

LUNAR ROCKS AND MINERALS¹⁾

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INTRODUCTION

Not many years ago the idea of bringing lunar rocks back to earth for laboratory investigation seemed to me to have an air of unreality about it. This was dispelled completely after my first visit to the Manned Spacecraft Center at Houston in 1967, when I saw the scale of preparations for the Apollo missions. Now, only a few years later, the first two manned lunar landings have been accomplished safely and are already receding fast into history.

In Manchester we were fortunate enough to be given small but in most respects more than adequate amounts of Apollo II samples for general mineralogical and petrological investigations. Like other groups of investigators we were required to report on our findings at a conference at Houston in January, 1970, about three months after receipt of samples, and there was the unusual feature of an agreement (completely honoured by the 140 or so groups of investigators) not to publish anything before that date. The account of the geological and geochemical aspects of lunar rocks and minerals which follows is based upon our own experience of the lunar samples at Manchester together with the reports presented by many investigators at Houston and subsequently published in *Science* (1970).²⁾

As anyone will see from the latter publication there was a planned degree of overlap in the approved

projects, so that several laboratories independently examined, in some cases the same circulated specimens, and in others different splits from single pieces of rock. It was perhaps not unexpected that there was a great measure of agreement concerning observations and descriptions, and even first order interpretations had much in common. I think everybody realised the dangers of extrapolating from one small sample to theories of lunar (and even solar) evolution, but some were more adventurous than others, and of course the further away from strict observation the more diversity ensued.

First, as to what was seen in the samples. Broadly, they can be categorised as crystalline rocks, breccias and dust. A survey of a large number of fragments gave approximate percentages: crystalline rocks about 52%, breccias about 35%, and the remainder largely glass or glass-coated fragments. In the general publicity on lunar samples, the crystalline rocks received rather less mention than the more news-worthy moon dust and the glass marbles seen in the dust and breccias.

CRYSTALLINE ROCKS

The crystalline rocks (figs. 1 and 2) are on the whole rather fine-grained, but do show a range of grain sizes (approx. 0.1 mm to 2 mm) and textures from what might be called, in view of their compositions, ilmenite basalts to ilmenite dolerites and micro gabbros. Many of the fine-grained rocks are vesicular, indicating a degassing process at or near the lunar

¹⁾ Voordracht uitgesproken tijdens de jaarvergadering.

²⁾ Vol. 167, no. 3918, p. 447-784.

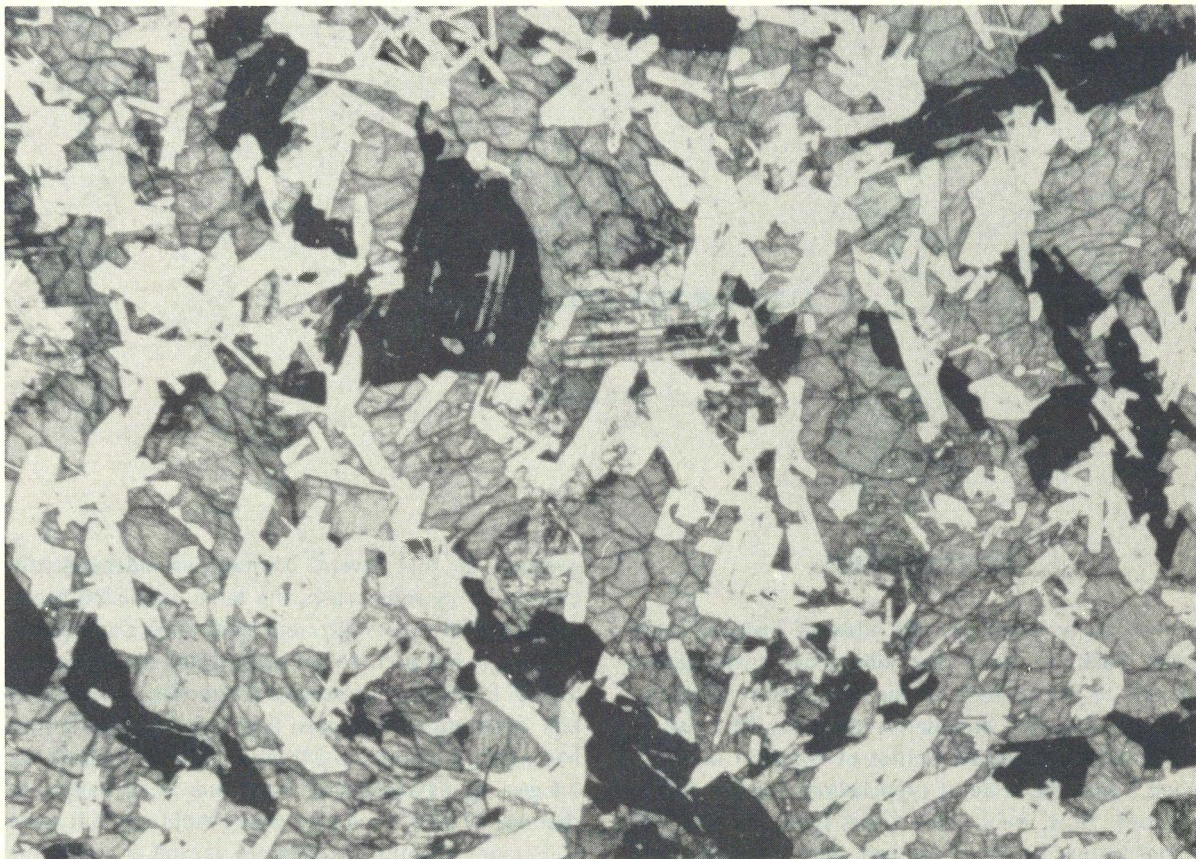


Fig. 1

Thin section of relatively coarse-grained crystalline rock (Apollo II; 10044) seen in plane polarised transmitted light. Ilmenite (black), pyroxene (grey) and feldspar (white) are easily recognisable. ($\times 25$).

surface, and the coarser grained rocks show vugs: both vesicles and vugs tend to be lined with well formed lustrous crystals.

The most abundant minerals of these basic rocks are pyroxene (often around 50% by volume), ilmenite and plagioclase feldspar of bytownite composition. Before describing details of each mineral, it is worth considering the variations in mineral proportions exhibited among the crystalline rocks as a whole. A number of investigators discerned a relationship between grain size and mineral content, ilmenite increasing and feldspar decreasing as grain size decreases, while pyroxene remains remarkably constant. (These trends are also consistent with the variations in chemical compositions as between coarse- and fine-grained rocks). The most common interpretation of grain size variation in terrestrial igneous rocks is

that it reflects rates of cooling, and variations in the proportions of heavy and light minerals in rocks are commonly taken to indicate crystal fractionation under gravity. The latter concepts do not lead, however, to a satisfactory explanation of the mineral modes of these lunar rocks, and it is possible that an overriding factor may be the viscosity of the melt which is an order of magnitude lower (Weill et al., 1970) than that for most terrestrial basaltic rocks. Crystal nucleation can be much affected by viscosity, and viscosity in turn will be very much dependent upon Ti content, so rocks with different Ti contents (hence ilmenite percentages) may crystallize differently. It is not easy to discriminate between two possibilities, either that the different rocks form a series deriving from a single magma source, or that they represent unconnected bodies of magma. Be-

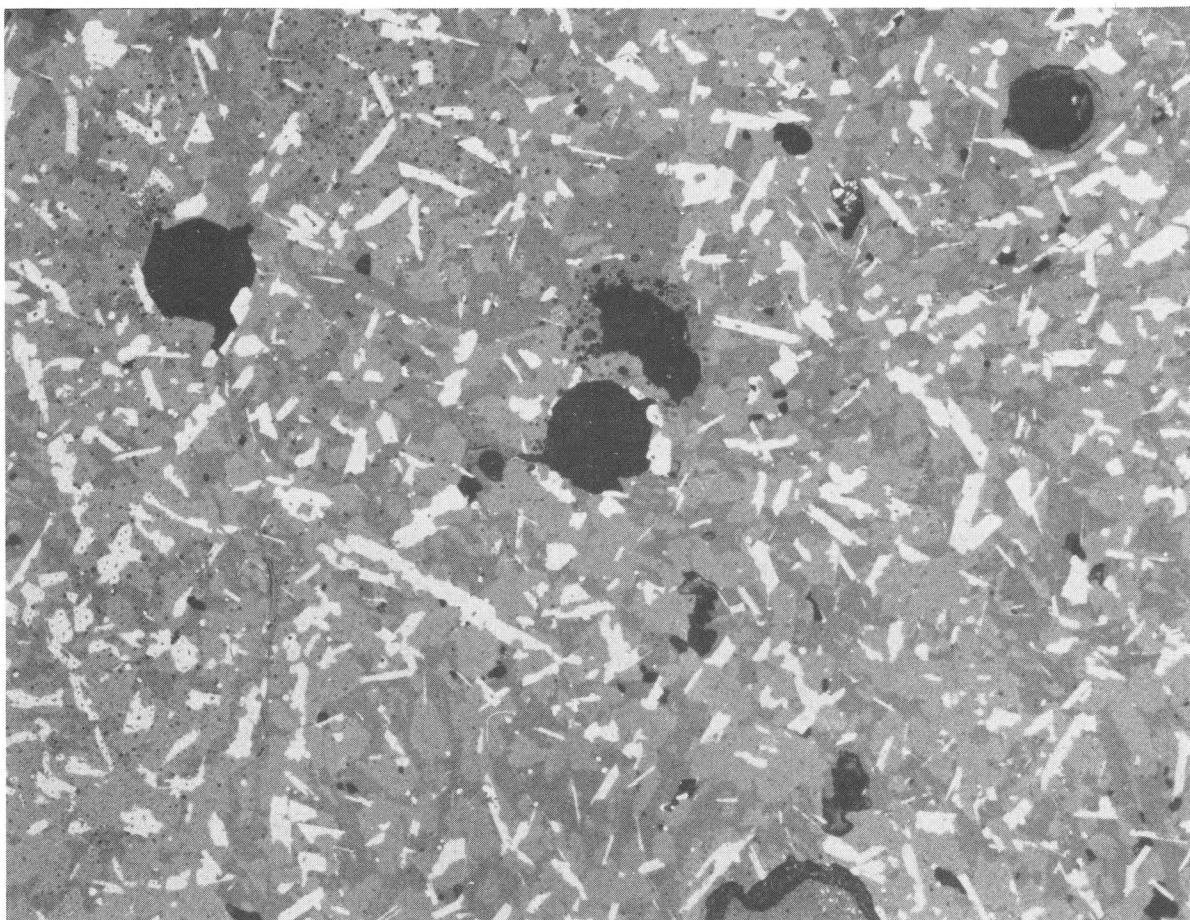


Fig. 2

Polished surface of fragment of fine-grained crystalline rock (Apollo II; 10085) showing ilmenite (white), pyroxene (light grey) and feldspar (dark grey). Vesicles are evident, some filled or partially filled with plastic embedding medium. ($\times 100$).

cause of meteorite activity on the moon, the provenance of Apollo II samples is uncertain; even though they were all retrieved from one small area of the lunar surface, a spatially widespread origin of the rocks cannot be ruled out.

Pyroxene is the most abundant mineral of the crystalline rocks, and shows many interesting features. Its composition can be said to lie in the augite to sub-calcic augite field (and more rarely pigeonite), but this allows considerable variation which is indeed exhibited. The variations in pyroxene composition are extremely wide, as shown in fig. 3, and can be interpreted in more than one way. The range from Mg to Fe enrichment is not unlike that shown by pyroxenes of many basic rocks and can be taken to mean a differentiation series with early Mg-rich and

later Fe-rich pyroxene crystallization. Similarly, the Ca-rich to Ca-poor trend (with more or less constant Mg) is akin to that observed in certain terrestrial tholeiitic lavas. However, it should not be forgotten that, except for zoned crystals (see below), we do not know the time sequence of crystallization, nor the true spatial relationships of the pyroxene crystals in the lunar rocks, and so the fractional crystallization trends might be illusory. The continuation of the apparent trends beyond the usual iron enrichment limit for terrestrial pyroxenes may be facilitated by the stability of high ferrous iron concentrations in the oxygen deficient lunar regime.

In addition to a wide range of compositions being shown from one grain to another, there is also considerable zoning within single grains, usually from

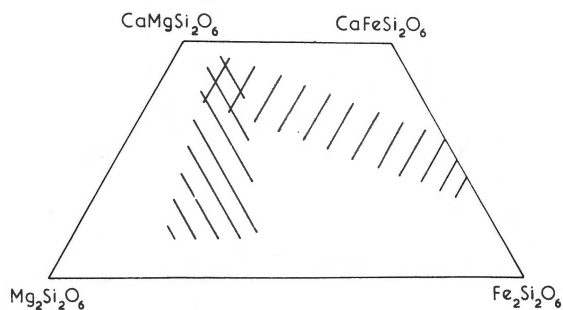


Fig. 3
Shaded area shows approximate ranges of composition exhibited by Apollo II pyroxenes as reported by the various investigating teams.



Fig. 4
Thin section (Apollo II; 10044) between crossed polars showing sub-grain misorientation in pyroxene grain. The largest grain of pyroxene has a dark band down the middle; the central sub-grain is very near extinction while the outer regions appear bright. Ilmenite, plagioclase feldspar and a small area of cristobalite can also be seen (X 50).

Mg-rich cores to Fe-rich margins. The zoning can be taken to indicate a somewhat rapid crystallization, although quite how rapid cannot easily be estimated. It is safe to say at least that crystallization was not so slow that adjustment of crystals and liquid to equilibrium could take place.

Both of the above compositional features are not uncommon in terrestrial pyroxenes, but the lunar pyroxenes also show a rather more unusual feature of sub-grain misorientations. These can be observed on a moderately large scale in the polarising microscope (fig. 4), where some grains show sweeping extinction over a wide angle, and others are split into a mosaic of subgrains with misorientations of up to about 5° . Smaller subgrains can be seen by electron microscopy, which also reveals dislocations running into subgrain boundaries, and it has been suggested (Baily et al., 1970) that these are evidence of an annealing stage in the crystalline history. Various possibilities for an annealing agency suggest themselves, as for example, initial rapid cooling on exposure of a magma at the lunar surface, followed by very slow cooling after formation of a solid "skin", or perhaps solidification at or near the surface, followed by re-heating through nearby meteorite impact. The sub-grain misorientations have generally been interpreted as arising during the crystallization process. Alternatively they could be a manifestation of shock metamorphism, but if this is so, then other minerals in the same rocks seem to be surprisingly little affected. In the breccias and dust, where shock effects are more prevalent, they serve to produce in the pyroxenes shock induced twin lamellae and these are rare in the crystalline rocks.

X-ray and electron diffraction studies of the lunar augites show them to be unmixed or partially unmixed into Ca-rich and Ca-poor lamellae of sub-microscopic width (fig. 5). On the evidence of the fine scale exsolution lamellae, it could be argued that the cooling rate cannot have been rapid enough for solidification as a glass or as a homogeneous pyroxene, but also that it cannot have been very slow, since in the latter case segregation into two phases on a coarser scale would be expected. The suggestion of annealing could also be invoked here, since a single phase produced on rapid quenching might be induced to exsolve two pyroxenes on subsequent heating (Brown and Gay, 1959).

One of two new minerals reported occurs in close association with the pyroxene. It is a pyroxenoid (Fe,

Ca, Mg)SiO₃, isostructural with pyroxmangite, but since it has a high ferrous iron rather than manganese concentration it has been named pyroxferroite.

The plagioclase feldspars in the Apollo II basalts show some variation (Ca, Na) in composition, including zoning, but over a narrower range than that exhibited in many terrestrial occurrences; this is probably a consequence of there having been little sodium available for the rock as a whole. This striking lack of sodium may have been a feature of the primordial lunar composition, or, it has been suggested, sodium might have been present originally (and may be present now at depth) but was lost by volatilisation when magma reached the lunar surface.

The ilmenites of the lunar basalts are significantly lacking in Fe₂O₃ as compared with terrestrial ilmenites. While many ilmenite analyses showed the stoichiometric proportion TiO₂:FeO = 50:50, several showed excess TiO₂ which could in some cases be attributed to the presence of a fine intergrowth with a Ti-rich phase, or the presence of Mg substituted for Fe, but where there was no evidence of such features, it has been suggested that some Ti may be in the trivalent state.

Ilmenite grains appear to be sensitive recorders of exposure to shock. Micrographs of ilmenite from breccia and dust frequently show shock lamellae, and electron micrographs show a high dislocation density. Both features are very much less evident in ilmenites of the crystalline rocks. While some of these characteristics may have been produced by the shock waves from large scale meteorite impact, exposure to small scale micro-meteorite impact may also have been involved. Shock effects are very much less evident in ilmenites of the crystalline rocks, indicating a degree of protection afforded to them in the latter environment.

Olivine is present to a small extent in the crystalline rocks, particularly in the fine-grained samples. Two kinds of olivine have been reported, Mg-rich probably early formed crystals, and fayalitic olivine associated with late stage crystallization. The forsteritic olivines have unusually high Cr and low Ni content as compared with terrestrial samples, and there is evidence for some of the Cr being present in the divalent state.

Free silica is present in the lunar rocks in the form of tridymite and cristobalite. While the stability fields of these polymorphs are known to be above 870° and 1470°C respectively at low pressures, their existence

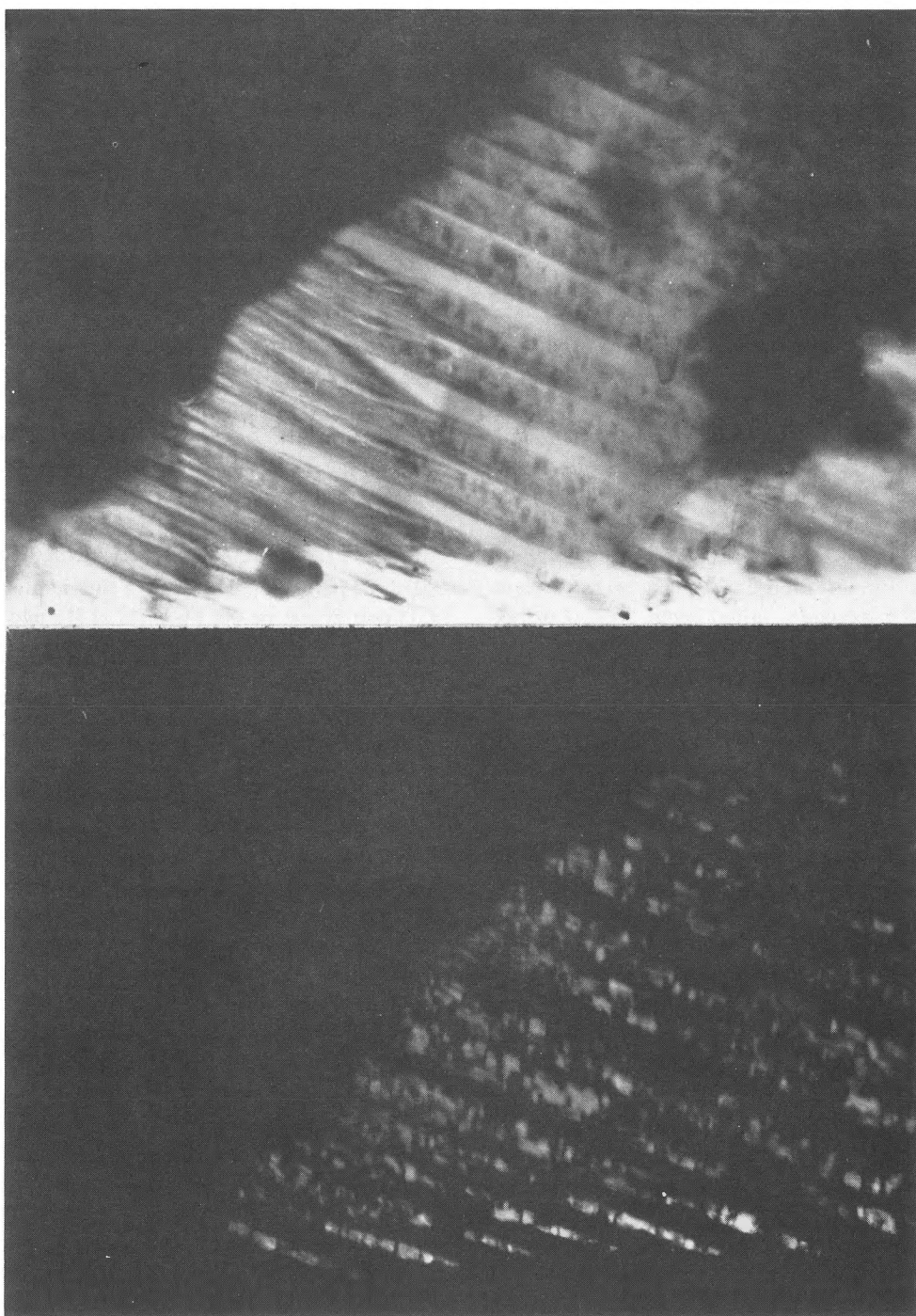


Fig. 5
Electron micrographs of lunar pyroxene grain showing augite and pigeonite lamellae. (Width of lamellae approx. $200\text{\AA}$).
top: bright field illumination.
bottom: dark field illumination.

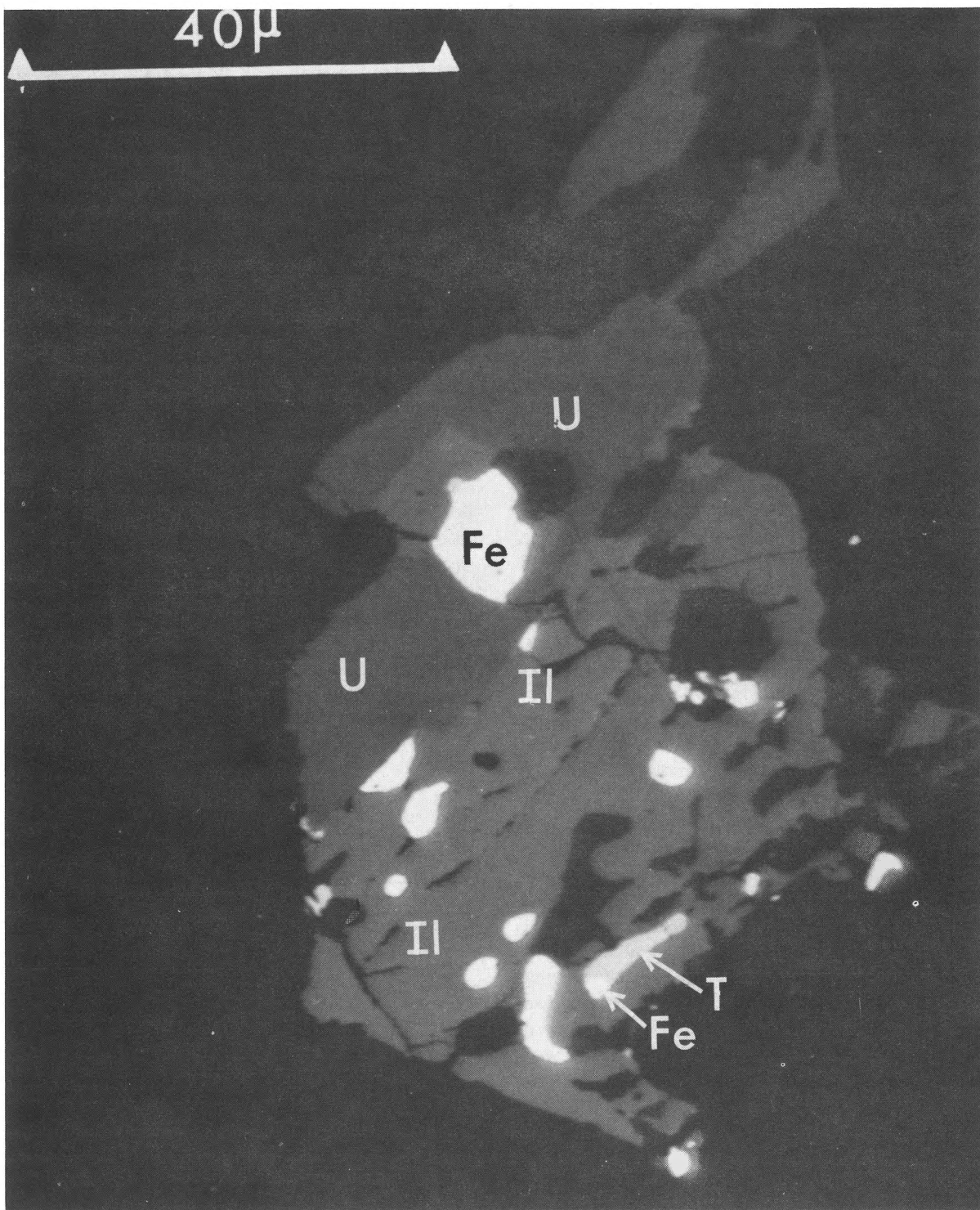


Fig. 6
Fragment of crystalline rock (Apollo II; 16144) seen in reflected light.
Il ilmenite, U ulvöspinel, T troilite, Fe native iron. (Silicates appear black).

metastably at lower temperatures is well known, and it is also quite possible for each to nucleate and crystallise below the minimum temperature of its stability field (F y f e, 1960). A small amount of an alkali feldspar has been found intimately associated with the silica phases, and together with them probably represents crystallization from residual liquids.

Several spinels have been reported in the Apollo II samples. Ulvöspinel occurs associated with ilmenite (fig. 6), whereas picotite occurs as inclusions in olivines. A spinel of unusual composition (Cr, Ti, Fe)₃O₄ has been reported and is thought to contain some Ti in the trivalent state. Very small amounts of magnetite have been reported by some investigators.

The second of the two new minerals reported is an Fe, Mg, Ti oxide which was first referred to descriptively as ferropseudobrookite. Later, it has been officially named armalcolite, a synthesis after the names Armstrong, Aldrin and Collins.

The only sulphide mineral reported is troilite, which occurs together with native iron (fig. 6). The assemblages FeS + Fe, rather than pyrrhotite with its iron deficiency, is a clear indication of low oxygen fugacity, and moderately low sulphur partial pressure. It is of interest also that the native iron in the crystalline rocks is virtually free of Ni and Co by contrast with the Fe-Ni alloy composition of the metallic particles found in the lunar dust and breccias. The troilite-iron assemblage probably represents crystallization from an immiscible liquid.

Apart from a few reports of very sparse or even single grains of phyllosilicates and an amphibole, no hydrous minerals have been observed in the lunar rocks. Apatite is present but has been confirmed as being fluorine- and chlorine- rather than hydroxyl-bearing. Some of the minerals found so far only as the odd grain or two were located among the lunar fines, and contamination by terrestrial material cannot as yet be ruled out. Others, however, were retrieved from vugs in crystalline rocks, or were found adhering to major Apollo II minerals, and are thus more authenticated.

Experimental studies at high pressures and temperatures on lunar rocks and on simulated lunar rocks show that for most relevant compositions, crystallization from a melt began at about 1200°C and that there was a rather narrow melting interval. The more or less cotectic crystallization of pyroxene, plagioclase and ilmenite can be taken to indicate that the

rock was formed as a last stage of fractional crystallization of a melt, or that it was the first product of partial melting of a rock of different composition. Experiments at different oxygen pressures confirm that the correct mineral assemblage is obtained only at p_{O_2} of the order of 10^{-12} atmospheres or less. A highly reducing environment is also attested to by several of the mineralogical features already described, i.e. native iron, virtual absence of Fe³⁺, abundance of Fe²⁺, and probable existence of Ti³⁺ and Cr²⁺. There still remain, however, the two possibilities that either this low oxygen pressure was a feature of the moon at an early stage in its formation, or that it is associated with later crystallization at or near the surface of a moon which had already lost its atmospheric gases.

An obvious question is whether or not the Apollo II basalt might be representative not only of the wide region of the Mare Tranquilitatis but also of the moon at depths beneath it. Assuming that the moon's interior is or has been hot, experimental work shows that the interior cannot have basaltic character, since at pressures of about 13 kilobars, corresponding to a depth of about 300 kilometres, and assuming temperatures above about 1000°C, the lunar basalt would be transformed to eclogite. The latter would have an appreciably higher density and this would not accord either with the observed density of the moon as a whole (not very different from that of the

TABLE I

Comparison of the chemical composition of an Apollo II anorthositic gabbro fragment with the composition of Tycho ejecta (Wood et al., 1970).

Element	Atomic percentage	
	Anorthosite	Tycho
C		<2
O	60.9	58 ± 5
Na	0.2	<3
Mg	4.1	4 ± 3
Al	11.3	9 ± 3
Si	16.2	18 ± 4
P		
S	5.4	6 ± 2
K		
Ca		
Ti		
Cr	2.0	2 ± 1
Mn		
Fe		
Ni		

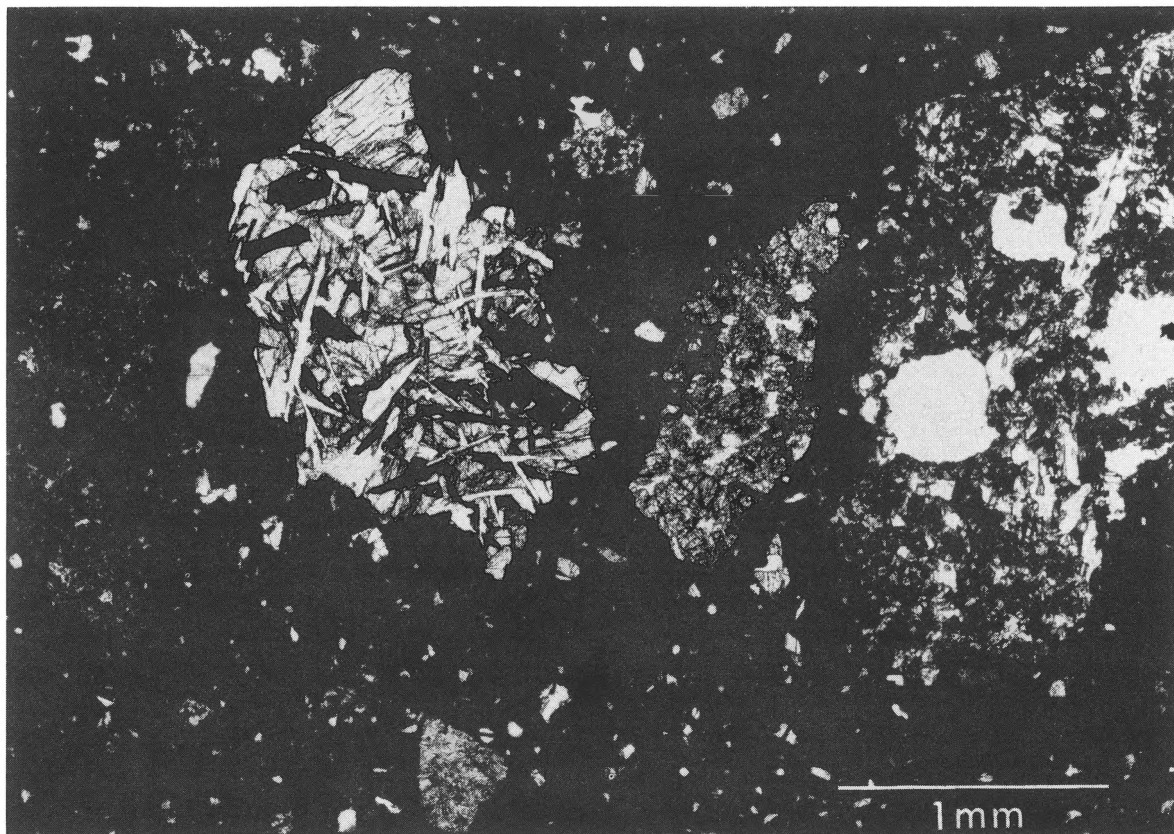


Fig. 7

Thin section of breccia fragment (Apollo II; 10046) seen between crossed polars, showing mineral grains and rock fragments of three different kinds.

basalt), or with the observed moment of inertia (O'Hara et al., 1970, and Ringwood and Essene, 1970).

In addition to the basaltic crystalline rocks, many investigators reported in varying degree of detail, the existence of light coloured rock fragments composed largely of calcic plagioclase and described as gabbroic anorthosite. It has been postulated that these fragments originated at some distance from the Apollo II site, possibly from the so called "lunar highlands". Their analyses match reasonably well (table I) with the analyses recorded by the unmanned Surveyor 7 spacecraft when it landed in a lunar highland region. It has been suggested that the lighter coloured rocks may represent an early formed lower density lunar crust, which was subsequently penetrated by the basaltic lavas during either internally generated or meteorite triggered volcanic episodes. It is, however,

also possible that anorthositic fragments may have been derived by a more local fractionation process from the same source as the basaltic rocks. Age determinations on the anorthositic rock and on the mountainous regions of the moon will clearly be highly significant.

BRECCIAS AND DUST

Studies of the lunar breccias show them to be agglomerations of rock and mineral particles together with glass and dust (fig. 7). The simplest interpretation of the breccias, and one which is supported by many observations, is that they are the result of the processes of fragmentation, melting, partial melting, sintering and welding, acting upon pre-existing crystalline rocks (and other breccias and dust) pre-

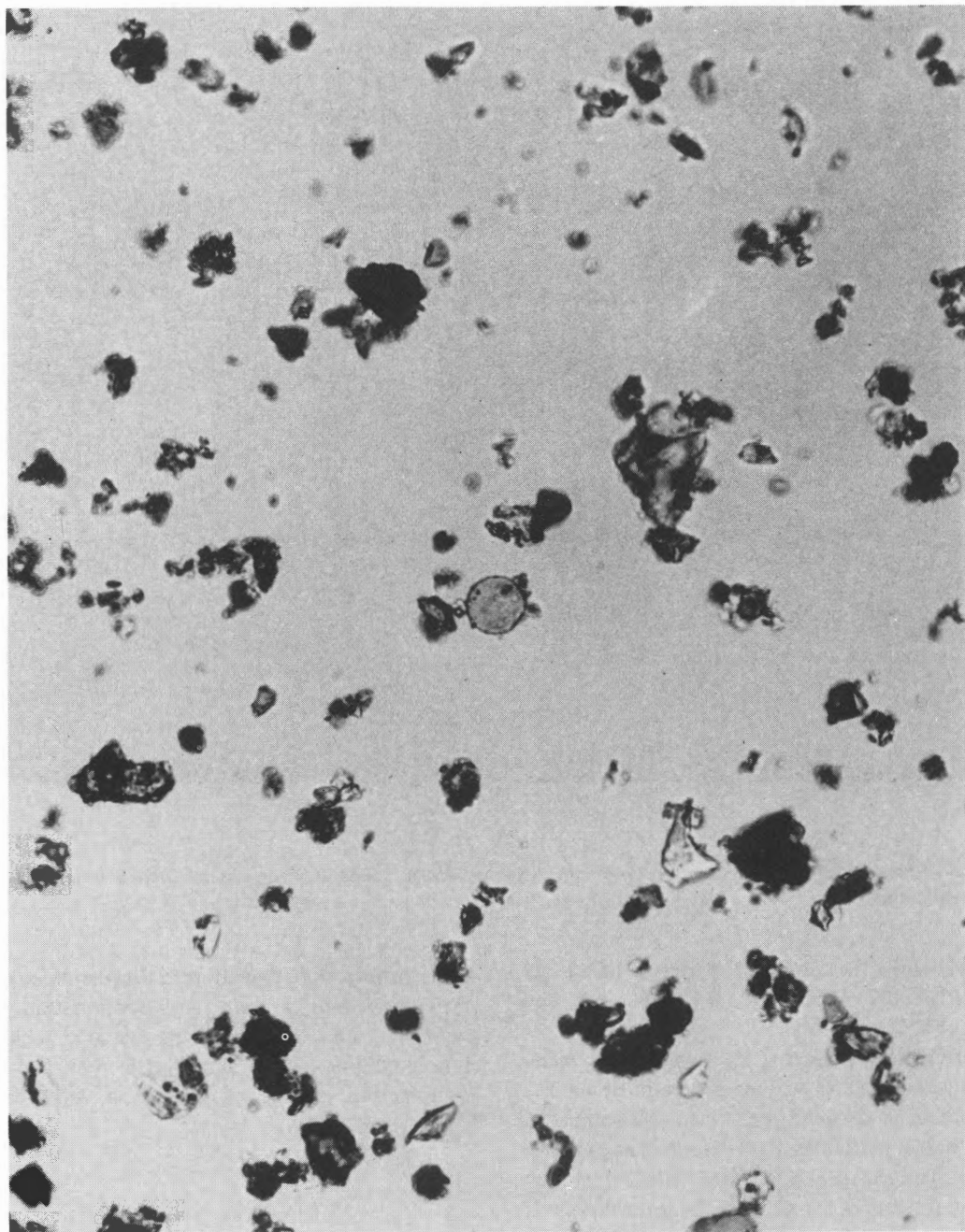


Fig. 8
Moon-dust (Apollo II; 10085) seen in transmitted plane polarised light, including a glass spherule (centre). Magn. $\times 100$.

sumably through meteorite impact events.

The dust itself is a mixture of crystalline and glassy fragments, and the latter contain angular and rounded (sometimes nearly spherical) particles (fig. 8). Repeated impacts may have been involved in

producing these fine particles. The glassy spheres are very varied in composition and character; some are homogeneous, some not, some occur with adhering smaller particles, some without. They have been described by some, rather picturesquely, as a "fiery

fain", and among several possible modes of origin, they may be the result of a meteorite induced spray of molten material, or of the volcanic eruption of lava spray into a vacuum. Fine glassy fragments (Pelées tears, Pelées hair) have of course been observed associated with terrestrial volcanoes, and man made examples are found in the "fly ash" of industrial furnaces.

METEORITES

Evidence of the presence or absence of meteoritic material on the lunar surface is obviously a matter of great interest. Small particles of Ni-Fe in the breccia and dust are taken to be clearly meteoritic origin. Apart from these, there are no clearly recognisable meteorite fragments, but an estimate has been made from the trace element abundances assuming high levels of certain elements (Ni in particular but also Cd, Zn, Ag, Au, Cu, Th) to be characteristic of meteorites. This estimate puts the amount of meteoritic material at between 0.1 and 1%. If an appreciable amount of this was of carbonaceous chondrite character, there ought to be present a higher level of carbon than that found, but perhaps volatilisation accounts for this deficiency, as indeed it might for the generally low abundances of meteoritic fragments of any kind.

CHEMISTRY

The major element chemistry of Apollo II samples is indicated in table 2. The most striking feature is the high Ti content corresponding to the abundance of ilmenite, and while Ti-rich rocks are now unknown on earth, they usually at the same time have appreciable alkali content. This is clearly now shown by the lunar rocks, and the question of loss of alkalis from the lunar composition as a whole (if it is truly a feature of the moon as a whole) has been referred to already. The high Ti content is not a ubiquitous feature of lunar rocks, as has already been shown by Apollo 12 results, and indeed it may be unrepresentative of the lunar surface. Chromium, zirconium and rare earth elements are also significantly at higher levels than in terrestrial rocks. Differences are notable in the chemistry of the different kinds of material (table 2) and these may be traced to a number of causes, but principally there is the likelihood that,

TABLE II

Analyses of lunar rocks (Agrell et al., 1970).

	Fine cryst.	Coarse cryst.	Breccia	Dust
SiO ₂	39.60	42.46	41.96	42.16
Al ₂ O ₃	9.51	10.21	11.85	13.60
Fe ₂ O ₃	0.06	nil	nil	nil
FeO	19.12	17.60	16.51	15.34
MnO	0.28	0.28	0.23	0.20
MgO	8.10	5.96	7.63	7.76
CaO	11.07	12.25	11.38	11.94
Na ₂ O	0.36	0.48	0.49	0.47
K ₂ O	0.05	0.11	0.20	0.16
H ₂ O ⁺	0.15	0.10	0.11	0.05
H ₂ O ⁻	nil	0.01	0.04	nil
TiO ₂	11.10	9.18	9.02	7.75
P ₂ O ₅	0.04	0.04	0.07	0.05
Cr ₂ O ₃	0.47	0.21	0.31	0.30
S	0.14	0.18	0.15	0.12
F	nil	nil	nil	nil
Fe	0.20	0.60	0.60	0.60
Total	100.25	99.67	100.55	100.50
Less S = O	0.04	0.05	0.04	0.03
Total	100.21	99.62	100.51	100.47

compared with basaltic rock, the breccia and dust both have components derived from petrologically different terrain. Such factors must also influence the trace element content.

In view of the overall character of the Apollo II lunar rocks, it is clear that they do not match at all closely any terrestrial rocks, or average earth crust composition, or estimates for the earth as a whole, or for the solar system, or meteorites of any kind, or tektites. The closest analogy is with basaltic achondrites. The overall depletion of such volatile elements (e.g. Bi, Hg, Zn, Cd, Th, Pb) with respect to solar abundances can be used to argue that lunar formation involved a fractionation process at a primitive stage at temperatures of the order of 1000°C.

AGES OF LUNAR ROCKS

The dating of the Apollo II crystalline rocks as 3.7×10^9 years old is unequivocal and of outstanding importance to selenologists. Not so clear is the meaning of the apparent age of 4.6×10^9 years for the breccia and dust. This seems to me to mean one of three things. First, that the figure is not a true age since it has been derived from material the particles of which are not petrologically cogenetic and which cannot be described as a closed system. Clarification by geochronologists is needed of the meaning of an "age" in these circumstances. The second possibility

is that the age given is an average of the true ages of particles in the breccia, and while some are basaltic rock particles with ages 3.7×10^9 years, others are considerably older than 4.6×10^9 years. A further possibility is that the crystalline rocks in the breccia, though apparently similar to the independent basaltic rock fragments, really represent an older generation of igneous rock. A detailed comparison of the mineralogy and chemistry of igneous rock fragments within and outside the breccia would seem desirable.

In discussing lunar geology, some mention should be made of fossils and sediments. One of the most exciting aspects of lunar investigations has been the search for evidence of life, either past or present. So far it must be stated that there is no such evidence. Biologists have looked for living organisms, and palaeontologists have looked for fossils but none have been found. Careful analyses have shown the presence of biologically important chemicals, but only at concentrations compatible with contamination by terrestrial materials. While metamorphic rocks did get an unsympathetically received mention at the Houston Lunar Science meeting, nobody to my knowledge mentioned sediments at all. Although topographical features of the lunar surface have been noted by some as reminiscent of terrestrial morphology associated with sediment formation, the rocks and minerals which we now have from Mare regions do not support this interpretation.

CONCLUDING REMARKS

Much has been said about the value or otherwise of going to the moon, and discussion of the point in general would be inappropriate here; whatever else is said, however, as geologists and scientists we must surely appreciate greatly this chance to examine the moon at close quarters. The retrieval of samples has made possible a very thorough examination by all manner of techniques yielding far more detailed results than could have been obtained by automatic instruments placed on the lunar surface. The collection of specimens by men rather than by machines has given further advantages, and I have no doubt that as future missions develop the selection of appropriate samples by an astronaut with good geological training will become increasingly important.

Increased knowledge of the moon is likely to give us increased understanding of the solar system and of the earth. The moon can be regarded as a sensitive

recording instrument with a very long memory from which we can retrieve information concerning events in the solar system over a very long period. Because the moon is considerably smaller than the earth its history is probably a good deal simpler. For much of its history it has not been complicated by the effects of an atmosphere and it is less likely to have had complex recycling of crustal and mantle material.

The present conditions of the earth and moon follow largely from their initial compositions and thermal histories, neither of which we know very much about for either body. If we can study in detail rocks from a considerable number of sites on the moon, we may be able to deduce its thermal history and this could help in unravelling that of the earth.

It will be noted that most of the observations I have mentioned in the above account are capable of at least two explanations. The first Apollo investigations of lunar samples have provided a few answers and many more questions. However, an important step on the way to understanding is surely to ask the right questions.

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