POST-APOLLO LUNAR SCIENCE

Report of a study by the
Lunar Science Institute
July 1972

LUNAR SCIENCE INSTITUTE

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SUMMER STUDY ON POST-APOLLO LUNAR SCIENCE

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PREFACE

As the end of the Apollo lunar missions approaches, there is much concern for the continued development of the lunar sciences. It is most important that the limited sums available be spent wisely, if the huge investment in Apollo is to reap the scientific return that is still largely latent in the photographs, the telemetry tapes, and the returned samples.

Accordingly, the Lunar Science Institute assembled at the University of California, San Diego a group representing the various lunar sciences for the week of July 10, 1972 to examine the post-Apollo situation. This Report is the result of that brief Summer Study.

The types of scientific analyses that should be undertaken and the priorities involved received the main thrusts of attention by the Study, and these matters are treated in Chapter III, the heart of this Report.

To set the stage properly, however, Chapter II presents a short summary of the present state of Apollo Lunar Science. Moreover, a future return to the Moon, manned or unmanned, should be planned in the context of what Apollo accomplished and what, in the light of Apollo, are the outstanding questions. These matters are briefly addressed in Chapter IV.

A few words on the manner of composing the Report are in order. Most of the text was generated during the one week at La Jolla, with the help of background "position papers" that many participants prepared and circulated in advance of the Study. The Executive Committee structured the outline of the Report, and its members served as focal points to bring together a preliminary draft at the Study. The Chairman and the two Co-Chairmen subsequently distilled and collated the material. All participants were asked to comment on the next-to-final draft, and we have tried to reflect the prevailing views in this final version.

The principal conclusions of the Study appear as a set of general recommendations, summarized in Chapter I (pp. 4-5), along with the more detailed and specific recommendations summarized in Section B of Chapter III (pp. 31-35) and Section B of Chapter IV (pp. 74-75).

J. W. Chamberlain
Director
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Houston
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Acknowledgments

The Lunar Science Institute gratefully acknowledges the time and effort donated by the participants at this Study. In a period when travel funds are scarce it is worth noting that as a rule the LSI was not able to pay the travel expenses for invitees. Most participants attended at the expense of travel funds in their research grants. Special thanks are due our hosts at UCSD: Drs. James R. Arnold, Gustaf O. Arrhenius, Kurt Marti, and Harold C. Urey.

J. W. C.

CONTENTS

CHAPTER I

INTRODUCTION

A. SIGNIFICANCE OF LUNAR EXPLORATION

The mission of Apollo 17 will mark the end of the exploration of the Moon as presently scheduled by the United States. As the Apollo program ends it will be only 3½ years since man first set foot on the Moon and only slightly more than 14 years since the Soviet Luna 3 obtained the first pictures of the far side of the Moon. The intervening period has been marked by an intensive effort in lunar exploration involving a large number of spacecraft, unmanned as well as manned.

To ensure that man derives full benefit from this effort is a major task for the scientific community in the future. In recognition of this fact, the Lunar Science Institute, this past July, convened a group of scientists to take stock of the progress in lunar science to date; to identify objectives for future work; to define a program for the next three years with emphasis on maximizing the return from the data and materials presently at hand; to identify the resources, facilities, and organizations essential to execute such a program; and to draft a preliminary plan for lunar science over the long term.

Any future plans for scientific study of the Moon and of materials collected from the Moon properly require an evaluation of potential yield and a justification for national support. *A vigorous program of lunar science investigations is both an essential and profitable undertaking in basic scientific research.*

The national program of lunar exploration now culminating in Apollo has provided access to one of the great reservoirs of information vital to our understanding of the universe. The Moon is a scientific treasure-house for information on origins of terrestrial planets, the materials that compose them, and the energy sources that drive them. A carefully planned effort of lunar science investigations will advance our understanding of how our own planet evolved and how it continues to evolve. Some specific examples of research with great potential in this direction can be cited.

¶ Our first look at the Moon, from its surface, has shown us the outer part of the Moon has been naturally processed to produce a 70-km crust of unusual composition resting on a deeper layer with contrasting physical properties. Chemically, this lunar crust is unlike the great bulk of the continental crust of the Earth, but it has some fundamental similarities to the relatively rare bodies of gabbroic igneous rock from which are drawn the Earth's rare but vital deposits of nickel, platinum, and titanium. Such terrestrial ore deposits are the products of concentration by geochemical processes from unknown sources, probably layers within the deeper Earth which formed early in its chemical evolution. Our studies of the lunar crust promise to give us basic information on how the raw materials of a newly-formed planet proceed through the various processes that lead to the concentration of elements.

¶ A second major discovery of work on the lunar surface is that natural radioactive elements— uranium, thorium, and potassium — are locally concentrated to levels that are orders of magnitude greater than those observed in any other known extra-terrestrial materials. This localized concentration is further evidence that the causal concentrating processes, which are likely to have operated on the Earth, are initiated in the earliest phases of planetary evolution.

These elements also constitute the radioactive heat sources that sustain the thermal engine of our own planet. The observed radioactivity levels and the limited measurements of the surface heat flow on the Moon suggest that long ago the Moon's thermal state was perhaps as active as the Earth's. The Moon's engine apparently has nearly stopped. Thus, exploration of the actual distribution of the radioactive elements and their consequences on the Moon can provide a whole new insight into general planetary thermal regimes. The resulting knowledge is directly applicable to understanding the energy system that drives the Earth.

It is only in the last decade that a satisfactory concept of the dynamics of the Earth's crust and mantle (manifested in earthquakes and volcanic eruptions) has been developed.

This vigorous system provides the available sources of terrestrial geothermal power. The initiating mechanism and driving energy for this system are of paramount interest and the Moon is a key to understanding this problem.

¶ Life on our planetary surface is sustained by radiation from the Sun. In addition to sunlight, however, the Sun emits great streams of nuclear particles that for the most part do not reach the Earth's surface because of the terrestrial atmosphere and magnetic field. One of the great triumphs of space exploration has been the measurement of these solar emissions as they exist today. But prior to the return of lunar samples there was no way to study the Sun's *past*. Because of its lack of atmosphere the Moon preserves a record of the long-term history of the Sun.

Similarly, the Moon, along with the rest of our solar system, has been moving through the Milky Way Galaxy throughout its history, and it may have encountered many different environments, such as interstellar dust clouds and the debris of exploding stars. The Moon may hold the record of such past events.

The Apollo program has provided the list to this new level of scientific potential. But a sustained national effort is necessary to convert these significant possibilities into real scientific products. It is in man's nature to develop new capabilities, to perceive and define new dimensions in the physical universe, and to continue exploration beyond his planet.

B. ORGANIZATION OF THE REPORT

Chapter II of this report is primarily a summary status report on lunar science. Since the end of the Apollo program is an important milestone in the program, Chapter II was written under the assumption that the objectives of the Apollo 17 mission will be accomplished.

Chapter III deals with the immediate post-Apollo period, which is the main subject of this Report. In the planning for this period, no new flight programs for lunar exploration are considered. The lunar-science program for the post-Apollo period is based mainly on the analysis of Apollo results.

In Chapter IV we consider future lunar exploration a decade or so following Apollo. The Study assumed that flight programs would possibly be undertaken during this period, although it made no attempt to define a preferred set.

C. MAJOR RECOMMENDATIONS

The most important recommendations are given here, in order of priority, although parts (a), (b), and (c) of the first recommendation are in no preferred order.

1. The tasks now being carried out by NASA to preserve and describe the samples, data, and photographs, and to make them available to the scientific community must continue. Failure to do this would mean loss of a prime opportunity and in some cases the total loss of data [reference page 62].

(a) *The lunar sample curatorial facility at MSC is absolutely essential to lunar science objectives.* Scientific study of the samples would be impossible without the curatorial support, and severe degradation or effective loss of the samples would follow any termination of this service [reference page 62].

(b) The Apollo Lunar Science Experiment Package (ALSEP) geophysical stations, which will reach their full potential after Apollo 17, have special long-term value because they form a network of continuously recording sensors. Preliminary results strongly suggest that some major questions about the interior of the Moon are likely to be settled by the data which will be collected during the lifetime of the stations. *We strongly urge that the ALSEP network and the subsatellite be operated continuously as long as significant new findings come out of their operation* [reference page 45].

(c) Particular rectified photomaps, topographic maps, and geological maps, obtained from the original photographs, are essential as a base for the plotting of other Apollo results; moreover, they represent the information base for any future lunar missions. *It is recommended that selected raw photographic observations be processed to obtain a usable* *scientific product* [reference page 66].

2. If the full implications of the data and samples are to be realized, it is necessary that a diverse range of scientific research groups be involved in a coordinated attack on critical problems. *We strongly urge that the program which supports appropriate investigators for analysis and synthesis be continued at a substantial level while fruitful new results are being achieved* [reference page 68].

3. The intimate involvement of the scientific community, through advisory panels such as Lunar Sample Analysis Planning Team (LSAPT) and the Lunar Sample Review Board (LSRB), has played a key role in the scientific aspects of the Apollo program. *We urge continuation of these scientific advisory groups, with some augmentation of their functions to reflect an increased emphasis on geophysical and photographic data analysis* [reference page 69].

4. Although the date is uncertain, we will be going back to the Moon. *We recommend that a small, selective program of mission planning be maintained to provide the desired continuity between the present and future.* Concurrently, a compatible program of instrument definition should be carried out to provide a basis for future experiments [reference page 88].

5. Remote sensing from lunar orbit is a whole new area whose importance was demonstrated by the Apollo program. Results acquired to date have shown that fundamental insights can be obtained on questions of planetary structure and evolution. *We therefore recommend that a high-inclination orbital mission be regarded as a major priority in the first stage of any future lunar exploration.* Such a mission would determine a wide spectrum of geophysical, geochemical, and geological variables on a planet-wide scale [reference page 55].

6. International cooperation has been an important aspect of lunar research. *We recommend that every effort be made to encourage this aspect, including the undertaking of joint and multi-national lunar missions* [reference page 90].

CHAPTER II

SCIENTIFIC ACCOMPLISHMENTS OF LUNAR EXPLORATION

In the essays that follow, we describe the major scientific findings of the Apollo program. The information returned from the Moon in the form of samples, experimental data, and photographs enables a new understanding of our planetary system. We emphasize the substantial progress achieved in the past three years as a result of the Apollo missions. This chapter sets the stage for the major recommendations that are taken up in Chapter III. The essays are organized around four major problem areas, and entail the synthesis of information from many specialties. These problem areas are:

The lunar surface
The lunar interior
The Moon-Space interface
The origin and evolution of the Moon

This section closes with a look at the major problems faced by lunar science now. Although these problems fall in the same categories as they did before Apollo, the knowledge gained since then has thoroughly transformed the scientific viewpoint.

A. THE LUNAR SURFACE

The lunar surface has been observed photographically and the soils and rocks formed at the Apollo landing sites have been directly sampled. The scientific task is to understand the state and history of the major surface features — the dark maria; the light, cratered highlands; the great ring basins; the rilles; the halo craters; the bright, ray craters; etc. The lunar landings have provided the essential samples by which the surface can be understood in terms of rocks and chemical elements.

Composition.— The Moon is now known to be a highly complex body. It is chemically layered; radioactive elements are more abundant in the crust than in the deeper interior. The Moon therefore, was either formed as a layered body or has been partly or wholly differentiated. Volcanic activity was important in the development of the surface features of the Moon and has produced regional variations in composition of the surface. Contrary to some previous hypotheses, no parent material from which known meteorites or tektites could have been derived has been found on the Moon.

The dark lunar plains are formed by basaltic lava flows, which erupted from the interior of the Moon. The lunar basaltic lavas are similar to basaltic lavas on Earth. The lunar basalts, however, are richer in iron and titanium and poorer in alkali elements than common terrestrial basalts.

The highlands of the Moon, which contain the oldest lunar rocks, consist largely of feldspathic rocks, including a nearly pure feldspar rock called anorthosite. This discovery was not anticipated prior to lunar exploration, and it is a finding of major significance in our understanding of the evolution of planetary crusts.

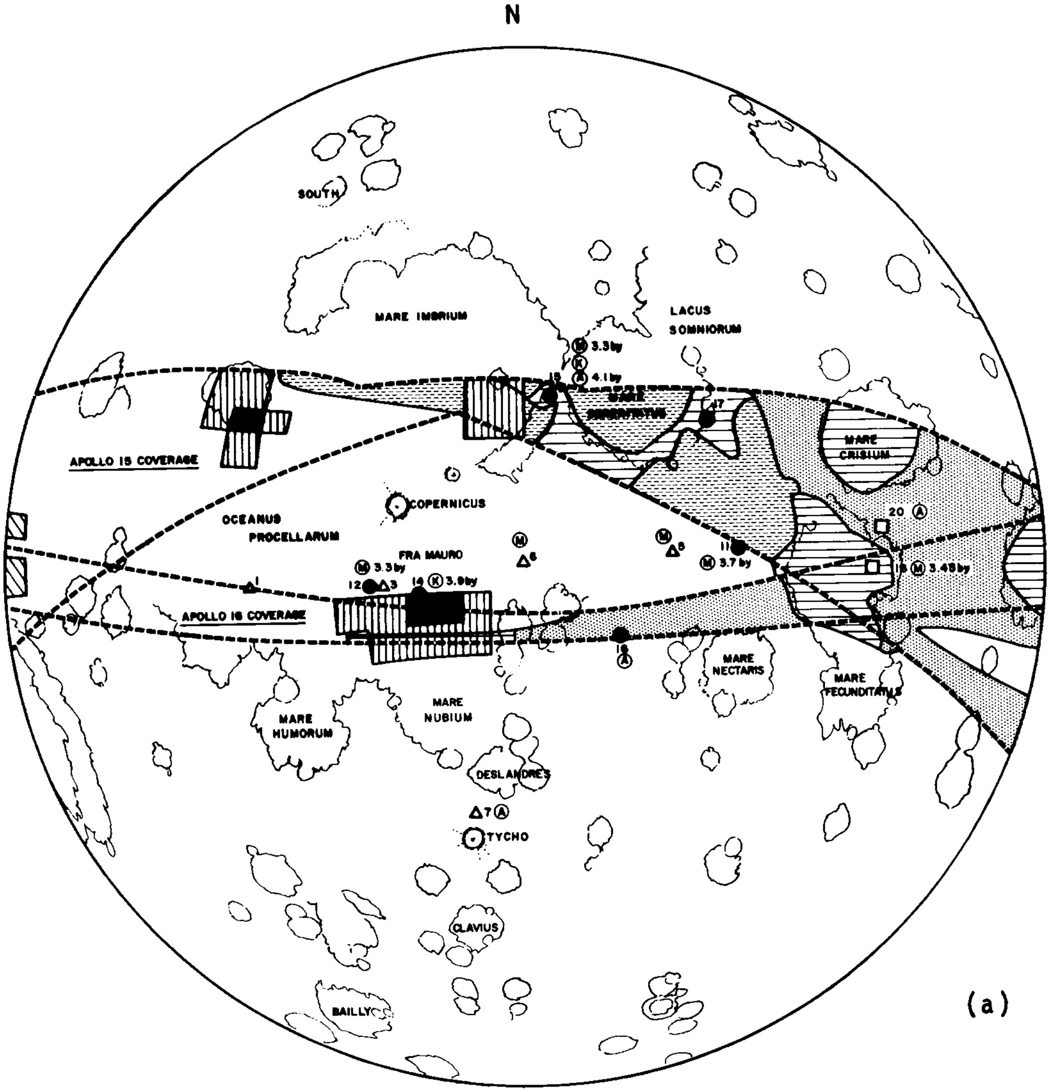
A third rock type (called norite or *KREEP*) is basaltic in general composition, but much richer than other lunar basalts in potassium (*K*), *R*are-*E*arth *E*lements, and *P*hosphorus, as well as uranium, thorium, and other trace elements. Material rich in potassium, uranium, and thorium has been shown by orbital experiments to be concentrated in the region of Mare Imbrium and Oceanus Procellarum.

One of the most striking observations in studies of the returned lunar samples is that, in all cases, the rocks, minerals, and glassy soils are virtually devoid of water. There is strong evidence, furthermore, that the entire crust of the Moon has never been exposed to the influence of water, at least throughout its presently decipherable history. The absence of water affected the physical chemistry of lunar lavas; their temperatures were higher than the temperatures of lavas on Earth, and the lunar lavas crystallized into a distinctive assemblage of minerals. Water-free lunar rocks also have different electrical, seismic, and optical characteristics than rocks on Earth.

Lunar rocks crystallized in an environment much lower in oxygen than terrestrial rocks. The low abundance of oxygen is reflected in the compositions of the minerals and in the presence of free metal alloys in the rocks.

The surface rocks of the Moon are deficient in almost all relatively volatile elements, in comparison with the Earth and with meteorites. This deficiency indicates either that the Moon formed from different material or that the volatile elements have been partially driven off by heating early in lunar history.

Structure.— In contrast to the Earth, mountain ranges on the Moon are arranged in concentric rings around huge circular basins. Extensive evidence indicates that these basins and the surrounding mountains were formed by impacts. The multi-ringed basins are found in roughly equal numbers on both the near and far sides of the Moon; basins on the near side are partially filled by basaltic lava flows, whereas those on the far side, in general, are not. The far side, on the average, is also a few kilometers farther from the Moon's



(a)

LEGEND

SITE

- ● O APOLLO
- △ SURVEYOR
- □ LUNA
- by BILLIONS OF YEARS

CHEMISTRY

- Ⓜ MARE BASALT
- Ⓚ "KREEP"
- Ⓐ ANORTHOSITE

Al/Si RATIO (X-RAY FLUORESCENCE)

- LESS THAN .35
- .35 TO .45
- MORE THAN .45

K, U, Th (γ-RAY SPECTROMETER)

- LESS THAN 76 CPS
- 90 TO 93.5
- MORE THAN 93.5

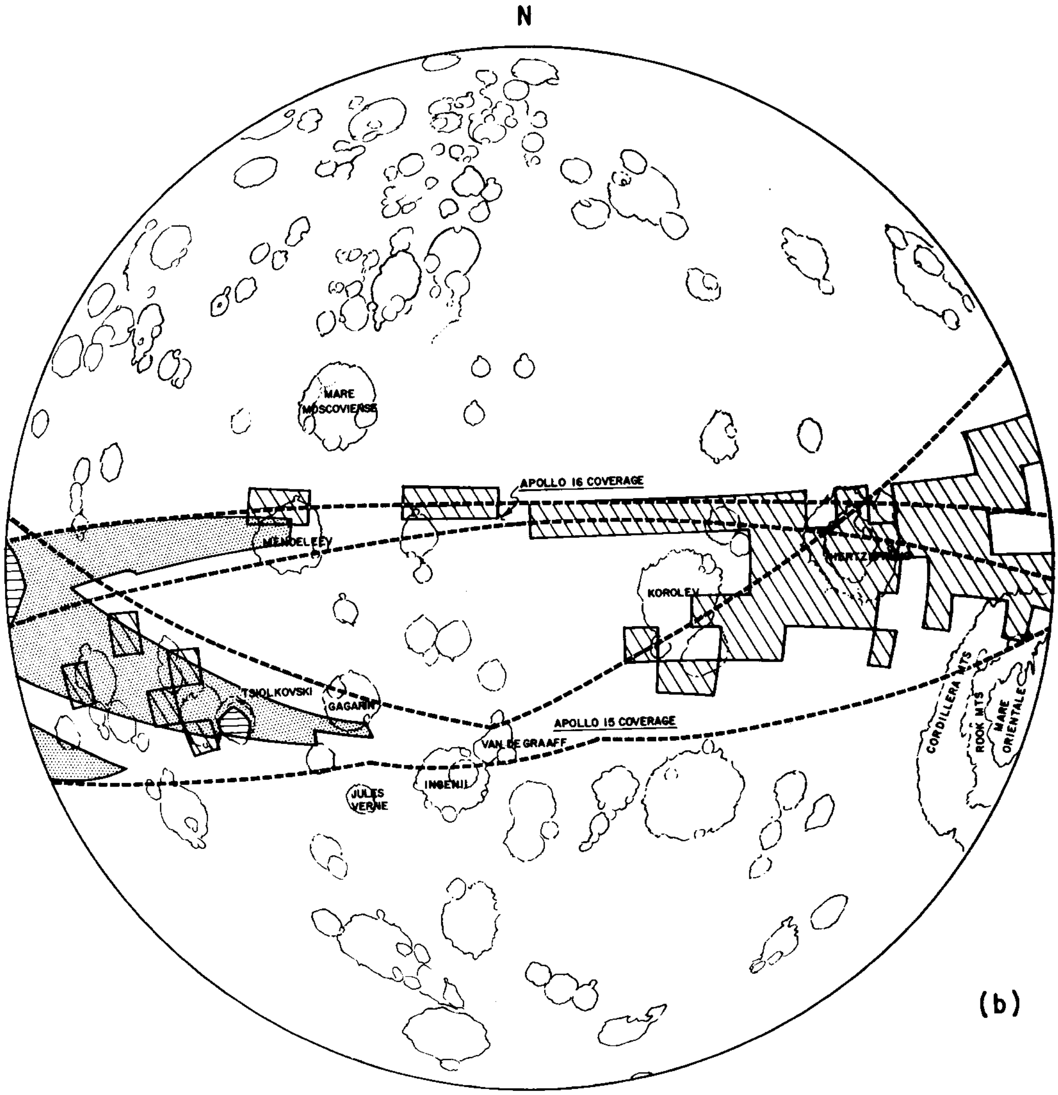


Fig. 1. Base maps of the (a) earthward and (b) far-side lunar hemispheres showing the portions of the surface scanned by the orbiting science packages on board the Apollo 15 and 16 spacecraft. The x-ray fluorescence experiment measured the Si/Al ratio in the top few microns (10^{-4} cm) of the sunlit surface. Notice the contrast in surface composition between mare (Si/Al < .45) and highland (Si/Al > .45) regions. The gamma-ray experiment mapped the concentrations of uranium, thorium, and potassium (dominant radiogenic materials) in the top meter of the lunar surface along the various ground tracks. Notice that the earthward surface possesses higher observed radioactivity levels (> 90 cps) than the far side (< 76 cps). Orbital observations will eventually allow the extension of surface data (note the Apollo, Surveyor, and Luna landing sites) to all portions of the lunar surface.

center of mass. The causes of these major asymmetries are as yet unknown.

Impact Processes.— The lunar surface has been bombarded by meteorites and larger objects that produced craters ranging in diameter from less than 1 μm (10^{-6} m) to about 1,000 km (a range of about 12 decades). The larger impact events produced major craters and caused large parts of the lunar crust to be broken, to be transported great distances across the lunar surface, and to be reconstituted into layered deposits. Rocks in some of these deposits have been transformed by heat; some rocks may have recrystallized from impact-melted liquids.

Repetitive bombardment by all sizes of meteorites over long periods of time has produced a generally fine-grained, stratified layer of debris, called the regolith, which now blankets nearly all parts of the lunar surface. The regolith differs from place to place in thickness, but is typically a few meters thick on the maria. The debris is composed mostly of rock types that immediately underlie the regolith. Part of the rock fragments in the debris have been dispersed across the lunar surface by impact (thus extending our knowledge of the surface from a limited number of sample sites). The regolith also contains abundant impact-produced glass, breccias*, and a few percent of meteoritic material.

Record of the Lunar Surface Environment.— The layers of the regolith preserve a detailed record of meteorite, solar-particle, and cosmic-ray bombardment. The surfaces of rock grains are impregnated with hydrogen, rare gases and other elements transported from the sun in the solar wind; solar-wind elements embedded in breccias extend this record of solar chemical composition to earlier times. From study of the regolith we now know that the average flux of high-energy, solar-flare particles has been constant, within the limits of detection, for at least the last 5 million years.

Transport of lead and other volatile elements as vapors, and mobilization of gaseous components such as argon, occurred as the lunar surface-material became heated; some of the volatile constituents are deposited in the regolith.

Atomic nuclei produced by cosmic-ray bombardment provide a measure of the residence times of material in the upper few meters of the regolith. Individual coarse-rock fragments found

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* A breccia is a rock formed by welding or cementing together of a mass of fragments from the regolith — usually as a result of meteorite impacts.

on the surface have resided within a few meters of the surface from a few million years to 500 million years. Parts of the regolith are known to have remained undisturbed for several hundred million years.

The interaction of the lunar surface with the space environment is discussed further in Section C.

Lunar Surface History.— Isotopic analyses of samples from its surface show that the Moon, as a body, was formed 4.6 billion years ago. It is similar in age to the Earth and to other objects in the solar system.

Absolute ages have been determined for several points on the lunar geological time scale. Most of the recognizable major geologic events occurred during the first 1.5 billion years of lunar history. Except for minor lava flows and a relatively small number of large impact craters, the face of the Moon has remained largely unchanged in the last 3 billion years.

Over the last 3 billion years, the Moon has been bombarded by meteorites and by objects which formed large craters at an average rate roughly comparable to the present rate or the rate in the recent geological past. Between 4 and 3.2 billion years ago, however, the average rate of bombardment of the Moon was higher; during this period, the rate of bombardment declined rapidly with time. The bombardment histories of the Earth and Moon probably have been parallel for at least the last 4 billion years.

The full record of bombardment of the Moon prior to 4 billion years ago has not yet been worked out. It is known, however, that the average rate at which very large craters were formed during the earliest period of lunar history was much greater than the average rate in the last 4 billion years. Many large objects collided with the Moon during the earliest period; the last of the big objects (about 50 km to 100 km diameter) fell about 4 billion years ago.

Vast floods of basaltic lava poured out on the lunar surface between 3.75 and 3.2 billion years ago. During this time, the temperature of the lunar interior, at the depths from which these lavas came (about 100 km), was between 1150° and 1250° C. These basaltic eruptions occurred significantly later in time and were not directly related to the formation of the large multi-ringed basins.

Absence of Life and Biogenic Compounds.— No living or fossil organisms have been discovered in the lunar surface materials. The oldest rocks collected (4 billion years) indicate that the lunar environment has always been hostile to life. It is virtually certain that life could never have developed on the Moon. No pathogenic effects of lunar materials on terrestrial organisms have been encountered.

Carbon compounds of biological type are absent, within the present limits of detection (parts per billion in lunar samples). Only small amounts of total carbon, typically up to 200 parts per million, are present. The highest concentrations are in fine-grained debris, where the carbon is derived mainly from the solar wind and from meteorites. Simple carbon compounds identified are methane and small hydrocarbons and carbides, but the precise nature of the bulk of the carbon remains unidentified. Other reactive species of carbon compounds are present, such as cyanides and nitrides, which are likely precursors of the minute traces of amino acids generated by aqueous leaching of the samples in the laboratory.

The carbon chemistry of the interaction of the solar wind with the mineral grains of the lunar regolith is a phenomenon of general relevance for planetary systems. Such processes may also contribute to the formation of the vast interstellar clouds of simple organic compounds recently observed by microwave spectroscopy.

Validation of Planetary Exploration Techniques.— Techniques for remote sensing of physical and chemical characteristics of planetary surfaces have been validated by direct observation of lunar surface material. It is now possible to measure surface slopes, roughness, dielectric constant, temperature, and chemical composition from an orbiting spacecraft using radar, optical, infrared, and gamma- and x-ray instrumentation. These techniques have been developed and checked to the point where they can be used reliably for broad-coverage lunar-mapping missions or for planetary orbiters or flybys. Some of these techniques may also be used to advantage in Earth-based telescopic observation.

B. THE LUNAR INTERIOR

Our knowledge of the lunar interior consists of inferences based on geophysical data and on the chemistry and mineralogy of the surface samples. Especially important have been the moonquake and artificial-impact recordings by the ALSEP seismometers. The major results to date, the existence of a crust, and the low level of dynamic activity of the interior, have major implications for the evolution of the Moon.

Internal Structure.— We know now that the Moon is a layered body. In the eastern part of Oceanus Procellarum, the crust is about 70 km thick, and overlies a solid mantle. The crust, in turn, is divided into two parts which are covered by

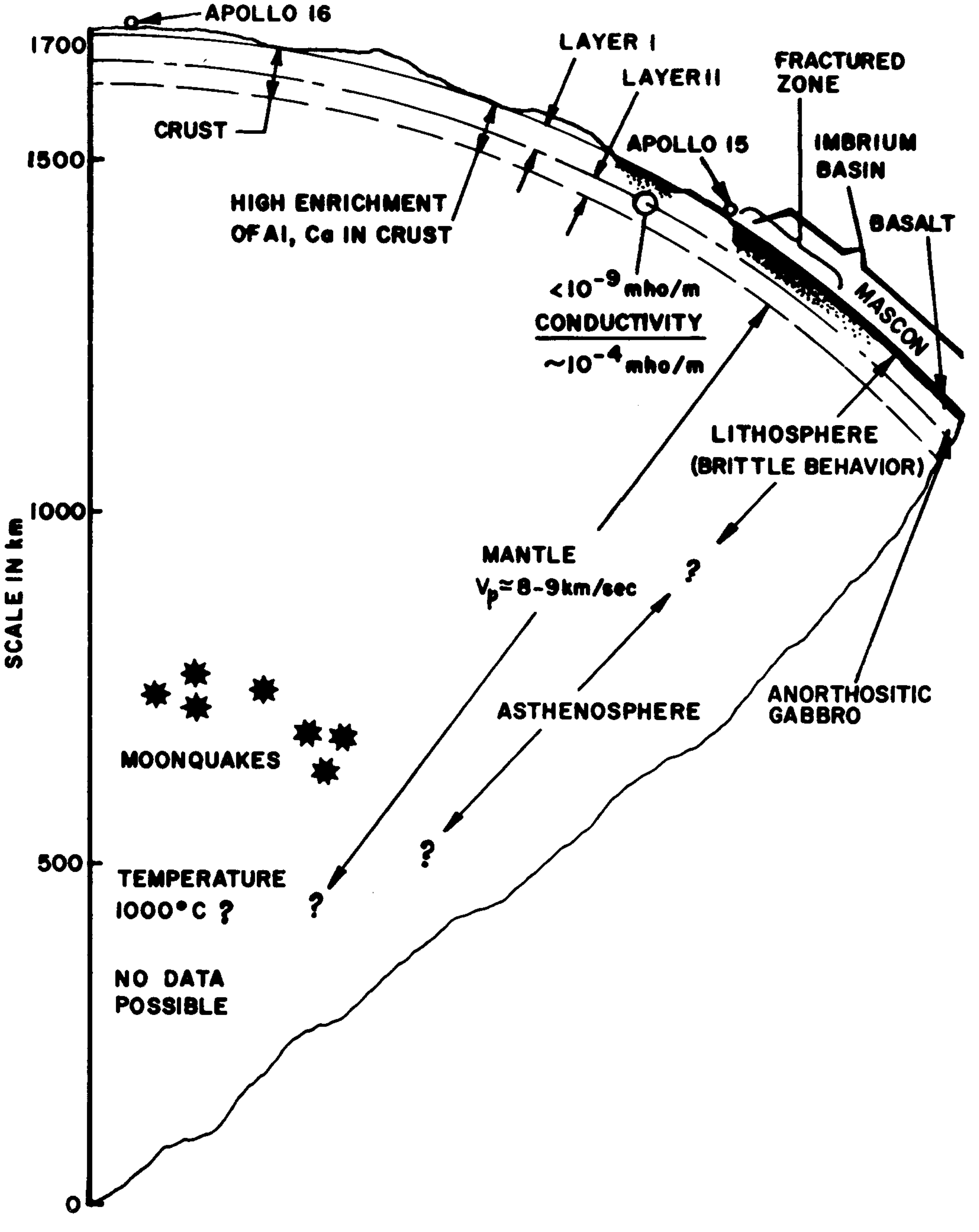

Fig. 2. Geophysical interpretation of the structure of the Moon to scale.

a thin veneer of regolith. From the study of lunar samples, from the orbital geochemical experiments and from the measured seismic velocities, the two principal layers have been inferred to be Al-Ca rich gabbros (anorthositic gabbros) and the basalts that fill the mare basins.

The composition of the surface rocks, the seismic-velocity determinations, and constraints imposed by the mean density and moment of inertia make it appear likely that the upper mantle of the Moon (*i.e.*, below the crust layer) is pyroxene-rich. Olivine and spinel and possibly plagioclase are likely to be present in smaller amounts. There is as yet no specific evidence of striking differences between the deep interior composition and that of the upper mantle.

The Gravity and Figure of the Moon.— Determination of the gravity field has revealed the presence of striking anomalies, the mascons, coinciding with major ringed basins. There are also smaller amplitude variations in the field on a broader scale, not obviously associated with topographical features. The gravity anomalies associated with mascons have excess mass at least 800 kg/cm^2 over the major basins — Nectaris, Crisium, and Serenitatis — for which low-altitude orbital-tracking data are available. The gravity anomalies can be most simply explained by disk-shaped bodies near the surfaces of the basins. Mascons are found in all dark, circular mare basins larger than 200 km in diameter.

All ten of the 100-km diameter craters that have been sampled have negative gravity anomalies, indicating local uncompensated mass deficiencies. The excess mass of the mascons and the fact that the surfaces of the maria lie below that of the surroundings can be understood if the lower density crustal rocks have been replaced by higher density basalts. The mascons are associated with basins that have persisted for more than three billion years. To support the mascons requires that the outer few hundred kilometers of the Moon have enormous strength or a very high viscosity. The lunar lithosphere is therefore thicker than that of the Earth. Seismic signals from man-made impacts and from moonquakes originating about 800 km deep support this interpretation. This conclusion is also consistent with the relatively low temperatures inferred from the electromagnetic transient response of the Moon.

The Moon's internal density has other regional variations, which produce broad scale gravity anomalies. Furthermore, the center of mass is about 2 km closer to the Earth than the center of figure. Varying crustal thickness has been suggested as a cause of these phenomena.

Internal Temperature and Radioactivity.— The present temperature distribution in the lunar interior has been determined for the radioactivity, magmatic history, and accretional temperatures of the Moon. The single heat-flow determination at the Hadley-Apennine region of about 30 erg/cm^2/sec is higher than that estimated from thermal-history calculations, based on chondritic radioactivity abundances. If this heat flow is representative of the average flux for the Moon, then large amounts of radioactivity concentrated near the surface are required. This result implies once again that the Moon is layered, owing to differentiation or to non-uniform accretion or to both.

From the orbital gamma-ray studies, an estimate of the lateral variations of the distribution of radioactive heat sources has emerged. Regions of high surface radioactivity in the Imbrium-Procellarum region appear to be associated with the lunar rock type referred to as KREEP (*cf.* p. 7).

The eddy-current response of the Moon to solar wind magnetic-field variation has been used to infer that the Moon appears, electrically, to have a very insulating outer shell. Comparison of the electrical conductivity values in the deeper interior with laboratory measurements on rocks is suggestive of temperatures around 800-1100 °C.

Chemical Composition of the Interior.— Neither the mare basalts nor the feldspar-rich rocks of the highlands have compositions that are consistent with the mean density of the Moon. Both of these rock types would undergo phase changes to higher density materials at fairly shallow depths, which would give too high a lunar mean density. Therefore, additional compositional changes or melting must be assumed to occur at depth. Consideration of the mean density indicates that the Moon must also have less metallic iron than the Earth. All parts of the Moon that have been sampled indicate that the bulk composition is not chondritic. Crustal rocks of the Moon and their source materials are depleted in several classes of elements (*e.g.*, chalcophile, siderophile and alkali) compared with chondrites and the Earth. This difference implies that the lunar material was subjected to high temperatures at the time of the crustal formation or before accretion. The sources of the rocks are considerably enriched in refractory elements with respect to chondrites. These elements (*e.g.*, Ba, the rare earths, Zr, Ti, etc.) are commonly concentrated when partial melting processes occur.

The mare basalts were derived by melting at temperatures ranging from 1100-1250 °C. The vapor-phase associated with these melts had higher CO/CO_2 and H_2/H_2O ratios than terrestrial basalts. On the basis of phase-equilibrium arguments the source of the basalts in the mantle is shallower than 500 km. Both mare basalts and rocks of non-mare origin cannot be derived directly from partial melting of the same source material. Thus, either material of different composition was added in the final processes of lunar accretion or considerable initial chemical differentiation took place prior to the formation of the rocks that are now observed on the surface. The chemical activity of oxygen and water in the outer 200 km of the Moon is considerably lower than that in the Earth's crust and its upper mantle. This low water content is also inferred from the very low attenuation of seismic waves in the lunar crust.

There has been no certain indication of any gas released from the Moon's interior. The mass spectrometer planned for Apollo 17 has the best chance of establishing the limits and nature of any gas that is being expelled.

Seismicity.— A large number of very small moonquakes have been detected by the Apollo seismic network. The largest quakes have equivalent Richter magnitudes between 1 and 2. The total seismic energy-release within the Moon appears to be about eight decades less than that in the Earth. The moonquakes appear to be concentrated at great depth — between 800 km and 1000 km, which is deeper than any known earthquake. The absence of both larger moonquakes and shallower moonquakes implies a less dynamic interior than the Earth's. This could mean that a global convection system such as has been postulated for the Earth does not exist in the Moon. The cause of deep moonquakes is controversial, but because of their correlation with lunar tides, tidal stresses must play an important role in triggering them. The source of energy is probably thermal.

From the nature of the seismic signals and the physical characteristics of returned lunar rocks, the Moon appears to be covered by an extremely dry, highly heterogeneous layer extending to a depth of between 10 and 20 km. Cratering processes have undoubtedly played a dominant role in the formation of this zone. Other forms of heterogenity, such as layered sequences of lava flows and regolith may contribute to the general complexity of this zone.

Magnetic Fields.— Prior to Apollo, it seemed unlikely that lunar magnetism would be of much interest. Explorer 35 had shown that at a distance of a few hundred kms from the lunar surface no permanent lunar fields could be detected, and hence the Moon did not have any planetary-wide magnetic field comparable to that of the Earth.

The principal magnetic results of Apollo are:

(1) the measurement of natural remanent magnetism (NRM) in returned lunar samples;

(2) the observation of local surface fields of tens and hundreds of gamma;

(3) the detection of remanent fields by the

subsatellite magnetometers.

Although there remains considerable doubt as to the mechanisms by which the NRM was produced, there is little doubt that much of it is of lunar origin. Moreover, remanence is stable, which could be due to weak-field cooling of fine particles of metallic iron. This suggests the presence of fields of 10^2 — 10^3 gamma throughout the period during which the crystalline rocks formed.

The steady fields observed with surface and subsatellite magnetometers are attributed to the remanent magnetism of surface and near-surface ferromagnetic material. The surface fields at the landing sites are localized with a scale size of kilometers or tens of kilometers. The subsatellite, on the other hand, detects fields of larger scale representing a degree of homogeneous magnetization of sources 10 or 100 km in size. It has been suggested that the different scale sizes of the fields can be explained by assuming an initially homogeneously magnetized crust, which was later broken up by impacts.

Fields of 10^2 or 10^3 gamma* are required to generate the remanent magnetism giving rise to the fields we now measure. The origin of these fields is the central and unsolved question in lunar magnetism studies. Since the Moon has no present dipole field, one interpretation is that the Moon had a liquid core, rich in metallic iron, which behaved as a dynamo for at least a part of early lunar history. Alternatively, an appeal could be made to fields of external origin. For plausible rates of tidal friction, the Moon could never, however, have remained close to the Earth except for a time short compared to 800 million years. Solar and solar-wind fields seem no more plausible as causes of the remanent magnetization.

If the field was internally generated by a metallic-fluid core, then the lunar interior must have been hot enough to melt iron during the first 1.5 billion years. This would be hot enough to strongly differentiate the Moon. Dynamical arguments based on the mean density and moment of inertia imply that a metallic core would have a diameter less than about 0.2 of the lunar radius, large enough to sustain the fluid motions required to generate dynamo action.

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* This is 50 to 500 times less than the Earth's field, but 20 to 200 times greater than the field in the solar wind.

C. THE MOON-SPACE INTERFACE

The flux of particle fields and radiation from the Sun and of meteorites upon the lunar surface has left evidence of the history of the solar system imprinted on the surface materials. The complex and unique conditions which occur at this interface with space play a major role in giving the surface of the Moon its appearance and in giving the lunar soil its many novel characteristics.

Solar-Wind Particles.— Although the solar wind has been studied for years by unmanned satellites, the lunar program has contributed the following important new information:

(a) From solar-wind ions captured in Al foils and subsequently analyzed in the laboratory, it has been possible, for the first time, to obtain isotopic information on heavy rare gases. This information is fundamental to the understanding of the evolution of the Earth's atmosphere.

(b) Lunar samples give a wealth of information about atoms originating from the Sun that are directly implanted. This information is basic to an understanding of the Sun and all other solar system objects. Particularly important have been the studies of surface-implanted ions of Kr and Xe. These elements show isotopic differences, still unexplained, between the Earth's atmosphere and also meteorites. Deuterium has been shown to have a very low abundance with respect to hydrogen.

(c) A^{40} is greatly in excess of what is expected; the most likely interpretation is that the A^{40} was originally emitted by the Moon and was then re-implanted by interaction with the solar wind.

(d) Amorphous surface films, very likely produced by solar-wind bombardment, are observed on many lunar grains. Artificial irradiations produce similar films whose thicknesses vary with bombarding energy. These observations indicate that the lunar soil will be useful in studying the ancient solar wind and its energy fluctuations.

(e) The concentrations of hydrocarbons (mainly methane and ethane) are observed to correlate with the solar wind irradiation of different lunar soils. It is possible that these compounds are formed in the superficial layers of individual dust grains that have been heavily irradiated with solar-wind ions. Since inter-stellar space contains both dust clouds and sources of energetic particles, it is possible that these processes are important for organic synthesis in the Galaxy as a whole. Part of the effects may also be due to local melting by meteorite impact with subsequent redeposition as surface layers.

(f) Related studies in lunar soils on the light stable isotopes of C, N, O, Si, and S have shown significant departures from terrestrial and meteoritic values; values are also different than in the lunar basalts themselves and are apparently produced by the unique irradiation and bombardment history of the soil. Nitrides, cyanide, and phosphides, as well as benzene, also are present and their production may be due to similar processes.

Solar Flare Particles.— As a result of the Apollo program, dramatic progress had been made in the study of solar-flare particles. The three most important discoveries are the following:

(a) The energy spectra of heavy solar particles down to energies of 10 KeV/neutron have been established. The energy spectrum of solar-flare electrons is now known to energies below 1 KeV. These are improvements of at least two decades in the energy regions which carry the most physical information about the basic flare-acceleration processes.

(b) The relative abundances of very heavy nuclei have been determined for a sample (Surveyor III Glass) exposed to several major flares. The unexpected discovery (now confirmed by independent satellite measurements) is that the lowest energy solar cosmic rays are highly enriched in very heavy nuclei compared to normal solar material. This is the first demonstration of the preferential heavy-ion acceleration by a natural particle accelerator. This discovery casts an entirely new light on two decades of solar and cosmic-ray research, during which a basic assumption has been the absence of such preferential acceleration processes.

(c) For the first time, information about the solar-flare activity on the Sun over geologic times has been obtained. This information is contained in the induced radioactivities and nuclear-particles tracks produced in the outer layers of lunar surface material. One important conclusion is that the average solar-flare activity has not changed appreciably over the past few million years. It has also been shown that solar flares were active at least 0.5 billion years ago and probably back to the original formation of lunar surface. The observed constancy of solar flares suggest that major climatic changes that have occurred during the last million years have not been associated with large-scale changes in solar activity as had previously been postulated.

Lunar Atmosphere.— There are three major sources for the past and contemporary lunar atmospheres:

(a) outgassing of the lunar interior, especially during extensive periods of igneous activity;

(b) transient atmospheres arising from meteorite impact with rapid redeposition of condensibles;

(c) emission of ions implanted from solar wind.

Prior to Apollo, optical and radio observations had been used to set lower limits on the density of the lunar atmosphere; apart from that, nothing was known. The Apollo program has demonstrated that the contemporary Moon has a tenuous, sporadic atmosphere and has given several indications of a denser atmosphere in the past.

Two lunar experiments capable of detecting particles in the 20 eV to 3.5 KeV energy range have detected gas clouds associated with the impact of man-made objects, such as the Saturn IVB stage, as well as natural objects. Continued data analysis from these experiments, coupled with the additional surface experiments from Apollo, should serve to define the production, composition, and diffusion of lunar gas clouds.

At least three indicators for past lunar atmospheres have been found. The first of these is a high abundance of Ar^{40} apparently reinjected into the lunar soil by interaction with the solar plasma. A related observation is the presence of large amounts of xenon, apparently derived from decay of extinct isotopes early in the history of the solar system, in at least one lunar breccia. The xenon comes out at low temperatures and may have gone through a reimplantation process. Finally, regional variations of characteristic lead isotopes have been found. This indicates local production and redeposition of volatile elements early in the history of the Moon.

Magnetic Properties.— Prior to the Apollo program magnetic fields did not play a role in the theories of origin and evolution, and the Moon was generally considered to be magnetically uninteresting. The Apollo program has yielded two major discoveries that completely change the picture. The first is the discovery of fossil magnetism on the Moon [*cf.* p. 16]. The second is that electromagnetic induction in the Moon leads to the formation of a well defined time-dependent magnetosphere.

Facing the solar wind the magnetosphere is compressed into the lunar crust while on the other side it is blown out into the lunar cavity. The existence of a lunar magnetosphere defines a broad new class of planetary magnetospheres and strong dynamo fields. It also provides an important constraint on models of the charged-particle environment of the Moon and other bodies of this type.

D. THE EVOLUTION OF THE MOON

The major outcome of lunar science is the recognition that the Moon has evolved as a planet very differently than has the Earth. The Moon went through a period of major igneous activity and a high rate of impact during its first 1.5 billion years. Since then, its thermal and mechanical activity has been almost nil; if our exploration of the Moon had taken place 2.5 billion years ago, few aspects of the Moon would have been different. Figure 3 is an overall view of this evolution. The importance of the first 1.5 billion years lies mainly in its implication for the Earth and the solar system. Nowhere else do we have access to as detailed an ancient record of planetary evolution.

Chemical and Isotopic Composition.— The bulk composition of the Moon is not primitive (*i.e.*, solar or chondritic). Apart from the obvious depletion in gaseous elements (H, He), the following differences have emerged:

(a) Volatiles (elements volatile below about 1000 °C): The essential lack of hydrated minerals in lunar rocks suggests that neither crystallization in the presence of water nor erosion by water occurred to a detectable extent. The abundance of indigenous carbon is strikingly low; crystalline rocks contain only 1-20 ppm of C. Soils contain larger amounts of C (up to 200 ppm), but this carbon is largely of external, solar-wind origin. Nitrogen is equally rare. The Moon is, and probably always has been, an exceedingly inhospitable environment for organic chemicals, prebiotic or biotic. Relative to their terrestrial counterparts, lunar rocks consistently are 3- to 10-fold depleted in Na and K. They are depleted by even larger factors (10 — 100) in elements of higher volatility, such as Pb, Bi, Tl, Br, etc. All these depletions seem to reflect an initial deficiency, not a subsequent loss.

(b) Refractories (elements with condensation temperatures above about 1200 °C): The lunar crust (mainly anorthosite and norite) contains many refractory elements (Al, Ca, Sr, Ti, Zr, Th, rare earths) in so high an abundance that at least the source region (upper 200 — 300 km) must originally have been enriched 3- to 10-fold over solar (or chondritic) abundances. This conclusion is based both on the thickness of the crust (70 km, approximately 9 percent of the mass of the Moon) and the mantle composition implied by the mare and non-mare volcanic rocks.

(c) Noble Metals: Metals such as Au, Ir, Re, Ni, etc., are depleted in lunar surface rocks to 10^{-4} — 10^{-5} their solar abundance. The depletion pattern differs from that on Earth, gold being more strongly depleted in the Moon by two decades.

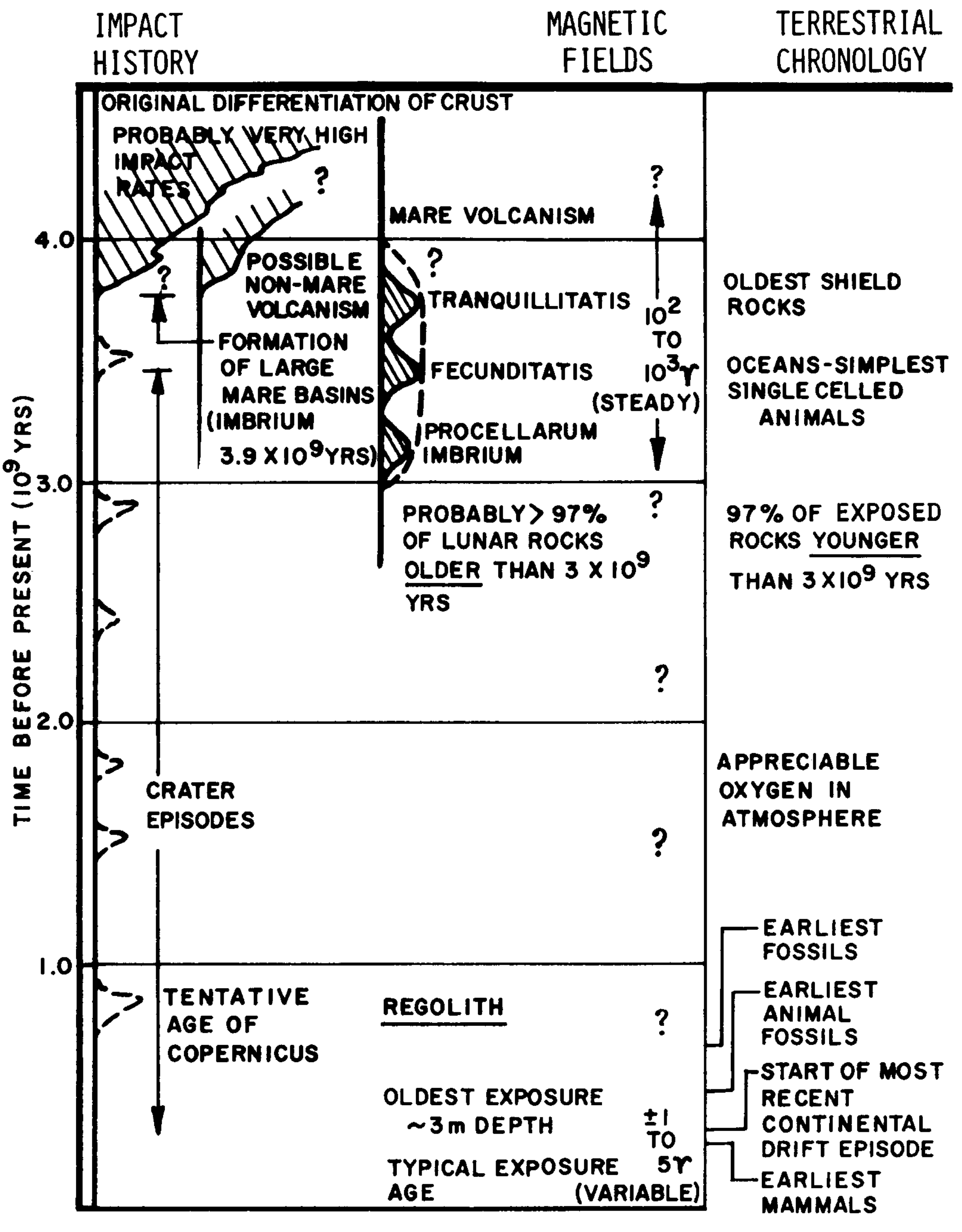

Fig. 3. Chronological interpretation of lunar history based on Apollo results.

This difference suggests that the Moon lost its noble metals in a separate event, under different physical and chemical conditions than did the Earth.

Condensation Temperature.— The Moon could not have condensed from the solar nebula in a simple event at one temperature and have its observed composition. Instead, it seems that the Moon is a mixture of materials that separated from the nebula over a wide range of temperatures. The fact that the Moon contains more than its cosmic share of refractories and much less than its cosmic share of volatiles suggests it had a high condensation temperature. Yet the amount of oxidized iron in lunar basalts suggests equilibration of the iron-bearing part of the condensate at approximately 200 °C. (Similar temperatures are inferred from abundances of volatile metals and the O^{18}/O^{16} ratio.) Probably all materials that accreted into the Moon were initially at that temperature.

Lunar Asymmetry.— The Moon is asymmetric physically (shape) and chemically (distribution of maria, and of KREEP). Either the Moon was sectorally heterogeneous in chemistry from the outset (perhaps it accreted from dissimilar moonlets), or processes operated asymmetrically in or on it. The geographic asymmetry was known before Apollo and has always been a puzzle.

Igneous Activity.— Igneous activity has been wide-spread on the Moon. All the samples returned are igneous rocks or breccias that clearly were derived from igneous rocks (based on their chemical composition and high-temperature mineralogy). No samples of "primitive" lunar material have been collected. It was not at all clear before Apollo that this would be the case. One widely held view was that the Moon had accreted cold, and had not been heated sufficiently by internal radioactivity to melt.

Although igneous activity was very extensive (depths to at least 100 km must have been largely melted to produce the observed lunar crust), it was restricted in time. Radiometric dating has revealed no igneous rocks younger than 3.2 billion years, and the level of seismicity of the Moon is too low to support the idea that igneous activity continues to this day. Probably, as a result of the short duration of igneous activity on the Moon, chemical differentiation has not proceeded to an advanced degree, and the suite of rocks produced is nowhere near as complex as that observed on Earth. The vast majority of samples of pre-mare lunar rock examined fall into one of two broad categories: anorthositic rocks, and noritic (KREEP) rocks.

Formation of the Crust.— The Moon is a layered planet; a crust (about 70 km thick) of low-density (about 3.0 gm/cm^3)

material overlies a higher density (about 3.35 gm/cm^3) mantle. This structure has been inferred from seismic and gravity measurements. The chemical differentiation that produced this layering was at least partly, perhaps wholly, a result of the igneous activity described above. There was no knowledge of a lunar crust before Apollo; indeed the moment of inertia of the Moon suggested that it was nearly uniform, and, hence, undifferentiated throughout. The existence of a crust makes the Moon more Earth-like, hence, potentially much more interesting than we had expected.

The pre-mare igneous rocks so far dated were formed 4.0 to 4.1 billion years ago. However, the isotopic ratios of initial strontium and lead in some of these rocks show that they must have formed into a differentiated lunar crust even earlier in lunar history, probably 4.5 billion years ago. Additional definitive marks of this early history can be expected from the decay products of extinct radioactivities such as ^{244}Pu.

The crust of the Moon consists largely of anorthositic rock, a result that was almost totally unexpected. Speculative pre-Apollo papers named many other rock types as candidates for the substance of the lunar surface. Anorthosites are rare and enigmatic on the Earth. The existence of an anorthositic crust on the Moon raises the important possibility that the early Earth passed through such a stage.

Mare Filling and Volcanism.— The mare regions were filled with low viscosity basaltic liquids or ash flows, permitting wide areas to be covered with a single flow. These basaltic rocks are igneous products of a chemical differentiation due to internal heat sources. The times of mare fillings lie in the interval 3.2 to 3.7 billion years ago. Since these samples represent the youngest widespread lunar surface material, it must be concluded that regional lunar volcanic activity stopped about 3 billion years ago.

Impact History.— The large mare basins represent the last stages of impact of large bodies on the surface of the Moon. The ubiquitous and profound cratering of the highlands on all scales is in some way a record of this period of impact and cratering. The Apollo age dates indicate that the Imbrium basin, the second youngest of the mare basins, was formed 0.5 billion years after the Moon's accretion. This raises various possibilities about the cratering history during the first half billion years. The rates of impact may have been so great at times that most of the large craters formed never survived to leave any record. A critical problem is to determine the time span for the basin-forming impacts and the nature of the impacting bodies. Such evidence is required to determine whether the basins were related to a special collisional event, the time of capture of the Moon, or the gradual sweep-up of small bodies from terrestrial space, the asteroid belt, or elsewhere.

The craters on the mare surface are a record of impacts since 3 billion years ago. The average cratering rate has been much lower than during the first 0.5 billion years. A limited number of medium sized (20 — 100 km) craters such as Copernicus and Tycho have been formed since 3 billion years. The times are uncertain, although study of particles in the soil at Apollo 12 suggests that Copernicus may have been formed 850 million years ago.

Early Lunar Magnetic Fields.— Remanent magnetic fields found in lunar samples, at Apollo landing sites, and over large regions scanned by the subsatellites indicate that magnetic fields were present at the lunar surface during the period of igneous activity. The critical point for lunar evolutionary theory is that fields of 10^2 or 10^3 gamma were required to generate the remanent magnetism now found. The origin of these fields in which remanence was initially acquired is the central and unsolved question in lunar magnetism studies (*cf.* p. 20).

Thermal History.— The seismological data are held to indicate a relatively cool and inert Moon to 800 km depth; a low temperature is also inferred from the response of the lunar magnetic field to solar wind transients. Both lines of evidence suggest a central temperature well below the melting point of ultramafic rock. In apparent contradiction are the remanent magnetic indications of an appreciable field more than 3.2 billion years ago, which probably required a dynamo generated by a convecting fluid iron-rich core. Also, the existence of the mare basalts indicates sufficient heat at depths less than 500 km to generate large-scale volcanism between 3.2 and 3.7 billion years ago. Thus, a central problem is to explain a constant cooling of the interior.

The deep interior of the Moon must have been solid since about 3.2 — 3.9 billion years ago (and probably since the very beginning) in order to support the mascons and the unequal moments of inertia. However, this conclusion stands in conflict with the magnetic data which suggest that the Moon had a fluid core 3 — 4 billion years ago (*cf.* p. 17).

The outer 100 km or more of the Moon melted at least 4.3 billion years ago, forming a lunar crust consisting largely of anorthosite and norite (*cf.* p. 23). It is not clear whether this melting took place immediately after accretion, or several hundred million years later. In the former case, very rapid accretion (no more than 10^6 yr) — or possibly electromagnetic induction by interaction with the solar "hurricane" of a superactive early Sun — is required. In the latter case, some of the heat would be furnished from internal sources (*i.e.*, radioactivity), but a major part would still have to be provided during or soon after accretion.

E THE ORIGIN OF THE MOON

To understand the early history of the solar system it is necessary to know the bulk chemical composition of the planets and their satellites, and to know the chemical rules that govern the assembly of planetary bodies from a cosmic cloud of dust and gas. Prior to lunar exploration it was commonly and naturally assumed that the mean composition of the terrestrial planets was closely similar to the composition of chondritic meteorites. Only very fragmentary data on the mean composition of larger bodies was available, and there was strong evidence that chondritic meteorites were a rather unfractionated sample of the Sun for those elements that form rocks at low temperatures. The investigation of the Moon during the last decade, however, has provided compelling evidence that the mean composition of the terrestrial planets is not at all that of chondritic meteorites.

It now appears that both the Moon and the Earth were accumulated from material that was highly fractionated relative to the solar abundances. This fractionation consists of depletion of a large number of easily condensable elements as well as the obviously volatile species (H_2O, CO_2, CH_4). The Moon and the Earth are thus enriched in the refractory elements which include the heat-producing elements U and Th. Our conception of the solar system processes which generated the planets has been greatly altered. We now consider that a wide spectrum of planetary objects were formed which ranged from accumulations of material enriched in refractory elements (the terrestrial planets) to relatively unfractionated bodies represented by the major planets and all of the low density objects in the solar system. The Earth no longer appears peculiar, but seems to be one of the typical "spectral" types. The planets preserve for us a record of the history of the early solar system and thus provide a basis for reconstructing the accumulation processes that governed planet formation. The mechanism for the accumulation of solid bodies from dust and gas remains a fundamental problem that must be deduced from the compositions of the planets. It now appears possible to determine the duration of the accumulation processes and the time-scale required for chemical segregation within the planets. The Moon has proven to be the first sizable planetary body that preserves the early stages of internal segregation and also shows that the actual accretion process, and major collisions, extended for a much longer period than was considered before.

The establishment of an absolute chronology of major events in lunar history has revealed a remarkably complex and rich early history, extending from 4.5 to approximately 3 billion years ago. This is in strong contrast with both common pre-Apollo schools of thought: that either the Moon was geologically active throughout most of its history or that it was essentially dead since it was first formed. The major impacts that produced the mare basins occurred at least 700 million years after the Moon's formation. Widespread flooding of those basins by volcanism extended to at least 3.2 billion years. Whatever the origin of the impacting objects (local or distant) the fact that such impacts occurred as recently as 3.9 billion years ago suggests the possibility that the Earth suffered similar bombardment which may have strongly affected the early geologic record.

The lunar studies of the last decade have not produced conclusive evidence against any of the theories of the Moon's origin. However, many significant compositional differences between comparable terrestrial and lunar rocks have provided additional constraints that are difficult to explain by the hypothesis that the Moon was fissioned from the Earth.

F. CURRENT MAJOR UNSOLVED PROBLEMS

In the brief period that man has had to make direct observations of the Moon there have been dramatic discoveries even though the data are new and there has been little opportunity to digest and integrate the many results. Some results answer long-standing questions such as "Are there ancient rocks preserved on the Moon?" We find that there are. Some results clarify our understanding so that we can proceed to ask further, more penetrating questions. Other discoveries pose unanticipated questions such as "Why are the lunar materials magnetized?"

In the following paragraphs we touch on some of the major unsolved problems in lunar science from the limited perspective of rapidly unfolding events. The problems are presented in terms of three larger questions: (1) What was the history of the Sun and other objects in the Galaxy? (2) How did the Moon accrete and what happened during its very early history? (3) What was the thermal history of the Moon?

History of the Sun and Possibly of Other Objects in the Galaxy, as Recorded in the Lunar Surface.— Can the record of cosmic ray and high energy solar particle-flux be extended back through a time scale on the order of the lifetime of the Sun; if so, does the record over the lifetime of the Sun show changes larger than those seen in the few million years so far studied? Is there a correlation between the high energy particles in the solar wind and thermal emissions from the Sun? Can those parts of the solar emission record preserved in the lunar surface be used as indicators of total solar energy flux? Do such changes bear on major changes in the Earth's climate in the past?

Can the record of solar chemical composition and physical processes in the solar corona, in the form of tracks and particles trapped in the lunar regolith, be extended back through a time scale on the order of the age of the Sun?

Are there other phenomena preserved in the irradiation record of the lunar surface which would apply to such problems as the origin and residence time in the Galaxy of cosmic rays, and the evolution of the source regions of the solar particles? Does the lunar surface material contain supernova products such as super-heavy elements and undiscovered fundamental particles?

Accretion and the Early History of Bombardment of the Moon.— The Moon and other planets grew from materials that probably were different in composition from place to place in the solar system and that changed with time. What were these variations and how were they related to the evolution of the Sun and the general processes of planetary formation? How did the chemical differences control the subsequent evolution of the planets?

It is possible that we observe in the most ancient parts of the lunar surface a partial record of the birth of the Moon. The rapid bombardment of the Moon during part or all of the time between 4.6 and 4.0 billion years ago may reflect the last stages of infall or accretion of objects (planetesimals) from which the Moon itself was formed. Alternatively, this bombardment may have been a consequence of the capture of the Moon by the Earth. To determine whether either hypothesis is correct, it is critical to know how the rate of bombardment changed with time. Did the infall of objects decline steadily during the first billion years of lunar history, as the remaining planetesimals were swept up into growing planets? If so, in what regions of the solar system were the late-falling objects stored so that they were not swept up earlier?

How far back in time can we trace the bombardment record? Extrapolation of the impact history back beyond 4.0 billion years suggests that no craters older than about 4.2 to 4.3 billion years may be preserved. If the Moon was captured, the oldest features might be as young as 4.0 to 4.1 billion years. Is any part of the most primitive lunar crust preserved? Are the asymmetries in the figure of the Moon inherited from this period?

The large multi-ringed lunar basins were created by the impact of very large bodies during the first billion years of lunar history. One of the youngest of these basins was formed less than 3.8 billion years ago. What were the compositions of the impacting bodies that formed these basins and what was the time interval during which the exceedingly large impacts took place? Did these bodies represent the kinds of objects from which the rest of the Moon was formed, or were they different in composition and derived from a different region of space?

Knowledge of the bombardment history of the Moon has direct application to the Earth. The earliest recognizable rocks on Earth are 3.5 to 3.9 billion years old, and were formed during the time that the rate of impact on the Moon was still high, but declining rapidly. These ancient terrestrial rocks should be investigated to determine whether they reflect a high rate of bombardment similar to that observed on the Moon for this time range. The rarity of rocks on Earth older than 3.0 billion years may simply be due to the continuing evolution of continents, their destruction and regeneration through time. On the other hand, the apparent absence of rocks on Earth greater than 4.0 billion years old could be the direct result of a very high rate of impact during the early part of the Earth's history.

Differentiation and Thermal History of the Moon.— The structure and composition of the deep interior are unknown. Is there a core? If so, what is it made of and when did it form? Did a core dynamo magnetize the ancient lunar rocks? If it did, why is it no longer active?

We know that the Moon is compositionally layered, but we do not yet understand the full significance of this observation. To what extent has the Moon differentiated by magmatic processes, and what is the distribution of the differentiated products? Are the lunar crust and interior complementary differentiates? What is the significance of regional variations of radioactivity in crustal rocks? Did initial processes of accretion or differentiation result in significant outgassing of the lunar interior? Specifically, did early formation of the crust release volatiles to a transient atmosphere?

The history of heating of the Moon and magmatic activity is very imperfectly known. To begin with, when was the crust of the Moon formed? Was magmatic activity continuous in the period 4.0 to 4.6 billion years or did magmatism related to crustal formation terminate until the maria began filling with lava? Are the earliest volcanic (extrusive) rocks those in the maria? If not, what is the nature of earlier volcanic rocks? How long after formation of the major lava flows of the maria did minor volcanic activity persist? Why did major volcanic activity cease? Is there any connection between the presence (and the later disappearance) of a lunar magnetic field and the history of lunar volcanic activity? Why are the mare basalts effectively restricted to one side of the Moon?

There are major questions related to the sources of heat leading to lunar magmatic activity and how they changed in relative importance with time. For example, what was the nature of the heat source that initiated melting to produce mare basalts?

In order to answer these questions and many others, a wide range of scientific activities will be required. Many valuable new data are expected from the Apollo 17 mission. Of equal or greater importance will be information extracted from the existing resource of Apollo materials — samples, data, and photos, as the opportunity becomes available to study them in depth. Much of what we seek to know involves further characterization or description of the Moon as it is now — the nature of its interior, the physical makeup of the highlands crust, the areal distribution of rock types, etc. Equally, effort will be devoted to interpreting and synthesizing the data, into the design of crucial sample or data analyses aimed directly at the larger questions.

In the following chapter we recommend a strategy for the orderly pursuit of these objectives. This program requires effort on both the descriptive and the interpretive aspects of the Apollo results. It is a program for the utilization and exploitation of these results, both in the immediate future and over the long range.

A look ahead to the need for future lunar exploration is provided in Chapter IV. Consideration is given to the most appropriate types of lunar visits and to the necessity of early planning for this second phase of lunar exploration.

CHAPTER III

A STRATEGY FOR LUNAR SCIENCE AFTER APOLLO

A. INTRODUCTION

The termination of the Apollo flight program after Apollo 17 leaves the scientific tasks undertaken by Apollo substantially unfinished. Most of these tasks can proceed only after the samples, geophysical data, and remote-sensing data have been returned and suitably described and deposited in an archive. A great deal of work thus remains to be done. The rationale for this work grows directly out of the existence of the data and samples obtained by the Apollo program. In this chapter we recommend a strategy for the orderly completion of the Apollo science objectives. It consists of three major types of activity.

¶ A mission-oriented phase, involving the completion of preliminary examination of the samples and data, will end about mid-1974.

¶ A basic-description phase, in which the samples and data are comprehensively and broadly studied, with the object of putting them in a proper archival setting, should diminish by mid-1976.

¶ Problem-oriented investigations, aimed at using the data base for research on the broad and fundamental questions, will be the intellectual core of the program. While much work of this type will be concurrent with the mission-oriented and basic-description activities, it will continue for many years.

B. SUMMARY OF RECOMMENDATIONS BY PROGRAM AREA

We here summarize all the recommendations of this chapter, noting page numbers where they are developed.

LUNAR SAMPLE ANALYSIS

1. *We recommend that a program of basic description of the samples be supported, following the end of mission-related sample examination.* Support of the Principal Investigator (PI) program and the activities of the sample Curator at the present level of

effort is needed to complete the basic description by mid-1976 [reference page 36].

2. *We recommend a long-term program of problem-oriented studies of lunar samples, to carry through the late 1970's.* The nature of this work dictates that continuity be maintained while letting the level of effort drop somewhat below that required to complete the basic description [reference page 36].

3. *We recommend that the transition from mission-oriented research to basic-description and problem-oriented research be accompanied by steps to ensure the vitality of the involved scientific community.* Annual review of the program should be conducted to permit the elimination of unproductive measurements and disciplines in favor of new, creative investigations. *We urge recognition of the continued need for a critical mass of scientists in the key discipline areas— this implies several PI groups in each key area* [reference page 43].

4. *We urge that the lunar science facilities and staff at the Manned Spacecraft Center be maintained as a continuing and integral part of the total program.* The services of the Curator and his staff cannot be kept at a high caliber without the collaboration of a first-rate lunar science laboratory. The role of the curatorial facility as an interface between lunar sample investigators and the sample collection is similarly dependent on the maintenance of the MSC lunar science effort [reference page 43].

5. The review function now carried by the Lunar Sample Review Board (LSRB) should be continued by this board or its successor. The LSRB should increase its proportion of members from outside the Lunar Sample Program [reference page 44].

GEOPHYSICAL EXPERIMENTS

1. *We strongly urge that the ALSEP geophysical network be continuously monitored as long as it continues to provide data important to the outstanding scientific questions* [reference page 45].

2. *We recommend that the present ALSEP investigators, as well as possible new investigators, be supported for at least 2 years of effort* to complete the basic description of the data from the stations. This consists of a thorough characterization and first order analysis of the significance of the data returned [reference page 52].

3. *We recommend that the ALSEP geophysical network be regarded as a national lunar facility with data available to all qualified investigators.* NASA should plan for an orderly transition to

this mode of handling the data, including support for maintenance and transcription of data tapes. Support should be provided for qualified investigators to analyze data from the network [reference page 52].

4. *Synthesis and understanding of the significance of the geophysical data is dependent on supporting studies as well.* Selected investigators should be funded for germane work related to the geophysical results— including theoretical, laboratory, and geological studies [reference page 52].

5. *We recommend that a committee of outside scientists be established, on the model of the LSRB, to maintain cognizance over the scientific effort in geophysical data analysis,* including the review of proposals for this purpose [reference page 70].

REMOTE SENSING

1. *We urge that support be provided for basic description of the data returned by the Apollo missions.* This will entail the following tasks: reduction and analysis of the geochemical orbital data; processing of the photographic data; and preparation of maps for support of geological, geophysical and geochemical studies [reference page 60].

2. Ground-based studies are becoming increasingly productive of new information and are a remarkable economical way of getting new types of knowledge about the Moon. *We urge continued support of the ground-based program of lunar observations* [reference page 61].

3. Future lunar and planetary exploration will become increasingly dependent on sophisticated and presently untested methods of remote sensing. *Continued effort to maintain experimental competence in this area will be essential* [reference page 61].

SAMPLE CURATORIAL FACILITIES AND DATA ARCHIVES

1. The integrity of the sample collection, presently maintained by NASA at the Manned Spacecraft Center, must be preserved as a matter of fundamental national policy in order that current and future experiments of great potential significance in our understanding of the solar system will not be compromised. *The lunar sample curatorial facility at MSC is absolutely essential to lunar science objectives.* Scientific study of the samples would be impossible without the curatorial support and severe degradation or effective loss of the samples would follow any termination of this service [reference page 62].

2. *The present system of archives for instrument data (magnetic tapes) should be preserved,* but an advisory committee should be organized to review the current procedures and recommend policies and procedures necessary to prevent the loss of useful data, and to improve the access to data by all qualified investigators [reference page 64].

3. *We recommend that a commitment be made to the long term preservation of Apollo flight film,* with carefully controlled access to the films by approved scientific investigators, through the continued support of an organization such as the MSC photographic laboratory [reference page 66].

4. *All of the archives must ultimately* (a) maintain the safe and controlled storage of samples and original data, (b) catalog the contents of the collection, (c) have procedures that permit access to the data for research, and (d) provide for the release of information to scientists and to the public [reference page 62].

ADVISORY COMMITTEES

1. *We recommend that an advisory committee (LSAPT or its successor) of sample investigators from outside NASA be continued to advise NASA on lunar sample allocations and on the welfare of the lunar sample collections* [reference page 69].

2a. *We recommend that an advisory committee of scientists from outside NASA (LSRB or its successor) be continued to advise NASA on the relative merits of lunar sample research proposals and to review the scientific productivity of the lunar sample program* [reference page 69].

2b. *We recommend that the responsibilities of the committee that reviews lunar sample proposals be expanded to include proposals to study lunar surface and orbital data and data synthesis studies* [reference page 70].

3. *We recommend that MSC form a standing advisory committee of non-NASA scientists which would maintain oversight* of

(a) the archiving, distribution and analysis of data and photography,

(b) the operations of the geophysical experiments.

This committee would have functions analogous to those of LSAPT involving the many operational aspects of the geophysical and photographic data [reference page 54 and 70].

4. *We recommend that lunar program office of NASA*

Headquarters form an advisory committee of non-NASA scientists from the lunar program. We consider it appropriate that part of all of the membership of this Headquarters committee should be drawn from the several MSC committees discussed above (sample allocations, proposal review, data, photography), since members of these operational committees are closest to the problems and opportunities of lunar science at any given time [reference page 71].

5. *We recommend that special* ad hoc *panels be convened under the aegis of the LSI to conduct critical reviews of the health of certain program areas* [reference page 70].

6. *We recommend that proposal reviewing committees maintain continual re-examination of their procedures to ensure the integrity of the advisory system with respect to questions of conflict of interest* [reference page 70].

SPECIAL AREAS

1. *The administrative structure of the lunar program in NASA Headquarters should be arranged to maximize communication with the planetary program* [reference page 72].

2. *Selected critical investigators in meteoritics and Earth science should continue to be included in the program in support of the overall objectives of lunar and planetary research* [reference page 72].

3. *We recommend that a special report be produced on the quarantine experience of the Apollo program,* to critique it, and to set guidelines for any future quarantine program. It is desirable that the quarantine consumption of samples in future situations be kept to an absolute minimum [reference page 73].

C. THE LUNAR SAMPLE ANALYSIS PROGRAM

Strategy for Sample Studies.— The Apollo missions have provided an extraordinarily diverse and valuable collection of lunar samples. These samples include materials typical of the front side of the Moon, the solar system, and cosmic debris. They may also include materials from great depths within the Moon. An appropriate investigation of these scientific treasures requires participation by the scientific community and a concerted effort by NASA to preserve the integrity of the collection while making the materials available for this investigation.

One year after the return of Apollo 17, the provisional categorization of the lunar samples will have been established by a study of about 25 percent of the total material. This categorization will be the product of an intensive effort by some 800 scientists working in about 180 groups under the constraints of mission schedules. This work has already been extremely fruitful, and further important discoveries will no doubt be made as it is completed.

The completion of this first-generation analysis with the partial categorization of the Apollo 17 samples will be an important milestone. However, a large fraction of the soil and rock samples from the six different landing sites will not have been categorized during the mission-oriented phase of the study. The completion of the basic description of these samples will require a level of effort approximately equal to that of the mission-oriented phase, continuing for a period of perhaps two years or so beginning in 1974.

The types of studies undertaken to date have revealed a variety of diverse and interesting characteristics that are related to both lunar and solar history. The assembly of these observations into a meaningful history will involve much more detailed studies of some samples than was possible during the mission-oriented phase. It will also depend on the development of tools and technology that are particularly suited to the study of small samples. This immediate post-mission period requires a parallel and major effort in both sample study, and in topographic and photogeologic analysis. All of these efforts are necessary in the same time period in order to develop a basic scientific framework.

Subsequent to the completion of the more thorough analysis and categorization of the basic-description period, the scientific investigation should change into a *problem-oriented phase*. Several activities related to the basic data acquisition and reduction will be completed, permitting a decrease in the commitment of resources in that phase. The problem-oriented phase will involve a new and refined definition of the scientific activities. It will require the application of both new approaches and new techniques. A problem-oriented approach has characterized many activities within the Lunar Science Program from the beginning of the Apollo 17 mission, and we believe that this approach will, in the post-1976 period, dominate the scientific studies on lunar samples. This can, of course, only be carried on successfully with maintenance of the lunar samples in a pristine state.

The three phases of sample studies can be summarized as follows:

¶ *Mission-Oriented Phase*

The final phase of mission-oriented Apollo activity is concerned with completing the preliminary and, in some cases, detailed descriptions for a representative portion (about 25 percent) of the lunar samples from each mission. This mode should cease about mid-1974 with the completion of the processing of the Apollo 17 samples. A major re-evaluation of the PI (Principal Investigator) work force would then be appropriate, prior to entering the next mode of operation.

¶ *Basic-Description Phase*

This mode of operation is intended to conduct and document the basic inventory of all the samples returned by the Apollo missions, essentially setting the Apollo sample collections onto a proper museum footing. Each sample will require detailed description and analysis, comprising photography, basic mineralogy-petrology, and major-element chemistry. Together with site photography, photogeology and cartography, and ALSEP and orbital data, these basic descriptions will permit rock samples to be placed in the local and regional geologic context. The synthesis of all available data will be an important activity to achieve this end. Only then can we consider that the sample collections for Apollo missions have been properly documented and each sampling site characterized. Much of the long-term scientific potential of the Apollo missions will never be realized unless this task is adequately carried out. Completion is targeted for roughly a two-year time-span terminating in mid-1976.

¶ *Problem-Oriented Phase*

The completion of the mission-oriented phase and the basic-description phase studies should result in an adequate data-base for the lunar science acquired by the Apollo missions. Problem oriented work, which is of course a continuing PI activity, should then become the mainstream activity. Proposals should be invited, judged, and funded on this premise so that the on-going program for 1976 will truly be problem-oriented rather than sample-oriented. A somewhat lower level of effort than required during the basic description phase will be adequate.

> This redirection will be a major task facing the lunar science community near the end of the two-year basic-description period during which there should be greater redirection of effort towards the solution of major problems rather than the acquisition of data within the narrow context of single investigations.

Probable Emphasis in Sample Studies.— Although most of the large rocks at a lunar site are locally derived, the smaller rocks and fragments come from wider areas of the lunar surface. Detailed information concerning the occurrence of distant major impacts and other events may thus be obtained by recognizing and documenting the less abundant types of small particles in the regolith. Careful studies of soil samples and of the stratified cores enable chronological accounts to be derived of the evolution of the regolith. Such lunar-impact chronology should be a major objective in the problem-oriented phase. It will never be possible to get such a direct picture of the Earth's history on account of erosion and crustal movements, but knowing what happened on the Moon will help fill in some of the gaps.

Long-term study of the fines will require a variety of techniques, including the most sensitive and delicate available for the study of micron-size particles. Automation of the equipment will be desirable in view of the large number of particles to be screened (1 gram of soil smaller than 1mm diameter may contain as many as 10^7 particles).

The potential of the fines for resolving the evolution of the environment in time and over large areas of the lunar surface is so great that a significant level of scientific activity in the problem-oriented phase of sample studies should and will be concentrated in the following areas:

¶ The very large surface-to-volume ratio of small grains means that the maximum enhancement of the solar wind and low-energy solar flare and cosmic ray records is found in the finest regolith materials. These will be among the most important samples for investigation of the dynamics and the chemical composition of the solar corona.

¶ Details of the low-energy irradiation record apply directly to such significant lunar problems as the dynamics of regolith development. There is a strong possibility that the record could show regional variations correlating with paleomagnetic field intensity. A low-energy component originating in the lunar atmosphere may eventually yield a measure of the outgassing history of the lunar interior.

¶ A variety of volatile elements and compounds is mobilized from lunar surface materials by solar heating or by thermal pulses associated with impact and volcanic events. Recondensation of some volatiles on grain surfaces provides a means for studying the lunar surface inventories of these species and the details of the transfer processes. The mobilization of Pb provides a powerful chronological tool for the eventual dating of major heating events in the history of the lunar surface.

¶ As pointed out above, a major goal in the study of fine regolith material must be to identify the geologic source regions for components contributed to the soils by various kinds of rocks. It is clear that improved models of grain-transport mechanisms are going to be of key importance in this effort, particularly models of transport by large impacts up to and including the scale of the Imbrium event. A basic question is whether other grain-transport processes, perhaps driven by electrostatic charge separation, are significant in the lateral dissemination of fine-grained silicates over long periods of time.

¶ Reading and interpreting the environmental record in breccias, and in particular in soil breccias, in a reasonably comprehensive way will be fully as challenging and potentially as important as similar studies of the soils. A different and key element of breccia history is the truncation of exposure of the interior matrix grains to the low-energy lunar-surface environment at the time of breccia formation. In order to specify quantitatively the slice of surface history represented in a soil breccia, a way will have to be developed to date the breccia-formation event; efforts to do this have so far not been successful.

Other types of samples that will receive particular attention are:

¶ Samples from the deep crust and upper mantle. Though some clues to the Moon's interior composition will be available from seismic data, only the laboratory study of actual samples can provide sufficiently detailed information (*e.g.* on composition and age) for an accurate reconstruction of the Moon's differentiation history.

¶ Very old and very young rocks. Preliminary examination of samples from the first five lunar landing sites has failed to yield samples older than 4.1 billion years or younger than about 3 billion years, although such material almost certainly exists. There are excellent possibilities that the record can be extended in both directions by comprehensive study of the samples, particularly in the uncharted interval 4.1 to 4.6 billion years.

¶ Ejecta from distant craters. Such material gives compositional information for distant parts of the lunar surface and may make it possible to estimate the date of the impact (which is useful for extending the lunar time scale).

¶ Planetesimal debris. The ancient highlands regolith is likely to contain the debris of objects that fell on the Moon in the final stages of its accretion, including the bodies that produced the mare basins. Chemical and chronological studies of this material may shed some light on the nature of these objects, whether they belonged to one or several populations, and whether any of them were compositionally similar to the Earth or Moon. Some of these materials may also occur in breccias. Here again, the all-important first step will be to trace each component to its source.

Results from Soviet Samples.— The United States and the Soviet Union have exchanged lunar samples and scientific information. The Soviets, using unmanned spacecraft, returned fine-grained soil from the Luna 16 and Luna 20 missions. The principal value of the Russian samples is to extend knowledge of the lunar surface to two more locations, both of which are remote from Apollo landing sites.

As a result of the early Apollo missions, U. S. scientists substantially improved their capabilities for analyzing the very fine particles that comprise the bulk of the lunar soil. This improved technology permitted investigators to conduct highly sophisticated measurements on the few grams of Russian samples that were later made available. The scientific results stemming from analysis of these limited samples are impressive, and enhance our confidence in gaining important results from future unmanned missions, including possible landings on Mars.

New Equipment.— At most participating institutions, the equipment used in the analysis of Apollo samples was designed before Apollo 11 for the initial phase of the work. With few exceptions, this original equipment has provided all of the data from the Apollo sample analysis program. However, this initial analysis will be completed during the post-Apollo phase and certain additional equipment will be required to realize the full benefit of the Apollo program.

This new equipment would include improved versions of instruments now in use, perhaps versions that are based upon new techniques, as well as entirely new types of instruments. The latter are required because the lunar samples have properties that were not predicted and thus require new techniques.

Consider, for example, the surface properties of lunar dust grains. As has been discussed, the individual grains contain in their very outermost layers large concentrations of elements injected by the Sun. If the depth-dependence of these injected elements can be determined, it will be possible to study the past record of the Sun's activity. Many other important phenomena, including the production of hydrocarbons and carbides also appear to be associated with implantation in surface layers.

The current techniques that have been used to study the surface layers include study of chemical reactions, measurement of the temperature-release patterns of gases upon heating, and direct observation by electron microscopy. None of these techniques gives the type of information that is needed to study the important surface phenomena in the required detail.

The final techniques that will be the most useful in delineating the surface properties are now known. However, it is certain that artificial irradiations, using particles similar in composition and energy to those produced by the Sun, will be required. This will probably require new equipment, since no lunar sample investigator foresaw this possibility.

It is also clear that certain relatively new experimental techniques look particularly promising and have a high probability of producing important results when applied to the lunar soil. These possibilities include ion microprobe analysis, heavy charged-particle resonance nuclear-reaction spectroscopy, charged-particle x-ray fluorescence, and Auger electron spectroscopy. New equipment will likely be needed in all these areas.

The example cited could be multiplied many times over in considering the various aspects of sample analysis; the provision of additional instrumental support is thus an essential part of the ongoing science program.

Because the resources that can be devoted to equipment will necessarily be limited, consideration should be given to sharing of equipment by major installations. For example, individual investigators should be encouraged to visit other laboratories to use certain specialized pieces of equipment. Such cooperative efforts should also serve to stimulate interaction between different disciplines.

Supporting Studies.— An eventual goal is to integrate all of the useful knowledge from telescopic studies, photographs, astronaut observations, sample investigations, data from instruments emplaced on the lunar surface or flown in orbit, experiment, and theory. In particular, there is a close interrelationship between investigations of returned samples and the study of the local and regional geology of the landing sites from which the samples were taken.

In the period immediately following each mission, parallel major efforts are required in sample description and preparation of topographic, geologic, and sample-location maps of the site. These efforts are aimed at understanding the events that occurred at each site and the relationship of the samples to the site and of the site to the rest of the Moon. The studies of both samples and the geology of each site during the mission mode period are, however, necessarily preliminary and incomplete for two reasons. First, there is insufficient time to complete the work. Second, the essential feedback and interplay between data on samples and information on site geology cannot progress far until substantial data of both types has been obtained. As this iterative process proceeds, the relationships discovered between characteristics of the samples and the sample sites suggest new investigations of the samples and new information to be sought from the photographs and other records of the sites. Important new questions and new directions of study will continue to arise in the basic-description and problem-oriented periods.

To understand where each sample came from and what events are recorded in it will require a careful unravelling of the post-depositional cratering history of the site. This study starts with a photogeologic study of the landing site to trace crater ejecta blankets and ray-deposits back to their place of origin and to put them in their proper time sequence. Optical studies of the returned samples aid in identifying the various rock types collected in the lunar photographs, thus helping to define the volume percentages of each class of returned sample.

Macroscopic study of rock samples is closely related to investigations of the sample sites and is, at present, quite incomplete. With a few exceptions, the textures of original rock surfaces and structural features, such as layering found in microbreccias, has scarcely been investigated at all. This kind of work requires access to preserved individual rock specimens at the curatorial facility, thorough documentation by close-up photographs, and examination under the binocular microscope. The shape of a rock, and differences in texture of different faces or parts of a rock surface, are closely related to its occurrence on the lunar surface and to the detailed history of fragmentation, erosion, and transport of the rock. Studies of this kind are critical to an understanding of the dynamics of the regolith.

After the initial cartographic and geologic maps are prepared, it is useful to prepare cross sections to show three-dimensional relationships. An intensive synthesis effort must be carried out in cooperation with other investigators to show the relation of the petrology, topography, and ages, etc. of samples to their locations. Exposure ages of rocks and data on cores must be tied to the same three-dimensional network. The maps and sections become case-sheets that many other investigators can use for other studies during the problem-oriented phase.

During this work, the identification of strangers among the samples will lead to a search for their source and, therefore, a limited characterization of that source unit. This will force an extension of the landing site study outward by correlation with photogeologic, topographic, surface-emplaced experiments, and orbital data.

The careful characterization of the landing sites assists in answering the questions of how typical are the units sampled and what are the variations, how extensive are they, and what part of lunar history do they represent? Further, the samples thrown into the sites constitute fragments of other units not directly sampled, and should add important elements to the lunar evolutionary story.

Recommended Policies for Sample Research.— There are two overriding considerations in the future program of lunar-sample research:

¶ Sufficient people of quality must be kept in the program to insure that the major scientific discoveries inherent in the lunar samples be realized in a time at least comparable to the time it took to mount and fly the missions.

¶ The sample-management program should be sufficiently flexible and open to permit the introduction of new people (particularly young people) and new ideas. Lunar-sample research must not be considered as the domain of a closed club.

To maximize the scientific discoveries will require a long and ongoing program in certain, but not all, areas. In the early days of Apollo it was important to perform certain basic measurements in order to adequately characterize the samples to plan science for the ongoing missions. It was also important to test a variety of techniques, including those whose importance for lunar research was uncertain. This situation is now changed. Certain techniques have been tried and have been found not to yield significant information on important scientific problems. And, although the sample collection is still far from completely characterized, at least a set of basic measurements exists. In the future we expect that there will be less need to pursue certain techniques and less need to continue to simply characterize the nature of the lunar samples.

The problem now becomes one of exploiting the sample collection to obtain the maximum amount of information in the general scientific problem areas that we have discussed previously. This goal should be the primary basis for the evaluation of future scientific work.

We propose a system of scientific review and evaluation basically similar to the present structure. Individual research proposals should be judged by a body of scientific peers; this body should include a reasonable percentage of persons knowledgeable about the goals and accomplishments in the lunar program. Scientists outside the lunar program should also be included in the review process.

The decision as to who should be encouraged to continue should not depend on the experimental techniques employed. The primary criterion is the breadth and depth of the scientific output. The same instruments in the hands of different investigators can yield totally different results depending on the nature of the problems attacked and the competence and imagination of the individuals involved.

In areas that are deemed most crucial, there should be two groups at an absolute minimum. Healthy competition will ensure that the results will continue to be produced at a high level of quantity and quality. In certain scientifically important and productive areas it will be important to have more than the absolute minimum of investigators. Still other areas deemed major but not crucial can be covered by single groups.

The present system has designated certain investigators as three year PI's. In this category are included groups with high special competence whose scientific productivity has been clearly demonstrated. We urge that this system be continued. However, these investigators should be annually reviewed (as should all other investigators) for their scientific output to ensure a continuing high level of lunar research.

It would be a mistake to include in the program only those people and those techniques that are known to be productive. A certain fraction of the work should be of a more or less speculative nature, the success of which cannot be guaranteed, but which has the possibility of opening new directions.

The opportunity to propose lunar sample investigations should be promulgated annually and proposals should be reviewed on a continuing basis.

With the exception of certain government laboratories and foreign PI's, lunar sample investigations have been closely linked to funding. It should, however, be possible to propose scientific investigations that require lunar samples but no money. It is essential for the preservation and intelligent use of the lunar-sample collection that such proposals be subjected to the same careful review process, and by the same review body, as those proposals requiring funds.

The stipulation that the reviewing be a continuous process is essential for proposals of this nature. If an imaginative man with an important new idea is faced with a long and cumbersome process in obtaining samples, he may become discouraged and abandon the project before it has been given a chance. This would clearly result in a sterile in-grown program.

By its very nature lunar science is multidisciplinary. Working-groups attacking common problems from several points of view should be encouraged.

D. THE GEOPHYSICAL PROGRAM

Introduction.— By the end of the Apollo 17 mission, we will know a great deal about the lunar interior. Many significant questions pertaining to structure, state and composition of the lunar interior can be answered by further monitoring of the ALSEP network. Some examples are: Does the Moon have an iron rich core? If so, what is its radius? Is it molten? What is the structure of the lunar crust in highland areas? What is the composition of the mantle?

Significant questions also remain with respect to the evolution of the Moon. The Moon is not tectonically inert, but is less active than the Earth. Some questions are: What are the structural manifestations of the Moon's thermal history? What is the origin of the broad variations in the Moon's gravity field: irregularities frozen into the lithosphere or convection currents in the central core? What is the source of energy being released by moonquakes? What is the nature of present degassing?

The Moon has proven to be an excellent place to determine the interplanetary flux of meteorites, using the seismic network. For the first time, it is possible to obtain quantitative estimates of the numbers and masses of meteorites in the kilogram mass range. To fully exploit this, it is necessary to have continuing observations. On Apollo 17, the lunar ejecta and meteorites experiment (LEAM) will monitor fluxes of much smaller particles. It is important to continue the operation of this experiment for some years in order to fully exploit its capability. With the deployment of the last ALSEP station in Mission 17, the Apollo network will have achieved its full capabilities for many experiments.

Man has no control over natural events (moonquakes and meteorite impacts), and the large events that give the most information about the deep interior are rare on the Moon. Significant progress will require the accumulation of data over a period of many years. It is therefore essential to continue the operation of the Apollo Lunar Seismic Network as long as useful data are being obtained. Since we do not know the size, time, or location of meteorite impacts, artificial sources (for which all these parameters are known), are essential calibration points. Hence, all possible opportunities of impacting a space vehicle on the Moon should be examined with a view to providing vitally needed seismic sources. Of highest priority is the location of a man-made impact in the highlands, which would enable a determination of the thickness and elastic properties of the highland crust.

At the same time, it is important to continue laboratory investigations of the elastic properties of lunar and terrestrial samples in order to aid the interpretation of lunar seismic data. It would also be useful to examine photographs of areas overflown more than once, to search for new features possibly associated with meteorite impacts.

ALSEP and Subsatellite Experiments.—

¶ *Charged Particle Experiments.*— The charged particle experiments on ALSEP are designed to solve lunar exterior and interior problems. The CPLEE (charged particle lunar environment experiment) and SIDE (suprathermal ion detection experiment) are means of measuring the lunar atmosphere and degassing of the interior, while the solar wind is continuously monitored by the SWS (solar wind spectrometer). In addition, the Apollo 15 subsatellite continues to produce useful data on particles and fields. Thus a broad spectrum of problems peculiar

Table 1

SUMMARY OF PRESENT APOLLO INSTRUMENTS (INCLUDING THOSE PLANNED FOR APOLLO 17)

LUNAR SURFACE EXPERIMENT ARRAY	DATE OF ACTIVATION	DATE OF TERMINATION
APOLLO 11		
Passive Seismic (ALSEP)	20 July 1969	10 Aug 69 (Command Loss) Jan 70 (Telemetry Loss)
Laser Ranging Retro-Reflector	20 July 1969	Still Functional
APOLLO 12		
Passive Seismic (ALSEP)	19 November 1969	Still Functional
Lunar Surface Magnetometer (ALSEP)	19 November 1969	Failed
Solar Wind Spectrometer (ALSEP)	19 November 1969	Still Functional
Suprathermal Ion Detector (ALSEP)	19 November 1969	Still Functional
Cold Cathode Ion Gauge (ALSEP)	19 November 1969	Failed 14 Hrs After Turn-On
APOLLO 14		
Passive Seismic (ALSEP)	5 February 1971	Still Functional
Active Seismic (ALSEP)	5 February 1971	Still Functional
Suprathermal Ion Detector (ALSEP)	5 February 1971	Still Functional
Charged Particle Lunar Environment (ALSEP)	5 February 1971	Still Functional
Cold Cathode Ion Gauge (ALSEP)	5 February 1971	Still Functional
Laser Ranging Retro-Reflector	5 February 1971	Still Functional

(TABLE 1 CONTINUED)

LUNAR SURFACE EXPERIMENT ARRAY	DATE OF ACTIVATION	DATE OF TERMINATION
APOLLO 15		
Passive Seismic (ALSEP)	31 July 1971	Still Functional
Lunar Surface Magnetometer (ALSEP)	31 July 1971	Still Functional
Solar Wind Spectrometer (ALSEP)	31 July 1971	Still Functional
Suprathermal Ion Detector (ALSEP)	31 July 1971	Still Functional
Heat Flow (ALSEP)	31 July 1971	Still Functional
Cold Cathode Ion Gauge (ALSEP)	31 July 1971	Still Functional
Laser Ranging Retro-Reflector	31 July 1971	Still Functional
APOLLO 16		
Passive Seismic (ALSEP)	21 April 1972	Still Functional
Active Seismic (ALSEP)	21 April 1972	Still Functional
Lunar Surface Magnetometer (ALSEP)	21 April 1972	Still Functional
Heat Flow (ALSEP)	Failed	
APOLLO 17	10 December 1972 (Planned)	
Heat Flow (ALSEP)		
Lunar Ejecta and Meteorites (ALSEP)		
Lunar Seismic Profiling (ALSEP)		
Lunar Atmospheric Composition (ALSEP)		
Lunar Surface Gravimeter (ALSEP)		

(TABLE 1 CONTINUED)

LUNAR ORBIT SUBSATELLITE	DATE OF ACTIVATION	DATE OF TERMINATION
APOLLO 15 SUBSATELLITE	4 August 1971	No Magnetometer Data;
S-Band Transponder	4 August 1971	Partial Particle
Charged Particle Detectors	4 August 1971	Detector Data;
Magnetometer	4 August 1971	Still Functional
		For Gravity Data
APOLLO 16 SUBSATELLITE	24 April 1972	Terminated 29 May 1972
S-Band Transponder	24 April 1972	
Charged Particle Detectors	24 April 1972	
Magnetometer	24 April 1972	

to the physical state of the lunar interior as well as the cislunar plasma (in which the Moon is embedded) can be examined. The problem of the lunar atmosphere and reimplantation of Ar^{40} can, for example, be best understood if one considers the electric fields in the lunar neighborhood that are at least partially a consequence of the plasma environment.

It is clear that the plasma and field environment in the lunar neighborhood represents the archetype of the class of atmosphere and planetary bodies free of dynamo fields, such as Mercury, the asteroids, and planetary satellites lying outside the magnetosphere of the parent planet. Thus, the lunar plasma and magnetic field environment is worthy of study in this broader context.

Little has been learned to date about degassing products from the Moon and we consider this to be a potentially important clue to the nature of the interior. The mass spectrometer to be flown on Apollo 17 represents an important tool for this purpose, and given successful operation of this experiment, long term monitoring for gas-release associated with seismic or volcanic events is important. The interrelation between this experiment and the SIDE and vacuum gauges is particularly important if clear degassing events can be detected.

¶ *Magnetic Fields*.— The magnetometer experiments have been used to observe the profile of interior bulk electrical conductivity from which deep temperature is inferred. The determination of the profile is presently resolution-limited by a restricted body of data. Future analysis of the electromagnetic response of the Moon needs to consider the problem of uniform sources in the solar wind of magnetic fields and the asymmetries caused by the plasma flow. Since the statistical accuracy is to a large extent governed by the available body of data, it is essential to collect future data from the lunar magnetometer. Improvement of the accuracy and resolution of the conductivity profile requires continued acquisition of both LSM (lunar surface magnetometer) and Explorer 35 data. There is hope that with sufficient data the higher order interaction which dominates the crustal response can yield a value for the thermal gradient, a key parameter in determining a global average heat flux.

If Explorer 35 fails, the LSM's can still supply important magnetic field data on the lunar surface. The interpretation of the charged particle experiments requires a knowledge of the magnetic field and its variations. This is a complex issue; charged particle orbits in the thermal and epithermal range investigated by SWS, SIDE, and CPLEE are dominated by the local electromagnetic field.

¶ *Gravity.*— Much has been learned about the Moon's internal heterogeneity, isostasy and crustal rigidity from studying its gravity field with the S-Band Transponder experiment. Detailed gravity information about many local features (*i.e.*, craters, mare, highlands, etc.) including structure of the mascons has been acquired by the Apollo 15 subsatellite. Long-period acquisition of the subsatellite data will also enable, in combination with Lunar Orbitor data, a refined determination of the moments of inertia. This information, in turn, would place more stringent limits on core size and density. We urge continued acquisition of these data for at least another three years, the time it will take the low pericenter to sample the entire accessible part of the Moon. The surface gravimeter placed by Apollo will yield information on the tidal responses of the Moon, which may be a significant increment to the seismological information. However, continued operation for several years is necessary to determine satisfactorily some of the tidal periodicities. The major tasks are, however, in data analysis and interpretation, as discussed below.

¶ *Laser Ranging Retro-Reflector.*— There are three retro-reflectors now in place on the lunar surface, in a triangular network. The main scientific results that will be obtained fall into two categories: study of the physical motions of the Moon and study of motions of the Earth. The refinement of the motion of the Moon ideally requires continued monitoring of the retro-reflector network from one major Earth-based telescope over 18.6 years, the period of nodal revolution. Analysis of these data to determine the physical librations will yield improvements in our models of the elastic and dissipative properties of the Moon.

> The retro-reflectors also provide an important method for studying motions on the Earth, including continuous monitoring of phenomena such as the Chandler wobble and sea-floor spreading. These observations require the use of several laser telescopes on the Earth. In order to exploit this most fully, it will be necessary to continue to develop low-cost laser telescopes that can be dedicated primarily to obtaining these observations.

Data Analysis.— Certain Apollo systems have generated and will continue to generate an abundance of data that requires considerable thought and experimentation, as well as routine processing, to be exploited fully. Under the press of mission responsibilities only a preliminary analysis of these data has been achieved. With the continuing return of data from the entire ALSEP network (including Apollo 17), data processing and systematic interpretation will require major efforts in the coming years. For example, inferences concerning the distribution of internal electrical conductivity from lunar interaction with the solar wind still require more elaborate physical modeling of the Moon *and* the solar wind, as well as more sophisticated statistical analyses. Accurate determination of the harmonic coefficients of the gravitational field will require computer experimentation to get the optimum solution. Dependent on these orbital analyses are a better value of the moment of inertia, which is the primary constraint on density distribution, and improved measurement of the external shape of the Moon, through altimetry and through photogrammetric analysis of the metric photography. The resulting control system is the basis for a detailed map compilation.

Supporting Studies.—

¶ *Geologic Site Studies.*— To draw inferences about the lunar interior from geochemical data, detailed analyses should be made of the geological setting of the samples collected at all Apollo sites.

¶ *Laboratory Experiments.*— The most important eventual result of geophysical measurements on the Moon's surface and from circum-lunar orbit should be definitive determination of the composition, physical state, and temperature of the lunar interior. To infer temperatures and compositions from seismic velocity and electrical conductivity data, laboratory measurements are needed on likely lunar materials at comparable temperatures and pressures. Thus far, most of the inferences made have been based on laboratory data obtained from measurements of terrestrial rocks. In view of the greatly different conditions of formation (such as the absence of water), it is important that these measurements be done on suitably synthesized material or if necessary on lunar rocks.

One of the greatest puzzles in the lunar data is the remanent magnetism. Further laboratory work on lunar samples is necessary to infer the origin of this magnetization and the strength of the magnetizing field. In addition, there should be experimentation with possible magnetization mechanisms which might be important in the particular environment of the Moon but which have had little consideration in terrestrial palaeomagnetism.

To provide a background for models of lunar evolution, a more detailed chemical classification of lunar materials must be developed. Laboratory work is needed for this classification, including not only analyses of lunar rocks, but also meteoritic and terrestrial specimens for purposes of comparison.

¶ *Systematic Apollo Site-Science Synthesis.*— Each Apollo site has been the object of intensive multidisciplinary studies. These investigations need systematic integration for each site with a view to:

(a) Compiling all data of a given type produced by different investigators.

(b) Compiling data from different types of investigations on the same or related suite of samples.

(c) Completing the sample analysis coverage by different investigators so as to provide an adequate picture of all important geologic, geophysical, and geochemical parameters.

(d) Providing a multidisciplinary interpretation of the total physical, chemical, and geological character and evolution of the local region samples.

(e) Providing a multidisciplinary interpretation of the major geophysical environment at each site.

¶ *Theoretical Modelling and Syntheses.*— Theoretical formulation of models to synthesize new information about the Moon obtained during the Apollo program is still in a formative stage. Mathematical models used to discuss the data on the Earth may be too limited because the relative roles of pressure and temperature are different in the Earth and in the Moon. A more fundamental discussion of the thermal history of the Moon taking into account all physical processes of heat generation and transfer is required. Density stratification of an initially heterogeneous body, and the differentiation processes, should be investigated mathematically. Techniques for the mathematical analysis of electromagnetic, seismic, and tidal response of a heterogeneous Moon must be developed. Inverse-problem formulations, as applied to the above problems, are also needed. Further study of the dynamo theory of the generation of planetary magnetic fields is needed especially with regard to lunar applications.

Recommendations.—

¶ We urge the continued monitoring of the ALSEP stations and the remaining subsatellite for the next 5 to 10 years depending on the lifetime of the experiments and the significance of the results.

¶ The program so far has lacked a scientific advisory panel similar to LSRB and LSAPT for the ALSEP and surface experiments. Because of the large irreplaceable data-reservoir being generated and the importance of this information to lunar studies, *we recommend* that a scientific advisory structure be set up to review proposals, operations, data-reduction, and analysis. This panel would consider ALSEP and other relevent experiments and would review them periodically or when there were significant status changes either planned or due to instrument failures.

¶ The continued operation of the lunar network should be as a long-term NASA facility. This mode requires that data be recovered, formatted, and documented in a way that makes it readily available for all approved investigators. It is important that adequate funding be committed to ensure that this program is properly carried out.

¶ Further scientific analysis of the data being returned by the lunar network should include ongoing studies and interdisciplinary studies. Proposals for this scope of work should be reviewed by a scientific advisory panel.

¶ The science community should be encouraged to conduct theoretical and model studies with data already available. Work on the relevant physical properties of lunar samples and Earth analogues is needed.

E. THE REMOTE SENSING PROGRAM

Introduction.— Remote sensing of lunar characteristics naturally divides into two sets of investigations; those done in lunar orbit and those done from the Earth (including observations from balloons and Earth satellites). Investigations done from lunar orbit have the capability of covering large areas—for a polar mission of sufficient duration this is the whole Moon. Ground-based remote sensing can deal with the whole front face and is not restricted to mission-oriented timing. Many such observations are currently under way and are fruitful and inexpensive.

There is an essential complementarity between the science done at the surface, at specific landing sites, and that carried out through remote sensing. The remote-sensing data extend our surface findings, taken on a tiny and not necessarily representative fraction of the Moon, to much broader regions. They allow us to learn what is typical and general, as well as to provide a map of regions or provinces with special characteristics. The surface findings validate the remote data by providing "ground truth." Detailed examination of surface material makes it possible to achieve a real understanding of the properties observed remotely so that interpretation can reasonably go beyond the stage of evaluating isolated physical or chemical parameters.

Orbital Measurements — A major unknown is the distribution of geochemical provinces on the lunar surface. The surface soil samples so far taken are dominated by three major geochemical components. Mare basalt, a basaltic material rich in trace elements (KREEP), and a Ca- and Al-rich series of anorthositic affinity have been seen in varying proportions in the samples so far returned. The Apollo 15 and 16 orbital x-ray and gamma-ray sensors have defined regions apparently dominated by each of these components in the restricted areas overflown. This includes approximately 20 percent of the lunar surface, all within the band from 30° N to 30° S.

Patterns in the orbital geochemical data indicate that lunar radioactivity is concentrated in the maria of the western front face. Generally the Al/Si ratio is high in the highlands and low in the maria (*cf.* Fig. 1, p. 8).

If we can safely generalize from the patterns of the areas so far mapped, we can ask the following questions: How did this surface distribution arise? How were they initially distributed and how has that distribution been modified by later events? The answers may be a key to the origin and evolution of the Moon. The studies will certainly require correlation with photogeologic mapping and with various geophysical sensor data.

Electromagnetic exploration from orbit has consisted of the multi-frequency bistatic experiment flown on Apollos 14, 15, and 16. The surface electromagnetic probe and the orbital imaging radar planned for Apollo 17 have high potential for probing the surface to a depth of a few kilometers and answering basic questions about layering, crustal structure, and the size and extent of suspended blocky material.

Several comparisons have been made between bistatic data and other results. For example: the bistatic slope data have been correlated in detail over several limited areas with photogrammetric work, to the extent that it is now known that the slopes deduced are measured over a scale of approximately 200 radio wavelengths. Further, comparison with photogeologic maps shows that this radar technique can map lunar topography with 10-meter resolution to high accuracy irrespective of terrain type.

There is clear evidence that further comparisons are needed, for the radar data cover certain limited areas which exhibit a frequency-dependent scattering response. The interpretation is not clear. The radar data alone will not produce the answers; detailed comparisons must be made with all available photographic, electromagnetic, and chemical-composition data.

At the end of the Lunar Orbiter Program, a large quantity of photographic data was on hand that served as the basis for scientific investigations of the Moon. Charts and maps were produced showing the probable regional distribution of rock units and their relative ages. Such studies were highly useful in selecting Apollo landing sites.

From an analysis of Apollo photographs and of laser altimeter data, it is possible to make maps showing local relief, regional slopes, and the precise shape of the Moon along the whole orbital track. For the first time, the photointerpretation of the kinds of rocks and their distribution can be plotted on a topographic base map. In addition, the geochemical data and magnetic and gravity data can be cross-correlated with photographic textures and the topography.

Measurements from orbit of the magnetic fields in the vicinity of the Moon have shown that remanent magnetism is measurable essentially everywhere in the 30° N to 30° S region so far covered. They suggest that its distribution is related to surface features.

These measurements also show that the Moon interacts electromagnetically with its charged-particle plasma environment. Also, in conjunction with simultaneous surface measurements, they have provided models of the distribution of electrical conductivity throughout the Moon.

The Moon is a unique plasma laboratory which cruises through the solar wind and the Earth's magnetotail. The interactions present cannot be duplicated in an Earth-based laboratory. Their understanding contributes to our understanding of the Earth's plasma environment.

Several additional major problems can be addressed in the post-Apollo period using the information obtained by the orbital sensors.

¶ Study of the geochemical and geophysical differences between the lunar near side and far side may allow us to distinguish among the hypotheses that the differences are due to (a) inhomogeneous accumulation, (b) early differentiation, or (c) long continued differentiation and evolution.

¶ Study of the lateral inhomogeneities and differences among the various highland terrains and mare lava fields may permit us to distinguish between regional and local scales of chemical differentiation.

¶ Study of the distribution of the magnetic deviations and gravity anomalies may clarify the origin and evolution of mascons.

¶ Study of photographs and other data on sinuous rilles may help to determine their origin, and their role in formation of the lunar crust.

¶ Study of the texture, patterns and distribution of great landslides like the ones at Tsiolkovsky and Taurus-Littrow may clarify the role of gravity sliding and mass wasting in the shaping of the lunar surface.

Ground-Based Measurements.— Ground-based observations of the Moon can be currently divided into studies of reflected solar radiation, emitted thermal radiation, and radio wavelengths. Each spectral region yields a different type of information on the lunar surface.

Analysis of the spectral distribution of reflected radiation (0.35 to 2.5μ m) from the Moon provides information on the surface mineralogy (primarily the pyroxene composition), on the crystal/glass ratio in the soil, and on the titanium content of the glass phase. Telescopic observations of each of the landing sites yield reflectance curves that are in close agreement with reflectance measurements made on returned samples. This finding permits extension of knowledge about surface composition from the limited areas of the landing sites to the rest of the front side of the Moon. Integration of telescopic observations with measurements of lunar samples had led to the following conclusions:

¶ Pyroxenes in the mare basalts are on the average more calcic than those in the highland rocks this observation holds on a regional basis.

¶ Highland and mare soils were not derived exclusively from their respective underlying rocks, but are partially contaminated by one another. Impact mixing of soils has occurred on a regional basis; however, it has not completely destroyed areal compositional contrasts.

¶ Glass is a ubiquitous component of lunar soils; the amount of glass is a function of the length of time a given surface has been exposed to micrometeroid bombardment. Bright fresh material generated by impact decreases in albedo with time due to the addition of glass to the soil. Titanium is the main agent that causes lunar glass to be dark. Dark glass, in turn, is a major contributor to the darkness of the soil.

¶ Mare background surfaces, mare bright craters, highland background material and highland bright craters each have characteristic spectral reflectance curves. This result has, for example, led to the conclusion that the craters Copernicus and Aristarchus both expose highland material, suggesting therefore that they have penetrated the mare fill.

Polarization measurements at visible wavelengths together with consideration of the Moon's photometric function support the idea that a fine-grained soil is ubiquitous over the lunar surface, but that many relatively fresh craters expose fields of blocky material as well.

Observations of emitted radiation from the Moon have been of three types:

¶ Determinations of surface temperature and cooling rates during lunations and eclipses.

¶ A search for *reststrahlen* bands.

¶ Determination of the Christiansen frequency.

Temperature maps have been made of the front side of the Moon at several phase angles and during eclipses with a precision on the order of a degree centigrade and with a spatial resolution of approximately 10 km. These data have shown that temperature differences and cooling rates are controlled by the amount of exposed rock and by the geometry of the surface.

Reststrahlen bands, arising from Si-O resonances in the silicates and indicative of gross-rock composition, have not been unambiguously identified in remote observations of the lunar surface. The absence of these bands is due principally to the finely particulate nature of the lunar soil. However, heated silicate powders, including the lunar soil, have an emittance maximum in the spectral region of 6-9 microns. This maximum, known as the Christiansen frequency, is related to gross-rock composition. A few balloon-borne measurements of the lunar surface show a thermal maximum that correlates well with lunar sample measurements.

Of the observations in the thermal infrared regions, the measurements of the Christiansen frequency are of special interest. They appear to provide compositional information that is distinct from any other remote measurement.

Recommendations.— Orbital remote-sensing experiments have produced a large body of data. Although each experiment has its own, unique data-reduction problems, most of the data can be processed to the point of scientific analysis. It is now clear that while most of the computational effort can be completed in the first year post-mission, there will be important work to be done after that time. While each experimenter probably can reduce his sensor information to an "in-house" usable form in the first year, to make it intelligible and complete for other research groups will require an additional support period of about two years. Continuity is important, particularly in the immediate post-Apollo years, for data available only to the "in-house" level may be lost ot other investigators.

¶ *We urge that support be provided for basic description of the data returned by the Apollo missions.* This will entail the following tasks: reduction and analysis of the geochemical orbital data; processing of the photographic data; and preparation of maps for support of geological, geophysical, and geochemical studies.

The study of photographs and allied remote-sensing data is a major effort in itself. Two modes with different time frames are recommended.

(1) Preliminary Studies

(a) Photographic mosaics at a scale of 1:1,000,000 constructed of all metric photography. Selected large-scale maps of critical areas constructed with minimal selenodetic control.

(b) Photogeologic maps and preliminary plotting of remote-sensor data. Both of these tasks can be completed in 1 year.

(2) Detailed Studies Done in Parallel with the Preliminary Studies.

(a) Construction of a metric control-network incorporating the laser altimetry data. This task would require about 1½ years.

(b) Construction of low and high-resolution contour maps at scales of 1:5,000,000 to 1:250,000 from all metric pictures, and at scales of 1:100,000 down to 1:10,000 from selected panoramic photographs, based on preliminary studies.

These maps should be largely finished in roughly the following $1\frac{1}{2}$ years.

(c) Photogeologic mapping, integration of remote-sensing data, and synthesis, to be completed in the following two years. The total period is approximately five years.

It is hard to predict further into the future. It may be that, at the end of five years, the work will have been sufficiently integrated into the general body of scientific knowledge that its support can be phased out as a specific NASA responsibility.

The importance of continuing ground-based observations throughout this period must be strongly emphasized. Observational techniques have been rapidly improving at both optical and radar wavelengths. It is highly desirable that all of these observations be integrated with the Apollo results.

Ground-based radar measurements of the lunar surface have produced detailed maps at several wavelengths. The maps are picture-like in quality and produce an image both of the surface and the near surface to depths of many meters at some wavelengths. The combination of Apollo orbital and surface results with the radar data should make detailed interpretation in geologic terms possible. When combined with the extremely precise topographic work now possible with very long baseline interferometry techniques this will mean that nearly the whole front side of the Moon can be mapped and tied back to known surface conditions. Second, the cross-calibration produced will be very valuable to the planetary program and man's understanding of the planetary system.

¶ Ground-based studies are becoming increasingly productive of new information, and are a remarkable economical way of getting new types of knowledge about the Moon. *We urge continued support of the ground-based program of lunar observations.*

¶ Remote sensing methods are in their infancy

> as tools of planetary exploration. In a very real sense the Apollo remote sensing experiments are serving to provide the first good test of concepts which will be central in future solar system exploration. *Continued effort to maintain experimental competence in this area is essential.*

F. CURATORIAL FACILITIES FOR SAMPLES AND THE DATA ARCHIVES

The collection of lunar samples, instrument data, and photography from Apollo is a unique and irreplaceable resource that must be zealously conserved, yet also made available for scientific study. The nature of this task is outlined in the following paragraphs. *We recommend steps to ensure both the conservation and availability of these resources.* In a period of budgetary stringency, it is important not to overlook the necessity of access services, as no other elements of the program can proceed for long without them.

Lunar Sample Curatorial Facility.— At the close of Apollo, there will be available for scientific study approximately 300 kilograms of lunar materials, consisting of perhaps 20,000 individually identified samples. As materials are studied and returned by investigators, the number of subsamples which must be cataloged and stored will increase markedly and, eventually, several hundred thousand subsamples will exist.

Degradation of the sample collection can be minimized only if proper storage conditions and handling procedures are maintained. To retard reaction with the atmosphere and to reduce the hazard of chemical contamination, most lunar materials are presently stored under dry nitrogen in glove-box cabinets. Materials returned by investigators are stored in ways consistent with their history.

We recommend that the highest priority must be given to the preservation of the lunar sample collection under controlled conditions in the facility at MSC. Within the scope of this recommendation, it is imperative that the present facilities for storage and handling of lunar samples in protected environments must be maintained; and that access to the collection must be carefully controlled and must follow established procedures.

Evaluation of the degradational effects of storage procedures, improvement of the procedures and facilities, and documentation of unpreventable degradation must be a continuing activity.

During the mission mode, the study of samples has been limited largely to (1) the preliminary examination of samples as they are received and (2) samples provided to investigators. All materials will not have been described even in cursory ways by the end of Apollo 17. We recommend that the sample collection must be thoroughly studied to achieve a standard minimum level of description and documentation.

Specifically, after Apollo 17, with the help of members of the PI community, the curatorial staff should undertake a program of redescription of samples to bring the descriptions to a standard minimum level. Preliminary examination work, such as initial opening and description of lunar core tubes, must be completed.

Although the number of investigators may diminish as routine characterization of samples is completed, the sophistication of sample requirements will certainly increase. Support for inspection of samples in the curatorial facilities and for preparation of special samples for investigators must be maintained. *It is essential* that facilities and staff be maintained to provide for detailed studies by principal investigators. Specifically, *we recommend* that

¶ The curatorial facility should be maintained at approximately its present level for preparation of materials to sample investigators.

¶ Procedures for working with lunar samples must be maintained, and all persons working with samples in the curatorial facility must be trained in their use. Detailed documentation of sample processing must be continued.

¶ When the Apollo 17 sample distribution has been completed, steps should be taken to establish within the curatorial facility a special area where investigators can personally examine samples under the controlled-environment conditions without interfering with other curatorial responsibilities.

¶ A library of microscope slides of lunar samples must be maintained for inspection in the curatorial facility and for circulation to investigators.

Documentation of the sample collection is now undertaken at three levels: (1) Sample descriptions and data, (2) sample history information, and (3) sample accountability information.

The sample descriptions that have been circulated in the form of preliminary sample catalogs have been derived from examinations conducted in limited time periods following each mission and are not uniform in information content. A wealth of information has been gained in the detailed scientific study of the samples, and it must be integrated with the original descriptions. Sample histories are maintained, but they are not available in organized form for many Apollo 11 and Apollo 12 samples. *We recommend* that unified sample catalogs should be prepared, incorporating descriptive data obtained in the preliminary examination and any reexamination in the curatorial facility, as well as selected descriptive information resulting from PI studies.

In addition to the catalogs, it is also important that:

¶ Indices to available photographs, descriptions, analytical data and published information should be prepared.

¶ Sample history information be maintained, including information on samples returned by investigators, to ensure that appropriate samples are provided for future generation experiments. Information for samples handled in early parts of the program must be brought to a standard minimum level of uniformity.

¶ Sample accountability information must be maintained to provide control over the distribution of materials.

Displays of samples are now prepared in response to requests by the Public Affairs Office, NASA. The samples are accompanied by meager descriptive information. The Office of the Curator does not presently carry on any other programs of an educational nature.

We recommend that a more active policy of sample display and documentation be undertaken. Lunar sample displays should be upgraded to establish the importance of samples to science, by the developments of high quality descriptive information. Procedures should be developed, such as circulation of microscope slides to universities, by which lunar material and information can be made available for educational purposes. A lunar sample museum should be established, probably at MSC. The samples would tell the story of lunar science through the use of selected lunar samples. Furthermore, informative pamphlets, books, and news releases should be proposed to acquaint the scientific community and the public with opportunities and accomplishments of the lunar science program.

Depository and Data Retrieval Methods for ALSEP and Orbital Data.— The original FM data tapes (*i.e.*, the range tapes) are shipped from the network receiving stations to the data-processing center at MSC. At MSC, data for each experiment are stripped from the range tapes and formatted to produce sets of data tapes compatible with a general purpose computer. These tapes are shipped to each of the principal investigators for analysis. The original range tapes are then shipped to the National Space Science Data Center (NSSDC) at Goddard for long term storage. In storage, the range tapes have a shelf life of about 20 years. New digital data tapes can be made from the stored range tapes, if required. However, selected sets of the formatted digital data tapes must also be stored since they constitute the basic data to be supplied to investigators.

Assuming the continued operation of the ALSEP stations, several thousand digital data tapes per year will be acquired from the various orbital and surface experiments. It is impractical to maintain a complete library of digital data tapes for all experiments and to regenerate these at two-year intervals, which would be required to ensure their continued fidelity. However, much can be done by the experiment teams, which have been responsible for the major data-processing effort, to reduce the volume of digital data deposited in an archive to a manageable level without elimination of important data. For example, nearly all experiments have had intervals of anomalous behavior during which the output data are seriously degraded. These data can be removed from the archive set. In other cases, such as the seismic experiment, transient phenomena (moonquakes and meteorite and man-made impacts) are of interest. These represent a small fraction of the total volume of data and, once identified, can be stored on "event tapes" for use by other investigators.

We recommend that the principal investigator for each experiment

¶ provide a complete description of the experiment including the hardware, its performance capabilities, and calibration data;

¶ define the data set to be provided to the central repository for distribution to other investigators, and prepare and submit the data within one year after initial receipt of the data;

¶ publish a user-oriented quarterly "Experiment Bulletin" (or "Mission Bulletin," where appropriate) describing instrument performance, anomalies in performance, and events of particular significance that occurred during the period covered by the Bulletin;

- ¶ conduct symposia designed to acquaint potential investigators with the details of the experiment, limitations of the data obtained, and the nature of the data-set provided for distribution.

We further recommend that data from orbital and surface experiments be stored and maintained by NSSDC, which should

- ¶ be responsible for proper storage of data and rapid response to scientists' requests for use, where such requests are in accord with an approved study;

- ¶ publish and distribute supporting materials prepared by the principal investigators as described above;

- ¶ appoint a representative for each experiment who would be cognizant of the details of the available data and who would serve as a point of contact with the NSSDC for a given experiment.

Photographic Records.— In addition to Earth-based photography of the Moon and to the photographs obtained by the unmanned Ranger, Surveyor, and Lunar Orbiter spacecraft, the Apollo missions will have returned some 30,000 photographs of the lunar surface. About half of the Apollo photographs will have been taken with the Hasselblad cameras on Missions 8 through 17, both from orbit and on the surface. The other half are the photographs of the Metric cameras (over 10,000) and the Panoramic cameras (about 5,000) that will have been flown on Apollo missions 15, 16, and 17.

Only a negligible fraction of the photographs has been studied in detail, primarily in support of Apollo mission operations. Also, most of the Metric and Panoramic camera data are yet to be reduced to a usable form. The storage and processing facility at the MSC photography laboratory is inadequate to meet all of the requirements for preserving the Apollo photographic material for the post-Apollo period, partly because of other NASA programs.

Because of the urgent need to assure preservation, documentation, and dissemination of the photographs, *we recommend* establishment of an Apollo photographic archive closely associated with the MSC photographic laboratory. (The National Space Science Data Center at Goddard, Maryland, should be maintained as a photographic depository for general public use.)

This new organization should be responsible for:

¶ Storage and preservation of the original Apollo flight films, making them available for scientific measurements. (The original flight film is presently unaccessible to the scientific community.)

¶ Accessible storage of 2nd- to 4th-generation film negatives and positives, as well as paper prints of all available photography.

¶ Distribution of photographic material to principal investigators. (This activity will require the continued support of the photographic laboratory.)

¶ Documentation and description of the photographic records and their quality.

The organization should be staffed with trained technicians who understand the scientific value of the photography as well as its limitations.

We further recommend continuation of the systematic reduction of Metric and Panoramic camera records for making topographic maps and related products. The Metric camera data should eventually be utilized in making:

¶ Orthophoto maps of all the overflown areas at 1:250,000 scale with 50-200m contours, and keyed to the Lunar Aeronautical Chart (LAC) system (about 600 sheets).

¶ New base maps of LAC areas covered by the Apollo 15-17 photography at 1:1,000,000 scale with 100-400m contours (about 20 LAC sheets).

¶ A controlled photo base at 1:5,000,000 scale for correlation of remotely-sensed data (one sheet).

The Panoramic camera photography should eventually all be rectified to allow making:

¶ Uncontrolled photomosaics of high resolution quality.

¶ A limited number of large scale maps at 1:10,000 to 1:50,000 with 10-100m contours of special areas that require detailed study.

We recommend that combined indices and catalogs of all Apollo photographs and related products be compiled and widely distributed. Readily accessible catalogs would remedy the virtual lack of knowledge of the available material and its utility, and it would encourage a wider participation in photographic analysis and interpretation.

Publication Centers.— The panel recommends that

¶ A periodic publication similar in scope to the "Lunar Science III" (Revised Abstracts of the papers presented at the Third Lunar Science Conference) be instituted in order to ensure publication of much analytical data that otherwise would not appear in the literature. This should be a referencable periodic publication consisting strictly of research findings.

¶ A complete set of journals, reprints, preprints, and special documents and publications dealing with lunar science be collected in at least one library. A periodic listing of new additions should be made available to all who are interested.

¶ A center be established for storage and retrieval of *all* published and unpublished lunar scientific data. The center would receive reduced research data from all PI's in form of preprints and reprints, and it would ensure that all lunar data are entered into an archive. Storage in a computer is potentially desirable to facilitate retrieval of data. Before a system of data storage is chosen, NASA should explore in detail the needs of the scientific community.

G. ADVISORY COMMITTEES

The involvement of non-NASA scientists in advisory groups has worked well, providing an excellent flow of information at operational levels between NASA-MSC and scientific community. We have looked into the advisory needs of the post-Apollo lunar program, and offer recommendations to adopt the present committees to the post-mission period and to improve liasion where possible.

A summary of advisory committees to the present lunar program appears as Appendix C to this Report. We note that the policy-level committees — the Physical Science Committee of SPAC and the Space Science Board of the NAS — adequately represent lunar science. Further comment on these groups is beyond the scope of this study. We will deal with the advisory groups at the operational level — the Lunar Sample Analysis Planning Team (LSAPT) and the Lunar Sample Review Board. We will recommend additional groups at this level.

Lunar Sample Analysis Planning Team.— LSAPT is currently responsible for recommending detailed plans of allocation of lunar samples to PI's for study. These allocations are based on a continuing assessment of the state of progress in characterizing the samples in the lunar collections, particular gaps in our understanding, and important opportunities, the abundance or scarcity of each type of sample in the collections, and the interests and capabilities of all the PI's in the program. We consider that the allocations are performed most knowledgeably by a committee of sample investigators, and that it is desirable to have the process of allocation and distribution clearly visible and accessible to the community of sample investigators, as it is under the LSAPT advisory arrangement.

In addition, LSAPT monitors procedures and equipment in the LRL and Curatorial Facility, as they effect the integrity of lunar samples. This requires the continuity of effort of a standing committee, relatively frequent meetings at MSC, and a close relationship between the committee, the Curatorial Facility, and the MSC Director of Science and Applications.

We recommend that an advisory committee (LSAPT or its successor) of sample investigators from outside NASA be continued to advise NASA on lunar sample allocations and on the welfare of the lunar sample collections.

Lunar Sample Review Board.— The LSRB as a Lunar Science Institute committee, is currently responsible for evaluation of research proposals submitted by scientists wishing to study lunar samples. The LSRB recommends on acceptance or rejection, and priorities of the various research projects. LSRB periodically reviews the broad outlines of the sample analysis program, and identifies overworked areas where redundant investigations can be eliminated, as well as thinly populated but important areas, where additional investigators should be encouraged to apply. We consider that proposals are most knowledgeably evaluated by scientists with backgrounds similar to those of the proposing investigators, and that it is desirable to have the process of proposal review clearly visible to the community of sample investigators, as it is under the LSRB advisory arrangement.

We recommend that an advisory committee of scientists from outside NASA (LSRB or its successor) be continued to advise NASA on the relative merits of lunar sample research proposals, and to review the scientific productivity of the lunar sample program.

Several new classes of lunar science proposals are anticipated, especially those concerned with analysis of lunar surface and orbital data (beyond the original PI's who acquired the data), and data synthesis proposals. We consider that these proposals ought to be handled in a manner similar to lunar sample proposals and that it is equally desirable to have these proposals reviewed in a way that is visible to the scientific community.

We recommend that the responsibilities of the committee that reviews lunar sample proposals be expanded to include proposals to study lunar surface and orbital data and data-synthesis studies, and that the membership of the committee be appropriately modified.

The LSRB and LSAPT procedures for maintaining perspective and preventing conflicts of interest have worked remarkably well. However, in a period when priorities are changing and competition for support is becoming sharper, *we recommend* that the advisory groups conduct careful reexamination of their procedures to ensure the integrity of the advisory system with respect to conflict of interest questions. To this end, it seems desirable that about half of the proposal-reviewing committee should consist of persons from outside the lunar sample analysis community.

In addition, where major program areas require critical review, *ad hoc* panels should be convened from time to time to provide the broadest possible perspective. A particular need now exists to obtain an assessment of the health of the program in the areas of bioscience and physical properties: *we recommend* that the LSI bring together special panels composed largely of non-program PI's to conduct this assessment.

Advice Regarding Geophysical and Photographic Data.— The Apollo program has yielded assets other than lunar samples: functioning geophysical observatories on the Moon and in orbit around it, accumulations of surface and orbital geophysical data taken over a period of three years, photographic and chemical surveys of the lunar surface made from orbit. No plan has been made to integrate the studies of these bodies of data, no steering committee has been set up to monitor the day-to-day activities of the geophysical stations, and we need to consider whether adequate provisions have been made to reduce all the data and photographs to usable form and to store them in such a way that they will be preserved for and accessible to future generations.

Analogous responsibilities in the lunar sample program have been assigned to LSAPT. We believe that similar committees operating in the data and photographic areas would maximize the scientific return from these resources and would act to ensure their preservation. *We recommend* that the MSC Director of

Science and Applications form standing advisory committees of non-NASA geophysicists, geochemists, photogeologists, and photogrammetrists, which would:

¶ Examine present plans for reduction and archiving of data and photographs and recommend procedural changes as needed.

¶ Continuously review the operation and state of health of ALSEP stations and subsatellites and recommend on their useful lifetime and level of operation.

¶ Organize broad integrated studies of the lunar data and photography.

Advice to the Program Office at NASA Headquarters.— Lunar science is represented at NASA Headquarters by a lunar program office. At present this office has insufficient liaison with members of the advisory committees and from the lunar science community in general. At MSC, operations related to lunar science have benefited greatly from the free flow of ideas and opinions between scientists and management, made possible by the present advisory system. We believe that a similar dialogue between NASA Headquarters and the lunar science community (through their representatives on an advisory panel) would benefit both parties. *We recommend* that the lunar program office, NASA Headquarters, form an advisory committee of non-NASA scientists from the lunar program. We consider it appropriate that part of the membership of this Headquarters committee should be drawn from the several MSC committees discussed above (and which are concerned with sample allocations, proposal review, data, and photography), since members of these operational committees are closest to the problems and opportunities of lunar science at any given time.

The committees discussed would exercise substantial influence in the field of lunar science (as those now in existence have in the past), and pains must be taken to prevent an in-group of senior scientists from monopolizing the advisory structure.

H. RELATIONSHIP OF LUNAR STUDIES TO OTHER SCIENCE

Much of the fundamental knowledge needed for an understanding of the Moon has traditionally come from other areas of science: geology, meteoritics, astronomy, etc. It is expected that this dependence will continue during the post-Apollo period, as new facts accumulate and new problems come into focus. In addition, many of the findings and techniques of lunar science have implications for other fields.

Two main types of interaction exist between lunar science and other areas of science:

¶ Lunar studies have something to offer to other sciences. This spin-off extends to numerous activities, including basic physics and chemistry, as exemplified by major improvements in trace analysis for elements (such as Pb) used in dating studies.

¶ Other disciplines contribute to lunar studies. Examples have included particle physics and experimental petrology.

All the post-Apollo science (*e.g.*, analysis of lunar samples, data from instruments on the lunar surface, photo analysis of surface and orbital photography, etc.), would benefit from greater exchange of information between lunar scientists and the overall scientific community. One way in which this might be effected would be through co-sponsorship by NASA of suitable meetings. This type of activity is especially appropriate in the absence of mission constraints. One example of the "gaps" it would be desirable to close is that between lunar research and studies of other bodies in the solar system. For example, there is at present very little dual membership in the Apollo and the Mariner and Viking programs. The administrative structure of the lunar program in NASA Headquarters should be arranged to maximize communication with the planetary program.

Terrestrial and meteorite analogies have been demonstrated to be essential for the interpretation of the lunar data and an understanding of lunar processes. Certain experimental and theoretical studies such as high-temperature chemistry and ion-implantation and cratering mechanisms are of proven relevance. Such work is most fruitful when carried out as an integral part of, or in close coordination with, the corresponding lunar studies. It is important to the success of the post-Apollo program that this dovetailing be maintained and improved. The distinction between Supporting Research and Technology (SR&T) efforts and the actual work with Apollo data and materials is becoming increasingly artificial. Since the rapidly-developing understanding of the Apollo data will obviously be the best basis for future lunar exploration, most of the functions of the SR&T in this area should be re-evaluated at an early date. *We recommend* that lunar science in the post-Apollo period maintain its broadly based interdisciplinary character. Selected critical investigators in meteoritics and Earth science should continue to be included in the program in support of the overall objectives of lunar and planetary research.

The relevance of bioscience to lunar studies has changed as a result of the Apollo findings. *We conclude* that although continued routine searches should be made for viable or fossil micro-organisms and organic compounds of biological significance there appears to be no justification for any substantial effort in this area.

Quarantine of the first lunar samples was justified by the idea that any nation bringing back extraterrestrial material had an obligation to the world to be certain that it was not harmful. It is essential, however, to reduce the substantial amounts of material used in quarantine studies. In the future there is a possibility that Martian samples may be brought back to Earth. Quantities are certain to be smaller than those obtained from the Moon. The lesson of the lunar quarantine should be clear; tests should be much more efficent without reducing the ability to detect pathogenic agents. *We recommend* that a report be prepared summarizing the experience and technology of the recent lunar quarantines and that NASA utilize this experience to improve its quarantine procedure for future materials.

There is justification for using the only sterile extraterrestrial samples now available (the lunar samples) for tests of life-detection devices (Viking) to be sent to other planets. Such request for lunar samples, as with all others, should be evaluated by the Lunar Sample Review Board.

CHAPTER IV

FUTURE LUNAR EXPLORATION

A. INTRODUCTION

Although the date is uncertain, man will return to the Moon. It is essential, therefore, that modest but carefully organized efforts in mission planning and hardware development be continued.

In our consideration of future lunar exploration no attempt was made to recommend a specific program. Instead, keeping in mind the scientific questions set down in Chapter II, we tried to define the requirements for sampling and measurement, identify methods and types of missions by which to achieve these requirements, select the most likely targets, and define some essential support efforts in research and technology.

The following discussion is of course based upon our present knowledge of the Moon. Thus, continuous modification will certainly be required as results continue to come in from Apollo. Nevertheless we would stress that, with our present knowledge of the Moon, even a limited program in the future can provide essential information.

We have also identified a major flight priority for the near future: A high-inclination orbital mission for geochemical, geophysical, and geological mapping of the Moon belongs uniquely between the Apollo flights and any future program of missions.

B. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. We have recommended a priority list of major scientific landing targets for future lunar missions. This list demands far broader landing capabilities than Apollo, including far side and polar sites [reference page 76].

2. Future exploration intended to maximize scientific return will require further major improvements of sampling and geologic exploration techniques. These cannot be detailed at this time, but the guiding philosophy is to improve the capability in:

(a) horizontal and vertical mobility (unmanned and manned rovers and flyers);

(b) surface navigation;

(c) sampling and documentation (including deep drilling;

(d) active geochemical and geophysical sensing;

(e) portable geochemical sensors to serve as guides in sampling;

(f) base-station sample study, processing, selection, and packaging [reference page 81].

3. We have recommended the new geophysical experiments which now appear most important for future lunar missions. We have also reiterated the need to continue operation of the existing ALSEP stations [reference: Recommendations pages 4 (1-b), 32, 81].

4. The most significant measurements on lunar materials are the isotopic ages, with appropriate data on their petrological and geological context. We see little probability that credible measurements of this kind will be possible without return of the samples to Earth laboratories, for at least the next 10-15 years [reference page 85].

RECOMMENDATIONS

1. Remote sensing from lunar orbit is a whole new area whose importance was demonstrated by the Apollo program. Results acquired to date have shown that fundamental insights can be obtained on questions of planetary structure and evolution. *We therefore recommend that a high-inclination orbital mission be regarded as a major priority in the first stage of any future lunar exploration.* Such a mission would determine a wide spectrum of geophysical, geochemical, and geological variables on a planet-wide scale [reference page 88].

2. *We recommend that a small, selective program of mission planning exist to provide the desired continuity between the present and future* [reference page 88].

3. International cooperation has been an important aspect of lunar research. *We recommend that every effort be made to encourage this aspect, including the undertaking of joint and multi-national lunar missions* [reference page 90].

C. SITES FOR FUTURE EXPLORATION

The six Apollo landings will have covered less than half of the major scientific targets for *manned* landings that were identified* in 1967. Almost none of the prime sites for *unmanned* landings has been explored. This situation is a consequence of a policy decision to postpone completion of this original, highly ambitious program for the scientific exploration of the Moon. Further, everything that we have learned to date indicates that the original exploration design is still scientifically valid. Thus, a great deal remains to be done.

However, because of existing and foreseeable pragmatic constraints, it is necessary to redefine the next series of scientific targets. Our purpose is to specify a set of such targets for the record, without stipulating either the schedule or the methods for their achievement. Each site or region has been selected for exploration because of its potential for contributing answers to a variety of first-order topical problems related to the nature and evolution of the lunar surface. These targets are described in order of priority below.

Farside Upland and Mare Terrains.— All of the Surveyor, Apollo, and Luna missions (a total of 14) have been directed to the near side of the Moon, most of them clustered around the sub-Earth point. Therefore, from a purely exploratory point of view, it is desirable to make a first reconnaissance of the far side. In addition, however, there are compelling scientific reasons for sampling this region: a) An average increase of elevation of 3 km on the far back side relative to the near side suggests a thicker crust. b) Compositional differences exist for the major element and radioactive element abundances of the far and near side. c) The general absence of mare fill, again relative to the near side, indicates a different igneous history. It would be of great interest to compare the composition of far-side and near-side lavas. d) The great distance from the Imbrium basin assures the collection of rocks unrelated to that event, this being in notable distinction to previous Apollo missions. e) The geometry of the combined magnetosphere of the Earth-Moon system in relation to the solar wind suggests a distinctly different solar wind exposure environment for the far side of the Moon.

A possible site is the crater Tsiolkovsky, an area in which one could sample central peak material (presumably

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* *Lunar Science and Exploration*, 1967 Summer Study held at Santa Cruz under auspices of MSC. NASA-SP-157.

deep-seated rocks), mare materials, and crater wall and ejection materials — all in one mission.

Younger Ringed Basins.— The large ringed basins on the lunar surface are the largest recognized features attributed to impact by extra-lunar bodies. These impacts may have been the final phase of planetary accretion. In addition to the enormous variety of phenomena associated with their production, they represent first-order perturbations of pre-existing surface structures, and, possibly, crustal layering. The magnetic and gravitational properties may show considerable anomalies. These regions may be our best source of samples of the deeper crust (below 25 km) and even the mantle (below about 70 km).

The Orientale Basin is an appropriate site for this investigation. A landing at the edge of the central mare would permit sampling of rocks upthrust or ejected from depth in addition to sampling of the central lavas, presumably young on the basis of crater density. As discussed below, the younger lavas are interesting from a number of points of view. A visit to the Orientale ejecta blanket would also be extremely important, but might require another mission.

Polar Landing Mission.— Past lunar missions have been concentrated in low-latitude regions, largely because of operational constraints. At present, near- *versus* far-side asymmetries are recognized in many lunar characteristics. Exploration of lunar polar regions would provide information on variations in polar highland material relative to that in the equatorial highlands. Polar sites should be ideal for obtaining samples containing trapped volatiles and light elements and samples that may have been shielded from the solar wind by local relief. Active experiments, *e.g.*, releasing gases and studying their migrations, would be desirable near the poles. Measurements of the magnetic field and the interior electrical conductivity should be extended to provide high-latitude coverage.

Younger Volcanics.— A wide variety of volcanic features and thus, of scientific topics as well, is included under this heading. The youngest volcanic rocks so far dated are 3.2 billion years old. In order to extend to later times our knowledge of the thermal, chemical, magnetic, radiative, and bombardment history of the Moon, it is important to find igneous rocks of younger age. Ages of possible sites may range from about 0.5 to 2 billion years. It is possible that these young volcanics originate with source material from locations deeper than 500 km or so and thus that the lavas will contain information on sources that are different from those that produced the mare basalts collected to date. Photographic and spectroscopic information strongly suggest that rocks ranging over a wide petrologic spectrum and age range exist on the relatively uncratered plains of northern Oceanus Procellarum and on the volcanic ridge along which are situated the Marius Hills, the Aristarchus Plateau, and the Rümker Hills. Dark halo craters such as Copernicus H, which is superposed on Copernicus ejecta, and the several "cinder-cones" are other possible sites.

Extended Lava or Lava-Regolith Sequences.— So far, some 10 to 15 individual lunar lavas probably have been sampled, but no incontrovertible bed rock samples have been obtained. Apollo 15 observations and photography clearly indicate that a lava sequence is accessible in the wall of Hadley Rille, and detailed examination of orbital photos will doubtless reveal other sites where stratified lava flows and interlayered fragmental materials can be profiled vertically.

These lava sequences will provide detailed information on volcanic processes, the lateral and vertical characteristics of individual flows, the differences between flows, and the time intervals between volcanic events. Samples from sequential flows will provide a paleomagnetic record of field strength and direction.

Such samples will also facilitate the detailed examination of any regoliths that develop on a lava flow before it is covered by another flow. In general, this fragmental lava would contain information on soil-forming processes during a discrete period of time early in lunar history and would provide a record of early solar activity.

Areas of Transient Activity.— Telescopic observations compiled over many years indicate the existence of certain regions in which transient events or gaseous phenomena occur. These sites include Aristarchus, Alphonsus, and Plato. If certain of these sites can be demonstrated to be seismically active and if orbiters and landers indicate the presence of volatiles, then it would be important to visit those specific sites and to establish long-term bases.

Samples from these sites might include released gases, encrusted and otherwise modified "country" rock, and recent volcanic rocks. As will be discussed subsequently, deployment of heat probes, gas sensors, seismic stations, and other long term monitors is essential. Systematic geologic exploration to establish the nature and evolution of the lunar setting for the transient events should be carried out. The search for accumulations of trapped volatiles would be given a major emphasis.

KREEP Source.— Fragmental rocks and debris highly enriched (with respect to other lunar rock types), in radioactive, rare-earth, and other refractory elements have been found at several Apollo sites ringing the Imbrium basin. The material studied to date occurs mainly as small fragments, but a few larger rock fragments containing this component, which has come to be known as KREEP (or norite), have been recovered. Many of these have textural features indicative of a late addition to the KREEP. Lunar soil layers in the western half of the lunar near side contain up to 75 percent KREEP, and recently analyzed highland soils contain up to 15 percent of this material. It is now evident that the evolution and emplacement of the KREEP are significant phenomena in the geochemical evolution of the Moon. Location of the source rocks, and field study and collection of such rocks would contribute significantly to our understanding of the chemical differentiation and thermal history of the Moon.

Orbital x-ray and gamma-ray experiments suggest that this material is most abundant in the northwest quadrant of the near-side hemisphere. It also seems to be concentrated in the area of Van de Graaff crater on the far side.

Rilles in Different Terrains.— The variety of rille types on the lunar surface surely reflect a variety of origins. Some straight and arcuate rilles are almost certainly of fault origin, but there is no consensus about the origin or origins of sinuous rilles. Studies at the Apollo 15 site revealed that the upper part of the Hadley Rille wall is composed of a few lava flows. Other rille walls in highlands presumably contain different materials and records.

Extensive exploration of selected rilles would include exploration and sampling of source craters, and detailed sampling of exposed rille wall outcrops for the reasons discussed in Section 5. Sampling of crater ejecta and regolith adjacent to the rille margins would provide data with which to evaluate and extend present cratering theory, especially as it applies to the depth of origin of ejecta as a function of its position in the ejecta apron.

Extended Highlands Sampling Missions.— To date, only two highland sites have been sampled directly: central (Apollo 16) and eastern (Luna 20) highland near-side areas. Compositional data have been obtained with Surveyor 7 at Tycho in the highlands in the southern half of the near side. In general, the available data on these highland soils indicate an anorthositic gabbroic composition with varying amounts in the approximate range 5-15 percent of KREEP. Since the highlands occupy about 70 percent of the near side of the Moon, disproportionately few missions have covered this type of terrain. Orbital data suggest compositional differences between different parts of the front-side highlands and these differences are partially confirmed by preliminary Apollo 16 and Luna 20 data. Sampling of widely different sites would permit extensive studies of the lateral and vertical variations in highland material, breccia formation as a function of cratering, thick sequences of regolith in highland terrain, and characterization of any highland volcanic rocks found. A wide selection of sites would provide the greatest probability of finding the oldest rocks. All of these investigations should lead to an understanding of early crustal evolution. Some of these sites would most likely be included among the desirable polar missions.

Extensive Latitudinal and Longitudinal Mare Sampling.— Extensive mare sampling would provide information regarding the lateral (and possibly local vertical) variability of composition and age of mare lavas. It would also permit mapping the distributions of widespread exotic components such as KREEP, green glass, red glass, meteoritic components, and any others that may be encountered. Further, it would permit the examination of the latitudinal dependences of solar wind components and solar flare products in regolith materials. Finally, it would contribute greatly to the data on mare structures and thus on geological processes.

The acquisition of these data requires mission sets. Some of these requirements would be met by specific scientific missions cited above. The coverage could be extended, however, by using a multiple unmanned return vehicle approach. This approach, in fact, might be an ideal way to obtain extensive areal coverage.

Revisiting an Apollo Site.— The post-Apollo studies of returned samples and data from surface and orbital measurements may well identify an Apollo site as appropriate for further investigation, that is, the first generation of exploration and sample investigations may indicate previously unrecognized possibilities for solving major lunar problems that would be available on a second visit at the same site. For example, the Apollo 15 site would be attractive if the coverage in dimensions and geologic opportunities could be extended beyond that provided in the Apollo 15 traverses. Specific tasks might include sampling the higher stratigraphic portions of the Apennine front; profiling and sampling the rille wall and floor, and characterizing the longitudinal structures of various lithologic units cropping out at the rille edge; visiting the volcanic rocks of the North Complex; and exploring St. George crater. This mission would require expanded mobility and stay-time capabilities.

Such missions would facilitate the reactivation of stations in the original Apollo surface network.

Further, they offer the additional possibilities of using previously emplaced hardware and previously obtained photographic record as parts of a controlled experiment to characterize the present lunar environment. The value of this approach has already been established by this use of the Surveyor III components and imagry, but the value of a return to an Apollo site would be many times greater because of the variety of materials available, the greater detail of the photographic documentation, and the longer interval before the site is revisited.

Methods.— A variety of methods has been employed in manned and unmanned lunar exploration and the corresponding systems have evolved from the simple to the complex. Future exploration intended to maximize scientific return (*i.e.*, manned missions) will require further major improvements in sampling and geologic exploration techniques. These techniques cannot be detailed at this time, but the guiding philosophy is to improve the capability in: (a) horizontal and vertical mobility (unmanned and manned rovers and manned flyers; (b) surface navigation; (c) sampling and documentation (including deep drilling); (d) active geophysical and geochemical sensing; (e) portable geochemical sensors to serve as guides in sampling; (f) base laboratory sample study, processing, selection, and packaging.

D. GEOPHYSICAL AND GEOCHEMICAL MEASUREMENTS IN FUTURE EXPLORATION

In the following paragraphs, under each of the principal subject areas, the geophysical and geochemical measurements that now seem to be required to answer the main scientific questions are described.

Internal Structure.— Seismic methods provide the most direct data for the study of the structure of the lunar interior by defining velocity profiles, discontinuities, major layers, and molten zones. Seismic data (velocity profile and attenuation) can be interpreted, with the aid of laboratory and other data to infer the temperature and chemical composition of the interior.

By the end of the Apollo program we anticipate that the structure of the lunar crust and upper mantle will be known in one general area. It may be possible to establish some major boundaries in the deeper interior. The tidal gravimeter can provide data on the gross elastic properties of the interior. The probability of large natural energy sources (meteorite impacts and moonquakes) providing additional seismic information before the end of 1973 is difficult to estimate, but appears to be low. Observation over a long period of time is essential in order to benefit from large natural seismic sources. Location and timing of such events require at least three stations.

A significant contribution to understanding the lunar interior could come from the present network of ALSEP (Apollo Lunar Science Experiment Package) stations if they operate for several more years. With this in mind we must make recommendations to cover the immediate post-Apollo period as well as distant future.

- ¶ Maintain ALSEP seismograph network as long as useful data are being received.

- ¶ Utilize artificial impacts, large and small, while seismic stations are still in operation.

- ¶ Maintain at least one seismic station after ALSEP's are turned off in order to monitor natural seismicity and meteorite impacts. If large moonquakes occur at all, they would be infrequent. Thus monitoring over a long period is essential.

- ¶ Upgrade capability of the present network stations. One additional station on the back side, for example, would make it possible to determine the average seismic velocity through the lunar interior and the presence or the absence of a fluid core. In addition, such a station will make it possible to locate moonquakes and impacts on the back side and to determine if front side — back side asymmetry is also reflected in current tectonism.

- ¶ If extensive exploration becomes possible again, a new seismic network is most essential to improve global coverage.

Far-Side Gravity and Lunar Asymmetry.— Far-side gravity measurements are outstanding and important observations in order to understand better the lunar mechanical and thermal regimes. With both new and far-side coverage, surface and crustal effects can be evaluated and inferences concerning the deep interior can be made. Determinations of the gross mass effect of mascons would shed some light on the displacement of the center of mass from the center of figure and possibly on the crustal thickness of the near versus the far side. The degree of isostasy of the large depression on the far side that was detected with the laser altimeter on Apollo 15 could be evaluated and thus implications concerning the Moon's viscosity over geologic time would be made. Information on the presence or lack of mascons in the large ringed basins Hertzsprung and Korolev would greatly assist in the development of theories on mascon formation.

The best method for obtaining these data is a polar orbiting spacecraft. A laser altimeter similar to the one used during the Apollo missions would be excellent. The gravity is obtained by relay satellite tracking of a low altitude spacecraft (partial additional coverage could be obtained from the Apollo 15 subsatellite) or by a gradiometer with recording capabilities. The two-satellite relay approach seems more desirable since (1) its data type will be convenient to integrate with existing results; (2) it can be used also for navigational accuracy and orbital dynamic studies; and (3) the gradiometer has yet to be tested in space as a capable system. A surface gravity traverse would enhance the description of mascons and other local anomalies.

Precise determinations of the physical librations of the Moon have been obtained with data from the Laser Ranging Retro-Reflector (LR^3) and will provide ratios of the moments of inertia, (C-A)/I, describing the low-order gravity field. At present there is excellent agreement between the lunar ranging and heliometric determinations. However, an improvement in the determination of the gravity field is needed to obtain a better oblateness $(C-A)/MR^2$, to find the physically significant quantity I/MR^2 to the accuracy needed. While intensive analysis of existing data will yield some improvement, the greatest assurance would be attained by orbiting additional satellites at intermediate inclinations (40° to 75°).

Internal Properties.— Electromagnetic excitation of the deep interior of the Moon by hydromagnetic waves in the solar wind has been used to infer the bulk electrical conductivity profile. Resolution of the data is restricted by the limited frequency range and a restricted quantity of high-grade data.

Improvement of resolutions would be a significant aid in inferring models of the deep structure as well as improving estimates of temperature at depth. For this work it is necessary that a surface magnetometer be emplaced. An optimum location would be on the lunar equator, for the most straightforward geometry, but an important additional constraint is a small local permanent field.

It is essential that the incident wave field in the solar wind be determined simultaneously with the surface measurements. The latter requires a lunar orbiter.

Heat Flux.— Heat flow from the lunar interior is a measurable quantity and may be used as a boundary condition on lunar thermal models. The present flow is derived principally from (1) radioactive heat generation, (2) initial heat, and possibly (3) other sources such as tidal dissipation. It is not possible to derive either initial distributions of temperature or heat sources from heat flux measurements alone.

What then can global measurements of heat flow tell us? In the limit they provide (a) an estimate of total radioactivity if flow-production equilibrium is assumed and initial heat is neglected, (b) the present flow of fossil heat as well as that due to non-radiogenic sources, if radiogenic sources are neglected, and (c) an estimate of the temperature gradient in the outer few hundred kilometers (given a value for the thermal conductivity). The above items set boundary conditions on lunar thermal models.

The present status of lunar heat-flow measurements consists of one direct observation at the Apollo 15 site of 0.79 μcal/cm sec, a value seven times that expected on the equilibrium assumption that the Moon has bulk chondritic U abundance, the observed K/U ratio in surface rocks of 2 x 10^3, and Th/U = 4. The measured value is greater than any value previously predicted on theoretical grounds or measured by either microwave observations or from electromagnetic wave interaction with the Moon. The observed *in situ* result reflects either extraordinary U concentrations in the Moon, or special, local conditions. One additional observation remains to be made by the Apollo 17 mission.

Terrestrial methods of determining internal temperature gradients can supplement direct methods and therefore are worthy of exploration. Among these are: (1) passive microwave observation of subsurface temperature, (2) determination of global average temperature gradients from observation of electromagnetic wave interaction with the Moon (discussed above), (3) observations of variations in thermo-luminescent behavior with depth in regolith core samples. The first method (thus far involving only terrestrial observations) is troubled by imperfect knowledge of global microwave properties at the relevant frequencies, as well as any knowledge of what a global average near-surface stratigraphic column might be. The thermal gradients determined are uncertain, and no independent estimates of thermal conductivity can be made. While spatial resolution would be improved by microwave observations from orbit, the other fundamental difficulties remain. The method deserves further theoretical and experimental study. Electromagnetic sounding that involves both surface and orbiting magnetometers is the most promising means presently available of obtaining estimates of deep interior temperatures. Further theoretical analyses of such data to obtain electrical conductivity profiles is required. In addition, the conversion of electrical conductivity so obtained to temperature is a difficult matter requiring further experimental and theoretical study.

Examination of thermo-luminescent behavior in core samples returned by Apollo 12 led to determination of thermal gradients in the regolith (unrelated to diurnal effects) of approximately 2°K/m. This value is surprisingly close to the gradient observed at Hadley Rille (1.75°K/m). This method deserves close scrutiny as a possible means of estimating heat flows at sites where cores taken at sufficient depth are available.

Lunar Magnetism.— The discoveries of a stable remanent magnetization in the Apollo rock samples and evidence of large-scale (10^2 km) field sources in the lunar crust are puzzling. Evidently an unsuspected complex and fundamental phenomenon awaits detailed exploration.

A future program could answer many important questions about the lunar magnetic field. Of paramount importance is the mapping of magnetic anomalies and the determination of the strength and direction of magnetization associated with the various magnetic anomalies, as indicated by limited observations from Apollo surface magnetometers and subsatellites. Determinations of this nature could probably be best done from a low-altitude polar orbiting satellite coupled with a laser altimeter for determining the topography. By use of this technique it may then be possible to piece together the picture of whether the early field of the Moon was of internal origin and if so whether it is global in nature. Anomalies associated with surfaces of various ages might also give an idea of the time variation of the field. This may be revealed by both mapping and sample study. The use of surface magnetometers on a traversing vehicle over specific features would also be very important since this could be used to determine the direction of magnetization of *in situ* rocks. A profile approaching Hadley Rille for example could have determined the strength and direction of magnetization of the lava flows.

Bulk Composition.— Determination of lunar bulk chemical composition is of fundamental importance since it allows comparison with the bulk composition of the Earth, cosmic abundances, and those of meteorites with a view to understanding the principles of chemical fractionation in the solar nebula. Understanding of bulk composition may also allow us better to define the compositions of the various layers and evolution within the lunar interior. Such data may also provide information in determining the origin of the Moon.

Bulk composition is determined by indirect methods:

¶ Surface chemistry and mineralogy and petrology.

¶ Seismic and electromagnetic properties.

¶ Bulk density and moments of inertia.

¶ Phase-equilibrium experiments based on the above to determine the permissible compositions of sub-surface layers.

The most important information to be gained is composition and mineralogy and petrology of lunar samples. Landing areas that offer possibility of collecting material from depth are highly preferable. Although the Apollo program has provided considerable information on the composition of the lunar surface, much additional sampling and orbital geochemistry remains to be done.

Automated chemical and mineralogical analyses on the lunar surface are necessary to extend the real coverage beyond that provided by returned samples. Suitable techniques include x-ray diffraction, x-ray fluorescence, and an α-scattering device. Additional supplementary information may be gained from Earth-based spectroscopic observations.

Lunar Chronology.— Age determinations of lunar samples are of paramount importance in establishing (1) an absolute time-scale for lunar events and (2) data points required for determining a lunar evolution and thermal history. Present returned samples give ages spanning at least one billion years of lunar history. Without additional sampling of what appear to be youngest and oldest areas, it is not possible to determine the span of magmatic activity in lunar history. Age determinations can be performed at present only by returning samples to Earth, and although some possibility exists in the future for performing age determinations on the lunar surface by automated methods, such determinations would be vastly inferior and would clearly lack credibility compared with age measurements on returned samples. A detailed understanding of the geological context of the sample and its mineralogy and petrology are required in order to interpret correctly the measured age. Returned samples have the added major advantage that the analyses can be improved with future developments in geochemical instrumentation.

Regional Geology and Lateral Variations.— To ensure that the Moon has been adequately sampled for geochronology, bulk compositional estimates, and geophysical parameters, it is necessary to make both orbital measurements and traverses across the lunar surface. The results obtained should be put in their geological and regional geophysical context so that all data can be interpreted in terms of surface composition and structure and their extension into the deep crust. Local geology is determined by traverse observations, future geological maps compiled from previous photography, and a future program of lunar orbital photography.

In order to determine unambiguously lateral variations on the lunar surface, the following should be emphasized:

¶ An unmanned roving vehicle with a range of about 1000 km capable of basic geophysical and geochemical observations.

¶ The return of lunar samples from many sites for sophisticated studies on Earth.

These specific recommendations can be further amplified and justified. The need for adequate geochemical sampling on a regional basis argues for the lunar rover to have the capability of measuring major and minor elemental abundances.

Traverse gravimetry and magnetometry should also be emphasized. Perturbations of those orbits which have passed over mascon basins at low altitude indicate that the mass anomalies are shallow discs, rather than deeply buried spheres. The exact nature of these mascons is still controversial; traverse gravity observations would be useful for (1) accurate assessment of mascon basin edge effects; (2) accurate downward extrapolation of subsatellite tracking data; and (3) assessing a detail of mare — highland contact zones on a regional basis.

All of the orbital experiments have emphasized that the Moon is indeed a heterogeneous and laterally variable body. The surface magnetometers deployed on past Apollo missions and the rudimentary maps from the Apollo 15 and 16 subsatellites have revealed that lunar magnetization is variable and involves large volumes of the lunar crust. A traverse magnetometer is needed for (1) ground truth information; (2) assessment of structural boundary effects; (3) determinations of the direction of magnetization over features of known topography; and (4) tying together subsatellite observations. A global map of the lunar magnetic field would be a valuable tool toward understanding the evolution of the lunar curst.

Variations in regolith thickness tell much about the evolution of the lunar surface. This could be easily studied by electromagnetic sounding and seismic techniques on a lunar rover. An array of observing stations can also be established with a lunar rover.

Degassing and Atmosphere.— Lunar cinder cones and the high abundance of vesicles in some mare basalts attest to the presence of volatile components in the interior of the Moon. In addition, the unconfirmed but tantalizing evidence of possible present day degassing from the SIDE experiment and other observations of lunar transient phenomena are worthy of further study. The mass spectrometer on Apollo 17 will extend these investigations. If positive results are obtained, we will get much needed additional information, not only on the nature of volatiles and reduction-oxidation conditions in the lunar interior, but also on planetary atmospheres.

The problem is best attacked by the use of geochemical devices measuring the lunar atmosphere at the surfaces. Such instruments would be most effective in areas where transient phenomena are known to occur; complementary to these studies are the measurements from orbiting vehicles, and the collection of samples from such areas and Earth-based observation of transient phenomena.

Earth-Based Observations.— Earth-based observations should continue in conjunction with the LR^3 experiment. Additional remote mapping by ground based telescopes, Skylab, and other Earth-orbiting missions could expand the spectral mapping coverage.

E. THE INTERIM PERIOD

The period between the time of the Apollo missions and the next extensive exploration of the lunar surface is fully as important to a successful program of space exploration as are the periods of actual mission operations. A reasonable return on our national investment in the Apollo program requires extensive study of the information and materials returned by the Apollo missions. It also requires additional accumulation of data leading to a precise definition of the problems to be attacked in the return phase of exploration. During this period, several modest lunar missions will be invaluable for filling the many gaps that exist in our present store of data.

Planning for the Apollo missions was based almost entirely on geologic and topographic interpretations of the available orbital photographs, simply because photographs were the only source of detailed knowledge of the lunar surface during the planning stage. It is vital that recent information from the Apollo samples, geophysical instrument, surface photographs, and orbital spectrometers, as well as maps from these data be used to form exploration plans for future lunar missions.

Polar-Orbiting Mission for Full Coverage, Remote Sensing of the Moon.— *The first priority* of future lunar exploration should be a polar-orbiting satellite equipped with photographic-, compositional-, radioactivity-, magnetism-, and other remote-sensing systems. Such a survey stands at a pivotal point between truly completing the yield from the Apollo science program and planning further lunar exploration. We now have less than 20 percent of the Moon covered by the Apollo orbital science. These have been tied to the lunar surface by a few important points of "ground truth". The polar mission would permit extending this type of lunar mapping to the entire Moon and provide a comprehensive data base for effectively planning any future scientific exploration of the lunar surface.

A continuing program of photogeologic mapping (scale 1:1,000,000) at a significant level over the next decade will be required to permit us to best evaluate possible sites for future surface studies.

We recommend that a small, selective program of mission planning exist to provide the desired continuity between the present and the future.

If a close relationship is maintained with other scientific mission programs being flown in this period (in particular, the Earth resources and astronomy programs), much can be accomplished without large resources. Since scientific mission opportunities usually appear on short notice, such a continuing development program is the way to ensure the availability of modern instrumentation at reasonable cost.

There are several types of experiments besides photography which today appear promising. In the geochemical area there are the x-ray and gamma-ray systems. In both cases major advances in the number of elements mapped and the ease and accuracy of concentration measurements are now possible. A well-planned mission including advanced sensors of both types could be expected to produce useful data for as many as 20 elements, including most of those of great geochemical interest.

The laser altimeter is a vital component of this system. A future program might employ either a returned system or a very high-bit-rate television system. A mission length of two weeks is required and a month is highly desirable. This task could be carried out by manned or unmanned spacecraft.

Visible and near-infrared spectral imaging scanners are another class of high-bit-rate instruments that can provide very desirable complementary data on the same spacecraft. Technological advances may make it possible for the spectral scanners to assume the overall high-resolution imaging task with the telemetry link, making returned film unnecessary.

A third class of sensors has lower bit requirements and is best served by long life-time, special environmental requirements (*e.g.*, magnetic cleanliness), and low orbits. These instruments could be best served in a subsatellite or independent launch mode with a life-time of, say, a year. A partial list of such experiments is as follows:

¶ Magnetic survey

¶ Gravity

¶ Solar wind

¶ Plasma experiments (magnetosheath, magnetotail)

¶ High energy particles (solar flare and cosmic ray package)

¶ Astronomical use of x-ray and x-ray geochemical sensors.

Finally, orbital radar experiments with higher bit rates may be very attractive for geological mapping, exploration of sub-surface regions, and measurement of thermal properties.

Geophysics Station Emplacement.— As our knowledge of the Moon increases, the relevance of geophysical data to samples and to future sampling requirements becomes more evident. The theories that are presently evolving concerning the compositional nature of the deep interior of the Moon are based largely on studies of surface rock samples. Additional information is required concerning the physical, thermal, and magnetic properties of the lunar interior to understand more fully the composition of materials formed at great depths, and also to help in recognizing them if encountered on the surface. To obtain this information will require a more complete seismometer and magnetometer network and more heat-flow measurements. A network of more instruments, spread over a wider area of the Moon, will produce far more abundant and more precise data than does the present limited network.

F. INTERNATIONAL COOPERATION

There has been an important element of international cooperation in lunar research since its inception. Prior to the first landing, the Moon was declared an international object, not subject to territorial acquisition by sovereign states. The memorial plaque left on the Moon by the Apollo 11 astronauts stated that they came "in the name of all mankind." The scientific samples returned from the Moon by both the United States and the U.S.S.R. have been made available to scientists of all nations. More recently, the U.S.S.R. and the United States have proposed a joint mission in Earth orbit.

The exploration of space is an enormous undertaking, with consequences to all peoples of the Earth. Pictures of our planet taken from the Moon tend to put the problem in its proper perspective.

We, therefore, wholeheartedly support international cooperation in lunar exploration, and hope that new and imaginative ways will be found to continue and increase the cooperative, international aspect of lunar research. A growing understanding between peoples based on working together on problems of mutual interest that transcend the interests of individual nations, may well be one of the most fruitful aspects of the space program.

Appendix A

FREQUENTLY USED ACRONYMS

ALSEP — Apollo Lunar Science Experiment Package

APT — Apollo Photographic Team

CPLEE — Charged Particle Lunar Environment Experiment

JPL — Jet Propulsion Laboratory

KREEP — *K* (potassium), *R*are-*E*arth *E*lements, *P*hosphorus

LAC — Lunar Aeronautical Chart

LEAM — Lunar Ejecta and Meteorites (Experiment)

LRL — Lunar Receiving Laboratory

LR^3 — Laser Ranging Retro-Reflector

LSAPT — Lunar Sample Analysis Planning Team

LSI — Lunar Science Institute

LSM — Lunar Surface Magnetometer

LSRB — Lunar Sample Review Board

LSSG — Lunar Sample Steering Group

LSWG — Lunar Sample Working Group

MSC — Manned Spacecraft Center

NAS — National Academy of Sciences

NASA — National Aeronautics and Space Administration

NRM — Natural Remanent Magnetism

NSSDC — National Space Science Data Center

OSS — Office of Space Science

PALS — Post-Apollo Lunar Science

PI — Principal Investigator

PSAC — Presidents' Science Advisory Committee

PSC — Physical Sciences Committee

SIDE — Suprathermal Ion Detector Experiment

SPAC — Space Program Advisory Council

SR&T — Supporting Research and Technology

SSB — Space Science Board

SWP — Science Working Panel

SWS — Solar Wind Spectrometer

Appendix B

SUMMARY OF THE APOLLO SCIENCE PROGRAM

A. SAMPLE ANALYSIS

The most important body of scientific information so far obtained from the Moon is the extensive set of data on the chemical, isotopic, and physical characteristics of the lunar rocks and soil samples. These samples have already provided the essential elements of an absolute lunar chronology. They have led to models of lunar composition and evolution quite different from those anticipated prior to their return. The analysis of thousands of individual grains taken from different soil samples has shown that the returned lunar samples include materials that come from points far from the sampling site; moreover, it has been shown that breccias, which are compacted, fragmental rocks, preserve a record of the movement and consolidation of materials during the earliest times in lunar history. A beginning has also been made in determining the long-term history of solar radiation from the interaction of solar flare particles with the lunar rocks.

The scope of participation in the present sample analysis program is summarized in Tables B1 and B2. The resources and research efforts of about one-half of the PI groups listed in Tables B1 and B2 are essentially 100 percent committed to the analysis of lumar samples. The program carried on in many of these institutions is based on unique research capabilities and skills developed particularly for the analysis of lunar samples. In many cases, equipping these laboratories has involved very substantial capital investments in facilities that have extended analytical capabilities far beyond those required for the study of terrestrial samples. Many of the impressive achievements in the analysis of lunar materials came from facilities and personnel that were especially built and trained for this task. Developing these laboratories required order of magnitude increases in sensitivity and accuracy for many techniques and involved a level of control of contamination that had never been achieved before. The success and viability of an ongoing program of lunar sample analysis will depend heavily on the ability to maintain those lunar sample research centers whose capabilities probably would never be duplicated for other types of research.

The results of the Sample Analysis Program have shown that it is particularly important that an active research group be maintained in close proximity to the lunar sample collection at the Manned Spacecraft Center. The functions of this group are twofold: (1) To provide research capability for materials that often cannot be practically transported away from the main collection and (2) To provide the technical know-how that is required to preserve the integrity of lunar samples and insure their proper scientific use.

Implementation of the Sample Program requires extensive support of the Curatorial Facility at the Manned Spacecraft Center for handling, storing and distributing the lunar rocks and soils. The magnitude of the effort can be envisioned by considering that the total quantity of distinct samples allocated already numbers in the thousands while the number of separate catalogued items is expected to soon be in the tens of thousands.

B. SCIENTIFIC INSTRUMENT DATA ANALYSIS

The data acquired from analysis of lunar samples has been extremely impressive. There would be, however, more severe limitations imposed on the interpretation of that data were it not for over 30 geophysical and geochemical instruments which has been emplaced or used on the lunar surface or which has been flown in lunar orbit. That instrumentation has been designed for the investigation of the structure and energy region of the lunar interior, for the study of the surface environment, and for purposes of extrapolating the point measurements made at the landing sites.

The present program is supporting reduction of geophysical and geochemical data from four Apollo Lunar Surface Experiments Packages (ALSEP's), three Laser Ranging Retroreflectors (LR^3's), two orbital subsatellites and two Scientific Instrument Modules flown in orbit during missions. The Apollo 17 mission is scheduled to include an ALSEP with many new experiments, three new traverse geophysics experiments, and three new orbital instruments. Although some of the above experiments are no longer operational, many continue to operate and acquire new data. Some, in fact, such as the seismometers and LR^3's, are more valuable than ever now that they are operating in a network mode. All indications point to several more years of life for some of the ALSEP's and to several decades for the LR^3's.

C. PHOTOGRAPHIC ANALYSIS

There are between one and two thousand surface photographs taken on each Apollo mission. They are used immediately after each flight to document sample location, orientation, and geologic context and to aid in the interpretation of the geologic history of the landing site. In contrast to the first use, the second is expected to continue long after the missions cease and will include detailed photointerpretation, photometry, and photogrammetry.

Apollo orbital photography includes thousands of Hasselblad 70 mm photographs (resolution about 50-100 m.) taken from the Command Module on all lunar flights and Mapping Camera (resolution about 20 m) and Panoramic Camera (resolution about 2 m) photography taken on Apollo 15 and 16 (planned on Apollo 17).

The Mapping Camera photography will be used primarily for the creation of a well-controlled selenodetic coordinate system and subsequent production of appropriate topographic maps and photomosaics. In turn, these products are expected to be used for photogeologic and lunar-figure studies and for the plotting of orbital science data.

Both the Hasselblad and Panoramic photography can be used "as is" for detailed photointerpretive studies. In addition, rectified Panoramic imagery will be available and will be used for, among other things, the production of large-scale (*e.g.* 1:10,000) topographic maps of landing sites and special features (rilles, domes, craters, etc.).

Analysis of Apollo photography has been in progress for several years and has been a major part of the landing site studies by Field Geology Principal Investigators. The scope of studies has been increasing, however, with the advent of the Mapping and Panoramic photography and the appointment last year of 13 Principal Investigators whose major efforts focus on photoanalysis.

D. SYNTHESIS

The Lunar Exploration Program has encompassed four flight programs and numerous Earth-based studies. Each has resulted in the acquisition and analysis of voluminous data and subsequent reports on the findings. The amount of data and the numbers of investigators have been so great that, combined with the rapidity of data acquisition, the net result has been an accumulation of a large number of fragments of the picture of lunar history. It is now time to pull the pieces together, *e.g.*, to relate the sample results to the photogeology, to tie orbital results to Earth-based remote sensing, to filter and evaluate the conflicting data and to apply the lunar results to planetary exploration. The net result of this activity, broadly termed the Synthesis Program, will be to show conclusively how scientifically fruitful the lunar program has been and to set the stage for future lunar programs whatever and whenever they may be.

Table B1

SUMMARY OF LUNAR SAMPLE PROGRAM

	FY68	FY69	FY70	FY71	FY72	FY73
NUMBER OF PI'S						
Domestic	84	105	115	143	132	110
Foreign	29	49	75	65	51	40
NUMBER OF INSTITUTIONS	33	61	88	118	110	80
DOLLARS (MILLIONS)	3.1	4.2	9.0	12.0	10.0	9.6

APOLLO 14 — 17 PRINCIPAL INVESTIGATORS

189 Total

134 Domestic (64 different institutions, 28 states + Virgin Islands)

55 Foreign (40 different institutions, 15 countries)

TABLE B2

DISCIPLINE BREAKDOWN OF LUNAR SAMPLE PROGRAM

DISCIPLINE AREA	PRINCIPAL INVESTIGATORS DOMESTIC	PRINCIPAL INVESTIGATORS FOREIGN
MINERALOGY/PETROLOGY		
Mineralogy/Petrology	6	6
Non-Opaques	4	2
Opaques Mineralogy	4	1
Glass Studies	5	1
Mineralogical Techniques	4	1
Experimental Petrology	4	4
Statistical Rock Studies	3	0
Soil Studies	5	1
Shock and Textural Studies	5	1
Regional Geology	1	0
	41	17
BIOSCIENCE		
Microbiology	1	0
Micropaleontology	1	0
Plants	2	0
Carbon Chemistry	7	1
	11	1
ENGINEERING STUDIES	2	0

DISCIPLINE AREA	PRINCIPAL INVESTIGATORS DOMESTIC	PRINCIPAL INVESTIGATORS FOREIGN
PHYSICAL PROPERTIES		
Elastic Sound Velocity	2	2
Electrical	5	1
IR/Optical	4	2
Magnetic	6	2
Mag. Res./Mossbauer	4	0
Thermal	4	0
Thermoluminescence	1	2
Tracks and Radiation Damage	4	2
Other Physical Properties	7	1
	37	12
GEOCHEMISTRY		
Age Determination and Radioactive Isotopes	6	3
Stable Isotopes	3	2
Major Elements	2	5
Trace Elements	10	5
Cosmic-Ray Effects	14	5
Other Geochemistry	6	1
	41	21

Appendix C

ADVISORY COMMITTEES CONCERNED WITH LUNAR SCIENCE

Physical Sciences Committee (PSC).

1. Chairman - W. A. Fowler.

2. Members - approximately 10, including Wasserburg, Gast, Wetherill, from the lunar science community.

3. PSC reports to Associate Administrator of NASA (H. Newell). It is one of four committees in the Space Program Advisory Council (SPAC), Chairman Brian O'Brien, which reports to Deputy Administrator of NASA (G. Low).

4. PSC advises on broad policy matters, but not balance of effort between various possible space programs (This type of advice comes from SSB.)

Space Science Board (SSB), National Academy of Sciences.

1. Chairman - Charles Townes.

2. Members - approximately 24 (including three Earth Scientists).

3. NASA asks SSB for advice on specific programs or mixes of programs.

Lunar Sample Steering Group (LSSG).

1. Chairman - H. Smith.

2. Members - 5 (NASA).

3. Reports to Associate Administrator for Space Sciences.

4. Among other things, reviews recommendations of LSRB and LSAPT.

Lunar Sample Working Group (LSWG).

1. Chairman - J. Pomeroy.

2. Members - 7 (NASA).

3. Reports to LSSG.

4. Among other things, reviews recommendations of LSRB and LSAPT.

E. Lunar Sample Review Board (LSRB), Lunar Science Institute.

1. Chairman - R. Phinney.
2. Members - approximately 16 from scientific community, outside NASA. Most are lunar sample P.I.'s.
3. Reports through Lunar Science Institute to Science and Applications Directorate, NASA-MSC, and ultimately to Apollo Lunar Exploration Office, NASA-HQ.
4. LSRB evaluates research proposals submitted by prospective lunar sample investigators, recommends acceptance or rejection of individual proposals, periodically reviews balance of overall sample analysis program.

F. Lunar Sample Analysis Planning Team (LSAPT).

1. Chairman - J. Lovell.
2. Members - approximately 12 from scientific community, outside NASA (one exception, currently). Most are lunar sample P.I.'s.
3. Reports to Science and Applications Directorate, NASA-MSC, and ultimately to Apollo Lunar Exploration Office, NASA-HQ.
4. Recommends on allocation of specific lunar samples for analysis to specific approved Principal Investigators. Formulates plan for comprehensive study of the sample collection from each mission, considers sample requests made by P.I.'s. Reviews and monitors procedures and equipment in LRL and Curatorial Facility, as they affect distribution of lunar materials and long-term integrity of residual lunar collection.

G. Science Working Panel (SWP).

1. Chairman - J. Lovell.
2. Members - approximately 20.
3. Reports to Science and Applications Directorate, NASA-MSC.

4. Recommends on use of time on the lunar surface; development and use of science hardware for the Apollo missions; crew training operational support; and data analysis.

H. Apollo Photographic Team (APT).

1. Chairman - F. Doyle.

2. Members - 8 (non-NASA).

3. Reports to Science and Applications Directorate, NASA-MSC.

4. Advises on photographic hardware and on photographic aspects of mission operations and astronaut training.

PSC and SSB render high-level, broad policy advice. SSB and LSRB are the only advisory committees outside NASA.

LSSG and LSWG are in-house panels, and are included here only because they are closely involved in (*i.e.*, review the recommendations of) LSRB and LSAPT functions.

SWP and APT recommend on mission operations, and hence they will be phased out after Apollo 17.

Subject Index *

* Experiments, institutions, and committees are usually referenced by their acronyms (*cf.* Appendix A).

Subject Index

SUBJECT INDEX

Subject Index

Subject Index