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**1. Constraints on Structure and Composition of the Lunar Interior: I**

Bender, P. L., Hauser, J. P., Mulholland, J. D., Shelus, P. J., Sinclair, W. S., Slade, M. A., and Williams, J. G.: 'Lunar Moments of Inertia Constraints from Lunar Laser Ranging'.

Among the parameters being determined by the Lunar Laser Ranging Experiment are the lunar moment of inertia parameters  $\beta = (C - A)/B$  and  $\gamma = (B - A)/C$  and some of the third degree gravitational harmonics. Combining the most recent laser ranging determined values of  $\beta = 631.1 \pm 0.4 \times 10^{-6}$  and  $\gamma = 226.8 \pm 1.0 \times 10^{-6}$  with a lunar orbiter value of  $J_2 = 204 \pm 3 \times 10^{-6}$  gives the moment of inertia constraint  $C/MR^2 = 0.394 \pm 0.006$ . Virtually all of the uncertainty in the last value comes from  $J_2$ . Differencing the ranges between the different lunar reflectors allows the lunar physical libration parameters and the differential lunar reflector coordinates to be determined to very high accuracy with little corruption due to lunar orbit or Earth related quantities. Such solutions will be discussed.

Albee, A. L., Chodos, A. A., Dymek, R. F., Gancarz, A. J., Goldman, D. S., Papanastassiou, D. A., and Wasserburg, G. J.: 'Dunite from the Lunar Highlands: Petrography, Deformational History, Rb-Sr Age'.

Five fragments of highly-crushed dunite (72415 to 72418) were collected at Apollo 17 Station 2 from a single  $10 \times 20$  cm clast in Boulder #2, which is a metaclastic blue-grey breccia (72435). It is logical to expect a lunar dunite to provide some insight into the composition of the lunar mantle, the origin of the ANT-rock suite, and possibly the character of primitive crustal-differentiation processes. Such insights are complicated by the complex history of deformation undergone by this sample. However, despite the complex history, Rb and Sr appear to have remained undisturbed and this rock is inferred to be a product of primary lunar differentiation.

Rounded clasts composed of large (to 10 mm), single crystals of pale-green, translucent olivine are enclosed in a granular, white matrix composed predominantly of olivine. The matrix formed simply by crushing without recrystallization and has the same composition ( $Fe_{0.86-0.89}$ ) as the olivine clasts. Other minerals, which include plagioclase, Cr-spinel, high- and low-Ca pyroxene, and Fe-metal, occur as clasts within the matrix and included within the olivine clasts. In both cases the habit of each of these minerals is similar.

Large, single olivine crystals have pronounced undulatory extinction and planar partings resulting in a mosaic of rhomb-shaped domains bounded by partings of strain-bands. Small ( $\sim 50 \mu m$ ) oval or equant olivine grains, with relatively uniform extinction, are aligned along some of these strain-bands. Some of the planar partings appear to be decorated with minute beads, which are apparently Fe-

metal, and some terminate in a string of Fe-metal beads. Most of the clasts are single olivine grains. However, zones of symplectic intergrowths, and rarely, aggregates of plagioclase laths associated with pyroxene granules, occur within the clasts. These zones are interpreted as relic grain boundaries and as primary crystallization features. Similar aggregates of plagioclase laths ( $An_{88-92}$ ) and pyroxene granules also occur as broken fragments within the matrix. Olivine is dusted with tiny ( $<1 \mu m$ ) inclusions, which appear to be predominantly Fe-metal in some areas and predominantly spinel in other areas. Cr-spinel also occurs in olivine as discrete inclusions (up to  $25 \mu m$ ).

Symplectic intergrowths of Cr-spinel + high Ca pyroxene  $\pm$  low Ca pyroxene  $\pm$  plagioclase  $\pm$  Fe-metal occur as tiny, ovoid inclusions in olivine, along relic grain boundaries, and as broken fragments within the granulated matrix. Felty aggregates of shocked and recrystallized plagioclase ( $An_{94-97}$ ) with minor pyroxene also occur as ovoid inclusions within the olivine clasts and as broken fragments in the matrix.

Isotropic and trace element analyses were done on selected materials from sample 72417, which include a small 'total rock chip', a 2 g total rock, and hand-picked fragments rich in simplistic intergrowths. All samples were free of lunar exterior surfaces and were cleaned of adhering lunar soil. The differences in trace element concentrations between the total rock samples are due to biased sampling. There is considerable depletion of Sr in the small 'chip' compared to the other samples. Leaching the total rock in  $HNO_3$  &  $HCl$  showed that K and Rb are readily removed.

Pb isotopic data on the leach of the total rock give a model age of 4.48 AE which is significantly younger. If the Rb-Sr data represent a true internal isochron, then this dunite must be one of the earliest lunar differentiates. The value of  $I$  is low enough to be compatible with such an interpretation. A value greater than BABI would render this interpretation questionable. Because of the complex nature of this rock and the low trace element concentrations these results must be confirmed. The low laboratory blank levels have no significant effect on the Rb-Sr data. It is possible that the trace element concentrations, the isotopic compositions, and consequently the age result from the addition of extraneous lunar materials during the complex history of the dunite. Such materials include the matrix of the enclosing K-rich breccia (72435), clasts of anorthositic rocks, and lunar soil. However, the small 'total rock chip', which critically controls the age, has K/Rb much less than any of these contaminants and less than mare basalts. Therefore, the possibility of contamination by these materials may be excluded. This is also true for the 2 g total rock and the symplectic intergrowths, with regard to the high Rb/Sr contaminants. As there is no evidence for contamination from either petrographic or trace element data, we tentatively conclude that this rock must represent a very early differentiate, derived from the upper lunar mantle. This rock is so depleted in trace elements (including U and Th) that it cannot represent the source reservoirs from which younger basaltic magmas were derived. This rock must represent a cumulate formed during early lunar differentiation and associated differential gravitational settling.

Ringwood, A. E. and Green, D. H.: 'Maria Basalts and Composition of Lunar Interior'.

The compositions of maria basalts were determined principally by partial melting processes in their source regions followed by fractional crystallization near the surface. Detailed studies of Apollo 12 and 15 basalts showed that a limited degree of near-surface fractionation had occurred, controlled mainly by the separation and accumulation of olivine. The high abundances of Cr and V (which are rapidly depleted by near-surface crystallization) also demonstrated the limited role of near-surface crystallization. Basalts which were erupted at the lunar surface as primary liquids and which had suffered little or no fractionation en route from their source regions may be recognised by the application of chemical and petrological criteria combined with demonstrations that the cores of the earliest formed crystals are isochemical with the liquidus phases of the whole rock as determined experimentally.

The compositions of such basalts place constraints upon the compositions of their source regions which can be established by determining experimentally the nature and compositions of near-liquidus phases over a wide range of  $P$  and  $T$  conditions. These experiments demonstrate that the Mg/Mg + Fe ratio of the source region of maria basalts ranges between 0.75 and 0.80. A notable feature is that plagioclase does not occur near the liquidus of the vast majority of returned basalt macrospecimens (exceptions are 12038, Luna 16 and some of the Apollo 11 ophitic basalts). The marked under-

saturation of plagioclase in most basalts, particularly those which can be demonstrated to have erupted as liquids, proves that the source material from which they formed by partial melting did not contain plagioclase.

Measurements of the compositions of near-liquidus phases from Apollo 11, 12, 15 and 17 basalts demonstrate that they were formed by varying degrees of partial melting of a source composed dominantly of subcalcic pyroxenes with some olivine, at pressures between 10 and 20 kb. Apollo 12 parental basalts appear to have segregated at 10–12 kb, 1320–1370°C whilst Apollo 15 parental basalts (including Green Glass) segregated at 15–17 kb, 1400–1450°C. Compositions of liquidus pyroxenes observed at 10–20 kb on Apollo 11, 12, 15 and 17 basalts imply that the source region contained 4–5 percent of CaO and Al<sub>2</sub>O<sub>3</sub>, i.e. about twice the chondritic abundances of these components. It is suggested that a wide range of other highly involatile oxyphile elements, e.g. U, Th, Ba, Sr, REE, Zr, Sc also occurred in the source region at approximately twice chondritic levels.

Abundances of incompatible elements (e.g. U, Ba, La, Nb, Zr) in maria basalts range more or less continuously from 10 × chondritic to 100 × chondritic. Assuming that these elements are almost completely partitioned into the melt, then their abundances are inversely proportional to the degrees of partial melting. Apollo 15 Green Glass has a bulk composition closely related to maria basalts and contains incompatible elements at about 5 × chondritic levels. Experimental studies show that Green Glass can be formed by 40–60% of partial melting of the same source region inferred from other maria basalts. This again implies a source region containing about twice the chondritic abundances of involatile elements.

A self consistent model of maria basalt genesis has been constructed on the basis of experimental petrology investigations. The source material (Mg/Mg + Fe = 0.75–0.80, CaO, Al<sub>2</sub>O<sub>3</sub> = 4–5%) consists of subcalcic pyroxenes plus some olivine. Apollo 11 and 17 basalts represent 2 to 5% partial melts of this source, whilst Apollo 12 basalts represent 10 to 15% partial melts. Residual phases are clinopyroxene, orthopyroxene ± olivine. Apollo 15 olivine basalts represent 10 to 20% partial melts. With increasing degree of partial melting, residual clinopyroxene melts incongruently to orthopyroxene plus liquid. Green Glass represents 40 to 60% partial melting at 10–20 kb, ~1450°C, leaving residual orthopyroxene and olivine.

The source composition derived for the maria basalts is believed to have been originally representative of the entire Moon, which accreted homogeneously from material of this composition. An earlier inference that the Moon may have accreted inhomogeneously is abandoned. Formation of the lunar highlands requires a thorough differentiation of the outermost 300–400 km of the Moon, about 50% of its volume. The heating required for this differentiation was probably supplied by gravitational energy of accretion which implies an accretion time scale smaller than 1000 yr. Such a short time scale can be achieved only for accretion from material in earth orbit – e.g. coagulation of a sediment ring. Accretion as an independent planet from sun-orbiting material would be much too slow to cause heating of the exterior.

Generation of maria basalts between 3 and 4 b.y. ago is believed to be caused by heating from U and Th in the deep interior (below 400 km) which was not affected by the early lunar differentiation. The heating led to convective instability and upward rise of diapirs of primitive source material, accompanied by partial melting. The diapirs rose to within 200–400 km of the surface before magma segregation occurred.

Differentiation affected the entire lunar interior below 400 km leading to extraction of U, Th, and K via the generation of basaltic magmas which were intruded upwards into the outer 400 km. Redistribution of radioactive heat sources in this manner could be responsible for the apparent cessation of volcanism about 3 b.y. ago. Only a small proportion of the magmas reached the surface. Most crystallized at depth, often to form dense eclogite bodies. Sinking of some of these eclogite bodies might be connected with current seismic activity.

Temperatures in the source regions of basalt magmas between 3.2 and 3.8 b.y. ago would have been in the vicinity of 1250°C (Apollo 11, 17) to 1450°C (Apollo 15). Allowing for radioactive heating in the source regions caused by 2 × chondritic abundances of U, Th, and K/U of 2000, the temperature in the deep interior of the Moon soon after its formation 4.6 b.y. ago was about 900–1000°C. Since accretional heating does not make an important contribution in the very deep regions of the lunar interior, it is concluded that the ambient temperatures in the Earth's vicinity during accretion of the Moon must have been high and probably in the region of 900–1000°C. This is consistent with the depletion of volatile elements in the lunar interior.

Thermodynamic calculations show that silicates containing the FeO/FeO + MgO ratios inferred

for the deep lunar interior cannot condense directly from the solar nebula in this temperature range. The temperatures required would be below 300°C which is much too low. It appears that the material of the lunar interior originally condensed (or equilibrated) with a gas phase depleted in H<sub>2</sub> relative to H<sub>2</sub>O by one or two orders of magnitude, as compared to the solar nebula. Such an environment could have been provided by a primitive atmosphere 'blown off' from the Earth.

Mizutani, H. and Osako, M.: 'Elastic Wave Velocities and Thermal Diffusivities of Apollo 17 Rocks'.

This paper presents new experimental results of elastic-wave velocities and thermal diffusivities of Apollo 16 and 17 rocks. The compressional- and shear-wave velocities of one Apollo 16 rock, 61175,22 and four Apollo 17 rocks, 70215,30; 73235,18; 74275,25; and 77017,24 were measured at pressures up to 10 kb. The thermal diffusivities were measured for sample 70215,30 and 77017,24 as a function of ambient gas pressure from 1 bar to 10<sup>-6</sup> torr.

Elastic-wave velocities were measured with the pulse-transmission method using 10 Mhz PZT transducers. The thermal diffusivities were measured with the Ångstrom method.

Both samples 61175 and 77017 were light gray anorthositic gabbro of very low coherence. Sample 70215 is a fine-grained basalt. Sample 73235 is a meta-breccia containing large white lithic clasts. Sample 74275 is a porphyritic basalt.

Like the results of Apollo 11 to 16 rocks, the velocities increase rapidly with pressure for the initial few kilobar. The compressional- and shear-wave velocities of sample 70215, 73235, and 74275 give very similar velocity-pressure curves to each other's. The velocity data of these are almost same as those of crystalline lunar basalts from previous Apollo missions and considered to be typical of the seismic velocities in the lunar crust. The elastic-wave velocities of the anorthositic rocks (61175,22 and 77017,24) studied in the present work are very low in the lunar crust condition. The low velocities of the anorthositic rocks are due to low cohesion of these rocks; high pressure only does not improve the mechanical cohesion of granular grains. From the experimental fact of the low velocities of the lunar anorthositic rocks, we question the simple identification of the second layer in the lunar crust with the anorthositic layer. Based on the velocity data of the terrestrial anorthosite, the compressional-wave velocity of the crystalline, porefree anorthosite is estimated to be about 7.0 km s<sup>-1</sup> which is the velocity observed in the lunar crust from 25 to 60 km. However, the anorthositic rocks from the lunar surface give the velocity smaller than 7.0 km s<sup>-1</sup> even at  $P = 10$  kb. In another word, the lunar anorthositic rock does not give the right velocity of the second lunar crustal layer by only the self compression.

Thermal diffusivities were measured for a fine-grained basalt 73235, 18 and an anorthositic gabbro 77017,20. The thermal diffusivity of the anorthositic gabbro is  $1.5 \times 10^{-8}$  cm<sup>2</sup> s<sup>-1</sup> at  $T = 400$  K and  $P = 10^{-3}$  torr, whereas that of the lunar basalt is  $4.6 \times 10^{-8}$  cm<sup>2</sup> s<sup>-1</sup> at the same condition. The lower thermal diffusivity or lower thermal conductivity of the anorthositic rocks than that of the lunar basalt may have significant effect on the thermal state of the lunar interior. Since the crust of the lunar highland is believed to be anorthositic, the thermal conductivity in the highland is substantially lower than that in the mare region. Combined with the low concentration of radioactive elements in the highland, the lower thermal conductivity in the highland indicates higher temperature profile than that in the mare region, if the surface heat flow is same in the both regions.

Toksöz, M. N., Dainty, A. M., and Solomon, S. C.: 'A Summary of Lunar Structural Constraints'.

Lunar seismic data, density models and thermal calculations are combined to specify the structure and properties of the lunar crust and mantle.

Utilizing the seismic data to specify the thickness and density of the lunar crust and the calculated temperature profiles, spherically symmetric models of the density distribution in the Moon are computed to satisfy the Moon's mass and the latest value for the mean moment of inertia  $I/MR^2 = 0.395$ . Within the present uncertainties in these parameters it is not possible to specify a unique density model for the lunar interior. Among the acceptable density models is that of a chemically and mineralogically homogeneous lunar mantle with an average density at surface temperature and pressure of  $\rho = 3.4$  to  $3.5$  g cm<sup>-3</sup>. The average compressional velocity in the lunar mantle is still uncertain, with a possible range of 7.7 to 8.3 km s<sup>-1</sup>. Until these limits are narrowed, mineralogical constraints

cannot be imposed on the mantle composition. On the basis of mass and moment of inertia limits, the upper limit for the radius of a possible metallic (Fe rich) lunar core is about 500 km. This upper limit is raised to 700 km for an Fe-FeS core on the sulfur-rich side of the eutectic composition.

The physical properties of the outer layer of the lunar crust may partly be determined from the scattered envelope of seismic waves and from the velocity gradients with depth. To a maximum depth of 20 km, the crustal rocks contain microcracks. If the mean free path is defined as the distance over which one half of the energy is scattered from a plane wave, the surface scattering layer is only a few mean free paths thick. Most of the scattering takes place within the upper 5 km of the lunar crust. The seismic  $Q$ , or quality factor controlling dissipation, is about 5000 in this layer, implying extremely dry conditions.

Ganapathy, R. and Anders, E.: 'Bulk Compositions of the Moon and Earth, Estimated from Meteorites'.

The compositions of the Earth and Moon have been calculated on the assumption that these planets formed by exactly the same processes as the chondrites. The basic framework is the condensation sequence of the elements from a solar gas, augmented by 3 fractionation processes observed in chondrites: fractionation of early condensate and of metal from silicate, and partial remelting of the condensate.

The proportions of the components in a differentiated planet can be estimated from abundance ratios of elements that belong to different components but do not readily fractionate from each other in igneous processes. We used the following (mass) ratios for the Moon and Earth, in conjunction with absolute values for U (59 and 18 ppb) and Fe (9 and 38%): K/U = 1625 and 9440; Ti/U = 0.0028 and 0.277; FeO/MnO = 82 and 62.

Thirteen volatile elements of  $T_{\text{cond}} < 600\text{K}$  (Cd, Hg, B, In, Tl, Pb, Bi, Cl, Br, I, H, C, and N) tend to be incompletely condensed in chondrites, to a degree that is hard to predict in advance. For the sake of definiteness, we have therefore assigned these elements to a special, volatile-rich component, containing the first 10 elements in cosmic proportions and the last 3, in the amounts found in C3 chondrites, relative to Tl.

Strangway, D. W. and Sharpe, H. A.: 'Models of Lunar Evolution'.

Many workers have presented models of lunar evolution which involve an initially cold Moon and which was heated from the outside during the terminal stages of lunar accretion. We have examined a model which has the following constraint imposed on it.

1. The presence of a well-defined crustal structure, implying differentiation of at least the outer 150 km.
2. The seismic evidence for a core which will not transmit S-waves implying partial melting at a depth of about 1000 km.
3. Heat flow observations which imply that the global heat flow is about  $30 \text{ ergs cm}^{-2} \text{ s}^{-1}$ .
4. The presence of mascons and low order gravity harmonics implying that the outer part of the Moon at least has been relatively rigid since 3 b.y. ago.
5. The delay of up to 500 m.y. in the time between the giant impact and subsequent mare filling.
6. The presence of a magnetic remanence in most returned lunar samples and lunar magnetic anomalies implying the presence of an ancient magnetic field. This may be due to an early dynamo, to transient phenomena associated with shock or to a cold lunar interior carrying the memory of an ancient field. In this latter case the Moon would have warmed up after most of the activity of mare formation and lost this memory. We have chosen to consider the implications of this model for the origin of the field. This keeps much of the interior below  $770^\circ\text{C}$ , the Curie point of iron, for the first 1-1.4 b.y. of its history.

If we consider these constraints we are faced with a maze of conflicting requirements, which at first glance appear to be mutually exclusive.

We have followed the procedures used by others in developing a model of thermal evolution. This model involves an initial thermal, accretional pulse on the outer part of the Moon. The K/U ratio

was chosen to be 2000, corresponding to lunar values and a variety of evolution models calculated on the assumption that thermal transport is by conduction and by radiation and by convection in the fluid state. The uranium concentration and lattice conductivity were permitted to vary and the solidus of a model lunar pyroxenite was chosen.

A Moon which had a history of this type would still have a rather specific difficulty in that the outer parts would cool rapidly and it would be difficult to generate the mare basalts. One method of creating the basalts is to consider the thermal effect of a giant impact. This would tend to remove the radioactivity from the vicinity of the basin (since this is concentrated in the upper layers) and to generate a thermally insulating ejecta blanket. Temperature differences up to 500°C at a depth of 100–200 km can be attained in this way in the ring surrounding the ejecta blanket. This effect could lead to the generation of basalt at depth beneath the highlands while allowing the impact site to cool and become strong enough to sustain the gravity effect due to the loading by basalt. This can also account for the negative rings surrounding the mascons. The large negative gravity anomaly associated with Mare Orientale in this model is due to the fact that by the time this impact formed (3.6 b.y.) the crust had cooled enough to become rigid so there was little isostatic compensation and little basalt formed.

There are many possible thermal evolution models for the Moon. This is only one of these, but it can account for many of the observed constraints by having a relatively cool Moon which had only a thin molten layer early in time and has only recently become warm enough in the deep interior to approach the melting point.

Smith, J. V.: 'Origin of Moon by Disintegrative Capture with Chemical Differentiation Followed by Sequential Accretion'.

Most ideas on the Moon's origin fall into the categories of simple capture without disintegration, simple fission, volatilization-condensation, and simultaneous accretion of Earth and Moon as binary planets. Chemically, ideas for the inferred bulk refractory composition of the Moon include accretion of the Moon as a high-temperature condensate, perhaps inside the orbit of Mercury; special processes when the Moon is in Earth orbit; single-stage volatilization of Earth-derived vapor; and volatilization at the Moon's surface; all bulk compositions would be modified by crystal-liquid differentiation.

The present model expands on the ideas of Ruskol, who considered development of a circum-terrestrial swam. and of Kaula and Harris who considered dynamics of capture. It also uses some ideas of Öpik for impact of Earth-bound bodies during tidal recession of the Moon. Density variation of the Roche limit, and momentum effects of Earth-bound debris, are used to give chemical differentiation, as well as the usual volatility and crystal-liquid effects.

I. Orthodox processes of condensation and accretion from the solar nebula are invoked to produce near-radial swarms of planetesimals plus minor debris about the Sun. Chemical differentiation is assumed to correlate mostly with distance to the Sun. Collisional heating results in a metal core and silicate mantle of larger bodies with loss of volatiles. The proto-Earth and pre-Moon are planetesimals with similar bulk starting compositions.

II. The proto-Earth interacts with bodies in similar orbits principally by direct collision or by near-collisions. Debris already in Earth orbit increases the capture probability. Near-collisions result in disintegration with material sprayed onto the Earth, into Earth orbit, or into escape orbits.

III. The Roche stability limit applies to a tiny, rotation-locked, non-turbulent liquid satellite in a circular orbit. Inside the Roche distance, the self-gravitation is insufficient to balance differential gravitation from the central body. The Roche distance is *not* fixed for the Earth at 2.88 radii. It is actually proportional to the inverse one-third power of the satellite density. Naively a differentiated satellite with a liquid iron core (7 g cm<sup>-3</sup>) and a liquid silicate mantle (~3 g cm<sup>-3</sup>) could lose the silicate under the Roche condition near 3 radii whereupon the iron core could be stable down to 2.24 radii. Accretion from a hot cloud of immiscible iron and silicate droplets could begin with the iron droplets at 2.24 radii, followed by mantling with silicate. The actual situation involves turbulence for liquids, cohesion for solids, the shape of the orbit, the rotation, etc. Nevertheless the variation of Roche limit provides a possible mechanism for separating denser from lighter materials.

IV. Disintegration into Earth orbit would be affected by mechanical stability. Partial melting of the incoming satellite plus tidal heating during encounter would be important factors. Ductile iron should form more massive fragments than brittle silicates. Feldspar is more prone to shock deformation and

melting than olivine and pyroxene. Elastic collisions between two populations result in the more massive population losing velocity and being preferentially captured by Earth. A mass gradient with feldspar fragments favored at high radial distance might occur.

V. Of many possible scenarios, the following is fairly simple. In addition to capture and near-capture of minor planetesimals and debris (with decreasing flux, of course), the Earth near-captured a large planetesimal (pre-Moon) which disintegrated into hot debris. Much of the pre-Moon (especially the iron-rich material) was incorporated into the Earth but some stayed in orbit. High temperatures caused loss of volatiles (as in Ringwood's volatilization model), and collisions resulted in a radial gradient of decreasing mass. A hot iron-rich baby Moon accreted near the Roche limit for iron, receded and accreted a silicate-rich mantle. The iron-sulfur core of the spinning Moon developed a dynamo producing a magnetic field: further tidal recession plus rotation-locking between Moon and Earth ultimately led to factors which reduced the driving force of the dynamo, but not before extrusion of the last mare basalts.

Crystal-liquid differentiation stripped the core and mantle of light, fusible material leaving a stable ferro-magnesian mantle and concentrating radioactive material at the temporary surface. This surface material was rejuvenated as accretion proceeded.

The outer part of the ring of debris accreted into moonlets, and captured further material from Sun orbits. In general these moonlets would be dominated by ferromagnesian and feldspars. The content of volatiles and feldspars should increase for the more distant moonlets. The moonlets would be captured as a result of tidal recession of the baby Moon and by orbital perturbation of the moonlets during collisions with incoming bodies. A catastrophic perturbation of several moonlets might occur leading to near-simultaneous capture of several moonlets. The temperature of the moonlets could be low (several hundred °C), but capture by the growing Moon at low velocity ( $\sim 3 \text{ km s}^{-1}$ ) would increase the temperature. The low velocity would result in accretion of most of each moonlet with little loss to Earth. Planetesimals from sun orbit might also collide with the Moon, but the high velocity of impact would yield an explosion with little direct accretion (though exploded material might be captured later). The growing Moon would undergo continual crystal-liquid fractionation with reworking of fusible material.

Finally at about 4 g.y., the last large moonlets would be captured producing most of the circular basins. The dynamics of capture depend on the orbital parameters and nature of the perturbing force. One possibility is that at least the later impacts tended to occur at low velocity on the far side, bringing in large quantities of feldspar and Mg-rich pyroxene, which formed thicker ejecta blankets on the far than on the near side. If this can be justified dynamically, it may provide an explanation for the offset of the center-of-mass from the center-of-volume. Wood showed that moonlets exterior to the Moon's orbit would tend to impact on the far side of the Moon, but further study is needed of the ballistics, impact processes and petrologic consequences. With a thinner crust on the near side, one can postulate that mare basalts would easily penetrate the crust into impact basins on the near side but would rarely penetrate the crust on the far side. With this model, a problem arises in providing missiles to impact on the near side for production of the circular mare basins. One possibility is serious perturbation of exterior moonlets in near-circular orbits by interaction with bodies from sun-centered orbits. Unfortunately a process like this is *ad hoc*, and difficult to quantify.

Asymmetry of the Moon might also result from or be augmented by the differential gravitational field from Earth. One possibility is a second-order tidal effect on a rotation-locked Moon which helps to concentrate dense Fe, Ti basalt at the near side: however, the first-order tidal effect should affect both front and back. An interesting item for study is convection of a liquid satellite under the differential gravitational field of the primary body: this might lead to asymmetric differentiation of crystals and liquid.

The number of models for generation of mascons is too big to list here. For low-velocity impacts, substantial accretion of the incoming body should occur: e.g. Gold proposed that mascons resulted from contrast of accreted material with thick unconsolidated crustal debris. Isostatic uplift plus extrusion of Fe, Ti basalts undoubtedly complicate the problem and a complex model is needed.

Mineralogical study of breccias and soils has shown no clear-cut identification of debris from accreted moonlets. If the lunar crust is indeed composed largely of such impact debris, the moonlets would be dominated by similar minerals and rocks to those produced by melting of the early Moon. Evidence has been produced on the content of various trace elements of accreted debris, suggesting that the impacting bodies have distinctive chemical compositions. At first sight, this argues against the bodies belonging to a common population as implied here for the Earth-bound population (but *not* the Sun-

bound ones). However, the major chemistry of the accreting bodies might be dominated by silicates, and the distinctive differences might result from capture of Sun-bound projectiles while the bodies were still in Earth orbit.

Many possibilities are apparent and the model is presented in the spirit of Chamberlin's multiple working hypotheses.

Wood, J. A. and Mitler, H. E.: 'Origin of the Moon by a Modified Capture Mechanism, *or* Half a Loaf is Better than a Whole One'.

Capture of the Earth's Moon, intact, from an independent heliocentric orbit is dynamically difficult to accomplish and thus inherently improbable. If a candidate for capture passed within 2.5 Earth radii of the Earth's center (the Roche limit), it would be disrupted by tidal stresses. Öpik has recently drawn attention to differences in the subsequent orbits of the fragments produced by such an event. Assume a non-spinning object of substantial dimension entered the Earth's Roche limit at parabolic velocity: all fragments would be endowed with this same velocity at the moment of disruption. For those fragments detached from the near-Earth face of the object, however, this would amount to less than the parabolic velocity, since the distance from these fragments to the center of mass of the Earth is appreciably less than was the distance between the centers of mass of the original object and the Earth. These fragments would be projected into closed, elliptical orbits about the Earth. Conversely, debris from the farthest-out face of the object would be lost from the Earth in hyperbolic orbits. It is important to recognize that this *partial* capture of the substance of a passing object into geocentric orbit does not depend upon a special three-body configuration of Sun-Earth-object, or upon loss of orbital angular momentum to a tidally distorted Earth, or upon any other dissipative process; it follows naturally and inevitably from simple considerations of orbital mechanics.

Clayton, R. N., Grossman, L., and Mayeda, T. K.: 'Oxygen Isotopic Compositions of Lunar Soils and Allende Inclusions and the Origin of the Moon'.

In order to account for the high refractory and low volatile element concentrations in lunar rocks compared to chondrites, several workers have postulated that the Moon is highly enriched in high-temperature solar nebula condensates such as the Ca-Al-rich inclusions in the Allende meteorite. In this paper we present the results of simultaneous measurements of  $\delta\text{O}^{18}$  and  $\delta\text{O}^{17}$  in lunar, terrestrial and meteoritic materials and discuss the origin of the Moon in the light of these data.

Runcorn, S. K.: 'On the Internal Dynamics of the Moon'.

Three lines of evidence concerning the internal dynamics of the Moon have emerged during the Apollo programme which challenge comparison with what is known about the Earth (and Mars)

(1) present internal activity in the Moon: the occurrence of moonquakes and the phenomenon of lunar transient events.

(2) evolution of its internal constitution: the lava now proved to originate internally in a former lunar 'asthenosphere', the chemical differentiation required to separate the 'anorthositic' highlands.

(3) its thermal evolution: the apparent absence of extensive volcanism in recent times, the thick lithosphere necessary to support the mascons.

By comparison with the Earth (1) is weak, (2) is fully comparable and (3) shows a great contrast in the last 3000 m.y. Very tentatively Mars appears intermediate between the Earth and Moon in respect of its internal dynamics.

One speculates that the differences between these three bodies is connected fundamentally with their sizes. Clearly if temperature, rather than pressure or composition is the critical parameter differentiating between a rigid solid behaviour over the lifetime of the body and a fluid of very high viscosity, then the difference in the thicknesses of their rigid lithospheres must arise from them having different vertical temperature gradients. This is easily explained on a common thermal model with comparable density of heat source per unit volume and the different ratios of surface area to volume.

The non-hydrostatic figures of the Moon (and of the Earth and Mars) – or at least the lower



harmonic components – have been postulated to result from convection below the lithosphere. For the Moon two pieces of evidence for this hypothesis are compelling:

(1) the discrepancy between the ellipticity of the best fitting second harmonic surfaces and the dynamical ellipticity, which demonstrates the existence of internal density differences with angle.

(2) the agreement between the ellipticities of the highlands' surface and the much later lava surfaces of the maria, which show the present non-hydrostatic shape to have been produced subsequent to the filling of the maria basins, requires a mechanism which can, like convection, change its pattern in time.

Hydrostatic head arguments (after J. A. Wood) can account for the excess (about 1.5 km) filling of the circular maria resulting in the mascons. The discovery in the geometrical libration data of a systematic height difference between the surfaces of the irregular and circular maria, shows that the latter have fallen 1.5 km in 3000 m.y. Thus a cylindrical fault system extending through the lithosphere must surround the circular maria. Potential energy is therefore released at the average rate of  $10^{18}$  erg  $y^{-1}$  adequate to explain the moonquakes. The clustering of the locations of lunar transient events around the circular maria are also thus explained.

The remanent magnetization of the lunar lavas, discovered in the Apollo samples, and the highlands, inferred from the subsatellites, requires the presence of a lunar magnetic field of internal origin. Determinations of its intensity will decide between the alternative theories of a dynamo in an iron core which through decay of the heat sources has ceased to operate in the last 3000 m.y. and the Urey-Runcorn theory of a permanent magnetization of an undifferentiated Moon acquired from an early solar system magnetic field, now destroyed by the heating of the deep interior above the Curie point.

The thermal convection model of the Moon inevitably entails a rigid lithosphere which thickens with time. Thus the absence of any phenomenon remotely comparable with continental drift is understandable in the decipherable history of the lunar surface, but very early large horizontal displacements of the crust may have occurred, and the asymmetry of the near and far sides of the Moon may be explainable on this hypothesis.

The further analysis of global surveys is crucial to many of the problems discussed. For example, determination of the small dipole field of the Moon could give information concerning the distribution of crustal magnetization. This might be determined from the long period of Explorer 35 data. Possible further polar orbiter magnetic field data might enable the global variation of magnetization direction to be determined.

Wänke, H., Palme, H., Baddenhausen, H., Dreibus, G., Jagoutz, E., Kruse, H., Spettel, B., and Teschke, F.: 'Composition of the Moon and Major Lunar Differentiation Processes'.

New data from our multielement analysis program (58 elements including all major and minor elements) on 18 samples of Apollo 16 and 17 confirm the element correlations observed previously. The two component model for the bulk composition of the Moon, as it was presented by us last year is based on the K/La ratio. In this model the Chondritic Component (ChC) was not very well defined. As it was emphasized by Anders volatile elements like Mn, Na, K and to some extent also S and other elements are always observed in constant abundance ratios in chondrites, but with different depletion factors relative to the Fe, Mg silicates. The volatile fraction of the chondritic component can be estimated from the FeO/MnO correlation. An appropriate amount of FeS (assuming a C 1-chondritic Mn/S-ratio) has been added to the oxidized Fe to get the total iron content of the Moon (10.4%). Because of the low density of the Moon the content of metallic iron must be close to zero. In this way a refined two component model is set up in which the ChC seems now better defined. The new calculations yield a somewhat lower value for the High Temperature Component (HTC, 60% as compared to 69% in the previous model). The calculated bulk composition of the Moon has also slightly changed.

The K/La correlation holds for the large concentration range observed for these two LIL-elements. The Na/Eu ratio covers the same two groups of elements, but the observed concentrations vary within a much smaller range. Nevertheless, the point for our model moon falls well within the field of the observed ratios. As already observed also Fe and Sc are at least weakly correlated. However in this case our model moon is far off the observed concentrations and ratios. This seems to indicate a somewhat inhomogeneous accumulated Moon with a higher concentration of HTC material towards the center. This conclusion is supported by similar considerations involving the refractory element vanadium (observed concentrations below our calculated value) and the element chromium belonging to the ChC (observed concentrations above the calculated value). The refractory siderophile elements

highly enriched in the HTC (Ir, Re, Os) would also be preferentially concentrated in the interior of the Moon and e.g. the chondritic Re/Ni ratio in lunar basalts is not in contradiction with a high fraction of HTC in the Moon.

If the HTC fraction increases towards the center of the Moon the heavier chondritic component must be enriched in layers beneath the crust. Hence, the low density crust would be compensated in order to satisfy the constraint given by the moment of inertia.

The high enrichment of U and Th in a lunar interior consisting of nearly 100% HTC together with its high accretion temperature ( $>1200\text{K}$ ) would produce the first partial melt in roughly 100 m.y. Uranium, Th and the other LIL-elements would concentrate in this melt and thus brought to the surface. The relative constancy of the LIL-element patterns in the two major lunar rock types (KREEP-basalts and gabbroic anorthosites) is assumed to reflect the fractionation due to the first partial melt. In a subsequent partial melting process mare basalts with different LIL-element patterns are produced.

## 2. Characterization and Evolution of the Lunar Crust: I

Adler, I., Andre, C. G., Bickel, A. L., Lum, R. S., Podwysocki, M. H., Trombka, J., and Weidner, J. R.: 'An Analysis of the Apollo 15 X-Ray Fluorescence Experiment for Detailed Lunar Morphological and Geochemical Parameters'.

X-ray fluorescence data gathered during the Apollo 15 flight while in lunar orbit were analyzed to determine the most efficient, consistent and sufficient summarization technique for the quantification of geochemical parameters. The goal of the task was to produce and test the resolution and reliability of Al/Si and Mg/Si intensity ratios in order to distinguish relatively small lunar features. Portions of Maria Tranquillitatis and Serenitatis were chosen as test areas because of (a) the large areal extent of the available coverage, (b) the density of the data points allowing comparison with the calculated ratios across several overlapping orbits in order to test the duplicability of the values and (c) the desire to correlate outstanding physiographic features in what appears in a casual inspection as a homogeneous mare surface.

In order to determine the resolving capability of the system, 8 second data, the shortest time integration collected, was selected for the study area using a series of culling criteria. These included spacecraft elevation above the lunar surface, spacecraft attitude, and statistical reliability of the generated ratio data as determined by the calculated ratio errors and telemetry information. The resulting areal distributions of the Al/Si and Mg/Si ratios were then analysed using trend surface analysis to determine the spatial relationships of the data. Both normalized and non-normalized data were used in this technique, the former being used so that additional statistical tests could be made on the result of the analysis. Analysis of variance was applied to the trend surface output to determine those surfaces with significant improvements in the information level of the model. A randomization process was also applied to the areally distributed data to test for spatial structuring. Additional trials were made with 16 second data using a sliding average (sliding window) to gain statistical reliability and the same modeling techniques were then used.

Results indicate that although the 8 second data are highly variable, Al/Si intensity values are not randomly distributed. Moreover, variations along orbit paths accounted for a significant amount of the information contained in the data. Examination of the trend surface analyses indicated that a second order surface, showing high Al/Si values in the highlands to the north and south of the maria and low values in the basins proper, provided the most suitable model for the test area. The residuals plot allowed delineation of adjacent orbits with like characteristics which could be correlated with some surface features. Application of the same techniques to the 16 second Al/Si ratios, with the addition of an additional culling criterion of the solar energy level, gave more reliable results with further demarcation of material types. Average values of Al/Si intensity ratios could then be calculated for those areas which behaved in a similar fashion.

Using the results of the trend surface analysis, deviations from the regional model can be isolated. The craters Dawes, Bessel and the Jansen series can be distinguished by their higher Al/Si intensity ratios compared to their surrounding mares. Transitions between mares and highlands are relatively sharp. Areas of mare floor are distinguished where Al/Si ratios deviate considerably from the local mean.

Due to higher 'noise' levels, Mg/Si ratios could not be treated in the same fashion. Additional work is being carried out to interpret this data.

Steele, I. M., Smith, J. V., and Irving, A. J.: 'Mineralogical Studies of Crustal Rocks – Anorthosites; Norites; Armalcolite and Ilmenite'.

Our mineralogical studies on the above types of lunar samples are summarized below; complete manuscripts were submitted to *American Mineralogist*. *Major conclusions are:*

- (a) at least in part, the accessory phases (pyroxene, silica, ilmenite) in anorthosites result from exsolution of minor elements from plagioclase;
- (b) the parent liquid of anorthosites had an mg value of 0.7–0.8;
- (c) Apollo 17 soils from the Sculptured Hills contain a coarse-grained noritic component with enigmatic diopside bearing veins;
- (d) the morphology of the Sculptured Hills may in part be due to norite intrusions;
- (e) Zr-armalcolite and Cr-Zr-armalcolite coexist with Mg-rich silicates in recrystallized Apollo 17 breccias in contrast to ilmenite which coexists with less Mg-rich silicates;
- (f) armalcolite is probably the stable Ti-oxide phase in the upper lunar mantle.

1. *Anorthosites*: Lunar anorthosites are characterized by high-Ca plagioclase with low contents of minor-elements (Fe, Mg, K) and by minor accessory minerals (pyroxene, silica and ilmenite). Textural and compositional data indicate solid-state equilibration. If the bulk pyroxene (usually augitic) is primary, experimental partition relations suggest mg ~ 0.4 for the parent liquid. On the basis of: (a) pyroxene nucleation at twin boundaries; (b) homogeneous compositions of pyroxenes both within and adjacent to plagioclase; (c) chemical composition of lunar plagioclase, we suggest that at least some, if not all, accessory phases have exsolved from plagioclase. The parental plagioclase had appreciable Ca(Fe, Mg) Si<sub>3</sub>O<sub>8</sub> in solid solution similar to Fe-Ti-basalt plagioclase, but at low temperatures this component exsolved as augite and silica.

Based on the above mechanism, mg of the parental anorthositic liquid can be estimated from mg of the presumed parent plagioclase estimated from the composition of pyroxene inclusions but modified by the retained Mg and Fe in the plagioclase. Experimental data relating liquid-plagioclase Fe, Mg partitioning indicate that the liquid producing the anorthosites had mg ~ 0.7–0.8. This value rather than the previously derived value of 0.4 is consistent with a primary differentiation of the Moon from a liquid giving rise to anorthosites, ultrabasics (mg ~ 0.9) and the ANT suite. The characteristic low minor-element content of most if not all ANT plagioclase probably results from low-temperature equilibration.

2. *Norites*: Coarse-grained lunar rocks with igneous textures are rare; most have been severely altered by impact and thermal metamorphism. Apollo 17 1–2 mm fines from Sta. 8 (Sculptured Hills) contain a minor coarse-grained noritic component with preserved primary igneous features. These grains consist of 1–2 mm, single, unshocked orthopyroxene crystals (En 77–81, Fs 20–16: confirmed by X-rays) with enclosed or attached grains of plagioclase (An 92–95, Fe 0.15 wt.%, K 0.10 wt.%); grain boundaries suggest an igneous origin. Mesostasis areas rich in Ba, K, P and Si occur within some pyroxene grains. No silicate exsolution was observed (by optics or X-rays) in the pyroxene. Minor element data (Cr, Al, Ti) for the orthopyroxene are in the range for pyroxenes from both ANT and Fe-Ti-basalts.

Veins of diopside with minor chromite (Cr<sub>2</sub>O<sub>3</sub> 55.6 wt.%), iron, silica mineral and troilite occur within two pyroxene crystals. Exsolution is not responsible because the diopside is too Mg-rich and the veins are irregular. Fluid (liquid or vapor) intrusion, with possible fractional crystallization, produced these veins.

The association of the noritic fragments with Sculptured Hills' soil may be significant. The morphology of the Sculptured Hills is different from the surrounding massifs and no explanation has been proposed. We suggest that these hills and similar features may be coarse norite intrusions either not affected by impact or uplifted by major impacts. Better examples of this rock type may be found; an obvious candidate is 78235 – a coarse (1–5 mm) mafic-plagioclase rock sampled at Sta. 8.

3. *Armalcolite and Ilmenite*: Meta-breccias from all Apollo 17 stations contain minor Ti-oxide phases with textures suggesting late growth relative to the matrix silicates. Microprobe data for

silicates show a narrow range of variation for any one fragment and thus a bulk mg value can be assigned to each fragment. The term Cr-Zr-'armalcolite' is used purely for convenience, but we think that it may not be a member of the pseudo-brookite family. Microprobe data for coexisting oxides show: (a) armalcolite (Zr- or Cr-Zr) occurs with olivine if  $mg > \sim 0.75$ ; (b) ilmenite occurs with olivines of lower mg; (c) at  $mg \approx 0.75$  both ilmenite and armalcolite coexist suggesting a reaction at this mg value; (d) the distribution coefficient ( $K_D = (Mg/Fe)_{\text{oxide}} / (Mg/Fe)_{\text{olivine}}$ ) for Zr-armalcolite ( $K_D \approx 0.29$ ) is distinctly different from that of Cr-Zr-armalcolite ( $K_D \approx 0.12$ ), which is additional evidence for a structural difference as previously proposed.

Ilmenite shows high MgO contents, consistent with the high mg value ( $\sim 0.7$ ) of the breccia.  $K_D$  for ilmenite/olivine is 0.125 for Apollo 17 breccia indicating temperatures of about 900°C for equilibration. Relative temperatures for breccia equilibration could be estimated for MgO contents of ilmenite or recrystallized breccia by comparison. CaO contents differ between Fe-Ti-basalt ilmenite (CaO  $< 0.10$ ) and breccia ilmenite (CaO  $> 0.10$  wt. %).

The apparent stability of armalcolite with Mg-rich silicates suggests that it is the stable oxide phase in the Moon's mantle if the latter consists of Mg-rich mafics. The early crystallization of armalcolite may have been an efficient means of concentrating Ti in the lunar mantle during an early lunar differentiation.

Roedder, E. and Weiblen, P. W.: 'Petrology of Clasts in Breccia 67915'.

Rock 67915 is a 2.6-kg feldspathic polymict B4 breccia (dark matrix, light clasts) from Outhouse Rock at Sta. 11. It shows two large ill-defined whiter areas in a darker gray matrix; on the sawn surface the color contrast is greatly enhanced, but both these parts are themselves made of smaller clasts. No individual crystals are recognizable to the eye.

Forty-two probe mounts were made from various clasts in this complex polymict breccia. Although these clasts are quite variable in appearance, they are surprisingly similar in composition. The complex nature of the rock makes quantitative estimation of clast population hazardous at best, but 95% of the rock consists of clasts ranging in composition from gabbroic to troctolitic anorthosite, set in a matrix of similar composition. Most clasts consist of crystal fragments of plagioclase and less abundant pyroxene and/or olivine embedded in a matrix of finer fragments of these same three minerals. Individual homogeneous clasts are generally only a millimeter or less in size. With a few exceptions, both opaque minerals and K-rich areas are either very scarce or completely absent in both clasts and matrix. One generalization is that the clasts made of fine crystal fragments tend to be either quartz- or olivine-normative gabbroic anorthosite, whereas those with coarser crystals are more commonly troctolitic anorthosite. Although the compositional range for the bulk of the clasts is rather small, the range of textural states is large, as is the range of shock metamorphic effects. These features will be described in greater detail in a later paper by another consortium member (B. N. Powell).

The gabbroic anorthosite clasts have been described previously. Most of the troctolitic anorthosite exists in three textural categories. The most common, presumably metamorphic in origin, consists of plagioclase and less abundant olivine fragments,  $\geq 100 \mu\text{m}$ , set in a granoblastic matrix of finer grained plagioclase (An<sub>93</sub>; anal. 1). About 10% of the matrix consists of olivine (Fo<sub>70-80</sub>; anal. 2) in 10- $\mu\text{m}$  grains, mainly along plagioclase grain boundaries. A second type, much less common, consists of lathlike decussate plagioclase ( $\sim$  An<sub>94</sub>) and interstitial olivine ( $\sim$  Fo<sub>72</sub>); it resembles the basalts in texture, and may have formed from rapid quenching of impact-generated troctolitic liquids. A third type occurs as a relatively large clast in 67915, 12, and consists of large, equant subhedral plagioclase crystals (An<sub>95</sub>) set in a matrix of surprisingly iron-rich interstitial olivine (Fo<sub>56</sub>). Although both minerals are badly fractured and in part sheared by impact shock, the original texture appears to be of cumulus origin.

The remaining 5% of the clasts in 67915 include a wide variety of rock types; several unique clasts may be of meteoritic origin. In addition to these individual, unique clasts, there are clasts of sodic ferrogabbro, mare basalt, and peridotite, judging from mineral analyses of the phases present. No additional clasts of the distinctive sodic ferrogabbro described earlier have been found, but sheared concentrations of mineral fragments, (plagioclase  $\sim$  Ab<sub>34</sub>, ferropigeonite  $\sim$  Fs<sub>65</sub>, and cristobalite), presumably from this rock type, are present in several samples of the breccia. The total quantity of sodic ferrogabbro in 67915 cannot be large, however, as it is very high in K<sub>2</sub>O, and the whole rock is extremely low in K<sub>2</sub>O.

Basalt clasts are a relatively rare component. Although most apparent basalt clasts prove to be troctolites with decussate texture, at least one small one is a normal mare basalt in texture and mineralogy, complete with high-K plagioclase and late stage concentrations of K and Ba. If this is truly a fragment of mare basalt, it raises several problems, in particular as to its age of formation.

Several clasts of peridotite composition have been found. One of these consists mainly of augitic pyroxene ( $\text{En}_{45}\text{Wo}_{33}\text{Fs}_{20}$ ; anal. 3) with a minor amount of exsolution resolvable (wt. % CaO varies from 15.4 to 18.2), olivine ( $\text{Fo}_{60-62}$ ), plagioclase ( $\text{An}_{82-87}$ ), and ilmenite ( $\text{MgO-2.97 wt. \%}$ ). Although badly shocked and polygonized, an original igneous texture is apparent. Another very unusual clast of peridotite consists mainly of orthopyroxene (opx) crystals containing perhaps 5% of oriented lamellae of clinopyroxene (cpx) as much as  $10\ \mu\text{m}$  thick. The size and large difference in composition between the cpx lamellae ( $\text{En}_{41.5}\text{Wo}_{42.3}\text{Fs}_{16.2}$ ; anal. 4) and the opx host ( $\text{En}_{66.2}\text{Wo}_{3.9}\text{Fs}_{29.9}$ ; anal. 5) suggest a relatively low equilibration temperature, perhaps  $1000^\circ\text{C}$  (4). Several coarse crystals of twinned but compositionally similar cpx occur in the same clast; these, however, are uniform, i.e., lack lamellae. Olivine ( $\text{Fo}_{65}$ ; anal. 6) and plagioclase ( $\text{An}_{93}$ ; anal. 7), plus minor amounts of ilmenite ( $\text{MgO-3.71\%}$ ), chromite, troilite, and 2.30% nickel iron make up the balance. Embedded in the opx crystals are clots of small crystals of plagioclase ( $\text{An}_{93}$ ) and olivine ( $\text{Fo}_{73}$ ). Fine intergrowths of opx ( $\text{En}_{62}$ ) and troilite occur throughout the clast, mainly interstitial to or completely within olivine grains. One large, strongly curved olivine grain appears to have been partly replaced with this intergrowth. A possibly important feature of both peridotite clasts is the relatively high  $\text{K}_2\text{O}$  in the plagioclase (0.10–0.21%), in contrast with the bulk of the plagioclase in 67915, in which  $\text{K}_2\text{O}$  is below the detection limit ( $<0.05$ ).

Schonfeld, E.: 'Component Abundance and Evolution of Regoliths and Breccias: Interpretation by Mixing Models'.

Mixing models can be used to understand the evolution of regoliths and breccias. The composition of soils and breccias depends on the availability of the rock types at a certain time, location, and the intensity of the planetesimal bombardment. The possibility that VHA basalt and Low K Fra Mauro basalt (LK-FM) are mixtures was investigated using the published chemical composition of these rocks and a weighted least-squares mixing model technique. There are difficulties in generating these rocks by differentiation. VHA and LK-FM have very similar relative concentration patterns for U, Ba, Ce, Sm and Yb that are almost identical to the pattern found in KREEP. It is difficult to generate this pattern by different degrees of partial melting from the same source. Also the majority of these samples have considerable amounts of meteoritic contamination. One simple way to generate these rocks would be to mix KREEP with other rock types that have relatively low concentrations of U, Ba, Ce, Sm and Yb. The results of the mixing model calculations using the published analysis of up to 27 elements show that it is not possible to generate these rock types by using only mare basalts, 'anorthosites', KREEP, meteoritic component (met), and granite (gr). Another possible rock type is dunite and has been found only in small amounts. If dunite is included as another component, then the mixing model calculations show that it is *possible* to generate VHA, LK-FM and other rock types by mixing dunite, 'anorthosite', and KREEP. There is an approximate trend line between KREEP and (spinel) troctolite. (Spinel) troctolite can be a mixture between 'anorthosite' and dunite, but the trend line suggests that (spinel) troctolite is a rock type and not a mixture. The deviations from the trend line could be caused by sampling errors and/or the variable composition of the (spinel) troctolites. In conclusion it appears that it is possible that the highlands are 'contaminated' with KREEP, and that dunite and/or (spinel) troctolite are significant rock types.

*Apollo 15 regolith and breccia.* The most abundant component in the Apennine front is the brown-glass matrix breccia. The chemical composition of this breccia is very similar to the composition of soil 15101 and has slightly higher concentration of Ti, Fe, and K than LK-FM 15. LK-FM can be modeled as a mixture of about 18% KREEP + 17% Dunite + 62% 'Anorth' + 0.8%gr. Preliminary mixing model calculations on soil 15101 and other Apollo 15 breccias, suggest that the brown glass-matrix breccia = LK-FM 15 + ~15% Mare + ~10% green glass + (variable) KREEP. This may be an example of breccia and regolith evolution where we start with a rather 'old breccia' (LK-FM) and other components are added progressively.

*Apollo 16 samples.* Mixing model calculations were performed on 9 Apollo 16 samples using the chemical analysis of about 26 elements. After the 'Anorth' component, the most significant component

appears to be KREEPy 16 (average of 65015, 60315 and 62235). KREEPy 16 can be modeled as a mixture of about 51% KREEP + 34% 'Anorth' + 15% Dunite + 0.9% gr. The lowest amount of KREEPy 16 was from the soils from North Ray crater (67601, 67461) and rock 68415. Sample 68415 contains meteoritic contamination and gives a very good fit as a possible mixture. Simple mixtures of VHA + 'Anorth' + Met and LK-FM + 'Anorth' + Met gave in all cases poor fits for Mg. Therefore, there appear to be no significant amounts of VHA and/or LK-FM in the Apollo 16 soils, whereas KREEPy 16 appears to be the main contributor of LIL elements.

*Apollo 17 regoliths.* A preliminary mixing model analysis was performed on the chemical composition of 16 Apollo 17 soils. Two sets of components were tested. In the first case KREEP, dunite, 'anorth', mare basalt 17, orange glass, granite, and met. components were used. In the second case KREEPy 17 (noritic breccia) and anorthositic gabbro from 17 were used instead of KREEP and 'anorth'. In both cases the fit was similar and quite good, with the exception of soil 76501 that required a component with more Mg, such as 76055, or a 5% excess dunite. Also instead, of KREEPy 17 other components were tested such as VHA and LK-FM. In most cases KREEPy 17 gave a better fit. Therefore, it appears that KREEPy 17 and anorthositic gabbro 17 are significant components in the Apollo 17 regoliths. The elements used in the mixing model are those published with the exception of Zn. In a few cases other elements were included such as Li, Ce, Sm, Eu, Yb, U and Th with similar results. The amounts of orange glass have an uncertainty of about 35%. The meteoritic contamination is based mainly on Ni and is 'equivalent' to about 1 to 2% CC-1, granites in all cases are less than 0.3%. The Apollo 17 site has similarities with the Apollo 15 site in the sense that in both places the abundance of mare basalts is inversely proportional to the abundance of 'anorthositic' material. The ratio of KREEPy 17 to anorthositic gabbro 17 is different in the North and South Massif regoliths. In the case of sulphur it was assumed that the meteoritic component is negligible. The good sulphur material balance suggests that there is no bulk volatilization of S in these regoliths.

Laul, J. C. and Schmitt, R. A.: 'Siderophile and Volatile Trace Elements in Apollo 17 Boulder-2 Rocks and Soils'.

Eighteen trace elements have been measured by RNAA in 6 samples of 5 rocks from a 2 m boulder-2 (STA 2, Wasserburg boulder consortium) and 4 soils of the S. Massif and one valley soil. Based on the physical description and chemical compositional data the boulders are metaclastic, medium K KREEP type rocks.

The rocks have a high content of siderophiles (2-4% Cl) and show fractionated patterns having an ancient meteoritic component. These patterns are similar to those first found by the Chicago group (Anders *et al.*) in soil separates of highland soils, 14142 and 14146. We have analyzed the same suite of elements except Ge in these samples. Following the Chicago approach, we find that 5 samples of 4 rocks have Ir/Au ratios of 0.44, which is typical for the LN group, probably LN<sub>2</sub> group. However, the 72335,2 sample has a high Ir/Au ratio of 0.84 and belongs to the DN group. It is noteworthy that rocks 72315 (medium K KREEP rock) and 72335 (anorthositic gabbro) with two different ancient projectiles in them, are rocks separated by ~18 cm in the same clast of boulder-2. The difference in the Ir/Au ratios is attributed to either poor sampling (less likely) or to a case of two stage impact projectiles. The LN components are attributed to the Imbrium basin. It seems improbable that the 2 m boulder was ejected >600 km by the Imbrium basin forming event. We propose that the ancient meteoritic planetesimal (pre-Imbrium) which formed the Serenitatis basin had a composition similar to LN character of the Imbrium basin planetesimal.

The S. Massif soils near the boulders have in general high Ir/Re/Ni/Ag/Au ratios relative to the rocks. This is expected if the soils contained a mixture of ancient meteoritic component and micro-meteorites of Cl composition. Variable amounts of Ni and Au and a constant ratio of Ni/Au were found in duplicate analyses of 72501 soil; this seems to confirm the extraneous addition of Cl material.

Strong correlations of the refractories Ba and La versus U are evident. A mixing line passing through high K KREEP and soils suggests an appreciable component of high K KREEP to the soils. On the other hand, the valley soil 75081, with high ratios of Ba/U = 370 and La/U = 29, which are similar to Apollo 11 10084 soil, deviates from the mixing line, and this implies that the valley soils have little KREEP in them.

Cesium varies over a 5-fold range in content in the boulder-2 rocks and shows no correlation to U. Such variable ratios of Cs/U suggest selective volatilization of the heavier alkalis during cratering,

brecciation and metamorphic processes. Variable Rb/Cs ratios of 19, 25, 29, and 33 found in the 4 'high alumina' rocks of boulder-2 indicate significant fractionation for the heavy alkalis. For these same 4 rocks, the Na<sub>2</sub>O and K<sub>2</sub>O abundances were fairly constant. Such heavy alkali fractionation suggests variable time-high temperature exposures for these 4 rocks. On the other hand, the relatively uniform Sb and Zn abundances in these 4 rocks is unexpected if these rocks were exposed to such variable conditions.

Chou characterized Cd, In and Zn among other volatiles as atmophile. Accordingly, it is expected that these elements should show considerable enrichment in the boulder shadow soil relative to the exposed soil. Our systematic study of 4 shadowed and exposed soils rejects the labile hypothesis. On the other hand, if these soils are relatively young, a test of the volatile transport hypothesis by our data may be invalid. Chou *et al.* further speculated that the labile elements should also show evidence of movement from highlands to the lower mare areas. Such volatile element movement should be observed at the Apollo 17 interface between STA 2, as representative of highland avalanche material, and the mare soils in the valley. A comparison between the S. Massif soils and the valley soil 75081 does not support such labile processes.

Chang, S., Gibson, E. K., Jr., and Lennon, K.: 'Abundances of C, N, H, He, and S in Apollo 17 Soils from Stations 3 and 4: Implications for Solar Wind Exposure Ages and Regolith Evolution'.

Abundances of C, N, S, H, He, and metallic Fe have been measured in two suites of Apollo 17 fines. One suite of samples is a trench sequence from the rim of Ballet Crater at station 3. These include: 73221,7, a skim sample of the thin 0.5 cm layer of medium gray soil; 73241,5, a light gray soil from the upper 5 cm of the trench which overlies a marbled zone; and 73261,8 and 73281,6, which represent the medium gray and light gray portions of the marbled zone, respectively. The second suite of samples includes 74220,84, the orange soil, and its companion gray soils 74240,16 and 74260,7. The methods of gas extraction by acid hydrolysis and stepwise vacuum pyrolysis followed by combustion are described elsewhere.

Consistent intra-sample abundance patterns for solar wind derived C, N, and H species show up clearly in the data obtained. These patterns define the following decreasing order of solar wind exposure experience by the samples: 73261,8  $\geq$  73221,7 > 73281,6 > 73241,5  $\approx$  74240,16  $\approx$  74260,7  $\gg$  74220,84. This sequence is also reflected in the He contents of the station 3 soils; however, the gray soils from station 4 appear to have anomalously high He abundances relative to C, N, and H. This probably reflects the greater amounts of ilmenite in the valley soils. Because of the chemical reactivity of solar wind C, N, and H ions, their retention in soils is expected to be relatively independent of soil mineralogy.

At all localities observed on the light mantle, a layer of light gray subsurface material occurs 5 to 10 cm below the medium gray surface soil. At station 3 accumulation of surface material was apparently interrupted by formation of Ballet Crater. Significantly, the solar wind exposure experienced by the light gray subsurface layer (73241,5) is about half that of the light gray portion of the marbled zone (73281,6). If these two samples have a common origin as has been suggested, the reason for the difference in exposure times is not clear. One explanation may be that the accumulation rate of this material was not constant, but, rather, slowed with time leading to a gradient decreasing with depth of solar wind exposure for soil grains. Alternatively, deposition of the light gray layer may have been accompanied by some grain size sorting which enriched the bottom layers in coarse particles and the upper ones in fine particles and led to apparently higher bulk concentrations of solar wind species in the upper layers. In either case, the impact event would have caused (a) inversion of strata, placing the layers of light gray soil least enriched in solar wind species at the very surface, and (b) marbling, the latter involving the soil layers more enriched in solar wind material which originally interfaced with the medium gray surface soil. Deposition of medium gray surface soil then resumed. This hypothesis for regolith evolution at station 3 can be tested when results from other analyses of the soils are reported and samples from drive tubes 73002 and 73001 become available for study. The similarity in solar wind exposure of 73221,7 and 73261,8 suggests that the gray surface soil may be accumulating at essentially the same rate as it did prior to the marbling event. Determination of the age of Ballet Crater should permit estimation of the accumulation rate of light mantle regolith.

The sulfur data conform with the simple mixing model proposed by Gibson and Moore: soils from station 3 derived predominantly from sulfurpoor massif material are low in S ( $< 700 \mu\text{g g}^{-1}$ ), and

soils from station 4 which contain a large sulfur-rich mare basalt component are high in S ( $> 1000 \mu\text{g g}^{-1}$ ). Despite its mare basalt chemistry, the S content of orange soil is anomalously low and calls for a unique high temperature history. One very interesting result is that sample 73221,7 is very depleted in S relative to its companion soils. This observation suggests that either recent lateral mixing of soil on the light mantle with sulfur-rich foreign components is slow compared to regolith accumulation of the upper 0.5 cm of light mantle is derived in part from different source rocks than the underlying layers of soil. However, grain compositions do not reveal gross mineralogic differences in these soils.

Simulation studies of solar wind related processes will also be reported. These include determination of implantation efficiencies of simulated solar wind C and N ions into bulk lunar fines and ilmenite targets.

Hübner, W., Kirsten, T., and Kiko, J.: 'Rare Gases in Apollo 17 Soils with Emphasis on Analysis of Size and Mineral Fractions of Soil 74241'. —

The rare gas contents of eight Apollo 17 soils covering all major regolith types of this landing site have been analyzed. The major implications from these data were recently discussed and will be elaborated in the forthcoming Proceedings of the 5th Lunar Science Conference. In this report we restrict our selves to the discussion of soil 74241 ('control soil'), adjacent to 'orange soil' 74220 (Rim of Shorty Crater). Our previous analyses of 74240 indicated that this soil is unusual in various respects and deserves further studies. Consequently we have performed a detailed analysis of 74241.

1. *Grain Size Analysis:* 7 grain size separates between 12 and 272  $\mu$  define a similar surface correlation for all major implanted rare gas isotopes. If  $n$  is defined by  $C \sim d^{-n}$  ( $C = \text{ccSTP/g}$ ;  $d = \text{grain diameter}$ ), we obtain  $n \sim 0.6$  for  ${}^4\text{He}$ ,  ${}^{20}\text{Ne}$ ,  ${}^{36}\text{Ar}$ ,  ${}^{84}\text{Kr}$  and  ${}^{132}\text{Xe}$ . This value is typical for mare soils and implies considerable migration times after implantation (slow gardening) rather than fast burial. We cannot confirm the appreciably higher  $n$ -values reported by Hintenberger and Weber. By special efforts we were able to prepare an extremely fine size fraction of  $\leq 2.5 \mu$  diameter. Even with the help of SEM-observation, the mean effective diameter of this fraction could only be estimated. Within this uncertainty implanted gas concentrations in  $\mu$ -particles still follow the  $n = 0.6$ -line for all rare gases (e.g. 0.73 ccSTP ${}^4\text{He/g}$ ). From this it follows that the quantities of implanted solar flare ions in lunar soils are negligible compared to solar wind ions.

The composition of the SUCOR-component was determined from the grain size fractions. The inferred ratios  $({}^{22}\text{Ne}/{}^{21}\text{Ne})_T = 32.2$ ;  $({}^{36}\text{Ar}/{}^{38}\text{Ar})_T = 5.35$  are almost identical with the ratios directly measured in the  $\leq 2.5 \mu$ -fraction. A  ${}^{21}\text{Ne}$ -cosmic ray exposure age of  $170 \pm 30$  m.y. was calculated making the usual assumptions. The  ${}^{38}\text{Ar}$ -exposure age is higher but inaccurate because of the large amount of trapped Ar.

2. *Mineral Separates:* Particularly, ilmenite separates of lunar soils have often been analyzed, but so far there has been no comprehensive attempt to analyze *all* major constituents of any lunar soil for rare gases, except for single grains. We undertook this task aiming at (1) the explanation of particularities of soil 74241, (2) the understanding of composite soil patterns in general.

*Parentless  ${}^{40}\text{Ar}$  and K-Ar Retention Age.* One unique feature of 74241 is its exceptionally high  ${}^{40}\text{Ar}/{}^{36}\text{Ar}$  ratio of 7.65. The  $({}^{40}\text{Ar}/{}^{36}\text{Ar})_{\text{SUCOR}}$ -ratio varies both with composition and with grain size! (Agglutinates 6.1; bulk 7.65;  $\leq 2.5 \mu$ : 9.46; 2.5–12  $\mu$ : 8.24; 12–24  $\mu$ : 7.21; 24–60  $\mu$ : 6.87). These large variations cannot be explained simply by radiogenic  ${}^{40}\text{Ar}$ . The variability prevents the calculation of K-Ar retention ages from grain size fractions, since the usual  ${}^{40}\text{Ar}$  vs  ${}^{36}\text{Ar}$ -plot is invalid. Our data, as well as those of Hintenberger and Weber are, in spite of their calculations, consistent with any K-Ar age between 0 and 4 b.y. Work on etched samples is in progress. Our observation together with the high concentrations of volatiles observed by Jovanovic and Reed support a very early solar wind irradiation but they add also a new aspect to the K-coating hypothesis. Note that the depression of  ${}^{40}\text{Ar}/{}^{36}\text{Ar}$  ratios in agglutinates, if caused by regolith dynamics must have occurred in *ancient* times as nearby orange soil strata were well preserved since Shorty Crater excavation.

*Cosmic Ray Exposure Ages.* The more reliable  ${}^{38}\text{Ar}$  exposure ages for ilmenite, pyroxene and feldspars range from 285 to 350 m.y. The  ${}^{21}\text{Ne}$  exposure ages are significantly lower. In particular, the plagioclase age is only 60 m.y. If this is interpreted in terms of fractional losses, and we have no better alternative, then we note a surprising similarity between Ne–Ar fractionation patterns of implanted



gases and of spallogenic gases in the various minerals. It seems that the extent of possible  $^{21}\text{Ne}$ - and even  $^{38}\text{Ar}$ -losses has previously been underestimated.

#### *Trapped Gases.*

The diffusion properties of the major constituents of lunar soil are such that at lunar surface temperatures, severe and selective elemental fractionations occur between He, Ne, and Ar, but not between Ar, Kr, and Xe. Consequently, Ar or even Xe rather than He or Ne should be used to characterize the total amount of gas implanted into a soil.

The *absolute* gas concentration ( $^{36}\text{Ar}$ ) of a soil is governed by its agglutinate content more than by anything else. Note that ilmenite has the *lowest* Ar, Kr, and Xe-concentrations next to orange glass (less outward diffusion, less inward migration).

The *fractionation pattern* of a bulk soil is determined by its modal composition. Only the analysis of mineral separates can lead to the detection of intrinsic solar wind abundance variations.

Ilmenite has the least elemental fractionation. The diffusion properties of pyroxene are very remarkable. It is heavily depleted in He but very little in Ne (next to ilmenite). It indicates that the lunar surface temperature is intermediate between the critical temperatures for the onset of He and Ne diffusion in pyroxene. The He-Ne-Ar pattern of pyroxenes may become a sensitive thermometer.

The etching of scoriaceous (ropy) glass reveals that gases included in cavities and microbubbles are better preserved than those in the surface layers of the glass. Devitrification of glass also increases the retentivity.

$^4\text{He}/^3\text{He}$  *Ratio*. One is tempted to link the exceptionally high ( $^4\text{He}/^3\text{He}$ )<sub>T</sub>-ratio of 3100 and the high ( $^{40}\text{Ar}/^{36}\text{Ar}$ )<sub>SUCOR</sub> ratio of 74241 to a very early solar wind irradiation. However, the data obtained from the mineral separates call for a cautious interpretation. They provide evidence for *isotopic* fractionation due to solid state diffusion. Ignoring those cases for which  $^4\text{He}_R$ ,  $^4\text{He}_{\text{reimplanted}}$ , and  $^3\text{He}_C$ -corrections create ambiguities, we may safely state that the ( $^4\text{He}/^3\text{He}$ )<sub>T</sub> ratio in scoriaceous glass is 30% higher than in ilmenite. The most likely explanation is isotopic fractionation after implantation. Space limitation forces us to postpone the discussion of many more features implicit in the data until the publication of the forthcoming Proceedings.

Huneke, J. C., Jessberger, E. K., and Wasserburg, G. J.: 'The Age of Metamorphism of a Highland Breccia (65015) and a Glimpse at the Age of its Protolith'.

We report here an attempt to decipher the age of the protolith of breccia 65015 using the  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  technique. Petrographic and Rb-Sr isotopic studies have shown the presence of clasts which have not been brought into chemical equilibrium with the recrystallized ground mass. Studies on such rocks are important in penetrating the time barrier at ~ 4.0. AE reflecting the terminal lunar cataclysm and are applicable to the characterization of the early lunar crust and the time scale for its evolution.

Ar analyses were made on a whole sample and mineral separates (two plagioclase, a pyroxene and a pyroxene with 4% whitlockite [Ph-A]), using 30-50 heating steps to provide high resolution in  $^{40}\text{Ar}/^{39}\text{Ar}$  variations. It was anticipated this would allow the contributions from relict retentive phases to be isolated. A low resolution experiment would not show this fine structure, but would give age plateaux at 3.9 to 4.05 AE for all samples between 500-900°C. Above 900°C, pyroxene. Ph-A and whole rock ages all decrease sharply, while both plagioclases show a rapid increase in apparent age. For plagioclase B, the highest age of ~ 4.5 AE is approached in a regular sequence of precise data. This increase in apparent age of the plagioclase is unusual. Plagioclase separates have typically exhibited well defined age plateaux, with the one exception of plagioclase from rock 68415, where the ages increased to ~ 4.5 AE in a pattern very similar to that observed here, 68415 also contains large plagioclase relicts to which the age of ~ 4.5 AE in the last Ar release can be ascribed, although Sr isotopic equilibration with the matrix is indicated.

Of the K in 65015, 90% resides in an irregularly dispersed, very fine quintessence which contributes a large fraction of the total  $^{40}\text{Ar}$  at low temperatures, as demonstrated by the high K/Ca in these releases. Plagioclase B is ~ 99% pure, but an admixture of only 1.5% quintessence could account for two thirds of the K. In contrast, plagioclase has ~ 13% Ca whereas quintessence has only 2% Ca. Thus  $^{37}\text{Ar}$  from the plagioclase samples is related almost entirely to release from the plagioclase, not

high K-low Ca impurities, and a true plagioclase plateau should be associated with  $^{37}\text{Ar}$  release. The data presented this way show the distinct peak at  $\sim 600^\circ\text{C}$  in the high K/Ca regime which, instead of being interpreted as an intrinsic part of the plagioclase plateau, is identified in the  $^{37}\text{Ar}$  plot as a minor contribution from an admixed high-K phase. There is a reasonably well defined plateau corresponding to a K/Ca of 0.005 appropriate to plagioclase and extending over 35% of the  $^{37}\text{Ar}$  release. It is most reasonable to associate this plateau with plagioclase which has completely lost  $^{40}\text{Ar}$  in a metamorphism at 3.98 AE and to associate the age peak at  $\sim 600^\circ\text{C}$  with the crystallization of quintessence at the same time. About 15% of the  $^{37}\text{Ar}$  release from plagioclase B and  $\sim 5\%$  from plagioclase C can be related to high ages, in striking agreement with  $\sim 14\%$  and  $\sim 8\%$  inferred from Rb-Sr studies of the same separates. This provides a very important argument for the association of the  $\sim 4.5$  AE age with unequilibrated plagioclase clasts, and it is thus plausible to correlate this age with the plagioclase clasts which have not been thoroughly equilibrated and outgassed during the metamorphism at 3.98 AE. These results support reports by other workers on evidence for more ancient lunar sample ages. The firm assignment of a precise time to a part of a  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  release pattern requires a more complete understanding of the nature of  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  variations. Spallation  $^{38}\text{Ar}/^{37}\text{Ar}$  in plagioclase B was found to be 10% higher in the last 15% of  $^{37}\text{Ar}$  release, indicating an older exposure age for the same plagioclase showing high  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  ages. This suggests that the protoliths of many impact breccias may include material which resided for some time in the outer few meters of the lunar surface prior to the metamorphism.

Ar ages and trapped Ar compositions were measured for green glass and devitrified spheres hand-picked from the Apollo 15 breccia 15086 from Elbow crater. All of the spheres are presumed co-genetic. Electron probe measurements of green glass and devitrified spheres show very similar compositions. The devitrified spheres have 595 ppm K, compared to 175 ppm K in the green glass. Since K is very low, only a few high K particles are necessary to significantly effect the total pattern. An effort was made to avoid such contamination, which may nonetheless have occurred.

$^{40}\text{Ar}$  must be separated into trapped and radiogenic contributions, which is attempted here using isotope correlations in a differential thermal release experiment. The compositional variation trajectories observed are complex. The low temperature releases are dominated by the consecutive release first of an  $^{40}\text{Ar}$ -rich, then an  $^{36}\text{Ar}$ -rich trapped Ar. No precise trapped Ar composition in the green glass is defined by the correlation of more than a few consecutive data points. Except for the two highest temperature releases, the data above  $760^\circ\text{C}$  form a roughly linear array which intersect the ordinate at nearly the total trapped Ar composition. The array is not precise, and no constant trapped Ar composition is clearly established. The two highest temperature releases are well outside this correlation, trending in the direction of excess  $^{40}\text{Ar}$ . The reason for this, whether it is indicative of inherited  $^{40}\text{Ar}$ , a redistribution of  $^{40}\text{Ar}$  or K, or possibly an experimental artifact, is not established. The trajectory of green glass compositions is strikingly similar in its major features, including the high temperature trend, to that observed for 74220 orange glass, the only other glass measured in comparable detail.

Compositional variations in Ar released from the devitrified spheres are also complex. The trapped Ar variations at low temperature are similar in both samples. Higher temperature data scatters, but tends to converge with the K-derived  $^{39}\text{Ar}/^{40}\text{Ar}$  of the green glass. Several measured  $^{39}\text{Ar}/^{40}\text{Ar}$  of the devitrified spheres are larger than the extrapolated  $^{39}\text{Ar}/^{40}\text{Ar}$  of the green glass, giving younger apparent ages for those releases. This observation is not sensitive to the assumed trapped Ar composition. Ar compositions from the devitrified spheres do *not* trend to exceptionally low  $^{36}\text{Ar}/^{40}\text{Ar}$  and  $^{39}\text{Ar}/^{40}\text{Ar}$  in the high temperature release as observed in the glasses.

Ages of both green glass and devitrified spheres, corrected for trapped  $^{40}\text{Ar}$  using a trapped ratio of  $^{36}\text{Ar}/^{40}\text{Ar} = 1.23$  are presented. The data which are highly uncertain in K-derived Ar composition due to large trapped Ar contributions involve only the first 17% of  $^{39}\text{Ar}$  release. These data characterize the trapped Ar. An age of  $3.29 \pm 0.06$  AE is inferred for the green glass from the  $1075^\circ\text{C}$  and  $1195^\circ\text{C}$  points, which contain 45% of the  $^{39}\text{Ar}$  release and relatively small amounts of trapped Ar. Inclusion of the subsequent  $1320^\circ\text{C}$  release would reduce the age by only 0.02 AE. This age for the green glass confirms the age of  $3.38 \pm 0.06$  AE previously reported and more firmly establishes the time of origin of the green glass during Imbrium mare flooding and a probable origin in volcanic activity during this period. For the devitrified spheres, the last 65% of  $^{39}\text{Ar}$  release yields an average age of 3.1 AE, only slightly younger than the age of the green glass.

These analyses serve to illustrate the complexity in trapped Ar compositions. This problem must be seriously addressed in any  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  analysis of samples exposed to solar wind. The systematics of  $^{36}\text{Ar}/^{40}\text{Ar}$  vs  $^{39}\text{Ar}/^{40}\text{Ar}$  variation are somewhat better defined in the glasses compared to the devitrified

spheres, and future studies should recognize both this and the decreases in apparent age which seem to be associated with the devitrification.

Haines, E. L., Hutcheon, I. D., and Weiss, J. R.: 'Excess Fission Tracks in Apennine Front KREEP Basalts'.

Whitlockite grains from two small Apennine Front KREEP basalt fragments have been found to contain extremely high densities of fission tracks. The observed track densities exceed the contribution from spontaneous fission of  $^{238}\text{U}$  by factors ranging from  $\sim 6$  to 20 times. Track excesses are not correlated with the measured uranium contents of individual phosphates. This behavior suggests large variations in the Pu/U ratios among phosphates within a single basalt fragment.

The apparent upper limit on crystallization ages of lunar rocks of 4 Gy has been interpreted as the result of the wide distribution of material excavated during the Imbrium impact or as the termination of very heavy meteorite bombardment. The Apennine Front appears to have been uplifted during or subsequent to the Imbrium event, e.g. as a crater rim or subsidence scarp. As such, the Front may contain material crystallized before the Imbrium event whose track record was not erased during the uplift.

Our whitlockite grains were found in basalt fragments selected from the 1–2 mm size fraction of soil 15272 (station 6) recovered from the Apennine Front. Three hundred nineteen fragments were originally selected from eight Apollo 15 and 16 soils for mounting, polishing, and microprobe examination. Only twenty of these fragments contained phosphates of adequate size ( $\geq 40 \mu$  large dimension) and only two fragments, both KREEP basalts, had phosphates with decipherable fission track records. Tracks were revealed in the whitlockites by etching with 0.1%  $\text{HNO}_3$  for 10 sec. Tracks typically 0.5–1.0  $\mu$  in length were counted on plastic replicas of the grains with a scanning electron microscope (SEM). Track densities in the 15 whitlockites studied varied from  $13.4 \times 10^8 \text{ cm}^{-2}$  to  $\geq 60 \times 10^8 \text{ cm}^{-2}$  and were generally uniform. Areas with large gradients or poorly developed tracks were not analyzed. Tracks were also revealed in accompanying apatite grains (after longer etching times) but were heterogeneously distributed and exhibited large and irregular variations in track length. We attribute this behavior to thermal annealing in apatite. Uranium concentrations of individual phosphates were measured by fission track activation before etching, and electron microprobe analyses were performed on newly polished surfaces after etching.

Two aspects of the particle track record are apparent and merit special attention: (1) The observed track densities are extremely high, about an order of magnitude higher than track densities in typical lunar phosphates. (2) The observed track densities in individual phosphate grains *do not* correlate with the respective uranium contents. The normalized ratios vary by a factor of  $\sim 4$  among the grains within one fragment.

To obtain the track density excess in these unique samples, we subtracted the contributions of all known sources from  $\rho_{\text{obs}}$ . The density of heavy cosmic rays was measured in U-poor plagioclase lathes in a sister grain. It varies from  $\lesssim 1 \times 10^8 \text{ cm}^{-2}$  at the center of a 1 mm grain to  $\sim 4 \times 10^8 \text{ cm}^{-2}$  70  $\mu$  from the surface. No phosphate listed in Table I was closer than  $\sim 70 \mu$  from the surface. Spallation was estimated to be  $\lesssim 3 \times 10^8 \text{ cm}^{-2}$  from the  $^{38}\text{Ar}$  exposure age of a similar soil fragment. Reactor induced fission was measured but insignificant. The contributions from thermal neutron-induced fission of  $^{235}\text{U}$  and high energy cosmic ray induced fission of  $^{232}\text{Th}$  and  $^{238}\text{U}$  are more difficult to estimate due to uncertainties in the exposure history of our soil fragments and in the Th/U ratio in whitlockite. The observed track record cannot be dominated by any source whose contribution is proportional to the uranium concentration. Thus, barring unexpectedly large values for the Th/U ratio ( $\sim 100$ ) or a very long exposure history ( $\sim 4$  Gy), induced fission cannot account for the observed track density. Similarly the record cannot be dominated by a source which is uniform throughout the rock. The normalized track excesses remaining after the subtraction of these contributions vary by an order of magnitude. The most conservative position we may take is that the entire  $\rho_{\text{obs}}$  for the two whitlockites with lowest excesses, 33A and 33FA, is due to known sources. We define these two excesses  $\equiv 0$  and calculate a uranium correlated and an uncorrelated source. The normalized excesses thus derived range from  $\equiv 0$  to 13.

Normalized track excesses average  $\sim 8$ , or  $\sim 7$  for the conservative position, which may be compared with a normalized excess of 0.5 in 14321 reported by Hutcheon and Price. The magnitude of the excess is suggestive of a substantial contribution from the spontaneous fission of  $^{244}\text{Pu}$ . If we postulate an

initial Pu/U = 0.02, the average excess is consistent with a track retention age for these fragments of 4.3 Gy.

Nunes, P. D., Tatsumoto, M., and Unruh, D. M.: 'U-Th-Pb Systematics of Some Apollo 17 Samples'.

Apollo 17 mare basalts 75055, 75035, and 74275 have U, Th, and Pb contents like those of Apollo 11 low-K basalts. Highland gabbro 77017 has somewhat higher U, Th, and Pb concentrations similar to highland basalt 68415.

Mare basalts 75055 and 75035 plot within error of concordia at 4.49 and 4.50 b.y., respectively, extremely close to where Apollo 16 highland basalt 68415 plotted (4.47 b.y.). Highland anorthositic gabbro 77017 plots slightly below but within error of concordia and has a  $^{207}\text{Pb}/^{206}\text{Pb}$  age of 4.45 b.y. The clustering of these data in the 4.45- to 4.50-b.y. region of concordia is perhaps more than coincidence and may well reflect a major period of lunar differentiation at that time. The ~4.5-b.y.-old refractory phase, inferred from Pb data volatilized at 1350°C, in Apollo 12 and 14 soils may well be reflecting this same event. Although the Apollo 17 mare basalts crystallized ~3.8 b.y. ago as evidenced by Rb-Sr internal isochrons and  $^{39}\text{Ar}$ - $^{40}\text{Ar}$  gas retention ages, we believe that the whole rock U-Th-Pb systems were little affected and continued to reflect early differentiation of the source rocks. A very old (~4.42 b.y.) whole-rock Rb-Sr isochron age of Apollo 16 KREEP rocks was recently emphasized as likely reflecting early lunar differentiation. The sparsely cited whole-rock Rb-Sr isochron ages of Apollo 11 mare basalts ( $4.42 \pm 0.12$  b.y.), and Apollo 11, 12, and 15 mare basalts ( $4.56 \pm 0.34$  b.y.) now take on new significance. We believe that U-Th-Pb and Rb-Sr whole-rock data of all types of igneous lunar rocks (KREEP, highland gabbros and basalts, and mare basalts) reflect at least one pre-'Imbrian' (i.e., pre-~4.0 b.y.) event - the oldest being 4.4 to 4.5 b.y. old. Apollo 17 mare basalt sample 74275 with a  $^{207}\text{Pb}/^{206}\text{Pb}$  age of ~4.24 b.y. may or may not reflect a distinct event at about this time as suggested by whole-rock Rb-Sr data.

Breccia 78155 and 'gabbro' 79155 both contain excess Pb relative to U and may have suffered complex histories. In any case, the excess Pb in 'gabbro' 79155 and the slightly higher U and Th contents as compared to Apollo 17 mare basalts suggest to us that this rock incorporated a significant portion of regolith during crystallization.

Except for soil 72701, all Apollo 17 soils analyzed by us contain excess Pb relative to U. The scatter in these analyses is outside of analytical error and may well reflect mixing of three or more different components.

Of particular interest is orange soil sample 74220, which consists mostly of glass spherules. U and Th contents of the soil (about 0.16 and 0.56 ppm, respectively) are quite similar to those of Apollo 17 mare basalts. The Pb isotopic composition of the orange soil is remarkably non-radiogenic relative to all other lunar leads so far analyzed. We have analyzed water and acid leaches, the resulting residue, and various size fractions of the orange soil for U, Th, and Pb. Pb in this soil was not easily leachable with water, indicating that the Pb is not a surface coating of an easily soluble compound such as  $\text{PbCl}_2$  or  $\text{PbBr}_2$  on the glass spherules. However, the Pb was easily leached with dilute acids and the Pb isotopic compositions in the  $\text{H}_2\text{O}$ , 1.5N HCl and concentrated  $\text{HNO}_3$  leaches are very similar, suggesting a rather homogeneous, relatively non-radiogenic lead was incorporated in the glass spherules. The residual lead from the leach experiment is far more radiogenic than the leach leads but not quite as radiogenic as Apollo 17 basalt leads.

Data of size fractions of orange soil 74220 are also plotted in this paper ( $^{206}\text{Pb}/^{204}\text{Pb}$  vs  $^{207}\text{Pb}/^{204}\text{Pb}$ ). The finest fraction (acetone float) contains 8.6 ppm Pb and the least radiogenic lead ( $^{206}\text{Pb}/^{204}\text{Pb} = 20.53$ ;  $^{207}\text{Pb}/^{206}\text{Pb} = 23.93$ ;  $^{208}\text{Pb}/^{206}\text{Pb} = 38.62$ ), whereas the  $> 150 \mu\text{m}$  fraction of glass spherules contains only 0.54 ppm Pb and the lead is more radiogenic ( $^{206}\text{Pb}/^{204}\text{Pb} = 38.43$ ;  $^{207}\text{Pb}/^{204}\text{Pb} = 29.25$ ; and  $^{208}\text{Pb}/^{206}\text{Pb} = 55.06$ ). Pb concentrations and isotopic compositions in the other fractions progressively change between these two end members, but the U and Th concentrations in all fractions are similar. These results indicate that one kind of lead (and other volatiles?) was incorporated into the spherules after their formation. The excess lead should have evolved in a  $\mu_1$  ( $^{238}\text{U}/^{204}\text{Pb}$ , normalized to today's value) of about 35 (assuming a two-stage, U-Pb evolution history starting at ~4.65 b.y. ago), which is significantly lower than  $\mu$ 's for the source of lunar basalts ( $\mu = 150$ -300) and KREEP-type rocks (600-1000). Thus the excess Pb of the orange soil evolved in a U-poor environment compared to other lunar rock leads, although the origin of the Pb (lunar or extralunar) is as debatable as the origin of the glass spherules.

Hinthorne, J. R. and Andersen, C. A.: 'Uranium-Lead and Lead-Lead Ratios in Lunar Samples 66095 and 12013 by Ion Microprobe Mass Analysis'.

The 'rusty rock' 66095 is important to the interpretation of lunar surface processes because the high volatile element contents (including thallium and lead unsupported by either thorium and/or uranium) could be the result of either lunar outgassing or of a carbonaceous chondrite meteorite impact. Our ion microprobe studies of probe mount 66095,81 have demonstrated that the thallium and lead are localized in distinctly different areas of the rock, suggesting that Tl and Pb may not have had the same origin. Thallium concentrations (a few ppm) are found to be associated only with Ni-Fe grains which are of probable meteoritic origin, and the unsupported lead is found in several areas rich in chlorine and iron similar to the goethite-chloride-sulfate regions found associated with troilite alteration rims. No thallium, uranium or thorium was detected in these areas enriched in lead. The 207/206 and 208/206 ratios of the lead found in four such Cl-rich areas are presented. The approximate abundances of  $^{206}\text{Pb}$  in the regions analyzed (30–40  $\mu\text{m}$ ) are also given.

Leaching experiments have shown that lead similar in isotopic character is released from a bulk sample of 66095 by water and dilute acid washes. Thus, the easily leachable lead of reference (3) is possibly associated with the goethite and Cl-rich regions of troilite alteration as is the lead. This would indicate that the leachable leads had the same origin as the Cl, S and OH, of the alteration region, i.e. the source is a carbonaceous chondrite impact rather than the Moon itself. Further leaching of 66095 with strong acids produced lead of a more radiogenic character and also produced the major fraction of Th and U contained in the rock. The phases being dissolved by the strong acids are probably the kinds of minerals in which the U and Th are concentrated during crystallization – phosphates, zircon, zirconolite, tranquillityite, etc. Presently, we are attempting to locate such U-rich phases in 66095 so that radiogenic lead crystallization ages may be determined.

Additional microanalysis of individual uranium-bearing phases in the light-colored portion of 12013,14 (a polished probe mount) confirm our previous lead 207/206 for this material.

Our Pb-Pb and U-Pb ages for this mineral grain closely match the concordant data of Tatsumoto for fragment #45 of the light-colored part of 12013. The close correlation of these ages for the single mineral and bulk material is further confirmation of a common origin for the vein and the rest of the light material. Measurements are in progress to determine additional U-Pb and Pb-Pb ages in the dark material and possibly locate phases in both the light and dark portions from which there has been some loss of radiogenic lead as suggested by Tatsumoto.

Further evaluation of our Pb-Pb data on 15555, 14310 and 68415 indicates that the apparent systematic error of about 70 m.y. previously reported with respect to Rb/Sr, K/Ar and Ar/Ar methods on the same rocks is essentially eliminated by using the more accurately determined decay constants for uranium:  $\lambda^{235} = 9.485 \times 10^{-10} \text{ yr}^{-1}$  and  $\lambda^{238} = 1.5525 \times 10^{-10} \text{ yr}^{-1}$ . These decay constants have been used in calculating the ages reported in this paper.

Meyer, C., Jr., Anderson, D. H., and Bradley, J. G.: 'Ion Microprobe Mass Analysis of Plagioclase from 'Non-Mare' Lunar Samples'.

The highly cratered surface of the lunar highlands and the dominantly metaclastic texture of the samples returned from these regions indicate that these samples have had a very complicated history. If lunar scientists are to understand the origin of the lunar crust then it is important to know if these 'non-mare' samples represent chemical systems set by endogenous igneous processes or if instead their bulk chemistry is the accident of some extensive mixing processes. Comparison of detailed analyses of the clasts in these complicated 'non-mare' samples with their bulk composition can provide important criteria for deciding which 'non-mare' samples may represent true rock types. A common feature of many of the metaclastic 'non-mare' samples is the occurrence of abundant small grains (50–500  $\mu\text{m}$ ) of calcic plagioclase (An95–98). Trace element analyses of these grains can be important criteria for deciding whether they are phenocrysts which at some time crystallized from a magma with the composition of the bulk rock or if they are instead xenocrysts which somehow got thoroughly mixed into the sample without being reequilibrated with it.

#### *Analytical Method*

We have used the ARL Ion Microprobe Mass Analyzer (IMMA) to measure the abundance of Li, Mg, Ti, Sr and Ba in small spots (10–20  $\mu\text{m}$  diameter) on the surface of plagioclase grains in polished

thin sections. An ion beam of 20 kV negative oxygen is used to sputter the sample (sample current  $5 - 15 \times 10^{-9}$  A). We have used the abundances of the major elements (Ca, Al, Si) as internal standards for the computerized data reduction procedure known as CARISMA. We have found that it is important to make corrections for interferences by atomic and molecular ions and have also applied a correction factor to the CARISMA output derived by analyzing terrestrial plagioclase standards with the same instrumental operating conditions. Lake County is our most homogeneous standard, and we have used the calibration factors derived from it to adjust all our lunar data. Limited mass resolution ( $\sim 300$ ) prevents accurate measurement for those elements whose masses are nearly the same as molecular ions formed from the major elements. For example,  $Al_2^+$ ,  $CaO^+$  and  $CaOH^+$  interfere with the  $Fe^+$  isotopes and  $CaSiO^+$  and  $CaAlO^+$  interfere with  $Rb^+$ . For this reason we are not able to accurately measure small amounts of Rb and/or Fe in plagioclase. Such molecular ion interferences are also the reason why our instrument cannot be used for age determinations by the Rb-Sr technique. We have carefully studied these interferences for which we do not make specific interference corrections to show that they are less than 5% of the count rate. For example,  $Si_2O_2^+$  is less than 3% of the  $^{88}Sr^+$  at 200 ppm Sr.  $^{24}Mg^+$  is corrected for  $^{48}Ca^{++}$  by measuring  $^{40}Ca^{++}$ . Our maximum sensitivities in cps per ppm are on the order of 250 for Li, 50 for Mg, 45 for K, 3 for Ti, 20 for Sr, and 10 for Ba.

### Results

The Li, Sr and Ba values for plagioclase from 15415 and 67075 are in fair agreement with previous analyses of bulk samples by isotope dilution. 68415 – Helz and Appleman describe probable relict inclusions of low Fe plagioclase in 68415. Our analysis of similar inclusions (Grains A and B) did not differ significantly from our analyses on the large phenocryst and we were not able to establish further evidence for the origin of these interesting grains. Zoning in trace elements in the large phenocryst was found to be irregular. 14310 – The trace element content of plagioclase from 14310 shows that the lowest Ba is in the most calcic plagioclase with zoning towards higher  $Na_2O$ . The increase in Sr at the margin is caused by coprecipitation of other phases which select against Sr forcing it to go into the liquid faster than the plagioclase can use it up. The relatively high Mg and Ti values are typical of plagioclase crystallizing from basaltic melt. We have also used the ion probe to establish upper limits for  $Y < 6$ ,  $Zr < 2$  and  $Ce < 6$  ppm. These values are more nearly consistent with partition coefficients than the previously published analyses for these elements in plagioclase mineral separates because of the unavoidable contamination in these separates. No relict plagioclase inclusions were found in 14310, 23. 15022, 2, 9 – The plagioclase in this sample of KREEP basalt is zoned in Ba, Li and Sr similar to 14310. 65015 and 62235 – These samples of metaclastic ‘KREEP basalt’ from the Apollo 16 site have abundant grains of calcic plagioclase. Their low contents of Ba distinguish them from the plagioclase in 14310. Small grains of plagioclase rich in trace elements are also present in this rock but are hard to analyze by ion probe because the beam overlaps on surrounding material. 61156 – This sample is an example of ‘VHA Basalts’ which has relict clasts of large plagioclase. 12033, 85C and 14321, 17E.

### Discussion

Calcic plagioclase is commonly the most abundant mineral of samples from the lunar crust and is also one of the first-forming phases in melts of highland composition. The wide range in trace element composition which we have found in the plagioclase in these samples indicates that there was a wide variety of rock types in the lunar crust before it was brecciated and sintered to its present state.

The distribution of Ba, Li and Sr between basaltic liquid (represented by the composition of the bulk rock) and the first forming plagioclase can be calculated using our data for the concentration of these elements in the (Ca-rich) centers of the largest phenocrysts of 14310 and 68415.

Although these rocks have compositions similar to lunar soils (14163 and 67601), they appear to have been completely melted. They apparently crystallized slowly enough to partition Ba and Li, but rapidly enough to not have initially partitioned Sr.

On the other hand, our analysis for Ba in the xenocrysts in 65015 and 62235 are more than an order of magnitude too low for these grains to ever have been in equilibrium with a melt the composition of the bulk rock. Thus these KREEP-rich metaclastic rocks must be mechanical mixtures of at least two types of material. The observation that these clasts are rather small and evenly distributed throughout the matrix indicates that the preexisting lithology for these rocks was an early regolith derived by comminution and mixing of both KREEP and anorthositic materials. Some lunar anorthosites (67075) apparently have relatively lower Sr contents than others. Our analyses of the plagioclase

clasts in 65015, 62235 and 61156 also show low Sr content which is a partial explanation for the low Sr of Apollo 16 and VHA basalt materials. However, the relatively high Li content of these xenocrysts distinguishes them from 67075. Possibly Li has diffused into these clasts from the surrounding matrix during the lithification of these samples.

### 3. Exchange of Material and Energy Between the Moon and Its Environment: I

Thiel, K., Damm, G., Herr, W., and Baer, K.: 'Simulated Cosmic-Ray Induced U-Fission Tracks in Artificial Lunar Soil and Implications for the U-238 Fission Track Dating of Lunar Surface Samples'.

Cosmic ray-bombardment of the lunar surface was simulated by a 600 MeV-proton-irradiation of ~ 170 kg artificial lunar soil. The proton flux within this thick target was controlled by means of the spallation reactions Al-27 (p, 3p 3n) Na-22 and Al-27 (p, 3pn) Na-24 induced in high purity Al-monitor foils. Using U-glasses containing 0.1% UO<sub>2</sub> as fission track detectors, *p*- and secondary *n*-induced U-fission tracks were recorded as a function of depth within the target and the distance from proton beam center respectively. The proton flux and fission track data obtained at normal *p*-incidence during the experiment were transformed under simple assumptions to an isotropic 2 $\pi$ -influx of 600 MeV-protons on the lunar surface. The production rate of *p*- and *n*-induced U-fission tracks turned out to be strongly depth dependent. At depths < 50 g cm<sup>-2</sup> the production rate  $q_i$  of induced U-fission tracks in the glass was > 10<sup>-10</sup> tracks cm<sup>-2</sup> s<sup>-1</sup>/(proton cm<sup>-2</sup>·s<sup>-1</sup> ppm U). For comparison the production rate  $q_s$  of U-238 spontaneous fission tracks was calculated from the known data of our monitor glass to be ~ 1.1 × 10<sup>-11</sup> tracks cm<sup>-2</sup> s<sup>-1</sup>·(ppm U)<sup>-1</sup>. Using this figure and the fission track results from the simulation experiment the fraction  $q_i/(q_i + q_s)$  of induced U-fission tracks was calculated as a function of depth. This fraction does not depend on the specific properties of the track registering material. The fraction  $q_i/(q_i + q_s)$  is given for three different *p*-fluxes at the lunar surface corresponding to the maximum, minimum and time average solar activity. Adopting the energy spectrum of cosmic ray protons having a maximum around 600 MeV these experimental results represent a good approximation to the irradiation conditions on the actual lunar surface. The portion of cosmic-ray induced U-fission tracks in any U-containing track recording material at the lunar surface varies between 40% and > 95% of the total of the U-fission tracks. The contribution of induced tracks to spontaneous U-fission tracks only becomes negligible at depths  $\gtrsim$  200 g cm<sup>-2</sup>. A high fraction of cosmic-ray induced tracks can explain unrealistic high ages of glass spherules from soil samples of Apollo 14-17 and Luna 16 and 20 which went up to 6 × 10<sup>9</sup>a.

The importance of a clear distinction between *p*- and *n*-induced U-fission tracks in extraterrestrial track detectors and spontaneous fission tracks as proved by our experiment demands a careful revision of all U-fission track ages of lunar surface samples so far published.

In the same experiment the depth dependence of radiation induced thermoluminescence (TL)-intensity was measured in plagioclases. The data which were corrected for an isotropic 2 $\pi p$ -influx, too, give the thermally 'undisturbed' TL-depth profile for artificial lunar soil. Using temperature gradients which were known from two Apollo landing sites, it was possible to calculate two temperature disturbed TL-depth profiles from the simulation experiment.

Rancitelli, L. A., Perkins, R. W., Felix, W. D., and Wogman, N. A.: 'Anisotropy of the August 4-7, 1972 Solar Flares at the Apollo 17 Site'.

The Apollo 17 mission samples of unique value for the study of the interaction of solar protons with the lunar surface. This was, of course, due to the fact that prior to the Apollo 17 mission a pair of giant solar flares occurred, August 4-7, 1972, producing relatively high concentrations of both short and long-lived cosmogenic radionuclides in the lunar surface which could be accurately measured in the samples returned from the mission. The initial observations based on the observed concentrations of <sup>7</sup>Be, <sup>22</sup>Na, <sup>26</sup>Al, <sup>46</sup>Sc, <sup>48</sup>V, <sup>51</sup>Cr, <sup>54</sup>Mn, <sup>56</sup>Co, <sup>57</sup>Co, <sup>58</sup>Co and <sup>60</sup>Co were presented at the Fourth Lunar Science.

Briefly, they established an energy-intensity relationship and defined the integrated proton flux above 10 MeV as 7.9 × 10<sup>9</sup> p cm<sup>-2</sup> s<sup>-1</sup>. This exceeded the total integrated flux incident at the lunar surface for the past several years. The August flares were far more rigid ( $\alpha \sim 3.1$ ) than the average

recent rigidity or the average rigidity for the past million years ( $\alpha \sim 3.1$ ) as indicated from  $^{22}\text{Na}$  and  $^{26}\text{Al}$  depth profile measurements. The radionuclide content of a unique Apollo sample 76240, a shadowed soil from beneath a boulder, suggested that the rigidity of solar proton flux was a function of the incident angle. This sample which was shielded from solar flare protons from all directions except the northern horizon by a large boulder indicated that a larger proportion of high energy incident protons arrived at the lunar surface from lower angles than from the normal incident direction. However, uncertainties in the depth of burial of the soil and the precise degree of shielding imposed by the overlying boulder prevented us from precisely describing the anisotropic properties of the August 1972 solar flares. We have since been able to describe this anisotropy by analyzing the  $^{56}\text{Co}$  and  $^{54}\text{Mn}$  content of 4 soil and 7 boulder chips which had well known lunar surface orientations.  $^{54}\text{Mn}$  and  $^{56}\text{Co}$  are an excellent pair of radionuclides for determining the rigidity of the August 1972 solar flares. Both of these are produced almost entirely from iron, yet  $^{56}\text{Co}$  is a very low energy product, whereas  $^{54}\text{Mn}$  is a relatively high energy product with a threshold of 25 MeV.

The observed  $^{56}\text{Co}$  to  $^{54}\text{Mn}$  ratios corrected for galactic proton production for the Apollo 17 samples and the approximate angle of the surface of the rock samples relative to the horizontal are presented. The surface angle of these samples is an estimate from the Interagency Report: Astrogeology 71, however it is sufficient to indicate the extreme dependence of the ratio of these isotopes on the surface sample's orientation. The samples that had their surface at the greatest angle relative to the horizontal plain showed the lowest  $^{56}\text{Co}$  to  $^{54}\text{Mn}$  ratio. This ratio is, of course, very sensitive to the hardness of the incident solar flare energy spectrum. For example, the 3 chips from the same boulder, 76255, 76275 and 76295, which had high surface angles relative to the horizon, had very low  $^{56}\text{Co}$  to  $^{54}\text{Mn}$  ratios. Unshielded soil samples 71041, 75061, 76261 and 78481 as well as rock sample 78135 were essentially horizontal to the lunar surface. All these samples had high  $^{56}\text{Co}$  to  $^{54}\text{Mn}$  ratios indicative of a less rigid incident proton spectrum than those samples which were inclined to the lunar surface. The implication of these observations is that there was a much lower ratio of low to high energy protons arriving at the lunar surface at low angles. Thus a high degree of anisotropy exists which is a function of the incident angle. Sample 76295,0 was taken from an essentially vertical surface and had one of the lowest observed  $^{56}\text{Co}$  to  $^{54}\text{Mn}$  ratios, 1.85. This would be comparable to an alpha value of less than 1, thus an extremely rigid spectrum. Anisotropy is also indicated in soil sample 76240 taken from beneath the overhang of the very large boulder at Station 6. Here, the  $^{56}\text{Co}$  to  $^{54}\text{Mn}$  ratio of 2.54 is much lower than the value of 6 in the adjacent solar sample 76261.1 Since only protons of low incident angle could strike soil sample 76240,2, this is substantiating evidence on anisotropy favoring high energy protons at low angles. While all of the boulder chip samples were taken from southeast or east faces of lunar surface boulders, soil sample 76240 was shielded except from the north. Thus, angular anisotropy appears to be independent of compass direction.

O'Kelley, G. D., Eldridge, J. S., and Northcutt, K. J.: 'Concentrations of Cosmogenic Radionuclides in Apollo 17 Samples: Effects of the Solar Flare of August, 1972'.

The techniques of nondestructive gamma-ray spectrometry have made it possible to study in some detail the irradiation history of lunar samples by measuring the concentrations of radionuclides produced by solar and galactic cosmic-ray bombardment. Samples from the Apollo 17 mission proved to be of great significance to such irradiation studies because, prior to collection, these samples had been subjected to bombardment by the intense solar flare of 4-9 August 1972, the largest solar cosmic-ray event ever observed. Additionally, the Apollo 17 samples were obtained using the most advanced sampling and documentation procedures of any lunar mission.

Beginning only six days after splashdown, we analyzed 22 samples from Apollo 17 for cosmogenic radionuclide content. The equipment and methods of nondestructive gamma-ray spectrometry are essentially those we developed for use in other Apollo missions.

The pattern of radionuclide concentrations is quite distinct from that of any previous mission. The large enhancement of the yields of  $^{22}\text{Na}$ ,  $^{54}\text{Mn}$ , and  $^{56}\text{Co}$  is due to the August, 1972 solar flare. The high intensity of the flare made it possible for us to identify  $^7\text{Be}$  in a lunar sample for the first time: in skim soil 73221 we were able to detect  $450 \pm 350$  dpm  $\text{kg}^{-1}$  of  $^7\text{Be}$ .

Because chemical analysis data are lacking for most of the samples reported here, detailed interpretations cannot be made in some cases. However, the chemical analyses reported by the Preliminary Examination Team show that the major element compositions of rocks and soils at Taurus-Littrow



are similar to those of the Apollo 15 site. Further, the chemical behavior at the various sampling stations appears to be sufficiently regular to permit us to estimate target element concentrations where needed to obtain semi-quantitative interpretations of radionuclide yields.

Samples from previous missions typically showed  $^{26}\text{Al}/^{22}\text{Na}$  ratios  $\geq 2$ , if the  $^{26}\text{Al}$  had achieved its saturation value. The ratio  $^{26}\text{Al}/^{22}\text{Na}$  in most Apollo 17 samples is close to unity, because the solar flare bombardment more than doubled the amount of  $^{22}\text{Na}$  present before the flare occurred. Uncertainties in chemical composition make it difficult to identify samples of low exposure with respect to the 0.74 m.y. half-life of  $^{26}\text{Al}$ . Some of the samples show evidence either of partial shielding or unfavorable orientation with respect to the solar proton flux. Although complete documentation is lacking for 70185 and rake sample 78597, their low radionuclide content suggests partial shielding from solar protons. Additionally, 70135 and 76295 are boulder chips whose orientations provided partial shielding from the solar flare.

The high yields of  $^{46}\text{Sc}$  in the Apollo 17 surface samples arise from the intense solar proton irradiation. Concentrations of  $^{46}\text{Sc}$ , corrected for galactic cosmic-ray production in iron, correlate well with estimates and measurements of titanium target element concentrations in these samples. Because over four months elapsed after the August flare before collection of samples at Taurus-Littrow, the 16-day  $^{46}\text{V}$  had decayed to about the level expected for bombardment of iron by galactic protons.

Both  $^{56}\text{Co}$  and  $^{54}\text{Mn}$  are produced by solar proton bombardment of iron. The  $^{56}\text{Co}$  concentration in thin surface samples is especially useful as a monitor of total proton flux, since the threshold for the  $^{56}\text{Fe}(p, n)$  reaction is only about 6 MeV. Information on the rigidity of the flare can be derived from the yields of  $^{54}\text{Mn}$ , a product of higher energy proton bombardment, with a threshold of about 25 MeV. Data on 71135 and 71136, chips from a basaltic boulder, skim soil 73221, and trench top 79221 all proved to be useful samples for estimating the roton flux and rigidity of the August 1972 flare. Although some uncertainties exist concerning chemical data for some samples, we estimate the integrated proton flux for the August 1972 flare  $J(> 10 \text{ MeV}) = 1.9 \times 10^{10} \text{ cm}^{-2}$ . This may be compared with a recent compilation by King, in which the proton flux integrated for August 4-9 is given as  $2.25 \times 10^{10} \text{ cm}^{-2}$ . If the proton energy spectrum is expressed as the function  $E^{-\alpha}$ , the rigidity parameter  $\alpha$  is about 1.8. Thus, the August 1972 flare had a much higher average energy than other flares of cycle 20.

Yokoyama, Y., Reys, J.-L., and Guichard, F.: ' $^{22}\text{Na}$ - $^{26}\text{Al}$  Chronology of Lunar Surface Processes'.

The method is based on the fact that  $^{22}\text{Na}$  and  $^{26}\text{Al}$  were produced on lunar surface through similar reactions, but with different half-lives: the activity of  $^{22}\text{Na}$  ( $T_{1/2} = 2.6 \text{ yr}$ ) in a sample can be saturated in several years, whereas the saturation takes about 2 to 3 m.y. for  $^{26}\text{Al}$  ( $T_{1/2} = 7.16 \times 10^6 \text{ yr}$ ).

Up to the present, more than 300 determinations of the pair  $^{22}\text{Na}$ - $^{26}\text{Al}$  have been made in many laboratories on the samples returned from Apollo 11 to 177 missions. The  $^{26}\text{Al}/^{22}\text{Na}$  ratios of about 30 samples were unusually low, and attributed to the undersaturation of  $^{26}\text{Al}$  activity, but with a certain reserve because very unusual chemical compositions could also explain the unusual  $^{26}\text{Al}/^{22}\text{Na}$  ratios.

In the present work, all data available up to present were normalized for their chemical compositions, and compared with the general distribution pattern of the pair  $^{22}\text{Na}$ - $^{26}\text{Al}$ , in order to see if the samples are saturated in  $^{26}\text{Al}$  activity or not.

A striking feature is that there are more unsaturated samples than saturated ones among the samples taken on the rim of North Ray Crater (at station 11) and also on the rim of Buster Crater (at station 2), whereas saturated samples dominate at the other stations.

North Ray Crater is a large young crater (900 to 950 m across) which was, for the first time in lunar exploration, investigated along its rim, and several samples were taken from large boulders for the age determination. The formation of North Ray Crater was dated to be 35 to 50 m.y. by rare gas and track studies. Four chips were sampled within a freshly broken spall zone surrounding a percussion cone. The depth of the spall zone (i.e., the thickness of the material removed) is approximately 2 to 3 cm. Since the penetration depth of solar cosmic rays (S.C.R.) is about 2 to 3 cm, just the material containing the S.C.R. products should be removed by this impact. Indeed, the three of them, 67935, 67936, and 67937 were reported as unsaturated in  $^{26}\text{Al}$ . It was confirmed by the present work. The other chip taken from the same zone (67955) was saturated. Another chip, 67915, was taken from the area about 2 m away from the spall zone, but of the same boulder (South Boulder). It was unsaturated in  $^{26}\text{Al}$ .

These facts suggest a rather complex history of this boulder. Two chips taken from a white breccia show that one is saturated (67475) and the other is probably not (67455). Among 6 small breccias studied, three (67095, 67115, 67975) was unsaturated. The fact that about half of samples are unsaturated in  $^{26}\text{Al}$  activity suggests that either this region was recently bombarded with an intense flux of relatively small (and probably secondary) projectiles, or these unsaturated fragments are the same origin.

Buster Crater (90 m in diameter) is a fresh and probably primary crater. Six rock samples which can be associated with the Buster ejecta blanket with high confidence were collected at its rim. Five of them were measured and three was unsaturated in  $^{26}\text{Al}$ . The dating by rare gas- and track-methods are not yet reported for these samples (a soil sample taken on the rim, 62241 shows an exposure age of 56 m.y. The short exposure age (about one million years) deduced by the  $^{22}\text{Na}$ - $^{26}\text{Al}$  data may be the age of a post-cratering recycle event rather than the age of Buster Crater itself, because a rock sample, 62235 rested completely saturated in  $^{26}\text{Al}$  on the rim, that is improbable if the crater formation is so recent.

Among the Apollo 15 samples studied, the exposure history of anorthosite, 15415 seems interesting. The  $^{26}\text{Al}$  activity of  $116 \pm 9$  dpm  $\text{kg}^{-1}$  and  $^{26}\text{Al}/^{22}\text{Na}$  ratio of  $3.2 \pm 0.5$  are apparently in the range of saturation. After the normalization for the chemical composition, the  $^{26}\text{Al}$  activity of  $68 \pm 6$  dpm  $\text{kg}^{-1}$  and the  $^{26}\text{Al}/^{22}\text{Na}$  ratio of  $1.8 \pm 0.3$  were obtained. The sample 15415 was taken from the Top of a poorly indurated breccia, 15435. From its position, the sample 15415 should be well irradiated for S.C.R. The expected saturation  $^{26}\text{Al}$  activity of the sample having 4 to 5 cm thickness is about 110 dpm  $\text{kg}^{-1}$ . Since the rare gas exposure age of this sample is 100 m.y., the sample should be saturated for galactic cosmic rays (G.C.R.), which is estimated to be 55 dpm  $\text{kg}^{-1}$ . About a quator of the saturation for S.C.R. gives an exposure age of  $0.4 \pm 0.4$  m.y. for S.C.R. The breccia, 15431 from which 15415 was picked up is also unsaturated and shows the same age. Keith *et al.* suggested that the unsaturation of the very friable breccia 15431 is due to a rapid erosion. It is therefore possible that the anorthosite 15415 was incorporated in the breccia and 'weathered out' very recently to the actual 'come and sample me' situation on top of sample 431-435. It was very fortunate for the astronauts and the lunar sample investigators. A friable green clod, 15426 taken at the same station 7 as that of 15415 is also unsaturated, indicating also rapid erosion.

Durrani, S. A., Fremlin, J. H., and Hwang, F. S. W.: 'Thermoluminescence of Apollo 17 Fines'.

The natural and induced thermoluminescence of lunar soils returned from the Apollo 17 mission have been investigated. The specimens are fines or grains of less than  $106 \mu\text{m}$  in diameter and were collected from different locations and different depths by the Apollo 17 crews. All specimens but one showed appreciable amounts of natural glow. The preservation of the natural thermoluminescence in specimens increases significantly with the depth of burial. Specimen 78481,20 is a skim soil of upper  $\frac{1}{2}$  to 1 cm depth and it contains natural glows only in the temperature region above  $220^\circ\text{C}$ . This indicates that the high ambient temperature on the surface of the Moon during the daylight period has annealed the low temperature thermoluminescence which was induced by radiations in space. Specimen 72501,49 was collected at a depth of 4 cm from the surface on a steep uphill slope. Even this specimen shows a well preserved natural glow in low temperature regions. This indicates that the thermal insulation of the lunar soil is very effective. This probably is due to the surface dust being in a hard vacuum and to the fact that the contact among grains is poor because of loose packing. The best preserved natural glow was found in specimen 78421,22 which was collected at a depth of 10 cm from the surface of a 25 cm deep trench. In addition to the thermal screening effect by the top soil, this specimen must have been lying in the shadow of the trench wall, because of the low glancing angle of the Sun on the surface of the Moon, ever since its formation. This shadowing effect can be seen from the well preserved natural glow of the specimen 78442,1 which is a very cohesive soil from walls of that trench. The specimen 74220,96 ( $< 63 \mu\text{m}$ ) is the exciting 'orange soil'; it contains more than 95% of glass in orange color and a very low concentration of plagioclase. This specimen came from a depth of about 5 to 8 cm below the surface but did not give any natural glow at temperatures below  $480^\circ\text{C}$ . This specimen was irradiated with beta particles ( $0.5 \text{ Ci, Sr}^{90}$ ) and its thermoluminescence sensitivity is about 10 times smaller than that of the other Apollo 17 specimens. This low sensitivity is attributed to its low concentration of plagioclase.

The emission spectrum of all the specimens were analysed with a set of optical filters with different

transmission bands. The glow of each specimen was divided into different emission temperatures and also normalized to a standard dose and a standard weight. The emission intensity of a given temperature is corrected for the quantum efficiency of the photomultiplier tube and the transmission band of the filters, and then plotted against wavelength in a linear scale. The emission spectrum of the specimen 74220, 96 shows differences from the other Apollo 17 specimens and specimens from previous missions.

Successive doses, ranging from a few kilorads to a few megarads, were added to these natural samples. The response to  $\beta$ -particle-irradiation of these samples is linear to about 1 megarad, then the total glow area between room temperature and 480°C is saturated with higher doses. This behaviour is generally found in other specimens from the previous missions. The integrated areas of glows of various temperature ranges were plotted against the dose added. The 'Half Dose' was determined for the high temperature glow of each specimen and from this the storage temperature of the specimen on the Moon was estimated. The storage temperature was then used to check the depth where the specimen was found. The depth obtained from calculation was found to be in general much shallower than the actual depth where the specimen was collected. This probably is due to the fading of the natural thermoluminescence at ambient temperature since their arrival. The other explanation for this finding is that we have underestimated the thermal wavelength on the surface of the Moon. Previously, the thermal wavelength on the surface of the Moon was estimated to be about 24 cm for fines and 500 cm for rock chips. From our calculation, using the actual depth where the specimen was found, the thermal wavelength in lunar fines should have been 10 times longer than had been estimated.

The trapping parameters, trap depth and frequency factor were determined using the initial rise technique. The results agree with the electron trapping model and are also consistent with the previous results.

Borg, J., Maurette, M., Walker, R. M., and Zinner, E.: 'Apollo 17 Lunar Surface Cosmic Ray Experiment – Measurement of Heavy Solar Wind Particles'.

The Apollo 17 Lunar Surface Cosmic Ray Experiment (LSCRE) consisted of a series of metal foils and nuclear track detectors designed to measure light and heavy solar wind particles as well as more energetic solar and galactic nuclei. One half of the experiment was mounted in the Sun and the other half in the shade for a total of 45.5 h on the Moon. During this time the flux of protons of energies  $> 3$  MeV did not exceed that of quiet Sun conditions. However, proton and He fluxes in the range of 0.3 to 1 MeV  $\text{nuc}^{-1}$  as measured on Vela, Pioneer 10, and Imp 7 were about a factor of 10 higher than normal quiet time levels during the second half of the period of deployment. We report here fluxes of solar wind particles based on an analysis of the mica detectors. Results for more energetic particles have previously been reported by us and the G. E. and Berkeley groups. The abundances given by the Berkeley group for particles with energies from 0.2 to 40 MeV  $\text{nuc}^{-1}$  indicate a mixture of solar and galactic particles.

*Calibration Experiments:* Heavy ions of solar wind energy ( $\sim 1$  keV  $\text{nuc}^{-1}$ ) produce shallow pits in etched mica. We used two different etching times and two methods of observations to study particles in different mass ranges. Samples etched for 10 min in a 40% HF solution at 30°C were studied using Pt-C replicas and a transmission electron microscope. Samples etched for 2 h were silvered and studied with an optical microscope using interference contrast in reflected light (Normaski method for Zeiss microscopes). The shorter etching was used for the abundant lighter elements (CNO to Fe), the second for less abundant heavier masses. Calibration irradiations were made with 0.9 keV  $\text{nuc}^{-1}$  ions of O, Ne, Ar, and Fe at fluxes between  $5 \times 10^8 \text{ cm}^{-2}$  and  $5 \times 10^{11} \text{ cm}^{-2}$ . Pit size distributions and registration efficiencies were measured as a function of temperature to account for annealing on the Moon and to separate charge groups by differential annealing. Pit sizes for all ions range from zero to a maximum of 0.8  $\mu$  after a 10 min etch. The pits produced by Fe ions are deeper than those produced by O and the former can clearly be separated from the latter. No difference in pit morphologies was found for Fe<sup>+</sup>, Fe<sup>++</sup>, and Fe<sup>+++</sup> calibration ions. After 2 h etching, Kr, Xe, and Pb give pits that increase in average size with increasing mass. Calibration experiments show that the pit distributions for these heavier elements are modified by the presence of large numbers of lighter Fe ions. The lunar environment was simulated by studying the registration and annealing of heavy particles in samples that also contained  $1.5 \times 10^9$  Fe ions  $\text{cm}^{-2}$ . As a function of annealing temperature, there is a flat maximum for the efficiency of detecting large pits at the presence of Fe background between 150°C and 200°C. Measure-

ment of the registration of Mn, Kr, and Xe as a function of bombarding angle showed only small effects.

*Abundance of Fe-Group Elements:* The mica samples exposed in the Sun had fifty times as many small pits as those exposed in the shade. Applying both scanning criteria, we derive a flux of Fe group particles of  $3.1 \pm 0.8 \times 10^4 \text{ s}^{-1} \text{ cm}^{-2}$ . Unfortunately, no satellite data of the proton solar wind are available for the same period. Assuming the average proton flux of  $2.4 \times 10^8 \text{ s}^{-1} \text{ cm}^{-2}$ , we obtain a Fe/H ratio of  $1.28 \times 10^{-4}$ . This value is subject to changes awaiting the still outstanding measurements of the light rare gas abundances from the metal foils. For the moment it exceeds the only other direct observation from a satellite of  $3.45 \times 10^{-5}$  and the solar system abundances of  $2.85 \times 10^{-5}$  by a factor of four. Taking into account our errors, we can rule out an overabundance of Fe in the solar wind by more than a factor of 5. Because of the extreme shallowness of oxygen pits and the large errors on the registration efficiencies, only a crude upper limit estimate can be made on the CNO abundance. We obtain a value of  $1.2 \times 10^6 \text{ s}^{-1} \text{ cm}^{-2}$  which is a factor of 4.3 above the solar system abundance (again assuming a proton flux of  $2.4 \times 10^8 \text{ s}^{-1} \text{ cm}^{-2}$ ).

*Experimental Results on Large Pits:* We previously reported a puzzling lack of large pits. We now understand that this is due to a combination of the suppression of large pits by the background of small ones and annealing effects on the Moon. Our conclusions on the abundance of extremely heavy ions is limited by a background of pits produced by the more energetic particles that were present in the interplanetary medium during the mission. Calibration irradiations with Na, Ar, and Fe ions with energies up to  $30 \text{ keV nuc}^{-1}$  have shown that pits from such particles are very shallow and cannot in many cases be distinguished from solar wind pits.

Keith, J. E. and Clark, R. S.: 'The Saturated Activity of  $^{26}\text{Al}$  in Lunar Samples as a Function of Chemical Composition and the Exposure Ages of Some Lunar Samples'.

It has long been recognized that measurements of the activity of cosmic ray and solar proton induced radionuclides provides the most unequivocal evidence for recent exposure (as opposed to cumulative exposure, provided by tracks, etc.) in extraterrestrial objects. However, in order to calculate an exposure age some estimate of the saturated  $^{26}\text{Al}$  activity must be made. Such estimates have been made from internal evidence for meteorites, and we present here an analogous estimate for the saturated  $^{26}\text{Al}$  activity in lunar samples derived only from lunar data.

Since Apollo 12, some lunar samples have been described as unsaturated in  $^{26}\text{Al}$ . No method of identification of unsaturation that was free of assumptions about the appropriateness to lunar samples of non-lunar data was available, however. In this paper we present such a method; we remove the variation in the  $^{26}\text{Al}$  specific activities of a selected set of lunar samples due to the variation in their chemical composition and their surface to volume ratios, leaving only the errors in the measurements and the variation in the activity due to the variations in the conditions of irradiation to vary randomly. In the process of finding a subset of the original set of samples we shall use internal consistency arguments as well as physical intuition to guide us in improving the regression model and in selecting samples to eliminate from the saturated set.

In selecting our original set of samples we look for those samples that have as little as possible non-random (man-made) alteration, that might reasonably be expected to have maintained their shape for the last few million years (no fines) and for which the chemical composition is known and the  $^{26}\text{Al}$  activity was measured on the whole rock. As a result of the search, 28 such cases were found.

The internal consistency arguments mentioned above will involve our requirement of good behavior on the part of the residuals; that neither the observed value, nor the predicted value of  $^{26}\text{Al}$  activity, nor any of the independent variables display a significant correlation with the residuals. We shall start by regressing the observed value of the  $^{26}\text{Al}$  activity of the Apollo 11, 12, 14 and 15 samples on the silica, alumina and magnesia contents of these samples. There appears to be a rather compact group of points with four conspicuously low – those due to 12034, 12064, 14301 and 15265. The first three of these four have previously been described as unsaturated. We discard them and try again. In order to obtain good behavior in the residuals we are forced to add three more variables to the model which accommodate the variation in the  $^{26}\text{Al}$  activity due to variation in the surface to volume ratios in the

samples:  $[\text{SiO}_2]w^{-1/3}$  (where  $w$  is the weight of the sample in kg and  $[\text{M}_x\text{O}_y]$  is the percent oxide). Since the exposed surfaces of lunar samples are known to have strong activity gradients due to solar proton bombardment, this is not an unexpected result. Proceeding in this fashion through many trials which we do not have room to describe, we show that the saturated  $^{26}\text{Al}$  specific activity of our saturated subset can be represented by:  $^{26}\text{Al}(\text{dpm/kg}) = 0.652[\text{SiO}_2] + 2.50[\text{Al}_2\text{O}_3] + 0.560[\text{Al}_2\text{O}_3] \times w^{-1/3} + 2.28[\text{MgO}]w^{-1/3}$ .  $\text{Sy}/x = 5.54$ ,  $F = 1670$ . Other independent variables (e.g.  $[\text{MgO}]$ ) turn out to be not significant, and the residuals are well-behaved. Note also that no member of the original set identified as unsaturated failed to also be so identified by our selection process.

We have developed a systematic method of predicting the saturated  $^{26}\text{Al}$  specific activity of lunar rock samples from various readily observable variables. From this two major consequences flow: by postulating a one-step elevation to the surface from depths sufficient to produce only negligible  $^{26}\text{Al}$  activity, one can calculate the most probable length of time that the samples have been exposed on the lunar surface. These 'exposure ages' should be regarded as upper limits (because the  $^{26}\text{Al}$  production rate may have been nonnegligible, as in the case of 12034 which was found in a trench). A new, more quantitative measure of the recent deep gardening of the lunar regolith is also made available: since 6 of 27 samples found on the lunar surface have been shown to be unsaturated, the probability of choosing another unsaturated sample is  $0.22_{-0.11}^{+0.18}$  (90% confidence limits).

Hörz, F., Hutcheon, I. D., Macdougall, D., Morrison, D., Price, P. B., and Schneider, E.: 'Rock 72315: A New Lunar Standard for Solar Flare and Micrometeorite Exposure'.

For two years the profile of solar flare Fe tracks in the Surveyor glass filter has served as the standard from which surface exposure ages and erosion rates of lunar rocks, as well as micrometeorite fluxes, have been derived. In this paper we show that lunar rock 72315, from an Apollo 17 boulder, promises to become a new standard for solar flare spectra during the last  $\sim 10^5$  yr. Our track profile was measured in a mm-sized feldspar crystal at the surface of the rock. Crater counts were made on two areas near the crystal. Both studies show that a large fraction of the present surface of the rock was freshly exposed about  $10^5$  yr ago. In fact, astronaut Jack Schmitt thought the rock was a large clast because of its lighter (fresher) appearance than the surrounding material of the boulder.

A section of the feldspar crystal  $\sim$  normal to the exposed surface was etched in a boiling solution of 1g NaOH:2gH<sub>2</sub>O for times of 2 min for TEM (+ replica), 7 min for SEM, and 20 min for optical microscopy (+ silvering).

In order for rock 72315 to serve as a solar flare standard that is completely independent of Surveyor glass it would be necessary to date its exposure time by  $^{26}\text{Al}$ .

Fechtig, H., Hartung, J. B., Nagel, K., Neukum, G., and Storzer, D.: 'Microcrater Studies, Derived Meteoroid Fluxes and Comparison with Satellite-Borne Experiments'.

#### *Lunar Microcraters*

A special study of microcraters on sample 60015,35 was made. Pit diameters were measured optically down to  $17 \mu$ . A rough coating of accretionary material prevented scanning electron microscope observation of pits less than  $10 \mu$  diam. However, micron-sized pits were counted on  $0.5 \text{ mm}^2$  of the smooth surfaces of larger,  $100\text{-}\mu$ -diam glasslined pits. These data combined with earlier results for 60015 yield a size distribution over the pit diameter range from 1 to  $500 \mu$ .

The solar flare track exposure age of 60015 was found to be  $10^5$  yr, based on a revised track production rate. Complete microcrater spall zones were easily observable on 60015. The spall-to-pit-diameter ratio averaged about 4 for 70 microcraters with pits between 45 and  $380 \mu$  in diam. The coating of 60015 was initially glass a few mm thick but has devitrified to elongate plagioclase crystals with 2- to  $50\text{-}\mu$  dimensions, and pyroxene-composition interstitial material. Point electron microprobe analysis for Fe, Mg, Ca, Al, and Si of glasses lining several  $100 \mu$ -sized pits shows no indication of material in the pit glasses that is outside the range in composition of the host sample phases. Either the projectile material composition is similar to the host material composition or little or no projectile material remained in the pit glass.

Craters counted and measured on samples 69935,18; 60315,29; 63503,17; 70215,34; 74275,36;

and 79155,19 yield size distributions similar to those reported previously. Minimum exposure ages for these samples, based on mm-sized microcrater counts, range between  $10^5$  and  $10^6$  yr.

#### *Laboratory Simulation Experiments*

Using an electrostatic dust accelerator projectiles in the mass range between  $10^{-10}$  and  $10^{-16}$  g were accelerated to velocities between 1 and 30 km  $s^{-1}$ . Using a lithium plasma gun projectile masses between  $10^{-5}$  and  $10^{-8}$  g were accelerated to velocities between 2,5 and 18 km  $s^{-1}$ . Projectile materials were aluminium, carbon, iron, and glass and target materials were glass, norite, stainless steel, aluminium and copper.

A primary result is that for normal impacts, through the whole velocity range, the ratio of the spallation zone diameter to projectile diameter,  $D_s/d$ , is proportional to the  $2/3$  power of the impact velocity, thus  $D_s/d \sim v^{2/3}$ . For the electrostatic accelerator experiments the ratio of the microcrater pit diameter to projectile is also proportional to the  $2/3$  power of the impact velocity, thus  $D_p/d \sim v^{2/3}$ . Plasma gun experiments, however, produced mainly pitless craters. The ratio  $D_s/d$ , seems to increase slightly with increasing mass. From experiments showing pits,  $D_s/d$  increased a factor of 2 as projectile mass increased from  $10^{-21}$  g to  $10^{-6}$  g. The results are almost independent from the projectile material but depend strongly on the target material or target strength. The impact kinetic energy,  $E$ , is proportional to the crater Volume. Using a formula from Gault, valid for mm-to-cm-sized projectiles, these results can be represented by changing slightly the constants:

$$S_s = 10^{-3.077} \rho_t^{-1/3} \rho_p^{+1/3} E^{1/2.65},$$

where  $\rho_t$  and  $\rho_p$  are target and projectile densities, respectively.

#### *Meteoroid Fluxes*

From each lunar sample with a known crater population and a known solar flare track exposure age one may calculate the corresponding average interplanetary dust flux. From the results of the Pioneer 8/9 dust experiments and from the results of the HEOS dust experiment it is known that micrometeorite trajectories are extremely anisotropic due to different orbital characteristics for different-sized particles. The micron-sized component of dust approaches the Earth-Moon system from the apex direction (direction of Earth's motion) at an average velocity of about 8 to 10 km  $s^{-1}$ . Submicron-sized particles tend to approach from the direction of the Sun at velocities greater than 50 km  $s^{-1}$ . Using these numbers the cumulative flux-vs-mass curves for these samples were calculated.

Fluxes from satellite-borne experiments are only about 1 order of magnitude higher than those from lunar data. This difference may be due to incorrect earlier assumptions of an isotropic flux and a  $2\pi$ -exposure geometry or to an increasing meteoroid flux with time.

Brownlee, D. E., Hörz, F., and Rajan, R. S.: 'The Ancient Micrometeorite Flux'.

It is possible to detect long term variations in the micrometeoroid complex by analysis of solar flare tracks and micrometeorite craters on surfaces extracted from lunar and meteoritic breccias. Gas-rich meteorites provide surfaces which were exposed to micrometeoroids and solar flare particles for a short period some time in the interval beginning with the dissipation of the solar nebula and ending probably about 4 b.y. ago. Unmetamorphosed lunar breccias potentially are capable of providing surfaces exposed for varying intervals over the past 4 b.y.

On exposed surfaces, measurement of the ratio of crater density to solar flare track density yields a determination of the micrometeoroid flux. The uncertainties in this process are exposure geometry, track fading and possible long term changes in the flux of solar flare particles. In spite of these problems however, it appears possible to measure the ancient micrometeoroid flux with order of magnitude accuracy on unmetamorphosed surface exposed in the distant past. Additional information on the ancient meteoritic complex can be gained by measurement of crater size frequency and analysis of crater morphology. The size frequency can be converted to a meteoroid size distribution and crater shapes can be used to determine certain physical particle parameters such as shape and density. Crater depths can also be used to obtain a crude estimate of impact velocity.

To date microcraters have been found on glass spheres extracted from the gas-rich howardite Kapoeta, from the low grade lunar breccia 15086 and tentatively from the howardite Malvern. Analysis of craters and solar flare tracks in kapoeta indicates that, at the time gas-rich meteorites

formed, the micrometeoroid complex was very similar to that observed today. The flux, size distribution and physical particle properties appear to have been roughly equivalent to similar parameters of contemporary micrometeoroids as implied by analysis of craters on lunar surfaces with recent exposure histories. A similar but somewhat tentative conclusion is reached from analysis of green glass spheres from 15086. Craters on 15086 are morphologically similar to modern craters indicating roughly similar particle shapes and densities. Although detailed track work has not been done on cratered spheres, statistical comparison with other analyzed spheres from 15086 implies an order of magnitude agreement between the modern micrometeoroid flux and that when 15086 was formed. A key problem in determining the evolutionary history of the micrometeoroid complex is the ability to determine when surfaces inside an ancient breccia were actually exposed. The  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  age for the green glass spheres is 3.4 b.y., but presently this age can only be considered an upper limit for the time at which the craters on 15086 were formed. There is a real difficulty for low grade lunar breccias in that while 'educated-estimates' can be made of the time of compaction, in reality only upper limits can be established. On the other hand, meteoritic breccias appear to have had much simpler histories and it seems very probable that dating their glass component may date the time of compaction. At the present time an  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  age is being determined for glass from Kapoeta and Malvern.

Detection of time variations in the micrometeoroid complex is of considerable interest in the light of influences which could have caused past changes. The microparticle complex in the inner solar system is a quasi-stable system in which particle lifetimes on the order of  $10^4$ - $10^5$  yr necessitate a constant supply of new material in order to maintain stability. There is considerable (although not conclusive) evidence that the major particle source at the present time is short period (SP) comets. Collisions and the fact that particle lifetimes are longer than SP comet lifetimes tend to stabilize the number of particles in the solar system. However, fluctuations on the order of a factor of 10 can be expected due to the uneven rate of production of SP comets capable of putting particles with bound orbits into the inner solar system. In addition to these relatively short term fluctuations (millions of years) it is also possible that the rate of comet ejection into the inner solar system has undergone a long term secular change due to a general depletion of the Sun's comet inventory. Nezhinskij has shown that as a result of stellar perturbations the half-life of the comet cloud is approximately 1 b.y.

Flux changes in the past can also be expected because of large fluctuations in the density of interstellar grains in the solar system. Micrometeorite experiments on Pioneer 8/9 have shown that a non-negligible fraction of interplanetary particles have hyperbolic orbits and are interstellar in origin. Because of the highly nonuniform distribution of dust in the Galaxy it is not unreasonable to expect that, several times during the past 4.6 b.y., the particle contribution by the interstellar medium could have exceeded the contribution by SP comets.

A final effect of particular importance to the Moon is the enhancement of the particle flux at the time of formation of mare basins. An Imbrium sized cratering event could easily inject a mass of debris into solar orbit which would exceed Whipple's estimates for the total mass of particulates in the solar system. Although the lifetime of this debris would be short, it does seem possible to find ancient breccias which would have recorded the enhanced micrometeoroid flux. Enhancements of this type would be easily distinguishable from enhancements due to comets or interstellar particles because debris from the Earth-Moon system would have Earth-like orbits and hence would re-impact the lunar surface at relatively low velocities ( $< 10 \text{ km s}^{-1}$ ). Because of the lower impact velocity a suite of craters from this type of event would be systematically shallower than typical contemporary lunar craters.

#### 4. Characteristics and Movement of Materials in the Lunar Regolith: I

Brunfelt, A. O., Heier, K. S., Nilssen, B., Steinnes, E., and Sundvoll, B.: 'Elemental Composition of Apollo 17 Fines'.

The abundances of 32 elements in seven samples of fines returned by the Apollo 17 mission have been determined by neutron activation analysis. The samples show great variation ranging from nearly mare basaltic (75061) to essentially non-mare (72501) composition. The fraction of mare basalt in the samples is in good correspondence with the geological features at each sampling site. The major elements and some trace elements determined in the soils give linear plots versus the Al content. This has been shown earlier for Fe and Ca. If the soils are assumed to be derived from a simple two-compo-

ment mixing, the composition of the end members can be estimated from such plots. Based on rock analyses by Apollo 17 PET we may assume 5.0% Al in the average Apollo 17 basal and 0.5% Ti in the non-mare derived fraction. This gives the composition of the end members. The mare component is very similar to the Apollo 11 type B basalt showing low K and Rb content and depletion of the light REE (La/Sm = 0.58). A higher Cr content and a lower level of REE and Th is however evident in the Apollo 17 basalt. The non-mare component, presumably derived mainly from the local highland formations, is different from the Apollo 16 fines with respect to a lower content of Al and Ca and a higher content of elements associated with ferromagnesian minerals. This reflects less anorthitic and more pyroxene-rich rocks than in the Apollo 16 area. As indicated by Apollo 17 PET the major non-mare rock types in the Taurus-Littrow area are anorthitic rocks and noritic breccias. On the basis of their data, the non-mare component deduced from our data approximates a 50-50% composition of the two rock types, at least as far as major elements are concerned.

Fines collected near the North Massif and Sculptured Hills seem to be depleted in elements associated in the KREEP component (K, Rb, Ba, La, Hf, Ta, W, Th, U) as compared to the South Massif derived soils. This has also been shown for P, Zr and Y.

Fines 74261 sampled near Shorty Crater exhibits an unusually high content of Cu, Zn, and Ga relative to most other known lunar materials. A high content of the alkali elements compared to Al is also evident in this soil.

Data for 22 elements in separated fractions from 78501 are compared with the bulk fines. Separates of plagioclase, clinopyroxene and ilmenite from basalts 70017, 71075, and 75035 are under investigation with respect to their trace element composition.

Taylor, H. C. J. and Carter, J. L.: 'Apollo 17: Comparative Petrology of Fines from Taurus-Littrow'.

Soil samples 74220 and 74241 were collected on the south rim crest of Shorty Crater located near the edge of the light mantle deposit. The orange soil (74220) forms a band with sharp boundaries between two gray soils (one of which is 74241). A  $\frac{1}{2}$  cm thick soil layer was reported as mantling the sampling locality. Soil sample 75081 was collected from the regolith surface on the southwest rim of Camelot Crater located on the mare plain and is believed to represent a sample of the dark mantle material. Objectives of this study were to examine the differences in composition of mineral fragments from the various soil samples in an attempt to characterize the nature of the major rock types contributing to the makeup of the soils. Analytical techniques have been described in Taylor and Carter.

Comparative chemistry of individual mineral fragments from soil sample 75081 and the mineralogical constituency of rock fragments from Camelot Crater infer that the dark mantling material deposited on the valley floor merely consists of comminuted mare basalt 'subfloor' material. Olivines from dark mantle soil 75081 are distinctly different in Fo content from olivines of the STA. 4 orange and gray soils. Olivines from gray soil 74241, however, coincide rather closely in Fo content with the orange soil (74220) olivines. Such a feature may be caused by (1) mixing of soil components, (2) a genetic relationship of (3) an introduction of olivine fragments from a soil unlike either the gray or orange soils. The first explanation is unlikely because of (1) the relatively ungardened nature of orange soil 74220, (2) the broader range in Fo content of 74220 olivines, (3) the lack of orange glass associated olivines in gray soil 74241, and (4) studies of trapped gas contents of the orange and gray soils which showed that orange soil 74220 is contaminated by material which is not similar to gray soil 74241. The similarity of the CaO vs Fo content of free olivines from orange soil 74220 and gray soil 74241 and the different range of dark mantle olivines from soil 75081 may require a genetic relationship between the orange and gray soil olivines. Alternatively, if olivines were introduced to the orange and gray soils at Shorty Crater from a source such as the  $\frac{1}{2}$  cm thick soil layer overlying the sampling area, the olivine chemistry requires the exotic component to be different from the mare-basaltic dark mantle olivines sampled at Camelot Crater and represented here in soil sample 75081.

Most pyroxenes analyzed in soils 74220, 74241, and 75081 are similar and greatly resemble those pyroxenes in mare basalt fragments from the Camelot Crater area which are representative of the subfloor basalts. Dark mantle soil (75081) pyroxenes were found to be characterized by a generally lower Ti-Al enrichment than was observed in the pyroxene populations of the orange and gray soils at Shorty Crater. The more Mg-rich pigeonites and the orthopyroxenes in all of these soils are not characteristic of the mare-type ilmenite basalts and resemble closely pyroxenes of the anorthositic gabbro group (ANT or recrystallized noritic breccias) of rock fragments which is the dominant rock type in samples representative of the South Massif.



Most plagioclase fragments from dark mantle soil 75081 have chemical characteristics analogous to plagioclase in ilmenite basalts from Camelot Crater interpreted as subfloor material. A major mare-basaltic component is represented by plagioclase fragments in dark mantle soil 75081 and complemented by olivine and pyroxene chemistry of this study, adds support to the suggestion that the dark mantle deposit is merely comminuted subfloor basaltic material. The orange and gray soils from Shorty Crater contain smaller relative amounts of this mare component as shown by the larger components of Ca-rich plagioclase. Most plagioclase from 75081 is characterized by a high FeO content (0.27 to 0.69 wt. %) and values of  $An_{74-89}$ , relative to plagioclases of the anorthositic gabbro group of highland rocks which rarely exceed 0.35 wt. % FeO and are generally more calcic than  $An_{90}$ . Orange (74220) and gray (74241) soils from Shorty Crater are seen to contain (1) a major component of the anorthositic gabbro group of highland rocks, (2) a minor component of the dark mantle component previously described, (3) a KREEP-like component (characterized by  $An < 90$  and  $FeO < 0.3$  wt. %), and (4) a component characterized by plagioclases with higher FeO contents than those in the 75081 (dark mantle) plagioclases. This fourth component may represent a mare-basaltic material that is of a slightly different bulk chemistry than that represented by plagioclases from dark mantle soil 75081. This fourth component may reflect (1) the bulk chemistry of the mare-type gray soil (74241) at Shorty Crater, or (2) the bulk chemistry of the  $\frac{1}{2}$  cm soil layer covering the sampling area. The former interpretation support (1) a genetic relationship between mare-basaltic fragments in the orange and gray soils at Shorty Crater and (2) a mare-basaltic component in gray soil 74241 unlike that of the dark mantle soil (75081) from Camelot Crater. The latter interpretation supports the suggestion of a chemically distinct lithological component acting as a contaminant in both the orange and gray soils; a contaminant possibly induced accidentally (during sampling) from the  $\frac{1}{2}$  cm soil layer at Shorty Crater but which was not specifically sampled.

Bansal, B. M., Nyquist, L. E., Rhodes, J. M., Rodgers, K. V., Shih, C., and Wiesmann, H.: 'The Relationship between Geology and Soil Chemistry at the Apollo 17 Landing Site'.

Major and trace element data obtained by x-ray fluorescence analysis are presented for 19 soils and 12 rocks from the Apollo 17 landing site. These results, together with our previously published data for 17 soils and 13 rocks, and additional data obtained by isotope dilution for lithophile elements in several soils, are used to examine the compositional diversity of the Apollo 17 soils with respect to their spatial distribution, inferred stratigraphy, and the prevailing major rock types.

The rock data indicate that, with a few exceptions, three distinct, chemically defined, rock types have been sampled: sub-floor basalts from the valley floor, and KREEP-like noritic breccias and anorthositic gabbros from the North and South-Massifs. In addition, there are aluminum, magnesium and iron rich variants of the noritic breccias (73235, 76055, 72275) a dunite clast (72415), a troctolite (76535), and the orange soils (74220).

The soils at the site have a wider composition variation than those sampled at any previous landing site, ranging from soils that closely approach the sub-floor basalts in composition, to aluminous soils from the South Massif. Within this range, three chemically distinct groups can be recognized, largely on the basis of minor and trace element data, each group relating to a specific spatial and geological feature of the landing site.

*South Massif and Light Mantle Soils:* Soils from stations 2 and 2a are remarkably uniform in composition and, apart from a small (5–10%) basaltic and orange glass component, are intermediate in composition between the KREEP-like noritic breccias and anorthositic gabbros. If this material is representative of the South Massif, the massif should consist of almost equal proportions of noritic breccias and anorthositic gabbros. This is in conflict with the preponderance of noritic breccias in the returned sample collection and suggests that they have been sampled preferentially to more friable anorthositic material.

The uniformity of these soils contrasts markedly with the wide diversity of the valley floor soils, and is surprising in view of the substantial compositional differences between the two major rock types sampled at the South Massif. Such disparity between soil and rock variance appears to be a feature of the lunar highlands, and may be attributed to either (a) extensive and highly efficient mixing of soils early in lunar history, or (b) the derivation of the soils by ablation from rocks that have been intimately mixed, at the outcrop scale or larger, during periods of extensive impact and brecciation.

*Valley Floor Soils:* Soils collected at stations 1, 4, 5 and the ALSEP site form a coherent group,

the chemistry of which is dominated by sub-floor basalts. The compositional variation within the can be attributed to mixing comminuted basalt, and variable amounts of orange glass, with aluminous South Massif soils. The fact that this inferred aluminous component corresponds closely with the South Massif soils and not with any major rock type provides further evidence for the existence of a soil that was well-homogenized prior to basalt extrusion. The basaltic component of the soil is dominated by high titanium basalts similar in composition to 70017. In contrast, lower titanium, quartz normative basalts (e.g. 75055) do not appear to be volumetrically significant at the Apollo 17 site. Soils from stations 1 and 5 contain the largest basaltic component, whereas the gray soils from station 4 contain the highest proportion of massif material.

*North Massif and Sculptured Hills Soils:* Soils from stations 6, 7, and 8 are broadly comparable in composition in that they are more aluminous than the valley floor soils, but contain a greater proportion of basalt than do the South Massif soils. Station 9 soils, although containing larger amounts of basalt, are chemically closer to this group than to any other. The compositional variations within this group cannot be accounted for by mixing basalt with South Massif soils. It is necessary to postulate a different, fairly uniform massif component, higher in aluminum and magnesium and lower in lithophile elements (K, Rb, P, Zr, Y, Nb) than the South Massif material. Again this component does not correspond with any single dominant rock type, but may represent a well-mixed massif soil containing more anorthositic gabbro than noritic breccia, and also substantial amounts of troctolite similar in composition to 76535. It is therefore inferred that the lithologies of the North Massif and Sculptured Hills differ from those of the South Massif in that the former contain a higher proportion of anorthositic rocks, such as anorthositic gabbro and troctolite, and lesser amounts of KREEP-like noritic breccias.

Eberhardt, P., Eugster, O., Geiss, J., Graf, H., Grögler, N., Guggisberg, S., Jungck, M., Maurer, P., Mörgeli, M., and Stettler, A.: 'Solar Wind and Cosmic Radiation History of Taurus-Littrow Regolith'.

Trapped solar wind and cosmic ray produced noble gases and Ar<sup>39</sup>-Ar<sup>40</sup> ages in soils and rocks from the ALSEP site (station 0, deep drill core), the south rim of Shorty Crater (station 4), and rim of Camelot Crater were investigated.

#### *Deep Drill Core*

The 'exposure ages' calculated from the concentration of stable spallation isotopes are surprisingly uniform over the whole length of the core. The lunar material sampled over the whole length of the deep drill core had thus received the same dose of energetic particles with the exception of the top few tens of centimeters (samples 70008.192 and 70181.9). The exposure to cosmic radiation cannot have occurred in situ in an essentially static regolith as the cosmic ray intensity in 3 m depth is attenuated but at least a factor of 10. Other regolith models explaining the observed profile are:

(a) *Mixed regolith.* Mixing of the regolith over the whole depth of the drill core with a characteristic time constant of the order of  $10^8$  to  $10^9$  yr would obliterate the original depth dependence of the concentration of cosmic ray-produced spallation isotopes and lead to an essentially depth independent exposure age. A total exposure time of  $2 \times 10^9$  yr with present day cosmic ray intensity is required to explain the total amounts of spallation products present in the core. The integrated amounts of trapped solar wind Xe in the core correspond in this model to a minimum exposure time of  $3 \times 10^9$  yr (assuming present day solar wind flux and no contribution from the lunar atmosphere). The lower exposure age of the top few tens of centimeters as well as the lower trapped solar wind concentration in 70008.192 can be explained by the recent ( $< 10^8$  yr) addition of unirradiated material to the surface layer. Camelot may be tentatively identified as the source of this fresh regolith component.

(b) *Accumulating regolith.* Continuous accumulation of preirradiated material also leads to an essentially depth independent exposure age profile for greater depth. Continuous accretion with a rate of 2.5 mm  $10^6$  yr of preirradiated material (preirradiation of 200 to 400m.y. duration, randomly variable with time) would reproduce the exposure age profile observed in the Apollo 17 deep drill core. This accretion rate corresponds to a cumulative regolith thickness of 10 m in  $3.7 \times 10^9$  yr (age of Apollo 17 basalts).

Both models cannot account for all the observed regolith properties. It seems unlikely that well defined strata, as observed near Shorty Crater or in the deep drill core, could survive a thorough mixing. No obvious source for the preirradiated material in the accumulating regolith is evident. Material from the North and South massive might contribute to the valley regolith. However, because of the different chemistry, it could not be the dominant source. Most likely, no simple process alone is responsible for the evolution of the regolith, and continuous accretion, deposition of slabs of material as well as in situ mixing are all together important processes. The results of the neutron stratigraphy measurements will give additional important clues on the regolith dynamics at the Apollo 17 landing site.

### *Shorty Crater*

Beds of orange and black soil occur at Shorty Crater and the regolith is certainly not well mixed at this site. This fact is also evident in the exposure ages and solar wind concentrations of the different soil types sampled at station 4. Both grey soils, collected adjacent to the orange soil band, have exposure ages and concentrations of trapped solar wind gases very similar to other Apollo 17 surface soils. The exposure age of the orange soil and the black soil from the bottom of the double drive tube are approximately a factor of 10 lower than the surface soil. These two soils were virtually not exposed to the solar wind, the trapped gas concentrations are only  $\sim 10\%$  and  $\sim 0.1\%$  respectively compared with the grey soil's. The exposure age of a basaltic rock from the rim of Shorty is essentially identical with the age of the orange soil. The following tentative sequence of events would be compatible with the noble gas data. After their formation,  $3.6 \times 10^9$  yr ago, the orange soil and the basalt 74275 were immediately ( $< 10^7$  yr) shielded from cosmic rays and solar wind. Only 20 to 30 m.y. ago, during the formation of Shorty Crater, rock 74275 was ejected and the orange and black soil layers lifted to their present position close to the surface. Somewhat puzzling, if substantiated by further measurements, is the apparent higher exposure age of the black soil relative to the orange soil. Sample 74001.15 was collected in a depth of  $155 \text{ g cm}^{-2}$  where the cosmic ray intensity is already reduced by approximately a factor of 2.5, whereas 74220 was collected close to the surface. Stronger preirradiation of 74001 shortly after its formation would be a possible explanation.

Gibson, E. K., Jr. and Moore, G. W.: 'Total Sulfur Abundances and Distributions in the Valley of Taurus-Littrow: Evidence of Mixing'.

Total sulfur abundances have been measured in 31 Apollo 17 soils, basalts and breccias using the procedures of Gibson and Moore. Calibration standards were NBS steel 55e ( $S = 110 \pm 10 \mu\text{gS/g}$ ) and USGS reference rock BCR-1 ( $S = 464 \pm 10 \mu\text{gS/g}$ ). Sulfur values obtained in this study are similar to the X-ray fluorescence values reported in the Apollo 17 LSPET report. Powders used for 17 of the samples analyzed were the same splits used for the Apollo 17 LSPET studies.

Apollo 17 basalts have unusually high sulfur contents (1580 to 2770  $\mu\text{gS/g}$ ) as compared to Apollo 12 and 15 basalts and terrestrial basalts. However, sulfur concentrations are almost identical with those reported for the Apollo 11 basalts (mean value = 2200  $\mu\text{gS/g}$ ). Apollo 17 basalts have sulfur contents 10 to 100 times greater than some fresh Hawaiian basalts which contain 20 to 200  $\mu\text{gS/g}$ . Enrichment in sulfur for Apollo 17 and 11 titanium-rich basalts as compared to those from other mare sites indicates a higher sulfur content in the lunar magma(s) which generated these basalts. Enrichment in sulfur required pS<sub>2</sub> values greater than that normally found for terrestrial magmas. Sulfur is usually found as FeS, an accessory phase, in lunar basalts. A negative correlation between % metallic iron and sulfur content for Apollo 17 basalts occurs. This correlation suggests that a portion of the metallic iron in lunar basalts may result from desulfuration of the melt prior to crystallization from the lunar magma.

Sulfur contents for the three major rock types found at the Apollo 17 site vary with their major element chemistry. Basalts with FeO contents between 18 and 20% have sulfur concentrations between 1580 and 2770  $\mu\text{gS/g}$ .

Two anorthositic rocks have S contents of 270 and 368  $\mu\text{gS/g}$  while their FeO content varies between 5.14 and 6.19%. Anorthositic gabbro 77017 which has been severely shocked resulting in glass injection throughout the fractures has a sulfur content of 955  $\mu\text{gS/g}$ . Higher S suggests addition of S to the sample during the cataclastic event which introduced the melt into the fractures of the sample.

Noritic breccias which have FeO values between 8.70 and 11.58% have S contents between 720 and 950  $\mu\text{gS/g}$ . These abundances are intermediate to those of the Apollo 17 anorthositic and basaltic

rocks. Three separate samples from the noritic breccia 76315 produced S values of 755, 950 and 785  $\mu\text{gS/g}$  for (1) composite sample, (2) dark gray phase and (3) blue-gray phase respectively. The narrow concentration range indicates that for the 3 separate samples analyzed, sulfur distribution is similar throughout the sample. Dunite clast 72415 contained the lowest sulfur content ( $44 \pm 10 \mu\text{gS/g}$ ) of any Apollo 17 sample examined. The low sulfur content was similar to those measured for the white portion of the black and white breccias from Apollo 16. However, these two samples differ widely in their chemical compositions. Both the anorthositic materials and the dunite clast are low in the sulfur content. Soil breccia 79315 contains a sulfur value ( $1020 \mu\text{gS/g}$ ) intermediate between the massif samples and subfloor basalts. The differences in S content between massif samples (275 to 950  $\mu\text{gS/g}$ ) and mare basalts (1580 to 2770  $\mu\text{gS/g}$ ) indicates either that highland materials were initially low in sulfur or they have been efficiently outgassed and depleted in sulfur relative to mare basalts.

Orange soil 74220 has a chemical composition similar to the Apollo 17 titanium-rich basalts. However, its sulfur content is only 550 and 750  $\mu\text{gS/g}$  (2 separate sample allocations). The low sulfur content, in light of the basaltic composition, shows that whatever mode or origin chosen for the orange soil (fire fountaining or impact derived), the process was extremely efficient in removing sulfur from the sample, or we are looking at material from a different source with the same major element chemistry. Low sulfur content along with associated surface correlated volatile elements and compounds is consistent with the fire fountaining hypothesis because terrestrial pyroclastic materials with similar morphologies are also extremely depleted in sulfur relative to the source materials. The depletion in sulfur indicates severe outgassing of the material during the pyroclastic event and associated elevated temperatures. The extremely low vesicularity of the orange glass supports the hypothesis that the samples were nearly completely 'degassed'.

Twelve Apollo 17 soils have sulfur concentrations ranging from 550 to 1300  $\mu\text{gS/g}$ . Those soils collected at both the North and South Massifs have sulfur concentrations below 1000  $\mu\text{gS/g}$  with the exception of soil 78501 (1125  $\mu\text{gS/g}$ ) collected at the Sculptured Hills Station. Soils collected on the Taurus-Littrow valey floor, which were associated with the subfloor basalts, have sulfur concentrations greater than 1000  $\mu\text{gS/g}$  with the exception of the orange soil, which apparently is a special case.

Total sulfur contents of Apollo 17 soils can be accounted for by a simple mixing model between the mare basalts which are enriched in sulfur and massif materials which are depleted in sulfur. A direct correlation between the percent basaltic component in the soils with total sulfur content of the soils is presented. The percent basaltic component is obtained from the petrographic study of Apollo 17 soils by Heiken and McKay and the Apollo 17 Sample Catalog. Additional mixing models constructed by Schonfeld for Apollo 17 soils indicates that around 1 to 2% meteoritic component (based upon the Ni content) is present in the Apollo 17 soils. Gibson and Moore have shown that sulfur can be volatilized slowly from lunar soils at temperatures as low as 750°C and such surface processes as micro-cratering, vapor transport and lunar outgassing may move small amounts of sulfur around on the lunar surface. However, the major process which accounts for sulfur abundances in lunar fines is mixing of sulfur-rich components such as mare basalts with sulfur-poor materials like anorthosite and noritic breccias.

Macdougall, D., Hutcheon, I. D., and Price, P. B.: 'Irradiation Records in Orange Glass and Two Boulders from Apollo 17'.

*Orange glass from subsurface samples 74220 and 74261* – The possibility that the bright orange material at station 4 represented recent lunar volcanism drew widespread interest to this sample. We have measured particle track densities, diameter distributions and annealing behavior as well as uranium concentration in the orange glass.

The major particle track features of the glass are: (1) in 74220 the total measured track density in individual spheres ranges between  $1.5 \times 10^6$  and  $10^8$  (median  $5 \times 10^5$ ) for 16 spheres. For 15 spheres from 74261 the range is  $2.2 \times 10^5$  to  $1.3 \times 10^7$  (median  $4.5 \times 10^5$ ). (2) Roughly 10% of the spheres in sample have track density gradients indicative of unshielded exposure on the lunar surface. (3) For fixed etching conditions, the measured track diameter distributions in individual spheres vary depending upon track density. Spheres with low track densities ( $(1-3) \times 10^5 \text{ cm}^{-2}$ ) have the largest track diameters. (4) Annealing experiments show that iron nuclei tracks are partially erased by heating at 200°C for 1 h, and that fission tracks (both spontaneous and induced) are completely erased by heating at 450°C for 1 h. These conclusions were drawn from measured track density distributions for

groups of spheres heated at various temperatures between 150 and 500°C for 1 h. Relative to the distribution for unheated spheres, samples heated at 150 and 200° show a progressive shift toward lower track densities (fading of cosmic ray Fe tracks); between 200 and 300° the distribution is relatively stable (mostly unaffected fission tracks) while at 350° and above another progressive shift toward lower track densities is noted (fading of fission tracks). No natural tracks remain after 1 h at 450°C; neutron-induced fission tracks also anneal under these conditions. (5) The uranium concentration in the glass, measured by counting induced fission tracks in an adjacent mica detector, is quite homogeneous with an area-weighted average (15 spheres) of 155 ppb for 74220 and 159 ppb (15 spheres) for 74261.

From the above the following conclusions can be drawn. The diameter distributions and annealing data indicate that most (50–100%) tracks in spheres with densities of  $(1-3) \times 10^5$  tracks  $\text{cm}^{-2}$  are fission tracks. This is also borne out by the fact that neutron-induced fission tracks in the same spheres have a diameter distribution similar to (but on the average ~10% larger than) the natural tracks. This slight size difference may indicate minor annealing (up to ~20% based on typical calibration curves) of the spontaneous fission tracks at lunar surface temperatures. The expected fission track density for 0.16 ppm uranium and an age of  $3.7 \times 10^9$  yr is  $2 \times 10^5$  tracks  $\text{cm}^{-2}$ , taking into account the experimentally determined etching efficiency of 0.6. A 20% annealing correction would reduce this to  $1.6 \times 10^5$ . Thus, contrary to some other interpretations we believe the fission track record in the orange spheres to be compatible with the  $^{40}\text{Ar}$ – $^{39}\text{Ar}$  age.

Soil 74220 was collected from a distinct layer extending from approximately 5 to 7.5 cm below the lunar surface. Soil 74261 was collected from the gray soil zone at the end of the same trench. Both samples may include material from the overlying surface soil; in fact this is the probable source for the ~10% of solar flare irradiated orange glass in each sample. Since the soil is well stratified with distinct upper and lower boundaries, it has probably never been vigorously mixed. Using the median track density, the in-situ galactic cosmic ray exposure age is  $2.5 \times 10^6$  yr for soil 74220. (A correction of  $2 \times 10^5$   $\text{cm}^{-2}$  has been subtracted from the median density given above in view of the fission track contribution.) Because of the much longer (~30 m.y.) Ne exposure age the orange glass must have been within ~1 m of the lunar surface but below ~15 cm for ~30 m.y. at some time in its history, and at its present position for only  $2.5 \times 10^6$  yr.

*Apollo 17 boulders*—Our interest in the Apollo 17 boulders has been directed toward an understanding of individual boulder history through determination of particle track exposure ages, erosion rates, etc., and also toward a search for pre-compaction irradiation effects and breccia formation effects in general through the use of high voltage electron microscopy. The data presented below were gleaned for the most part from small, sometimes undocumented chips in a preliminary allocation. It is expected that much more comprehensive information will be available at the time of the Fifth Lunar Science Conference.

One unexplained phenomenon which has hindered the track studies up to the present is the peculiar etching behavior of many of the feldspar grains, particularly in our samples of 72255. After standard etching procedures (using an etching solution of  $\text{lgNaOH}:2\text{gH}_2\text{O}$ ) feldspar surfaces are frequently irregular and 'bumpy', presumably due to non-uniform dissolution of the surface, making track observations difficult and perhaps introducing errors if track etching is as irregular as is surface dissolution. Optical microscope observations are possible in areas of low track density if surfaces are lightly polished to remove irregularities after etching; however, scanning electron microscopy of areas with densities  $\lesssim 10^8$   $\text{cm}^{-2}$  is very difficult. Although we have not noticed this effect in feldspars from other missions, it is apparently widespread among Apollo 17 samples as we have observed similar behavior in numerous surface soil samples, in other boulder samples, in basalt 71055 and occasionally in Apollo 17 deep core samples. The peculiar etching behavior may be related to small-scale chemical irregularities. Shock would appear to be ruled out as an explanation since shock effects are common in feldspars of similar bulk composition from other missions, yet the etching abnormality seems restricted to Apollo 17 samples.

*Boulder 1, Station 2 – 72255*: Preliminary studies of two interior pieces from this sample indicate an upper limit to the track exposure age of 15–20 m.y. Exposure ages determined by track methods, in the context of the large boulders, require some explanation. They do not necessarily bear any relation to the time at which the boulder rolled to its present location. Lunar surface photographs show considerable debris, including large fragments, surrounding the boulders. Because of the steep depth dependence of the particle track production rate, the surface under a spalled off fragment of typical thickness 10 cm is essentially virgin from a track point of view. Thus we expect that particle

track exposure ages determined at different locations on the same boulder will reflect the local rate of large-scale discontinuous erosion, and will not necessarily be the same.

*Boulder 2, Station 2 – 72315:* An exceptionally young solar flare track exposure age of  $10^5$  yr has been calculated. *72335:* We have examined only a 60 mg undocumented chip, supposedly a surface sample, although without a discernible track density gradient at the edges examined. However, a gradient typical of solar flare track gradients was observed to extend over several feldspar grains in the chip interior. Maximum observed track densities were  $> 5 \times 10^8$  cm<sup>-2</sup>, falling to a minimum of  $\sim 3 \times 10^7$  and rising again. We have observed large variations ( $\approx$  a factor of 6) in track density between adjacent olivine grains and variations in track density of more than  $20 \times$  between adjacent olivine and feldspar grains. Possible explanations: (i) 72335 might contain a few pre-compaction irradiated grains. (ii) The interior track density gradient and the occasional high track density feldspar may be due to an unusual exposure geometry created by the presence of numerous nearby vugs in the exposed surface. (iii) Track density differences among adjacent olivines may be due to shock or thermal annealing. *72355:* We have examined a documented interior slab that was cut roughly parallel to and  $\sim 3$  cm below the exposed boulder surface. Track densities in feldspar range between  $2\text{--}5 \times 10^8$  cm<sup>-2</sup>. A tentative exposure age of 10–20 m.y. for this part of the boulder can be assigned.

High voltage electron microscope studies of the boulder samples will proceed as soon as the refurbishment of the 650 kV microscope is completed.

Silver, L. T.: 'Patterns of U-Th-Pb Distributions and Isotope Relations in Apollo 17 Soils'.

Thirteen surface soils collected at the major features visited in Taurus Littrow valley were surveyed for their U,Th,Pb abundances and isotopic systematics. Nine aliquots from throughout the Apollo 17 deep drill core were analyzed similarly. Volatile lead components in six samples have been isolated and evaluated including 'orange' and 'gray' soils at station 4.

Average uranium and thorium levels in the surface soils of the valley floor are 0.344 ppm and 1.09 ppm, respectively. Similar levels are observed in the deep drill core. It is noteworthy that these are the lowest average values observed at any Apollo mare site. The Th/U ratios in the valley soils, averaging 3.14, are distinguishably lower from all other mission sites except Apollo 16. There appears to be a significant increase in radioactivity in the lower 160 cm of the deep drill core. This correlates with other evidence for a discontinuity in the drill core stratigraphy. Values of U and Th concentrations rise progressively in suites collected from the bases of the Sculptured Hills, North Massif and South Massif. Th/U ratios show comparable increases. The serial variation appears to reflect the degrees of mixing between valley floor and massif components. The South Massif soils, the most radioactive observed here, are comparable in level to those observed in the Descartes region and much less radioactive than 'highland' soils from Apollo 14 and 15.

The lead concentrations throughout the valley range from 1–2 ppm, generally correlating with the associated uranium and thorium. Conspicuous exceptions are the soils from station 4, 'Shorty' crater rim, which are at the 3 ppm level, reflecting the anomalous volatile element content of these soils reported by many other workers. Lead in the deep drill core is generally similar to other values observed on the valley floor. Both concentration and composition data indicate that the 1–15 ppm levels of terrestrial lead contamination observed in Apollo 15 and 16 deep drills are not present in this core. Estimated upper limits for possible contamination are shown in table 1, and are all less than  $0.2 \mu\text{g g}^{-1}$  except for 70006,7 which appears to have a possible  $0.4 \mu\text{g g}^{-1}$  contamination. Whether this is derived from the drill or from subsequent sample processing has not been determined. This improvement of lead background by 1–2 orders of magnitude is a significant achievement by NASA.

The isotopic composition of leads in all samples (corrected for blanks of less than 3% of the sample lead except in the cores) is shown. The leads are typically less radiogenic than those observed from other mission sites. They reflect the lower radioactivity levels found at Taurus Littrow and the presence of widely dispersed trace to significant contributions from the anomalous leads associated with the soils from station 4. These soils, particularly 74220, are 4–10 times richer in <sup>204</sup>Pb and have the lowest <sup>206</sup>Pb/<sup>204</sup>Pb ratios observed in the lunar collections from all missions. They are characterized by <sup>207</sup>Pb/<sup>206</sup>Pb ratios which are much higher than those of any other leads at this site and their presence as a component in the soils can be easily recognized. Valley floor and drill core samples are estimated to derive from 5 to 50% of their lead from components similar to the leads at 'Shorty' crater. <sup>238</sup>U/<sup>204</sup>Pb ratios range from 50 to 100 in valley surface soils and are as low as 30 in drill stem unit 70008. In

contrast soils from the massifs have much lower  $^{204}\text{Pb}$  concentrations, with  $^{238}\text{U}/^{204}\text{Pb}$  values from 100 to 250. Other contributions to the lead isotopic compositions in the valley floor soils can be identified in the local basalts, debris from the adjacent highlands, and from variable amounts of volatile radiogenic lead.

Some very distinct and unusual patterns emerge from this data. The U-Th-Pb systems of the valley floor generally show excess leads and reverse discordant older model ages in the vicinity of 4750–5000 m.y. In contrast, the rake soil 72500 from the toe of the South Massif shows nearly concordant model ages at 4440–4530 m.y. Sample 73221 from the light mantle slide apparently derived from the South Massif shows slightly older ages at 4650–4750 m.y., as do the two soil samples from the North Massif. Samples from the Sculptured Hills are nearly identical with the valley floor systems. Thus, a reversal of the hitherto consistently relation observed of older model ages in highlands compared to mare surfaces apparently has been introduced by the presence of the 'orange' soil and its kindred on the valley floor. This must reflect, also, a paucity of  $^{207}\text{Pb}$ -rich systems in the breccias which comprise the massifs.

Studies of volatile leads in massif soils indicate another important anomaly. The rake soil from station 2 contains almost none of the ancient, low-temperature volatile lead characteristic of most highland soils. Very little is indicated in the other three massif soils. It is difficult to understand how these massif slopes which have existed since before Serenitatis volcanism, and show no great colluvial accumulations at their base, have failed to accumulate such a component. Has mass-wasting been more active over the long history of the valley than has been previously recognized?

The distribution of the  $^{204}\text{Pb}$ -rich component on the valley floor is so widespread as to indicate that the orange soil kindred may exist at the top of the basalt flow system over a broad region of the valley. In the upper 60 cm of the drill core, in a zone characterized by abundant basaltic fragmental debris, orange glass is conspicuous and the soil yields the highest model ages encountered. This is 4 km east of 'Shorty'. This zone appears to be part of a young ejecta blanket from a relatively large crater such as nearby Camelot, or from the secondary crater cluster which lies to the east of the LM, which penetrated into the basaltic sub-regolith.

Volatilization studies of the station 4 soils have revealed that 60 to 80% of the total lead and even more of the  $^{204}\text{Pb}$  is released below 600°C. The isotopic composition of 74220 low temperature lead is the most primitive observed in lunar materials. The residual lead is a relatively young radiogenic component. The 2 gray soils, 74240 and 74260, also contain large quantities of low temperature volatile leads rich in  $^{204}\text{Pb}$ , but they differ systematically from 74220 in an enrichment in a second very ancient radiogenic component. A multi-component solution suggests directly.

Duennebieber, F. K., Kovach, R., and Watkins, J.: 'Results from the Lunar Surface Profiling Experiment'.

The lunar seismic Profiling Experiment is an array of four geophones in a triangular array about 100 m on a side (with one geophone in the middle) deployed at the Apollo 17 landing site (Kovach and Watkins). Study of the signals received from eight explosive packages deployed at from 0.1 to 2.7 km from the array and from the Apollo 17 LM impact at a range of 8.7 km yields a model for the near-surface lunar structure. The compressional velocities and layer thicknesses are given below:

$V_p$ (m s <sup>-1</sup> )	h (m)
100	8.5
400	195
1190	990
> 2280	?

The 100 m s<sup>-1</sup> layer is assumed from its presence at the other Apollo sites; the transition from 100 m s<sup>-1</sup> to 400 m s<sup>-1</sup> may be gradual. The 1190 m s<sup>-1</sup> layer may be thicker than indicated if the velocity of the next layer is greater than 2280 m s<sup>-1</sup>. The model indicates that soil extends to a depth of no greater than 8.5 m.

An unexpectedly large number of natural seismic events have been observed by the Lunar Seismic Profiling experiment in the passive listening mode. During a four day listening period in July, 1973, an average of more than three events per hour were observed. Study of these events suggests that most are small moonquakes occurring near the lunar surface. Many of the signals match each other in

every respect implying identical source and eliminating the possibility of meteoroid impact sources. From the characteristics of similar events observed by the short period components of the Passive Seismic Network, slumping of soil on lunar slopes triggered by diurnal thermal variations is suggested as a possible source mechanism (Duennebier and Sutton). This mechanism may be important in the erosion of lunar slopes. Further study of these events (termed thermal moonquakes) recorded on the Apollo 17 array may yield source locations necessary to verify the proposed mechanism.

Criswell, D. R. and Lindsay, J. F.: 'Thermal Moonquakes and Booming Dunes'.

Lunar surface microseisms ( $f \simeq 4 - 8$  Hz and  $0.2 < A$  (nm =  $10^{-9}$  m)  $< 2$  vertical amplitude,  $\bar{A} \simeq 0.6$  nm) have been detected. Most of these events, which originate within a radius  $r < 4$  km of a given ALSEP station, are thought to be produced by the thermally induced slumping of lunar soil on steep slopes such as those on Cone Crater (A-14) or at Hadley Rille and Mount Hadley (A-15). This interpretation, if qualitatively correct, means that the short period seismometers (A-11, 14, 15 and 16) and geophones (A-17) at these Apollo sites monitor local non-meteoritic surface erosion rates in real time. The key question is 'How is the total energy ( $E_0$ ) of each slumping event related to the amplitude of the observed microseism?' Booming dunes are rare terrestrial dunes whose sands emit a very low frequency ( $f < 100$  Hz) noise and/or note during slumping. Very efficient conversion of slumping energy into vibrational seismic energy has been observed. It has been suggested that lunar slumping events might also boom because the booming process could reduce the lunar erosion rates inferred from thermal moonquakes by  $10^6$  to  $10^9$ , could provide a simple explanation for the repetition of complex slumping patterns from one lunar day to the next, and be consistent with the narrow bandwidth of the thermal moonquakes.

Surface explosions over a range of detector/explosion separations were employed in the Active Seismic Experiment (ASE) to establish an empirical relation between disturbance energy ( $E_0$ (ergs)),  $A$ (nm), and  $r$ (km)

$$E_0 = r^2 A^3 / K^2, \quad (1)$$

where  $K = 7 \times 10^{-7}$  nm-km/ergs  $\frac{1}{2}$  (4; 5). Enormous erosion rates would be required to sustain the observed thermal moonquake activity at Fra Mauro if this small a value of  $K$  were applicable to slumping-to-seismic energy conversion. To illustrate, assume slumping inside Cone Crater ( $r \simeq 1.5$  km,  $\bar{A} \simeq 0.6$  nm) produced the 350 events presently observed each lunar day. The total annual release of energy would be  $7 \times 10^{15}$  ergs which means that  $V \cdot h = 2 \times 10^{13}$  cm<sup>4</sup>/y<sup>-1</sup> where  $V \sim$  the volume  $ad \sim h \sim$  the decrease in center-of-mass height of the slumping material (slumping energy =  $Vhg_1$ ,  $\rho = 2$  gr cm<sup>-3</sup>,  $g_1 = 167$  cm s<sup>-2</sup>). At this rate the interior slopes of Cone Crater (diameter  $\simeq 350$  m) would be reduced by  $5^\circ$  from their maximum possible inclination (dynamic angle of repose  $\simeq 35^\circ - 40^\circ$ ) to less than their static angle of repose in the order of  $10^2$  yr. Exposure ages of  $3 \times 10^7$  yr or  $3 \times 10^5$  slumping periods ( $\simeq 3 \times 10^7 / 10^{+2}$ ) have been ascribed to Cone Crater ejecta. Adjustment of  $K$  upward by factors of 30 to 100, in analogy to the greater seismic coupling efficiency of earthquakes than surface explosions only marginally reduces this dilemma. However, if a lunar 'booming' process operated at only 5% efficiency  $K$  could be multiplied by approximately 7000 and slumping rates would be multiplied by  $2 \times 10^{-8}$  (i.e.  $5 \times 10^9$  yr for  $5^\circ$  slump of interior walls of Cone Crater). Booming events of  $2 \times 10^4$  ergs would suffice rather than the  $10^{12}$  ergs implied by Equation (1).

Accounts of booming dunes, which incidentally are visually and mineralogically indistinguishable from silent dunes, have been woven into the legends of eastern desert regions for over 2000 yr and are mentioned in British scientific articles as early as 1812. General conclusions drawn from several different tests are: (1) narrow single and multiple peaks are easily generated between 50 and 80 Hz (note the corresponding power spectral density trace); (2) mechanical to seismic conversion efficiencies the order of 1% to 5% are achievable; (3) the output can be modulated by different forcing profiles but the basic frequency range is not changed; (4) significant output does occur for  $f < 20$  Hz; and (5) there is no readily perceptible difference between the transient vibrations produced by shaking a quantity of booming sand in a bottle which is initially at atmospheric pressure (760 torr) and then evacuated to 1.5 torr just as theory predicts.

Other features of thermal moonquakes are consistent with the booming process and the very small slumping volumes implied. Thermal moonquakes have a narrow frequency distribution as do booming dunes. Some thermal moonquakes display an evolving sequence during the lunar day which is very



faithfully repeated from one day to the next. Purely by way of illustration, it has been suggested that the soil of the complicated slumping pattern, which could extend over a wavelength or so, is restored each lunar night to its pre-slumped condition. In the booming process local slopes would control the spectral outputs of each event and the very slight displacements required of each event in the sequence would permit the slumping of each element to continue over many cycles before significant local slope changes occurred. The roles of grain surface morphology, grain composition, grain shape, total  $Q$ , and the presence of an atmosphere are under investigation. The booming process, once understood, through a systematic laboratory and field program may provide a diagnostic technique for studies of grain adhesion, size distributions, slumping rates, and surface seismic properties over kilometer sized areas on the Moon and Mars as well as on the Earth.

Bjorkholm, P. J. and Gorenstein, P.: 'Variation of  $^{222}\text{Rn}$  to  $^{210}\text{Po}$  Activity Ratio on the Lunar Surface as Observed by the Alpha Particle Spectrometer'.

Papers presented at the Fourth Lunar Science Conference, reported the detection of areas on the lunar surface characterized by  $^{222}\text{Rn}$  activity or by  $^{210}\text{Po}$  activity. The detector was the Alpha Particle Spectrometer aboard the command/service module of Apollo 15 and Apollo 16.  $^{210}\text{Po}$  is a descendant of  $^{222}\text{Rn}$  and has an effective half life of 21 yr. The areas of the Moon having the strongest activity are the crater Aristarchas, the crater Grimaldi, and the edges of many lunar maria with Mare Fecanditatis and Mare Crisium showing the strongest signals among those observed.

We hypothesize that emanation of  $^{222}\text{Rn}$  is characterized by a strong time dependence. If this is correct then the ratio of  $^{222}\text{Rn}/^{210}\text{Po}$  activity will not be equal to its equilibrium value of approximately one-half and will show differences from one lunar region to another. To test this hypothesis we have examined the activity ratio at various locations on the lunar surface. We find that it varies from greater than 2.2 at Aristarchas to less than 0.4 at the edges of Mare Fecanditatis. This result supports the idea that  $^{222}\text{Rn}$  is being released episodically at various locations on the Moon.

Stoener, R. W. and Davis, R., Jr.: 'The Fast Neutron Production of  $^{37}\text{Ar}$  in the Deep Drill String and the  $^{222}\text{Rn}$ , U, He and Hydrogen Contents'.

The production of fast neutrons in the lunar soil by galactic and solar cosmic rays was measured utilizing the fast neutron reaction  $^{40}\text{Ca}(n, \alpha)^{37}\text{Ar}$ . A set of soil samples ( $< 1$  mm) from the deep drill string, the trench dug at station 8, and three associated surface samples were vacuum melted and analyzed for  $^{37}\text{Ar}$  by procedures previously described. The calcium content of several of these samples have been determined by other investigators who found the calcium content is essentially constant (7.8–8.0%). The  $^{37}\text{Ar}$  activities reported here and their respective calcium contents may be combined with similar data previously reported on the Apollo 16 deep drill sample to obtain the production of  $^{37}\text{Ar}$  from calcium as a function of the depth in the lunar soil. The  $^{37}\text{Ar}$  production rate at the surface is  $0.35 \text{ dpm g}^{-1} \text{ Ca}$ , a value derived from measurements from the top of the Apollo 16 drill stem, and then reaches a maximum at a depth of  $40\text{--}50 \text{ g cm}^{-2}$  and then decreases exponentially with depth, exhibiting a mean free path of  $240_{-30}^{+20} \text{ g cm}^{-2}$ . The two scooped surface samples (depth of 0 to  $4.5 \text{ g cm}^{-2}$ ) were considerably higher than was observed in the surface samples from the Apollo 16 deep drill stem. The high values at the surface can be attributed to the intense solar flare of August 4–10, 1972 that occurred 126 days prior to the mission. The  $^{37}\text{Ar}$  activity at the surface of the Moon must have been in the range of 8 to  $12 \text{ dpm g}^{-1} \text{ Ca}$  at the end of the flare bombardment.

In addition we measured the  $^{39}\text{Ar}$ , tritium,  $^{222}\text{Rn}$ , helium and hydrogen released from these samples. The  $^{222}\text{Rn}$  activity and the helium and hydrogen contents obtained by vacuum melting and the uranium contents measured on an aliquot sample are presented. The  $^{222}\text{Rn}$  is produced by the  $^{238}\text{U}$  decay, and should reflect the uranium content ( $0.740 \text{ dpm } ^{222}\text{Rn ppm}^{-1} \text{ U}$ ). Our measurements show that in general the  $^{222}\text{Rn}$  extracted is lower than expected from the measured uranium content by approximately 20 percent, but two of the samples were 27% higher. The procedures used were checked with W 1 standard samples, and it was found that the  $^{222}\text{Rn}$  released agreed ( $\pm 4\%$ ) with the amount expected from the uranium content of the sample. There is no clear explanation of the apparent lack of correspondence between the  $^{226}\text{Ra}$  and  $^{238}\text{U}$  concentrations. We obtained similar results in the Apollo 16 core, comparing  $^{222}\text{Rn}$  activities to Silver's uranium contents.

The hydrogen and helium contents in the deep drill string increase with depth. The H/He content is relatively constant, with an average value 10. This value is close to the value of 7 to 10 observed in solar wind.

## 5. Characterization and Evolution of the Mare Basins: I

Schaeffer, O. A. and Husain, L.: 'Chronology of Lunar Basin Formation and Ages of Lunar Anorthositic Rocks'.

We report on the  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  ages for lunar anorthosites 60015 and 60025 as well as two anorthositic coarse fine fragments 72503,8,12 and 78503,7,1. Argon release patterns are presented.

Rock 60015 weighs 5.57 kg. It is a coarsely crystalline cataclastic anorthosite consisting of highly strained plagioclase. The plagioclase contains myriads of bubble-like inclusions which appear to be glass. The rock was apparently severely shocked, raised almost to the melting point and is coated with a dark gray vesicular glass. This rock gives a well defined  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  plateau age of  $3.55 \pm 0.05$  Gy and is the youngest anorthosite to be found on the Moon so far.

Rock 60025, 1.8 kg is a cataclastic anorthosite. It shows well developed shock lamellae and linear chains of low-relief isotropic inclusions (along the shock lamellae) that may represent incipient melting. This rock is similar to the coarse fine anorthositic fragments which give ages in excess of 4.2 Gy. Rock 60025 gives a plateau at high temperatures with an age of  $4.18 \pm 0.06$  Gy. This is the first instance of a large rock giving an age distinctly in excess of 4.0 Gy.

Rock 72503,8,12 is a gray green recrystallized breccia with poikiloblastic texture. This rock shows a well plateau age of  $3.96 \pm 0.02$  Gy with some drop off at the highest temperatures.

Rock 78503,7,1 is a gabbroic anorthosite which shows shock features. This rock gives a well defined high temperature plateau age of  $4.13 \pm 0.03$  Gy and is one of the first old rocks to be reported for the Apollo 17 site.

Impact generated breccia and cataclastic rocks such as those dated here were returned by each of the Apollo-mission. In fact, the Apollo 14 and 16 samples are predominantly this rock type. As these materials form a morphological unit which appears to be widespread and contemporaneous, it appears that except for the very friable soil breccias, the impact generated rocks are for the most part related to the major multi-ring impact basins. On the near side of the Moon there are then such structures clearly visible. Starting with the youngest, these are Orientale, Imbrium, Crisium, Humorum, Nectaris, Serenitatis, Fecunditatis, Tranquillitatis E, Tranquillitatis W and Nubium. Each of the basins has an extensive ejecta blanket. The Moon thus should be covered by a series of layers of ejecta. By observations from terrestrial cratering and lunar ejecta it was possible to estimate the thickness of the ejecta layers at any particular site. The striking result is that all the Apollo landing sites Imbrium ejecta predominates in the upper 100 m. On the other hand, if one considers the radiometric ages for the impact generated breccias at all the Apollo sites, the age  $4.00 \pm 0.05$  Gy predominates. It appears then reasonable to assign this age to the Imbrium event which means in addition that the rocks in the Imbrium ejecta blanket were reset either by the impact or in the ejecta blanket itself. The ejecta may have been hot enough to reset the radiometric clocks.

It is concluded that the multi-ring lunar basins were spread over hundreds of millions of years and not a group in a relatively short time near 4.0 Gy ago. The widespread occurrence of the 4.0 Gy age in lunar rocks from the different Apollo sites is thus due to the widespread occurrence of substantial Imbrium ejecta which lies on top and is the most likely to be sampled. It would appear then that after the lunar crust formed there was an era of multi-ring basin formation lasting until about 3.9 Gy ago. This era was followed by an era of basalt flooding of the basins and low lying areas on the lunar surface which lasted until about 3.1 Gy ago. At this time all major activity ceased.

The K-Ar clock is reset by the diffusion of argon. It has been estimated that a temperature of  $400^\circ$ - $700^\circ\text{C}$  may be adequate to degas a rock of argon in a geologically short time. Approximately one year at  $700^\circ\text{C}$  and  $10^4$  yr at  $400^\circ\text{C}$ . The Rb-Sr ages for the highland rocks is defined by the analysis of a rubidium rich finely crystalline mesostasis often called quintessence. The resetting of the Rb-Sr clock by the homogenization of such a mineral assemblage is quite likely for the pressures and temperatures accompanying the formation of an ejecta layer.

The morphology of the large ring basins indicates a temporal sequence of some extent. Among other observations the rings of the older basins are considerably more eroded than the rings of the younger

basins. The ejecta from older basins are most likely found at the landing sites where the Imbrium ejecta is expected to be the thinnest, that is the sites farthest removed from Imbrium. These are the Apollo 11, 16 and 17 landing sites. The Apollo 11 site is flooded with Mare basalt which covers all the basin ejecta. At the Apollo 16 site the upper 200 m of the surface is expected to contain a substantial contribution of Nectaris ejecta with smaller amounts of Crisium and Humorum ejecta. Rock 60025 reported here as well as four rocks reported earlier have ages distinctly older than 4.0 Gy. The oldest of these have radiometric ages near  $4.20 \pm 0.05$  Gy which may be the time of the Nectaris event. The time of the Crisium and Humorum events should then lie between 4.0 and 4.2 Gy ago. As the Apollo 17 landing site is closer to the Crisium basin than either the Nectaris or Humorum it is possible that 78503,7,1 is a sample of Crisium ejecta. The Crisium event would then be  $4.13 \pm 0.03$  Gy ago. Rock 66043,2,4, a feldspathic interstitial igneous rock, with an age of  $4.13 \pm 0.0569$  may also be a sample of Crisium ejecta.

From crater counts and from the observation that Orientale ejecta does not appear on the surface of the Mare basalts, the Orientale event should be older than the surface mare flows. The oldest mare basalts dated radiometrically lie between 3.7 and 3.8 Gy (basalts at Apollo 11 and 17 sites). On the other hand, Orientale is younger than Imbrium. The Orientale event should thus lie between 3.8 and 4.0 Gy ago. There are several samples from Apollo 14 and 16 sites which have radiometric ages of  $3.85 \pm 0.05$  Gy (3) (10). These rocks may represent Orientale ejecta. These considerations lead to the following ages for the multi-ring basin events:

Orientale	$2.85 \pm 0.05$
Imbrium	$4.00 \pm 0.05$
Crisium	$4.13 \pm 0.05$
Humorum between	4.13 and 4.20
Nectaris	$4.20 \pm 0.05$

A given rock is not necessarily a sample from the ejecta of a multi-ring crater event. There are numerous intermediate size craters which contribute a small but not necessarily negligible amount of material to the lunar surface. The rock 60015 reported here with an age of  $3.55 \pm 0.05$  Gy is probably ejecta from an intermediate size crater. It is interesting to note that this rock releases more than half its argon above 1600°C. It would appear that this rock was severely heated so that it lost not only all its argon but also most of the potassium from the least retentive mineral sites.

Turner, G., Cadogan, P. H., and Yonge, C. J.: 'The Early Chronology of the Moon and Meteorites'.

$^{40}\text{Ar}$ - $^{39}\text{Ar}$  ages of samples from Apollo 16 and 17 have been determined and in the case of highland material continue to be dominated by material from which  $^{40}\text{Ar}$  was outgassed 3.95 Gy ago. An up to date summary of our data will be presented at Houston. We have earlier argued that much of this outgassing probably occurred when the highland breccias, or their precursors, were at some depth below the lunar surface. The lunar heat flow 4 Gy ago coupled with the blanketing effect of a fragmented outer layer would be sufficient to maintain the ambient temperature at depths below a few km at a level sufficient to inhibit argon retention. On the assumption that the rocks examined are basin ejecta and not debris from smaller, more recent Archimedean age craters, we, and others, have argued that the highland ages indicate the times of formation of several of the large lunar impact basins;  $^{40}\text{Ar}$  retention is presumed to commence when the present highland material was excavated from depth.

Whether these major impacts represent the final stages of lunar accretion or an episodic burst of bombardment is an open question. An episodic bombardment could have resulted from the debris of a major collision in the asteroid belt or alternatively if the moon was captured 4 Gy ago by collision with a circumterrestrial debris swarm. The record prior to 4 Gy appears to have been crased in most samples analysed and this had led us to institute a search for thermal effects in meteorites in the period 4.5 to 4.0 Gy using the  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  technique. Meteorites appear to have suffered less from outgassing events in this period and may therefore provide clues to the early collisional history of the solar system and, by inference, of the Moon.

We have selected a number of meteorites having total fusion K-Ar ages around 4 Gy and high U, Th-He ages (in an attempt to avoid meteorites which may have been involved in the recent '500 m.y.' event. This method of selection was not entirely successful in that we found several of the published total fusion ages to be inaccurate presumably due to the use of nominal K contents. A number of

chondrites analysed showed minimal argon loss and 'plateau' ages in the range 4.55 to 4.60 Gy, comparable to published Rb-Sr mineral isochron ages. In all cases the ( $^{40}\text{Ar}/^{39}\text{Ar}$ ) release pattern showed the high temperature dip common in lunar samples. Until this decrease is fully understood the plateau ages must be regarded as tentative but the lunar experience suggests that they probably represent a meaningful age and are certainly quite adequate for a preliminary  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  survey of meteorite ages.

Two of the samples analysed so far show rather clear evidence of outgassing around 3.9-4.1 Gy. ago, (Appley Bridge (LL6) and Mangwendi (LL6)). These low ages may represent collisional reheating or alternatively may be due to cooling of the parent body. ( $^{40}\text{Ar}/^{39}\text{Ar}$ ) ratios increase with extraction temperature indicating the retention of argon from an earlier period and this may be easier to understand in terms of collisional reheating.

The number of samples analysed so far is too small to draw any major conclusions with regard to the lunar bombardment but it seems evident that, if we are dating collisional reheating, major collisions occurred elsewhere than on the surface of the moon 3.9 Gy ago.

In addition to the age determinations referred to above we have investigated the argon retention characteristics of grain size separates from irradiated and unirradiated samples of lunar anorthosite, 67075. Argon is released more easily from the *unirradiated* samples, the release pattern being shifted by about 200°C to lower temperatures. This contrasts with the opposite effect observed in other lunar samples. These experiments indicate that anorthosite is less retentive than earlier assumed and reduces the depths previously calculated for which argon retention is inhibited by the ambient temperature. In the course of this experiment we were able to determine the  $^{37}\text{Ar}$  half live from a comparison of ( $^{38}/^{37}\text{Ar}$ ) ratios in samples analysed 155 days apart. The value obtained ( $35.3 \pm 0.2$ ) days is in agreement with the value currently in use ( $35.14 \pm 0.10$ ) days.

We are also performing experiments aimed at understanding the systematics of  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  release patterns. The results of these will be briefly reported at Houston.

Morgan, J. W., Ganapathy, R., Higuchi, H., Krähenbühl, U., and Anders, E.: 'Lunar Basins: Tentative Characterization of Projectiles, from Meteoritic Elements in Apollo 17 Boulders'.

*Ancient Meteoritic Components.* Like other highland breccias, Apollo 17 rocks seem to contain debris of basin-forming objects, as manifested by  $10^2$ - $10^3$ -fold enrichments in Ir, Re, Au, Ni, and Ge over indigenous levels. Several discrete components can be recognized on the basis of Ir/Au, Re/Ir, and Ge/Au ratios. Some tentative assignments can be made by comparing the relative frequency of these components at different landing sites with calculations of ejecta thicknesses. We shall use Ir/Au as the diagnostic ratio (corrected for the indigenous contribution and normalized to CI chondrites). In order to spread out the points and to reveal any correlations with rock type, we have plotted Ir/Au vs Rb.

The components of Ir/Au  $\approx$  1.0 and 0.8 probably represent Nectaris and Crisium. At Apollo 16, they are found in dark-matrix breccias from Stations 11 and 13 which underlie the cataclastic anorthosites identified as deep ejecta from Nectaris. We favor a Nectaris origin for the 1.0 component, because of its greater abundance at Apollo 16 and its presence at Luna 20. By analogy to the stratigraphy of Apollo 16, as revealed at N. Ray Crater, all but the bottom portion of the thick Crisium blanket at Luna 20 should consist of deep ejecta, uncontaminated by projectile debris. It will be overlain by a thin blanket of meteorite-bearing Nectaris material. The source crater of Luna 20 soil, Apollonius C, should have ejected mainly Nectaris material.

Thus we assign a Crisium origin to the component of Ir/Au  $\approx$  0.8, found in boulder 72255-72275. This is consistent with the high stratigraphic position of this boulder, and the rarity of this component at other sites.

The most prominent grouping at Apollo 17 (Ir/Au  $\approx$  0.5) is assigned to Serenitatis. This leaves one group unassigned, at Ir/Au  $\approx$  1.5. It may be related to Tranquillitatis, if this basin was excavated by one large rather than two small projectiles, or to the cryptic basin at  $10^\circ\text{N}$ ,  $16^\circ\text{W}$ .

*Boulders, Igneous Rocks.* From our limited sampling, it seems that the *blue-gray* breccias have the least variable composition, with respect to both meteoritic and non-meteoritic elements. Clast and matrix from Phinney's boulder 76315 look nearly identical. Both plot in the Serenitatis cluster, along two samples from S. Massif (73235 and 73275; the former has unusually high Br, Zn, and Cd contents, however).

The *green-gray* breccias, judging from Chao's boulder 77135-77075, are more heterogeneous. Matrix and black dike material are nearly identical, as is the poorly characterized 77135,10 (though it has a different, Imbrian meteoritic component). However, troctolitic clasts 1 and 2 are lower in alkalis and U and have distinctly different meteoritic components (Nectaris and unassigned; the latter is also represented by 78155). Our interpretation requires that the green-gray breccia comprises Serenitatis ejecta, which became remobilized at some later time and incorporated clasts from younger basins.

Wood's *gray* boulder 72255-72275 is also heterogeneous. The two matrices and clast 2 are almost identical, but the black rim of clast 1 is richer in Rb, Cs, U and shows a somewhat different meteoritic pattern. The rim may represent ejecta plastered on in flight. The black-and-white basaltic clasts are not perceptibly enriched in meteoritic elements and thus represent uncontaminated igneous rocks. The basalt is nearly two orders of magnitude richer in Ge than other lunar igneous rocks; this lessens the reliability of Ge as a meteoritic indicator element. Troctolite 76535 is exceedingly low in nearly all elements measured by us; this is consistent with a deep-seated origin.

*Volatile Enrichment.* In contrast to Apollo 16, only one anorthosite, 78155, shows the enrichment in Tl, Cd, and Sb which we attributed to fumarolic volcanism. The orange soil 74220 is enriched in Ag, Br, Zn, Cd, and Tl, compared to ordinary lunar rocks or soils, but is quite low in siderophile meteoritic elements. An indigenous source seems to be required for the volatiles. Judging from our data on soil separates, much of the enrichment seems to reside in the orange glass fraction. We see no significant enrichment of volatiles in the two shadowed soils 72321 and 76241.

Baldwin, R. B.: 'On the Origin of the Mare Basins'.

The mare basins were formed as a result of giant impacts of planetesimals. These impacts were so vast that the lunar rocks locally behaved essentially as fluids, giant tsunamis formed the multiple ring surrounding the main basins. The energies of the waves outward fluidized the previous surface and destroyed practically all pre-existing craters.

If the earliest observable crater is  $4.5 \times 10^9$  yr old, the half life of the crater forming bodies in the first third of the Moon's existence was  $2.5 \times 10^8$  yr. If, as isotopic ages seem to indicate, the oldest remaining craters are only  $4.2 \times 10^9$  yr old, the half life is  $1.84 \times 10^8$  yr. These bodies could not have been Earth satellites but can be interpreted as forming a new type of primitive asteroid in eccentric solar orbits.

The further backward we go in time, the greater were the relative and absolute numbers of the smaller crater forming asteroids in proportion to the larger bodies.

Adams, J. B., McCord, T. B., and Pieters, C.: 'Evidence for Regional Occurrence of Orange Glass and Related Soils'.

Pre-mission photogeology of the Taurus-Littrow region called attention to a very dark material that appears to blanket portions of the mare plains, including many craters. This material was thought to extend into the Apollo 17 landing site, and, in fact, samples returned from the dark valley floor are referred to as 'dark mantle'. Inspection of the typical Apollo 17 mare soils, however, shows a mature, agglutinate-rich regolith.

Spectral reflectance measurements were made using a telescope for a 10 km area (Littrow DMM) of well developed dark mantle 50 km northwest of the Apollo 17 site. Comparison of the telescopic spectral reflectance curve with laboratory curves of typical Apollo 17 mare soils reveals that the two units are not the same. The Apollo 17 soil (for example 75081) is instead very similar to the Apollo 11 soil.

The orange soil (74220) and the related black-sphere soil (74001) are minor but conspicuously unusual components of the mare regolith at Apollo 17. Reflectance measurements show that while the orange glass has no recorded telescopic equivalent, the spectrum for the black-sphere soil contains the principal elements of the telescopic curve for the dark mantle deposits. The spectral features of sample 74001, however, are approximately 10 times exaggerated over the telescopic curve. This suggests that 74001 is an essentially pure sample of dark mantle material, and that the surface deposits of dark mantle observed telescopically are mixed with agglutinate-rich regolith. This interpretation is supported by laboratory spectra of other samples of Apollo 17 soil (e.g. 79221) that contain up to 18% of dark

glass spheres and whose spectral character approaches that of the telescopic dark mantle material.

It is concluded that the photo-geologically defined dark mantle outside the Apollo 17 site contains dark-sphere soil (like 74001) as a major *component*, and that this material is only a minor constituent of the soil (2–18%) within the Apollo 17 site. We suggest that the term 'dark mantle' *not* be used for the dark agglutinate-rich regolith. Only the dark-sphere component of the Apollo 17 soils could be termed a dark mantle deposit.

Heiken, McKay and Brown have presented evidence that the dark spheres are the devitrified equivalents of the orange glass spheres and that these are of pyroclastic origin. If this is true, the extensive areas of dark mantle appear to be pyroclastic deposits as was suggested by McGetchin and Head. We have mapped these deposits on the basis of their spectral reflectance properties using a vidicon image device.

Thus, from the spectral reflectance evidence the Apollo 17 dark-sphere soil (and the orange glass equivalent) are samples of an important unit of regional extent, not only in the Taurus Littrow area, but possibly including the 'black spots' elsewhere on the Moon.

Head, J. W.: 'Lunar Dark Mantle Deposits: Possible Clues to the Distribution of Early Mare Deposits'.

A series of low albedo deposits of varying distribution and real extent have been mapped on the lunar surface. The deposits are characterized by their low albedo relative to other lunar geologic units, their post-Imbrium event but pre-latest mare age, their concentration in and near upland areas adjacent to maria, and their apparent smooth surface which gives the appearance of mantling underlying topography. From east to west, the major occurrences of dark mantle deposits include (1) the Taurus-Littrow region (SE edge of Serenitatis); (2) the Sulpicius Gallus region (SW edge of Serenitatis); (3) Mare Vaporum region (primarily to the SE of Vaporum); (4) Rima Bode region; (uplands south of Rima Bode); (5) Sinus Aestuum region (southeast of Sinus Aestuum); (6) Copernicus region (SE of Copernicus), sparsely cratered aspect cited as evidence of Copernican age but this study suggests that the area is simply one of several ray/secondary excluded regions surrounding Copernicus; (7) Alphonsus crater floor; several small dark mantle patches associated with linear rilles and asymmetric craters; upper bounds on age uncertain; (8) Mare Humorum, (near the crater Doppelmayer at SSW edge of Mare Humorum); relations to central mare not clear; (9) Aristarchus plateau; extensive development on plateau in north-central Procellarum around Schroter's Valley.

At the Apollo 17 landing site (Taurus-Littrow area) the majority of soils overlying the subfloor basalts are composed of comminuted basalt fragments, agglutinates, and 5 to 20% of orange and black spheres. Laboratory reflectance spectra obtained for components of these soils indicate that it is the black spheres which most closely resemble typical telescopic spectra for the Littrow dark mantle area, and that these are somewhat different than the subfloor basalt spectra. These observations are interpreted to mean that it is the admixture of dark spheres which is responsible for the characteristic dark mantle development and that without the dark spheres, the subfloor basalt would resemble the Apollo 11 landing region. The orange and black droplets have been interpreted to have formed in lava fountains of low viscosity lunar basaltic magmas and it has been shown that lunar pyroclastic deposits should appear as a smooth mantling material rather than typical terrestrial cones because of lunar gravity and lack of atmospheric drag. Age dates and chemical similarities suggest that the orange and black droplets were part of the same period of volcanism, about 3.63 b.y. to about 3.83 b.y. which produced the subfloor basalts. From consideration of the samples and geology of the Apollo 17 region it is concluded that the dark mantle component represents a pyroclastic phase of very early Ti-rich mare basalt flooding at the edge of the Serenitatis basin. The background subfloor basalt is very similar to Apollo 11 type basalts. Subsequently, subsidence occurred in the Serenitatis basin and a younger, less Ti-rich basalt was emplaced, embaying the dark mantle deposits. The general lack of subsidence of early mare deposits in Mare Tranquillitatis in part precluded their later burial. The subsidence of Serenitatis was followed by major flooding which buried the more extensive mare deposits which were probably similar to Apollo 11 and 17 basalts in composition. Thus the early volcanic dark mantling deposits in the uplands and valleys at the edge of the Serenitatis basin undoubtedly represent more widespread Ti-rich early volcanic deposits which have subsequently been covered. Old upland dark mantling deposits in other areas may therefore be indicators of the distribution and composition of more extensive early mare volcanism.

The distribution of dark mantling material in uplands surrounding mare basins has always been an intriguing characteristic of these deposits and has served to differentiate them from the mare lavas which tend to pond in low areas. Although dark mantle is seen in upland areas surrounding the valleys at Taurus-Littrow, photographic 6, 8, 9 and spectral information suggest that it is less extensive and apparently thinner. Consideration of lunar pyroclastic processes suggests that the thinner upland mantle may not always represent discrete sources in the uplands but may instead often be deposited from sources in the surrounding valleys. Terrestrial lava fountains ranging up to 500 m in height have been noted. Extrapolation to lunar conditions suggests that lava fountains of comparable size located in the valleys could easily spread a veneer of dark mantling material over the surrounding highland massifs. Therefore, it is possible that a small number of significant sources associated with the extrusion of mare lavas could as easily be responsible for the dark mantle as a large number of sources spread throughout the adjacent uplands.

Features associated with several dark mantling deposits suggest that they may represent major source regions for lunar lavas. The coincidence of Serenitatis and Imbrium radials and lunar grid directions in the Taurus-Littrow area, and its structural significance has been noted. Associated deep fractures may have localized early lava extrusion. Similarly, fractures and rilles in the Rima Bode area and major sinuous rilles in the Aristarchus Plateau suggest that many dark mantle deposits represent pyroclastic lava fountain deposition associated with major source areas of lunar lavas.

Lunar dark mantle deposits show variations in terms of their spectral reflectivity and radar backscatter characteristics. In particular, most of the eastern dark mantle deposits show spectral and radar characteristics similar to those at the Apollo 17 site. However, western dark mantle deposits are relatively redder.

The lunar dark mantle deposits discussed here are believed to represent pyroclastic fire fountain deposits localized around source regions (fractures, sinuous rilles) for early mare lavas. In the equatorial belt from Copernicus east to Taurus-Littrow the dark mantle deposits generally share the characteristics of early Ti-rich lavas of the Tranquillity type but are embayed by later 'redder' mare of the Serenitatis type. Based on the relationships described above these dark mantle deposits are believed to be indicators of the presence of more extensive Ti-rich early mare deposits underlying the surface of Mare Serenitatis, Mare Vaporum, and Sinus Aestuum. The western dark mantle deposits, in particular the Aristarchus Plateau, are interpreted to be pyroclastic source regions for the early 'redder' western mare deposition.

Lucchitta, B. K. and Schmitt, H. H.: 'Orange Material in the Sulpicius Gallus Formation at the Southwestern Edge of Mare Serenitatis'.

Orange material was observed and photographed in the dark mantle of the Sulpicius Gallus Formation on the southwestern rim of the Serenitatis basin. The association of orange and dark material is of special interest as the two materials were observed and sampled by the Apollo 17 crew on the rim of Shorty crater in the valley of Taurus-Littrow.

The Sulpicius Gallus Formation was defined by Carr, who considered it to be of Eratosthenian or Imbrian age. Its surface characteristics and albedo are very similar to those of the dark mantle in the Taurus-Littrow area: The Sulpicius Gallus Formation generally is smooth and appears relatively uncratered; it seems to drape over the underlying landscape, covering mountains, low hills, and older mare; it tends to presently exist as thick deposits in topographic lows and to leave hilltops exposed as bright areas; and it is embayed by younger mare. Dark material also appears to occur beneath younger mare near the edge of the Serenitatis basin, where a young crater ejects dark material, and larger young craters have a dark layer on their inside walls. The dark material seems to be relatively unconsolidated; it moves downslope readily, and craters within it are rapidly degraded to create a smooth surface of apparently young age. The Sulpicius Gallus area differs spectrally from other dark mantle areas in appearing reddish in earth-based color images, whereas many other very dark areas on the Moon appear bluish using instrumental determinations.

The Apollo 17 original photographic film and visual observations show that the orange material occurs only within dark material on older mare and highlands, it is absent on unmantled, younger mare. The orange material is found predominantly as halos, patches, or rays around fresh, bowl-shaped craters ranging from less than 50 m to about 250 m in diam. Craters of similar size, shape and freshness with white halos, mixed halos, or without halos are also common. White-halo craters tend to

occur near topographic highs, and orange-halo craters near lows, however, all orange-halo craters are located in patches of dark material. Locally orange material is found on the rims and the walls of more subdued, older craters that have been degraded to deep or shallow inverted cones. Orange and red material also occurs as prominent streaks parallel to white and brown streaks aligned downslope on the steep walls of a kidney-shaped depression and a graben with darkly mantled rims. Three layers were recognized in these rim mantles as sources of the streaks: in descending order, an orange-brown layer near the surface (probably regolith), an orange layer, and a red layer. The red material also is present as discrete subsurface masses resembling dikes where it has been exposed by younger impact craters.

The orange material locally underlain by red material probably occurs in the subsurface to a depth of about 50 m, either as continuous layers on an undulating surface, or as discrete pockets embedded in dark material. Excavation by impact formed the orange helos. It seems most likely that the orange and red materials are of volcanic origin, perhaps the product of fire fountains, and that they are equivalent in age or younger than the older mare lavas.

Even though the general characteristics of the Sulpicius Gallus dark mantle are similar to those of the dark mantle in the Taurus-Littrow area, and a similar origin is suggested, the high abundance of orange material visible from lunar orbit is distinctive to the Sulpicius Gallus Formation.

Mao, H. K., El Goresy, A., and Bell, P. M.: 'Orange Glasses: Reaction of Molten Liquids with Apollo 17 Soil Breccia (70019) and Gabbro (79155)'.

Orange glasses similar to the Apollo 17 orange soil (74220) have been discovered as a quenched, frothy coating on the surfaces of soil breccia (70019) and gabbro (79155). The crystal field spectra of these coatings are nearly identical with those measured on the orange soil suggesting that the color is caused by the interaction of the absorption of Fe(II), Ti(III), and Ti(IV). The orange glass coatings exhibit flow banding and are fraught with bubbles and vesicles giving evidence of a gas phase. Compositional variation within the bands has apparently been caused by reaction with the soil and rock to which it adheres. Fine-grain soil covers the outer surface of the glass and obscures its color.

Chemical reaction of the molten liquids with the soil and gabbro can be seen in the remarkable quench texture. Three previously unreported reactions have occurred: 1. Reaction between silicate liquid and armalcolite to form ilmenite and ilmenite separately; 2. Reaction between silicate liquid and rutile to form zones of armalcolite and ilmenite; 3. Armalcolite appears to have formed by a breakdown of ilmenite accompanied by the production of metallic iron and the release of oxygen. There is a suggestion that implanted solar wind gases played a role in the volatile phase.

This study of orange glasses suggests that a special or unique process for the formation of glass spheres in the Apollo 17 soils is not required. Preliminary data imply that the liquids from which the orange glasses formed were abundant at the Apollo 17 site. There is textural evidence of shock-impact in 70019 and 79155 but this is not necessarily related to the origin of the liquids.

The study of the orange glass coating may provide data with far-reaching implications on the chemical history of the lunar regolith: A. Evidence of the process of formation of a liquid unrepresentative of any known lunar rock type; B. Quenched reactions of molten liquid with components of the regolith; C. Origin in the development of the lunar regolith.

Cadenhead, D. A. and Buerger, W. G.: 'Gas Interaction Studies with Lunar Orange Soil 74220, 29'.

Ever since its discovery during the Apollo 17 mission, the orange soil has been the subject of considerable interest because of its unusual nature. The present consensus of opinion would seem to favor a volcanic origin and we would like to present here, outgassing and gas interaction studies which support this view. The sample was placed in an ultra high vacuum system previously described, outgassed and then exposed to both molecular and atomic hydrogen. After each exposure, the sample was again outgassed and the nature and relative quantities of the various gases released were recorded.

*Pretreatment.* Since the initial outgassing of any lunar sample may provide valuable information on its origin, special precautions were made to insure minimum contamination. Our assumption was that an initial low temperature outgassing would remove all physisorbed (but not chemisorbed) contami-



nants. Prior to insertion of the sample in the U.H.V. system, the entire system was baked out at 350°C overnight to attain a background pressure of  $5 \times 10^{-10}$  torr. The sample was inserted in the system by opening up only the immediate vicinity of the sample chamber. Since it proved impossible to maintain a continuous nitrogen atmosphere during transfer, the sample was briefly exposed to air. System and sample were then outgassed at 150°C for eight hours and at 25°C for approximately six months. The final background pressure, while still at room temperature, was  $2 \times 10^{-10}$  torr. The temperature was then raised to 400°C at approximately  $2^\circ\text{C min}^{-1}$  with outgassing spectra being recorded every five minutes. Gas release, as expected, was not substantial until approximately 150°C was reached.

*1st Outgassing.* The primary peak observed on this first outgassing was that of water vapor (250–275°), the amount observed being approximately double that obtained for equal amounts of samples 14163,111 and 15565,3G. Moreover, the impression gained from the pressure measuring gauge, the residual gas analyser when under rapid scan and the ion pump controller current was that the gas was being released in a rapid sequence of small bursts rather than in a continuous stream; an observation not previously made. In addition, substantial amounts of  $\text{N}_2/\text{CO}$ ,  $\text{CO}_2$  and  $\text{SO}_2$  with traces of  $\text{H}_2$  and (somewhat surprisingly) HCl. These data should be compared with those of Gibson and Moore on a similar sample. At the conclusion of this experiment, the temperature was raised to 450° for 2 h to reduce gas emission below 400°C to a hopefully insignificant level. The final pressure attained, however, was only  $10^{-8}$  torr.

*2nd Outgassing.* The sample was now exposed to  $2.5 \times 10^{-2}$  torr of molecular hydrogen at 150°C for 36 h. Previous experience has shown us that, under these conditions, hydrogen dissociatively chemisorbs on lunar samples. At the end of this time, the sample was allowed to cool while being continuously Vac-Ion pumped. Substantial amounts of water vapor were seen at low temperatures but amounts appeared to fall off rapidly with increasing temperature. There was no doubt that this water was immediately formed on exposure of the sample to hydrogen since the enhancement of the water peak was apparent each time hydrogen was admitted to the system. Other peaks observed were  $\text{N}_2/\text{CO}$  and again some HCl. The precise quantitative data for this particular experiment are somewhat in doubt, however, because of the not insignificant background pressure of  $10^{-8}$  torr. At the conclusion of this experiment the entire U.H.V. system was baked out at 200°C for three hours using a triple-stage liquid-nitrogen trapped mercury diffusion pump. The working system was then isolated and Vac-Ion pumped until a background pressure of  $5 \times 10^{-10}$  torr was attained.

*3rd Outgassing.* The sample was once again exposed to  $5 \times 10^{-2}$  torr of molecular hydrogen, this time at room temperature. A thoroughly outgassed tungsten filament was switched on for one hour at 1250°C in order to produce high concentrations of hydrogen atoms. The system was then outgassed from 25 to 400°C. Substantial amounts of water vapor were again observed at low temperatures (25–75°C), the amount of water released with increasing temperature decreased until the temperature approached 400°C. In addition, substantial amounts of methanol were observed at low temperatures ( $\sim 75^\circ\text{C}$ ). At the conclusion of this experiment, the sample was again outgassed for 2 h at 450°C. A satisfactory background pressure of  $5 \times 10^{-10}$  torr was then obtained at room temperature.

*4th Outgassing.* The conditions prior to the second outgassing were essentially repeated [ $5 \times 10^{-2}$  torr  $\text{H}_2$  at 150°C for 36 h]. Again, a low temperature water peak was observed ( $\sim 150^\circ\text{C}$ ) with a rapid fall in amount until the temperature exceeded 400°C. Methanol was not detected during this experiment.

*Conclusions.* The large amount of water vapor seen at higher temperatures (200–400°C) during the first, but not subsequent, outgassing experiments suggests that it, at least in part, arises from origins other than the solar wind. The presence of  $\text{CO}_2$  and  $\text{SO}_2$ , as has been pointed out by Gibson and Moore are indicative of a volcanic origin for 74220. Our water vapor observations, including the curious release pattern, would seem to support this conclusion and the small amounts of HCl provide further evidence. (Part of the water vapor and possibly all of the HCl during the second outgassing would appear to have been due to improper cleaning of the system after the 1st outgassing.)

The failure to produce large amounts of water in the 200–400°C range is ascribed to the absence of an extensive amorphous layer in the orange soil. The more rapidly released water vapor at lower temperatures (2nd, 3rd, 4th outgassing) is assumed to originate primarily from hydrogen interaction with the external (accessible) surface.

The methanol observation during the 3rd outgassing experiment undoubtedly arose through the tungsten filament having trace carbon impurities. This carbon and atomic hydrogen must have interacted with the oxygen in the soil to produce methanol. Since carbon is present in the solar wind, particularly during solar flare periods, the observation is not without some significance.

Brown, G. M., Peckett, A., Emeleus, C. H., and Phillips, R.: 'Mineral-Chemical Properties of Apollo-17 Mare Basalts and Terra Fragments'.

Nine polished thin-sections have been studied petrographically and the mineral assemblages characterised by electron microprobe analysis. The mare basalts are from the LM-ALSEP stie (70017,109; 70035,16; 70215,142), Station 1A (71055,66), Station 4 (74275,83) and Station 5 (75035,72). Terra samples from Station 6 (76535,50) and 7 (77017,69) of the North Massif, and Station 3 (73235,59) near Lara crater.

The three terra samples are characterised by very calcic plagioclase (An95) in contrast to the mare basalts (An87-79). One is a plutonic fragment (allivalite), one a troctolite-rich breccia enclosed by titaniferous basalt, and the third a complex breccia with rhyolite fragments and allivalite-type fragments. The six basalts are broadly comparable with the Apollo 11 basalts in their titaniferous character and in the remarkable uniformity of the Al:Ti ratio of 2:1 in all but the latest-stage pyroxenes. However, the group can be sub-divided into two different types (olivine basalts and ferrobasalts) with possibly a third transitional type, based chiefly on olivine, pyroxene and oxide amounts and compositions.

*Terra allivalite (76535)*. Plagioclase (56%), olivine (38%) and two pyroxenes (5%) make up this ultrabasic, coarse grained (av. 8 mm) rock, with only traces of Ni iron and chrome-spinel. The plagioclase is An95 and contains abundant planar 'decorations' of a metal phase. The olivine is Fo87 and its Cr<sub>2</sub>O<sub>3</sub> is very low (0.04-0.12%). The iron contains 22% Ni and 4% Co. Pyroxenes and chrome-spinel occur as a reaction symplectite along olivine-plagioclase boundaries, where bars of olivine (5-10 $\mu$ ) alternate with bars of Opx + Cpx (5-10 $\mu$ ) or chrome-spinel (1 $\mu$ ). The Opx is magnesian bronzite (Wo2 En87 Fs11) and the Cpx is diopsidic augite (Wo46 En50 Fs4). Both have relatively low Al, Ti and Cr but show an equilibrium-type distribution between the two phases. The spinel is extremely rich in Cr and Al but variable from grain to grain (e.g. Al<sub>2</sub>O<sub>3</sub> from 14.7 to 19.2 wt %). TiO<sub>2</sub> is remarkably low (< 1%). The rock is typical of the ANT suite in being rich in Mg and poor in Cr. In its low Ti content it represents the opposite extreme from the Apollo 17-type mare basalts. Olivine banding and symplectite intergrowth suggest some deformation and recrystallisation.

*Troctolitic breccia (77017)*. An oval fragment (1  $\times$  1 $\frac{1}{2}$  cm section) of feldspathic breccia contains patches of troctolite, and the whole is rimmed by a skin of titaniferous basalt. The troctolite contains calcic plagioclase (An95) but the olivine is not very magnesian (Fo61). The breccia matrix contains the same olivine and plagioclase compositions, and fragments of pigeonite (Fs30). The material is not therefore comparable with the allivalite. The fragment must have been transported in a young mare flow. The olivine basalt rind contains augite rich in Al and Ti, very similar to the local Type I (see below). Thin veins of yellow glass pervade the breccia and are also of titaniferous olivine basalt, suggesting rapid chilling of the lava against the xenolith.

*Polygenetic microbreccia (73235)*. Contains fragments of calcic plagioclase (An94) and zoned magnesian olivine (Fo87-81) with low Cr<sub>2</sub>O<sub>3</sub>, indicating a source related to the allivalite. Also bronzite (no Cpx), patches of potassic rhyolite (SiO<sub>2</sub> 74%, K<sub>2</sub>O 10.2%, Na<sub>2</sub>O 0.4%), and purple chromian pleonaste. Grains of chrome-alumina spinel show the unusual composition of those in the allivalite, supporting a related source.

*Mare basalts I*. Two basalts (70215 and 74275) resemble the rind to the breccia (77017) in being strongly titaniferous. They are olivine basalts, with distinct and often skeletal phenocrysts of a fairly magnesian olivine (zoned, Fo80-69). Modally they are richer in opaque oxides than the other basalts (31-37%) and poorer in plagioclase (6-19%), while they lack free silica and contain the most olivine (9-14%). The texture is very fine-grained, being dominated by acicular laths of ilmenite. Sample 70215 is strongly quenched and heterogeneous, with dark patches of variolitic, feldspar-poor areas. The plagioclase is An83-85, Armalcolite and intermediate chromian ulvöspinel are common to all the Apollo 17 basalts examined, and exsolved rutile in the low-magnesium ilmenites. The pyroxenes are unique to the Type I basalts. They are all purplish calcic augites (ca. Wo45 En38 Fs17) with high contents of TiO<sub>2</sub> (to 6.8%), Al<sub>2</sub>O<sub>3</sub> (to 8.3%) and Cr<sub>2</sub>O<sub>3</sub> (to 0.8%). Even so, they retain the Al:Ti ratio of 2:1 characteristic of Apollo 17 and Apollo 11 pyroxenes.

*Mare basalts II*. A tendency (shown by Type III) is characterised particularly by sample 75035, which is a 'ferrobasalt' and an extreme case. It contains no olivine, the most cristobalite (6%) and the most plagioclase (33%) of the basalts. Also abundant tranquillityite, ilmenite with low Mg/Mg + Fe (0.5 to 5.3), and ulvöspinel with little Cr. The pyroxenes show the continuous-series feature shared with Apollo 11, from subcalcic augite (ca. Wo30 En45 Fs25) to pyroxferroite (Wo16 En3 Fs81).

They contain only moderate Al, Ti and Cr, with Al:Ti from 2:1 to 1:1 in the pyroxferroites (suggestive of trivalent titanium).

*Mare basalts III.* This third type shows affinities with both I and II, and may be an intermediate stage either in a crystal fractionation or a partial melting sequence. Samples are 70017, 70035 and 71055. They contain much less olivine (1%), less opaques (23%), more plagioclase (25%), and some cristobalite (1.5%), compared with Type I, and differ from Type II in the same constituents conversely. The olivines are less magnesian (Fo71-58) than in Type I, whereas in Type II, olivine is absent. The irons are virtually Ni-free (Type I irons contain 1% Ni). Tranquillityite, baddeleyite, Zr-armalcolite, armalcolite, ilmenite, troilite and rutile are present, in common with Type II in particular. Sample 70035 shows most affinity with Type II, having ulvöspinel rims to chromian ulvöspinel cores, and pyroxferroite-type rims to the pyroxenes. The probable 'link' feature of Type III is shown especially by the pyroxenes. The cores are of calcic augite (4.3% Al<sub>2</sub>O<sub>3</sub>, 3.5% TiO<sub>2</sub>) and they zone in a complex manner to either subcalcic ferroaugite or to pigeonite. Pigeonites are unique to Type III. A preliminary look at 71055 (work in progress) indicates crystallization of extreme Type I pyroxene cores (6% Al<sub>2</sub>O<sub>3</sub>, 5% TiO<sub>2</sub>) before plagioclase and ilmenite began to crystallize.

*Basalt relations.* There appears to be a sequence, Types I → III → II, related to decreasing melt temperatures. Early phases in the sequence are Al-Ti-rich augite, magnesian olivine and armalcolite. Pigeonite, ilmenite and plagioclase follow and are succeeded by ferropyxene, ulvöspinel and cristobalite. The allivalites from the terrae are, in sharp contrast, greatly depleted in Ti and Cr, and greatly enriched in Mg (olivine and pyroxene), Ca (plagioclase) and Ni (iron).

El-Goresy, A., Ramdohr, P., Medenbach, O., and Bernhardt, H.-J.: 'Taurus-Littrow Crystalline Rocks: Opaque Mineralogy and Geochemistry'.

Opaque minerals in samples 74220, 74242, 74243, 70215, 72015 and 79155 were studied in reflected light and with the electron microprobe. The samples studied include a variety of rocks: microgabbros, pyroxene rich basalts, and vitrophyres. The opaque minerals encountered in the studied samples are: armalcolite, ulvöspinel, ilmenite, rutile, Al-Ti-chromite, cobaltian metallic Fe, and minor baddeleyite, tranquillityite and zirconolite. The frequency of the Fe-Ti oxides among each other depends on the grain size which is again a function of the cooling history. *Chromian ulvöspinel* occurs in the various rock types mainly as discrete idiomorphic grains either as inclusions in the pyroxene or in the plagioclase rich silicate groundmass. No chromite cores were observed. In addition to the isolated ulvöspinel grains two unique assemblages were encountered (1) *ulvöspinel as inclusion in armalcolite* without any reaction. (2) *Ulvöspinel + rutile* also without any reaction between them. No evidence for subsolidus reduction of ulvöspinel to ilmenite + chromite + Fe (1) was found. Our probe analyses indicate that the TiO<sub>2</sub>/TiO<sub>2</sub> + Cr<sub>2</sub>O<sub>3</sub> + Al<sub>2</sub>O<sub>3</sub> ratio varies only between 0.3 and 0.5. In the fine grained basalts there is textural and chemical evidence for (a) *exsolution of ilmenite* and (b) *reaction between the basaltic melt and the crystallized ulvöspinel*. Both processes seem to go hand in hand giving rise to *ilmenite + Al-Ti-chromite*. This newly formed Al-Ti chromite deposited around the ilmenite exsolution lamellae and at the boundary between the ilmenite reaction rim and the host spinel. Optical properties and chemistry differ considerably from chromite formed by subsolidus reduction of ulvöspinel. Compared to the parent spinel this chromite is considerably enriched in Al<sub>2</sub>O<sub>3</sub> (20.5%) and has a higher MgO content (5.82 vs 4.2%). During subsolidus reduction the 'exsolving' ilmenite becomes enriched in MgO, whereas during the reaction between ulvöspinel and silicate melt the *host spinel will be enriched in both trivalent cations and Mg<sup>+2</sup>*. This partitioning is significant and may be used as an additional criterion for recognition between secondary chromites formed by the two different processes. Sample 74242 contains a *unique fragment consisting of 60% cobaltian Fe, 30% chromite and 10% anorthitic maskelynite + barian K-feldspar (3.7% BaO) + orthopyroxene*. Individual grains of ilmenite occur at the boundary between chromite and metal. This lithic fragment may represent a new rare type *perhaps a lunar pegmatite* and demonstrates that *metal rich lenses or dykes are expected to be present in layered mare basins*.

In coarse grained microgabbros ilmenite is the dominant opaque and armalcolite is only an accessory phase occurring mainly enclosed in the pyroxene. The amount of armalcolite increases in the fine grained pyroxene rich basalts and vitrophyres. Two optically distinct armalcolite types were encountered: a tan variety occurring mainly as idiomorphic inclusions in pyroxenes, and a grey variety usually mantled by ilmenite and enriched in vitrophyres. Quantitative electron microprobe analyses

indicate that the two types differ in their minor element chemistry: the *grey type being enriched in Cr<sub>2</sub>O<sub>3</sub> and MgO* compared to tan armalcolite. We find textural evidence for ilmenite rim to be formed due to one of the following processes: (a) Reaction between basaltic liquid and armalcolite (b) Reaction between armalcolite and metallic Fe (c) simple overgrowth of ilmenite on preexisting armalcolite and (d) partial breakdown of armalcolite to rutile + ilmenite. Reaction a is predominant in the vitrophyres. *Armalcolite with ilmenite reaction rim which in turn is surrounded by a new armalcolite reaction rim* was also observed indicating that fluctuations in  $f_{O_2}$  and/or temperature took place during the crystallization of the Fe-Ti oxides. Reaction b is mainly observed in the medium grained basalts and is characterized by the *assemblage armalcolite + ilmenite + Fe*. Our numerous probe analyses indicate that the *majority of armalcolites are cation deficient (total cations range from 2.91 to 2.97)*. Furthermore, while the 8 f site is stuffed with Ti<sup>4+</sup>, the divalent cation (Mg<sup>2+</sup>, Fe<sup>2+</sup>) do not exceed 0.85. Probably the trivalent cations are also located in the 4c site. *Two distinct cationic substitutions* were discovered in the grey armalcolite a Mg<sup>2+</sup> + Cr<sup>3+</sup> + Fe<sup>2+</sup> for Ti<sup>4+</sup> connected with reaction between basaltic liquid and armalcolite b Mg<sup>2+</sup> + Cr<sup>3+</sup> + Ti<sup>4+</sup> for Fe<sup>2+</sup> connected with the reaction armalcolite + Fe Ti-rich cation deficient armalcolite + ilmenite. In sample 75055 a breakdown of tranquillityite to ZrO<sub>2</sub> + ilmenite + pyroxene was observed. In the same sample zirconolite with more than 20% Y<sub>2</sub>O<sub>3</sub> was encountered. Baddeleyite in the studied samples contains the highest HfO<sub>2</sub> content ever found in a lunar mineral (2 wt %).

## 6. Nature of Impact Processes and Their Effects on Lunar Materials : I

Moore, C. B., Lewis, C. F., Cripe, J. D., and Volk, M.: 'Total Carbon and Sulfur Contents of Apollo 17 Lunar Samples'.

Total carbon and sulfur abundances have been run in a suite of Apollo 17 fines, breccias and rock samples. The analytical techniques utilized were the same as those used for Apollo 11 through Apollo 16 samples. The results given are from samples provided during the regular sample allocation. Carbon analyses done during the Apollo 17 lunar sample preliminary examination are also presented.

The analytical results for total carbon and sulfur follow the same pattern as those of the earlier Apollo missions. Fines and dark soil-breccia samples generally have higher total carbon contents than do the fragmental rock-breccias and igneous rocks. It is of importance to note that the total carbon contents of the Apollo 17 basalts are similar to those found for the Apollo 11 basalts. For the Apollo missions 11 through 16 the trend for total carbon in rocks was constantly downward from 60 to 70  $\mu\text{g g}^{-1}$  in the Apollo 11 basalts to lows of less than 5  $\mu\text{g g}^{-1}$  in the Apollo 16 anorthosites. The return to higher values for the Apollo 17 rocks indicates that the trend was a real one and not due to improved contamination control in the sample handling procedure. Likewise the total sulfur contents in the Apollo 17 basalts and associated fines returned to the higher values, in the greater than 1000  $\mu\text{g g}^{-1}$  range, found in the related Apollo 11 samples. Total carbon values obtained for different splits of the same sample run during both the preliminary examination and later show the same range in values found in replicates run for earlier missions. The decrease in total carbon content in the gabbroic breccia 78155 from 85  $\mu\text{g g}^{-1}$  to 21  $\mu\text{g g}^{-1}$  may be attributed to the fact that the preliminary examination sample was from a rock surface and may have contained high carbon fines particles. The second analysis of the orange soil 74220 gave a much lower value of 5  $\mu\text{g g}^{-1}$  than the preliminary value of 100  $\mu\text{g g}^{-1}$ . The lower value is preferred.

Most of the fines samples are gray to black in color and are similar in total carbon content to the normal mature fines of earlier Apollo missions. There is a correlation of total carbon content and the sample collection station. Individual samples from each station show lower ranges in total carbon content than samples between stations. Such variations may be attributed to grain size differences and percent agglutinates at the different areas in the Taurus Littrow landing site. Inspection of both of these parameters for the preliminary examination data shows direct correlations between them and the total carbon content. Fines samples from Steno Crater have consistently lower total carbon contents than the mature fines indicating that they are in part composed of rock fragments from the cratering event that have not had surface exposure to solar wind. These samples together with those from Shorty Crater exhibit the largest mean grain sizes and the lowest agglutinate contents of the fines samples studies. The orange soil 74220 from Shorty Crater has the largest mean grain size and essentially

no agglutinate content. The fines samples collected at station 8 from different depths in a trench shows no significant differences in either total carbon or sulfur content.

Total sulfur contents of lunar fines are also well correlated with the sample collection stations. Those from the valley center have higher total sulfur contents than those along the massifs reflecting the higher mare basalt percentage in their make-up. Basalt sample 75035 with  $3140 \mu\text{g g}^{-1}$  total sulfur has the highest total sulfur content we have measured in a lunar sample.

There is no indication from the data found in the analysis of the Apollo 17 samples that our previous conclusions that most of the carbon in the fines is of solar wind origin and most of the sulfur is of lunar origin should be modified.

Hamilton, P. B., McEwan, W. S., Nagy, B., Nagy, L. A., Sill, G. T., and Urey, H. C.: 'Carbon Compounds in Apollo 17 Lunar Samples: Indication of Cometary Contribution to Breccia 78155?.'

Vacuum pyrolysis-mass spectrometric analyses were carried out on seven samples collected by the Apollo 17 astronauts. The samples analyzed were one breccia (78155), one basaltic rock (71055), the 'orange soil' (74220) and other fines (78501, 74240, 71501, 78221). The analyses were concerned mainly with the abundances of the carbonaceous gases: methane, carbon monoxide, and carbon dioxide.

The fines are noteworthy not only because of their variable  $\text{CH}_4$ , CO and  $\text{CO}_2$  contents, but also because of the variable abundances of other volatiles: water, hydrogen sulfide, sulfur dioxide and hydrocarbons, particularly the ethylene and propane ions. Some of these compounds, such as water, may be reaction products which developed during pyrolysis. The 'orange soil' contained both the lowest carbon content and volatiles. Microscopic examination in transmitted light revealed that the glass beads varied in size between  $10 \mu\text{m}$  and  $102 \mu\text{m}$  and that they were abundant in this sample. The glass beads did not contain inclusions which were commonly seen in other fines. The color of the glass beads varied between orange and yellow color or opaque in the 'orange soil'. The rest of the material appeared to be glass fragments of irregular shapes and of varying sizes. After pyrolysis at  $1000^\circ\text{C}$  the beads and glass fragments appeared opaque; again there were no detectable inclusions. Several small fragments seem to have aggregated and stuck together forming clusters during heating. The 71501 fines sample was particularly rich in sulfur compounds (10 ppm) and low molecular weight hydrocarbons (14 ppm).

Breccia 78155 was the most volatile rich of all samples analyzed. The  $\text{CH}_4$ , CO, and  $\text{CO}_2$  content represented a total of 267 ppm carbon. Hydrocarbons (exclusive of methane) were present in approximately 60 ppm quantity; the most intense ion was  $m/e = 43$ . This sample contained hydrogen cyanide ( $\sim 5$  ppm), hydrogen sulfide ( $\sim 6$  ppm), as well as elemental sulfur. Water was the most abundant of all the volatiles, but again, this may have been a reaction product. Sulfur dioxide was absent; this along with the fact that carbon monoxide was three and one-half times as abundant as carbon dioxide indicates that the reduced species of carbon and sulfur were more abundant than the oxidized species. HCN,  $\text{C}_2$ ,  $\text{C}_3$  and  $\text{C}_4$  hydrocarbons are all reminiscent of the non-metallic species detected in cometary spectra, i.e. CN,  $\text{C}_2$  Swan bands and  $\text{C}_3$  bands. The contrast between breccia 78155 and basalt 71055 regarding their carbon contents and volatiles was striking. The only carbon compound found in the basalt was carbon dioxide, i.e. the oxidized species; whereas the breccia was rich in the more reduced carbon monoxide, methane and the higher molecular weight hydrocarbons together with elemental sulfur and hydrogen sulfide. One may note that cometary spectra typically reveals reduced species of carbon, nitrogen and oxygen. It is not unlikely that this breccia or its components could have been involved in some cometary impact on the lunar surface.

Wszolek, P. C., O'Connor, J. T., Walls, F. C., and Burlingame, A. L.: 'Thermal Release Profiles and the Distribution of Carbon and Nitrogen among Minerals and Aggregate Particles Separated from Lunar Soil'.

Soil sample 10086D was separated into fractions according to size, density, and magnetic susceptibility. The size fractions  $105\text{--}420 \mu$ ,  $37\text{--}105 \mu$ , and  $< 37 \mu$  were obtained by wet sieving with methanol. Size fraction concentrated in very fine particles  $< 5 \mu$  and  $5\text{--}10 \mu$  were obtained by application of Stoke's Law for settling rates in methanol of particles from a portion of the  $< 37 \mu$  fraction. The  $37\text{--}105 \mu$  fraction was further separated with diiodomethane and mixtures of diiodomethane and

acetone whose densities were adjusted with appropriate sink-float standards. Subsequent magnetic susceptibility separations were carried out with a Frantz isodynamic separator. All parts of this separator which came into contact with the samples were coated with Teflon. The distribution of particle types in each of the fractions was determined with a petrographic microscope; detailed descriptions of the fractions and the weight distribution of the total recovered material are presented. A small portion of the  $< 37 \mu$  fraction of 10086D was etched slightly with a dilute solution of HF (1 vol. 40% HF to 250 vol. water).

Separated fractions have been pyrolyzed under vacuum at a linear temperature program rate of  $25^\circ\text{C min}^{-1}$  from ambient to  $1400^\circ\text{C}$ . All gaseous species evolved were continuously monitored using a high sensitivity, high resolution MS-902 mass spectrometer coupled to a computer. Total carbon (released as CO and  $\text{CO}_2$ ) and total nitrogen (released as  $\text{N}_2$ ) were determined by integrating the temperature release profiles for these gaseous species. The amount of CO evolved by the samples is a better measure of their carbon contents since most of the  $\text{CO}_2$  is terrestrial contamination and is released below  $600^\circ\text{C}$  during pyrolysis.

The data show that carbon and nitrogen are concentrated in the  $< 5 \mu$ ,  $5\text{--}10 \mu$ , and  $< 37 \mu$  size fractions of 10086D and in the separates from the  $37\text{--}105 \mu$  fraction which contain high proportions of glassy aggregates. Those fractions consisting chiefly of the minerals plagioclase and pyroxene, on the other hand, have the lowest concentrations of carbon and nitrogen. These results agree in general with total carbon values for glassy agglutinates and feldspar isolated from several Apollo 15 soils and with the data for concentrations of carbide and methane in agglutinate and mineral fractions separated from 10086D fines. Fractions 6 and 12 contain very high concentrations of carbon although the aggregates in these fractions amount to only about 20% and 30%, respectively. It may be significant that these aggregate grains contain opaque minerals, probably mostly gas retentive ilmenite, and might therefore suffer less loss of carbon containing gases at the higher temperatures ( $\geq 600^\circ\text{--}800^\circ\text{C}$ ) associated with agglutinate and breccia formation.

Distinctive temperature release profiles for CO,  $\text{CO}_2$ , and  $\text{N}_2$  were obtained for the various separated fractions. Most of the carbon and nitrogen was released as CO and  $\text{N}_2$  below  $900^\circ\text{C}$  from the following samples:  $< 5 \mu$ ,  $5\text{--}10 \mu$ ,  $< 37 \mu$ ,  $< 37 \mu$  slightly etched, and fraction #7 (plagioclase). Each of these samples exhibited a bimodal evolution of CO and  $\text{N}_2$  at  $600^\circ\text{--}850^\circ\text{C}$  and  $950^\circ\text{--}1200^\circ\text{C}$ , with the lower temperature regions predominating by factors of about three or more. High temperature ( $950^\circ\text{--}1200^\circ\text{C}$ ) evolution of  $\text{CO}_2$  was observed only for the  $< 37 \mu$  fraction and the  $< 37 \mu$  slightly etched sample. In striking contrast, the coarser size aggregate-rich fractions  $37\text{--}105 \mu$  and  $105\text{--}420 \mu$  and fractions #1 and #4, i.e. glassy aggregates which together make up about half of the  $37\text{--}105 \mu$  sample, evolved most of their CO and  $\text{N}_2$  above  $950^\circ\text{C}$  up to  $1200^\circ\text{C}$ . All of these samples also released  $\text{CO}_2$  at  $1000^\circ\text{--}1200^\circ\text{C}$ . These data suggest that surface related, recently implanted solar wind carbon and nitrogen are mostly associated with the lower temperature region of the characteristic bimodal evolution pattern of bulk lunar soils whereas the volume related carbon and nitrogen components are mostly associated with the higher temperature region. This interpretation of the data is supported by the evolution of  $^{13}\text{C}$  predominantly in the region  $750^\circ\text{--}900^\circ\text{C}$  from plagioclase artificially irradiated with  $^{13}\text{C}$ .

All of these temperature release profiles taken together suggest that substantial alteration of carbon and nitrogen occurs during aggregate formation in lunar soils. The preliminary data for the  $< 37 \mu$  etched sample indicate that its gas release profile is not substantially changed despite the loss of over half of the carbon and nitrogen. This result suggests that physico-chemical removal of the C and N alone, by diffusion losses during heating of grains to  $\geq 800^\circ\text{C}$  for example, would not enhance the relative amounts of carbon and nitrogen phase(s) represented in the  $950^\circ\text{--}1200^\circ\text{C}$  evolution. The profiles for the aggregate particles may reflect the proposed synthesis of additional amounts of carbide during agglutinate formation. Indeed our profiles for CO and  $\text{CO}_2$  from the aggregate particles resemble those generated by a synthetic mixture of cohenite and silicate minerals in which CO is released predominantly over  $900^\circ\text{C}$ .

Allen, R. O., Jr., Jovanovic, S., Reed, G. W., Jr., and Showalter, D.: <sup>204</sup>Pb, Bi, Tl and Zn in Apollo 16 Samples and Inferences on the Lunar Geochemistry of <sup>204</sup>Pb based on Meteoritic and Terrestrial Sample Studies'.

The concentrations of primordial Pb and <sup>204</sup>Pb and of Bi, Tl and Zn have been measured in Apollo 16

samples and in Apollo 17 orange soil by neutron activation techniques. In addition, in order to gain some insights into the possible geochemistry of the heavy metals in lunar samples, selected meteoritic and terrestrial samples were studied. These included basaltic achondrites, metallic spherules from Meteorite Crater, Arizona; Disko Island basalt and metal from this basalt.

Apollo 16 samples from Stone Mountain (64501, 64801), from the North Ray crater ejecta blanket (63501) and from station 1 on the rim of Plum crater (61221) were measured. Breccias 61016 and 66095 which have unusually high halogen contents were studied – since labile  $^{204}\text{Pb}$  and Bi fractions correlated with halogens were observed in Apollo 14 and 15 samples. Another high halogen containing sample, Apollo 17 orange soil 74220, was also measured. As in previous studies the samples were leached for  $\sim 10$  min in a hot aqueous solution of  $\text{HNO}_3$  at pH 5–6.

The  $^{204}\text{Pb}$  contents of a few ppb in the Apollo 16 soils are similar to those in other lunar soil samples. Bi concentrations in soils are 1–2 ppb and Tl are few ppb. The orange soil is distinct in having an order of magnitude more  $^{204}\text{Pb}$  and Bi and 3–4 times more Tl than any other soil measured. The fractions of leachable  $^{204}\text{Pb}$  and Bi are similar to those of other soils. The breccia 66095 has a high  $^{204}\text{Pb}$  and Bi content; however, it has an order of magnitude more Tl than the orange soil. Breccia 61016 has a  $^{204}\text{Pb}$  content of  $\sim 5$  ppb like most soil samples but it is enriched in Bi and Tl.

The correlations of  $^{204}\text{Pb}_m$  with metal,  $^{204}\text{Pb}_l$  and  $\text{Bi}_l$  with  $\text{Br}_l$  and  $\text{Bi}_r$  with  $\text{P}_2\text{O}_5$  reported for samples from Apollo 14 and 15 do not appear to apply for most of the Apollo 16 samples measured. These samples may represent the early crust altered by events that mixed materials from various sources (depths?). The components of this mixture, never homogenized on a regional basis, may have been subjected to local alteration due to impact melting, shock brecciation and metamorphism. In comparison samples from the Apollo 14 and 15 sites appear to have undergone a less complicated evolution since they have preserved a more or less common record.

The lunar chemistry of  $^{204}\text{Pb}$  in Apollo 14 and 15 samples involved extraction of some of this Pb into a metal related phase and the association of the remainder with halogens. A possible parallel in the geochemistry of lunar samples with the non-lunar systems listed above was explored. No leach data were acquired since leaching was done primarily to remove terrestrial contamination. The achondrites may be magmatic differentiates from which a metal phase has been separated. For comparison with lunar samples the heavy metals in two basaltic achondrites were measured. The results suggest that  $^{204}\text{Pb}$  is highly partitioned into the silicate phase if the iron meteorites are representative of the metal phase. This is also true for Bi on the basis of its concentration in iron meteorite troilite and possibly also for Tl.

The metal in basalt from Disko Island was formed *in situ* by the reaction and equilibration of basaltic magma with carbonaceous shales. This highly reduced basalt may be compared with lunar samples. The  $^{204}\text{Pb}$  and Tl are enriched in the silicate relative to the metal and the Bi is enriched in the metal. On the basis of these results  $^{204}\text{Pb}$  is not partitioned into Disko basalt metal as it appears to be in metal in lunar samples.

The impact of iron meteorites causes the ejection of spherules of metallic Fe containing eutectics with Fe, FeS and  $\text{Fe}_3\text{P}$  components. The structures are similar to some found in lunar metal. We have separated the metal phase from associated oxides and silicates in spherules from Meteorite Crater, Arizona. The metal bearing phase constituted about 36% by weight of the spherule mass and after separation was 90–95% pure. The  $^{204}\text{Pb}$  content in the metal phase is 122 ppb. The spherules themselves contain  $< 62$  ppb  $^{204}\text{Pb}$  and this limit is consistent with most or all of the  $^{204}\text{Pb}$  being in the metal. The high concentration of  $^{204}\text{Pb}$  accommodated in this phase is probably due primarily to the presence of the eutectic. Troilite from the Canyon Diablo meteorite contains 73 ppb  $^{204}\text{Pb}$ .

The  $^{204}\text{Pb}$  contents of lunar samples are too high to be attributed to Pb in the metal only. The  $^{204}\text{Pb}$  contents of iron meteorites (metal + troilite) are too low to account for the  $^{204}\text{Pb}$  in lunar samples. A mechanism then has been operative on the Moon that concentrates  $^{204}\text{Pb}$  in a metal associated phase. The results discussed above suggest that the process of spherule formation is an efficient way to accomplish this. Most of the metal in lunar samples is endogenous according to a number of investigators. A constraint on the mechanism by which the metal is formed is that it must cause the extraction of  $^{204}\text{Pb}$  into the metal or metal related phase at least in basaltic samples. A Canyon Diablo spherule type process would require that S be involved. Lunar fines contain from 0.05–0.1 wt % S, which if associated with the 0.1–0.5 wt % metal could provide the troilite and/or eutectic. The amount of S and its isotopic composition varies with the apparent maturity of the soil. Whereas the metal can be formed *in situ*, the incremental S must be introduced from an external source. Since most of the  $^{204}\text{Pb}$  is associated with the metal, increments of  $^{204}\text{Pb}$  with increasing metal must also be supplied

from an external source. Since the  $^{204}\text{Pb}$  in metal of  $\sim 10^{-3}$  ppb is too high to be attributed even to meteoritic troilite another source is necessary. A lunar source would require transporting the  $^{204}\text{Pb}$  and probably S to surfaces from which it may become incorporated into splatter material involved in agglutinate formation. According to McKay et al., agglutinates form in finer grained, more highly comminuted soils. These would supply both the surfaces for deposition of Pb and S and the heating and melting, caused by micrometeorite impacts, that could promote metal-eutectic formation and Pb extraction.

If such a mechanism can account for the behavior of  $^{204}\text{Pb}$  in Apollo 14 and 15 samples lack of conformity by Apollo 16 samples which contain similar amounts of  $^{204}\text{Pb}$ , metal and sulfur may be due to lack of homogenization, as suggested earlier, or may be chemical. In these highly anorthositic samples an alternate site may compete with the metal-eutectic for the Pb.

Barnes, I. L., Garner, E. L., Gramlich, J. W., Machlan, L. A., Moody, J. R., Moore, L. J., Murphy, T. J., and Shields, W. R.: 'Isotopic Abundance Ratios and Concentrations of Selected Elements in Apollo 17 Samples'.

*Introduction.* In previous reports we have presented the results of multielement analyses of samples returned by the Apollo 14, 15 and 16 missions. We have now extended this work to include samples from the Apollo 17 mission. The objective was, as before to obtain concentration and isotopic ratio data for a variety of elements on the same identical sample so that all effects of subsampling could be removed and the analytical results for all elements directly related. The elements determined include lead, uranium, thorium, rubidium, strontium, potassium and nickel.

*Analytical Procedures.* The detailed analytical procedures have been described. The appropriate Standard Reference Material (SRM) was analyzed with each elemental analysis so that the error limits normally associated with the standard analysis are directly applicable. Three or more blanks were prepared and analyzed for each elemental analysis and where deemed appropriate separate isotopic composition blanks were analyzed.

*Discussion.* The isotopic ratios of rubidium and the more refractory elements uranium and nickel showed no evidence of fractionation and were identical within experimental error with those found for terrestrial materials. The Pb-U-Th model ages for 72501 soil from the South Massif area are nearly concordant at 4460 m.y. and are nearly identical for those found for 15495 while those for 75081 (Camelot) show extensive reversed discordance [ $^{206}\text{Pb}/^{238}\text{U} > ^{207}\text{Pb}/^{206}\text{Pb}$ ] falling between those found for 64801 and 68501.

As found for all soil samples previously analyzed the Apollo 17 samples show potassium isotopic fractionation of up to 1% of the  $^{39}\text{K}/^{41}\text{K}$  ratio. If the mechanism for fractionation of potassium involved ionization as a result of temperatures generated by meteoritic impact then it might be expected that, because of the very similar ionization potentials of Rb and K (4.1 and 4.3 eV), similar fractionation would be expected (though to a somewhat lesser degree for Rb due to the higher mass). We have not found any evidence for Rb isotopic fractionation.

If a diffusion mechanism is involved then it becomes even more difficult to explain the fractionation of K and not Rb since, as has been shown by Gibson *et al.*, Rb is at least as volatile as K, if not more so, in these soils. There also is a suggestion in the available data that the fractionation of K is dependent on the geographical location of the sampling site becoming greater nearest the lunar poles. It is possible that the amount of K fractionation may be used to correct for the losses of other volatile elements from a particular sample but much additional work must be done before this may be realized.

Blanford, G., McKay, D., and Morrison, D.: 'Accretionary Particles and Microcraters'.

*Accretionary Particles:* Accretionary particles are small, primarily glassy fragments adhering to host surfaces. We have examined accretionary particle populations on a number of surfaces varying in exposure geometry, composition and length of exposure. Disk and disk-like accretionary particles occur only on surfaces which have a co-existing microcrater population, and the density of these accretionary particles per unit area increases as the density of microcraters increases. Continuous deposition of accretionary particles results in the continuous renewal on a small scale of the host surface



as successive generations of accretionary particles cover and obscure pre-existing generations. Such a surface can be considered to be saturated with accretionary particles.

The morphology of disks and disk-like accretionary particles suggests that they are formed by the impact and flattening of highly fluid glass droplets; the impacting droplets must have high temperatures and low viscosities at the time of impact. J. O. Isard (personal communication) indicates that viscosity of approximately 1 poise and a temperature on the order of 1200°C would be required. Consequently, the source of the molten droplets must be relatively close, probably within a few meters or less in order to maintain this high temperature. This restriction also requires that most droplets arrive at relatively low angles or straight line trajectories; parabolic trajectories are largely precluded because the flight times would allow the droplets to cool and harden prior to impact.

The relative abundances of accretionary particles and co-existing microcrater populations are variable indicating that the rate of accumulation of accretionary particles is variable. Ratios between accretionary particles and microcraters of a given diameter vary from greater than 10 to less than one, with the lower ratios more typical of millimeter and submillimeter regolith particles. Particles from 72311 and 15001 (Apollo 15 drill core) have been observed with  $2$  to  $5 \times 10^7$  craters  $\text{cm}^{-2}$  of  $0.1 \mu$  diam which is equivalent to 15015,21 in craters per  $\text{cm}^2$ , but with only about 1% of the surface area covered with accretionary particles, whereas rock 15015,21 is approximately 100% covered by accretionary particles. Where the ratio between accretionary particles and microcraters is low on regolith particles, the microcrater populations occur in depressions effectively shielded from low angle trajectories. This also implies that the areas containing the microcrater populations subtended a small solid angle. In contrast to regolith particles all of the rock surfaces (glasses) which we have examined (15015, 15017, 60095, 79115) have more accretionary particles than microcraters. These surfaces vary in crater density by a factor of 50, and accretionary particles are from 6 to 100 times more abundant than microcraters. The slope of the size frequency distribution of well developed accretionary particle populations on rock surfaces is approximately  $-1.5$  in the  $0.1$  to  $1.0 \mu$  range extending in some cases to  $10 \mu$  diam particles before steepening sharply to higher values.

Data from Apollo 17 rocks indicate that accretionary particles may have an effect on the size frequency distribution of larger craters in certain situations.

Microcraters on Soil Particles: Data on the size frequency distributions of submicron craters suggests the presence of two groups. One population is characterized by relatively steep slopes in the  $0.1$  to  $1 \mu$  diam range and slightly steeper slopes ( $-2.0$  vs  $-2.5$ ) in the  $1.0$  to  $10 \mu$  diam range. The second population is characterized by a flatter slope (approximately  $-1$ ) vs the  $1.0$  to  $10 \mu$  diam range. We have examined soil particles from 72321 (Apollo 17, Sta. 2), 75081 (Apollo 17, Sta. 5), and 15001,34 (bottom of Apollo 15 drill core at 240 cm) to determine whether or not these populations persist on relatively old surfaces. All of the distributions observed have steep slopes (approximately  $-2.0$ ) comparable to those first determined by Schneider in the  $0.1$  to  $1.0 \mu$  diam range. The Apollo 15 deep core material was deposited at least  $400 \times 10^6$  yr BP and therefore the microcrater populations observed were produced at least before  $400 \times 10^6$  BP. We have not observed microcrater populations with size frequency distribution slopes less than  $-2.0$  on any of the particles examined. We conclude that the group of microcrater populations characterized by a slope of approximately  $-2.0$  in the  $-0.1$  to  $1.0 \mu$  diam range were being produced  $400 \times 10^6$  yr BP as well as in the more recent past.

Klein, L., Kritchevsky, G., Hopper, R. W., and Uhlmann, D. R.: 'The Formation of Lunar Glasses'.

In a continuing investigation of the conditions for forming glasses in the lunar environment and the information provided by such glasses and partially devitrified bodies about thermal history, attention has been directed to two compositions (60095 and 65016) which were found as largely-glassy bodies of relatively large mass (46.6 and 21.0 g respectively) as well as to the Apollo 15 green glass. Experimental determinations of the viscosity and crystal growth rate have been effected over a wide range of temperature for the 60095 and 65016 compositions, and are presently underway on the Apollo 15 green glass material. These data are then combined with theoretical kinetic analyses to obtain the desired information about glass formation and thermal history.

The viscosity data were in all cases obtained on synthetic materials prepared from reagent grade raw material powders. The techniques of sample preparation have been described in detail elsewhere and involve melting under conditions of low oxygen activity to simulate the  $\text{Fe}^{2+}$ /total ratios of the lunar compositions. Viscosities in the molten range were obtained using a rotating-cylinder viscosi-

meter. Viscosities greater than about  $10^8$  P were determined using a bending-beam viscosimeter. Both viscosimeters were provided with a low- $H_2$  forming gas atmosphere to maintain the  $Fe^{2+}/total$  Fe ratios of the starting materials.

The apparent activation energies for viscous flow in the high-temperature and low-temperature regions are about  $60 \text{ kcal mole}^{-1}$  and  $145 \text{ kcal mole}^{-1}$  for the 65016 composition and about  $55 \text{ kcal mole}^{-1}$  and  $155 \text{ kcal mole}^{-1}$  for the 60095 composition. These values lie in the range of those found previously for other lunar compositions.

Under all conditions where it could be determined, the interface morphology was observed to be faceted. In all cases, the crystals propagated from the external surfaces into the interiors of the specimens. The thickness of the external crystal layer after a given time of heat treatment at a given temperature was found to be uniform within about 5%; and the thickness was observed to increase linearly with time.

The growth rates, determined from the slopes of the thickness vs time relations. Similar variations of growth rate with temperature are found quite generally for glass-forming materials. The maximum in the growth rate curve reflects a competition between the driving force for crystallization and the molecular mobility.

The variations of growth rate with undercooling below the liquidus have been combined with the corresponding variations of viscosity to construct the reduced growth rate  $U_R$  vs undercooling relations. Here  $U_R = u\eta/\Delta T$ , where  $u$  is the growth rate,  $\eta$  is the viscosity and  $\Delta T$  is the undercooling. The variation of  $U_R$  with  $\Delta T$  directly indicates the temperature dependence of the interface site factor, and hence serves to characterize the nature of the interface kinetic process. For the present compositions, as for all lunar compositions previously investigated, the  $U_R$  vs  $\Delta T$  relations exhibit positive curvature and are suggestive of growth by a surface nucleation mechanism.

To investigate further this possibility,  $\log(u\eta)$  vs  $1/T\Delta T$  relations have been constructed. Similar to the results obtained on other lunar compositions, these relations for the present compositions exhibit negative slopes and positive curvatures. The forms of these relations are inconsistent with the standard models for surface nucleation growth, but are in accord with recent computer simulations of crystal growth.

The experimental results on growth rate and viscosity have been combined with kinetic treatments of glass formation to evaluate the glass-forming characteristics of the present compositions. The estimated critical cooling rates for glass formation are consistent with experimental observations on both synthetic and natural lunar compositions. The inversion of the experimental observations of crystal distributions in the natural samples to determine their thermal histories are presently underway, and it is hoped that the results can be given in the verbal presentation.

Müller, O.: 'Solar Wind – And Indigenous Nitrogen in Apollo 17 Lunar Samples'.

We report on chemically bound nitrogen concentrations in various Apollo 17 lunar samples from the Taurus Littrow landing site. This work continues our earlier investigations of bound nitrogen in lunar material with the Kjeldahl method by Müller. This technique detects nitrogen only in a bound state and discriminates against molecular nitrogen  $N_2$  which may be derived from atmospheric contamination. We have analyzed eight Apollo 17 bulk fines of grain size  $< 1$  mm from different stations. Two of them have been separated into several grain size fractions to study the grain size dependence of nitrogen implanted by the solar wind. These are fines 74241,11, a gray soil beside orange soil, sampled at the rim of Shorty Crater, and fines 78501,26 collected from mountain slopes at the base of Sculptured Hills. Three rock samples, a crushed anorthositic gabbro, a homogeneous gabbro and a fine-grained basalt, have been analyzed to determine bound nitrogen indigenous to Apollo 17 rocks. Furthermore, the light and dark, noble gas-rich portions of the achondrite Kapoeta have been investigated to study possible contribution of solar wind nitrogen in the dark portion.

Bulk fines of the Apollo 17 sampling areas range in bound nitrogen contents from 23 to 73 ppm N. The fines 71501, 74241 and 75061 from the valley floor have nitrogen contents of 51,23 and 42 ppm N, respectively, and are distinctly lower in nitrogen than those from the mountain slopes (range 63 to 73 ppm N). Valley floor soil 70011, sampled at the Lunar Module, has 73 ppm N and is possibly exhaust contaminated. The seven Apollo 16 bulk fines, previously analyzed, vary in nitrogen from 70 to 124 ppm N, the Apollo 11 through Apollo 15 fines from 80 to 113 ppm N. The Apollo 17 bulk fines, especially the valley floor soils, contain the lowest amounts of bound nitrogen among all

Apollo fines analyzed so far. It is unlikely that the duration of solar wind irradiation, being the main source for nitrogen in lunar fines, was rather different for valley floor and mountain slope soils. According to trapped noble gas contents, the Apollo 17 fines are saturated with solar wind (Hübner and Kirsten, and Hübner *et al*). Correlation of nitrogen with trapped noble gases in fines will be discussed in the forthcoming paper. The low nitrogen contents of valley floor soils may be a function of agglutinate content and grain size distribution. Agglutinates are present in nearly all of the Apollo 17 soils, although in smaller proportions than in soils from the other mare sites. In fact, soil 74241 having the lowest nitrogen content is also very low in agglutinates. Moreover, the median grain size of valley floor soils 74241 and 75061 is around 100  $\mu\text{m}$ , respectively, whereas that of mountain slope soils 76501 and 78501 is 53 and 38  $\mu\text{m}$ , respectively, causing different shielding of fine grains to the solar wind.

The results of the grain size fraction analyses of Apollo 17 fines 74241 and 78501 are represented. Our previous data on Apollo 14, 15 and 16 fines are included for comparison. The nitrogen concentrations of sieve fractions are plotted versus the mean diameter. As approximate mean grain diameter of the fractions in  $\mu\text{m}$  3–12, <24, 12–24, 24–48, 48–60, 60–109 and 109–272 we have used 6, 8, 16, 32, 53, 79 and 164  $\mu\text{m}$ , respectively, in this plot. The data of fines 74241 sampled beside the orange soil at the rim of Shorty Crater show as in our previous studies a distinct increase of nitrogen with decreasing grain size. It is now commonly accepted that the surface-correlated nitrogen in lunar fines is mainly derived from the solar wind. The grain size fraction curve for 74241 is distinctly different from those of other lunar fines. The slope at small grain sizes is rather steep. With increasing grain size the nitrogen curve turns rather sharply and becomes nearly horizontal. Two features are remarkable: the nitrogen content at a very small grain size is with about 140 ppm relatively low, and likewise the concentrations of the larger grain size fractions, 13 to 19 ppm N. The grain size dependence of bound nitrogen for fines 78501 from the base of Sculptured Hills is also rather unique. The slope at smaller grain sizes is distinctly smoother than that of other fines, and the nitrogen content at a very small grain size is with about 120 ppm the lowest measured so far by us.

To learn more about bound nitrogen indigenous to lunar rocks we have analyzed rocks 77017, 79155 and 70215. They contain only less than 8 ppm N, respectively. Their nitrogen contents are similar to those of igneous rocks 12063, 12075 and 15556, previously analyzed. The low nitrogen contents of igneous lunar rocks suggest that indigenous nitrogen was low in abundance at the time of mineral formation billions years ago and demonstrates once more the severe loss of volatile elements in the early history of the moon.

The nitrogen results of the light and dark, gas-rich portion of the achondrite Kapoeta show that there was no significant contribution of solar wind-driven nitrogen to the dark portion. This result is surprising, because besides the trapped noble gases carbon is enriched in the dark portion by a factor of almost two relative to the light portion, Müller and Zähringer.

Total carbon and bound nitrogen data, and the C/N atomic ratios in Apollo 17 fines are also presented. Carbon data from. The ratios of six fines range from 1.68 to 2.80, and are in the average distinctly higher than those previously calculated for Apollo 14, 15 and 16 fines. The high C/N values of Apollo 17 soils approach those determined in the solar photosphere by analysis of atomic and molecular spectra (C/N = 3 to 4).

Merlivat, L., Lelu, M., Nief, G., and Roth, E.: 'Deuterium Content of Lunar Material'.

Previous experiments has shown that extraction of hydrogen gas from lunar material was not complete when degassing under vacuum. It is limited by an oxydation reaction starting at 575°C. In order to overcome this difficulty we have built a new extraction line, based on a flow system, working at atmospheric pressure.

The extracted gases are carried by helium. The flow value is 50 cc  $\text{mn}^{-1}$ . A typical line includes two successive traps. In the first one, gases condensable at liquid nitrogen temperature are retained. The second one, is kept also at liquid nitrogen temperature and, in addition is filled with charcoal. In this last trap, hydrogen is collected. We have four lines of this type. Each of these is used in a separate range of extraction temperature. The samples are heated up to 1200°C in quartz holder by a resistor oven. A constant heating rate of 4°C min is adopted. Degassing between 150 and 200°C is performed for 90 min before the gas collection. A thirty minutes period at 1200°C completes the whole heating. When the extraction procedure is completed, helium is evacuated from the whole of the installation.

Then the gas released from the traps react successively with vanadium at 800 °C. Vanadium acts as a chemical trap for all compounds except rare gases and hydrogen—namely, H<sub>2</sub>O is reduced in hydrogen. Then, hydrogen gas samples are transferred to ampoules filled with charcoal at liquid nitrogen temperature. The samples are ready for analysis by mass spectrometry. Before each experiment the quartz tube is degassed at 1200 °C. Afterwards, at this same temperature at which pollution by grease should most likely occur, blanks are run with free helium. The amounts of hydrogen and water collected are always smaller than 0.3 mm<sup>3</sup> S.T.P.

Discrepancies are observed between the deuterium content of hydrogen extracted from a same sample in the two techniques. Experiments are underway to elucidate this problem. However the following conclusions are independent of this fact because of a different order of magnitude.

1. In all runs except the first one, the amount of water extracted by the flow system is much smaller than it is under vacuum extraction conditions and the opposite is true for the hydrogen quantities. This correlates directly with the previous observations that under vacuum oxydation of hydrogen to water in presence of lunar material takes place. More precisely, the three experiments run with the fine sample 14003 have been made for purpose to check if the nature of the material used to wrap the Moon sample could catalyse the oxydation reaction. Experiments run with gold (a') instead of platinum (a) don't lead to drastic changes. Conversely in the flow system, the pressure of 760 torrs of helium lowers the probability of reaction of the extracted hydrogen with the oxydes of the lunar sample. The deuterium content of water measured in both types of experiments is in general agreement with the previous observations.

2. In both extraction procedures, the deuterium content of hydrogen extracted from fines and breccia displays a typical pattern. The second extracted fraction (~ 460°–725°) is always depleted in deuterium with respect to the first one and the third one. We tentatively explain the relatively higher value observed for the first fraction as the result of isotopic exchange between hydrogen and deuterium rich water. The main part of the latter is extracted when heating in the low temperature range. The second fraction represents mainly solar wind hydrogen which is known to be very low in deuterium. In the third fraction, deuterium formed by nuclear reactions mainly by spallation processes, is the origin of the increase in values of D/H ratios. For instance, during experiments on a basalt sample, 75.035, a very high value of the deuterium content, 258 ppm, has been obtained in the hydrogen extracted between 725 °C and 995 °C. *Such a value can in no case be explained by exchange or direct contamination with terrestrial water.*

3. We are still confronted with the problem of the origin of the water extracted from the samples. Contamination cannot be ruled out as its deuterium content is very similar to terrestrial water, though relatively high. The values around 155 ppm could be due to an isotopic enrichment accompanying an adsorption process on the lunar material.

In conclusion, though the origin of water collected is still uncertain, evidence for deuterium formed by nuclear reaction on the Moon has been given.

Buhl, P., Gay, M., Gehrke, C. W., Kuo, K., Pal, R., Ponnampereuma, C., Shimoyama, A., and Zumwalt, R.: 'Search for Amino Acids in Apollo 17 Lunar Soil Samples'.

Returned lunar samples 72501.62 and 70011.37 SECS were the subject of these investigations. Our primary aim was the identification of water extractable organic compounds by gasliquid chromatography (GLC) and classical ion-exchange chromatography (CIE) with particular emphasis on the amino acids. The aqueous extracts were prepared using the hydrothermal extraction method of Cheng and Ponnampereuma, (ACS MARM meeting Jan. 14–17, 1973). Other methods have been previously reported by Gehrke and Ponnampereuma, (Proceedings of the 4th Lunar Science Conference 1973).

The total procedural blanks for the analyses exhibited no amino acid contamination above the 0.5 ng g<sup>-1</sup> level by GLC and < 0.2 ng g<sup>-1</sup> level by CIE. Analyses by both GLC and CIE on the same sample extracts gave independent yet supporting data. The analyses included free amino acids (F) and amino acids observed after hydrolysis (H) of the aqueous extracts with 6 N HCl for 20 h. The amounts of Ala, Thr, Ser, Asp and Glu present in lunar soil, in nearly all cases, were less than 1 ng g.

In Apollo 17 (72501.62) glycine was found at 1.5 ng g (F) and 4 ng g (H) by CIE, and < 1 ng g for (F and H) by GLC. For sample 17 (70011.37 SECS) glycine was present at a level of (19 ng g F), and (11 ng g H) by CIE, and 12 ng g and 5 ng g respectively by GLC. The latter result appears to be contamination from rocket exhaust.

There are also significant quantities of derivatizable compounds which cannot be attributed to the presence of any known amino acids. These are under further investigation.

## 7. Exchange of Material and Energy Between the Moon and Its Environment: II

Hintenberger, H., Weber, H. W., and Schultz, L.: 'Solar, Spallogenic and Radiogenic Rare Gases in Apollo 17 Soils and Breccias'.

Rare gas concentrations and isotopic composition of four Apollo 17 soils (72701/25, 74260/9, 75061/21 and 75081/72) and two breccias (79035/15 and 79135/32) have been determined mass spectrometrically. In addition to our recently published analyses of different grain size fractions from orange soil 74220/47 and the reference soil 74241/24 we have measured the rare gases of a suite of grain sizes from 74260/9, the second reference soil to 74220/47 and from 75081/72.

The elemental rare gas ratios vary from soil to soil as a function of thermal- and irradiation history as well as their mineralogy. For trapped gases the ratio  $R(36) = \text{Ar}36/\text{Kr}84$  is relatively constant  $R(20) = \text{Ne}20/\text{Kr}84$  and  $R(4) = \text{He}4/\text{Kr}84$  ( $Q(20) = 1.7$ ;  $Q(4) = 4.4$ ). The variations of the relative abundances of the light rare gases are caused to a large extent by diffusion losses. As a rule, samples with high  $\text{TiO}_2$  contents show large ( $\text{He}4/\text{Kr}84$ )- and ( $\text{Ne}20/\text{Kr}84$ )-ratios, reflecting the higher retentivity of ilmenite for light rare gases.

The isotope ratios  $(\text{Ar}36/\text{Ar}38)_{\text{tr}}$  and  $(\text{Ne}20/\text{Ne}22)_{\text{tr}}$  are constant within  $\pm 2\%$ . The ratio  $(\text{Ar}40/\text{Ar}36)_{\text{SC}}$  of the surface correlated argon isotopes, however, shows large variations between 0.77 in 75081/72 and 7.6 in 74241/24 and the ratio  $(\text{He}4/\text{He}3)_{\text{tr}}$  varies also between 2740 and 3260 in the corresponding samples. Radiogenic Ar40 and He4 liberated from lunar material and adsorbed on the highly damaged grain surfaces or incorporated by some other mechanism into them may explain the correlation between  $(\text{Ar}40/\text{Ar}36)_{\text{SC}}$  and  $(\text{He}4/\text{He}3)_{\text{tr}}$ .

Of special interest are the two reference soils 74241/24 and 74260/9 to the orange soil 74220/47: Both exhibit high  $\text{He}4/\text{He}3$  and  $\text{Ar}40/\text{Ar}36$  ratios, their noble gas concentrations in bulk and grain size samples are very similar. From the grain size analyses we determined the radiogenic and spallogenic gas components. It follows that the exposure age of the reference soils with about 200 m.y. is high compared to the exposure age of the orange soil ( $\sim 30$  m.y.). On the opposite, the gas retention ages of the reference soils are  $< 500$  m.y., small in any case compared to the gas retention age of the orange soil ( $3.5 \pm 0.3$ ). One can assume that during an event which reduces the radiogenic Ar40 by a considerable amount, the trapped gases are lost or at least strongly depleted. Thus, the low gas retention age indicates that the trapped gases in the reference soils are the result of a relative recent solar wind irradiation. The high  $\text{Ar}40/\text{Ar}36$  and  $\text{He}4/\text{He}3$  ratios can, therefore not be attributed to a solar irradiation at a very early date.

Both analysed breccias appear as lithified soils because the matrix of these stones is matured with trapped solar wind rare gases.

Phinney, D., Baur, H., Frick, U., Funk, H., Schultz, L., and Signer, P.: 'He, Ne and Ar in Lunar Soil Mineral Separates'.

We have measured He, Ne, and Ar abundances and isotopic compositions in grain-size fractions of mineral separates from the soil 15421. The separates are: feldspars, green glasses, and a ferromagnesian mineral fraction which is labeled as olivine. The green glasses can be further subdivided into (i) clear green spherules, (ii) 'milky' green rounded particles, and (iii) broken fragments of (i) and (ii).

Gas concentrations occur in the following order (highest to lowest): olivine, feldspar, clear green spherules, and milky green glasses.

Grain-size fraction of feldspar and of clear green spherules show smooth anticorrelations of gas content with grain size.

Olivine gas amounts also correlate with grain size but less smoothly. This is the result of variable amounts of devitrified glass in the olivine fractions. The milky green glasses, for which analyses of all

grain sizes are not yet complete, have about a factor of 2 less trapped gases than the green spherules and give evidence of only a weak anticorrelation with grain size.

Hintenberger and Weber have recently discussed rare gas elemental ratio vs.  $\text{TiO}_2$  correlations in lunar soils. Our work indicates that the same degree of correlation can be had by plotting elemental ratios vs feldspar content, where the feldspar content includes the contribution from feldspar in soil breccia particles.

Among the isotopic ratio results, Ne in the green glasses and feldspars deserves special mention. The green glasses demonstrate simple 2-component behavior, the two components being solar and cosmogenic Ne.

Feldspar Ne shows 3-component behavior. From isotope intercept plots, one component emerges as a surface-correlated Ne with solar-like composition. Residual extractions (in connection with our diffusion studies on these minerals) indicate that cosmogenic Ne is also present. A third component ( $20/22 < 12$ ,  $21/22 < 0.15$ ) is, however, necessary to explain the observations.

Hodges, R. R., Jr., Hoffman, J. H., and Johnson, F. S.: 'The Lunar Atmosphere'.

The atmosphere of the Moon is so tenuous that it can be regarded as a collisionless exosphere in which atoms and molecules are gravitationally bound in ballistic trajectories between encounters with the lunar surface. Despite the small amount of gas, the vestige of atmosphere is an important indicator of lunar processes which produce atmospheric gases. Lack of a significant amount of lunar atmosphere can be attributed mainly to an efficient escape mechanism for particles that are too heavy to escape thermally. Neutral gas molecules or atoms are photoionized by solar radiation and then, in the absence of significant magnetization of the Moon, the  $\mathbf{v} \times \mathbf{B}$  field of the impinging solar wind accelerates the resultant ions. Roughly half of these ions impact the lunar surface, but the other half escape. The geomagnetic field inhibits this escape process over the Earth, while induced ionospheric currents apparently cause a deflection of the solar wind around both Mars and Venus, thus causing ions produced below the deflection boundary to remain in the planetary atmosphere.

Theoretical values for hydrogen and helium are based on calculations by Hodges, which are in close agreement with independent calculations of Hartle and Thomas. Daytime concentrations of hydrogen and helium may be expressed in two ways – in terms of downcoming bound particles which have completed at least one ballistic trajectory or as the total of bound and newly created upgoing molecules in initial trajectories. Owing to long residence times for neon and argon, differences between their respective bound and total concentrations are negligible.

Amounts of helium,  $^{20}\text{Ne}$  and  $^{36}\text{Ar}$ , which are known from Apollo 16 and Apollo 17 mass spectrometer data are in balance with the solar wind influxes of these species. The lack of a large accumulation of hydrogen in the lunar soil suggests that the solar wind influx of protons is similarly converted to a neutral gas, presumably  $\text{H}_2$ , to equalize rates of accretion and escape. Solar abundances of O, C and N probably exceed that of Ne, but atomic and molecular forms of these elements derived from the solar wind do not show evidence of a recognizable diurnal atmospheric oscillation in the Apollo 17 mass spectrometer data. The only reasonable interpretation of this fact is that ambient levels are small compared to the artifact background.

Atomic oxygen ions of the solar wind probably react with lunar materials even though oxygen is the major constituent of the Moon. Thus the lack of evidence of O or  $\text{O}_2$  in the atmosphere is understandable. Atmospheric forms of C and N are more reasonably expected. By analogy with the previously discussed hypothesis of the formation of  $\text{H}_2$ , it is expected that  $\text{CH}_4$  and  $\text{NH}_3$  should also be formed and released to the atmosphere. The large amount of oxygen in the soil may lead to production of CO,  $\text{CO}_2$  and NO, but these reactions may also be reversible. The alternative to atmospheric forms of C or N is that most of the solar wind influx of these elements is now being permanently implanted in the soil.

The presence of excess amounts of  $^{40}\text{Ar}$  trapped in returned lunar samples has been recognized by Manka and Michel, as evidence of  $^{40}\text{Ar}$  as an atmospheric gas. More recently,  $^{40}\text{Ar}$  has been identified in the lunar atmosphere by the Apollo 17 mass spectrometer. Since the only important source of  $^{40}\text{Ar}$  is radiogenic decay of  $^{40}\text{K}$  within the Moon, its presence in the atmosphere is evidence of a venting or degassing process, which surprisingly corresponds to about 0.4% of the total rate of production of  $^{40}\text{Ar}$  in the Moon.

One possible explanation of the large rate of release of  $^{40}\text{Ar}$  is that most of the atmospheric argon is produced deep in the lunar interior.

The regolith must be ruled out as an important source of atmospheric argon simply because of the magnitude of the loss rate, which corresponds to release of  $^{40}\text{Ar}$  at its rate of production throughout the upper 3 km of soil. Impact gardening may release a small fraction of the trapped argon from the soil, but the depth of this effect cannot be great enough to make a substantial contribution. Diffusion of argon out of small grains to a great depth also seems an unlikely explanation because this mechanism would not have produced a varying supply of argon.

Vondrak, R. R., Freeman, J. W., and Lindeman, R. A.: 'Measurements of Lunar Atmospheric Loss Rate'.

The primary method by which the lunar atmosphere is lost from the lunar environment is ionization by solar photons and solar wind followed by acceleration of the ions by the interplanetary electric field. This is an efficient escape mechanism even for those atoms which are too heavy to escape thermally. In this paper we present direct measurements of the loss rate of the lunar atmosphere to the solar wind. These data were obtained by the Suprathermal Ion Detector Experiment (SIDE), one of the ALSEP experiments on the Apollo 12, 14, and 15 missions.

Newly-formed atmospheric ions move under the influence of two electric fields: the interplanetary (solar wind  $\mathbf{v} \times \mathbf{B}$ ) electric field and the lunar surface electric field. On the lunar dayside the interplanetary electric field drives approximately 50% of the atmospheric ions into space. Near the terminators the lunar surface potential becomes negative, resulting in acceleration and implantation of ions into the lunar surface.

Observations of atmospheric ions by the SIDE detectors have been previously reported. The SIDE detectors look radially outward from the lunar surface and, consequently, are able to detect atmospheric ions accelerated by the interplanetary electric field most easily at the sunset and sunrise terminators. Ions are consistently observed at the terminator regions on every lunation, with the three most recurrent ion mass/charge ranges being 20–26, 34–38, and 40–44 amu  $q^{-1}$ . These heavy ions are thought to be of atmospheric origin because their energy distribution matches that expected from acceleration by the uniform interplanetary electric field of ions originating from neutral atoms distributed exponentially in altitude. A typical atmospheric ion event observed 1.5 days before sunset had an average flux of  $\sim 7 \times 10^9$  ions  $\text{cm}^{-2} \text{s}^{-1}$  in the energy range of 10–70 eV/q. The SIDE indicated that these ions had a mass in the range of 20–26 amu  $q^{-1}$ . Assuming proportionate fluxes over the entire lunar dayside due to interplanetary field acceleration leads to an estimated total atmospheric mass loss rate of approximately 5 gm  $\text{s}^{-1}$ .

This measurement of the atmospheric loss rate can be used to establish constraints on the present source of the lunar atmosphere. Assuming that the lunar atmosphere is in equilibrium requires that the loss rate be balanced by a comparable source rate of  $\sim 5$  gm  $\text{s}^{-1}$ . If the source is the solar wind, then at least 1% of the solar wind protons must react chemically with the surface materials to form heavy molecules. If the source is lunar degassing, then the Moon is presently about  $10^{-5}$  as geologically active as the Earth.

Limits to the size of the lunar atmosphere in the past can be established by computing the expected loss rates of denser lunar atmospheres. This requires consideration of the combined loss rate due to both thermal escape and interaction with the solar wind. By evaluating the minimum loss rate of lunar atmospheres of greater density than at present, an upper limit can be placed on the maximum size of the lunar atmosphere in the past.

Rees, C. E. and Thode, H. G.: 'Sulphur Concentrations and Isotope Ratios in Apollo 16 and 17 Samples'.

Sulphur concentrations and  $\delta^{34}\text{S}$  values have been measured for Apollo 16 and 17 samples. Experimental procedures have been described elsewhere. Reported sulphur concentrations have an estimated error of  $\pm 3\%$  while the standard deviation of an individual  $\delta^{34}\text{S}$  determination is  $\pm 0.07\%$ .

The results are in general agreement with previously determined values. The anorthosite sample 61016 is the first for which we have found a negative  $\delta^{34}\text{S}$  value. The coarse fines sample 68502 was crudely separated into magnetic and non-magnetic fractions with a hand magnet. These fractions have distinctly different sulphur concentrations while the  $\delta^{34}\text{S}$  values are similar and reflect the rock-like

character of the coarse particles. A small amount of fine material, initially adhering to the coarse particles, was washed off with acetone. This fraction has a much higher  $\delta^{34}\text{S}$  value.

The sieving experiment on 72501 extends the similar experiment on the Apollo 14 fines sample 14163. The tabulated results clearly show the increase of  $\delta^{34}\text{S}$  value with decreasing particle size. This strongly suggests that the high  $\delta^{34}\text{S}$  values are related to the high surface areas of the smaller particles. The following crude model yields surprising results. Consider a spherical particle of radius  $r$  with an outer shell of thickness  $a$ . The fraction,  $f$ , of the volume of the particle which is in the outer shell is:

$$f = \frac{\text{volume of outer shell}}{\text{total volume}} = \frac{r^3 - (r - a)^3}{r^3}.$$

Batts, B. D., Biggar, G. M., Billetop, M. C. J., Davis, P. R., Eglinton, G., Erents, S. K., Gardiner, L. R., Gowar, A. P., Housley, R. M., Humphries, D. J., Jull, A. J. T., Maxwell, J. R., Mays, B. J., McCracken, G. M., and Pillinger, C. T.: 'The Origin of Lunar Carbide'.

The concentration of carbide in lunar fines (estimated as  $\text{CD}_4$  from  $\text{DCl}$  dissolution) is related to both solar wind exposure history and  $\text{Fe}^{\text{II}}$  content of the sample. The  $\text{CD}_4/^{36}\text{Ar}$  ratio is proportional to the content of  $\text{Fe}^{\text{II}}$  (calculated as  $\text{FeO}$ ) in fines from the A11, A12, A14, A15 and A16 missions. Current results show that carbide in A17, L16 and L20 fines has the same exposure and  $\text{Fe}^{\text{II}}$  dependence. Limited data suggest that the key iron species implicated in the relationship is superparamagnetic iron,  $\text{Fe}^{\text{sp}}$ . An understanding of the role of  $\text{Fe}^{\text{sp}}$  is now being sought by acid dissolution studies and Mössbauer spectroscopic measurements of a variety of soils selected on the basis of  $\text{Fe}^{\text{II}}$  concentrations and solar wind exposure histories.

We have previously suggested that the finest ( $< 10 \mu\text{m}$ ) soil grains represent the main site for initial synthesis of carbon compounds and that the reactions occurring in these non-aggregated fine grains are important in understanding lunar carbon chemistry. Subsequent redistribution of carbon species and any further reactions which occur during the recycling of material *via* the formation and comminution of complex particles, such as glassy agglutinates and microbreccias, must be considered separately. Primary synthesis of  $\text{Fe}^{\text{sp}}$  and carbide in finest fines could be the result of solar wind ion implantation and/or meteorite impact cloud reactions. Each of the two basic processes may take place by one or more mechanisms. Solar wind ions could reduce silicate  $\text{Fe}^{\text{II}}$  to  $\text{Fe}^{\text{e}}$  by (i) preferential sputtering of the more electronegative elements (e.g. oxygen) or (ii) chemical reactions occurring during diffusion of the implanted species, particularly hydrogen, with or without heating or other activation. Carbide synthesis might occur in each case from simultaneously implanted carbon atoms. Reduction of silicate  $\text{Fe}^{\text{II}}$  to  $\text{Fe}^{\text{e}}$  might occur in the hot base surge accompanying a meteorite impact. The reducing gas cloud could be (i) predominantly hydrogen and  $\text{CO}$  released by pyrolysis of the soil, or (ii) the gas mixture in (i), with a greatly increased proportion of  $\text{CO}$ , if the meteorite is a carbonaceous chondrite. The presence of carbon species in the gas cloud might be expected to lead to the simultaneous formation of carbide.

The feasibility of each mechanism is being investigated by simulation studies using  $\text{Fe}^{\text{II}}$ -rich glass samples ( $\text{Fe}^{\text{II}}$  in the range 0–20%  $\text{FeO}$ , supplied by P. S. Irlam, Pilkington Bros. Ltd.) under the appropriate reaction conditions. The  $\text{DCl}$  dissolution method is used to detect the formation of either  $\text{Fe}^{\text{e}}$  or  $\text{Fe}^{\text{c}}$  with associated carbide. In a preliminary study, glass containing 4%  $\text{Fe}^{\text{II}}$  and 7%  $\text{Fe}^{\text{III}}$  was implanted with  $^{13}\text{C}^+$  ions. No conclusive evidence for the formation of  $\text{Fe}^{\text{e}}$  or carbide was found, even after heating at temperatures up to  $1000^\circ\text{C}$ . However, during the pyrolysis  $^{13}\text{CO}$  and  $^{13}\text{CO}_2$  were released, indicating that  $^{13}\text{C}$ -implanted iron-rich glasses exhibit some characteristics of lunar soils. A suite of samples irradiated by  $\text{D}_2^+$  ions is now under investigation.

To simulate the effects of meteorite impact gas clouds, powdered glass samples (average particle size less than  $20 \mu\text{m}$ ) have been equilibrated at fixed temperatures (in the range  $500^\circ\text{C}$ – $1000^\circ\text{C}$ ) in controlled  $\text{H}_2/\text{CO}$  or  $\text{CO}/\text{CO}_2$  atmospheres. These experimental conditions are probably more favourable for the reduction and carbide synthesis reactions than those prevailing at the lunar surface. However, preliminary results from samples heated in  $\text{CO}/\text{CO}_2$  at  $1000^\circ\text{C}$  show no measurable  $\text{Fe}^{\text{e}}$  or carbide. Similarly, neither species has been detected in samples of  $^{13}\text{C}^+$ -implanted glass which had been heated in a stream of  $\text{H}_2$  at  $500^\circ\text{C}$ – $700^\circ\text{C}$ .

After the initial formation of  $\text{Fe}^{\text{e}}$  in fine lunar grains, carbide could be generated by (i) subsequent implantation of solar wind carbon, or (ii) gas cloud reactions in which  $\text{CO}$  chemisorbed on exposed



metal is catalytically decomposed. Indeed, laboratory studies have already shown both processes to be possible.

Any Fe<sup>0</sup> synthesized in lunar soil by solar wind ion bombardment should be distributed only in the range of penetration of the ions: e.g. 2000 ± 500 Å for hydrogen. The proportion of Fe<sup>0</sup> exposed at the 'very surface' should be small. Conversely, reactions occurring in a gas cloud would be expected to generate only 'very surface' material. Housley *et al.* have shown the presence of iron particles (presumably Fe<sup>0</sup>sp) within the surface region and we are attempting to establish the relationship between these particles and the species which produce CD<sub>4</sub> on DCl dissolution. Preliminary results with a variety of surface-specific reagents suggest that most of the Fe<sup>0</sup> and carbide is not directly accessible to these reagents. About 90% of the Fe<sup>0</sup> is not attacked without concurrently destroying part of the silicate matrix, implying that solar wind implantation is the major mechanism for Fe<sup>0</sup> reduction.

Precise location studies should prove informative in regard to the redistribution processes occurring during the formation of complex particles from finer material. The carbide and CH<sub>4</sub> contents of a series of fractions obtained by disaggregating glassy agglutinates are being measured.

Kaplan, I. R., Kerridge, J. F., and Lesley, F. D.: 'Accumulation and Isotopic Evolution of Carbon on the Lunar Surface'.

Whereas the regolith at most Apollo landing sites is a heterogeneous mixture of chemically, and petrographically, distinct components, soil from the Apollo 16 site at Cayley-Descartes is more nearly homogeneous with respect to distribution of the major rock-forming elements. Apollo 16 soil samples may therefore be regarded as monitors for the interaction between the lunar surface and the interplanetary medium, with less risk of secular changes being masked by chemical or mineralogical differences. We exploit this feature to follow the development with time of the extralunar contribution to the abundance and isotopic composition of carbon.

The first step in our approach is to construct a model describing the accumulation of C in the lunar regolith as a function of time and the corresponding evolution of its <sup>13</sup>C content, expressed as δ<sup>13</sup>C. Then, since we lack a reliable measure of the surface exposure age of each sample, we eliminate this term by expressing C abundance as a function of δ<sup>13</sup>C. Finally, the model relationship between C and δ<sup>13</sup>C is compared with data for Apollo 16 samples.

In constructing the model we make the following assumptions:

- (1) Only the solar wind is considered as a source of extralunar C.
- (2) Some loss of C occurs as a result of hydrogen stripping. Solar wind H reacts with implanted C to form CH<sub>4</sub> most of which is subsequently lost by thermal diffusion. Isotopic fractionation occurs at this stage as a result of the mass dependence of the diffusion process.
- (3) Agglutination converts a proportion of the surficial, implanted C into a volume-correlated fraction, shielded from stripping. During agglutination C is lost from the molten material with no isotopic fractionation.
- (4) Impact comminution causes the surface area of lunar soil to increase with time, until balanced by the competitive effect of agglutination.
- (5) 'Recycling' of formerly volume-correlated C to fresh surfaces is ignored.

An expression for C content in terms of the various processes described above has been derived, but because of its length we simply state here the resulting equations for surficial, C<sub>s</sub>, and volume, C<sub>v</sub>, carbon in terms of *t* which we define as the average, cumulative residence time of a constituent grain on the very surface.

$$C_s(t) = \frac{Fq}{P + K} [1 - e^{-(P+K)t}] [A_0 + A(1 - e^{-Bt})]$$

$$C_v(t) = \frac{(1 - \gamma) FqP}{P + K} \left[ \frac{(A_0 + A)(1 - e^{-\gamma Pt})}{\gamma P} + \frac{A(e^{-\gamma Pt} - e^{-Bt})}{\gamma P - B} + \frac{(A_0 + A)(e^{-(P+K)t} - e^{-\gamma Pt})}{(1 - \gamma)P + K} + \frac{A(e^{-\gamma Pt} - e^{-(P+K+B)t})}{(1 - \gamma)P + K + B} \right] + C_0 e^{-\gamma Pt}.$$

F = flux of C in the solar wind. A value of 5 × 10<sup>-5</sup> μg cm<sup>-2</sup> yr<sup>-1</sup> is derived from Cameron's cosmic abundances and the measured solar wind proton flux.

$q$  = shape factor, since only one side of a grain is irradiated at a time. A value of 0.25 is taken.

$A_0$  = geometrical surface area of pristine ejecta, and

$A$  = increase in surface area on maturation. Comprehensive measurements of surface areas are not available for lunar soils. However, measurements of mean grain size for mature and immature soils suggest that maturation roughly doubles the initial surface area, so that the geometrical surface areas measured for mature soils, about  $200 \text{ cm}^2 \text{ g}^{-1}$ , lead to values for  $A_0$  and  $A$  of about  $100 \text{ cm}^2 \text{ g}^{-1}$ .

$y$  = fraction of material melted, and presumably decarbonised, during agglutination. Microscopic examination of agglutinates suggests a value of about 0.5.

$P$ ,  $K$  and  $B$  are constants describing the rate of agglutination, hydrogen stripping and maturation of surface area, respectively. Some tentative values are presented, pending more complete computer matching of coefficients based on additional experimental data. Values for  $K$  of  $\sim 10^{-5} \text{ yr}^{-1}$  were found to give reasonable results. Achievement of a mature surface area represents equilibrium between impact comminution and growth by agglutination. Thus  $B$  is closely related to the rate of agglutination,  $P$ , and initially the two are equated. We suspect that agglutination operates at a somewhat slower rate than does H stripping on account of the observation that  $\delta^{13}\text{C}$  appears to approach rapidly to a 'saturation' value. A value of  $5 \times 10^{-6} \text{ yr}^{-1}$  is thus assigned to both  $P$  and  $B$ .

Calculation of  $^{13}\text{C}$  abundance, and hence  $\delta^{13}\text{C}$ , follows that for  $^{12}\text{C}$  by adopting a value of  $5 \times 10^{-7} \mu\text{g cm}^{-2} \text{ yr}^{-1}$  for  $F$  and a value for  $K$  which is related to that for  $^{12}\text{C}$  by the reciprocal square roots of the isotope masses (in the form of methane), i.e.  $0.97 \times K(^{12}\text{C})$ . Delta values thus calculated are relative to the  $^{13}\text{C}/^{12}\text{C}$  ratio arbitrarily assumed for the solar wind. The initial value of  $\delta^{13}\text{C}$  for indigenous lunar C has a negligible effect on the values eventually achieved.

Because isotope results are measured relative to the PDB standard, calculated values have been translated onto the PDB scale. We have attempted this by assigning two alternative values to  $K$  and by constraining the model curves to pass through the point (180 ppmC; +13‰PDB), representative of a mature soil. The data are better matched by  $K = 10^{-5} \text{ yr}^{-1}$  but a value of  $1.8 \times 10^{-5} \text{ yr}^{-1}$  yields a value for the initial isotopic composition of the solar wind which is in line with our recent estimate. The general shape of the theoretical curve is followed reasonably well by the experimental data, despite some scatter. Note that samples 61221 and 67461 are, for various reasons, considered to be anomalous. A tendency for the lunar samples to exhibit more isotopic fractionation than predicted may be due to some diffusional loss of C in addition to that resulting from H stripping, e.g. during agglutination. The time associated with the maximum C enrichments found in Apollo 16 soils,  $5 \times 10^3 \text{ yr}$ , is barely compatible with the age of the regolith and the turnover rates inferred from drill stem data. However, this derived time is governed by the value taken for the cosmic abundance of C, for which an uncertainty of a factor of four is probably realistic. Note that, during the period of evolution of regolith grain size towards its equilibrium value, our measure of sample 'age' is not linearly related to others such as cosmic ray exposure age.

Chou, C.-L., Baedeker, P. A., Bild, R. W., Robinson, K. L., and Wasson, J. T.: 'Volatile Elements in Lunar Soils'.

Suites of soil samples have been investigated in order to search for trends associated with element transport through the lunar atmosphere. Eight elements were analyzed – three highly volatile (Zn, Cd, In), four highly siderophile (Ni, Ge, Ir, Au) and one moderately volatile and siderophile (Ga); analytical techniques are as described earlier. We find progressive enrichment of Cd with decreasing grain size in sieve fractions of soil 65500, and a two-fold enrichment in the shaded soil 76240 compared to its unshaded control 76260. Cadmium, like its congener Hg, appears to be highly labile on the lunar surface. In contrast, Zn and In concentration trends in these samples offer little or no evidence of highly labile natures.

Data on the unsieved soil offer a control on possible contamination during the sieving process. With the exception of Au in the three finest fractions, there is no evidence of contamination. The distributions with grain size of Zn, Cd, Ni and Ir are presented. Whereas Cd concentration increases by a factor of 6 between the largest and smallest size fractions, Zn increases by only a factor of about 1.3. In contrast to data obtained in a previous study of sieve fractions the siderophiles are slightly enriched in the coarser size fractions.

The Cd concentration observed in the shaded soil is 1.25 times higher than that of the highest value observed in any of the ten other Apollo-17 soils which we studied, and twice as high as in the

control. No other element shows significant enrichments in the shaded soil. A higher value of In in the unshaded control is tentatively attributed to contamination.

Our analyses of four samples from an Apollo-17 trench show no significant change in Zn or Cd content with depth; In shows no variation in the three lowest levels but a significantly increased level in the surficial sample (contamination?). That volatiles are not depleted in the skim sample is evidence against a transport mechanism involving surficial volatilization by solar particles or photons followed by trapping of that material which falls through interstices to lower soil levels.

Two Apollo-17 samples collected from the surface (72461) and to a depth of 4 cm (72441) below a 0.7 m boulder near the South Massif show no significant difference in their Zn, Cd and In concentrations, nor do these differ appreciably from those in other mature soils from this site.

We have followed up on our previous study of atmophilic elements at the Apollo 15 site by studying soil 15421 with unusually high and soil 15601 with unusually low content of orphan Ar<sup>40</sup>. Sample 15421 has remarkably high Zn, Cd and In contents, and extends the previously observed trends between these elements and excess Ar<sup>40</sup> upwards about a factor of 2. The high Zn and Cd values in 15601 cause it to fall away from the trends, whereas the In value follows the trend. Soil 15401 plots far away from the trends. There is no correlation between Zn, Cd, or In and solar rare gas isotopes. We interpret these data to indicate the mixing of normal, mature mare-type Apollo-15 soil with and ancient lunar component enriched in Ar<sup>40</sup> and magmatically released volatiles. The situation is complicated by indications that Zn and Cd are enriched and excess Ar<sup>40</sup> depleted in the pyroxenitic green glass from the Apollo 15 site. The high Zn and Cd content of the low excess-Ar<sup>40</sup> soil 15401 is almost certainly related to its extremely high green-glass content. Sample 15421 deserves thorough study to determine the siting of its Zn, Cd, In and excess Ar<sup>40</sup>.

Brandt, W., D'Agostino, M. D., Kamykowski, E. A., Padawer, G. M., and Stauber, M. C.: 'Concentration vs Depth Profiles of Carbon and Hydrogen in Lunar Rock Surfaces'.

The carbon and hydrogen content of lunar materials has been the subject of extensive research. In the case of lunar fines an approximately inverse variation of the carbon content with the mean grain diameter has been observed from which it has been inferred that the observed carbon is of solar wind origin. Probing techniques offering submicron depth resolution are able to reveal the implantation of a more energetic flux component and to trace the diffusion of surface carbon into deeper-lying regions. We report on such measurements in 62255,27, using the nuclear reaction  $^{12}\text{C}(d, p)^{13}\text{C}$  as the probing mechanism. The lunar rock sample was bombarded with deuterons from the Grumman Research Van de Graaff accelerator; reaction protons from the transition to the ground state of  $^{13}\text{C}$  were sensed in a surface-barrier detector positioned at  $130^\circ$  with respect to the incident beam direction. For 1.5-MeV deuterons, for example, more than 99% of the carbon constituency measured resides within  $4\ \mu$  of the surface. The technique offers a detection sensitivity of  $40\ \mu\text{g carbon g}^{-1}$  sample with a depth resolution of  $\sim 0.3\ \mu\text{m}$ . For each specimen surface probed (lunar exterior and interior) two distinct spatial carbon components were observed: a  $\sim 2\ \mu\text{g-cm}^{-2}$  surface layer and a volume distribution. The observed implantations are interpreted in terms of the carbon flux components of the solar radiation.

We also report on additional measurements of hydrogen depth distribution in the (lunar-) exterior surfaces of 61016,135 and 61016,171. These measurements utilize the resonant nuclear reaction  $^1\text{H}(^7\text{Li}, \gamma)^8\text{Be}$ , initiated by a fast  $^7\text{Li}^+$  beam. We have previously demonstrated a sensitivity of  $10\ \mu\text{g H g}^{-1}$  sample in lunar material with a depth resolution of  $\sim 0.2\ \mu\text{m}$ . For comparison we also probed a (lunar) interior surface of 68815,25. In each case the  $^1\text{H}$  concentration profile was measured to a depth of  $\sim 0.5\ \text{mg-cm}^{-2}$  ( $\sim 2\ \mu\text{m}$ ); absolute concentrations were inferred from calibration bombardments of Kapton (a polyimide) and of NBS-certified H in-Ti standards. We note that the concentration profile obtained in the 68815,25 surface, which had been shielded from the lunar exterior, does not differ significantly from the profiles in the exterior surfaces of 61016,135 and 171. This implies that the observed hydrogen in the latter samples was largely introduced subsequent to their retrieval from the lunar surface, and most likely occurred in the course of preparing the samples for analysis.

Burnett, D. S., Leich, D. A., and Tombrello, T. A.: 'Trapped Solar Hydrogen in Lunar Samples'

The Interaction of solar particle radiations with lunar surface materials has been studied using a re-

sonant nuclear reaction depth analysis technique to measure the depth distributions of hydrogen in lunar samples. Samples were irradiated with a  $^{19}\text{F}$  ion beam (16–18 MeV) and prompt  $\gamma$ -rays from the  $^1\text{H}(^{19}\text{F}, \alpha)^{16}\text{O}$  reaction were counted to measure the H content as a function of depth. The basic problem in the interpretation of these measurements lies in distinguishing the component of lunar H from terrestrial contamination, notably adsorbed  $\text{H}_2\text{O}$ . Contamination has been minimized for samples returned in a vacuum-sealed sample container (66044,8; 68124,3; and 68124,10) and handled entirely under dry  $\text{N}_2$  gas prior to our analysis in a clean, ultrahigh vacuum scattering chamber. In addition to data reported previously we have also analyzed for comparison surface glass from rock 65315 which was not returned in a sealed rock box. In all cases small amounts of surface adsorbed H ( $\sim 2 \times 10^{15}$  atoms  $\text{cm}^{-2}$ , equivalent to one monolayer of  $\text{H}_2\text{O}$ ), are routinely observed on *interior* rock samples which have been exposed only to dry  $\text{N}_2$  gas. The source of this adsorbed H is undoubtedly terrestrial (most likely the small residual  $\text{H}_2\text{O}$  content of the 'dry'  $\text{N}_2$  gas), leading to the inevitable conclusion that similar features observed on lunar *exterior* surfaces of the same samples, including samples from the sealed rock box, are also due primarily to terrestrial contamination. This type of profile is illustrated for the 68124,3 glass sphere. As noted previously, most lunar glasses appear to retain solar wind hydrogen very poorly; thus, it is likely that much of the near surface (less than  $0.1 \mu\text{m}$ ) H in 65315 is due to  $\text{H}_2\text{O}$  contamination from the LM cabin atmosphere. We conclude that storage in the sealed rock box samples as well.

Several of the exterior surfaces, notably 68815,27 and some Apollo 11 and 15 coarse fines have shown an additional broad peak with a maximum H content near  $0.1 \mu\text{m}$  and with a width of  $0.2\text{--}0.3 \mu\text{m}$ . While extensive penetration of a terrestrial contaminant cannot be ruled out as a possible origin for this H component, contamination appears unlikely for the following reasons: (A) Exposure of artificially radiation-damaged fused silica surface to  $\text{H}_2\text{O}$ , even in liquid form, produced no penetration of  $\text{H}_2\text{O}$  to depths greater than  $0.1 \mu\text{m}$ , even for surfaces which were heavily damaged with  $^{16}\text{O}$  ions prior to  $\text{H}_2\text{O}$  exposure. (B) It appears doubtful that the exterior surface of 68815,27, which had never been exposed to atmosphere, could have adsorbed such large quantities of  $\text{H}_2\text{O}$  while the exterior surfaces of other samples, such as 68124,3, returned in the same sealed rock box, showed only small quantities of surface (within  $0.03 \mu\text{m}$ ) adsorbed H. Given the known tendency of glasses to hydrate, the 68124,3 glass sphere would have been expected to absorb much more  $\text{H}_2\text{O}$  than the surface of a crystalline rock sample such as 68815. Because the H content in 68124,3 is much less, we regard this as a strong argument that we are primarily measuring solar H in 68815 at all depths.

Taking the above at face value, the bulk of the H content at depths between  $0.1$  and  $0.4 \mu\text{m}$  in all samples is best interpreted as true lunar H rather than terrestrial contamination.

At present, we have confined ourselves to the discussion of the type of profile exhibited by 68815. Although implantation of solar wind protons is the most likely source, the observed H profiles are significantly more penetrating than the expected  $0.01\text{--}0.02 \mu\text{m}$  implantation depths, in agreement with conclusions based on chemical etching experiments for implanted rare gases. If solar wind H is the source of the 68815-type profile, extensive modification by diffusion is implied. Diffusion rates for H in terrestrial silicates are too rapid to account for the observed concentrations; thus, it appears that some sort of trapping has slowed down the diffusion process. A hypothesis in which implanted solar wind H diffuses rapidly into (and out of) the samples with a small remnant of the implanted dose being retained in radiation damage traps seems plausible. The heavy radiation damage, as documented by high voltage electron microscopy, in the outer  $0.05 \mu\text{m}$  precludes the existence of isolated traps in this region. Beneath this depth relatively intense radiation damage (but below saturation levels) may persist to a depth of  $\sim 0.2 \mu\text{m}$ , corresponding closely to the radiation damage range of He ions with velocities near those of frequent high velocity ( $\sim 800 \text{ km s}^{-1}$ ) solar wind streams observed by satellites. The population of isolated radiation damage traps by diffusing solar wind atoms may then result in a hydrogen depth profile which reflects the distribution of radiation damage. A discontinuity in the radiation damage gradient (i.e., a change in the effective diffusion coefficient) near a depth of  $0.2 \mu\text{m}$  may account for the characteristic flattening observed in the measured H profiles below  $\sim 0.2 \mu\text{m}$ . In this region, diffusion is still controlled by radiation damage (due here to solar flare and suprathermal ions) but the gradient of traps is much less.

An alternative explanation for the observed H profiles is the direct implantation of 'suprathermal' (10–100 keV) protons. In this case, the measured H profiles would provide information about the energy spectrum of the incident protons. A reasonably good fit to the initial set of H profile data for 68815 can be obtained using the energy spectrum of Frank, assuming that no post-implantation diffusion occurs and taking into account the effects of erosion and of incidence from a solar direction.

A two-component energy spectrum is necessary to produce the characteristic bend in the profile near  $\sim 0.2 \mu\text{m}$  deep. An atomic erosion rate of  $5 \times 10^{-9} \text{ cm yr}^{-1}$  had been assumed, implying a long-term flux of suprathreshold protons of  $\sim 10^{13} \text{ cm}^{-2} \text{ yr}^{-1}$ , within a factor of about 3 of the instantaneous flux for the event reported by Frank. Since the long-term flux of protons in this energy range is likely to be a few orders of magnitude lower than the flux during such an event, it appears unlikely that the average flux has been high enough to account for the measured H profiles by direct implantation. However, little data has been obtained in this energy range, and it is possible that long-term fluxes may have been high enough to account for a significant portion of the H distribution or at least to account for a significant radiation damage gradient in the  $0.2$  to  $0.4 \mu\text{m}$  depth region.

Bastin, G., Comstock, G. M., Dran, J. C., Duraud, J. P., Maurette, M., and Thibaut, C.: 'Lunar Soil Maturation, Part III: Short-Term and Long-Term Aging of Radiation Damage Features in the Regolith'.

### 1. Introduction

The exposure of lunar dust grains in the solar wind and in fluxes of more energetic solar nuclei produce ultra-thin amorphous coatings and nuclear particle tracks respectively. A comparison of the 'old' fossil tracks and coatings to the 'fresh' ones obtained for calibration purposes during artificial irradiation of similar grains can give interesting information concerning both ancient solar radiation and lunar dynamic processes. However this comparison, unless properly corrected, is meaningless if 'aging' processes have modified the characteristics of the 'old' radiation damage features during the maturation of the lunar regolith. In this paper we essentially show that the tracks, but not the amorphous coatings, have been severely 'aged' and we discuss how to properly use both types of radiation damage features to study ancient solar nuclear particle fluxes.

### 2. Aging of Radiation Damage Features in the Regolith

2.1. *Laboratory evidence for short-term aging:* (A) *Tracks.* In lunar dust grains the following characteristics show first that the 'fresh' tracks (FT) produced with an artificial beam of 537 MeV iron nuclei at the University of Manchester are different from the 'old' fossil tracks (OT), essentially due to VH nuclei of solar origin, and then strongly suggest that VH tracks freshly registered in lunar dust grains should undergo a very rapid short-term aging during their first near-surface exposure on the Moon: 1. the FT unless artificially stabilized disappear very quickly by 'ionization' annealing in the electron beam of the 1.5 MeV electron microscope. On the contrary the OT are very stable under the beam; 2. by applying our newly developed 'GINT' method we found that the length distribution of the FT and OT are very different. For example in feldspar grains from rock 15475 the FT lengths are peaked at about  $L_0 \sim 36\mu$  with a relatively high proportion of tracks ( $\sim 107$ ) showing lengths greater than  $55\mu$ , after the 'normal' etching time,  $t_0$ . However, the FT lengths drastically vary with the etching time and a few tracks ( $\sim 0.1\%$ ) become etched to  $\sim 70\mu$  after increasing this time up to  $10t_0$ . In contrast the length distribution of the OT in the same grains (which are certainly non mature as they were shielded inside the rock) is narrowly peaked at about  $L_0 \sim 15\mu$  and does not show any marked change with the etching time. The OT shortening is even more pronounced in feldspars from mature soils where Population II tracks have lengths  $\sim 2\mu$ ; 3. in a given grain the OT etch at least 2 times faster than the FT; 4. during thermal annealings conducted for feldspars the FT show a striking low temperature fading which is not observed for the OT and which is extremely marked for both the high energy (537 MeV) and low energy (23 MeV) ends of the FT. In particular by using conditions that simulate a 72-h exposure of the FT in the 'lunar day time', the length distribution of the 537 MeV FT is already drastically modified with the shortest tracks being almost completely suppressed and the longest ones showing a shortening of about 75%. When the annealing is pursued at higher temperature ( $400^\circ\text{C}$ ) the large spread in the FT length distribution is considerably reduced as a result of the preferential fading of the high energy part of the tracks and becomes roughly similar to that observed for the OT in lunar igneous rocks. Finally both types of tracks disappear at much higher temperatures ( $\sim 700^\circ\text{C}$ ) with the OT being slightly more resistant than the FT; (B) *Amorphous coatings:* the thickness and the appearance of the amorphous coatings are not affected by short-term aging. Indeed, the old as well as the fresh coatings are observed unmodified in the HVEM over long period of time, at high beam current. Furthermore the fresh coatings do not show any low temperature annealing and they only disappear, as do the old coatings, at high temperatures ( $\sim 750^\circ\text{C}$  for 2 h).

2.2. *Lunar evidence for an additional long-term aging of the tracks.* The OT shortening is more marked for mature than for non mature soil sample and this indicates that subsequent to their short-term aging the OT suffer a long-term aging possibly due to their repeated near-surface exposure on the Moon. In fact there are at least 2 populations of tracks in 200 mesh grains: population I is characterized by a relatively low density of tracks ( $10^7$ – $10^8$  cm $^{-2}$ ) generally  $\sim 10\mu$  in length with a wide range of gradients ( $\Gamma = 1$  to 10) which are anisotropic; population II is characterized by much higher densities ( $\gtrsim 10^9$  cm $^{-2}$ ) of short tracks ( $L \sim 2\mu$ ) with significant but more shallow ( $\Gamma = 1$  to 3) and generally rather isotropic gradients. We interpret population I as being younger tracks formed when their soil layer was last near the surface and population II as being older more mature tracks which result from being processed through several ejecta layers and near-surface gardening processes. In the most mature soil samples we also discovered a 3rd population of very short tracks ( $L \sim 0.5\mu$ ) with even higher densities ( $\gtrsim 5 \times 10^9$  cm $^{-2}$ ) but we cannot be certain that they represent very mature OT, as they show no gradient.

2.3. *Nature of the short-term aging process.* In non-mature lunar dust grains the marked OT shortening is due to the lunar thermal cycle and proceeds via the rapid annealing of the high energy part of the tracks. Furthermore, the implantation of heavy doses of solar wind nuclei in lunar dust grains plays certainly a major role in the rapid stabilization of the OT against ionization and perhaps thermal annealings as we observed the latent FT only in grains that were exposed to heavy doses of simulated solar wind subsequently to the iron beam irradiation.

### 3. Radiation Damage Parameters (RDP) and Ancient Solar Nuclear Particle Fluxes

3.1. *RDP that are not affected by aging.* The thickness,  $\Delta$ , of the amorphous coatings and the proportion of coated grains,  $P(\Delta)$ , in a given soil sample seem to be the only RDP that are not modified by aging effects: 1.  $P(\Delta)$  is a useful 'solar wind' index that correlates well with other indices of soil maturity; 2. the distribution of the coating thickness,  $\delta(\Delta)$ , as a function of the depth in lunar core tube reflects the variation with time of the thermal properties of the ancient solar wind. So far no secular trend with depth has been found both in the Apollo 15 and 16 core tubes but various clear stratifications in  $\delta(\Delta)$  have been observed.

3.2. *RDP that are possibly affected by aging.* It is very difficult to decide whether or not the low energy tracks which produce the 'suprathermal' and solar flare track gradients (ST and SF gradients) are most affected by aging than the tracks that are totally registered deeper within a grain. With these reservations, the main results of our track gradients studies are: 1. the SF gradients associated to the 'older' population II are in general much less steep and more isotropic than those observed for the 'young' population I. Our theoretical simulations suggest that this maturation of the gradients is consistent with repeated exposures in different orientations and depths; 2. non-mature soils do not contain ST gradient; 3. the proportion of grains with ST gradients in mature soil samples do not seem correlated either with  $P(\Delta)$  or with the smaller proportion of grains showing large coatings ( $\Delta \gtrsim 800 \text{ \AA}$ ). This observation suggests that the ST gradients are not due to particles emitted in correlation with solar wind nuclei; 4. very few layers in the Apollo 15 core tube contain grains with ST gradients whereas all layers contain grains with SF gradients and this would be expected if most grains retain a thin shielding layer of 'sticky' micron-sized grains during their exposure on the top surface of the regolith.

3.3. *RDP that are severely affected by aging.* It is quite clear that aging processes have drastically modified the track parameters (total etchable length,  $L_0$ ; etching rate,  $V_0$ ; stability against thermal and ionization annealing) that are currently used in several applications of the track method to lunar samples. To understand the nature of the track aging processes as well as to learn how to 'demodulate' fossil track parameters from aging effects it is necessary to study the track length distribution and track etching rate, both for the OT and several types of FT, as functions of various environmental parameters. Lal was the first in 1969 to propose a very clever method to measure  $L_0$  values in meteoritic crystals in which both individual long OT and cleavages were used to inject the etching solution into the OT (TINT and TINCLES method respectively). When we applied these techniques to the tiny 200 mesh lunar dust grains containing severely aged tracks and very few cleavages many difficulties were encountered. For example the etching behavior was highly irreproducible from one track-or-cleavage to the other. Therefore we decided to develop a new method that we call the 'giant track-

track' method (GINT method) to minimize such difficulties. In this method an individual grain is irradiated with a high dose of 400 MeV argon ions ( $\approx 10^{13}$  cm $^{-2}$ ), that are perpendicular to the sample and collimated with a rectangular slit with a very small aperture ( $\sim 2\mu$ ). We thus get a 'giant' argon track resulting from the overlapping of many individual tracks and extending to depth of about  $60\mu$ , which has well defined geometrical and etching characteristics, and which can be used to measure in a reproducible way track length distribution from *the edges to the center* of a grain or rock.

Holmes, H. F., Fuller, E. L., Jr., and Gammage, R. B.: 'Some Surface Properties of Apoll 17 Soils'.

The surface chemistry of Apollo 17 lunar fines samples 74220,35 (the orange soil) and 74241,42 (the gray control soil) has been studied by measuring the adsorption of nitrogen, argon, and oxygen (all at 77K) and also of water vapor (at 20°C). There are general similarities and some marked contrasts between these fines and those from the Apollo 12, 14, and 16 missions. Similarities include: 1. Initially (prior to water adsorption) these two samples had a low specific surface area 2. There was no evidence for a pore system of the type that affects gas adsorption isotherms (i.e., gives rise to capillary condensation hysteresis loops and are less than a few hundred angstroms in size) as the initial nitrogen isotherms were completely reversible over the entire pressure range 3. Both samples were attacked by water vapor at high relative pressures. 4. The attack by water vapor increased the specific surface area and created a pore system which gives rise to a capillary condensation hysteresis loop in the isotherms.

The value for sample 74220 after outgassing at 300°C (pre-H $_2$ O) is in good agreement with that reported by Cadenhead (0.46 m $^2$  g $^{-1}$ ).

In spite of the general similarity of all the results obtained to date there are significant specific differences, not only between 74220 and 74241, but also between these two and the previously studied fines. Both of the Apollo 17 samples were hydrophobic in their initial interaction with water vapor (water surface areas were about half of the nitrogen value). This can be contrasted with the hydrophilicity of the previous samples. However, both of the Apollo 17 samples were strongly hydrophilic after the attack by water vapor at high relative pressures. The alteration of sample 74220 was completed with one cycle in water vapor to high relative pressures. This is a sharp contrast to Apollo 12, 14, and 16 samples where the alteration process continued through several cycles. This difference may be related to the very high glass content of sample 74220. Another difference in sample characteristics may be seen in the blocking action of irreversibly adsorbed water. That the dependence of specific surface area and the size of the hysteresis loop on outgassing temperature is due to the presence of irreversibly adsorbed water is shown by the fact that one can reverse the effect of outgassing at an elevated temperature by the simple expedient of irreversibly adsorbing water on the sample. In the case of sample 74220 the effect of irreversibly adsorbed water on the specific surface area and hysteresis is much less than that observed with previously studied samples. In this respect sample 74241 is intermediate between 74220 and the previous samples. In the case of sample 74241 (and the previous samples) there is an increase in both the specific surface area and the size of the hysteresis loop when the outgassing temperature is increased from 200 to 300°C. Obviously this is not the case with sample 74220.

The general nature of the attack of lunar fines by adsorbed water at high relative pressures can be explained on the basis of forming a system of pores having wide bodies and narrow openings, with the narrow openings as the site where irreversibly adsorbed water blocks access of nitrogen to the pore system. The mechanism for the formation of this pore system has not been firmly established.

Neither of the two Apollo 17 samples would chemisorb carbon dioxide, independent of the presence or absence of chemisorbed water. In the case of these two samples there is no danger of surface contamination due to chemisorption of carbon dioxide from terrestrial atmospheres.

## 8. Characterization and Evolution of the Mare Basins: II

Walker, D., Longhi, J., Stolper, E., Grove, T., and Hays, J. F.: 'Experimental Petrology and Origin of Titaniferous Lunar Basalts'.

Compositional variation of titaniferous basalts from Tranquility Base and Taurus-Littrow can be ex-

plained in terms of lowpressure, crystal-liquid fractionation. The compositions do not represent a series of primary melts from the deep lunar interior nor can they be interpreted as the residue of crystallization of any common (low titanium) basaltic magma. They can be interpreted as low-pressure melting products of a plagioclase and ilmenite bearing cumulate, or they can be interpreted as residual liquids from a titaniferous parent magma.

Crystallization behavior of titaniferous basalts can be modeled by phase relations in the system  $\text{FmO}-\text{FmTiO}_3-\text{FmSiO}_3-\text{CaFmSi}_2\text{O}_6-\text{CaAl}_2\text{Si}_2\text{O}_8$  where  $\text{FmO} = \text{FeO} + \text{MgO}$ . For phase relations involving ilmenite or armalcolite, a  $\text{FmTi}$ -oxidesaturated pseudo-ternary liquidus diagram can be constructed with  $\text{FmO}$  and  $\text{Px}/\text{Px} + \text{Plag}$  as coordinates. The multiple saturation curves were located by microprobe analyses of liquids generated in melting experiments in iron capsules in evacuated silica tubes on rock-powder samples of 70215 and 70017.

The crystallization sequence begins either with olivine (70017 ~ 1225°C) or armalcolite (70215 ~ 1195°C) but both compositions become doubly saturated by 1175°C. Slightly above 1150°C armalcolite reacts with the liquid to form ilmenite. Plagioclase appears (1140–1145°C) before pyroxene, which is present in both by 1135°C. Olivine has reacted away by 1125°C.

The compositions of Apollo 11 ilmenite basalts are also plotted in these projections. The separate symbols follow the classification of James and Jackson. The phase relations determined for the Apollo 17 material are also appropriate to the Apollo 11 basalt crystallization. James and Jackson's petrographic observation that pyroxene appears before plagioclase in the intersertal group and plagioclase appears before pyroxene in the ophitic group is a natural consequence of the positions of the rocks relative to the saturation volumes. The ophitic group variation can be interpreted as being controlled by these saturation curves. The intersertal variation parallels the variation of multiply saturated liquids but appears to be displaced slightly, indicating similar but not identical control.

Although we confirm the experimental work of O'Hara *et al.*, we doubt that these rocks represent the liquid dregs of a strongly fractionated more primitive magma. Our work on 12002, a primitive picrite, has shown that high-Ti liquid is indeed generated as the residuum. However, this material approaches ilmenite saturation only below 1125°C and would be equivalent only to the more siliceous (low FmO) varieties of the intersertal group. The ophitic group and most of the intersertal group compositions and petrography indicate a higher temperature history in which early saturation with a  $\text{TiFm}$  oxide phase occurred. The presence of magmatic armalcolite is inconsistent with the proposition that titaniferous basalts are the residual liquids of primitive basalt crystallization.

How then are they formed? It is possible that the titaniferous basalts represent low-pressure partial melts of a feldspathic cumulate produced in the crystallization of a primitive basalt if the source layer in the cumulate had excess ilmenite. It is also possible that these rocks were produced by low-pressure fractional crystallization of a titaniferous primitive magma. Such a magma could be produced by partial melting of an ilmenite bearing source rock at modest depth. For example, the vitrophyre 70215 would be in equilibrium with the assemblage olivine-pigeonite-ilmenite-spinel at a depth of 100 km (5kb). A liquid of this composition would be a suitable parent for both the Apollo 17 suite and Apollo 11 ophitic suite. A different parent liquid is required for the Apollo 11 intersertal suite, but the required differences may be small.

Lipin, B. R. and Muan, A.: 'Equilibria Bearing on the Behavior of Titanate Phases During Crystallization of Iron Silicate Melts under Strongly Reducing Conditions'.

Phases in which titanium is present as a major constituent (for instance ilmenite, spinel, armalcolite) are relatively abundant in lunar rocks from the mare regions, and serve as potential indicators of crystallization sequences and thermal history of these rocks. The interrelations among the various titanate phases under carefully controlled laboratory conditions have been delineated previously for a number of oxide combinations (e.g.  $\text{MgO}-\text{Al}_2\text{O}_3-\text{TiO}_2$ ,  $\text{MgO}-\text{Cr}_2\text{O}_3-\text{TiO}_2$ ,  $\text{FeO}-\text{Al}_2\text{O}_3-\text{TiO}_2$  and  $\text{FeO}-\text{Cr}_2\text{O}_3-\text{TiO}_2$ ). The present work deals with equilibria among titanates in the presence of a liquid phase in relatively simple model systems where the various parameters can be carefully controlled. The studies reported herein represent the initial part of an investigation of liquidus-solidus relations in the system  $\text{CaAl}_2\text{Si}_2\text{O}_8-\text{CaMgSi}_2\text{O}_6-\text{FeO}-\text{TiO}_2$  under strongly reducing conditions, and is concerned specifically with phase relations in the composition volume  $\text{CaAl}_2\text{Si}_2\text{O}_8-\text{Fe}_2\text{TiO}_4-\text{FeTi}_2\text{O}_5$  of the above system. Within this composition volume occur under equilibrium conditions the main titanate phases of lunar rocks (ilmenite, ulvospinel and pseudobrookite), as well as hercynite, in equilibrium



with a silicate liquid, with or without the presence of anorthite as a crystalline phase, depending on the composition of the mixtures. The interrelations among the various titanate phases and hercynite under these conditions is the main subject of this study.

Oxide mixtures of desired compositions were prereacted and preduced in CO<sub>2</sub>/CO atmospheres and subsequently placed in iron crucibles and sealed into silica glass capsules for equilibration under conditions approximating those prevailing on the lunar surface. Following equilibrations, the samples were quenched rapidly to room temperature and the phases identified by microscopy, X-ray diffraction and electron microprobe analysis.

Phase relations at liquidus temperatures in the system CaAl<sub>2</sub>Si<sub>2</sub>O<sub>8</sub>-Fe<sub>2</sub>TiO<sub>4</sub>-FeTi<sub>2</sub>O<sub>5</sub> are characterized by three piercing points with temperatures and phase assemblages as follows: at 1300 ± 5 °C ilmenite, ulvospinel, ferropseudobrookite and liquid are present together in equilibrium. Another piercing point at 1260 ± 5 °C is characterized by the coexistence of ulvospinel, ferropseudobrookite, hercynite and liquid. Finally, at 1270 ± 5 °C hercynite, ferropseudobrookite and anorthite are the crystalline phases in equilibrium with liquid.

Relations more closely approaching those of lunar rocks are obtained by adding CaMgSi<sub>2</sub>O<sub>6</sub> to the system. Preliminary data on the bounding system CaMgSi<sub>2</sub>O<sub>6</sub>-FeO-TiO<sub>2</sub> have established the coexistence of olivine and/or clinopyroxene in equilibrium with one or more of the titanate phases ilmenite, ulvospinel, or pseudobrookite within this model system at temperatures in the range of approximately 1250-1300 °C. These liquidus temperatures are lowered to approximately 1150-1200 °C in the system CaAl<sub>2</sub>Si<sub>2</sub>O<sub>8</sub>-CaMgSi<sub>2</sub>O<sub>6</sub>-FeO-TiO<sub>2</sub>, where one or more of the phases olivine, clinopyroxene, and anorthite coexist with liquid and one or more of the titanate phases ilmenite, ulvospinel and pseudobrookite. The sequences of appearance of the various titanate phases depend on the partitioning of cations between the liquid and the crystalline phases, and on the effect of cation combinations on the stability interrelations among the various titanates. The latter relations have been determined for a number of ionic combinations. Addition of Al<sup>3+</sup> or Cr<sup>3+</sup> to ilmenite decreases the stability of the latter phase relative to the phase assemblage spinel plus pseudobrookite at temperatures above the lower stability limit of pseudobrookite.

Rutherford, M. J., Hess, P. C., and Daniel, G. H.: 'Liquid Lines of Descent and Liquid Immiscibility in High Ti Lunar Basalt'.

Experiments have been performed on rock 70017,29 to derive a series of cogenetic salic liquids that represent potential end products of lunar basalt fractionated at low pressure. Rock 70017 (29 and 127) is a medium grained (<3 mm) porphyritic basalt composed of 22% ilmenite, 2% olivine (Fo<sub>74-65</sub>), 49% Ca-pyroxene (zoned En<sub>48</sub>Wo<sub>35</sub>Fs<sub>17</sub> to En<sub>31</sub>Wo<sub>23</sub>Fs<sub>46</sub>), 23% plagioclase (An<sub>88</sub>Ab<sub>11</sub> to An<sub>76</sub>Ab<sub>21</sub>Or<sub>3</sub>) and minor pigeonite (En<sub>63</sub>Wo<sub>7</sub>Fs<sub>30</sub>), cristobalite and mesostasis. Glass containing exsolved Fe-rich spherules is present in the cristobalite. The composition of these immiscible melts indicates that they are closer to the critical state than those in Apollo 11 basalts possibly due to higher temperature, or some compositional effect. In the experiments, chips of 70017,29 were wrapped in Mo foil, sealed in evacuated SiO<sub>2</sub> glass tubes and either partially melted or significantly melted and then recrystallized. Rocks with the composition of the resulting glasses were synthesized and used in subsequent experiments.

Representative compositions of the fractionated liquids show that as MgO decreases, TiO<sub>2</sub> decreases uniformly and SiO<sub>2</sub>, FeO, MnO and K<sub>2</sub>O increase. A liquid line of descent constructed with similar data for Apollo 12 basalts contrasts with this, but where the paths intersect, the liquids have similar major element concentrations. If the highly differentiated Apollo 12 liquids were to be fractionated at this point, presumably the liquid would then follow a path similar to 70017.

The significant results of the experiments on 70017 are that (1) only minor SiO<sub>2</sub> enrichment was achieved in the highly fractionated liquids although 95% of the basalt was crystallized, and (2) the immiscible liquid field has been approached and probably reached from the iron rich side.

The geological significance of the results is that (1) the field of liquid immiscibility was apparently reached with a randomly chosen fractionation path and major SiO<sub>2</sub> enrichment is not necessary to achieve it. (2) The amount of melt present at the onset of liquid immiscibility can be several times the amount of SiO<sub>2</sub> rich mesostasis, the Fe-rich fraction being camouflaged as additions to Fe rich minerals. (3) The amount of total immiscible melt in a lunar soil could be as much as 4 times the amount of granitic component if the latter were the result of liquid immiscibility, a fact which has a bearing on the trace element content of the soil.

O'Hara, M. J., Biggar, G. M., Humphries, D. J., and Saha, P.: 'Experimental Petrology of High Titanium Basalt'.

Experimental results for 28 synthetic compositions related to high Ti-basalt run in molybdenum capsules at the  $fO_2$  ( $f$  = clinopyroxene) of the Fe/FeO equilibrium. Primary liquidus fields of olivine, pigeonite, augite, anorthite, ilmenite and armalcolite are found, and the six fields must come close to conjunction in a cotectic liquid whose composition lies intermediate between 528 and 89, all six phases appearing almost simultaneously at the liquidus in such a liquid, at a temperature of close to 1145°C. The orange soil 74220 has a very high liquidus temperature, and extensive early olivine crystallization before the entry of other phases. Apollo 17 high  $TiO_2$  rock compositions show early crystallization of iron-titanium oxides and ferromagnesian silicates before anorthite appearance. The compositions of Apollo 17 rocks and soils resemble those of Apollo 11 materials, but are poorer in silica, and higher in  $Mg/Mg + Fe$ . The average rock composition erupted at the Apollo 11 site was that of a liquid in simultaneous equilibrium with many crystalline phases (including anorthite). Phenocrysts of anorthite, olivine, ilmenite, spinel and pyroxene were all present in small amounts in evidently rapidly quenched matrix among the lithic fragments in soils and breccias.

The chemical characteristics of the high titanium basalts and soils are best accounted for if the original magma was derived from the residual liquid in a high level magma chamber in which there was well advanced extreme fractional crystallization of anorthite-bearing cumulates. Eruption was followed by enrichment of the flow base in olivine and iron-titanium oxides relative to the upper parts. If such a model is adopted for Apollo 17 the orange soil must be regarded as an impact melt, an interpretation supported by the liquidus temperature which is exceptionally high for a magma of internal origin.

Fields in which pigeonite (PIG), anorthite (AN), olivine (OL), or titanium-rich oxide (TI-OXIDE) are the liquidus phases are indicated. Anorthite does not appear as a liquidus phase at this low oxygen fugacity in the compositions 1-9, 23, 56, 59, 69, 89 but its liquidus field lies very close to the surface defined by those compositions. Samples 28 and 38 both display anorthite liquidus as do samples 838, 538 and 528 which are intermediate between 8 and 38, 5 and 38 and 5 and 28 respectively. The narrow anorthite field indicated between the olivine and pigeonite fields thus expresses the composition region in which anorthite will most readily crystallize from  $TiO_2$ -rich magmas in the presence of olivine and pigeonite.

Duncan, A. R., Erlank, A. J., Willis, J. P., Sher, M. K., and Ahrens, L. H.: 'Trace Element Evidence for a Two Stage Origin of High-Titanium Mare Basalts'.

We have previously noted near constant ratios of certain pairs of elements (K/Zr, K/Ba, Zr/Nb, Zr/Ba) in Apollo 12, 14 and 15 samples, and have indicated that samples which are cumulates or are derived from cumulates (e.g. Apollo 16 anorthosites) are liable to show greater variation in these ratios.

Our data for Apollo 17 materials show perturbation of the inter-element relationships previously observed, exhibiting a systematic variation of many inter-element ratios with  $TiO_2$  content. The trends clearly represent mixing lines between a low  $TiO_2$  component with what we have come to call 'normal' lunar inter-element ratios and a high  $TiO_2$  basaltic component with severely perturbed ratios. It is apparent that the perturbed ratios must be characteristic either of the basaltic liquids or of a cumulus phase in the basalts. Since basalt 70215 has strongly perturbed ratios, and cannot texturally be a cumulate, we consider that in the general case it must be the Apollo 17 basaltic liquids which have the perturbed ratios.

Perturbations of many of the inter-element ratios (K/Zr, Zr/Nb, Zr/Ba) could be explained if high-Ti basaltic liquids were extensive melts of ilmenite-rich cumulates, assuming the high Zr contents of lunar ilmenites and Zr/Nb ratios of approximately 1 such as those in kimberlite ilmenites. Kimberlitic ilmenites seem relevant in view of their high Zr content (~1000 ppm) and the presence of armalcolite in kimberlite. However, the perturbation of K/Y and Zr/Y ratios in high-Ti basaltic liquids cannot be a consequence of their derivation from ilmenite cumulates since the Y content of lunar and kimberlitic ilmenites is very low. Armalcolite cumulates do not seem a suitable alternative in view of the low Zr content of most armalcolites. Other reported phases that are rich in Ti, Zr, Nb and Y (e.g. phase  $\beta$ , phase X, phase Y, etc.) do not seem suitable cumulus minerals in view of their

trivial abundance and very late stage of crystallization in lunar rocks. We conclude that there is strong evidence for derivation of high-Ti basalts by extensive melting or assimilation of an earlier Ti-rich cumulate but that the exact cumulus assemblage cannot as yet be determined.

Available data for Apollo 11 low-K, high-Ti basalts also show perturbed ratios and a comparable two stage model is applicable. The presence of a similar Ti-rich cumulate below two widely separated sites on the Moon leads us to speculate that such cumulates may have formed as a complement to the early anorthositic crust of the Moon.

Eggleton, R. E., Schaber, G. G., Thompson, T. W., and Zisk, S. H.: 'Lava Flows in Mare Imbrium, Part II: Evaluation of Anomalously Low Earth-Based Radar Reflectivity'.

A new comparison of photogeology with Earth-based mapping of color and radar reflectivity in the western two thirds of Mare Imbrium shows that, in general, good correlation exists between very weak 70 cm wavelength radar reflectivity and 'blue' mare deposits of Eratosthenian age and Imbrian age in the Imbrium Basin; the agreement is especially striking with the youngest Eratosthenian eruptives. Reflectivity variations on the 3.8 cm wavelength Earth-based radar maps agree generally with those at 70 cm but only poorly characterize mare units of different age in the Basin, possibly due mainly to a strong backscattering effect of the abundant 1 cm to 10 cm size rocks that are common to the explored mare surfaces.

The present study summarizes and evaluates those physical and chemical parameters that most likely could be responsible for the anomalously low radar backscatter; namely (i) low surface roughness and slopes at various scales, (ii) regolith and basalt substrate chemistry leading to high attenuation, (iii) low crater and surface rock frequency distributions, (iv) thick attenuating regolith. Thompson, *et al.* showed that rock populations on the surface and in the shallow subsurface in the vicinity of impact craters were directly responsible for observed positive thermal (infrared) and positive 3.8 cm and 70 cm radar anomalies. The present study and others have indicated, however, that the very weakest depolarized radar backscatter signals are probably not simply due to reduced surface rock populations, but instead may be sensitive to one or more parameters, such as TiO<sub>2</sub> content innate to mare materials with low visible albedo and 'blue' color.

Surfaces of the three different Eratosthenian basalt units in Mare Imbrium defined by Schaber dramatically decrease in radar backscatter ability with increasing youth. In test areas the percentages of area with 70 cm depolarized reflectivity less than 40–50% of the average intercrater level of reflectivity are: phase I, 17%; phase II, 33%; and phase III, 64%. The parameters responsible for abnormally weak diffuse scattering must increase substantially for lava phases I, II and III, respectively. Although the effects on the radar backscatter of regolith depth, crater populations and surface smoothness were investigated during the present study, none were found to satisfactorily explain the radar behavior. Chemistry-related, signal attenuation could locally be the dominant effect.

Lidsley, D. H., Hartzman, M. J., Kesson, S. E., and Cushman, M. K.: 'Fe-Mg-Ti Oxides in Lunar Mare Basalts: Chemical Evolution Interpreted from Experiment and Theory'.

The compositions of several lunar oxide minerals – most armalcolites and ilmenites, and some ulvöspinel – fall essentially in the system FeO–MgO–TiO<sub>2</sub>. Phase relations in this system can thus aid in the interpretation of the paragenesis of these minerals. Most armalcolites (Arm) are essentially solid solutions between FeTi<sub>2</sub>O<sub>5</sub> (ferropseudobrookite, Fpb) and MgTi<sub>2</sub>O<sub>5</sub> (Karooite, Kar); Fe/(Fe + Mg) is variable but tends to approach 0.5. Both textural reactions (many armalcolites are mantled by ilmenite) and melting experiments on lunar basalts strongly indicate that armalcolite is stable at high temperatures but tends to disappear by reactions of the type:

$(\text{Mg, Fe})\text{Ti}_2\text{O}_5(\text{Arm}) + \text{FeO}(\text{from melt}) = 2(\text{Fe, Mg})\text{TiO}_3(\text{ilmenite})$  (A) Analogy with the Fe<sub>2</sub>TiO<sub>5</sub>–FeTi<sub>2</sub>O<sub>5</sub> system suggested that armalcolite might be inherently unstable with respect to magnesian ilmenite plus rutile at low temperatures. This is confirmed by experiments in the join FeTi<sub>2</sub>O<sub>5</sub>–MgTi<sub>2</sub>O<sub>5</sub>: for example, Fe<sub>0.5</sub>Mg<sub>0.5</sub>Ti<sub>2</sub>O<sub>5</sub> is not stable below 1030 ± 10°C. Note that extrapolation of data obtained at high pressures suggests that the breakdown of pure MgTi<sub>2</sub>O<sub>5</sub> will occur near 600°C. The lowest temperature at which armalcolite of a given composition is stable: reaction with liquid or another phase will tend to increase the minimum temperature of stability. On the other hand, if com-

ponents other than  $\text{FeTi}_2\text{O}_5$  and  $\text{MgTi}_2\text{O}_5$  enter into armalcolite, it may be stabilized to lower temperatures than indicated. An important example of such stabilization is shown by experiments on Fpb (or Arm) plus  $\text{Fe}^\circ$  at temperatures 40–50°C below the minimum stability for each pure phase. The Fpb (or Arm) reacted with 2 wt%  $\text{Fe}^\circ$  to form ilmenite + Fpb (or Arm) with unit cell different from that of the starting material, and *no rutile*. The reaction for  $\text{FeTi}_2\text{O}_5$  appears to be:  $4\text{FeTi}_2\text{O}_5$  (Fpb) +  $\text{Fe}^\circ = 5\text{FeTiO}_3$  (Ilm) +  $\text{Ti}_3\text{O}_5$  (in solid solution with Fpb). The reaction of approximately 2%  $\text{Fe}^\circ$  corresponds to 10–15%  $\text{Ti}_3\text{O}_5$  entering into the solid solution. The exact reaction for  $\text{Fe}_{0.5}\text{Mg}_{0.5}\text{Ti}_2\text{O}_5$  is more difficult to determine, but the absence of rutile from the products at 980° strongly suggests that  $\text{Ti}_3\text{O}_5$  component also enters into solid solution with armalcolite. These results show that it is risky to melt high-Ti basalt in iron containers without evidence that it was saturated with  $\text{Fe}^\circ$  throughout its melting interval.

Molar volumes of armalcolites are approximately 10% greater than those of compositionally equivalent ilmenite + rutile ( $50.51 \pm 0.09 \text{ cm}^3 \text{ mole}^{-1}$ ) and geikielite + rutile ( $49.68 \pm 0.08 \text{ cm}^3 \text{ mole}^{-1}$ ) thus, it is expected that armalcolite will become less stable with increasing pressure.

The schematic T- $f_{\text{O}_2}$  section for part of the system Fe–O–TiO<sub>2</sub> serves as a model for several important reactions in high-Ti lunar basalts. The reaction  $\text{Usp} + \text{Fpb} = \text{Ilm}$  (Curve A), which is metastable with respect to oxide melting, is analogous to reaction (A) in basalts, with Usp proxying for FeO from the silicate melt at lower temperatures. Curve B is the lower stability limit for  $\text{FeTi}_2\text{O}_5$ . Curve C is the reaction  $\text{Ilm} = \text{Usp} + \text{Rut}$  and point D represents the combined breakdown and reduction reaction  $\text{Ilm} = \text{Usp} + \text{Rut} + \text{Fe}^\circ$ ; both reactions are observed in Apollo 17 basalts with the important difference that the presence of Cr in the spinel undoubtedly stabilized the breakdown assemblage to higher temperatures.

#### Ringwood, A. E.: 'Minor Element Chemistry of Maria Basalts'.

High pressure-temperature investigations on maria basalts have been used to infer the composition of their source region and conditions of formation. It was concluded that maria basalts formed by varying degrees of partial melting of a pyroxenite source region at depths of 200–400 km. The abundances of Ca, Al, and other elements possessing highly involatile oxides, eg. U, Sr, Ba, REE, were believed to be present in the source region at about twice chondritic levels. An acceptable theory of petrogenesis relating maria basalts to their source regions and based upon mineralogy and major element chemistry must also be capable of explaining the minor element chemistry of maria basalts. This objective has been difficult to realize.

The principal minor element characteristics which must be explained are as follows: (A) The abundances of incompatible elements (eg. U, Th, Sr, Ba, REE, Zr, Ta, Li) vary more or less continuously over a tenfold range from 10× chondritic (Apollo 15) to 100× chondritic (Apollo 11, hi K). If Green Glass is included, the total range is twentyfold. (B) Despite this very large range of *absolute* abundances, the *relative* abundances within this group rarely deviate from chondritic relative abundances by more than a factor of two. Yet the individual crystal-liquid partition coefficients for elements within this group vary considerably, eg. the coefficients for Yb and U in pyroxene vary by more than 100. (C) Titanium seems to behave as an incompatible element. The Ti/Zr ratios of most maria basalts and Green Glass (except Ap. 17) agree with the chondritic ratio within a factor of two. (D) The magnitude of the Eu (and Sr) anomalies show a general trend to decrease as the absolute abundances of incompatible elements decrease, eg. through the sequence Apollo 11 hi K, Apollo 11 low K, Apollo 14, Apollo 12, Apollo 15, Green Glass. This trend is also one of increasing degree of partial melting. (E) Whereas the absolute abundances of most incompatible elements vary by more than tenfold in maria basalts, the abundances of Sr vary only over a threefold range. (F) Many basalts exhibit significant (mostly  $\leq 2$  fold) depletion of light rare earths relative to intermediate REE. (G) Many maria basalts have Rb/Sr model ages of about 4.5 b.y. whereas their crystallization ages are 3.2–3.8 b.y.

Several hypotheses have attempted to explain the above characteristics. One proposes that maria basalts were formed by varying degrees of equilibrium partial melting of a source material containing incompatible elements at several times chondritic levels and in which plagioclase was an important component. This model fails since major element phase equilibria demonstrate that plagioclase was not present in the source region of most maria basalts during partial melting. Moreover, in view of the very different crystal-liquid partition coefficients for many incompatible elements, it is difficult to explain the small degree of fractionation within this group over a 20-fold total range of absolute

abundances. Some previous attempts to achieve this have used doubtful partition coefficients, and postulated mineral assemblages which were not permitted by phase equilibrium data. Finally, the model does not readily explain characteristics C, F and G above.

According to a second hypothesis, maria basalts were formed by equilibrium partial melting of pyroxene-rich cumulates which underlay and were complementary to the highland anorthositic crust. This model can explain the presence of Eu (and Sr) anomalies, the absence of plagioclase on the liquidus of maria basalts, the moderate depletions of the light rare earths and the 4.5 b.y. model ages. There are serious difficulties however. The model does not explain the correlation between the magnitude of the Eu anomaly and the level of abundances of incompatible elements, the inference that the anomaly decreases as the extent of partial melting increases and that for large degrees of partial melting the anomaly almost disappears, implying that the source region of maria basalts did not possess an intrinsic anomaly. The model also encounters difficulties in explaining characteristics A and B above. It is hard enough to explain these with a single stage of partial melting of relatively primitive material. To propose that patterns A and B above can be explained by partial melting of oncefractionated cumulates is scarcely credible. Moreover, it is difficult to provide acceptable heat sources for melting refractory cumulates. Most of the original U and Th will be in the highland crust, not in the cumulate layer. The high Ti contents of many maria basalts are unexplained since experiments show that Ti is a late-crystallizing component and enters early cumulates only in minor amounts. Other characteristics unexplained by this model are C and E above.

Difficulties with the above bulk equilibrium models suggest exploration of surface or local equilibrium models. We propose (a) that the bulk of the incompatible elements in the source region (including Rb, K) are located in accessory minerals. (b) that most of the Eu and common Sr are located initially in a refractory phase and that only limited equilibrium is reached so that most of the radiogenic Sr remains in the low melting accessory Rb, K phase, (c) that during partial melting, the accessory minerals containing the incompatible elements and Sr 87 enter the first increment of liquid in toto. This increment is immediately segregated from the system. With further degrees of melting, this liquid is diluted by major elements from the pyroxenite source whilst Eu and Sr are contributed by partial melting of the refractory phase.

An early version of this model proposing that the trivalent REE were contained in accessory phosphates whereas Sr and Eu were partitioned in pyroxenes explained in principle, characteristics A, B, D, E and G above. However C was unexplained and this version of the model requires modification. An extended hypothesis is presented below.

We consider that the Moon accreted from material which had ultimately formed by fractional condensation from a gas phase of appropriate composition. The essential members of the condensation sequence with falling temperature were perovskite, melilite, forsterite, enstatite, alkali feldspar. As the gas cooled over an extended period (> 100 yr) large megacrysts (> 1 m) were formed. Trace elements were partitioned into these phases according to equilibrium condensation and crystal chemical relationships. The following predictions can be made on these grounds: trivalent REE would mainly enter perovskite, most of the Eu and Sr would enter melilite together with an appreciable proportion of light REE, Rb would enter alkali feldspar. The moon accreted from a mixture of these condensates to form a disequilibrium mineral assemblage with a *bulk composition similar to that of the pyroxenite source region of maria basalts*.

After heating deep in the lunar interior, solid state reaction occurred around megacryst boundaries to form an equilibrium pyroxenite containing large unreacted cores of refractory melilite (or its high pressure derivatives) and perovskite. The latter mineral readily forms low melting point liquids when in contact with pyroxenes whereas melilite remains relatively inert. As partial melting commenced, all the perovskite and other low melting phases (eg. alk. feldspar) entered the first liquid which thereby received most of the incompatible elements (except Eu, Sr) present in the source region. This liquid was withdrawn as in the earlier model and diluted by liquids resulting from further degrees of partial melting of the equilibrium pyroxenite. Refractory melilite cores were gradually consumed, thereby supplying relatively constant amounts of Eu and Sr to liquids so produced. It is suggested that this model, in principle, is capable of explaining characteristics A, B, C, D, E, F, G above.

Barker, C. and Sommer, M. A.: 'Gas Release Patterns for 15016 and 15065 and their Significance'.

It is now well established that, in comparison with terrestrial rocks, the lunar samples are poor in both

gases and volatile elements (except for those introduced from the solar wind). Either crushing or heating can be used to release the gas from rocks for analysis. Interpretation of the composition of the gas released by crushing is complicated by adsorption of polar compounds onto the new surfaces generated by the crushing since this changes both the amount and composition of the gas. The gas released by melting rocks is also difficult to interpret because it may have come from many different sites within the rock. However, because each site has its own characteristic temperature for gas loss, a slow heating from room temperature to the melting point releases gases from the various sites at different times. This technique has been used in the present study.

A quadrupole mass spectrometer was used to monitor the evolution of gas from 15016:48 (basalt), 15065:44 (gabbro), ten terrestrial basalts and four chondrites. Heating rates of  $10^{\circ}\text{C min}^{-1}$  were used and the mass spectrum scanned continuously at  $137 \text{ s scan}^{-1}$ . Samples of approx. 20 mg were loaded into a side arm above an alumina sample tube and left under vacuum overnight. The outgassed alumina sample boat and tube were given a preliminary heating to  $1000^{\circ}\text{C}$  to remove adsorbed gas, cooled to room temperature and loaded with the sample by pushing it out of the side arm with a magnet. The lunar samples were loaded into the sample tubes in a nitrogen dry box.

All the samples studied showed three distinct episodes of gas evolution. For the terrestrial basalts the initial gas release, in the temperature range from 50 to  $500^{\circ}\text{C}$ , can be related to alteration, with the most highly altered samples giving the largest contribution, but even fresh samples also release gases (mainly  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ) in this range. Acid leaching reduces the amount of gas evolved and removes the carbon dioxide evolution peaks characteristic of carbonates. The lunar samples also evolve much of their gas in this low temperature range. This gas is richer in water and carbon dioxide than the gas released at higher temperatures. A  $\text{CO}_2$  peak, unrelated to the release of other gases, occurred at  $500^{\circ}\text{C}$  in both 15016 and 15065 and is thought to correspond to carbonate decomposition.

An intermediate-temperature gas release ( $700\text{--}1000^{\circ}\text{C}$ ) is present in both lunar samples. By analogy with the terrestrial basalts this is tentatively attributed to the rupturing of gas vesicles. The terrestrial basalts show a correlation between the amount of gas released by crushing and the size of the intermediate peak. No crushing experiments were carried out with the lunar samples.

The final gas release occurs near the melting point. Experiments with terrestrial samples indicate that this gas comes from melt inclusions, fluid inclusions or the mineral lattice. Fluid inclusions do not appear to be important in lunar samples and the contribution from the mineral lattice is small for samples which crystallized within a few miles of the surface. This suggests that melt inclusions are the main source of gas released from lunar samples at high temperatures. As the minerals crystallized, they trapped small volumes of the melt together with the gas dissolved in it. Thus the gas released from melt inclusions should be the best estimate of the composition of the gases associated with the magma. Samples 15016 and 15065 differ from all terrestrial basalts analyzed in having CO as the major component, with only minor amounts of  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{H}_2$  and other gases. The Allende chondrite is the only other sample which has evolved gas with a composition similar to that from the lunar samples. Gases react with one another very rapidly at high temperatures and it is probably misleading to quote compositions in terms of specific compounds.

Donaldson, C. H., Lofgren, G. E., Mullins, O., and Williams, R. J.: 'Experimentally Reproduced Textures and Mineral Chemistry of A-15 Quartz Basalts'.

The quartz normative (QN) basalts from the Apollo 15 site display a range of textures from vitrophyric to ophitic but only minor variations in bulk chemistry suggesting sampling from various positions in a single cooling unit. If these textures can be reproduced experimentally, it would be possible to determine the chemical fractionation and the emplacement history of this group of mare basalts. Accordingly we have crystallized a synthetic QN basalt composition at different cooling rates in an attempt to reproduce the textures and mineralogical trends observed in QN basalts.

The experiments were performed in a one atmosphere vertical furnace with oxygen fugacity ( $f\text{O}_2$ ) controlled by C-O gas mixtures and monitored with an oxygen electrode. Pellets of synthetic QN basalt glass were suspended on a Pt wire loop and melted for three hours at  $1255^{\circ}\text{C}$  with a  $-\log f\text{O}_2 = 11.9$  ( $25^{\circ}\text{C}$  above the liquidus). The charges were cooled  $200\text{--}230^{\circ}\text{C}$  ( $4^{\circ}/\text{hr}^{-1}$  run cooled  $120^{\circ}\text{C}$ ) at monotonic cooling rates between 2.5 and  $1260^{\circ}\text{C}/\text{hr}^{-1}$  and quenched. The  $f\text{O}_2$  changed continuously, in some runs increasing to 0.5 log units above ironwüstite (IW), in others remaining 0.5 log units below IW. Two charges were initially melted at  $1255^{\circ}\text{C}$  and then crystallized isothermally for 24 hrs, one at  $1188^{\circ}$  and the other at  $1160^{\circ}\text{C}$ , both about 0.4 log units below IW.

The minerals crystallized in the sequence chromite and metallic iron, olivine and pigeonite, augite, plagioclase, and ilmenite. Textures and grain size vary systematically with cooling rate. With decreasing cooling rate crystal morphologies change from dendritic → skeletal → equant and average grain size coarsens. At the slower cooling rates the pyroxene grain size becomes increasingly bimodal and the texture porphyritic. In the  $2.5^\circ \text{ hr}^{-1}$  run the pyroxene phenocrysts are set in a subophitic groundmass that has random fan spherulites of plagioclase and pyroxene.

Mineral chemistry has been determined on a few of the runs.

*Olivine.* Skeletal olivines in the  $1160^\circ\text{C}$  run are unzoned and range from  $\text{Fo}_{63}$  to  $\text{Fo}_{65}$ . Those in the  $30^\circ \text{ hr}^{-1}$  run are zoned from  $\text{Fo}_{63}$  to  $\text{Fo}_{54}$ . Ca contents range from 0.42 to 0.25 wt% and Cr, from 0.14 to 0.22 wt%.

*Plagioclase.* The plagioclase in the  $4^\circ \text{ hr}^{-1}$  and  $2.5^\circ \text{ hr}^{-1}$  runs is zoned,  $\text{An}_{97}$  to  $\text{An}_{94}$ , with less than 0.3 mole % Or. FeO contents range from 0.8 to 1.1 wt% and MgO, from 0.3 to 0.6 wt%. The synthetic plagioclases like the plagioclases from mare basalts are nonstoichiometric, but to a greater degree.

*Pyroxenes.* The pyroxenes in the isothermal runs are homogeneous and unzoned pigeonites. Comparison of their compositions indicates that the larger the degree of supercooling (the lower the crystallization temperature) the more CaFeAlTi rich and Mg poor they become. In cooling rate runs the phenocrysts have pigeonite cores and augite rims. The pigeonite cores are continuously zoned to more CaFeTiAl-rich and Mg-poor compositions. In the  $4^\circ$  and  $2.5^\circ \text{ hr}^{-1}$  runs the phenocrysts usually have sharp augite rims which initially zone to a more Ca-rich and MgFe-poor composition and then change to Fe enrichment and CaMg depletion. A few crystals in the  $2.5^\circ \text{ hr}^{-1}$  have zones transitional between augite and pigeonite. The groundmass pyroxenes of the  $2.5^\circ \text{ hr}^{-1}$  run are strongly zoned to more CaMg poor and Fe-rich rims and form a band across the middle of the pyroxene quadrilateral. For a given Wo content, pyroxenes in the  $30^\circ \text{ hr}^{-1}$  run are more Fe rich than those in the  $2.5^\circ \text{ hr}^{-1}$  and  $4^\circ \text{ hr}^{-1}$  runs. Comparison with the isothermal runs suggests that the pigeonite cores in the  $30^\circ \text{ hr}^{-1}$  run nucleated at  $\sim 1165^\circ$  while those in the  $4^\circ$  and  $2.5^\circ \text{ hr}^{-1}$  runs nucleated above  $1190^\circ$ . The more magnesian (higher temperature) pigeonite cores in the  $4^\circ \text{ hr}^{-1}$  run compared to the  $2.5^\circ \text{ hr}^{-1}$  run are attributed to more oxidizing conditions (0.75 log units) during the  $4^\circ \text{ hr}^{-1}$  run. Al and Ti increase uniformly from the pigeonite cores to the augite rims and groundmass augite. The trend is similar to that of 15499 lying below the 1:4 Ti:Al line. In the  $2.5^\circ \text{ hr}^{-1}$  run a few augite rims plot close to the 1:2 Ti:Al line. Minor element trends on an Al(VI) CrTi plot are dependent on cooling rate.

The close similarity between the porphyritic textures and mineral-chemical trends of the monotonic cooling rate runs and the QN basalts suggest that a two stage cooling history is unnecessary. From this study it is possible to quantify, in part, the cooling history of 15499. The pyroxene cores plot close to pyroxenes from the  $1188^\circ$  isothermal run suggesting that the magma cooled more slowly than  $30^\circ \text{ hr}^{-1}$ , but faster than  $4^\circ \text{ hr}^{-1}$ . The morphology of the pyroxene in 15499 compares favorably with the  $10^\circ \text{ hr}^{-1}$  run. The experiments show that the textural differences among QN basalts are a response primarily to monotonic cooling rate and that the differences in mineral chemistry are responses to differences in both cooling rate and fO<sub>2</sub>.

Lovering, J. F. and Wark, D. A.: 'Rare Earth Element Fractionation in Phases Crystallizing from Lunar Late-Stage Magmatic Liquids'.

The late-stage liquids produced during lunar magmatic processes are highly enriched in the rare earth elements (REE). A characteristic suite of REE-rich phases (including apatite, whitlockite, monazite, zirconolite, tranquillityite, baddeleyite and zircon crystallize from these liquids and may cause modification of the REE fractionation patterns within these liquids. Up till now REE fractionation patterns have been determined for co-existing REE-rich phases of only 3 of the 7 petrographically defined lunar rock groups defined from clasts in Apollo 14 and 15 breccias:

Group 2: Mare basalts 10047 and 14072.

Group 4: Monzonite clasts (numbers 1 and 2) in breccia 14305.

Group 6: Recrystallized breccias 14305 and KREEP-rich 65015.

*Apatites and Whitlockites:* For rocks with co-existing apatites and whitlockites (i.e. 14072; monzonite clast and matrix of breccia 14305; 65015) both have similar and relatively flat REE fractionation patterns which are also parallel to the patterns of the host total rock. The major difference between co-existing apatite and whitlockite patterns is the very marked negative Eu anomaly found in whit-

lockites while the apatites show either a very small or virtually zero Eu anomaly. A different set of conditions has apparently operated during the crystallization of 10047. In this rock virtually all the calcium phosphate present is apatite in which the REE fractionation pattern is different from all other apatites studied (which co-existed with major whitlockite), having a centrally humped pattern and a marked negative Eu anomaly. Apatite shows the most variation of any REE-rich phase studied.

*Zirconolite*: Zirconolites were studied in 10047, matrix of 14305 and KREEP-rich 65015. All show REE fractionation patterns which rise steeply from La to Sm, have a marked negative Eu anomaly and then remain virtually flat from Gd to Lu.

*Tranquillityite*: Only one grain was measured from 10047. The basic pattern is like that for zirconolite, plus a positive Pr anomaly.

*Baddeleyite*: Baddeleyite grains were analysed in 10047, 14072 and 65015. The accuracy is limited by the low abundance of the light REE's but the general pattern indicates a continued enrichment from the lightest to the heaviest REE's. Baddeleyite in 65015 seems to have a positive Eu anomaly.

*Zircon*: Zircons have been analysed from the monzonite (clast 1) and the recrystallized matrix in 14305. Both zircons show REE fractionation patterns which are rather similar to baddeleyite patterns.

*Monazite*: Monazite is a rare constituent of the mesostasis areas of the 10047. It shows a REE fractionation pattern which is grossly different from the trend of most other REE-rich phases in that the light REE's are highly enriched relative to the heavy REE's while a distinctly negative Eu anomaly is also observed.

The limited data available show differences in REE fractionation patterns observed for the REE-rich phases present in the lunar rocks and these differences suggest possible mechanisms for deriving either late-stage crystallizing liquids, or early-stage partial melt liquids exhibiting a variety of REE fractionation trends.

## 9. Characteristics and Movement of Materials in the Lunar Regolith: II

Horai, K. and Winkler, J.: 'Thermal Diffusivity of Lunar Rock Sample 12002,85'.

The thermal diffusivity of 12002,85 as a function of temperature and interstitial gaseous pressure was measured by the modified Angstrom method. In this method, thermal diffusivity is determined from the amplitude decay and the phase lag of a sinusoidal temperature wave transmitted through the sample. Sample 12002,85 is a rectangular parallelepiped with dimensions of  $0.33 \times 1.50 \times 1.60$  cm. The temperature wave was propagated parallel to the 0.33 cm side. On the assumption that a plane temperature wave travels from one of the two parallel surfaces of the sample to the other, and is totally reflected and that the amplitude of the reflected wave at the original surface is negligibly small, the diffusivity  $\kappa$  is determined from the amplitude ratio  $A_1/A_0 = 2 \exp(-\alpha l)$  and the phase lag  $(\phi_1 - \phi_0) = -\beta l$  using the relation

$$\kappa = \pi / \alpha \beta T, \quad (1)$$

where  $T$  is the period,  $A_0$  and  $A_1$  are the amplitudes of the temperature wave at the original and reflecting surfaces,  $\phi_0$  and  $\phi_1$ , are the phases of the temperature wave at the original and reflecting surfaces and  $l$  is the distance between the surfaces.

The relationship is valid for a plane wave propagating in a two dimensionally unbounded medium. It turned out that the thermal diffusivity determined by this relationship is dependent on the frequency of the temperature wave. The experimentally determined diffusivity is larger for longer period temperature waves. This is due to distortion of the wave form caused by finite sample dimensions. To avoid the uncertainty of this effect, several values for the period of the temperature wave were used. A single datum point is the average of four determinations with temperature wave periods of 30, 40, 50 and 60 s. Measurements were made in the temperature range between 85 and 450 K with interstitial atmospheric pressures of 1 atm and  $10^{-5}$  torr.

Sample 12002 is a porphyritic basalt. Like other lunar basalt, the thermal diffusivity of 12002,85 decreases with temperature. However, the value of thermal diffusivity exhibited by sample 12002,85 is considerably lower than that of Apollo 11 and 14 basalts. An anomaly in mineral composition (for example, an unusually high concentration of plagioclase) is a possible cause of this smaller diffusivity. We plan to carry out a modal analysis on a small fragment of sample 12002,85 to test the hypothesis.



It has been noted that porous rock samples exhibit a lower thermal diffusivity with reduced interstitial gaseous pressure. Our result also shows that the diffusivity is decreased by 30% as the interstitial atmospheric pressure is reduced from 1 atm to  $10^{-5}$  torr. The variation of thermal diffusivity with interstitial atmospheric pressure was measured at 85°, 315° and 450K. In this measurement, the period of the temperature wave was fixed at 45 s. A single datum point represents the average of more than two determinations at a fixed pressure. The data show that at 315° and 450K, the change in the thermal diffusivity occurs in the pressure range between 1 and  $10^{-2}$  torr, contrasted to the result obtained by Fujii and Osako who found that the change in diffusivity occurs between 1 atm and  $10^{-2}$  torr. At 85K, our data show that the diffusivity decreases in the pressure range between  $10^2$  and  $10^{-2}$  torr.

The decrease in thermal diffusivity at reduced interstitial gaseous pressure indicates that the gas filling the interstices of the porous rock sample is acting as a heat transporting medium. We want to determine whether conduction or convection is the principal mode of heat transfer in the interstitial gas. Thermal diffusivity as a function of temperature with 1 atm of He and Ar filling the interstices of the sample is represented. The data with He show higher diffusivity than that with Ar. Comparison with the data on thermal diffusivity and conductivity of gases, suggests that conduction is the dominant mode of heat transfer in the interstitial gas.

#### Cremers, C. J.: 'Thermal Conductivity of Apollo 16 Lunar Fines'.

Thermophysical property measurements for samples returned by the earlier Apollo missions are in the literature and have been summarized by Birkebak and Cremers. The measurements reported in the present paper are for the Apollo 16 fines only. If one is concerned with energy transfer on the surface of the Moon, either in the surface layer or in systems which might be used there, then the rocks are not of much importance. The Moon, at least in the regions so far visited, is covered to a depth of several meters or more with the fine material. Rocks and boulders are present but only randomly and relatively infrequently. Consequently, they represent more or less of a perturbation on the fine particulate nature of the surface layer and so energy transfer there depends for the most part on the properties of the fines.

This paper presents the thermal conductivity as a function of temperature over the approximate range of lunar diurnal temperatures. The density of  $1500 \text{ kg/m}^{-3}$  which is used corresponds approximately to that reported for the Apollo 16 core-tube samples and so it should be close to that at the mission site itself. There is some doubt as to whether or not these core-tube samples represent the actual site conditions. Recent temperature measurements at the Apollo 16 site can be explained only if densities there are considerably greater as if the material were behaving like a semi-rock. This question is not likely to be resolved until a new series of flights to the Moon is carried out.

#### Tittmann, B. R., Housley, R. M., and Cirlin, E. H.: 'Internal Friction in Rocks and its Relationship to Volatiles on the Moon'.

Our recent work showed that very small amounts of absorbed volatiles – only removed by outgassing in high vacuum and elevated temperatures – drastically increase the internal friction in terrestrial analogs of lunar basalt. Here new results are presented on the frequency dependence of the effect of outgassing in the analogs of lunar basalt along with some new data on other materials. This work shows that the effect of strong outgassing is qualitatively independent of the composition of the matrix and the shape and size of the pores. The frequency dependence data suggest that the effect will still be important at seismic frequencies. Therefore also presented are the results of a preliminary effort to use our data in placing constraints on the lunar outgassing history.

The key results are discussed below.

1. *Outgassing of various materials.* As shown a sample of commercial grade PZT (lead zirconate titanate) was found to undergo large increases in  $Q$  with outgassing similar to the terrestrial basalt. This ceramic has a moderate porosity but no fractures and is nearly homogeneous in composition. Similar to PZT in having no fractures and a uniform composition but being characterized by very small pores ( $\sim 40 \text{ \AA}$  diam) is Corning Vycor 7930, a glass composed of 90%  $\text{SiO}_2$  and filled with an interconnected system of pores (porosity 28%). The Vycor also showed a similar increase in  $Q$  with

outgassing so that we conclude that the effect arises from the adsorption of volatiles in porous materials qualitatively independent of the shape and size of the pores. As an alternative to outgassing by heat treatment in vacuum, a rock sample was subjected to a field of intense microwave radiation in order to remove the water with negligible heating of the rock itself. This experiment was performed with another terrestrial analog of lunar basalt with somewhat lower porosity than W-8. At a vacuum of  $10^{-6}$  torr with an exposure time of only 12 min, the  $Q$  improved by a factor of 10 confirming that increases in  $Q$  are due to strong outgassing independent of the procedure followed.

2. *Frequency dependence of  $Q$  in outgassed samples and its relationship to lunar outgassing history.* Table I shows data obtained on the frequency dependence of  $Q$  in outgassed samples. These limited results suggest that the effect of volatiles should be strong at seismic frequencies. The difficulty in removing the absorbed volatiles during outgassing treatments seems to imply that a monolayer or less is all that is required to increase internal friction.

Herminghaus, Ch. and Berckhemer, H.: 'Shock Induced Ultra-Sound Absorption in Lunar Anorthosite'.

Ultra-sound absorption measurements under 'lunar environmental conditions' have been carried out at lunar anorthosite sample 60015,33 with the aim to contribute to the understanding of the high  $Q$  derived from lunar seismograms.

A new technique, comparable to the reverberation measurements in room acoustics has been developed. This method allows  $Q$ -determination at rock samples of arbitrary shape in the frequency range 50 to 600 kHz in vacuum ( $10^{-4}$  torr) and at low temperatures ( $+20^{\circ}$  to  $-180^{\circ}\text{C}$ ). The sample is acoustically isolated from its surroundings. A short impulse introduced by a piezoceramic transmitter causes the sample to vibrate. The same transducer serves thereafter as an acoustical receiver for the exponentially decaying reverberations. For more details of the basic principles of the method, the experimental set up, and the evaluation technique reference is made to Ch. Herminghaus and H. Berckhemer and J. Drisler and P. Antony-Spies.

The result of  $Q$ -measurements at the lunar anorthosite in vacuum during repeated cooling and warming up at the frequencies 250 and 500 kHz is represented. Compared with the  $Q(T)$ -curves of terrestrial silicate rocks (volcanics, gabbros, feldspars and quartz of different grain size and texture), the  $Q$ -values of the lunar anorthosite are lower and surprisingly temperature independent. No high  $Q$ -values, however, as required to understand lunar seismograms were found. This has to be explained.

One remarkable result of our experiments with terrestrial rocks was the fact that after rapid cooling in a spray of liquid nitrogen,  $Q$  of the sample shows an irreversible lowering together with a flattening of the  $Q(T)$ -curve. This effect is most pronounced for originally high- $Q$  samples.

No difference in  $Q$  before (x) and after (.) this treatment can be observed. This is taken as a proof for a very high micro-crack density in this lunar surface rock sample. These cracks may have been created either by the multitude of temperature oscillations between lunar day and night and/or by meteoritic impact shock-waves. The importance of temperature induced microcracks, however, is pointed out by this paper.

Warren, N., Trice, R. E., and Anderson, O. L.: 'Seismic  $Q$  in a Scattering Medium'.

A study is being made of rock properties related to the attenuation properties of the lunar crust. The study is directed toward the problem of structure effects on the elastic and inelastic properties of a medium, and application of such data to the history and formation of the lunar crustal regions.

Two subjects are being emphasized in the study:

(1) The problem of the time decay of energy in a heterogeneous medium, in which the energy cannot be isolated in a single mode, and the determination of  $Q$  for such a medium, based on late portions of seismic coda. This portion of the study is applied to the problem of determining the  $Q$  of small rock samples by a pulse transmission technique and is extended to the problem of interpreting attenuation from the lunar seismic records.

At this date, results suggest that low-amplitude energy in coda decays relatively slowly, that is, implies a higher  $Q$  for a sample than that corresponding to earlier portions of a record. If mode

conversion is present during the acoustic propagation, then the measurement of the low-amplitude tail may yield a 'best' estimate of the attenuation of the medium. Noise level is expected to affect this estimate of  $Q$  from coda. The measured attenuation of lunar seismic signals may be influenced by constraints affecting attenuation determination from coda, the seismic signals being considered as low-amplitude coda with extremely low noise levels.

(2) The problem of the relation of rock structure or texture and attenuation. In particular, the effect on the elastic and attenuation properties of rock due to introducing fresh cracks is being studied.

At this date, results suggest that cracks may influence attenuation less and elastic moduli more than some other types of attenuating 'structures', such as imperfect (but welded) grain bonds and hydrous minerals.

Nakamura, Y.: 'High-Frequency Lunar Teleseismic Events'.

A small number of lunar seismic signals of distinctive properties lead us to believe that either there are some regions of more competent geologic structure than the normal, regolith-covered surface structure, or some impacting objects effect unusually deep penetration, or shallow tectonic moonquakes occur. A total of eleven such events have been identified to date, representing only about 0.2% of the events detected by long period seismographs.

Major characteristics of these events are: (1) Signals detected by the short period instruments (peak response at 8 Hz) are several times greater in amplitude than those on the long period instrument (peak response at 0.45 Hz). (2) Both  $P$ - and  $S$ - wave arrivals are distinctly observable, with greater amplitude for the latter and  $P$ -to- $S$  intervals ranging from 2 to 5 min. (3) The signal rise time of each phase is very short, indicating negligible scattering of seismic waves at the source region. (4) With the exception of the smallest event, the signals are detected by all stations. (5) The observed amplitudes range from a few digital units to nearly full scale (1023 digital units) at the highest seismometer gain. The amplitude of the largest event is thus nearly two orders of magnitude greater than that of the largest signal previously identified as a moonquake and is one of the largest seismic events observed to date. (6) Source locations are widely distributed and no two events occurred at the same location.

The most important data that would determine whether these events are of external (meteoroid impacts) or of internal (moonquakes) origin, namely, the precise depths of focus of these events, are lacking because of the poor accuracy of hypocenter determinations. However, the shear wave observed at station 15 from the March 13, 1973, event at an estimated distance of greater than 120 degrees, would have intersected the attenuation zone below the 1000 km depth if the depth of this event had been greater than 300 km. Because of the apparent lack of evidence against either one, we accept two working hypothesis: one of external origin and another of internal origin.

If these high-frequency teleseismic events are from meteoroid impacts, they must occur in a way grossly different from ordinary meteoroids impacting upon the typical lunar surface. The gradual rise and decay of signal strength of all artificial impacts and a large number of natural events are attributed to intense scattering of seismic energy in the highly heterogeneous surface zone that supposedly blanketed the entire Moon. In contrast, the high-frequency teleseismic events have nearly impulsive beginnings similar to those of moonquake signals, indicating that scattering of seismic energy near the source region is negligible. Therefore, if these events are in fact meteoroid impacts, one possible explanation for the unusual characteristics would be that the meteoroid impacted upon material of exceptionally high competency. This suggests either that the impact sites were relatively free of pulverized overburden, or that the penetration through the regolith was greater than normal.

On the other hand, events of internal origin would require regions where shallow moonquakes occur. All the moonquakes located previously occurred at depths greater than 700 km. Though the high-frequency teleseismic events have signal envelopes similar to those of known moonquakes, the former differ from the latter in four important characteristics: (1) frequency content is much higher; (2) some of them are stronger than the largest known moonquakes by several orders of magnitude; (3) they do not occur periodically as the moonquakes do; and (4) no matching signals have been found. The difference in physical properties of material in the source regions may account for these differences.

In summary, the small number of teleseismic events with unusual characteristics suggest that either (1) there are some regions of restricted extent where rock of exceptional competency with structural homogeneity is found near the surface, or (2) a class of rare impacting objects exist that can penetrate

to unusually great depth, or (3) a small number of moonquakes occur at shallow depth. The correct hypothesis may be determined from refined lunar models, where depth of focus may be determined with better accuracy than at present. Sites at which these unusual events originate should be considered as prime candidates for landing sites in any future lunar exploration program.

Kovach, R. L., Nur, A., and Talwani, P.: 'Implications of Elastic Wave Velocities Measured for Apollo 17 Rock Powders'.

The seismic velocity in the upper several kilometers of the Moon is known to increase with depth at a rate of  $2 \text{ km s}^{-1}$  per km. Rocks in the near surface of the Moon are so jointed and broken that their granular nature cannot be neglected. However, little is known about their mechanical behavior at elevated pressures corresponding to moderate depths of burial. One suggestion is that increasing compaction with depth in a rock powder can provide the necessary increase in velocity with depth which has been observed in the Moon.

We have measured the elastic wave velocities of four lunar rock powders 170051, 172161, 172701 and 175081 subjected to hydrostatic confining pressures ranging from 1 atmosphere to 2.5 kbars. The elastic wave velocities are reversible with pressure cycling, as has been noted for terrestrial rock powders.

Velocity-depth gradients of  $0.4$  to  $0.8 \text{ km s}^{-1}$  per km are observed but these gradients only persist to a pressure of 50 bars or so (depth  $\approx 1 \text{ km}$  in Moon). At higher pressures the velocity gradient decreases to values some 10 to 20 times less than the gradient at low pressures. The increase of seismic velocity with depth in the shallow lunar interior is much too great to be due simply to cold self-compaction of rock powder.

Our measurements would argue against the idea of cold accretion without extensive heating and it follows that temperature may have a larger effect on the seismic velocity in the lunar crust than heretofore believed. Preliminary experiments on terrestrial rock powders show that it is possible to achieve equivalence with solid rock velocities at relatively low temperatures.

Alvarez, R.: 'Electrical Properties of Sample 70215 in the Temperature Range of  $100^\circ$  to  $373 \text{ K}$ '.

Dielectric permittivity, loss tangent, and dc conductivity of solid sample 70215,14 have been measured at temperatures of  $100^\circ$ ,  $298^\circ$ ,  $315^\circ$ , and  $373 \text{ K}$ . Measurements were performed at a pressure of 1 torr of  $\text{N}_2$  or in vacuums of  $\sim 10^{-7}$  to  $10^{-8}$  torr; the sample was never exposed to the atmosphere. Dielectric properties were obtained in the 30 Hz to 100 KHz frequency range. The basic experimental procedure has been reported elsewhere. In comparison with other lunar material this sample presents a rather high dc conductivity. Sample 70215 has been described as a fine-grained basalt with a ground-mass (48% of rock) of Ilmenite (?), Pyroxene, and Plagioclase, and phenocrysts (52% of rock) of Ilmenite (?), Olivine, and Pyroxene. The results obtained may help characterize materials in the regolith and in the upper layers of the lunar basement.

Values of dielectric permittivity at 100 KHz vary from 6.25 at 100 K to 8.18 at 373 K; the lower frequencies, however, show a considerably larger scatter with temperature. This behavior is typical of dielectrics with non-negligible ohmic conductivities, in contact with metallic electrodes. Clustering of the data at the higher frequencies suggests that such an effect becomes negligible above 100 KHz and, thus, representative values of  $\kappa'$  may be taken at this frequency for temperatures of 298 K and above. The data at 100 K appears to be free of dc conductivity effects; consequently, all reported values are considered representative of the sample properties at this temperature.  $\tan \delta$  variations do not exceed one order of magnitude in the temperature range analyzed.

The behavior in the low-temperature region would suggest a change to extrinsic conduction (i.e., by impurities) if the sample were a crystalline specimen; however, it could also be explained in terms of thermally assisted tunnelling, after the conduction model for amorphous semiconductors proposed by Davis and Mott. Unfortunately only one conductivity value was obtained in the low-temperature region; more data at low temperatures is needed to pin down the actual electrical classification of the sample. The dashed lines indicate only a possible behavior between room temperature and 77 K (i.e., between values of 3.35 and 12.98 for  $1000/T\text{K}$ ); they may be in great discrepancy from actual conductivity values in such a region. The sample presents a non-ohmic behavior in the temperature range

analyzed; it is evidenced by increasing dc conductivities with increasing applied voltages. Conductivity values for voltages of 500 and 1000 volts, and temperature of 373 K were greater than  $10^{-7}(\Omega\text{-m})^{-1}$ ; they were not determined owing to limitations in the measuring range of the resistivity meter.

Lucke, R. L., Henry, R. C., and Fastie, W. G.: 'Far-Ultraviolet Lunar Mapping from Apollo 17'.

A far-ultraviolet (1200–1650 Å) spectrometer, described by Fastie, collected data on the local reflectivity of the Moon as it viewed the lunar surface from the Apollo 17 Service Module. The field of view of the instrument was, approximately, a  $30 \times 30$  km sq, or about 1 sq deg on the Moon's surface. The Moon's rotation caused the spectrometer to scan different portions of the surface as the instrument was carried across the sunlit hemisphere once each orbit. Spectra were accumulated for a total of 38 h, spread over a six-day period.

The light intensity received by the spectrometer was low near the terminator, increased to a maximum value at that point on the bright side at which the instrument looked most nearly down-sun, and then decreased again toward the other terminator. Superimposed upon this large-scale behaviour were numerous fluctuations from this general trend. Large fluctuations occurred near the terminators, largely due to local topography. Crater walls and mountainsides will either cast long shadows or catch direct sunlight near dawn and sunset, depending on which way they face. More interesting are fluctuations that occur far from the terminators. Analysis shows that mare material has, with a possible small wavelength dependence, a 5–10% higher reflectivity in the far ultraviolet than does highland material. This is in contrast to the visible, where the highlands reflect about 30 to 40% more than do the maria.

The well-known darkness of the lunar surface (in visible light) compared to, for example, freshly ground rock powders, has been attributed to various mechanisms which create an amorphous, iron-rich coating on grains of lunar soil. Glassy spheroids are also present. The formation of this coating gives an age-darkening effect which accounts for the brightness of fresh surface material (e.g. from young craters) relative to material that has been on the surface a long time. A reasonable explanation of the (visible) darkness of maria with respect to highlands was suggested by Adams and McCord, who pointed out that the basaltic maria have a higher iron content available for inclusion in a glassy surface layer than do the more anorthositic highlands, and that it is primarily iron that produces absorption in such a coating. These two effects—surface age and mineralogical composition—can probably also account for the Moon's ultraviolet reflectance properties. Since far ultraviolet radiation is very non-penetrating, its reflectance is primarily a surface phenomenon, dependent on the (complex) index of refraction of the surface of the reflecting object and essentially independent of its bulk properties. This should make ultraviolet reflectance more sensitive to a thin coating than visible reflectance is, and may mean that an ultraviolet map of the Moon could give better age and/or composition discrimination on the surface than a visible map. Such an ultraviolet map is in preparation. The higher albedo of the maria may be explainable in terms of the effect a higher iron content could have on the index of refraction of the soil grain's surface coating.

Laboratory studies made on powdered terrestrial rock samples show that the reflectivity of basaltic material is, like the Moon and unlike granitic material, nearly independent of wavelength throughout the 1200–1650 Å range. The relative importance of mineralogical composition in determining the ultraviolet reflection properties of lunar surface material is the subject of on-going study.

## 10. Characterization and Evolution of the Lunar Crust: II

Masursky, H.: 'The Moon – Crustal Evolution'.

The data on lunar shape from the laser altimeter on Apollos 15, 16, and 17 confirms the sparse information from Ranger, Surveyor and Lunar Orbiter and details the figure of the Moon with its low frontside and high farside. Only the lunar limbs, where astrometric determinations were made, lie at radii of 1738 km.

This asymmetry strongly implies that during the early Moon-wide differentiation a thin low density (anorthositic) crust formed on the Earth side and a thick crust on the far side. One hypothesis

that would explain the data states that mantle convection was active during the differentiation resulting in this asymmetric distribution of crustal material. The Moon would have had to have been gravitationally locked to the Earth to impose the observed geometry. Two other observations confirm the hypothesis of mantle convection proposed by Runcorn several years ago: first, the remnant magnetism in ancient rocks indicates possible dynamo action early in the Moon's history; second, the concentration of gamma radiation in the middle of the front and far sides reconfirms a possible biconvection cell with enhanced gamma activity over the vertical edges of the cells. Results from the X-ray fluorescence experiment confirm this distribution. That is, the highest areas topographically have the highest aluminum/silicon ratios. They are the most differentiated rocks and underlie the areas where the crust is thickest.

In this view, Oceanus Procellarum and the other irregular mare areas would indicate stripping of the low density crust and exposure of mare basalt overlying mantle in some areas and piling up of this crustal material in other areas. The circular mare basins with mascons record impacts with uplifted mantle in the central peak protruding into the crust overlain by a minimum thickness of mare basalt. The positive gravity anomaly is due to the lateral flow and intrusion of the denser mantle into the low density crust. This proposal is confirmed by the lack of coincidence of the circular positive anomalies around the Imbrium and Orientale basins with the mare basalt troughs. That is, the positive anomalies underlie the uplifted crustal blocks where the mantle lies at the highest elevation; negative anomalies lie under the troughs underlain by mare basalts rather than positive anomalies as in the conventional explanation.

Two areas on the front side overflowed by Apollo 16 stand high and are underlain by low density crust according to laser altimetry and radio tracking. The one is a volcanic crater chain east of Ptolemaeus; the other is the Apollo 16 landing site. This coincidence indicates that the peculiar textures in the Kant Plateau that lie athwart the Imbrium Sculpture may indicate a continuation of upland volcanism after the formation of the Imbrium basin by impact. In these two areas on the front side and in large areas near the crater Van de Graaff, on the far side, extrusion of volcanic rocks continued. These volcanic rocks were reworked by impact so that surface samples are impact breccias whose composition indicates differentiation to a rock entirely composed of feldspar before metamorphism by impact.

Recrystallization of the matrix of regional impact breccias strongly implies the emplacement of the continuous ejecta blanket as hot base surge deposits. Many orbital photographs as well as the collection of ray material from Copernicus at the Apollo 12 site validates the separation of impact ejecta into the ballistically deposited ray material and the surface flowage of the base surge deposits that form the continuous ejecta blanket. The ray material can form secondary surges that are seen in high speed films of experimental craters. No ubiquitous secondary surges make Cayley-like deposits that would cover the near side of the Moon as has been proposed. The interpretation of wide spread deposits as secondary surges is inconsistent with experimental cratering records and lunar photography.

The largest topographic difference on the Moon occurs between the eastern edge of the floor of Mare Smythii and the western edge of Van de Graaff. This relief of about 9.5 km is similar to the topographic difference between the floor of the Amazonis Basin and the top of the Tharsis ridge on Mars and the floor of the Pacific Ocean Basin and the top of the Andes on the Earth. Like these, it must represent a global-tectonic feature.

Arnold, J. R., Metzger, A. E., Reedy, R. C., and Trombka, J. I.: 'Element Concentrations from Lunar Orbital Gamma-Ray Measurements'.

Maps of the radioactive content of the lunar regolith, in regions overflowed by the Apollo 15 and 16 CSM, have already been presented. In the present paper we give data on the elemental concentrations observed over a set of major mare and highland regions, as deduced from the natural and cosmic-ray-induced gamma ray spectra observed. The elements reported are (TH + U), K, Fe, Ti, Si, and O. Silicon and oxygen concentrations do not vary over the lunar surface beyond our limits of error; this is consistent with sample observations. The data on the radioactive elements confirm and extend the information obtained earlier by less complete analysis. No major region so far analyzed shows a Th content lower than about 0.5 ppm. The K/Th (and presumed K/U) ratio rises in the 'coldest' regions of the lunar highlands. The Th level at the backside 'warm region' near Van de Graaff approaches 4 ppm.

The variation of Fe over the surface follows broadly the expected pattern, with high Fe in mare

regions falling to lower values in the highlands. The distribution of Ti seems to present some unexpected features. We expect later to present useful values for U and also for Mg, providing a cross-check with the X-ray data and extending the area of coverage for this element. We are not optimistic about the elements Ca and Al.

The method of data reduction is basically that described in a recent paper. A background due to natural and induced radioactivity in the spacecraft, the diffuse 'cosmic' gamma ray flux, cosmic-ray activation in the detector, and the spectral continuum from the Moon itself must be subtracted from the measured spectrum to obtain the discrete line spectrum. Part of this lunar continuum is itself dependent on the line flux, requiring iteration. In obtaining absolute concentrations from discrete line intensities of the natural radioactivities an absolute calibration is possible and the results are in good accord with ground truth. For the other elements the model is semi-quantitative, and the data are normalized to ground truth in areas well characterized by lunar samples and other studies (such as Mare Tranquillitatis).

There are interesting correlations with lunar topography and magnetic and gravitational features.

Wilshire, H. G.: 'Provenance of Terra Breccias'.

Samples returned from the lunar terra have a great variety of textures and a wide range of compositions. The textures are dominated by impact fragmentation and thermal metamorphism, but clues to the nature of the source rocks are found in varying degree in all the samples. The documented samples are divided into three groups on the basis of the information they yield about pre-excitation processes: (1) breccias with glassy to finely annealed matrices and clasts; (2) crystalline rocks in which pre-excitation texture is more-or-less intact; and (3) cataclastic breccias in which pre-brecciation textures are spottily preserved.

Rocks of the first group, the majority of returned samples, yield least direct information about their origin. These breccias have high matrix/clast ratios and the clasts are mostly fine-grained thermally metamorphosed fragmental rocks and fused materials. Many of the larger of these, however, contain a small percentage of hornfelses that are much coarser than the dominant clasts, and rocks with igneous textures, both volcanic and plutonic; they also contain large percentages of mineral debris in the 0.1 to 1 mm and larger size range. Much of the mineral debris in the Apollo 14 breccias is far too coarse to be derived from any lithic clasts other than the coarse hornfels and plutonic rocks. Moreover, the proportions of mineral species occurring as isolated clasts are in keeping with the feldspar-rich plutonic and coarse metamorphic rocks. These relations appear to be true of breccias from other terra sites as well but statistical data are not available.

At the opposite end of the spectrum is the small group of rocks whose pre-excitation crystalline textures have remained more-or-less intact. These are about equally divided among those with volcanic (e.g. 14053, 14310, 68415), plutonic (e.g. 15415, 69955, 78235), and coarse metamorphic (e.g. 78155, 76535, 72415) textures. The compositions of the plutonic and metamorphic rocks range from dunite through troctolite and norite to anorthosite, and may include Apollo 14-type K feldspar-quartz intergrowths as well. Compositions of rocks with volcanic textures range from mare basalt-like through norite or troctolite to anorthositic. Fine-grained compositional equivalents of the K feldspar-quartz intergrowths also occur (e.g. 12013).

The third group, embracing cataclastics and little-modified derivatives, lies between the two extremes. It is probably the most important group because it has enough members to be statistically useful and it retains many direct signs of its source materials. The cataclastics are typically found as clasts in little-reworked breccias. Where pulverization and cataclastic flow, have not been severe, the original very coarse grain size (> 5 mm, often > 10 mm) of many rocks is evident from relic lithic fragments and the dimensions of cataclastic flow structures in which mixing of pulverized mineral debris is not far advanced. Where cataclastic flow has been severe, the size of relic mineral debris frequently attests to coarse original grain size. Other signs of slow cooling history such as coarse exsolution lamellae in pyroxenes and coarse recrystallization textures are common.

A few of the cataclastics were derived from metamorphic rocks whose grain size is much larger than that of the typical metaclastic rocks, but the majority are clearly derived from a suite of coarse-grained plutonic igneous rocks. Cataclastic rocks derived from rocks with volcanic textures are rare. Basalt progenitors may occur in 14321 and in an Apollo 17 rock, but no rocks with volcanic texture form clasts in the simplest, least reworked Apollo 16 breccias. Inasmuch as the *matrices* of the least re-

worked breccias commonly have textures like those of volcanic rocks, it appears that such rocks are largely formed by impact fusion of plutonic rocks. Typical fine-grained hornfels are produced by less extreme fusion of the same source rocks whereas coarse hornfels probably formed as pre-excavation events in a slow-cooling environment.

Considering the extreme average composition of the lunar terra, it would appear that igneous fractionation, followed by a lengthy postconsolidation history, in an environment not frequently plumbed by impact is required. The textures of the source rocks of many of the breccias is consistent with their formation in a plutonic environment, at depths perhaps greater than 5–10 km, from which they were excavated by large, basin-forming events. Formation of such large volumes of extreme differentiates by fractionation in shallow magma chambers and eruption at the surface does not seem possible in light of the high impact flux during late crustal history, nor are the rock textures consistent with this view.

Dowty, E., Keil, K., and Prinz, M: 'Igneous Rocks from Apollo 16 Rake Samples'.

We report on 8 crystalline rocks from the Apollo 16 rake samples 1 possibly primary (plutonic) rock; 6 'melt' rocks; 1 mare basalt. In addition, 20 anorthosites (mostly cataclastic, some granoblastic, none with igneous textures), and a wide variety of recrystallized and non-recrystallized breccias, including 'poik' rocks are among the 151 rake specimens examined.

*Spinel Troctolite.* Rock 65785 is inhomogeneous, consisting of a finegrained feldspar-rich main mass and a coarse-grained troctolitic area ( $\sim 9 \times 4$  mm). The troctolitic part has plagioclase (65%, avg.  $An_{97}$ , 0.1–1.0 mm) and one 1.0 mm grain of Mg–Al spinel (5%,  $Cr_2O_3$  2.6–12.6%), poikilitically enclosed in a large olivine crystal (30%, avg.  $Fo_{83}$ ). The texture may be igneous, probably cumulate, but some metamorphic recrystallization cannot be ruled out. Accessories: very minor pyroxene, ilmenite, metallic Ni–Fe, troilite, zirconian rutile (3.8%  $ZrO_2$ ), whitlockite, Cr–Zr–REE–armalcolite, K-feld-spar, chromite, magnesium orthophosphate (probably farringtonite).

*Melt Rocks.* 60666 contains 1 very large relict plagioclase ( $An_{96}$ ). The melt portion consists of  $\sim 0.2$  mm phenocrysts or relicts of olivine ( $Fo_{93}$ ) in a fine matrix of feathery olivine and plagioclase ( $An_{96}$ ) with sparse Mg–Al spinel. Parts of the matrix may be glassy. Metallic Ni–Fe (4.21% Ni, 0.4–1.3% Co), troilite, schreibersite and very sparse chromite are present. 65779 is very fine grained, subophitic to intergranular; plagioclase needles are  $\sim 0.05$  mm long. Relict plagioclase grains ( $\sim 8.5\%$ ,  $An_{95}$ ) occur. Olivine is  $Fo_{78}$  and pyroxene is magnesian pigeonite. Accessories: ilmenite, Cr–Zr–REE–armalcolite, metallic Ni–Fe, troilite, schreibersite. 60615 is texturally similar to 65779, but somewhat coarser; elongate feldspars are  $\sim 0.1$  mm long. A few large plagioclase relicts ( $\sim 4\%$ ) are clearly distinguishable from the melt portion (both  $An_{96}$ ). Olivine is  $Fo_{86}$ ; pyroxene is somewhat similar to that in 60618, 1–2. Accessories: ilmenite, Cr–Zr–REE–armalcolite, metallic Ni–Fe, troilite, schreibersite and Zr-rutile (to 6.0%  $ZrO_2$ ). 60618, 1 is inhomogeneous; 60618, 1–1 is cataclastic spinel-olivine anorthosite; 60618, 1–2 is a melt rock containing abundant, irregular plagioclase grains ( $\sim 0.5$  mm, apparently relicts), elongate crystals ( $\sim 0.5 \times 0.1$  mm,  $An_{95}$ ), subophitic pyroxene, minor olivine ( $Fo_{82}$ ). Accessories: ilmenite, Cr–Zr–REE–armalcolite, metallic nickel-iron (2.7% Ni, 0.6–1.2% Co), troilite, schreibersite. 65795 is coarsegrained with abundant feldspar ( $An_{98}$ ), but grains are irregular and variable in size; some may be relicts. Pyroxenes are somewhat similar to those in 60635, and some are poikilitic; minor olivine is  $Fo_{69}$ . Accessories: ilmenite ( $\sim 2.6\%$  MgO), metallic Ni–Fe (5–25% Ni, 0.5–0.8% Co), troilite, high-silica glass ( $\sim 75\%$   $SiO_2$ , 7–10%  $K_2O$ ). 60635 has abundant ( $\sim 1.0 \times 0.4$  mm) laths or prisms of plagioclase ( $An_{94}$ ), with pyroxene plagioclase and accessories in the angular interstices. Accessories: nearly pure ulvöspinel ( $< 0.7\%$   $Cr_2O_3$ ), metallic Ni–Fe, troilite, K-feldspar.

*Mare basalt*, large lithic fragment in breccia 60639, has subophitic texture and mineral compositions typical of Luna 16 basalt. Plagioclase avg.  $An_{88}$ , olivine ( $Fo_{66}$ ), pyroxene generally zones from high-Ti augite to subcalcic ferroaugite, and ilmenite has low (0.5%) MgO. Low bulk FeO, high  $Al_2O_3$ , and intermediate  $TiO_2$  are within the range of Luna 16 basalts.

*Origin of the spinel troctolite.* Rock 65785 is one of the best possible candidates for a primary cumulate from the original differentiation of the lunar crust, as suggested by its overall composition, mineralogy and, possibly, texture. However, its origin is still uncertain because of the low (4.0 AE) age obtained with the ion microprobe on three armalcolite grains, some dissimilarities in composition and texture to the other spinel troctolite 67435, internal variations in spinel and olivine compositions, and



wide variety of accessory minerals. The possibility that it is an altered primary rock or a cumulate from a later primary liquid or from a shock-melt, cannot be ruled out.

*Origin of the melt rocks.* Three modes of origin must be considered: (1) primary liquids; (2) partial melting of a single rock type such as 'highland basalt'; (3) melting with or without differentiation of heterogeneous rocks or breccias. The primary liquid origin can be ruled out because most of the melt rocks show evidence for shock-melt origin, such as presence of relicts, textural and compositional inhomogeneities, schreibersite and 'excess' metal (whether schreibersite-metal blebs are meteoritic contaminants or in situ shock-produced on the Moon is uncertain; however, they are usually found only in rocks which otherwise appear to be shock melted, and not in presumed primary rocks). Furthermore, the bulk compositions do not show any particular concentration near the proposed primary liquid compositions 'Highland basalt' or 'VHA basalt'. The melt rocks cannot all be partial melts from a single parent composition, for example, of 'Highland basalt'. Partial melts of this composition are restricted to the dashed line in Fig. 3 and only one of the rocks (65779) approaches this line. Thus, the melt rocks apparently represent shock melts of heterogeneous highland soils, breccias or rocks. The most reasonable explanation for the heterogeneity of the highland materials is that they are composed primarily of heterogeneous, cumulate rocks. In many cases, the material which was melted was probably breccia or soil, and there was evidently some admixture of KREEP-like material with the cumulate ANT rocks.

Bansal, B. M., Hubbard, N. J., Nyquist, L. E., Rhodes, J. M., Shih, C.-Y., and Wiesmann, H.: 'Non-Mare and Highland Rock Types: Chemical Groups and their Internal Variations'.

Chemical data for non-mare and highland rocks exhibit a high degree of internal structure, i.e., consistent groupings are observed for major elements and lithophile trace elements. These consistent groupings suggest that homogenizing impact processes have not obliterated all traces of the chemical differentiation processes involved in lunar petrogenesis. These groups commonly have large and often parallel internal chemical variations, suggesting that original chemical compositions and internal variations have been basically preserved except for incorporation of a few percent of xenolithic material and an overlay of metamorphic effects.

A plot of MgO vs Al<sub>2</sub>O<sub>3</sub> illustrates the major chemical groups, the major internal variations, and the major immediate causes of the internal variations. Each of these groups is characterized by typical lithophile and minor element abundances.

Because of ubiquitous brecciation and metamorphic features, one must consider two possible hypotheses to account for the observed compositional groupings and their internal variation; (1) crystal-liquid fractionation of discrete magma types prior to brecciation and metamorphism and (2) mixing in conjunction with brecciation and metamorphism, and perhaps also impact generated partial fusion. Simple crystal-liquid fractionation will produce internal variations consistent with mineral control lines. Mixing, if extensive, will tend to eradicate inherent chemical variations. Local mixing may produce a new chemical group with internal variations caused by mixing two or more local rock types to varying degrees. Local mixing is detectable if the end members have chemical compositions which are impossible or difficult to relate by crystal-liquid fractionation, for example the 61016 mixing series.

The Apollo 12 and 15 mare basalts have been included to demonstrate that the olivine controlled fractionation trends for these rocks, closely parallel the major internal chemical variations of three other groups – Apollo 14 common KREEP, Apollo 16/Apollo 17 KREEP, VHA basalts, and possibly also spinel troctolite. This point is strengthened by the olivine control lines which also parallel these groups. Orthopyroxene, spinel and plagioclase control plays a subordinate role in the internal variation of these groups. Crystal-liquid fractionation is obvious for the mare basalts and strongly suggested for the other chemical groups. One could mix the VHA basalts, Apollo 16/Apollo 17 KREEP, and common Apollo 14 KREEP with dunite in order to produce the observed variation along the olivine control lines. However, such a scheme also demands the prior existence of these independent chemical groups. Extensive intergroup mixing is not supported by the data. However, 14310 type KREEP may be a shock melted mixture of common Apollo 14 KREEP and 'anorthosite'. Alternatively it may be a plagioclase rich member of the Apollo 16/Apollo 17 KREEP group. VHA basalts appear to owe their major internal chemical variation to olivine rather than to plagioclase, as suggested earlier. However 63335 and 60335 may represent VHA samples enriched in cumulate plagioclase.

The LKAS may represent the most widespread lunar crustal material and is perhaps the most ancient chemical composition widely accessible on the lunar surface. The samples returned by Apollo 16 and 17 and the orbital XRF data from Apollo 15 and 16 demonstrate that the dominant highland rock types have more than 24%  $Al_2O_3$ , perhaps rocks like 77017, 78155, 76230, 67955, and 66095,37 are typical. Other data are suggestive of an extensive regolith developed on material of approximately the average composition of these rocks. If the LKAS is a true regional rock series that owes its major internal chemical variations to the existence of a plagioclase-liquid system and if the samples 61016,79 plagioclase and 15415 are representative of the plagioclase and, further, samples like 77017 are representative of the equilibrium liquid, then one can use the low Sr 87/86 ratios of 61016,79 and 15415 as a basis for suggesting that this is the oldest chemical group. If the LKAS is valid and once was an equilibrium crustal-liquid system, then the total system must have had less REE, etc. and a somewhat larger positive Eu anomaly than samples like 77017. This positive Eu anomaly is evidence that these rocks did not directly originate by partial melting and suggests that they did not have a totally liquid precursor and that they never lost large amounts of plagioclase. In contrast the VHA and KREEP compositions are readily explained by partial melting of plagioclase rich source rocks.

No data tables are included because of space limitations. Such tables will be provided on request.

Hodges, F. N. and Kushiro, I.: 'Apollo 17 Petrology and Experimental Determination of Differentiation Sequences in Model Moon Compositions'.

The differentiation of the lunar crust and formation of the plagioclase-rich highlands presents one of the most interesting problems in lunar petrology. One possible approach to this problem is the experimental determination of phase relations in compositions that for one reason or another appear to be reasonable Moon compositions.

As a first step in the study of possible lunar compositions melting experiments have been carried out on Ca- and Al-rich aggregates from the Allende carbonaceous chondrite. It was found that over a wide pressure range spinel is the liquidus phase followed by aluminous clinopyroxene and plagioclase. Subsolidus phase assemblages are spinel and clinopyroxene  $\pm$  plagioclase or melilite depending upon the pressure. Melts formed from Allende aggregates are very low in silica and iron and greatly enriched in calcium and aluminum, resembling no known lunar rock type. It was concluded that the Ca- and Al-rich aggregates from Allende represent an unlikely composition for the moon.

Two different model Moon compositions, MC-1 and MC-2 have subsequently been studied. Olivine and spinel crystallize from melt of MC-1 composition over a wide range of temperatures (1200-1400°C) and pressures (1 atm.-at least 20 kb), with clinopyroxene crystallizing near the solidus. At subsolidus temperatures, olivine, clinopyroxene and chromite-rich spinel are the principal phases. Plagioclase was not detected in this composition. Melting experiments with the MC-2 composition indicate that below 9 kb olivine (FO<sub>98-96</sub>) is the liquidus phase followed by orthopyroxene, clinopyroxene and calcic plagioclase. Above 9 kb the order of crystallization with decreasing temperature is olivine, spinel, orthopyroxene and clinopyroxene.

The extreme difficulty of deriving a plagioclase-rich melt or cumulate from the MC-1 composition makes it an unlikely composition for the Moon. Complete or nearly complete melting of the MC-2 composition, followed by fractional crystallization in the outer portion of the Moon, could on the other hand produce the type of plagioclase rich melt necessary for formation of the lunar highlands. The production of a 60 km thick anorthosite layer from MC-2 would require the melting of at least the outer 200 km of the Moon, which after differentiation would consist of dunite (olivine), hercynite (olivine and orthopyroxene), pyroxene-rich gabbro and plagioclase-rich gabbro in order from bottom to top. This sequence is reasonable and we suggest that the MC-2 composition may be fairly near the bulk composition of the moon. On the basis of this model the undifferentiated portion of the moon (below 200 km) would consist of spinel lherzolite down to between 500 and 700 km and would consist of garnet lherzolite below that level. It is quite possible that a metallic phase (< 10%) exists within these deeper layers.

Basaltic crystalline rocks 70017 and 74275 are similar to Apollo 11 high-titanium basalts. 70017, a microgabbro with subophitic texture, probably represents the interior of a lava flow or sill. It consists principally of titanite (up to 3.6 wt %  $TiO_2$ ), pigeonite, plagioclase (An<sub>88-71</sub>) and ilmenite with minor olivine (FO<sub>67-59</sub>), armalcolite, spinel (Chr<sub>83</sub> ulvö<sub>57</sub> Sp + her<sub>10</sub>), cristobalite, tridymite, metallic

iron ( $\text{Ni} < 1 \text{ wt } \%$ ), triolite and various late stage minerals in residual rhyolitic glass. Ti-tanangite and pigeonite occur principally in complex intergrowths, some with a distinct hour glass pattern. Titanium and aluminum content in pyroxenes ( $\text{Al}:\text{Ti} = 2:1$ ) decreases with decreasing calcium content. Lowest titanium and aluminum contents are found in euhedral pigeonite included within plagioclase. The iron-enrichment trend in pyroxenes, toward the ferrosilite corner of the pyroxene quadrilateral, occurs only adjacent to residual glass and is much less extreme than the trend in Apollo 11 pyroxenes. Spinel occurs only within olivine, and armalcolite occurs only within pyroxene. The crystallization sequence is believed to be spinel, olivine, armalcolite, pyroxene, ilmenite (armalcolite reacts with liquid), plagioclase and residium.

Rock 74275, a fine-grained ilmenite basalt ( $\text{TiO}_2 = 12.5 \%$ , microprobe analysis of fused glass), has a well developed variolitic groundmass of clinopyroxene, plagioclase, ilmenite, tridymite, metallic-iron ( $\text{Ni} < 1 \text{ wt } \%$ ) and troilite. Micro-phenocrysts are olivine ( $\text{Fo}_{90-71}$ ), titanaugite (up to  $6.5 \text{ wt } \%$   $\text{TiO}_2$ ) and armalcolite rimmed with ilmenite. Titanaugite also occurs as glomerocrysts intergrown with and replacing olivine. Spinel ( $\text{Chr}_{36-34} \text{ ulv}\ddot{\text{o}}_{52-48} \text{ Sp} + \text{her}_{16-14}$ ) occurs only within olivine. Titanaugites are strongly zoned with respect to titanium ( $\text{Al}:\text{Ti} = 2:1$ ) but show very little tendency toward iron enrichment. Plagioclase occurs as small blocky grains with hollow cores and as elongate anhedral intergrown with clinopyroxene. Armalcolite without ilmenite rims occurs as inclusions within pyroxene. The crystallization sequence for 74275 is very similar to that for 70017. Texture and chemistry of phases indicate that the magma that produced 74275 rapidly crystallized spinel, olivine, pyroxene, armalcolite and possibly small amounts of plagioclase and ilmenite during its rise to the surface. The fine-grained intergrowth of plagioclase, clinopyroxene and ilmenite in all probability formed upon extrusion onto the lunar surface.

Rock 77017 is a partly crushed block of gabbro and anorthosite that has been invaded by liquid of mare basalt type. It was collected near the large boulder at site 7 and may have a similar origin. Uncrushed areas are of two types; poikilitic gabbro consisting of euhedral plagioclase ( $\text{An}_{97-94}$ ) and rounded olivine ( $\text{Fo}_{62-64}$ ) enclosed in large plates of pyroxene and troctolitic anorthosite consisting of plagioclase ( $\text{An}_{97-94}$ ), subhedral olivine ( $\text{Fo}_{62-60}$ ) and poikilitic ilmenite. Pyroxenes were probably originally augite and pigeonite; both are now exsolved on a scale too fine for accurate microprobe analysis. This sample quite likely is derived from a layered gabbro complex of highland affinities.

One thin-section (77017,71) consists of a rounded gabbro fragment surrounded by dark brown mare basalt glass ( $\text{TiO}_2 = 6.3 \text{ wt } \%$ ). The interior of the clast contains patches of pale brown to colorless glass that has the composition of high-alumina basalt ( $\text{TiO}_2$  1.8,  $\text{Al}_2\text{O}_3$  23.4,  $\text{FeO}$  7.4,  $\text{MgO}$  7.1,  $\text{CaO}$  14.1  $\text{wt } \%$ ). Where the two types of glass are in contact there is a relatively sharp break in composition with a plateau of intermediate composition. We believe that this is a result of mixing of the two melts, indicating that the high-alumina basalt melt is not simply a product of contamination of mare basalt by the highland type gabbro. The high-alumina basalt melt is probably a result of partial melting of 77017 gabbro brought about by heat from the surrounding mare basalt. Large scale partial melting of rocks similar to 77017 could be an important source of high-alumina basalts.

A clast of mare-type ilmenite basalt included within the mare basalt glass in 77017, 71 shows an extreme iron-enrichment trend in its titan-augites very similar to that observed in Apollo 11 samples ( $\text{Al}:\text{Ti} = 2:1$ ).

Rock 73235 is a complex breccia with a very fine-grained, slightly metamorphosed, dark brown matrix. Monomineralic clasts consist of plagioclase (with a wide range of shock features), olivine ( $\text{Fo}_{89-79}$ ), zoned pigeonite-subcalcic augite ( $\text{Ca}_{10}\text{Mg}_{60}\text{Fe}_{30}\text{-Ca}_{26}\text{Mg}_{44}\text{Fe}_{30}$ ), augite (near  $\text{Ca}_{45}\text{Mg}_{36}\text{Fe}_{19}$ ) containing very thin exsolution lamellae of orthopyroxene, augite ( $\text{Ca}_{43}\text{Mg}_{32}\text{Fe}_{25}$ ) with 10–15  $\mu\text{m}$  lamellae of orthopyroxene ( $\text{Ca}_{4.5}\text{Mg}_{45.5}\text{Fe}_{50}$ ), chrome-rich spinel ( $\text{Chr}_{68-58}\text{Sp} + \text{her}_{39-30} \text{ ulv}\ddot{\text{o}}_{6-1}$ ), dark red spinel ( $\text{Chr}_{31-10}\text{Sp} + \text{her}_{89-87} \text{ ulv}\ddot{\text{o}}_{2-1}$ ), pink spinel ( $\text{Chr}_{5-4}\text{Sp} + \text{her}_{95-96}$ ) and baddeleyite. Lithic clasts are relatively unshocked and consist predominately of a suite of gabbroic to anorthositic rocks containing plagioclase ( $\text{An}_{97-94}$ ), olivine ( $\text{Fo}_{79-73}$ ), orthopyroxene ( $\text{Ca}_4\text{Mg}_{73}\text{Fe}_{23}\text{-Ca}_4\text{Mg}_{77}\text{Fe}_{19}$ ) and minor clinopyroxene ( $\text{Ca}_{31}\text{Mg}_{48}\text{Fe}_{21}$ ). In one clast clinopyroxene occurs in a symplectite-like intergrowth with chrome-rich spinel, possibly representing residual liquid rather than solid state re-equilibration. One small clast consists entirely of an intergrowth of chrome-rich spinel and orthopyroxene, and one small clast of fine-grained spinel troctolite ( $\text{An}_{90-88}$ ,  $\text{Fo}_{86-82}$ ,  $\text{Chr}_{5-4}\text{Sp} + \text{her}_{95-96}$ ) was observed. Clasts of mare basalt were not observed in the two thin-sections examined (73235,65 and 69). All material observed in these two sections is of highland derivation, greatly resembling material returned by the Apollo 16 mission.

Jakeš, P. and Reid, A. M.: 'Chromium Partitioning Between Olivine and Pyroxene and the Redox State of Lunar Rocks'.

A substantial body of evidence indicates that lunar crustal rocks crystallized at lower oxygen fugacities than terrestrial crustal rocks.

In a reducing environment low oxidation states will occur for some transition elements and chromium, in particular, may be present as  $\text{Cr}^{2+}$  and  $\text{Cr}^{3+}$ . We make the assumption that  $\text{Cr}^{2+}$  is preferentially incorporated into olivine whereas  $\text{Cr}^{3+}$  predominates in oxides and in pyroxenes (though  $\text{Cr}^{2+}$  may also be present). It has been suggested that the high Cr contents of lunar olivines, in comparison to terrestrial samples, occur because  $\text{Cr}^{2+}$  could be incorporated into the olivine structure. Olivine and magnesian pyroxene are generally among the earliest phases to crystallize from lunar basalts and may record the state of the melt uninfluenced by the redox changes that accompany crystallization or subsolidus reduction. Under these assumptions the partitioning of Cr between olivine and pyroxene is a function of the ratio of  $\text{Cr}^{2+}$  and  $\text{Cr}^{3+}$  and thus of the redox state of the system. New data on Cr contents of pyroxenes and olivines in lunar rocks are summarized below and the hypothesis that Cr partitioning can lead to estimates of relative redox state of lunar rocks is explored.

It should be noted that evidence has been  $\text{Cr}^{3+}$  in lunar olivine: the presence or absence of  $\text{Cr}^{2+}$  could not be ascertained from the absorption spectra in the presence of substantial amounts of iron. Meteorites have also formed at low oxygen fugacities yet contain olivines with low Cr contents. Analyses of meteoritic silicates show that Cr is also very low in most pyroxenes coexisting with olivine and thus the partitioning of Cr between olivine and pyroxene is comparable to the lunar case.

Pyroxenes strongly fractionate Cr because of the strong octahedral site preference of  $\text{Cr}^{3+}$  and the Cr content decreases rapidly with increasing Fe in zoned pyroxenes from mare basalts. It is shown that the pyroxenes from different regions of the Moon occupy distinctly different fields on a Cr versus Mg/Fe plot, though all show the same general trend of decreasing Cr with Mg/Mg + Fe. Pyroxenes from mare basalts have higher Cr contents than pyroxenes from highland rocks, for the same Mg/Mg + Fe values. Apollo 12 and 15 mare basalt pyroxenes are more Cr-rich than those from Apollo 11 and 17. For a given mare basalt the core pigeonites and the most magnesian augites have similar Cr contents.

A range of Cr contents exists in lunar olivines from less than 0.01 wt. percent in some highland rocks up to 0.6 in some Apollo 12 mare basalts. Cr content increases inversely with the Mg/Mg + Fe ratio of the olivine for the mare basalts. Olivines in highland rocks have lower Cr contents than olivines in mare basalt but there is no well-defined trend with respect to Mg/Mg + Fe ratio. Within the mare basalt data the highest Cr contents are for olivines in the  $\text{Fo}_{65-80}$  range. Olivines from Apollo 12 basalts have the highest Cr contents followed in order of decreasing Cr by Apollo 15, 17 and 11, for the same Mg/Mg + Fe ratio in the olivine.

No reliable criteria are available to determine the specific olivine and pyroxene compositions that coexisted at equilibrium for lunar rocks containing a range of olivine and pyroxene compositions. Since olivine generally crystallizes early in lunar rocks we compare the total range of olivine compositions with the most magnesian pyroxene. From this plot it is possible to estimate the extent to which Cr is partitioned between pyroxenes and olivine and, if the basic assumption is correct, the relative redox state of the system. It is shown that Cr partitioning is distinctly different for different suites of rocks. The conclusions, under the above assumptions, are as follows.

1. The highland rocks are more oxidized than the mare basalts.
2. The Apollo 11 and 17 basalts are more oxidized than most of the Apollo 12 and 15 basalts.
3. There is a trend of decreasing redox state from highland rocks to Apollo 11 to 17 to 15 to 12 mare basalts that correlates with decreasing age of the rocks.
4. Luna 16 basalts occupy a field close to the Apollo 17 rocks and have characteristics transitional between highland and mare rocks. The Luna 16 age of 3.4 b.y., does not fit into the above sequence.

The different suites of lunar rocks may have crystallized under somewhat different oxygen fugacities and these may correlate with age so that the younger rocks are more reduced. The more reduced basalts, in this model, are more Cr-rich and Cr may be preferentially incorporated into partial melts under reducing conditions. The proposed sequence may be related to different source regions for the mare basalts, as might be produced by progressive degassing of the lunar mantle or by partial melting at progressively greater depths.

Weill, D., McKay, G., Kridelbaugh, S., and Grutzeck, M.: 'Evolution of REE, Sr and Ba Abundances During Lunar Igneous Differentiation'.

Experimental measurements of sol/liq distribution coefficients for plagioclase (PL) and clinopyroxene (CPX) permit systematic analysis of the evolution of abundance patterns. The contrasting effect of crystallizing PL and CPX can be seen, summarizing experiments at 1250°C in the 'near-basalt' system Ab-An-Di. The curve shows variation of  $D_{Eu}$  between limiting values of  $D_3$  and  $D_2$  calculated on the basis of an oxidation state distribution proportional to  $f_{O_2}^{1/4}$ . Experimental points are also shown.  $T$  variation is approximated by Arrhenius equations. A summary of the experimental data is shown. Differences between  $D_3$  and  $D_{Sr} \approx D_2$  are a measure of the maximum attainable Eu-anomaly, and the data unequivocally demonstrate a negative anomaly potential in CPX down to at least 1100°. The  $T$ -dependence of  $D_{Eu}$  is drawn assuming a lunar  $T-f_{O_2}$  trend of  $0.03 \times IW$ .

Crystallization at low  $P$  is approximated by the pseudoternary. Two contrasting crystallization sequences are shown along with a proposed highland avg. comp. Early igneous differentiation may have produced PL-rich high level crust with mafic complements at lower levels. The original comp. must be concentrated in mafic components relative to present highlands (HL). Points 1 and 2 are possibilities chosen to calculate the evolution of trace element abundances during fractional crystallization with variable  $D$ 's. A typical result is shown. The relative abundances developed in  $L$ , PL and CPX between 0.40 and 0.02  $L$  remaining is shown. Absolute and relative enrichments in the liquid at  $L < 0.10$  are grossly comparable to KREEP if the original liquid is assumed 10–15x chondrites. Sequence 2-3-R develops small positive anomalies in early stage  $L$  and less extreme late stage negative anomalies than sequence 1-R which is dominated by PL crystallization. Systematic differences also occur in the mineral phase patterns, but in the later stages of fractionation all patterns are similar to those found in lunar minerals and rocks. Based only on considerations of the general appearance of the abundance patterns of these elements, it is difficult to rule out the possibility that fractionated liquids of this type formed veins, dikes or sills in the early crust and are now contributing to the general KREEP level. The fine structure of the correlation between the Eu-anomaly (Sm/Eu) and the absolute enrichment in REE (Sm) shows that sequence 1-R results in Sm/Eu larger relative to Sm than found in KREEP. Fractionation sequence 2-3-R is more compatible with KREEP. Although PL is necessary for the Eu-anomaly signature of KREEP, sequence 1-R provides too much of a good thing. Enrichment of high crustal levels in PL probably resulted from gravity separation of mafics. We show the effect of removing sufficient OL and PX to change the bulk compositions of 1 and 2 to HL. The resulting patterns are compared to the HL REE abundances. Removing OL + CPX from 2 yields a pattern with slight relative enrichment in light REE similar to HL but also a small positive anomaly not suggested for HL. If half of PX removed is OPX (OL and OPX are assigned  $D \leq 0.01$ ), the anomaly is reduced, but the enrichment in heavy REE is high. Composition 1 (already close to HL) is not significantly affected by the process.

Partial melting may be a preferred mechanism for generating KREEP. Analysis of partial melting can best be visualized with D'agostino diagrams. The PL-CPX-(OL + OPX) triangle is contoured in  $D_{Sm}$  and  $D_{Eu}$ . For a given degree of equilibrium melting, each composition uniquely determines a set of Sm and Sm/Eu values.

Bansal, B. M., Haskin, L. A., Nyquist, L. E., Rhodes, J. M., Shih, C.-Y., and Wiesmann, H.: 'Chemical Evidence for the Origin of 76535 as a Cumulate'.

Sample 76535 from the North Massif at the Apollo 17 site is a coarsegrained troctolitic granulite rather well equilibrated by long annealing times. It has a modal analysis of 58% calcic plagioclase, 37% magnesian olivine, 4% bronzite, and approximately 1% interstitial material. The plagioclase aggregates average 7 mm in size; olivine aggregates approximately 5 mm. Bronzite crystals are smaller than 4 mm.

Samples of the whole rock plus carefully hand-picked plagioclase and olivine were analyzed for a series of trace elements by mass spectrometric isotope dilution, and the whole rock was analyzed for major elements by x-ray fluorescence.

The low concentrations of the REE, the large positive Eu anomaly, and the highly magnesian character of the olivine (Foss) suggest that this rock originally formed by crystal accumulation from a liquid. From the data available, various restrictions can be placed on the chemical composition of

the parent liquid. If the olivine and plagioclase crystals as analyzed are simply considered as having formed in equilibrium with a liquid which was cleanly separated from them, then by using values for REE distribution coefficients from the literature the range of possible rare Earth concentrations in that proposed parent liquid can be estimated. The liquid estimated in this manner has REE concentrations, including a significant Eu depletion, in the range found for Apollo 17 noritic breccias (KREEP) and intermediate to that for Apollo 16 KREEP and VHA basalt. If the Apollo 16 and 17 KREEP and VHA basalts are truly characteristic of frozen lunar liquids, then there were apparently liquids whose equilibrium and crystallization could yield olivine and feldspar with the rare earth concentrations observed for those minerals in 76535. This exercise, however, must be regarded as defining only an upper limit to possible REE concentrations of the parent liquid for this rock.

Cumulate rocks normally contain from a few to as much as 50% trapped liquid. As the trapped liquid crystallizes, growth of the original cumulus minerals continues until the composition of the liquid changes to the extent that further phases are produced. Most probably 76535 contained at least a few percent trapped liquid. The distribution coefficients (solid/liquid) for plagioclase and olivine are low. Therefore, trapped parent liquid even in small quantities would seriously affect the concentrations of the REE in the rock and in the constituent minerals. The long annealing time for the rock would tend to homogenize the portions of the major minerals from the trapped liquid with the cumulate portions. This process could also mask the original cumulus texture of the rock. During the formation of some cumulates, major minerals continue to grow in equilibrium with a relatively large body of parent liquid (adcumulus growth). The estimate made above would correspond to the most extreme possible case of adcumulus growth in which no parent liquid was trapped among the growing crystals. That is undoubtedly too severe an approximation.

A better estimate can be made by recognizing that some trapped liquid is undoubtedly present and assuming that the bronzite and interstitial materials were crystallized from the trapped liquid. The 4% bronzite corresponds to approximately 10% of the rock as being produced from trapped liquid. This assumes the composition of the peritectic and simultaneous presence of olivine, orthopyroxene, and plagioclase. A mass balance taking into account the estimated relative amounts of the REE in the cumulate and trapped liquid (orthocumulate) portions of the rock produces a parent liquid with rare earth concentrations approximately 30 times those in chondrites and with a slight Eu depletion. If the bronzite is, indeed, orthocumulate in origin, this also provides an upper limit to the concentration of the parent liquid. Since bronzite was not accumulating from the parent liquid, that liquid would have to crystallize still further olivine and plagioclase to reach the peritectic where bronzite could appear.

It is not clear whether the Eu deficiency observed for mare basalts and trace element-rich highland materials is a result of an overall lunar deficiency in Eu resulting from the conditions of planetary accretion or a result of internal differentiation of the accreted Moon. It is still possible to consider that the Eu that is missing in trace element-rich mare and highland materials was previously crystallized into feldspar during the early planetary differentiation. In view of this possibility, it is interesting to consider whether a liquid with no Eu depletion could have produced 76535 by crystal accumulation plus trapped liquid. The Eu anomaly for the hypothetical parent liquid of this rock disappears for a concentration for the parent liquid of approximately 15 times that found in the chondrites. This requires that the rock contain 20% trapped liquid, which is well within the range found for terrestrial cumulates and consistent with the requirement of additional crystallization of the trapped parent liquid prior to formation of bronzite.

There is some indication in the rare Earth distributions that complete equilibration of REE between plagioclase and olivine, as expected from the apparently long annealing times, has not occurred.

Bansal, B. M. Bogard, D. D., Nyquist, L. E., and Wiesmann, H.: '76535: An Old Lunar Rock?'

The suggestion by Gooley *et al.* that lunar sample 76535 formed at considerable depth as a result of crystal accumulation makes a determination of its radiometric age extremely important. We have carried out Rb-Sr measurements on separated minerals and K-Ar measurements on plagioclase separates and on a whole rock sample. We have not been able to obtain a completely unambiguous age at this time, apparently because of inherent complexities of the rock.

*K-Ar Results.* Plagioclase comprises 58% of the rock, olivine 37%, pyroxene 4%, and minor phases  $\leq 1\%$ . Two plagioclase separates ( $> 99\%$  pure) were prepared by Frantz and hand-picking from a coarsely crushed ( $\sim 0.5$ – $1$  mm grain size) portion of an original 4 gr sample; spits were prepared for

K and Ar analyses. An aliquot of the whole rock sample weighing 1.3 gr had been previously ground to fine grain size ( $\sim 50\mu$ ) and used for major and trace element chemistry by XRF and isotope dilution (2). Portions of this sample were used for K and Ar analyses. Potassium was measured by isotope dilution. Argon was measured mass spectrometrically by a standard addition technique using a gas pipette delivering calibrated amounts of atmospheric Ar. Argon was extracted from plagioclase #1 in a single melting stage. To insure that no significant amounts of adsorbed atmospheric Ar were contributing to the total  $^{40}\text{Ar}$ , the second plagioclase and the whole rock were extracted in three stages: 150°C, 350°C, and 1640°C. Only 1.7% and 3.3% of the total  $^{40}\text{Ar}$  released by the plagioclase and whole rock, respectively, were released in the two lower temperatures (with a larger amount released at 150°C) and this Ar was nearly atmospheric in composition.

The plagioclase and whole rock K-total  $^{40}\text{Ar}$  ages of 76535 are  $4.40\text{--}4.54 \times 10^9$  yr. However, this lunar sample apparently contains  $^{40}\text{Ar}$  which is not the result of *in situ* decay of  $^{40}\text{K}$ , as well as  $^{36}\text{Ar}$  and  $^{38}\text{Ar}$  which are not the result of cosmic ray interactions during its exposure age.  $^{40}\text{Ar}/^{36}\text{Ar}$  was plotted against  $^{38}\text{Ar}/^{36}\text{Ar}$ . The value for trapped  $^{38}\text{Ar}/^{36}\text{Ar}$  obtained (0.187) would be approximately correct for solar wind, atmospheric, or trapped meteoritic ('planetary') Ar. The value used for cosmogenic  $^{38}\text{Ar}/^{36}\text{Ar}$  (1.43) is that measured by Eberhardt *et al.* in a feldspar concentrate of 10003. The three samples analyzed all show  $^{38}\text{Ar}/^{36}\text{Ar}$  less than 1.43, and show a linear correlation within analytical uncertainties which intercepts the trapped  $^{38}\text{Ar}/^{36}\text{Ar}$  line at  $^{40}\text{Ar}/^{36}\text{Ar} = 36.6 \pm 2$ , and the cosmogenic  $^{38}\text{Ar}/^{36}\text{Ar}$  line at  $^{40}\text{Ar}/^{36}\text{Ar} = 104 \pm 1$ . Such a linear correlation could represent mixing of an excess component with  $^{36}\text{Ar}:^{38}\text{Ar}:^{40}\text{Ar} = 1:0.187:37$  and argon of composition  $^{36}\text{Ar}:^{38}\text{Ar}:^{40}\text{Ar} = 1:1.43:104$  produced *in situ* by radioactive decay and cosmic-ray interactions. Both plagioclase and the whole rock have Ca/K ratios of about 335, so that a mixing line would be generated if the composition of the excess argon remains constant. (Actually, radiogenic  $^{40}\text{Ar}$  and cosmogenic  $^{36},^{38}\text{Ar}$  production in the whole rock are both heavily dominated by the plagioclase.) The correlation can be used in two equivalent ways to correct for the apparent excess Ar: (i) the intercept value of  $^{40}\text{Ar}^*/^{36}\text{Ar} = 104$  can be multiplied by the cosmogenic  $^{36}\text{Ar}$  to give the radiogenic  $^{40}\text{Ar}^*$ ; (ii)  $^{40}\text{Ar}/^{36}\text{Ar} = 37$  for the excess argon can be multiplied by the excess  $^{36}\text{Ar}$  (total  $^{36}\text{Ar}$  minus cosmogenic  $^{36}\text{Ar}$ ) to determine the excess  $^{40}\text{Ar}$ , which is subtracted from the total  $^{40}\text{Ar}$  to yield the radiogenic  $^{40}\text{Ar}^*$ . Corrections to  $^{40}\text{Ar}$  for the plagioclase #1, plagioclase #2, and whole rock amounted to 9.5%, 2.2% and 21% respectively.

Corrections for excess  $^{40}\text{Ar}$  lower the plagioclase age to  $\sim 4.34 \times 10^9$  yr, and the whole rock age to  $4.14 \times 10^9$  yr. The latter is considered least reliable because it is more sensitive to the correction and because the ratio of measured cosmogenic  $^{38}\text{Ar}$  in the whole rock to that in the plagioclase is only 53%, whereas the ratio ought to be  $\sim 58\%$  if the whole rock sample contained a 'normal' amount of plagioclase. If one increases the corrected  $^{40}\text{Ar}$  content of the whole rock sample by a corresponding factor (10%) the corrected K- $^{40}\text{Ar}$  age becomes  $4.30 \times 10^9$  yr, in agreement with the plagioclase values. If the excess argon interpretation is correct, the plagioclase gas retention age of the rock is  $4.34 \pm 0.08 \times 10^9$  yr. The  $^{38}\text{Ar}$  cosmic ray exposure age is  $200 \times 10^6$  yr.

*Rb-Sr Results.* Several factors combine to make Rb-Sr dating of this rock difficult: (a) the Rb concentration of the whole rock is only 0.2 ppm; (b) almost all of the trace elements are concentrated in the plagioclase, and trace element abundances in the other major mineral, olivine, are very low; (c) plagioclase and olivine make up at least 95% of the rock, while minor phases which might concentrate trace elements are rare ( $< 1\%$  of the total rock). (d) The rock went through an extended period of annealing and recrystallization. It further appears from our data that the Rb-Sr systematics have been disturbed. The data do not uniquely define an isochron. Tie lines between the plagioclase/whole rock point and the three olivine data yield apparent ages of  $5.9 \pm 0.5$  AE,  $8 \pm 2$  AE, and  $5.1 \pm 0.4$  AE, respectively. Thus either we have unsuspected analytical difficulties or the system does not fulfill the criteria for a Rb-Sr age. We do not completely exclude the first possibility, but feel it is highly unlikely.

The olivine 2 and 3 data allow an interesting calculation. The olivine 3 separate is estimated to contain at least 95% olivine by weight. If olivine 3 is viewed as a two component mix of 'pure' olivine (#2) and a 'residue',  $^{87}\text{Rb}/^{86}\text{Sr}$  in the residue can be obtained with only slightly greater uncertainty than for the analytical precision of olivine 3. The corresponding  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio may also be calculated. This calculated point ( $^{87}\text{Rb}/^{86}\text{Sr} = 0.0666$ ,  $^{87}\text{Sr}/^{86}\text{Sr} = 0.7033$ ,  $+ 0.0005$ ,  $- 0.0003$ ) together with the plag/whole rock data yields an apparent age of  $4.4 + 0.6 / - 0.5$  AE, consistent with the K-Ar age. The initial  $^{87}\text{Sr}/^{86}\text{Sr}$  (I) obtained from the plag/whole rock is relatively insensitive to the age ambiguity. Assuming the K-Ar age (4.3 AE) yields  $I = 0.69913 \pm 6$ , i.e., essentially our BABI value. For  $T =$

= 3.7-4.6 AE,  $I = 0.69923-0.69905$ . Thus the  $I$  values accommodate the old age found by K-Ar but could also be consistent with  $(T, I)$  for a mare basalt like 70035.

Tera, F., Papanastassiou, D. A., and Wasserburg, G. J.: 'The Lunar Time Scale and a Summary of Isotopic Evidence for a Terminal Lunar Cataclysm'.

The Rb-Sr age of a low K basalt from Apollo 17 was determined to be  $3.64 \pm 0.09$  AE which is slightly younger than 75055 and indistinguishable from the low K Apollo 11 basalts. The distribution of magmatic or metamorphic events is well defined and does not differ greatly from our previous reports. No well defined crystallization age has been found in the 4.0-4.6 AE gap. A two point internal isochron on a dunite gives a Rb-Sr age of 4.60 AE and appears to be a rare survivor of early lunar differentiation, although Pb isotopic results give a somewhat younger age and may indicate a disturbed system. Further search for such survivors with adequate proof of their antiquity and a study of their characteristics is of prime importance in understanding the first 0.5 AE of lunar evolution. Studies of total rocks which appear to be consanguineous, suggest differentiation ages of  $\sim 4.4$  AE and may represent magmatic activity in the gap. Model ages on highland breccias from Apollo 17 lie between 4.4 to 4.6 AE and follow the general characteristics of many lunar rocks which point to an early lunar differentiation.

The existing Pb-U data for terra type rocks from Apollo 14, 15, 16 and 17 are presented. These data on a wide variety of lithic types form an extraordinary linear array and demonstrate a general genetic relationship between the terra rocks. Both total rock and internal U-Pb isochrons lie on this array. The observed  $^{238}\text{U}/^{204}\text{Pb}$  variations for the samples cover a range of  $10^4$ . We interpret this Pb-U fractionation to be largely the result of major impacts in which the Pb was vaporized by a special mechanism from the target rocks and redistributed over the lunar surface, enriching highland regolith (see soil field) and some rocks (15415, 66095, 60017) in Pb with an average  $^{207}\text{Pb}/^{206}\text{Pb} \sim 1.45$  as was identified in Apollo 14 rocks and as a coating of labile Pb on 15415. The residual metamorphosed targets were converted to high  $\mu$  rocks due to the removal of both *in situ* radiogenic Pb and primordial Pb. The extent to which major lunar magmatism due to internal heat sources took place at about the same time as the cataclysmic bombardment is an open question.

No precise time may be determined from this general array because it is nearly tangent to the concordia curve and there is some distinct scatter. Nonetheless, the data prove conclusively that there was widespread redistribution of radiogenic Pb, primordial Pb and U at 3.9-4.0 AE all over the Earth facing side of the Moon. This observation in conjunction with the sharp cutoff in crystallization ages at 4.0 AE, provides strong evidence for a terminal lunar cataclysm as identified previously (7.11). This cataclysmic event or cluster of events, which may have occurred over a 0.1 AE interval, is most reasonably associated with the formation of major lunar basins and temporally related magmatism such as inferred for 76535 and 68415. Certainly no evidence exists for producing troctolite 76535 by impact melting. This rock, which has  $\mu_1$  typical of the source material for basalts (13) was either intruded at depth and remained hot enough to permit continuous isotopic equilibration until the time of excavation, or else it is a near surface rock which was formed at  $\sim 3.9$  AE. The indirect evidence for early lunar differentiation is sufficiently strong to conclude that major planetary differentiation processes took place between 4.6-4.3 AE. From the data presented here we would conclude that the crust is 4.43 AE old for a simple two stage model; however, it is possible that about one-half of the crust formed between 4.6 to 4.5 AE, and the remainder evolved uniformly down to  $\sim 3.9$  AE, in which case  $I \text{ Pb} \approx 1.45$  would represent an average of the rocks sampled and mixed during the major impacts. Then the upper intersection with concordia is a type of average crustal age. These model ages for both the Earth and the Moon are distinctly lower than the  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  ages of meteorites. This difference of  $\sim 0.1$  AE is not yet resolved. Using the data for 15555, we note that they are not compatible with the values of 4.56 to 4.58 AE iterated by Tatsumoto *et al.* and may possibly be due to small analytical errors here or there or else reflect a multistage evolution in which the reservoir of the basalts was itself the product of an early differentiation lasting over 0.1 AE.

Epstein, S. and Taylor, H. P., Jr.: 'Oxygen, Silicon, Carbon and Hydrogen Isotope Fractionation Processes in Lunar Surface Materials'.

The sources of hydrogen so far definitely identified in lunar materials are the solar wind, cosmic-ray



spallation, and terrestrial H<sub>2</sub>O contamination. At the present time our data do not permit us to identify other possible sources of hydrogen, such as meteorites, comets, or primary lunar H<sub>2</sub>O. The major source of H<sub>2</sub> gas is clearly the solar wind, as shown by the fact that the H<sub>2</sub> in lunar soils and soil-breccias is almost completely devoid of deuterium. Spallation hydrogen is very deuterium-rich and has been observed in small quantities in the gas extracted from lunar surface rocks during fusion. New evidence for the presence of spallation deuterium is given by a  $\delta D$  value of +43‰ for an aliquot of gas from 14310 basalt. The deuterium concentration in the lunar H<sub>2</sub>O is similar to terrestrial water vapor from temperate climatic areas, but more importantly there is a relationship between the  $\delta D$  of the water in lunar soils and the H<sub>2</sub>O/H<sub>2</sub> ratio. This relationship is caused by cross-contamination of this water with oxidized solar wind hydrogen during its extraction from lunar materials. When the H<sub>2</sub>O/H<sub>2</sub> ratio is > 1, this cross-contamination is sufficiently small so that the  $\delta D$  of the water acquires its maximum value and remains roughly independent of the H<sub>2</sub>O/H<sub>2</sub> ratio. This 'plateau' in the  $\delta D$  value lies at about -120‰. We know that the bulk of this H<sub>2</sub>O lies on the grain-surfaces in the lunar soils, because of its ease of extraction, and because its presence is identified by abnormally low  $\delta O^{18}$  values in the oxygen stripped from the grain surfaces during partial fluorination experiments. However, it is still possible that some of this H<sub>2</sub>O is of true lunar origin. 'Rusty rock' breccia 66095 is an important sample in this regard, because it contains possible lunar goethite, abnormally large amounts of H<sub>2</sub>O, and is almost devoid of extractible H<sub>2</sub> gas. The ratio of H<sub>2</sub>O/H<sub>2</sub>  $\gg$  1. The average  $\delta D$  value of H<sub>2</sub>O extracted at room temperature by pumping in vacuum is -110 (7.5  $\mu$  moles H<sub>2</sub>O/g) and the average  $\delta D$  value of H<sub>2</sub>O extracted from 25° to 600° is almost the same, -97 (30  $\mu$  moles/g). This water was extracted in about 15 successive increments, with the largest portion driven off at ~50°-400°C. This detailed extraction procedure was used in order to be able to detect any water of highly unusual isotopic composition, such as water formed from oxidation of solar wind H<sub>2</sub>. No such unusual water was detected. Except for the final 4%, the range in  $\delta D$  values of the various aliquots was only -75 to -145‰. The highest temperature fraction of water had a  $\delta D$  of -196. Note that both  $\delta D$  values are identical to the  $\delta D$  'plateau' established for other lunar samples. Inasmuch as the low-T H<sub>2</sub>O from 66095, as well as the bulk of the H<sub>2</sub>O in lunar soils, seem to us to be due to terrestrial contamination, this suggests a similar origin for the high-T H<sub>2</sub>O in 66095.

Lunar basalts apparently contain about 10 to 40 ppm carbon with  $\delta C^{13} \approx -20$  to  $-30$ . Some of the higher concentrations may be attributable to slight contamination, because the most probable terrestrial contamination also has  $\delta C^{13} = -20$  to  $-30$ . Two new analyses of large, carefully handled aliquots of 14310 basalt by us give 17 and 14 ppm and  $\delta C^{13} = -25.3$  and  $-21.9$ , respectively. Thus measurements from several laboratories indicate that, in spite of the coincidence in  $\delta C^{13}$  between the basalts and contaminant carbon, most lunar basalts should have about 10 to 20 ppm of indigenous primary carbon. A much greater amount of carbon is present in lunar soils and breccias; this must have been added from the solar wind, from carbonaceous meteorites or comets, or from some unknown source elsewhere on the Moon. An approximate linear relationship exists between solar wind H<sub>2</sub> content and carbon content; this can be interpreted qualitatively as possible evidence for a solar wind origin for much of the carbon, although a meteoritic origin cannot be excluded as the total amount of meteoritic debris in the soil should also be a function of exposure time at the lunar surface. A knowledge of the isotopic composition of the carbon is critical as abundance measurements alone cannot distinguish between these various possibilities. The only two lunar samples we have found that seem to be clearly anomalous are 61221 and 74220 (orange soil). The orange soil sample, composed of tiny glass spherules, is anomalous because it probably lost most of its carbon at the time of its formation (it now has only 3.5 ppm carbon, the lowest value yet analyzed for a lunar sample). Sample 61221 is probably anomalous because it contains a major meteoritic (or cometary) component; this would explain why its high carbon content (97 ppm) is accompanied by a very low  $\delta C^{13}$  value ( $-13.9\%$ ) and low solar wind H<sub>2</sub> content. Carbonaceous chondrites have similar  $\delta C^{13}$  values.

Certain lunar breccias are enriched in O<sup>18</sup> relative to lunar basalts, suggesting they may in large part be derived from lunar soil; in some such examples there is independent petrographic and chemical evidence that support this hypothesis. The high  $\delta O^{18}$  values are accompanied by high  $\delta Si^{30}$  values, and it is known that these are a result of extremely large O<sup>18</sup> and Si<sup>30</sup> enrichments (up to +5 and +30%, respectively) on the surfaces of grains in all the lunar fines. These O<sup>18</sup>- and Si<sup>30</sup>-enrichments are directly related to the amount of solar wind H<sub>2</sub> in the samples and are a result of bombardment by meteorites, micrometeorites, and/or nuclear particles, with preferential loss of Si<sup>28</sup> and O<sup>16</sup>. Some of the  $\delta O^{18}$  and  $\delta Si^{30}$  surface enrichments of lunar fines are shown. These particular  $\delta O^{18}$  curves are atypical in that they do not show a smooth decrease in  $\delta O^{18}$  as the grain surfaces are 'stripped off'

during fluorination. Such irregular effects do not show up in the  $\delta\text{Si}^{30}$  curves, one possible explanation being that adsorbed low- $\text{O}^{18}$   $\text{H}_2\text{O}$  (or a hydrated mineral such as goethite) is present in the soils, thus complicating the  $\delta\text{O}^{18}$  record. A lunar soil breccia that has been heated or metamorphosed at temperatures above about  $600^\circ\text{C}$  will have lost most of its solar wind hydrogen and rare gases, but the grain-surface  $\delta\text{O}^{18}$  and  $\delta\text{Si}^{30}$  enrichments may be preserved. We do not yet know at how high a temperature these grain-surface isotopic effects disappear, but even if they are completely 'smoothed out' by diffusion during a metamorphic event, there will still remain a significant 0.3–0.8‰ whole-rock  $\delta\text{O}^{18}$  enrichment and a 0.1–0.5‰ whole-rock  $\delta\text{Si}^{30}$  enrichment. No lunar igneous process has yet been identified which can produce as much as a 0.3‰ enrichment in  $\text{O}^{18}$ . Even the peculiar 'granitic' breccia 12013 has a  $\delta\text{O}^{18}$  similar to lunar basalts. Therefore, it is likely that all significant  $\delta\text{O}^{18}$  enrichments in lunar materials are attributable to a lengthy exposure of the disaggregated material at the lunar surface. A good case can probably be made that essentially *all* 'volatile' elements on the grain-surfaces of the lunar fines are isotopically enriched in the heavy isotope (oxygen, silicon, carbon, sulfur, potassium, etc.).

Lightner, B. D. and Marti, K.: 'Lunar Trapped Xenon'.

Apollo 11 and 12 crystalline rocks contain only very small trapped gas components, which are masked by abundant *in situ* produced spallation and radiogenic components. Therefore, no information on the isotopic abundances of the trapped lunar xenon in these rocks has been obtained. The trapped gases in soils and soil-breccias, although sometimes altered by lunar-surface processes, are predominantly of solar origin. Several authors have reported large trapped and fission xenon components in some Apollo 14 breccias. A knowledge of the isotopic composition of trapped xenon is not only important in a spectral decomposition of xenon in lunar breccias but it may yield information on the genesis of breccias and the Moon in general. A study of trapped xenon will be most successful when applied to samples with short exposure ages.

The total xenon contents and isotopic compositions in several rocks are reported. It is apparent that the spallation component is predominant in crystalline rocks, but quite small in anorthositic breccias. This does not only reflect the abundances of the major target elements for spallation, Ba and REE, which vary considerably, but also the fact that the exposure ages of the investigated anorthositic breccias are all relatively short. Since their spallation components are small, it was possible to obtain accurate data for the trapped components in breccias 60025 and 62255. Trapped xenon is found to be the same in all temperature fractions, and its isotopic composition is consistent with that found in 14321. The fission component is small; therefore, relative abundances of the heavy isotopes can be well determined. In sample 62255, there is a small solar-type component, which affects the He, Ne and Ar isotopes, but not Xe. The temperature release characteristics show that these trapped lunar gases are tightly held and are only released at high temperatures together with the spallation gases. A particularly intriguing problem is the similarity in the fine structure at mass 129 of lunar and terrestrial xenon, when compared to solar xenon. The question of the origin of trapped lunar xenon is of obvious importance; several alternatives must be considered.

*Crater ages:* A comment on crater age assignments appears to be in order, since crater ages have been suggested in the literature which are based on single rock or soil analysis. At the Apollo 16 site, in our opinion, the only well documented crater age is that of North Ray which is 49 m.y. It is possible, but not certain, that the four available 2–3 m.y. exposure ages obtained from rocks 68815 and 69935, by Behrmann *et al.*, and from 60025 and 62255, in this abstract, do date the South Ray crater. The exact age, and the question of whether or not they are identical, depend on the choice of trapped krypton.

## 11. Nature of Impact Processes and Their Effects on Lunar Materials: II

Stoeser, D. B., Wolfe, R. W., Marvin, U. B., Wood, J. A., and Bower, J. F.: 'Petrographic Studies of a Boulder from the South Massif'.

The Apollo 17 astronauts collected four samples from Boulder 1 at Station 2, a visibly stratified boulder that appears to have rolled to its present position from high on the South Massif. Two of the

four samples (72275, 72255) have been studied by members of the CONSORTIUM INDOMITABLE, to which they were allocated.

The bulk composition of 72275 is intermediate between those of KREEP norite and lunar anorthositic rocks, being rather closer to the KREEP norite composition. 72255 appears (from petrographic examination) to be very similar in composition to 72275.

The boulder samples are polymict breccias, consisting of clasts embedded in fine-grained matrices. The four types of matrix material currently recognized in boulder samples are, in order of decreasing abundance:

(1) Light-gray, porous, friable, polymict breccia. Makes up the bulk of 72275; some present in 72255. Chemical composition very similar to the bulk composition of 72275.

(2) Medium-gray, non-porous, competent polymict breccia. Makes up the bulk of 72255. Probably very similar to (1) in composition. All gradations between (1) and (2) occur in 72255.

(3) Porous, friable zones of crushed pigeonite basalt (see below), largely uncontaminated by other lithologies. Fairly abundant in 72275.

(4) Light-colored, porous, friable, plagioclase-rich streaks and zones. Sparsely distributed in 72275 and 72255.

Principal types of clasts encountered to date, in order of abundance, are:

(1) Small, angular, monomineralic clasts of all the lunar rock-forming minerals. Abundances of mafic and feldspar clasts are comparable.

(2) Hard, dark breccia clasts, rounded in form and almost opaque in thin section. These are compositionally similar to 72275 overall. The clast population is composed largely of small (5–50 $\mu$ ) angular mineral clasts, with somewhat larger lithic and mineral clasts also included. The darkness of the clasts is due to very fine (0.1–0.5 $\mu$ ), evenly disseminated metallic iron. Dark breccia clasts sometimes have light-colored lithic cores, usually of anorthositic composition.

(3) Anorthositic clasts, granulitic in texture; types common in the soils and breccias of earlier missions.

(4) Cataclastic anorthosite clasts.

(5) Pigeonite basalt clasts, mostly (but not solely) in the zones of that material noted above. Pyroxene, mostly  $Fs_{25-35}$ ,  $Wo_{5-10}$ ; plagioclase,  $An_{89-96}$ ; K-rich mesostasis; minor ilmenite, spinel, olivine. (Pigeonite basalt has been observed only in 72275.)

(6) Troctolitic basalt clasts.

(7) Microgranitic clasts; highly varied in character.

(8) Breccia derived from a coarse, plutonic norite. Most is present in a single 2-cm clast in 72255, dubbed 'Civet Cat'.

We tentatively interpret the boulder as a large fragment of bedded deposits of ejecta from a single major cratering event, probably the Serenitatis basin-forming catastrophe. Some strata were laid down hotter than others, and these sintered (quickly, before temperatures equalized) into more resistant layers, such as the source of 72255. The dark breccia clasts are the most unusual aspect of the boulder specimens. Their internal structure is dominantly clastic and only very rarely do they contain vesicles, so they cannot be interpreted simply as devitrified blobs of impact-melted glass. They seem accretional in character. We suggest they formed by accretion of mineral fragments and melt droplets (sometimes upon larger lithic-fragment cores), in ballistic trajectory or in the base-surge aftermath of a basin-forming event. Enough melt component was present to bind the mineral fragments together and lend fluidity to the aggregation, accounting for the rounded shapes of the dark breccia clasts.

Chao, E. C. T. and Minkin, J. A.: 'The Petrogenesis of 77135, a Fragment-Laden Pigeonite Feldspathic Basalt – A Major Highland Rock Type'.

Sample 77135, 10 × 8 × 4 cm in size and weighing about 337 g, is a 'greengray breccia'. It is the youngest among the four samples collected from the Station 7 boulder.

Megascopically, 77135 is a gray, vesicular, fine-grained phyrlic crystalline rock containing scattered white feldspathic clasts and greenish yellow olivine xenocrysts. The matrix consists mainly of crinkly, pale brown pyroxene and grayish transparent plagioclase with black specks of ilmenite. Most of the sample is highly vesicular (designated below as part A) but a smaller part is less vesicular and finer-grained (designated below as part B). The grain size of the pyroxenes in the matrix ranges from approximately 0.2 to 0.8 mm in A and is less than 0.5 mm in B. Most vesicles are spherical and less than

2 mm in diam, but a few spherical and some elongated vesicles are as much as 1 cm. long. Some contain euhedral troilite.

Several kinds of xenoliths, mostly light colored, are enclosed in 77135. The most abundant kind is a light gray, vuggy, recrystallized troctolitic breccia with poikiloblastic orthopyroxene in the matrix. This breccia xenolith itself contains xenoliths of medium-grained olivine-rich troctolite and fine-grained granular troctolitic anorthosite and Ni-Fe particles. This type of xenolith is more abundant in B. (The largest clast of this kind is about  $3 \times 2 \times 1$  cm and is being studied in detail by the Station 7 boulder consortium.) Another type of material present as large clasts is white, fine-grained, recrystallized troctolitic anorthosite with a sugary granular texture. (One such clast,  $1.5 \times 1 \times 0.5$  cm, enclosed in A is also being studied by the consortium.) Small, dark, very fine-grained xenoliths are present, but they have not been studied. Rare spinel-bearing troctolitic xenoliths are also present.

This suite of xenoliths, more than one generation, is characteristically highly feldspathic, grading from troctolitic anorthosite to troctolite in composition. All are crystalline. Most xenocrysts are probably crushed derivatives of some of the coexisting xenoliths; most are either olivine (Fo<sub>71-92</sub>, some with rims near Fo<sub>71</sub>) or plagioclase (An<sub>79-97</sub> with rims ranging from An<sub>80</sub> to An<sub>95</sub>).

The matrix of 77135 consists of calcic plagioclase and poikilitic clinopyroxene with subordinate amounts of olivine and accessory ilmenite, interstitial K-rich material, apatite (?), troilite and metallic iron. The CIPW norm of the bulk rock gives about 53% plagioclase, 31% pyroxene, 13% olivine and 3% ilmenite. Texturally, the matrix is formed of abundant poikilitic clinopyroxene locally separated by patches of granular olivine and anhedral plagioclase. Plagioclase in the matrix occurs in two distinct morphological types: 1. as small, sharply defined laths or elongated platy inclusions (An<sub>91</sub>) in the poikilitic clinopyroxene, and 2. as stubby laths and anhedral grains associated with granular olivine grains (An<sub>89</sub>). Locally interstitial to the anhedral plagioclase are materials high in K<sub>2</sub>O. The poikilitic clinopyroxene grains are of both pigeonite and augite. Dominant is a very pale brown pigeonite with very low to low content of CaO (3.2-5.2 wt. %). (The identification of pigeonite is based not on the chemical data but on qualitative optical properties and X-ray powder diffraction and single crystal investigations.) Augite with higher birefringence and much higher calcium content is minor. Traces of orthopyroxene were also detected but its specific occurrence and significance is still being evaluated. Olivine occurs both as rounded inclusions in the pigeonite and as irregular grains associated with anhedral plagioclase. Ilmenite and metallic iron occur as interstitial material between poikilitic pigeonite and anhedral plagioclase. The sequence of crystallization appears to be (1) olivine and lath-shaped plagioclase, (2) poikilitic clinopyroxenes, anhedral plagioclase and granular olivine, and (3) ilmenite, troilite, metallic iron and potash-rich residuum.

The bulk chemical composition of 77135 including some of the xenoliths and many xenocrysts it contains is characterized by its moderately high SiO<sub>2</sub> (about 47 wt. %) and Al<sub>2</sub>O<sub>3</sub> contents (about 18 wt. %), relatively high MgO/FeO, and moderate contents of Na<sub>2</sub>O, K<sub>2</sub>O, P<sub>2</sub>O<sub>5</sub> and TiO<sub>2</sub>. It is a major rock type among the Apollo 17 samples returned. It is similar to a small group of Apollo 16 rocks represented by 60315, 62235, and 65015, and to a group of Luna 20 coarse fines particles, and to heterogeneous glasses of impact origin from Apollo 11, 12, 14, and 15. Some of the Apollo 16 rocks cited may have a metamorphic history and the glasses do not necessarily represent the same rock type. We wish to point out and emphasize that rocks with composition such as 77135 are widespread on the lunar surface, and it is probable that pigeonite feldspathic basalt like 77135 is more abundant than anorthosite in the lunar highlands.

Petrographic data obtained so far suggest that 77135 crystallized from a fragment-laden melt of pigeonite feldspathic basalt composition. We have not found any evidence of shock or thermal metamorphism after it crystallized. Whether the melt was of impact or igneous origin is not easy to determine. Its bulk composition plots near the plagioclase-pyroxene cotectic line in the ternary system forsterite-anorthite-silica, particularly if the olivine and plagioclase xenocrysts could be subtracted from the analysis. Age information and source area information are being obtained, hence it would be premature to speculate on its origin. We are, however, impressed with many arguments in favor of an igneous origin. These will be fully developed as the consortium investigation of this rock progresses.

The European Consortium, Agrell, S. O., Bowell, E., Dollfus, A., Dran, J. C., Eglinton, G., Geake, J. E., Maurette, M., Mays, B. J., Pillinger, C. T., Schultz, L., Scoon, J. H., and Signer, P.: 'The History of Lunar Breccia 14267'.

Rock 14267 was a 55 g polymict breccia from the ALSEP area of the Apollo 14 site. It is partially

glass coated and a few zap pits occur on the glass and rock surfaces. Dust coated regions exhibit complex structures built up by adhesion and most grains are rough on the micron scale. The optical properties of this type of surface resemble that of the lunar fines and the large scale lunar surface. The optical behaviour of the glass and freshly chipped interior surfaces do not reproduce the lunar polarisation characteristics.

The bulk composition of the rock determined from saw cuttings (%SiO<sub>2</sub> 48.35 TiO<sub>2</sub> 2.11, Al<sub>2</sub>O<sub>3</sub> 16.87, Cr<sub>2</sub>O<sub>3</sub> 0.19, Fe<sub>2</sub>O<sub>3</sub> 0.28, FeO 10.10, MnO 0.13, MgO 9.72, CaO 10.29, Na<sub>2</sub>O 0.90, K<sub>2</sub>O 0.78, P<sub>2</sub>O<sub>5</sub> 0.57, S 0.08) is similar to type C Fra Mauro basalt glass and to average dark metaclastic fragments from < 1 mm Apollo 14 fines. The matrix of the breccia is dark vitreous or just annealed, corresponding to Grade 2 of Warner. The 0.02–1 mm clast population is as follows: (%) glass ropey fragments 34.5, fine-grained metaclastics 44, basaltic 4.5, minerals 14, ultramafic 1.5, miscellaneous 1.5. Occasional cored lapillae occur. Glasses are dominantly quartz-normative Fra Mauro types with subordinate basaltic glasses.

Lithic clasts are pale and dark metaclastics with non-equilibrated porphyroclasts of olivine, orthopyroxene, clinopyroxene, plagioclase, ilmenite and spinel. Both mineral and lithic clasts show evidence of shock deformation.

Unique to this rock are a few microharzburgite fragments in which enstatite has undergone shock deformation to a fine-grained aggregate of clinoenstatite (En 90) associated with mosaiced olivine (Fo 89). Kinkbanding in hypersthene clasts does not show development of clinoenstatite (c.f. Tromsdorf and Wenk). It is possible that this deformation antedates the ejection of 14267 to the collection site. One small granitic clast of the pale metaclastics showed evidence of partial melting and the possible development of quench crystallites of clinohypersthene from protohypersthene.

The exposure history of 14267 has been studied using carbon chemistry, noble gas and track data. DCI dissolution of two interior chips released no CH<sub>4</sub> and only trace amounts of CD<sub>4</sub> (0.1 μg g<sup>-1</sup>) in accordance with either a low initial carbon content or a metamorphic history of Warner group 2 or greater. The concentration and isotopic composition of the light noble gases suggest that the trapped component of the gases is severely altered (e.g. <sup>20</sup>Ne/<sup>36</sup>Ar 0.8). Considerable loss of radiogenic <sup>4</sup>He and partial loss of <sup>40</sup>Ar have occurred; the U, Th/He age is 0.7 by whereas the approximate K/Ar age is calculated as 3.9 b.y. Exposure ages deduced from the spallogenic components are: <sup>3</sup>He 30 m.y., <sup>21</sup>Ne 60 m.y. and <sup>38</sup>Ar 100 m.y. A preirradiation of at least some of the constituent grains prior to compaction is indicated.

No radiation damage features, such as amorphous coatings or high density of latent tracks, characteristic of highly irradiated soil particles, have been observed. Moreover, no tiny micro-crystallites which would suggest the presence of partially-faded solar flare tracks (no longer observable directly as latent tracks), appeared in grains of 14267 until a fragment had been heated for 2 h at 800°C under vacuum. Similar microcrystallites may be usually induced by heating lunar fines and are found in mildly metamorphosed Apollo 11 breccias. Therefore, it is suggested that shock metamorphism, without a strong thermal effect, erased the latent tracks of 14267 without converting them to microcrystallites. The relatively narrow density distribution of etched tracks suggests a post brecciation galactic ray contribution and a VII exposure age of *ca.* 30 m.y. is deduced.

The above consortium investigations allow a tentative history for 14267 to be drawn:

Formation of this Warner metamorphic grade 2 rock from soil took place around 3.9 b.y. ago. The event could have been the result of a shock process in which the induced temperature did not exceed 800°C. A proportion of the constituent grains had experienced a prior irradiation by the solar wind; however, this must have been small, assuming that the temperature of compaction was as low as 700–800°C. After consolidation 14267 was buried at a depth greater than 2 m until ejection, presumably by the Cone Crater event, to the near surface of the Apollo 14 site about 30 m.y. ago. The temperature accompanying this event is unlikely to have been > 500°C.

Alexander, E. C., Jr., and Kahl, S. B.: <sup>40</sup>Ar–<sup>39</sup>Ar Studies of Lunar Breccias’.

*14301 and 14313.* Three Apollo 14 breccias, 14301, 14313 and 14318, contain fissionogenic Xe attributable to the decay of extinct <sup>244</sup>Pu but the effect is marginal in the case of 14313. We have previously reported that 14318 has an asonably well defined <sup>40</sup>Ar–<sup>39</sup>Ar age of 3.69 ± 0.09 b.y. and contains a large trapped Ar component with an unusual isotopic composition, (<sup>40</sup>Ar/<sup>39</sup>Ar)<sub>t</sub> = 13.68 ± 0.25. Megrue using a laser probe technique has presented evidence that 14301 contains 3.7 b.y. old clasts

and that the matrix of 14301 contains trapped Ar with  $(^{40}\text{Ar}/^{36}\text{Ar})_t = 14$ . We report here step-wise heating experiments on 14301 and 14313 designed to determine if a  $(^{40}\text{Ar}/^{36}\text{Ar})_t \sim 14$  is common to all three breccias and to see if Megrue's laser probe technique is directly comparable to step-wise heating experiments.

Neither 14301 nor 14313 yield isochrons on  $^{40}\text{Ar}/^{36}\text{Ar}$  versus  $^{39}\text{Ar}/^{36}\text{Ar}$  plots as did 14318. Rather the data scatter in a fashion which indicates that the two breccias contain variable trapped components. To resolve the variable trapped components we assumed that both of the breccias are  $3.7 \pm \pm 0.2$  b.y. old and calculated the composition of the trapped Ar in each temperature fraction.

Data for 14313 yield a very similar pattern. However, 14313 contains  $\sim 6$  times more  $^{36}\text{Ar}$  and the  $(^{40}\text{Ar}/^{36}\text{Ar})_t$  values are  $\sim 3.5$  times smaller with a total  $(^{40}\text{Ar}/^{36}\text{Ar})_t = 2.7 \pm 0.1$ .

Evidently laser probe and step-wise heating experiments yield different though complimentary data. The trapped gas that is evolved as a unique composition in the laser probe experiments is resolved into different components by a step-wise heating experiment.

The low temperature fractions contain much more  $^{40}\text{Ar}$  than the higher temperature fractions and even the latter do not yield  $(^{40}\text{Ar}/^{36}\text{Ar})_t$  values  $\leq 1$  which are typical of lunar soils. We speculate that the low temperature enrichment might be due to the trapping (in pores, bubbles, etc.) of an incompletely homogenized, localized 'internal atmosphere' rich in  $^{40}\text{Ar}$  during the formation of the breccias. In this context Heymann and Yaniv have demonstrated the existence of a pore gas in breccia 10065. Incomplete homogenization of rare gases in 14301, 14313 and 14318 is also indicated by the Xe data.

The  $(^{40}\text{Ar}/^{36}\text{Ar})_t$  ratios in these breccias are not constant and are probably accidents of the random details of the individual samples' formation. The three breccias were not formed in the presence of a unique trapped Ar composition.

15455. The results of  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  determinations on the dark and light portions of the 'black and white' breccia 15455 are given. Although the K/Ca ratio remains relatively constant both the light and dark phases contain the high temperature 'drop off' characteristic of many Apollo 14 breccias. Although the occurrence of this 'drop off' phenomena is restricted to breccias, Davis has recently shown that it is probably *not* a shock phenomena. The apparent younger age of the light portion is in direct conflict with the petrographic data which shows that the dark phase is intruding the light phase. The low age of the light portion is probably due to the less retentative nature of the white portion. (Note that 43% of the  $^{39}\text{Ar}$  in the dark phase is released by  $700^\circ\text{C}$  while 63% is released at the same temperature in the light phase.) The  $> 400^\circ\text{C}$  total age,  $3.92 \pm 0.04$  b.y., for the dark portion is the best estimate of the age of 15455.

The spallation data for 15455 are given. The line is fit to the  $500^\circ$  through  $900^\circ\text{C}$  fractions of both samples. The nominal exposure age is 215 m.y. However the ratio of the slope of the line to its ordinate intercept implies a value for  $P_{\text{K}^{38}}/P_{\text{Ca}^{38}}$  (the ratio of the production rates of  $^{38}\text{Ar}$  from K and Ca) of  $\sim 70$ . This high value is indicative of a 'soft' or shielded irradiation. The value of 215 m.y. is probably a lower limit to the exposure age of 15455. A long exposure age for 15455 indicates that mass wasting down the Apennine front in the vicinity of Spur crater is a slow process.

14270. Breccia 14270 is a typical A14 breccia complete with a high temperature 'drop off' in the  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  release pattern. The plateau age is  $3.94 \pm 0.03$  b.y. and the  $> 400^\circ\text{C}$  age is  $3.89 \pm 0.05$  b.y. The exposure age is 240 m.y. and the  $P_{\text{K}^{38}}/P_{\text{Ca}^{38}} \sim 1.6$  is indicative of a much 'harder' irradiation than that experienced by 15455.

Dunn, J. R., Fisher, R. M., Fuller, M. D., Nagata, T., Schwerer, F. C., and Sugiura, N.: 'Effects of Meteoritic Impact on Magnetic Properties of Lunar Surface Materials'.

The ferromagnetic constituents of Apollo lunar materials are metallic Fe-Ni alloys (with Co less than 2 weight per cent) in almost all cases. The saturation magnetization ( $I_s$ ) of lunar breccias and fines is larger than that of igneous rocks by about one order of magnitude. This fact could lead to a simple suggestion that the ferromagnetic metals in breccias and fines have mostly come from meteorites which impacted the lunar surface. The thermomagnetic curves of lunar materials have shown that the metals are either a single component of almost pure iron (with Co less than one percent) or a superposition of two components, i.e. the almost pure iron and kamacite of 3 ~ 13 weight per cent of average Ni content. Histograms of the observed ratios (kamacite/total ferromagnetic metal in weight =

$= m_k/m$ ) are presented. where the compositions of ferromagnetic metals can be classified into two distinct groups. With regard to the distinct grouping of  $m_k/m$  ratio, no essential difference can be observed between igneous rocks and breccias or fines.

On the other hand, the observed thermomagnetic curves of kamacite components in lunar materials are considerably different from those of synthesized Fe-Ni alloys of a single composition; particularly, the temperature range of the  $\gamma - \alpha$  transition in the former is significantly broader than that in the latter. This fact may indicate that the lunar materials contain kamacite grains of a broad variety of Ni content. Since the standard thermomagnetic curves of a binary system of Fe-Ni alloys are known, the spectrum of Ni content can be evaluated by numerically solving an integral equation representing the observed thermomagnetic curves which consist of those of Fe-Ni alloys of different Ni contents.

Summarizing these statistical results, the simple idea that the metallic Fe-Ni alloys of meteoritic origins have migrated only into lunar fines and breccias could hardly be accepted. The igneous rocks which contain a considerable amount of kamacite (15556 and 68415) may be products of the remelting of pre-existing lunar surface materials. A possibility of this type of lunar igneous rock has already been pointed out. Six samples of lunar breccias and fines contain only almost pure iron and very little kamacite. The abundant component of almost pure iron in sample 14053, which contains an anomalously large amount of metallic iron (1.01 weight %) as a lunar igneous rocks, is due to a product of the fayalite breakdown. Then, the abundant pure iron in breccias and fines also may be due to a similar mechanism. It is not clear yet, however, why the spectrum of Ni content in the kamacite component in lunar materials is similar to that of the carbonaceous chondrite.

Another remarkable effect of meteoritic impact on lunar rock magnetism is the magnetic hardening. Among 34 magnetically examined samples from Apollo 11 through 17 returned lunar materials, three samples (10048, 10085 and 60255) have an extremely stable component of natural remanent magnetization (NRM). These three samples are shock-metamorphosed breccias or coarse grains in soils, and consequently their coercive force ( $H_c$ ) and remanence coercive force ( $H_{RC}$ ) are very high compared with those of other lunar samples, namely,  $H_c = 50, 125$  and  $47$  Oe and  $H_{RC} = 520, 670$  and  $680$  Oe. for samples 10048, 10085 and 60255 respectively. Because of the high value of  $H_{RC}$ , the relaxation time of magnetization of single domain particles is much larger than the moon's age ( $4.5 \times 10^9$  yr) even at the lunar midday temperature. Thus, the stable component of NRM of these sample is considerably larger and extremely stabler than that of other lunar samples.

Axon, H. J., Goldstein, J. I., and Hewins, R. H.: 'Metal-Silicate Relationships in 2 Apollo 17 Soils'.

Over 220 of the most magnetic particles in 20 g of  $< 1$  mm Apollo 17 soil have been studied in pol-thin and polished sections. The samples, 75081,9 and 75081,54 from station 5 at Camelot crater in the valley floor and 78501,48 from station 8 at the base of the Sculptured Hills, are from sites covered by dark mantle material. The magnetic, metal-bearing particles in 78501 consist of 31% metal (free-standing or with minor peripheral silicate), 17% 'anorthosite', 15% agglutinate, 13% basalt, 7% glassy matrix breccia and 17% other categories. 'Anorthosite' is a series of fine-grained plagioclase-rich rocks classified as breccias with various metaclastic textures, hornfels (or granulite) with granoblastic textures and partly to wholly melted rocks with lathy plagioclase. These resemble Apollo 16 and Luna 20 anorthositic soil particles and are interpreted as secondary products of the original anorthositic crust. The Sculptured Hills may well be composed largely of the finegrained plagioclase-rich material. The proportion of metal particles with little or no adhering silicate was 0.07 wt% in 75081 and 0.03 wt% in 78501.

Almost 20% of the 78501 metal particles contain two or more phases ( $\alpha, \gamma, \text{FeS}, (\text{FeNi})_3\text{P}, (\text{FeNi})_3\text{C}$ ) and many of these show evidence of re-equilibration at metamorphic temperatures. Two phase particles are most abundant in anorthositic fragments and the fine scale of precipitates in some of the metal indicates rapid cooling of these rocks. On the other hand less than 5% of 75081 metal contains two or more phases. Metallic spheroids, globules and remelted metal form 3% of the 75081 particles and 8% of 78501. Most of these probably formed by selective melting of meteorites on impact. Metal with clearly preserved meteoritic structure was not observed.

The bulk Co and Ni analyses of one and two phase metal particles (circles) and of remelted metal (crosses) are presented. The meteoritic and basaltic (high Fe and high Co) metal composition ranges are outlined. The field between meteoritic and high Co may be designated super-meteoritic and that

between 1-4% Ni below and the high Co line sub-meteoritic. Most of the metal from soil 75081 falls in the high Fe range (59%) with 22% meteoritic, 11% high Co, 3% super-meteoritic and 5% sub-meteoritic. This is consistent with exposure by Camelot crater of subfloor mare basalt metal intermediate in composition between Apollo 11 (high Fe) metal and the more Ni-poor Co-rich Apollo 12 basalt metal, e.g., 12022. Most of the 78501 metal (44%) falls in the meteoritic range, along with 23% high Fe, 15% high Co, 13% super-meteoritic and 5% sub-meteoritic. 78501 metal compositions may be better understood by considering separate Ni-Co plots for metal in basalt, anorthosite, agglutinates and with little or no adhering silicate.

The Co-Ni distribution of metal in basalt is quite similar to that of the metal of Camelot crater soil 75081 after the meteoritic component is subtracted. A similar basalt component is present in the metal of 78501 but it is more clearly bimodal, suggesting derivation from two types of basalt with the more common type similar to Apollo 11 basalts.

The anorthositic fragments contain metal largely of meteoritic (69%) and super-meteoritic (23%) composition. When these analyses are subdivided into breccia, hornfels and melted subgroups they do not plot in different composition fields, suggesting that the metal compositions have remained essentially unchanged during their incorporation in this fine-grained suite. The meteoritic composition metal may be derived from meteoritic metal fragments incorporated when these anorthositic rocks were formed and/or from a liquid with a high initial Ni Co ratio, e.g., the primary lunar crustal melt containing metal from condensate or building-block planetismals. Crystallization of metal from such a melt would produce super-meteoritic compositions.

The free standing metal category has a distribution of metal compositions similar to a combination of basaltic and anorthositic metal. It is therefore likely that this metal was derived mechanically from these two source bedrocks. By contrast the agglutinates have an unusual distribution of high Co, meteoritic and super-meteoritic particles. They lack a basaltic component and possibly were generated during impact events directly on the Sculptured Hills rock.

A composite 78501 soil can be constructed by a simple two component mixing model involving the metal particles in basalt and anorthositic rock fragments in the measured ratios (45% basalt + 55% anorthosite). A third component in the form of meteoritic metal contributed from local cratering events would make a complete agreement with the measured Co-Ni distribution and allow for the increase in Ni content of soil 78501 of approximately 100 ppm over the local anorthositic rocks.

A similar composite, but with basalt in excess of anorthosite, might be proposed for the 75081 soil. However, the aluminous component is less abundant in this soil than in 78501 and anorthositic fragments are less than 2%. In addition, the meteoritic to super-meteoritic ratio is so much higher in 75081 than in the anorthositic category that very little of the metal in the meteoritic range could be derived from anorthosite. The major Ni enrichment in dark mantle soils such as 75081 must therefore be due to a local meteoritic source.

Senftle, F. E., Thorpe, A. N., Briggs, C., Alexander, C., and Minkin, J.: 'Antiferromagnetic (Néel) Transitions in Lunar Glass and Ilmenite'.

The existence of antiferromagnetic minerals such as ilmenite, ferrosilite, and ulvospinel in lunar rocks has been well established. Pickart and Alperin observed antiferromagnetic ordering in their neutron diffraction studies of some Apollo 12 rock specimens. Also, previous magnetic-susceptibility measurements which we made on a wide variety of individual lunar glass spherules from 4.2 to 300K did not directly reveal any antiferromagnetic (Néel) transitions which might be due to mineral inclusions within the glass matrix. Indirectly, however, we were able to infer the presence of antiferromagnetic inclusions in the glass from our previous measurements because the experimental magnetic-susceptibility data could best be fitted to an expression that contained the sum of temperature-dependent and temperature-independent paramagnetism and an antiferromagnetic term. The last term was significant in almost all the specimens studied. In the present study of 13 glass specimens, five individual glass spherules had relatively large antiferromagnetic terms and were selected for further examination. Careful susceptibility measurements were then made at closely spaced temperature intervals from 4 to 80K in an attempt to observe the Néel transitions directly. At least seven different transitions were observed in the five glass specimens. With the exception of a transition that corresponded to ilmenite in one specimen, the observed transitions did not correspond to any transitions in known antiferromagnetic minerals. The large number of unidentifiable Néel temperatures can



be explained if the antiferromagnetic mineral inclusions are members of a solid-solution series. Thus, for example, the observed Néel temperature of a given member of the  $\text{MgSiO}_3\text{-CaSiO}_3\text{-FeSiO}_3$  series may be significantly shifted from that of  $\text{FeSiO}_3$ , the antiferromagnetic end member of the mineral series.

It is interesting that the one type of glass in which a large ilmenite transition might be expected is the orange glass from Shorty crater. McKay and Heiken reported finding ilmenite in specimens of orange glass from the same location. The orange glass contains both high iron and titanium, but apparently this particular specimen contains very little ilmenite. Only a very weak transition was found in this sample at 56K, the Néel temperature of ilmenite.

Although the Néel temperature of terrestrial ilmenite is well known, it was thought advisable to repeat the measurement on lunar ilmenite. In addition to the well-known transitions at 55–56K, the lunar ilmenite also showed transitions at 11.3K and at 4.3K. Contrary to data in the literature, the 11.3K transition was also found in terrestrial ilmenite. A very weak transition was suggested at 4.3K, but, if present, it was severely masked by the strong paramagnetic component at this temperature. To make sure that the two low-temperature transitions can be ascribed to ilmenite rather than impurities, a study is also being made of high-purity synthetic ilmenite.

Pearce, G. W. and Usselman, T. M.: 'Grain Growth of Iron: Implications for the Thermal Conditions in a Lunar Ejecta Blanket'.

The grain size of iron particles in lunar breccias correlates with their degree of metamorphism and thus with mineral reequilibration. Breccias and soils typically contain an order of magnitude more iron than igneous rocks. If iron grain size is indicated by the magnetic division into superparamagnetic (SP;  $< 150 \text{ \AA}$  diam) single domain (SD;  $150\text{--}300 \text{ \AA}$ ), and multidomain (MD;  $> 300 \text{ \AA}$ ), soils are found to have predominantly SP and SD grains, breccias exhibit grain sizes from SP to MD, while igneous rocks generally only have MD iron. Breccias and soils are thought to be enriched in iron either by subsolidus or shock induced reduction or both. While reduction of metallic iron may occur during the formation of breccias, the dominant process affecting the iron particles is grain growth during heating and cooling of an ejected mass. Thus, the times and temperatures of experimentally determined iron growth may indicate the temperatures and cooling rates of the breccias in an ejecta blanket.

Samples of a synthetic Apollo II basaltic glass, which had been reduced to form SP and SD iron under controlled conditions, were placed in a silica glass tube, evacuated, and sealed. A titanium getter removed any oxidizing agents from the charge. The following procedure was used: (1) the sample was heated at  $750^\circ\text{C}$ . for 15 min, (2) the titanium foil was isolated from the charge by sealing the silica glass tube between the foil and the charge, and (3) the isolated charge was heated at  $750^\circ\text{C}$ . until a constant magnetic moment was achieved, indicating equilibration of the quantity of metallic iron in the system. At this point the metallic iron content and relative grain size served as the starting point for the grain growth experiments. The isolated charges in the silica tubes were placed in a furnace at the desired temperature. After a given time, the sample was quenched and measured on the magnetometer. After measurement, the charge was reheated to the same temperature, and the procedure repeated until the iron was essentially all multidomain or until the run times became excessively long.

The charges in the silica glass tubes were examined directly in a vibrating sample magnetometer. The  $J_r/J_s$  ratio and the shape of the magnetization curves were used to give the grain size range of the metallic iron. Curie point measurements indicated that the material being measured was indeed metallic iron.

A  $J_r/J_s$  representative of multidomain iron (determined by heating a sample at  $1000^\circ\text{C}$ . until the  $J_r/J_s$  reached a constant minimum value) was subtracted from the measured  $J_r/J_s$  of each point. The experimental data are shown, where the percent of the initial  $J_r/J_s$  is representative of the fraction of iron remaining in the single domain grain size range. The intercept of the curves with the time axis indicates the maximum time in which SD iron can survive at a given temperature.

The results suggest that iron grain size may be an effective time dependent geothermometer for lunar surface processes in the range of  $600^\circ\text{--}1000^\circ\text{C}$ . with limited applicability outside this range. For sites like Apollo 14 and 16 where breccias with widely differing iron grain size range are found, it can be concluded that time scales of the order of days to weeks were required to produce such a variety.

This time scale, similar to those found by other methods, is consistent with models of base surge ejecta deposits, while being too slow for impact and ballistic deposits and too fast for deep-seated thermal metamorphism.

Housley, R. M., Cirlin, E. H., and Grant, R. W.: 'Solar Wind and Micrometeorite Alteration of the Lunar Regolith'.

We have recently discussed a model for the formation of fine grained Fe metal in glass welded aggregates during micrometeorite impacts into the solar wind reduced surface of the regolith. Here we will, (1) elaborate on the reduction mechanism, (2) present new data on Apollo 17 samples and discuss its interpretation in terms of the model, and (3) discuss in terms of the model how magnetic measurements can be used to study regolith dynamics and to define and interpret lunar stratigraphy.

The present intensity of the solar wind is sufficient to saturate mineral grains exposed on the regolith surface with H in at most a few years. We have already discussed data indicating that at least initially a substantial fraction of the escaping H will leave as H<sub>2</sub>O, bringing with it O atoms from the regolith. In the lunar atmosphere a large fraction of this H<sub>2</sub>O will be photoionized within a few months and more than half of that will be swept off the moon by the solar wind while less than half will be reimplanted into the surface. Therefore within a few years a layer about 1000 Å thick on the outer surface of grains exposed on the top of the lunar regolith will be reduced to the point where the continuing inward and outward flux of H can no longer remove O. Since the gardening rate due to micrometeorite impacts is slow on this time scale, essentially every grain which has been exposed will have outer surfaces as fully reduced as possible by this process.

As a corollary to the above, essentially every micrometeorite will impact fully reduced surface material and hence if Fe containing grains are melted, the glass formed will be expected to contain fine grained Fe metal. We thus see that fine grained ferromagnetic metal (about 0.01–25 μm in diam) determined by Mössbauer spectroscopy or (about 0.01–1 μm in diam) determined by ferromagnetic resonance and reduced but isolated Fe<sup>2+</sup> atoms determined by the Mössbauer excess area are both expected to measure the 'surface exposure age' of fines samples in the same sense as do glass welded aggregate contents, solar wind rare gas and carbon contents, and fraction of grains with amorphous coatings or solar flare tracks.

All our best Mössbauer data on Apollo fines including remeasurements on old samples and our Apollo 17 results are presented. The universal inverse correlation of excess area with size fraction is maintained. The increase in excess area in the more magnetic fractions is easily understood since all glass welded aggregates are certain to have been on the very surface at some time. Choosing for uniformity the < 45 μm fraction, the ferromagnetic metal content and excess area divided by total Fe content in most cases correlate well with other measures of exposure age.

The fraction of the total Fe in a fines sample in surface layers potentially accessible for solar wind reduction is roughly the specific surface area × thickness × density. Taking respectively 0.33 m<sup>2</sup> g<sup>-1</sup>, 1000 Å, and 3 g cm<sup>-3</sup> gives 0.1 for this fraction. Since the actual fractions of Fe reduced in different samples are not small compared to this fraction, it seems likely that nearly all the Fe has been reduced in the surfaces which were actually exposed to the solar wind. This in turn suggests the possibility that other cations such as Ti and Si may also have been reduced.

The total Fe contents determined from the total area in the Mössbauer spectra are of relative significance only. The unknown f factors for all the minerals have been assumed to be 0.80, which is the correct value for Fe metal. In addition saturation corrections which should be applied could raise some of the values as much as 10%. Even with these shortcomings we believe the values listed provide a valid comparison between samples, a comparison which would not otherwise be possible for our size and magnetic separates. They also provide the best possible normalization for our excess area values since they were determined using the same procedures.

The single magnetic domain metal grains produced in lunar fines by surface exposure magnetize easily in small applied fields. This makes the low field magnetization of surface fines also a reasonable measure of surface exposure age. We have designed, constructed and tested a simple, portable apparatus for measuring this exposure age profile with high sensitivity and resolution in intact core and drive tube samples. If LSAPT permits, results will be presented and discussed in terms of regolith dynamics.

Prestel, D., Purcell, T., and Weeks, R. A.: 'Irradiation-Induced Paramagnetic Species in Lunar Plagioclases'.

In addition to electron paramagnetic resonance (EPR) spectra due to  $\text{Fe}^{3+}$ ,  $\text{Ti}^{3+}$ , and  $\text{Mn}^{2+}$  observed in lunar plagioclases, EPR spectra, observed in some lunar samples, may be due to paramagnetic states of defects in the crystal structure of one of the lunar minerals. Irradiation of a sample from crystalline rock 12021 enhanced the intensity of some of these paramagnetic states. We will show below that some of these states are due to defects in the crystal structure of the plagioclase fraction of lunar samples, and that the paramagnetic states of the defects are present in the as-received samples in low concentration ( $10^{14}$  to  $10^{15}$   $\text{gm}^{-1}$ ), but that the atomic configuration upon which the paramagnetic electron state is localized has a concentration sufficiently high to be a significant factor in the chemical anomalies that Wenk and Wilde describe.

Measurements of the EPR spectra at 9 GHz as a function of irradiation ( $^{137}\text{Cs}$  gamma rays) and annealing (100 to 550 K) have been made on plagioclase (plg) fractions ( $> 99\%$  plg) from 14053-47 and 14321-166 and on plg-rich ( $> 80\%$  plg) samples 67075-21, 67455-16, 60051-14, 60015-68, 62242-2, and 68416-13. The spectra observed in a sample of 60015-68 as received and after a  $5 \times 10^5$  R irradiation at  $\sim 330\text{K}$  are presented. A new component (labeled 'O' centers) and an increase in the intensity of the  $\text{Ti}^{3+}$  component are observed after irradiation. No other changes in the spectrum were found between 0 and 10 kG. Prior to irradiation, the spectrum of 14321-166 was similar to that of 60015-68, with the exception of the F component, identified in Fig. 2a, due to a contaminating ferromagnetic mineral phase. The irradiation-produced 'O' components, not present initially, are present after the irradiation. A similar effect was observed in the plg fraction of 14053-47. After irradiation there was little change in the intensity of the  $\text{Ti}^{3+}$  component in the spectra of either sample. The structure of some of the 'O' components and the effect of increasing the radiation dose at  $\sim 330\text{K}$  are presented. On the basis of the data for the plg fraction of 14053-47 and 14321-166, the 'O' components are assigned to the spectrum of the plg fraction. The complexities of the 'O' spectral components are represented. At least three distinct types, whose relative intensities are sample and temperature dependent, are resolved. The low-temperature irradiation also produced a new component in two of the samples whose spectra are shown, the 'E' component. This component has a shape and a  $g$ -value equivalent to those of a radiation-produced component in lunar pyroxenes (2). This component is resolved on the basis of its intensity as a function of spectrometer power as compared to that of the 'O' components.

Irradiation at 78K and measurement without warming the sample above the *spectrometer* temperature ( $\sim 100\text{K}$ ) produces a ten-fold increase in the intensity of the 'O' components. Hyperfine structure in the spectra of the 'O' components is not observed. The 'E' component disappears when the sample is warmed for 5 min at a temperature  $> 160\text{K}$ . The 'O' components disappear when samples are warmed to temperatures  $> 500\text{K}$  for 5 min. Reirradiation at 78K produces the same effect as the initial irradiation at 78K. The concentration of the defects at which the paramagnetic states are localized ranges from  $10^{18}$  to  $10^{19}$   $\text{gm}^{-1}$  in all of the samples. These defects thus comprise of the order of 0.1 atomic percent.

On the bases of these data, we conclude that: (i) the 'O' centers have a diamagnetic precursor state which may be either an 'electron' or 'hole' trapping site; (ii) at temperatures  $< 550\text{K}$  the 'O' centers are stable, but the paramagnetic states of the 'O' centers will anneal; (iii) the 'O' centers are structural defects of the plg fraction, (iv) the absence of resolved hyperfine structure indicates that the atoms on which the paramagnetic states are localized have a low ( $< 5\%$ ) natural abundance of isotopes with nuclear magnetic moments, and hyperfine interactions with nearest-neighbor nuclei are either weak or are not present; (v) the concentration of 'O' centers is high enough to be a significant factor in the chemical anomalies of lunar plg. It is difficult on the basis of these data to identify the atomic configuration on which the paramagnetic state is localized. We note that the  $g$ -values of the 'O' components are similar to those which have been observed for the spectral components of  $\text{O}^-$ ,  $\text{O}^{-2}$ , and  $\text{O}^{-3}$  produced by irradiation of diamagnetic oxides.

Griscom, D. L., Marquardt, C. L., and Friebele, E. J.: 'Ferromagnetic Resonance of Fine Grained Iron and Magnetite Precipitates in Simulated Lunar Glasses: Comparison with Lunar Soils'.

In order to better understand the ferromagnetic resonance (FMR) properties of returned lunar soils, FMR spectra have been obtained for two well-characterized simulated lunar glasses containing

microscopic and submicroscopic metallic iron particles and six simulated lunar glasses containing submicroscopic magnetite-like precipitates. The X-band FMR intensities of these samples were determined by numerical integration methods for the temperature range 5–573 K and comparisons were made with similar data for lunar soils from every Apollo exploration site.

*Glasses containing iron.* A sample of reduced simulated lunar glass of a composition similar to rock 10017 was provided by R. M. Housley. Housley (private communication) reported observation of iron octahedra  $\sim 5 \mu\text{m}$  and a total iron content determined by Mössbauer and susceptibility measurements of  $\sim 0.2 \text{ wt}\%$ . Multidomain (MD) effects in the FMR spectra of this sample have been described previously. The second sample was a glass of a KREEP composition which was reduced in an  $\text{H}_2$ -rich hydrogen-oxygen flame for  $\sim 1 \text{ min}$ ; the molten droplets were quenched in liquid nitrogen. FMR and electron microscopic evidence has indicated the presence of iron spherules  $\sim 0.02\text{--}0.05 \mu\text{m}$  in the latter sample.

*Glasses containing 'magnetite'.* A reexamination was made of a synthetic glass of a KREEP composition, previously shown by Mössbauer, x-ray diffraction, magnetic susceptibility, electron microscopy, and microprobe to contain magnetite-like precipitates. Other powdered glasses of KREEP and lunar-uplands compositions were subjected to simulated ash-flow processes involving fluidization by helium gas expanding vertically into a vacuum at ambient temperatures  $\sim 750^\circ\text{C}$ . As determined by FMR experiments, magnetite-like phases were precipitated in these samples by virtue of the presence of small amounts of  $\text{O}_2$  and  $\text{H}_2\text{O}$  ( $\sim 10^{-4}\text{--}10$  Torr) added to the helium. Water vapor appeared to be more efficacious than  $\text{O}_2$  for this process.

*Results.* By securing experimental baselines at each temperature, the total numerical second integrals of the FMR spectra were obtained for the samples containing MD iron. For the lunar samples and synthetic samples containing magnetite, a limited integral was obtained which excluded most of the MD iron contributions (if any were present). Both MD iron samples showed nearly linear increases in intensity with increasing temperature. The curve for the sub- $\mu\text{m}$  MD iron particles displayed about  $1/3$  the slope of the data shown. All magnetite-containing samples exhibited intensity peaks between 130 and 230 K; data for a KREEP sample subjected to an ash-flow process are illustrated. The curve for 75081,70 differs very little from curves obtained for other typical lunar soils.

*Discussion.* Although the literature does not deal adequately with the theory of the temperature dependence of FMR intensity, a good inference is that the intensity should be proportional to the average magnetization of the sample during the field scan. Thus, 'theoretically', the intensity of single-domain (SD) iron should vary as the saturation magnetization,  $M_s$ . Superparamagnetic (SPM) iron  $\gtrsim 60 \text{ \AA}$  should behave much the same as SD iron in a microwave resonance experiment. The intensity of MD iron will be affected by the microwave skin depth and, for particles  $> 1 \mu\text{m}$ , should increase with increasing temperature. The intensity of magnetite should vary as  $M_s$  above the Verwey temperature (120 K) but may decrease below that point due to a combination of line broadening and the failure to saturate the sample.