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Summary of Apollo 11 Lunar Science Conference

On 24 July 1969 the first samples from our sister planet, the moon, were returned to earth for direct scientific investigation. Prior to this, our understanding of the extraterrestrial universe derived from study of electromagnetic radiation from stars and planets, from study of cosmic rays, and from analysis of meteorites. Meteorites were, until the return of Apollo 11, the only extraterrestrial objects we could actually hold in our hands and scrutinize in the laboratory. Unlike meteorites, the lunar samples come from a good sized planetary object whose location is well known.

This volume is a compilation of the first systematic studies of these samples by more than 500 scientists from nine countries; it represents the initial scientific fruit of the courageous undertaking in which three men made the first voyage to the surface of another planet.

The variety and sophistication of the techniques used in the study of these samples draws heavily on the experience gained in the last 25 years in the study of meteorites and terrestrial petrology and mineralogy. The scope and quality of the analyses applied to the returned samples far exceed anything we could hope to achieve with remotely controlled devices even with the most advanced methods of modern technology.

The results of the studies of lunar materials are significant both for what they are and for the way in which they were achieved. They represent an effort which crossed many of the usual barriers between disciplines and scientific interest groups. The common objective, the study of the moon, has gone a long way toward establishing a new cosmopolitan science. We are confident that this close interaction of a large and diverse group of scientists will have the good effect of previous occasions in the history of science when circumstances caused scientists from a variety of backgrounds to work on a common effort. It is not surprising that at this early stage in a new era of study of a planet that there should be diversity in interpretation of observations and even some differences between the observations themselves. We do not propose to resolve these differences in this introductory summary. Our objective is to furnish a guide to the results and conclusions that are still in a state of ferment.

The samples from Tranquillity Base consist of basaltic igneous rocks, microbreccias, which are a mechanical mixture of soil and small rock fragments compacted into a coherent rock, and lunar soil. The soil is a diverse mixture of crystalline fragments and glassy fragments with a variety of most interesting shapes; it also contains small fragments of iron meteorites. Most of the rock fragments are similar to the larger igneous rocks and apparently were derived from them; the rocks in turn were probably once part of the underlying bedrock. A small number of the crystalline fragments are totally different from any of the igneous rocks of the Tranquillity site. There is a strong possibility that these fragments represent samples from the nearby Highlands.

Many of the rock surfaces and individual fragments in the soil show evidence of surface erosion by hypervelocity impacts. Examination of the surfaces of glassy objects which are themselves formed by impact processes shows that they contain beautifully preserved microscopic pits as small as 10 microns in diameter, which are the result of impacts by tiny high velocity particles. There is also evidence that the impact processes are accompanied by local melting, splashing, evaporation, and condensation.

The crystalline rocks, which have typical igneous textures, range from very fine-grained vesicular rocks to vuggy, medium-grained equigranular rocks. The most common minerals are pyroxene, often highly zoned with iron-rich rims, plagioclase, ilmenite, olivine, and cristobalite. Three new minerals occur in the igneous rocks. They are pyroxmanganite (a triclinic pyroxene-like mineral), ferropseudobrookite, and a chromium-titanium spinel. Free metallic iron and troilite, both of which are extremely rare on earth, are common accessory minerals in the igneous rocks. All of the silicate minerals are unusually transparent and clear, because of the complete absence of hydrothermal alteration or weakening. Laboratory experiments with silicate liquids similar in composition to the lunar liquids show that, at the time of crystallization, the observed phases can have coexisted only in a very dry, highly reducing system; the partial pressure of oxygen in this system is estimated to be 10^{-13} atmosphere. This is more than 5 orders of magnitude lower than that for typical terrestrial basaltic magmas. The very low abundance of ferric ions in pyroxenes, determined by Mössbauer spectroscopy and electron spin resonance, is further evidence for the low oxidation level of the magmas. The melting experiments also indicate that 98 percent of the primary igneous liquid crystallized in the temperature range 1210° to 1060°C, with minor interstitial liquids continuing to crystallize down to temperatures around 950°C. Microscopic and microprobe examination provides clear-cut evidence for the existence of an interstitial liquid rich in potassium and aluminum which probably was immiscible with the main liquid. It is further calculated that the viscosity of the lunar magmas was about an order of magnitude lower than that of terrestrial ba-

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saltic magmas. This characteristic may play a significant role in the explanation of the textural features, the differentiation mechanisms that produced the observed chemical composition, and the morphological features of the lunar seas themselves.

The chemical compositions of all the igneous rocks are remarkably similar except for the concentration of potassium, rubidium, cesium, uranium, thorium, and barium. These elements distinguish two groups of igneous rocks; in general, the fine grained rocks contain more of these elements than the coarse grained rocks. All rocks have unusually high concentrations of titanium, scandium, zirconium, hafnium, yttrium, and trivalent rare earth elements and low concentrations of sodium. One of the most striking features of the igneous rocks is the low abundance of europium relative to the other rare earth elements. Some of the more volatile elements—for example, bismuth, mercury, zinc, cadmium, thallium, lead, germanium, chlorine, and bromine—are significantly depleted with respect to their presumed abundance in the primitive solar system. The composition of the soils and breccias is similar to but distinguishable from the igneous rocks and clearly shows that they contain at least one other "rock" component distinct from the lunar basalts we have sampled. The soil is also enriched in nickel and volatile elements (cadmium, zinc, silver, gold, copper, and thallium) that occur in high abundances in carbonaceous chondrites. This enrichment is consistent with the observed occurrence of meteorite material in the soil.

Many elements such as potassium, rubidium, cesium, chlorine, and thallium that occur in very low abundance in the lunar igneous rocks are strongly enriched in terrestrial crustal rocks. These terrestrial rocks are the product of igneous differentiation and are either residual liquids or the low melting fraction. On a larger scale such processes have resulted in the strong enrichment of these elements in the crust of the earth. It has been suggested that the low abundance of these elements in rocks derived from residual lunar liquids is an indication that the whole moon is depleted in a number of volatile elements. If this inference about the bulk composition is correct, one can infer that the lunar material separated from a high-temperature dispersed nebula at 1000°C or higher.

The chemistry of the igneous liquids, in particular the coincidence of the high abundance of titanium, the separation of europium from the other rare earth elements, and the separation of barium and strontium, suggests that these liquids are the end product of an extensive fractional crystallization process. An alternative but less likely possibility is that these liquids were produced by small amounts of partial melting and subsequent segregation of liquid in the lunar interior.

High pressure and temperature experiments show that materials with the chemical composition of Tranquillity Base basalts would, at the conditions inferred for the lunar interior, have densities which far exceed the average density of the moon. It follows from these experiments that these basalts cannot represent the bulk composition of the moon.

The ages of the basaltic crystalline rocks were determined by ^{87}Rb-^{87}Sr and ^{40}K-^{40}Ar methods and show that they formed at 3.7×10^9 years ago. This age is supported by U-Th-Pb data. These results show that igneous rocks of the Sea of Tranquillity were melted (possibly extruded) and crystallized about 10^9 years after the formation of the moon. A single exotic rock fragment yielded an age of 4.4×10^9 years and indicates variability in age between different areas on the lunar surface. The relatively young age of the basalts shows that the moon has not been a completely dead planet from its formation but has undergone significant differentiation, at least locally, in a thin lunar crust. The time period prior to the 3.7×10^9 year event almost certainly is recorded in older Highland areas; it represents an interval where the earth's record has been obliterated. Therefore, much of the surface of the moon is of great importance in understanding the early evolution and differentiation of planets.

Some samples of soil and breccia give coneordant Pb-U-Th and Sr-Rb ages of 4.6×10^9 years. These samples, which are aggregates of highly varied rocks, minerals, and glasses of younger age, appear to provide an effective average of the lunar crust. This crust, originally of material 4.6×10^9 years old, underwent differentiation at later times but without the injection into the lunar crust of younger differentiated material which is enriched in rubidium, uranium, and thorium.

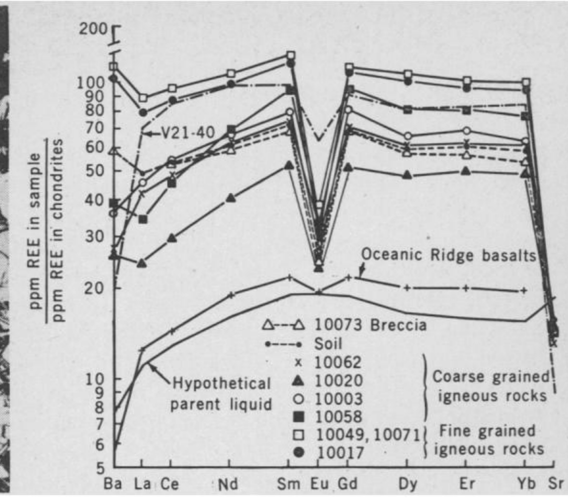
All of these observations show unequivocally that the materials on the surface of the moon are the product of considerable geochemical and petrological evolution. Thus, the ancient planetary surface we have sampled gives us a picture of the early evolutionary processes of a terrestrial planet which have hitherto been obscured from view.

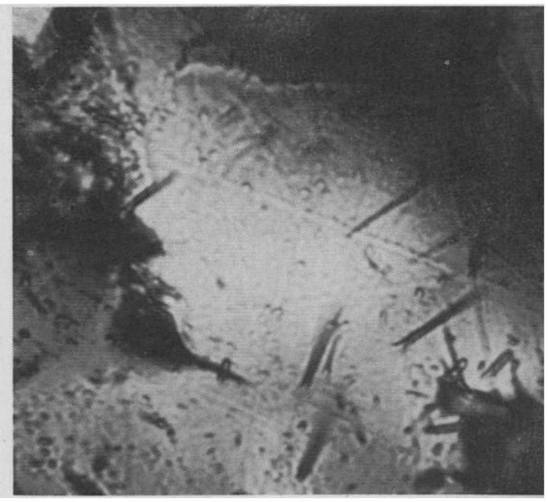
Physical properties of surface materials are important to the interpretation of a number of telescopic observations. The optical properties of the soil measured in the laboratory are in good agreement with those inferred from telescopic studies, indicating that a thin layer of soil must cover most of the moon. Spectral features determined in the laboratory owing to iron can be identified in the soil. Correlation of these features with telescopic studies suggests that the iron content of the lunar surface may vary. The measured dielectric constant of the soil is in accord with the known radar reflectivity of the moon, and the penetration depth suggests that the upper layers are electrically transparent. The measured thermal conductivity suggests that diurnal variations in temperature should extend to less than 1 meter in the soil regions. Thermoluminescence studies on two core samples showed clear evidence that there is a substantial diurnal variation in temperature 12 centimeters below the surface.

The interpretation of seismic experiments also requires a knowledge of material properties of the moon. Laboratory measurements of velocities of both P and S waves show that velocities crease rapidly with pressure to values similar to those observed for terrestrial rocks at 5 kilobars. The attenuation of sound waves decreases with pressure. The high pressure velocities are quite consistent with those observed in the Apollo 12 seismic experiments. The sharp increase in velocity and decrease in attenuation with pressure further suggest the possibility of a seismic wave guide at shallow depths on the moon.

Natural remanent magnetization has been found in the crystalline rocks and in the breccias. This suggests that the ancient moon may have had a magnetic field with a strength of a few percent of the earth's field. The field existing 3.7×10^9 years ago may have been the result of fluid motions in the moon's interior, an effect of the earth's field when the moon and the earth were closer together, or the result of processes not yet understood.

The atmosphere-free surface of the moon is a monitor of radiation from both the galaxy and the sun. The lunar samples are particularly valuable for





(Left) Thin section of lunar sample showing major minerals: (O) olivine, (P) plagioclase, (I) ilmenite, and (C) clinopyroxene. (Center) Chondrite normalized abundance patterns for nine rare earth elements and Sr and Ba. (Right) Etched cosmic ray tracks in a clinopyroxene crystal. Track densities indicate that this rock spent 6 million years exposed directly to space.

the study of low energy, weakly penetrating radiations. Furthermore, the lunar rocks have provided us with a sample of the gases blown off the sun in the solar wind. Thus the isotopic composition and relative abundance of certain elements in the sun can now be inferred from direct measurements. Studies of these gases (hydrogen, helium, neon, argon, krypton, and xenon) have given an upper limit on the deuterium content and an estimate of the magnitude of the $^{3}He/^{4}He$ ratio in the sun. Both of these results will lead to a better understanding of the evolution of the sun. Precise isotopic compositions determined for heavier rare gases permit us to better infer the evolution of the earth's atmosphere from the more primitive material of the sun.

Studies of stored nuclear tracks and induced radioactivities show clearly the effects of bombardment by solar flare particles (as well as galactic cosmic rays) and suggest that this activity has persisted without gross modification for long periods of time. Imbedded solar wind particles indicate large rare gas concentrations in both the breccias and fine particles and show that grains now well below the surface must at one time have been exposed at the very top. The studies of nuclear tracks confirm both the solar wind origin of the implanted rare gases and the inference regarding surface exposure of the samples.

By combining evidence from radioactive and stable nuclear reaction products and stored nuclear tracks, it is also possible to give new information on both lunar surface processes and the cosmic ray flux over long time periods. For example, it has been possible to determine the recent "top" surface of rock 10017 and at the same time demonstrate that the present "top" and "bottom" must have interchanged in the past; this rock was tumbled around on the lunar surface and partially buried. These studies have also shown that the rate of erosion of rocks on the lunar surface is about 10^{-7} centimeter per year. The abundance of cosmic ray produced nuclides shows that some rocks have been on or within several centimeters of the surface for at least 10 million years and within 1 or 2 meters for at least 500 million years.

The existence of complex carbon compounds in extraterrestrial materials would have great significance for the origin of life both on earth and other planets. The search for important protobiological compounds, such as purines, pyrimidines, amino acids, and porphyrins, was carried on with some of the most sophisticated and sensitive analytical techniques ever devised. Nevertheless, no unambiguous identification of indigenous compounds was made at extremely low levels of detection (usually less than 10 parts per billion). Contaminants from the exhaust from the lunar module and from terrestrial handling of the samples have been detected at these levels. The bulk carbon content of the soils, breccias, and igneous rocks ranges from 50 to 250 parts per million. The highest concentrations occur in the fine-grained portion of the soil; the lowest concentrations occur in the igneous rocks. Some methane and carbon monoxide are released by acid dissolution, but the majority of the carbon is not released until samples are heated above 800°C in a vacuum, when it comes off as carbon monoxide and carbon dioxide. The concentrations of carbon observed in the soils and breccias are approximately those expected from solar wind deposition. Graphite has been observed, but the precise nature of most of the lunar carbon remains to be defined.

Micropaleontological examination of the lunar sample by optical microscopy and by electron and scanning electron microscopy produced uniformly negative results. An intensive search for viable organisms employing a multitude of environmental and media combinations produced negative results, as did the one quarantine study.

The Apollo 11 samples were collected from a very tiny fraction of the moon's surface. Nevertheless, they have given a vast new insight into the processes that have shaped this surface and have established some significant limits on the rates and mechanisms by which it evolved. The results reported do not resolve the problem of the origin of the moon. However, the number of constraints that must be met by any theory have been greatly increased. For example, if the moon formed from the earth, it can now be stated with some confidence that this separation took place prior to 4.3×10^{9} years ago. Furthermore, such a hypothesis must now take account of certain definite differences in chemical composition. There is clear evidence in the chemical and petrologic observations that the surface of the moon is variable in both composition and age. It is therefore of great scientific importance to obtain materials from a variety of terrains and sites. Samples from the Highlands and from deeper in the lunar crust will probably be the next important milestones in the advance of lunar science.