PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Lunar chronology as determined from the radiometric ages of returned lunar samples

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Introduction

We have heard earlier in this Discussion Meeting that from the systematics of Sr and Pb isotopes in lunar samples, it is possible to ascertain that the Moon had a solid crust about 4.6 Ga ago, that is, very soon after the formation of the solar system. In addition, it would seem that the major ring-basins on the Earth side of the Moon were all formed before 3.8 Ga ago. After the formation of the basins by impact, there was extensive magmatic activity in the form of basalt flows, expecially in the major ring-basins. About 3.1 Ga ago, all major lava-flow activity on the Moon had ceased. This outline of lunar chronology is accepted in practically all proposed interpretations of the radiometric ages.

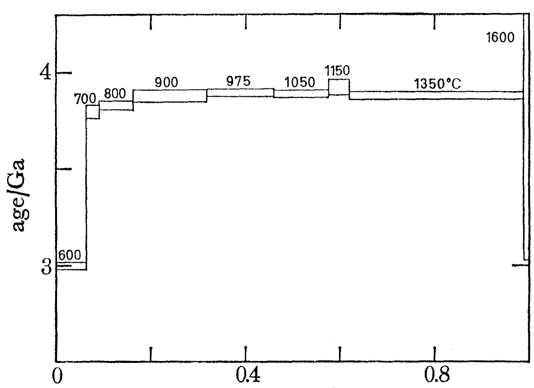
The first 600 Ma of lunar chronology is not as clear. During this time the multi-ring basins were formed. It has been proposed by G. Turner and by G. J. Wasserburg at this meeting, that the multi-ring basins formed in a rather short interval of time, perhaps as short as 100 Ma. This would imply an intense cratering rate some 3.9 Ga ago and a rapid decline in cratering rate thereafter. Such an event would have probably greatly altered the other bodies in the solar system, especially the Earth, and as such is of no small significance. It has been pointed out previously by Tera *et al.* (1974) that an alternative interpretation of the radiometric data is that widespread, simultaneous metamorphism (which the systematics of the lead isotopes in the highland rocks seems to imply) could as well result from a single widespread event such as Imbrium as from a multiple basin-forming sequence in a short period of time. In that case, the chronology of the multi-ring basins is an open question.

I should like to present arguments which lead to the conclusion that, indeed, Imbrium ejecta probably dominate most lunar highland samples and that it seems possible to date several major basins at times considerably older than 3.9 Ga ago.

Let me start by emphasizing what probably lies at the crux of the problem, namely the difficulty of ascertaining the point of origin of a given lunar sample returned by the Apollo program. It is almost impossible to say with certainty from which crater or from which volcanic process a given sample comes. One has only to look at a photograph of the Moon to realize that a crater only as big as Tycho can send ejecta over distances almost half way around the Moon.

Mare volcanism

Let us consider the problem in connection with the mare lava flows inside the multi-ring basins. One would like to know, for each basin, the time and duration of the volcanic activity. Ideally, one would like a core through the entire basalt sequence of flows. What one has on the other hand is a suite of rock samples which were selected from the lunar regolith by the Apollo astronauts. For the Apollo 11 return, for example, it is possible to say that a particular basalt represents with high probability a lava flow from Mare Tranquillitatis. Whether a given basalt represents the most recent, top flow or whether the basalt represents an older, deeper flow is not certain. One has no way of knowing whether all the flows were sampled or not. If one determines radiometric ages for a number of basalt samples and always obtains the same age, one would not know whether the basalt flows were all the same age or whether one had only sampled the last flow. If one finds a spread in ages for a given basin, one can conclude that volcanic processes in that basin took place over a time at least as long as the spread in ages. However, one may still have not sampled all the flows, and as a result the period of volcanism may have indeed been longer.



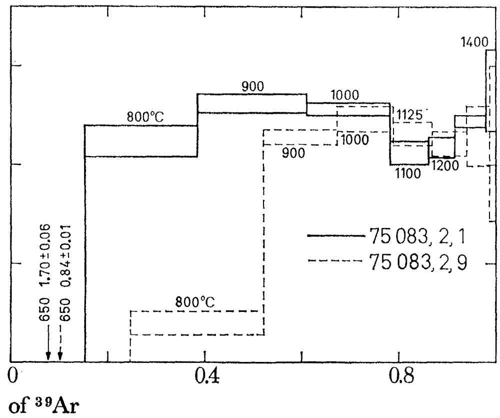


Figure 1. Temperature release pattern of argon from mare basalt 78503,7,2.

Figure 2. Temperature release pattern of argon from two illmenite basalt fragments.

Table 1. Duration of volcanism in mare basins

basin	Ga
Mare Imbrium	3.1–3.4
Mare Serenitatis	3.7–3.9
Mare Tranquillitatis	3.6–3.9

Turning first to the basalts from Mare Serenitatis, in figures 1 and 2 are shown the temperature-release profiles of argon from several neutron-irradiated Apollo 17 basalt fragments. Figure 1 shows a well defined argon release pattern with an age of 3.89 ± 0.03 Ga. The argon release patterns shown in figure 2 show more gas loss, with plateau ages of 3.78 ± 0.03 and 3.68 ± 0.04 Ga. Previous measurements (Huneke *et al.* 1973; Husain & Schaeffer 1973; Kirsten & Horn 1974; Schaeffer & Husain 1973; and Turner & Cadogan 1974) have shown a spread in ages from Apollo 17 samples of 3.68 to 3.89 Ga. Similar studies have been made for Apollo 11, Mare Tranquillitatis (Stettler *et al.* 1974), and Apollo 15, Mare Imbrium (Husain 1974). The results for the duration of volcanism in the three basins are summarized in table 1. As can be seen for each of the three basins studied, basalt flows took place over several hundred million years at least. In each case, the oldest flows probably post-date the basin formation by several hundred million years. So, either one has not sampled all the basalt flows or else the basalt flows did not start immediately after the basin formation. In the latter case, as the oldest flows in Mare Tranquillitatis and Mare Serenitatis are close to the age, as we shall see, of the Imbrium event, it is possible that the Imbrium event triggered the flows in the vicinity of Mare Imbrium.

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Chronology of basin formation

Let us now turn to the more controversial part of lunar chronology, that is, the time of formation of the major ring-basins. In considering all the radiometric ages made on highland-type rocks, one is struck by the preponderance of the age 3.95 ± 0.05 Ga (Kirsten & Horn 1974). In addition, the systematics of the lead isotopes in most lunar highland rocks seem consistent with a formation age of about 4.4 Ga and a metamorphic event which redistributed the lead about 3.95 Ga ago (Tera *et al.* 1974). On this basis, it is possible that the metamorphic event was caused by: (1) a widespread event on the Moon which is the formation of many major ring-basins and the accompanying formation of smaller craters in a short time, or (2) the preponderance of Imbrium ejecta at all the Apollo landing sites. The Rb-Sr ages and the lead-isotope systematics are incapable of providing a distinction. This is because many highland rocks are not datable by the Rb-Sr method, as they are too poor in Rb relative to Sr so that the radiogenic Sr is not observable. For the lead isotopes, the chord defined by the rocks lies so close to the Concordia line on a $^{207}Pb/^{206}Pb$ *vs.* $^{238}U/^{206}Pb$ diagram that whether a sample lies on the chord, or is concordant, is a moot question. In fact, an alternative interpretation of the lead data suggests that many samples are actually concordant with ages between 4.0–4.4 Ga (Nunes *et al.* 1974). The complete picture of the ages of highland rocks can, however, be obtained by the K-Ar method. As a result, I shall restrict the considerations of highland rocks to K-Ar ages. Of especial interest are the cataclastic anorthosites which probably are similar to the ancient lunar crust.

Most of the highland rocks are breccia and almost all are probably formed by an impact-metamorphic process caused by the impact of a large body with the lunar surface. In many breccias the different clasts show similar ages. There are also breccias where the ages of the clasts are different. There does not appear to be a correlation between petrology and age except that the oldest samples are predominantly anorthosites or plagioclase-rich troctolites. The highland rocks thus appear to be dominated by the ejecta from the major ring-basins. At the Apollo 14 site, the local sculpturing indicates that most of the surface material is derived from the Imbrium basin. The Apollo 16 site is difficult to identify from the surface morphology. At the Apollo 17 site, the massifs surrounding the landing site have been associated with the Serenitatis event. So, although it appears clear that most highland rocks represent ejecta from a major ring-basin, it is not clear for a given rock as to within which basin it originated. It is this uncertainty in assigning a basin to a given rock that leads to different conclusions concerning lunar basin-forming chronology.

If a given rock had crystallized in the crust of the Moon and was then ejected by a crater-forming process and subsequently, and relatively recently, was brought to the surface by a later cratering event, one can ask the question 'which event, if any, does the K-Ar method date?' Because so many of the rocks give an age near 3.95 ± 0.05 Ga, irrespective of petrologic type, it is likely that many of the measured K-Ar ages represent the time of a major crater-forming event and that subsequent movement in the lunar crust by smaller craters had little effect on the argon content. This is borne out by the fact that most rocks have relatively short (less than several hundred million years) cosmic-ray exposure ages, even though the K-Ar ages are 4.0 Ga or older. It is thus clear that relatively small cratering events, certainly for those craters less than 1 km in diameter, do not reset the K-Ar ages. If they did, a recent event would lead to considerable change in the argon release pattern. If one considers the kinetic energy of an impacting body in relation to the mass of the total ejecta, it is apparent that only a small amount of the mass can be melted. The most likely resetting mechanism is for the material to have been buried in the lunar crust sufficiently deep that the ambient temperature leads to an open system for times of the order of tens of millions of years. As pointed out by Turner *et al.* (1975), it is likely that a temperature of 200–300 °C is sufficient to completely degas the sample in a time of 50 Ma. This conclusion is based on diffusion of argon in plagioclase. If one considers the present day heat-flow in the lunar crust (Toksöz *et al.* 1975), one would expect to find, at a depth of ~ 90 km, a temperature of 250 °C. Models of the thermal history of the Moon predict a much steeper gradient in the past, so that 4 Ga ago a temperature of 250 °C was probably reached at about 10 km. As these models are based on conduction of heat only, then if there is appreciable convection in the Moon's mantle, the heat flow will be greater and the thermal gradient in the crust will be correspondingly greater. As a major basin excavates at least 30 km of material (some estimates are as high as 200 km) a great deal of the ejecta was at temperatures higher than that required for the rocks to be open systems, insofar as diffusion of argon is concerned, before the excavation. Estimates of thickness of ejecta away from the major basins (McGetchin *et al.* 1973) indicate that for Apollo 14, 16 and 17, the probable ejecta thickness is at least hundreds of metres. So it is likely that the present highland component of the regolith is composed mainly of ejecta from major ring-basins. The brecciated nature of the highland rocks is consistent with such an origin. The way is thus clear to obtaining a chronology of the basins – that is, to date the appropriate rocks which have been reset by the basin-forming events. The problem is to decide which rocks belong to which basins and it is this problem which leads to the present difference in chronologies between those presented here and those presented earlier in the Discussion Meeting by G. Turner.

Let us start with the Apollo 17 landing site, a bay of Mare Serenitatis surrounded by massifs which are presumably related to the Serenitatis event. As this site is closest to Serenitatis, one would as a first impression expect Serenitatis ejecta to dominate the samples collected. However, it is likely that a large amount of Imbrium ejecta is also present because of the proximity to Imbrium (estimates of McGetchin *et al.* 1973, place it as high as 100 m deep). From crater counts of several areas and from the sculpturing of the surface (Neukum, this Discussion Meeting), it is clear that Imbrium ejecta dominate the surface in certain areas near the Apollo 17 landing site. So, for a given rock, it is difficult to decide which ring basin was the point of origin. Even a rock which rolls down from the North Massif, which was uplifted by the Serenitatis event, may have been a part of the Imbrium ejecta overlying the massif.

There is, however, a coarse-grained trocolite (76535) which according to petrologic evidence (Gooley *et al.* 1974) was formed at least at 10 km and possibly as deep as 40 km in the lunar crust, and brought to the surface without shock features. It is most likely that such a rock came from Serenitatis, as it is difficult to see how a rock which crystallized at depth without shock features could be part of the ejecta from a distant basin. It is thus likely that the radiometric age of this rock dates the Serenitatis event. The Rb-Sr systematics of this rock (Bogard & Nyquist 1974) do not lead to a well-defined isochron, probably because the system was not completely open during its history before the Serenitatis event. A K-Ar study (Husain & Schaeffer 1975) indicates that the rock is 4.28 ± 0.03 Ga old, from the argon release of a neutron-irradiated sample of a plagioclase separate and a whole-rock fragment. The patterns are shown in figure 3. As indicated by the constant $^{36}Ar/^{38}Ar$ and K/Ca ratios, there is no trapped or solar-wind gas in this sample, in contrast to previous measurements (Bogard & Nyquist 1974).

This is even more evident if one plots the isochron ($^{40}Ar/^{36}Ar$ *vs.* $^{39}Ar/^{36}Ar$) as in figure 4. There it is seen that both lines (whole rock and plagioclase separate) have the same slope and both extrapolate to zero for solar-trapped ^{40}Ar. The age of Serenitatis on this basis is 4.28 ± 0.03 Ga. When we examine all the K-Ar ages reported from Apollo 17 (figure 5) it is seen that the radiometric age of about 4.0 Ga dominates the results. About half the dated samples have this age. Histograms for the landing sites of Apollo 14 and 16 (Kirsten & Horn 1974) show a similar feature. As Imbrium ejecta should dominate the surface regolith at all sites sampled by the Apollo Programme, because it is the last major crater near these sites, it is likely that this age is the age of the Imbrium event, that is, 3.95 ± 0.05 Ga.

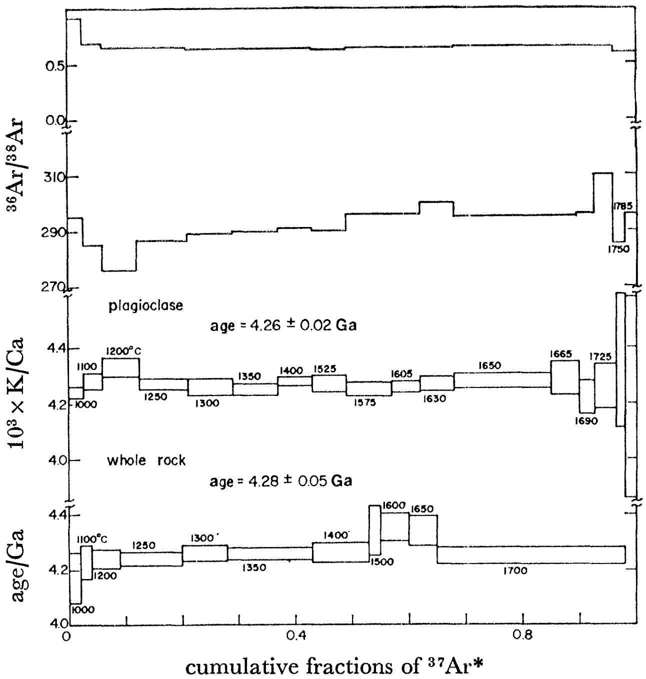

FIGURE 3. Temperature release pattern of argon from troctolite sample 76535.

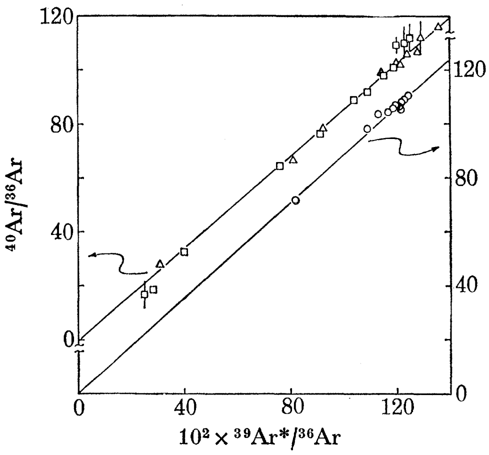

FIGURE 4. Argon isochron plot showing that troctolite 76535 contained no trapped argon. Note the shifted ordinates to display the fit of the points to the curves.

At the Apollo 16 site, on the rim of North Ray Crater, there is the great probability of finding Nectaris ejecta. At Apollo 16, it is very likely that North Ray Crater penetrated the Imbrium ejecta and as Nectaris is the nearest ring-basin, it is likely that the rim of North Ray Crater contains a major component of Nectaris ejecta. A number of samples collected there give a K-Ar age of 4.23 ± 0.05 Ga (Schaeffer & Husain 1973). This is likely to be the age of the Nectaris event. If we examine all the K-Ar results, we note that there are a number of samples with ages near 3.85 ± 0.05 Ga. As Orientale is the most recent ring-basin, it is suggested that these samples date the Orientale event (Schaeffer & Husain 1974). This view of basin chronology is summarized in table 2. On this basis, there is no need to squeeze all the major basins into a time span of 100 Ma. In fact, one is led to the view that the six most recent basins were formed over a time span of over 400 Ma. There are at least six major basins which predate Serenitatis. So it is likely that the cratering of the Moon started at the earliest times, and that roughly 3.9 Ga ago there were no longer sufficient large objects available to produce further major basins.

This view of the chronology was arrived at independently by Baldwin (1974) from consideration of the viscosity of the Moon's early crust as evidenced by the isostasy of crater rims. From these considerations, coupled with crater counts to get a relative time scale, it was possible to develop an absolute time scale independent of radiometric ages. This time scale is compared to the present interpretation of the lunar ages in figure 6. The two chronologies thus point to an extensive period of early bombardment, rather than one occurring over a short time.

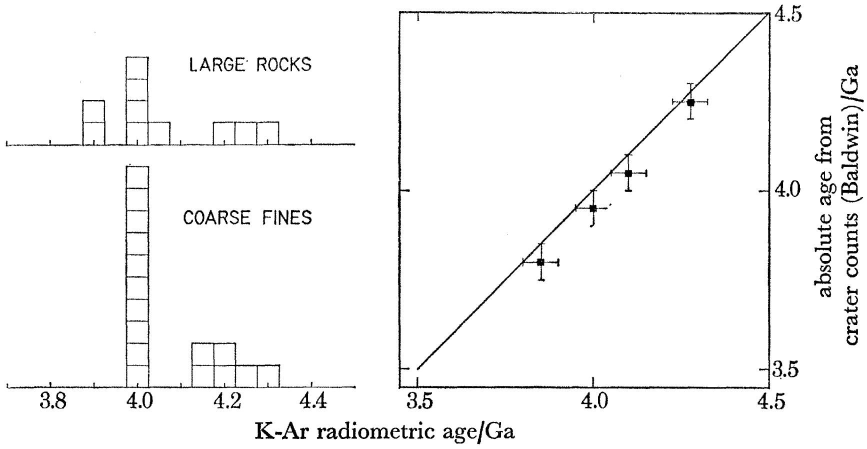

FIGURE 5 FIGURE 6

FIGURE 5. Histogram of K-Ar ages of highland rocks from the Apollo 17 site.

FIGURE 6. Comparisons of dating chronology based on K-Ar ages and crater counts combined with changes in viscosity each point represents a different event from the youngest. These are Orientale, Imbrium, Nectaris, and Serenitatis.

TABLE 2. MAJOR BASIN FORMING EVENTS

	Ga
Orientale	3.85 ± 0.05
Imbrium	3.95 ± 0.05
Crisium, Humorun	4.05–4.20
Nectaris	4.25 ± 0.05
Serenitatis	4.28 ± 0.03

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In response to remarks of G. Turner at the meeting, the essential difference in the age of Serenitatis proposed by Turner of 3.98 Ga and that proposed by me of 4.28 Ga is in deciding whether the boulders on the side, which have rolled outside the North Massif, are more likely to represent Serenitatis ejecta than a rock which was excavated from an extreme depth, namely 76535. While it is likely that boulders rolled down North Massif would be Serenitatis ejecta, it seems equally likely that they could as well be Imbrium ejecta. It seems to me more unlikely that 76535 could be excavated from great depth and transported from a distant crater, so that it would appear to me that 76535 is an appropriate marker for Serenitatis. One has the concurrence, then, that the ages found on the rim of the North Ray crater of 4.23 Ga would represent the Nectaris event.

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