THE MOON A NEW APPRAISAL FROM SPACE MISSIONS AND LABORATORY ANALYSES

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A Royal Society discussion held 9–12 June 1975, and arranged
by the British National Committee on Space Research
under the leadership of Sir Harrie Massey, Sec.R.S.,
G. M. Brown, F.R.S., G. Eglinton, F.R.S., S. K. Runcorn, F.R.S.
and H. C. Urey, For.Mem.R.S.

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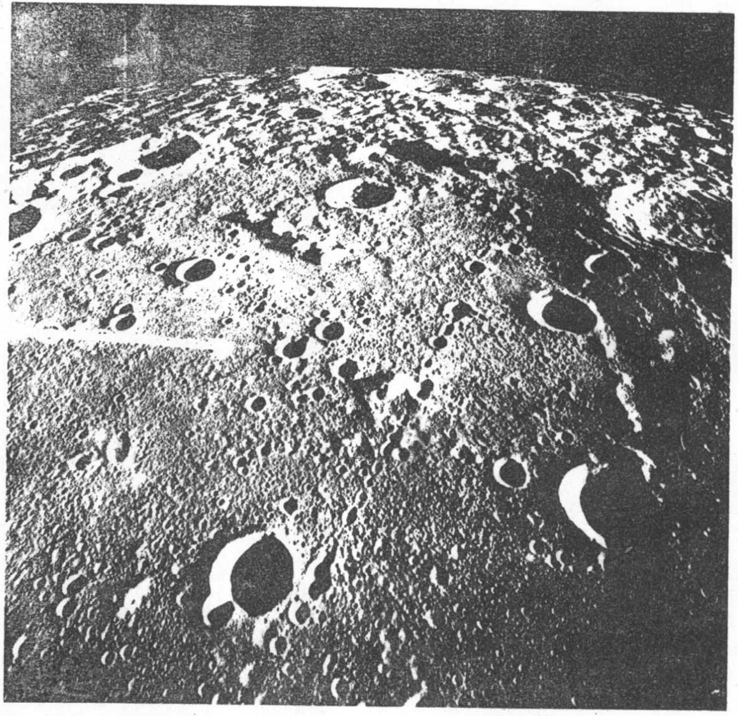

Above: Photograph of a boulder sampling station 6 at the Apollo 17 site: South Massif looms at the horizon.

Below: Apollo 16 metric photograph (2365) of the Mendeleev basin on the lunar far side. This view shows the southwest interior of the 300 km wide feature. A straight crater chain pointing toward the crater Tsiolkovsky lies on its floor.

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PREFACE

This volume presents papers delivered during the Royal Society discussion meeting held on 9–12 June 1975 under the auspices of the British National Committee on Space Research. The meeting was organized to present the findings of European and Commonwealth scientists who had participated in the analyses of lunar samples, both as principal and co-investigators in the Apollo lunar sample analysis programme and as analysts of the Luna samples provided by the U.S.S.R. Academy of Sciences under arrangements with national academies. Scientists from the U.S.A. and the U.S.S.R. were also invited to participate and so the meeting became sufficiently representative and its timing appropriate for the much needed attempt to review the whole of the work on lunar samples and the results of related space experiments. It was the purpose of the meeting, and of the Proceedings, to show how the new knowledge about the Moon, acquired over the recent decade from the intensive study made possible by the space technology developed in the U.S.A. and the U.S.S.R., had solved some and thrown light on other fundamental questions about the Moon. For practical reasons the meeting was overweighted in favour of British and European contributions; but this gave an opportunity for these laboratories to express their appreciation to N.A.S.A. and to the U.S.S.R Academy of Sciences for the opportunity to participate in a unique scientific programme. We hope that the publication will perform a service in bringing before scientists, and indeed the public in general, the remarkable increase in our understanding of the Moon which has resulted from the space programme and will show how international collaboration has been such an important feature of it.

At some risk of mistaking majority opinion for scientific truth, we would like to summarize the main advances. In the past many geologists underestimated the role of meteoritic impacts in the fashioning of the lunar surface. A small minority of the craters may be volcanic but diagnostic evidence to decide in a particular case whether a crater is endogenic is not available. Craters of all sizes from those with diameters of hundreds of kilometres down to microscopic ones are impact-produced. We know now that the Moon is covered by a thick regolith which records this incessant bombardment. Micrometeorite impacts stir the regolith and constantly expose soil particles to solar and galactic fluxes. The surfaces of grains become saturated with solar wind elements; the interiors contain myriads of radiation damage tracks left by solar flare cosmic rays. The large craters are the result of impacts on a scale with which we are totally unfamiliar on Earth. Indeed it has been the overwhelming dominance of impacts over the geological processes with which we are familiar on the Earth which has made it possible to learn so much about the overall chemical composition of the Moon from the relatively few landings. We now know that lunar chemistry differs significantly from that of meteorites and of the Earth in the relative paucity of the volatile, chalcophile and siderophile elements; this finding is clearly telling us something fundamental about the origin of the Moon. From classical studies the lunar surface was thought to be very ancient but the space programme has made this qualitative idea quantitative and a most remarkably complete series of dates for the major events in the Moon's history is now available. Petrologists have clarified the nature of the dark mare surfaces; they are of lava from the interior of the Moon but were formed by partial melting in a closed system – unlike terrestrial lavas – and the true interpretation of this is not yet clear. The composition of the highlands is that of a material which is more aluminium-rich than the interior of the Moon. Extensive early melting and differentiation of much of the Moon took place but the exact events, and particularly the source of the heat, are matters on which we are ignorant.

The physics of the Moon has yielded major surprises, such as lunar magnetism, mascons and moonquakes. The positive gravitational anomalies over the circular mare show that the lunar lithosphere is more rigid and thicker than that of the Earth: the circular mare were evidently impact basins which filled with lava to depths greater than that required for isostatic equilibrium. Although the Moon possesses no magnetic field today, the remanent magnetization of the returned samples seems best interpreted on the hypothesis that it possessed one early in its history: the presence of an iron-rich core in the Moon, capable of sustaining dynamo action in the past, is much debated. The moonquakes, though many orders of magnitude less in energy than earthquakes and clearly not associated with terrestrial-like plate tectonics, nevertheless give us a hint that the Moon's interior is not entirely 'dead', so that endogenic phenomena such as gas emissions, volcanism and convection in the interior, though controversial aspects of lunar studies, merit sober investigation. It is clear that the Moon is a much more fascinating object than it seemed even 10 years ago when the Royal Society last organized a lunar meeting (*Proc. R. Soc. Lond.* A **296**, 243 (1967). The processes on its surface and in its interior remain a fascinating contrast with the Earth providing a challenge to geophysical and geological imaginations. For example, the Moon emerges as a valuable recorder of solar system history with much of the record awaiting decipherment.

The origin of the Moon remains an enigma: this may seem remarkable in view of the great increase of our knowledge, particularly regarding events and evolution in the first 10^9 years when there exists no comparable knowledge of the Earth. The present rate of retreat of the Moon from the Earth determined from astronomical data and resulting from tidal friction, seems unlikely to have changed dramatically over the last 500 million years. A theory of the lunar origin in which the Moon is close to the Earth at an early stage is therefore attractive. Historically this is why the fission mechanism was suggested by G. H. Darwin. But the mechanics of this process is unclear particularly the angular momentum requirements: nor are the chemical differences between the Moon and Earth satisfactorily explained. The alternative of capture of the Moon requires an exceedingly improbable event, a theory which could not account for the satellites of other planets without additional assumptions such as gaseous planetary nebula. A third group of theories involve the condensation of material orbiting in the vicinity of the Earth during or after its accretion. But again, the chemical differences of the two bodies, especially in the abundance of iron are not explained. In the subject of the origin of the Moon there seems at present too many ad hoc suppositions and even miraculous coincidences: a sure sign that some key information or idea eludes us.

We wish to thank the staff of the Royal Society, particularly Mr P. Wigley and Miss P. M. F. Green, and Mrs E. Marshall of the School of Physics, Newcastle upon Tyne, for the major part they played in the organization of the meeeting and of its publication. It is also a pleasure to record our appreciation of the enthusiasm of those who attended, some from great distances and at a busy time, which made this meeting unique in the annals of the Royal Society.

G. M. Brown
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(*Discussion held* 9–12 *June* 1975 – *typescripts received various dates up to* 8 *March* 1976)

[15 plates]

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I. THE ACCUMULATION AND BULK COMPOSITION OF THE MOON

Outline of a lunar chronology

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Introduction

We present here an outline of lunar chronology and evolution based on analyses of the isotopic parent-daughter systems ^{87}Rb-^{87}Sr, U-Th-^{206}Pb-^{207}Pb-^{208}Pb and ^{40}K-^{40}Ar. An overview of the chronology will first be given, followed by an outline of the observational basis. A more complete discussion of ^{40}K-^{40}Ar results and their interpretation is presented in the paper by G. Turner in this volume. While the body of data on lunar materials is limited, the chronology for lunar evolution appears to be rather well defined. The samples which have been investigated represent mare basalts [returned by the Apollo missions (11, 12, 15 and 17) and by the Soviet Luna 16 mission] and terra rocks, which include non-mare basalts, anorthosites, troctolites and norites but are predominantly comprised of complex breccias [returned by Apollo 12, 14, 16 and 17 and Luna 20]. The mare basalts are associated with the late stage lava flows which covered the mare basins. These flood basalts have been broken up by impact processes but for the most part are associated with the local areas and have not been subject to major transport or metamorphism by impact. The highland rocks predate the mare lava flows but are not clearly associated with a particular magmatic or impact process. They may have been excavated from considerable depths and transported over wide distances. Impact metamorphism is certainly one of the critical stages in their development.

The techniques which permit the precise dating of lunar rocks are the result of a rapid development over the past nine years in mass spectrometric techniques, in refined chemical separation methods and mineral separation procedures, and in mineral identification and analysis. These methods have been applied most extensively to lunar problems, but in the future they will undoubtedly be utilized in a new generation of studies of meteorites and of terrestrial samples.

General outline

An overall summary of lunar chronology is given in the cartoon in figure 1. Mare volcanism is a clear manifestation of lunar igneous activity and is directly dated by analyses of basalt samples. The period over which mare basalts were extruded extends from 3.9 to 3.1 Ga. Clasts of mare basalts in the more ancient terra breccias are extremely rare. The rate of basalt flooding appears to have decreased with time between 3.9 and 3.1 Ga and mare volcanism seems to have terminated at about 3.0 Ga. The many suggestions of 'young' mare volcanism

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† Contribution no. 2705.

predicted by several workers based on photogeology have not been susbtantiated. In particular, the Apollo 17, site which was predicted before the mission to yield very young rocks, has instead yielded many basalt samples with ages of 3.8 Ga. The cartoon shown in figure 1, which was originally drafted before Apollo 17, showed a question mark over the small young volcano; the question mark has been deleted. The ages of lunar samples demonstrate that there has been no major lunar volcanism in the last 3.0 Ga. However, this does not necessarily mean that all lunar volcanic phenomena have ceased. This matter is not yet clear and it is important to keep an open mind to the possible continuation of lunar igneous processes into recent times.

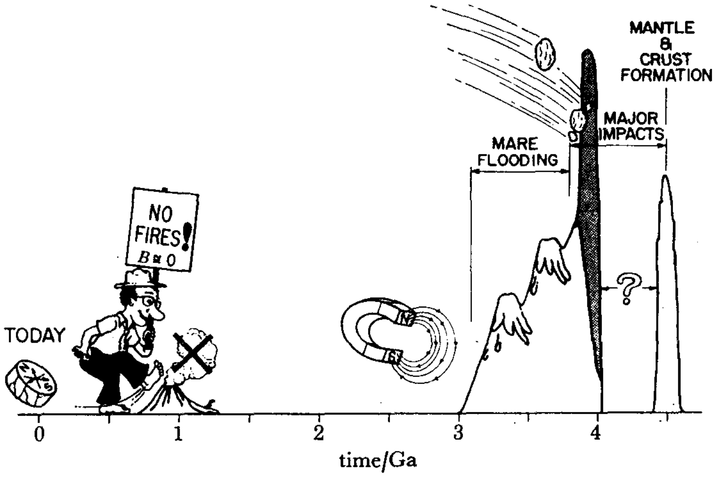

FIGURE 1. Cartoon showing the chronology of major lunar events as presently known or surmised.

Observations of 'transient' phenomena by several workers have suggested that some gaseous emanations from the lunar interior are occurring today. As we shall argue later, a special mechanism is required which permits the moon to be partially molten over its earlier evolution and then to become cool or rigid enough so as to suppress further volcanism. Rigidity of the lunar crust to support mascons is required while some mare volcanism was still going on.

A distinct period of major lunar igneous activity occurred approximately 4.5 Ga ago. This period is close to the time of formation of the moon and is associated with major lunar differentiation. The evidence for this igneous activity is both inferential and direct. Until recently there had been very little direct evidence of truly ancient lunar magmatic rocks. These ancient rocks occur as fragments within younger breccias or as isolated samples and are not obviously related to broad scale igneous morphologic features. Indeed, our ability to recognize primary lunar morphologic features other than impact basins and late mare floods has been very limited. The inferential data on early lunar processes is strong and is obtained from model ages of total rocks and soils. Demonstration of the existence of major early lunar differentiation and examples of the characteristic rock types produced during this process are of great importance since there are no observations of such processes on the earth and only fragmentary data from diverse meteorites. The duration of this early epoch of planetary differentiation is uncertain but appears to be about 0.2 Ga.

In the interval between about 4.4 and 3.8 Ga there is no *strong* evidence either direct or indirect for igneous activity on the moon. This lacuna in lunar history is indicated by a query mark in figure 1. The validity of assigning a long interval (~ 0.6 Ga) of quiescence following early lunar differentiation remains a fundamental question to be tested by careful observations. Some samples of a highland breccia from the Apollo 16 site yield ^{40}Ar-^{39}Ar apparent ages of up to 4.3 Ga (Schaeffer & Husain 1973). Comparable ^{40}Ar-^{39}Ar ages are observed in samples from highland breccias from the Apollo 17 site. It has not yet been possible to confirm these results by other methods. In some cases the nature of the events dated by the ^{40}Ar-^{39}Ar method is unclear. Because of the steep thermal gradient in the Moon, rocks that are originally at depth may undergo continuous ^{40}Ar loss and the ^{40}K-^{40}Ar system may be measuring the time at which samples were excavated from depth and brought to the surface, where the temperatures are much lower (Podosek *et al.* 1973). In this model the ^{40}Ar-^{39}Ar ages are interpreted as determining the time when fragments were excavated by large impacts during 4.6–4.0 Ga and which escaped recrystallization during the period 4.0–3.8 Ga.

There is abundant evidence of widespread shock metamorphism at a time of *about* 3.9 Ga, apparently in an interval from 4.0 to 3.8 Ga. This episode is reflected in partial to complete isotopic equilibration for all the isotopic systems so far studied. The rock types range from basaltic clasts in breccias to partially and locally recrystallized breccia matrices and to isolated fragments of plutonic rocks. Evidence for metamorphism in this period has so far been found in samples from all sites except Apollo 11 and Luna 16. This metamorphic episode represents a period of major lunar bombardment which has left a distinct imprint on materials covering the whole earth-facing side of the moon. It was first identified by our studies and was called the *terminal lunar cataclysm* (Tera, Papanastassiou & Wasserburg 1974). The question as to whether this was a distinct episode over a very narrow time interval or a series of events over ~ 0.2 Ga is not yet resolved. The terminal lunar cataclysm could represent the Imbrium impact, with a much larger ejecta blanket than predicted or, more plausibly, the formation of several major lunar basins in a highly restricted time interval. The discovery of major impacts at a time of 0.6 Ga after the initial accretion of planetary bodies (with a time constant of 0.01 to possibly 0.10 Ga) is itself of considerable importance. This phenomenon was certainly not predicted and has attracted several workers to propose storage mechanisms for the source of bombarding objects with long time constants (cf. Wetherill 1975). The implications of this late stage lunar bombardment for the cratering histories of all the inner planets have now been recognized by various workers, although the clear-cut applicability of the lunar bombardment time scale to Mercury, Mars and Venus is not self-evident.

The observation of a fossil lunar magnetic field is of major significance (cf. Strangway, Larson & Pearce 1970; Runcorn *et al.* 1970). As indicated in figure 1, the magnetic field was apparently present during the period of lunar volcanism between 3.9 and 3.0 Ga and is absent today. The existence of a field before 3.9 Ga is uncertain, since all of the rocks which are more ancient have been subjected to metamorphism during the terminal lunar cataclysm. The source of the ancient lunar magnetic field is a subject of intense interest, and a possible mechanism for its origin has been proposed (Runcorn & Urey 1973).

Rb-Sr AGES

Methodology

Since the chronology depends to a large extent on the Rb-Sr method, it is desirable to state the basic principles. If a rock system were to start at some arbitrary time with a uniform initial isotopic composition of Sr, then the different constituent phases will initially lie on a horizontal line (see figure 2). If the individual phases remain as isolated systems, they will follow the trajectories as shown by the arrows and will today define a straight line called an internal isochron.

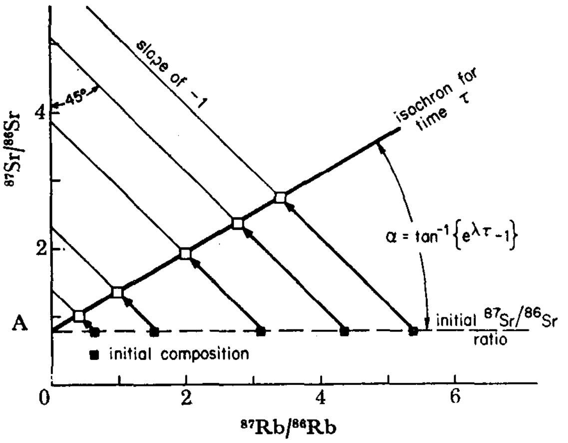

FIGURE 2. Rb-Sr evolution diagram for a set of closed systems with different ratios of Rb/Sr but which initially had the same isotopic composition (point A).

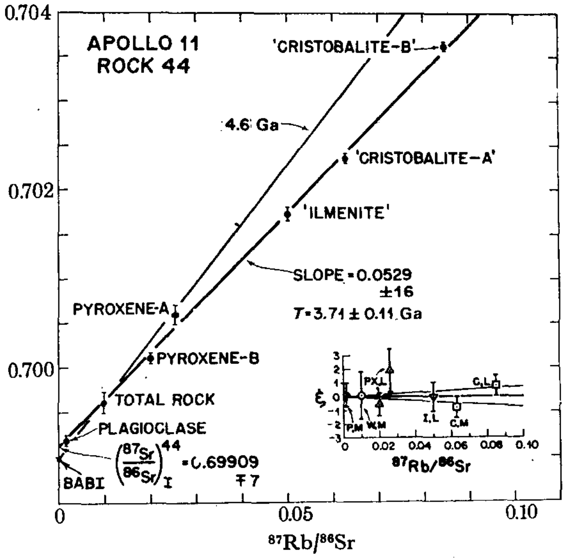

FIGURE 3. Rb-Sr data for a mare basalt from Apollo 11. Note that the initial value is above BABI. A 4.6 Ga line is drawn through BABI. The fractional deviation in $^{87}Sr/^{86}Sr$ of the data points from the best fit isochron are shown in the inset in units of 10^{-4}.

The slope of the line determines the age, and the point of intersection A determines the initial Sr isotopic composition. In every case it is necessary to establish whether a given linear data array is a true isochron representing several distinct phases and not simply a mixture of two end members without a strict time meaning. If the data points do not define a precise line, then the system is complex and neither the age nor the initial Sr are well defined. It should be noted that if, after some time τ', the system were again isotopically homogenized, then the new initial Sr isotopic composition would be increased to the value of $^{87}Sr/^{86}Sr$ for the total rock at the time of homogenization. This increase in the initial value with time will be used in our arguments. Given the initial value for the Moon at the time of formation, then it follows that any excess above this value for the initial $^{87}Sr/^{86}Sr$ value of a lunar rock must represent the passage of time in a lunar reservoir.

In addition to internal isochrons, the concept of model age is very useful. If a value for the isotopic composition of Sr can be chosen that represents the value when the moon was first formed, then we may calculate the model age of a sample relative to the lunar initial value.