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SUBJECT: Meeting Review: 1971 Lunar Science Conference - Case 340

DATE: March 10, 1971

FROM: N. W. Hinners

ABSTRACT

Significant results presented at the 1971 Lunar Science Conference held in Houston in January are herein reviewed. Intended for the non-specialist, this capsule summary is an updating of the status of lunar science since the 1970 conference rather than a complete review. As such, Apollo 12, Luna 16 and "re-visited" Apollo 11 data are utilized. Apollo 14 results are not yet of sufficient quantity (or quality) to warrant interpretation other than to say that the Fra Mauro samples appear to be what was hoped for - Imbrium ejecta.

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MEMORANDUM FOR FILE

The 1971 Lunar Science Conference was held January 11-14, 1971, in Houston, Texas. Although primarily a forum to present results of analyses of Apollo 12 samples and ALSEP data from Oceanus Procellarum, the conference also dealt with Luna 16 data (Mare Fecunditatis) and new information on Apollo 11 (Mare Tranquillitatis) samples. For this review, detailed references are omitted because their inclusion would double the size of this paper and because of the large number of overlapping and duplicate analyses; it is assumed that the reader is familiar with Apollo 11 results. The complete set of conference papers is expected to be published as one volume in the fall.

Crystalline Rocks

Grossly similar to those of Mare Tranquillitatis, the crystalline rocks from Oceanus Procellarum are basalts, either extruded on the lunar surface as fluid lava flows or intruded at shallow depths. The Procellarum basalts, however, were molten about 3.3 billion years ago as contrasted with ∿3.7 billion years ago at Tranquillitatis. These ages are based on rubidium-87 - strontium-87 and argon-39 - argon-40 age dating; it appears at this time that the uranium, thorium, and lead dates, ∿4 billion years in each case, are least understood in the sense that there

has been a complex evolution of those elements. Oxygen-isotope geothermometry and heating experiments indicate final crystallization at a temperature of $\sim$1100°C and, as indicated by the virtual absence of ferric iron, the presence of elemental iron, and the europium anomaly in the rare earth abundances, at very low oxygen partial pressures ($\sim 10^{-13}$ bar).

The main mineral phases of the Procellarum basalts are pyroxene, plagioclase, olivine and ilmenite but, as distinct from Tranquillitatis basalts, there is a greater variation in the relative amounts of pyroxene, plagioclase and olivine in individual rocks. Both textural and chemical results show that much of this variation of the silicates is caused by fractional crystallization in which early-crystallizing olivine and pyroxene gravitationally settled towards the base of the extrusive or shallow intrusive units, depleting the remaining silicate melt in those components. Such near-surface fractionation makes it difficult to estimate the bulk composition of the rocks which one needs in order to hypothesize accurately on the composition of the lunar interior.

Petrologic and chemical evidence indicates that at least two basaltic rock units, probably flows, were sampled at the Apollo 12 site. The distribution of the two sample types on the lunar surface was not random but correlates with their locations in the ejecta blankets relative to craters assumed to mark their source areas. This, then, allows one to reconstruct

the "stratigraphy" at the site using cratering mechanics models, which show that rocks from initially greater depth are concentrated, post-impact, near the tops of crater rims, whereas initially shallower rocks are found concentrated further out on the ejecta blankets.

In terms of average major-element chemistry, the Procellarum and Fecunditatis basalts (Luna-16) are similar to those at Tranquillitatis with the obvious exception of titanium (and potassium which might well be considered a minor element in these rocks) which also is reflected by a lower percentage of the mineral ilmenite ($FeTiO_3$). Because there is no evidence that suggests gravitational settling of ilmenite at any site (which could cause relative enrichments or losses similar to that observed for the Procellarum silicates), one may conclude that the source regions differ intrinsically in titanium content. One must remember, of course, that there are significant individual sample deviations from the average in the Procellarum basalts on account of the fractional crystallization.

Turning now to trace element chemistry, the reader will recall that the two types of Tranquillitatis basalt had grossly different trace element concentrations (e.g., the high potassium and rare earth basalt versus the low potassium and rare earth basalt). In contrast, the Procellarum basalts are generally similar to each other and most like the low potassium Tranquillitatis basalts. The basaltic chips in the Luna-16 core from

Mare Fecunditatis are grossly similar to the Procellarum and low-potassium Tranquillitatis basalts.

The Procellarum basalts examined (like those of Tranquillitatis and Fecunditatis) exhibit a depletion of so-called volatiles when compared with the earth and the chondritic meteorites. This depletion is particularly well demonstrated by the low contents of water, alkalies, and lead. The complete lack of fluid inclusions (water containing) and the practically complete lack of hydrous minerals (only a few crystals found so far) confirm the low water content of lunar materials. If one interprets the basalts as a partial-melting product of the lunar interior, then he must conclude that the source region is even more depleted in volatiles than the basalts. This is consistent with an interpretation of rare earth abundances which indicates that the source material is enriched in refractory elements. More convincing are the K/U and U^{238}/Pb^{204} values. Because uranium, generally considered to be a refractory element, is present in normal basaltic concentrations, the low K/U (1000-3000) and high U^{238}/Pb^{204} ($\sim$500-2000) indicate, relative to chondrites and earth, loss of the relatively volatile K and Pb. These data strongly indicate that lunar material cannot have originated by direct fission from the earth's mantle.

Rock 12013 from Apollo 12 caused much excitement when it was first examined by the Preliminary Examination Team on account of the large amount of light-colored, granitic component characterized by the minerals quartz and potassium feldspar. (The reader is advised that the term "granitic" is being

used only to describe a composition. This usage is not meant to convey any a priori implications regarding the mode of origin). Subsequent detailed examination indicates that the granitic component was injected (or "remobilized") as a silicate melt 4.0 billion years ago into a pre-existing dark basaltic soil or breccia whose age appears to be ∿4.5 billion years. Rock 12013 represents a frustrating sample in that its place of origin is unknown and it is much more complex than the simple interpretation above suggests. The significance of rock 12013 lies, however, in showing that granitic magmas can be produced without a sedimentary cycle (a long-standing controversy with regard to terrestrial granitic rocks) and that some lunar melting took place near the time of lunar origin. The specific mode of origin of the granitic component is still a mystery, but one possible mode may be related to silicate immiscibility. Some evidence for such a mechanism is provided by the fact that normal lunar basalts contain a small amount (a few percent at most) of a granitic component which appears to represent an immiscible phase which separated from the silicate melt late in the crystallization sequence (after ∿90% crystallization). Nonetheless, some sort of a concentration mechanism must be invoked; the mechanism currently in favor is "filter-pressing", whereby the residual silica-rich liquids are squeezed out of the crystal "mush", presumably by overburden pressure.

Soil

The soil at Procellarum, like that at Tranquillitatis, is, in large part, a product of meteoroid-impact comminution of the underlying basaltic rocks. Fragmental in nature, with a mean particle size of ∿40-60 microns, the soil contains abundant signs of the impacts, including shock features ranging from simple lamellae to complete vitrification. The soil layer depth ranges from less than half a meter on crater rims to several meters in intercrater areas (defining the soil depth as the depth at which large rock fragments are excavated by meteoroid impacts). Peculiar to the Procellarum site is the fact that the soil is quite heterogeneous in albedo, with obvious patches of lighter soil mixed with a more "normal" dark soil.

As do the Tranquillitatis soils, the soils at Procellarum give rubidium-strontium and lead-lead model ages (where one assumes the initial isotopic composition) clustering around 4.5 billion years, or what one would expect (wish?) to be the age of the moon. At Procellarum this clearly presents a problem (as it did at Tranquillitatis) in that the radioactive parent-radiogenic daughter content of the soil is greater than and isotopically different than that of the underlying rocks. This, then, requires that the soil must contain an old foreign component relatively rich in radioactive elements (thus swamping out the effect of the local rocks).

A detailed look at the chemistry of Procellarum soils shows them to be variably enriched, relative to the basalts, in a component designated by the oft-quoted acronym "KREEP," i.e., high in potassium (K), rare earth elements (REE) and phosphorus (P). It is the lighter soil samples which exhibit the greatest enrichment, apparently as much as 60% or more. KREEP is manifest in two forms: 1) rock fragments characterized by the essential minerals orthopyroxene (a very low calcium variety of pyroxene) and plagioclase and 2) a brown glass equivalent. Shock features are common in both. The chemistry and isotope systematics of the KREEP component appear to be sufficient to explain many of the chemical and age anomalies. Evidently representing an ancient lunar rock pre-dating the maria, the KREEP rocks resemble rather closely, mineralogically and chemically, both Luny Rock 1 (a Tranquillitatis fragment giving a model age of 4.4 billion years) and the dark portion of Rock 12013.

Another Procellarum "foreign" component (and in Fecunditatis samples) is represented by plagioclase-rich rock fragments (commonly shocked and with glass equivalents) also identified in Tranquillitatis samples and called "anorthosite." These anorthositic fragments caused considerable stir during Apollo 11 sample analyses, because the occurrence of such plagioclase-rich rocks somewhere on the moon is necessary to explain the europium anomaly in the mare basalts. (Under the

greatly reducing conditions present in lunar silicate melts, a significant proportion of the europium is in the +2 valence state rather than +3 like the other rare earths and, hence, is preferentially concentrated in plagioclase relative to olivine and pyroxene.)

Where do KREEP rocks and anorthosites come from? Not from any of the local lava flow units so far sampled. Several investigators have attributed a highlands source to the anorthosites based mainly upon their low density of ∿2.8 g/cc (the topographically higher highlands, in isostatic equilibrium, must be of lower density than the maria [∿3.3 g/cc]) and chemical similarity to highlands as determined by the Surveyor 7 analysis at Tycho. The KREEP component at Procellarum has been speculated to be derived from one or more of the following three sources: Fra Mauro formation (Imbrium ejecta) which occurs near the Apollo 12 Procellarum site; the submare surface at the site; or the Copernican ray which crosses the site. Because the pre-mare surface at Procellarum is probably Fra Mauro formation and because the Copernican impact penetrated some thickness (∿1 km) of Fra Mauro formation, it seems quite probable that the ultimate source of KREEP is Imbrium ejecta or Fra Mauro formation. Significantly, initial examination of Apollo 14 samples from Fra Mauro indicates much higher proportion of KREEPy material than at all lunar sites sampled thus far.

Breccias

The few large breccia samples returned from Procellarum contain a significant KREEP component similar to that of the light soils. Smaller breccia fragments (< 1 cm.) in the soil contain not only the KREEP-type fragments, but also representative local basaltic fragments and basaltic glasses. Grossly similar to those found at Tranquillitatis, the breccias at Procellarum have been formed by varying degrees of lithification of the soil fines. Lithification takes many forms ranging from simple compaction under impact craters to thermal welding (especially of KREEP-type) which perhaps occurred in a putative base-surge associated with a distant large impact.

Processes

Cratering is a dominant process in creating the surface fragmental debris layer, as evidenced by the crater density on the mare surface at Procellarum, by the impact pitted surfaces of rocks, and by the presence of shock features in the soil particles. Based on study of the impact-pit densities, cosmic ray exposure ages, and laboratory cratering studies, the new conclusion has been reached that the dominant mechanism of rock erosion is catastrophic rupture rather than the steady chip-chip of micrometeoroid bombardment. The long-term average rate of the latter is estimated to be only 2-4 Å/year. This is comparable to that attributable to solar wind or solar cosmic ray erosion by direct sputtering or by the flaking-off of radiation damaged layers.

Accurate estimates of solar wind or flare (solar cosmic ray) particle erosion rates were not possible before the return to earth of Surveyor 3 glass which was exposed to the space environment for 2.6 years. The estimated rates are established by comparing radiation damage track density versus depth profiles in rock surfaces with track profiles seen in the uneroded Surveyor 3 glass. That same glass shows that iron group nuclei are present in much higher abundance relative to helium, in solar cosmic rays, than previously thought and that one does not need inordinately long exposure times to obtain the large track densities seen in some soil particles and which has led to speculation that such particles are interplanetary dust accreted on the lunar surface.

It is becoming evident, although the details and relative magnitudes of the effects are debatable, that the solar wind and cosmic ray bombardment and micrometeoroid impact can alter the surface optical properties of lunar soil. Pertinent important observations include: 1) evidence for vapor deposited surface films (iron directly observed, lead indirectly observed); 2) an albedo-radiation track density correlation; 3) the ubiquitous presence (all Surveyor, all Apollo sites) of a thin layer (< 1 mm) of higher albedo surface soil overlying a darker subsurface soil (this light layer is not to be confused with the KREEP-enriched light soils); and 4) a particle surface depletion of light isotopes of carbon, oxygen, and silicon.

The postulated low erosion rate implies a slow turn-over rate for lunar surface material, consistent with the layering observed in a double-core taken at the Procellarum site. However, the Tranquillitatis and other Procellarum cores and even segments of the stratified core appear well-mixed on the basis of particle size distribution, radiation track densities, and solar wind gas content. This dichotomy may be resolved by attributing the derivation of individual layers to specific individual ejecta deposits from nearby craters, with such ejecta layers being derived from near-surface (few centimeters), well-mixed materials. It should be noted that one coarse layer in the stratified core is not well-mixed, has a low solar wind content, and contains particles with low radiation track density.

A face-value comparison of the crater density of the mare surface at Tranquillitatis with that at Procellarum, ($\sim$1.5:1 to 3:1 for craters > 1 km diameter) when matched up with the ages of 3.7 and 3.3 billion years, respectively, leads one to the conclusion that the rate of lunar surface cratering has decreased with time. Since the average highlands to maria crater density ratio is >32:1 and since highlands are unlikely to be older than 4.5 billion years, it follows that most of the decrease was in the first billion years. The cratering objects are thought to represent the last of the bodies accreting to form the moon.

The Apollo 12 ALSEP (Apollo Lunar Surface Experiments Package) solar wind spectrometer indicates that the solar wind impinges directly on the lunar surface, consistent with the large amounts of noble gases found in the lunar soil fines. Comparison with theoretical solar wind elemental and isotopic abundances and with results from analysis of the gases trapped in the aluminum foil of the Solar Wind Composition Experiment suggests that most of the gases extracted from the soil are of solar wind origin. Evidently only a small proportion is due to cosmic ray-induced spallation, natural radioactive decay (including fission), and trapped lunar "atmosphere." Inferring past solar wind composition appears possible but is complicated by diffusive loss of the surface-correlated solar wind gases. One of the anomalies noted in the Tranquillitatis results was an excess (compared with expected) of xenon-131 in the non-solar component. Further work indicates that this is due to a neutron-capture effect on barium-130, barium being abnormally high in some lunar samples.

As with Apollo 11 samples, there is remnant magnetism in the returned Apollo 12 samples, indicative of an inducing field of up to 2000-3000γ when the rocks cooled through the curie point some 3.3 billion years ago. The preferred inducing source seems to be an indigenous lunar field. The magnetometer on ALSEP detected a small ($\sim$38γ) steady magnetic field of presumably local but unknown origin. In addition to the DC field,

the magnetometer also records an AC induced field driven by the solar wind fields. A spectral analysis of the inducing, as compared to the driving, fields, allows one to estimate electrical conductivity of the lunar interior. This appears to average $\sim 10^{-4}$ mhos/meter at depths between about 50 and 1100 km and, may correspond to temperatures of less than $\sim$700°C. Below 1100 km, the conductivity is reported as averaging about 10^{-2} mhos/m corresponding to $\sim$800° - 1000°C. A preliminary interpretation also shows a conductivity "spike" at $\sim$150 km. depth which, assuming no thermal gradient reversal, would reflect a change in composition.

The apparent deep layering suggested by the electrical conductivity profiles is in contrast to the lack of layering in the upper 15-20 km. as reported by the ALSEP seismic experimenters based on analysis of spent spacecraft impacts. Although being seismically quiet, compared to earth, the moon does respond seismically to tidally induced stresses as evidenced by the correlation of moon quakes with lunar perigee. Most of these lunar quakes seem to come from the same area (a rille region near the crater Fra Mauro), in contrast to the random location of seismic events caused by meteoroid impact. The complex propagation of seismic energy in the lunar interior (the high Q and long duration) permits several models involving multiple scattering and is compatible with the possibility that individual near-surface lava flows are highly fractured and possibly thin in the aggregate.

Organic Material

Analysis of the Procellarum soil fines indicates ∿100 ppm of carbon, similar to that in Tranquillitatis soil. Most of this is evidently present as elemental carbon (solar winds source?), carbides (meteorite debris?) and methane, in order of relative abundance. Organic material present as amino acids and/or porphyrins is at the few tens of parts per billion level at most, and it has not been convincingly shown that contamination is not responsible for all organic matter so far reported. Searches for life-like morphologies have been completed negative.

Origin of the Moon, Meteorites and Tektites

The Conference was marked by a remarkable restraint (relative to the Apollo 11 conference) with regard to postulating schemes possibly relevant to the moon's origin. The most pertinent observation seems to be that the entire moon is depleted in volatiles relative to chondritic meteorites and earth which makes a "direct-fission-from-earth" origin highly unlikely. Models incorporating accretion of the moon from a geocentric "high-temperature-origin" swarm of matter have thus gained in popularity, although proponents of models involving capture see no reason to back off.

Compositional evidence accumulating suggests that most meteorites do not have a lunar origin, although there is still a weak possibility that some basaltic achondrites may have a

lunar origin. The existence of many lunar rock types which are not represented in meteorite collections provides compelling evidence that no meteorites have come from the moon. The general chemical similarity of basaltic achondrites with lunar basalts is, however, good evidence that similar igneous processes were at work in different planetary objects soon after the origin of the solar system.

Data now available indicate that tektites do not originate on the moon, but, on the other hand, they do not seem to originate anywhere if one looks at all the evidence. Such is the state of many "extraterrestrial" problems. We eagerly await the next Lunar Science Conference.

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