemical and probably occurs metastably. Splitting of the c^* axes (Δc^*) of pigeonite and augite sharing (001) permits identification of second generation exsolution lamellae. Second generation pigeonite has not inverted. Augite macrocrystals exsolved several sets of clinohypersthene lamellae on both (001) and (100) planes. Diffuse streaks parallel to a^* extend from the (001)-clinohypersthene reflections and show intensity maxima at positions expected for hypersthene reflections, indicating incipient inversion. An estimate of the extent of the inversion together with the magnitude of Δc^* and $\Delta\beta$ serves as a qualitative indicator of the cooling rate. Comparative studies show that *67075* pyroxenes coo.ed more slowly than Skaergaard pyroxene (EG 4430) and more rapidly that Stillwater pyroxene (M-50). On the basis of features observed in pyroxenes of *67075*, we infer an origin in a deep seated magma chamber (5–10 km) which existed during the formation of the primitive lunar crust.

Apollo 17 sample *77017,81* is a poikiloblastic anorthositic gabbro from the base of North Massif with ~ 75 % plagioclase, 5 % olivine, and 20 % pyroxene (subequal amounts of pigeonite and augite). A late shock event has caused partial granulation. The proportions and compositions of mineral fragments in the fine grained matrix is the same as in the uncrushed areas and fragments of the primary texture are preserved, indicating that the granulation episode was not accompanied by a significant transfer of material. The mineral clasts in the matrix show shock features: undulose extinction, mosaicism, and partial shock vitrification of plagioclase. Isolated, small patches of pale brown glass occur in the matrix.

The uncrushed areas are relatively coarse grained and show a well developed poikiloblastic texture, similar in most respects to that in Apollo 16 poikiloblastic rocks. Subspherical to subhedral grains of plagioclase and olivine showing no preferred orientation are enclosed within large poikiloblats (*ca.* 5 mm) of pigeonite and or augite. Where both pyroxenes occur in a single poikiloblast, they show an epitaxial relationship. Plagioclase grains contain small (< 50 μm) spherical blebs of olivine and vice versa, and where plagioclase crystals are in mutual contact, polygonal grain boundaries are developed, indicative of extensive subsolidus recrystallization. This conclusion is reinforced by the compositional homogeneity of the minerals. Olivine varies from $Fo_{60.2}$ to $Fo_{63.5}$, augite from $Wo_{37.4}En_{46.2}$ to $Wo_{34.7}En_{46.4}$, and pigeonite from $Wo_{10.7}En_{58.1}$ to $Wo_{9.3}En_{61.1}$. Complete analyses of selected grains are listed. Accessory minerals include ilmenite, trolite, Fe-Ni, and $MgAl_2O_4$ spinel.

Single crystal precession photographs of the pyroxenes indicate that the low Ca pyroxene is an untwinned pigeonite which has exsolved ~ 10 % augite on (001). No (100) exsolution lamellae were observed and the pigeonite shows no evidence of inversion to orthopyroxene. '*b*' type reflections are sharp and no diffuse streaks parallel to a^* are present. Cell dimensions of a typical pigeonite and its (001) augite lamellae are presented. Augite poikiloblasts show the inverse relationship, i.e., (001) clinohypersthene lamellae in an augite host. The lamellae are ~ 3 μm wide and resolvable in the microprobe. The data of Ross *et al.* (1) indicate that clinohypersthene of this composition formed at $T > 1160\,°C$, and the absence of inversion features imply relatively rapid subsolidus cooling. This temperature is probably close to or even above the solidus temperature of this rock.

The evidence outlined above is consistent with the following history for sample *77017*: (1) brecciation, partial melting (?), and transportation of primitive anorthositic gabbro crustal material in a large impact event; (2) deposition of this material in a hot, thick ejecta blanket with little mixing of other rock types; (3) ultrametamorphism (probably accompanied by a small amount of partial melting) at $T > 1160\,°C$; (4) cooling to ambient temperatures at a rate sufficiently rapid to prevent inversion and yet slow enough to form 3 μm lamellae; (5) excavation by a later impact event which produced the cataclasis and the shock features.

18. General Session.

Brownlee, D. E., Gault, D. E., Hartung, J. B., and Hörz, F.: 'Mixing of the Lunar Regolith'.

Because meteoritic impact is a random process, any given point on the lunar surface has experienced a unique history as compared to any other given point on the surface. Depth of regolith, regolith turnover rates, etc. cannot be described in meaningful terms with 'averages' as has been done in the past, particularly as applied to studies of track records of solar and galactic radiation, content and distribution of noble gases, impact produced glass agglutinates, etc. Stratigraphic layering in *all* core materials returned by Apollo and Luna missions emphasizes the uniqueness of any given spot on the Moon. On the other hand, the dominant role that impact has played in regolith formation suggests that any two spots at a given site on the lunar surface will have experienced similar histories that differ only in details to a greater or lesser degree by the vagaries of the random distribution of the impact events which contributed to the formation at each point. It can be shown that the probability P_u of a given point on the lunar surface remaining undisturbed by (i.e., lying outside) a crater of apparent diameter* D_a in a time interval t is

$$P_u = \exp\left(-\pi N t D^2{}_a/4\right), \qquad (1)$$

where N is the flux of the randomly distributed impacting bodies (per unit area and time) which produce the craters of diameter D_a. Similarly, it can be shown that

$$P_c(n) = P_u\,(\pi N t D_a{}^2/4)^n/n! \qquad (2)$$

is the probability P_c of a given point on the lunar surface having been covered by (i.e., lying within) exactly n craters of diameter D_a. Equation 2 is the Poisson probability function; values may be found in Molina (1942) for a range $n = 0$–153 and $(\pi N t D_a{}^2/4) = 0.001$–100. We have calculated additional terms up to $n = 10^6$.

The most significant result from the calculations is the large number of turnovers which occur in the upper 1 mm of the surface as compared to deeper layers. It is 99 % probable that the upper 0.5 mm is turned over almost 100 times in 10^6 yr while even at the 50 % probability level the 1 cm depth has yet to be disturbed; it requires 10^7 yr to assure (99 %) that the surface has been turned over to a depth of 1 cm at least once. Time scales for one turnover at 10 cm to 1 m depths are measured in 10^9 yr units, and it is not surprising that the A-15 drill core material returned from more than 2 m depth had lain undisturbed for about 500 m. As pointed out previously, it is only the upper 0.5–1 mm of the lunar surface that is subjected to intense churning and mixing by the meteoritic complex at the present time. This thin veneer of regolith should be considered a primary mixing layer of lunar materials from all points on the Moon and a major source for impact melts, agglutinates, and vapor products.

Crozaz, G., Drozd, R., Hohenberg, C., Morgan, C., Ralston, C., Walker, R., and Yuhas, D.: 'Lunar Surface Dynamics: Some General Conclusions and New Results from Apollo 16 and 17'.

Historical Flux of Micrometeorites. Based on a comparison of calculated values for various dynamic processes with experimental data, several workers have suggested that the flux of micrometeorites averaged over the last several million years was lower by an order of magnitude than present fluxes measured in satellites. Measurements of small craters on fresh glass surfaces has further supported this view. However, the mass of the micrometeoroids involved in these latter measurements is smaller than those responsible for the apparent discrepancies that led to the suggestion of a lower average flux. We have performed a critical review of existing data and see no compelling evidence for such a drastic reduction in the micrometeorite flux. Surface exposure ages for rocks based on track data range from $< 10^6$ to $\sim 5 \times 10^7$ yr. However, most of these ages are *maximum* ages. True surface exposure ages can be reliably determined only by detailed measurements of track gradients in rocks. The original estimates of average lifetimes of 2 to 6 m.y. for rocks in the size range of 1 to 10 kg appear compatible with existing data though occasional rocks with longer ages have been found. Comparison of erosion rates has been complicated by a confusion between micro and mass-wastage erosion and by speciously low (though irrelevant) estimates of microerosion rates $< 10^{-8}$ cm yr^{-1}. The experimental mass-wastage erosion rates from both track and radionuclide data of ~ 0.5 to 2×10^{-7} cm yr^{-1} agree with theoretical estimates. Our best estimates of the rate of production of impact pits > 500 μm in size lies in the range 1 to 5 cm^{-2} m.y.$^{-1}$. Although this is somewhat lower than theoretical estimates of 8 to 10 cm^{-2} m.y.$^{-1}$, most of the reference rock surfaces are $\gtrsim 2$ m.y. old and erosion effects may well account for the difference.

Ages of Specific Lunar Features. In a recent paper we have discussed the difficulties of associating individual exposure ages with the formation of specific lunar features and emphasized the importance of obtaining concordant ages using different methods on a suite of samples. Part of the problem is that primary ejecta may unearth secondary ejecta that previously lay close to the surface. Such samples give spuriously large spallation ages unrelated to the primary cratering event.

From the data for Apollo 17 samples, we now add the consortium boulder from Station 6 which we date at 21 ± 2 m.y. by ^{81}Kr–Kr. The estimated track age of 22 m.y. and the steep track gradient confirms our measurements of the time-averaged spectrum of galactic cosmic rays (8) and fills in a previously missing gap in time in the cosmic ray record. Although the initial data are poor due to the generation of large amounts of CO_2 (indicating a large carbon content, perhaps in the form of a carbonate mineral), we obtain a tentative ^{81}Kr–Kr age of 83 m.y. for 75035, collected from the rim of Camelot.

The coarse-grained layer in the deep drill stem extending from the surface to a depth of 1 m was tentatively associated with Camelot in the geology field report. Our initial track measurements at a level of 30 cm give a model age of 30 to 60 m.y. and tend to confirm this view. Track measurements at deeper depths drop off rapidly indicating that the layer has *not* been stirred to a depth of 30 cm.

The results indicate that considerable stirring and probable additions of new material have occurred in the first few cm of the regolith since Camelot was formed. The trench samples are unique among our Apollo 17 samples in having relatively simple track histories. The estimated age since deposition of the first 5 cm is 5 to 20 m.y. ago. If this material comes from the nearby 10 m crater, it demonstrates that the regolith at this site is not heavily irradiated at even modest depths. Both the shadow sample 76241 and the rock skim sample 76321 appear to be typical relatively mature soils.

Swann, G. A.: 'A Scheme for Estimating the Ages of Small Copernican Craters'.

Exposure ages for lunar materials whose total exposure histories on the lunar surface are established can be used to determine absolute dates for the events which exposed the materials. This technique has been applied rather extensively to the dating of source craters that exposed materials sampled by the Apollo missions.

A method for determining the relative ages of craters, based on size versus stage of erosion, which is especially applicable to those of the Copernican system, was developed for use in detailed mapping of the Apollo landing sites by Trask. By relating the techniques of exposure age dating with those of determining the relative ages of craters by their morphologies, one should be able to roughly estimate by their stage of erosion the actual age of small Copernican craters.

Trask's method of determining relative ages of craters is based on the following assumptions: (1) newly formed craters appear sharp with raised rims and rayed ejecta; (2) craters are subdued and are eventually destroyed by subsequent meteorite impacts; and (3) small craters erode at a greater rate and disappear in less time than do larger craters. These assumptions are well supported by thousands of examples of sharper craters superposed either on older more subdued craters, or on the ejecta blankets of older craters.

Some of the reported exposure ages are used here to develop a first approximation of a scheme from which an estimate, based on stage of erosion, of the ages of Copernican craters 10–1000 m in diam can be made. The size limit is imposed by the lack of sampling of the ejecta blankets of larger Copernican craters. A graph shows arbitrary break-points in time segments along the abscissa, chosen such that on a logarithmic plot the time increments are of essentially the same physical length. The exception is that the scales are shortened for the number 6 and 7 craters, which erode at a very rapid rate. No attempt is made here to evaluate the effects on erosion rates of the material in which the craters were formed. Variations in erosion rates of different materials are probably no greater than variations caused by uncertainties in applying absolute exposure ages to the events, or to the determination of the relative age bracket to which a crater should be assigned.

The system developed by Trask employs a numbering system of 1 to 6 for which 1 represents the oldest recognizable Copernican craters and 6 represents the youngest Copernican craters. A number 1 crater is shallow pan-shaped; a number 2 crater is shallow bowl-shaped; a number 3 crater is a bowl with a well defined break in slope at the rim; a number 4 crater has a raised rim with visible blocks near the rims of larger craters; a number 5 crater is a relatively sharp-rimmed crater surrounded by an identifiable ejecta blanket; larger craters are rayed and blocky; a number 6 crater has a very sharp rim, well developed rays, and if large enough to penetrate the regolith, many blocks on its rim and ejecta and abundant secondary craters. In the scheme proposed here a number 7 crater type is added which includes those small craters with sharply raised rims and abundant clods of regolith that are caused by the impact. This type of crater cannot be identified on orbital photographs because the clods are below the limit of photographic resolution, but was observed from the lunar surface during all Apollo landing missions. These craters are so young that the clods have not been broken down by micrometeorite impact.

Several difficulties are inherent in the scheme proposed here. The rate of erosion is much greater in the earlier stages of degradation than it is for older craters that have already been nearly obliterated. Thus the morphology of a crater changes more slowly with time. A more difficult problem lies in evaluating the effect of size on the apparent relative erosion rates. Mapping experience has shown that it is more difficult for workers to agree on the relative ages of older craters than it is on fresh craters, although experienced mappers will usually agree to within one crater number.

A third major difficulty lies in the exposure ages themselves. Before the exposure age of a sample can be considered as representative of a cratering event, it must be determined that the sample was actually exposed by that event, and that the sample has been subjected to only one exposure. Otherwise a multiple exposure history must be determined and the correct exposure time recorded in the sample's history correlated with the event being dated. Large rocks on crater rims are less likely to be eratics, or to have had multiple exposure histories, than are small rocks. However, on the older crater rims, it is likely that the presently exposed large rocks were originally overlain by rim deposits which were subsequently stripped by erosion. Thus, the ages reported in these cases probably represent minimum ages for the cratering events. Variations in reported exposure ages tend to increase with the length of exposure. These variations are probably due to a large extent to complications in the exposure history, and by contamination from sources of different ages. This contamination is especially likely in soils.

The exposure age events chosen to construct the curve are as follows: (1) the cloddy crater at station 9 (Apollo 15) is a type 7 crater; (2) the crater from which the station 2 boulder (Apollo 15) was ejected is a type 6 crater; (3) South Ray (Apollo 16) is a type 5 crater; (4) Cone (Apollo 14,) and North Ray (Apollo 16,) are type 4 craters, (5) Camelot (Apollo 17) is a type 3 crater; and (6) Copernicus (Apollo 12) and its associated secondaries are old type 2 craters (crater numbers that are not referenced were determined by the author). No type 1 crater can be identified as having been properly sampled for application to the construction of the curve. The base of the Copernican system is considered to be about 2500 m.y.

Although the scheme presented here attempts to bracket the ages of the different classes of Copernican craters only approximately, it should provide a useful way of estimating the ages of Copernican surfaces. For example, the ejecta blanket from a large crater, avalanche, or other type of deposit that has no craters older than type 4 should have been formed between 10 and 50 m.y. ago. Comparison of the population of number 4 craters on that surface with that of number 4 craters on an older surface should help to shorten the time range.

The exposure ages of a number of craters reported in the literature were not used in the actual construction of this scheme, because there were one or more reasons to suspect that the exposure age might not be representative of the cratering event. Some of these craters fit well into the scheme, others do not. In this respect the curve can be used also as one line of evidence for determining which crater or group of craters might be the source for a particular sample.

Clayton, R. N., Hurd, J. M., and Mayeda, T. K.: 'Loss of O, Si, S and K from the Lunar Regolith'.

Variations in isotopic compositions in lunar soils have been reported for several light elements: H, C, N, O, Si, S, K. Of these hydrogen, carbon and nitrogen are clearly dominated by the effects of addition of material to the soils from extralunar sources, as indicated by the much higher concentrations of these elements in the soils relative to igneous rocks. Several mechanisms have been proposed to account for the isotopic variability in the remaining four elements. It is the aim of this paper to present a unified model to account for all of the observations.

Oxygen, silicon, sulfur and potassium all have three or more isotopes in nature (all stable except for K^{40}), so that measurements of two independent isotope ratios can be made for each element to determine whether the observed fractionations are due to mass-dependent processes, such as chemical reactions or diffusion, or to some other processes specific to particular nuclides, such as nuclear reactions. Epstein and Taylor reported that variations in Si^{29}/Si^{28} were 1/2 as great as those in Si^{30}/Si^{28} in the same samples. Rees and Thode showed that analogous mass-dependent relations hold for variations in S^{33}/S^{32}, S^{34}/S^{32} and S^{36}/S^{32} ratios. In the present work ,measurements of O^{17}/O^{16} and O^{18}/O^{16} on partially reacted portions of soil 14163 also indicate a 1:2 relationship in magnitude of the isotope effects. A similar test for potassium can be made in principle, but it is very difficult due to the low abundance of K^{40}. At least in the case of oxygen the mass-dependent relationships probably rule out significant complication of the isotope effects by addition of extralunar material. All of the data on these four elements can be understood in terms of processes acting on indigenous lunar materials.

Other general observations of isotopic variability on O, Si, S, and K are as follows:

(1) All have very uniform composition in lunar crystalline rocks, indicating no earlier low-temperature processing.

(2) All show enrichments of the heavy isotopes in soils relative to rocks.

(3) The magnitude of heavy isotope enrichment in O and Si are correlated with one another and with various measures of soil maturity, such as noble gas content, metallic iron, particle tracks, etc.

(4) There is some evidence for surface correlation for the effects in O and Si and S.

(5) There is no heavy-isotope enrichment in O, Si and K in glasses, such as Apollo 15 green glass and Apollo 17 orange glass, which appear to have been exposed, while molten, to the lunar vacuum, but which have not been exposed for a long time on the surface.

Various models have been proposed to account for some of these observations, involving thermal volatilization or reaction with solar wind protons at high or low temperatures. It has not been established which mechanisms are dominant. The key to understanding the effects observed in these four elements may lie in the recent observations of sizable isotope effects in potassium. In this case, the chemistry of the element involved seems to allow no reasonable mechanism other than thermal volatilization, a process observed to occur in the laboratory under moderate conditions. However, observation 5 above implies that significant volatile loss with concomitant isotopic fractionation requires temperatures in excess of liquidus temperatures. Such temperatures are locally attainable in the regolith in micrometeorite impacts. Laboratory studies have shown that potassium and sulfur have rather similar volatilities in lunar materials, so that processes vaporizing significant amounts of potassium should also vaporize some sulfur.

Since there is a net enrichment of K^{41} and S^{34} in soils relative to crystalline rocks, material balance requires a depletion somewhere else. Analyses of K^{41}/K^{39} are too few to rule out the possible existence of a low- K^{41} reservoir on the Moon, but such a possibility seems much less likely for sulfur. A more probable explanation is that the S^{32}-rich and K^{39}-rich material has been lost from the Moon, presumably in the same high-temperature event which vaporized these elements. An estimate of the minimum loss of material can be made, assuming isotopic fractionations given by the inverse square root of the mass ratio, and assuming a Rayleigh fractionation in the vaporization process.

Typical values of δK^{41} for Apollo 15, 16 and 17 soils are $+5$ to $+8‰$, implying potassium losses on the order of 20–30 %. Values of δS^{32} range up to $+10‰$, implying sulfur losses in this same range. It is difficult to demonstrate losses of this magnitude from available elemental analyses of rocks and soils, particularly for potassium, due to ubiquitous admixture of a potassium-rich KREEP component to the soils.

A net loss of about 1 % would account for the observed overall enrichments of about 0.5 ‰ in δO^{18} and 0.3 ‰ in δSi^{30}. The experiments of Epstein and Taylor have shown that these overall enrichments are due to very much larger enrichments located in some small part of the soil which is especially reactive with fluorine. It is not easy to see how such isotopic enrichments could occur in thin surface films as a residue of a vaporization process. Furthermore, measurements in the present work of δO^{18} in separated glassy agglutinates from soils 14163, 15270 and 66081 show that the agglutinates are no richer in O^{18} than the whole soil from which they came. It is therefore proposed that these highly fractionated materials have been deposited on the soil grains from a vapor which was derived by micrometeorite impact, the fractionation having taken place in the lunar 'atmosphere'

Kaula, W. M., Lingenfelter, R. E., Schubert, G., Sjogren, W. L., and Wollenhaupt, W. R.: 'Apollo Laser Altimetry and Inferences as to Lunar Structure'.

The Apollo 17 altimeter worked excellently, and obtained 12 revolutions of data. For most of the nearside features, the altitudes are reasonably close to those measured by Apollo 15 where the ground tracks are within about 200 km of each other. The elevations of Mare Serenitatis and the two adjacent maria, Imbrium and Crisium, are virtually the same in the Apollo 17 data as in the Apollo 15. The Appenines and Taurus Mountains also have about the same elevations in the two orbits. However, further west there is some divergence; the Carpathian Mountains show up in the Apollo 17 data, and Oceanus Procellarum is perhaps 0.5 km lower under Apollo 17 than under Apollo 15. Two pronounced features unique to the Apollo 17 data are the deep craters Reiner and Neper, with depths of 5 and 6 km, respectively, below the 1738 km sphere. For a crater as small as Reiner (25 km diam) this depth is quite remarkable.

On the farside the appearance of the Apollo 17 profile is also similar to that of Apollo 15, but since the terrain is so much rougher, only a qualitative comparison can be made. Apollo 17 also shows a considerable depression around 180° long, but not quite as broad or as deep as shown by Apollo 15; the greatest depth is not quite 4 km below the 1738 km sphere. A best fit of a circle to the zero elevations on the Apollo 15 and 17 tracks obtains 950($\pm$120) km for the radius and 45°($\pm$4°)S, 181° ($+$5°)E for the center of this basin.

The Apollo 17 ground track intersects that of Apollo 16 (2) at an angle of 40° near longitudes 100°E and 80°W, both in terra terrain. Nonetheless, the two profiles agree within one-half km in these regions.

The mean radius and offset of center-of-figure from center-of-mass of the Apollo 17 track furthest from Apollo 15's track are similar to those from Apollo 15:

Track	Mean radius km	Offset km	Direction
Apollo 15	1737.3	−2.1	25°E
Apollo 16	1738.1	−2.9	25°E
Apollo 17	1737.4	−2.3	23°E
Weighted mean	1737.7	−2.4	24°E

In this weighted mean, double weight was given to the Apollo 16 values and single weight to the Apollo 15 and 17.

The Apollo 17 data obtained similar results to the earlier flights for the mean elevations by terrain type:

Terrain type	Portion of global surface	Apollo 15 track km	Apollo 16 track km	Apollo 17 track km	Weighted mean km
Farside Terrae	0.57	+1.9	+2.1	+0.9	+1.8
Nearside Terrae	0.23	−1.7	−1.2	−1.3	−1.4
Ringed Maria	0.06	−4.1	−4.1	−3.7	−4.0
Other Maria	0.14	−2.0	−2.5	−2.1	−2.3
Global mean	1.00				+0.2

The weighting ratio is again 1:2:1. In calculating the portions of the global surface for each terrain type, some nearside regions were classified as 'farside terrae': essentially, those areas dominated by pre-Imbrium terra and crater materials on the geologic map, south of a line varying about 40°S and north of 70°N.

In addition to the larger mean radius of 1738.2 km, global extrapolation by terrain type gives a different offset of center-of-figure from center-of-mass: −2.3 km in the direction 13°N, 3°W. This southward displacement agrees well with the estimate based on occultations.

The seismologically determined crustal thicknesses of 20 km mare basalt above 40 km of anorthositic gabbro appear to be representative of eastern Oceanus Procellarum. Assume that (a) the mean crustal thickness is 40 km under the 'other maria' terrain type, (b) ringed maria have a mean mass excess equivalent to 2.5 km of basalt, (c) other terrain types have zero mass excess or deficiency, and (d) the mean density difference between basalt and anorthositic gabbro is 0.4 g cm^{-3}. Then from the weighted mean elevations by terrain type the mean crustal thicknesses are calculated to be 74 km under farside terrae, 48 km under nearside terrae, and 5 km under ringed maria. The global mean is 61 km. Assuming this global crust to have 2.95 g cm^{-3} mean density, the balance of the Moon must have 3.39 g cm^{-3} mean density. Finally, if the Moon below this crust were of uniform density, the moment-of-inertia ratio I/MR^2 would be 0.3968.

The lunar ranging project has obtained values of 630.6 (± 0.5) $\times 10^{-6}$ for β, (C–A)/I, and 226.0 (± 3.0) $\times 10^{-6}$ for γ, (B–A)/I. The ranging project has also obtained from the physical librations values for the third harmonics which confirm the results of Sjogren much better than other solutions. This confirmation indicates Sjogren's second harmonics – 204.8(± 3.0) $\times 10^{-6}$ for J_2, (C–A/2–B/2)/MR^2, and 22.1(± 0.5) $\times 10^{-6}$ for J_{22}, (B–A)/4MR^2 – are probably the best. The formula in then obtains a plausible range for I/MR^2 of 0.3957 $\pm$ 0.059 to 0.3949 $\pm$ 0.0050. A fair compromise, allowing for the redundancy of data, is 0.3953 $\pm$ 0.0045 (standard deviation).

Papanastassiou, D. A., Rajan, R. S., Huneke, J. C., and Wasserburg, G. J.: 'Rb-Sr Ages and Lunar Analogs in a Basaltic Achondrite; Implications for Early Solar System Chronologies'.

In this report, we present age determinations on two clasts from the basaltic achondrite (howardite) Kapoeta. The basaltic achondrites have long been considered the products of magmatic differentiation of planets of sub-lunar size and bear close chemical and mineralogic affinities to lunar mare basalts. The similarity to lunar rocks extends to the existence of high amounts of surface correlated trapped gases in some of these meteorites and of grains irradiated prior to incorporation of these meteorites which are interpreted in terms of gardening and irradiation as seen in the lunar regolith. More recently, hypervelocity micro-meteorite craters have been observed on glass spheres and in chondrule like objects in Kapoeta. The irradiation dosages of the track-rich grains, and the rarity of glass and agglutinates suggest that the regolith on the parent body of Kapoeta was quite immature compared to the average lunar soil. The crystallization ages of the basaltic achondotes are important in elucidating the nature of the primitive Sr composition *BABI* obtained from a whole meteorite isochron. These ages are also critical in the interpretation of the excess fission Xe isotopes attributed to ^{244}Pu and in the determination of $^{244}Pu/^{238}U$ at the end of nucleosynthesis.

We have extracted two basaltic clasts (A and B) from Kapoeta, weighing 0.5 and 0.6 g. This meteorite is a polymict breccia and it is evident that small fragments of different rock types could yield a confused picture, although it may be possible to obtain a total rock isochron with a variety of clasts. Mineral separations were made following our scheme for lunar basalts. We obtained plagioclase and pyroxene separates as well as small amounts of interstitial material enriched in SiO_2 which acts as a carrier of Rb and Sr with relatively high Rb/Sr. For clast A, a two point line on the Rb–Sr evolution diagram corresponds to a time of 3.89 ± 0.05 AE and an initial $^{87}Sr/^{86}Sr$, $I = 0.69888 \mp 5$. Since this meteorite shows some evidence of moderate shock, it is evident that a two point line need not represent an isochron. For clast B, we have measured three separates. The three points lie on a straight line well within the error uncertainties and it appears that an internal isochron is well defined. As in the case of lunar samples, proving that we are not measuring simply a mixing line is not a simple task. For the remaining discussion and subject to further investigation, we shall assume that the data for clast B define a real isochron and that the two data for clast A also determine a true age. We note that both ages are relatively young and both clasts have inherited very primitive initial Sr. The ages of the Kapoeta basalts are distinct from each other but quite similar to ages of mare basalts. In the past, the strongest argument against the basaltic achondrites originating on the Moon has been the distinct $^{18}O/^{16}O$ values for the basaltic achondrites and lunar samples. However, the oxygen data have been obtained on eucrites and on one mesosiderite, but not on howardites. The low initial Sr of clast A, which is almost equal to ADOR and distinctly lower than all measured I values for lunar samples, appears to exclude the possibility that this meteorite has a lunar origin. If the basaltic achondrites do not come from the Moon, there must exist other bodies which have had a lunar type history. It is possible that the basaltic achondrites have a large age spectrum similar to lunar samples.

Some efforts have been made to obtain ages on basaltic achondrites using different methods. $^{40}Ar^{40}K$ and $^{40}Ar^{39}Ar$ studies by several workers show a large spread in ages and do not appear to yield easily interpretable results. No general rules appear to exist in the Ar–K age patterns for basaltic achondrites. The time scale over which these meteorites have undergone thermal disturbances ranges from 3.5 to 4.4 AE by ^{40}Ar–^{39}Ar studies. Total K–Ar ages on various mineral separates were done by Megrue (11) and were interpreted as giving ages, some of which are in the range reported here. However, his approach does not seem to yield results which would establish reliable ages, particularly when the possibility of gas loss is considered.

Ages of lunar highland rocks have strongly indicated an intense bombardment of the Moon at ~ 3.9 AE which appears to dominate the earlier history. In the case of Kapoeta, we observe that the events which resulted in the breakup of its parent body occurred at least as late as 3.6 AE and were less intense than in the case of the lunar cataclysm. This would indicate that some major collisions occurred in places distinct from the Earth-Moon system as late as 3.6 AE. Whether or not the 3.89 AE age of clast A can be associated with the events which led to the lunar cataclysm remains a tantalizing, but uncertain, possibility. We note, however, that at least one other object, the iron meteorite Kodaikanal, which is highly shocked, has an age of 3.8 AE, so that evidence for 'late' bombardment throughout the solar system may be found in the meteorites. The question as to whether the cratering time scale determined for the moon can be applied to other planets (e.g. Mars) depends on the extent to which it can be demonstrated (from the study of meteorites) to be a solar system wide phenomenon.

The young age for at least some basaltic achondrites and possibly for many meteorites, requires that properties of the early solar system (e.g., early solar wind) deduced from meteoritic evidence be re-examined and held in abeyance until the ages of the materials have been determined. In the case of Kapoeta, we conclude that the implanted solar wind gases and tracks must represent events extending over 1 AE after the formation of the solar system and not early solar processes. The problem of ^{244}Pu in particular needs to be re-examined. Rowe has identified significant amounts of ^{244}Pu fission Xe and ^{129}Xe from ^{129}I decay in a very dark calst from Kapoeta and some fission Xe, but no excess ^{129}Xe, in a dark matrix sample. This does not comport with the ages of clasts A and B; no significant Xe derived from in *situ* Pu or I decay should be identifiable in young (<4.0 AE) objects. A similar dichotomy exists in Stannern (10). If the ^{244}Pu fission Xe is produced *in situ*, this would indicate a range of clast ages in Kapoeta (and probably other achondrites) extending over 1 AE. If the Xe excesses are trapped and not associated with U and I, as demonstrated in lunar breccia 14318, then no chronological associati n can be made. In either instance, the use of achondritic information to determine nucleosynthetic and early solar system chronologies is subject to serious doubt.

One of the important facts proven by lunar exploration is that terrestrial type planets may be highly enriched in the refractory radioactive elements. This enrichment can be much greater than for the earth as was first clearly recognized by Gast (15). If we consider enrichments in U and Th of ten times solar abundances (as compared to a factor of five for the Moon), then it is possible to generate magmas in the interior of moonlets 200–400 km in radius at a time 0.5 to 1 AE after planetary accretion (i.e., magmas formed at 4.0 to 3.5 AE). This would avoid the requirement for special initial heat from accretion or extinct nuclides (magic ^{26}Al) or the requirement of an overly massive and unbreakable Moon as a parent body. Differentiation at 4.0–3.5 AE would produce basaltic lavas which would be injected into, and flood and incorporate an exterior rubble layer of truly ancient material. This ancient material could either remain undifferentiated during accretion or have been differentiated during or shorthly after accretion. Because of the more limited amount of melting, the preservation of ancient materials with Pu and I on mini-moons is much more likely than on lunar sized objects. This would provide a model which explains the observations on basaltic achondrites in the case where *some* of the basaltic material has a young age. The generation of basaltic achondrites at 4.6 AE would still require special heat sources. Even in a model where all materials are subject to planetary differentiation soon after accretion, the $^{244}Pu/^{238}U$ ratio would not be directly related to nucleosynthetic processes.