PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
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Absolute Time Scale of Lunar Mare Formation and Filling

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III. THE FILLING OF THE MARE BASINS

Absolute time scale of lunar mare formation and filling

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The high titanium basalts collected in the maria Tranquillitatis and Serenitatis crystallized 3.5–3.9 Ga ago. The ages of the low titanium rocks found in Oceanus Procellarum and on the eastern edge of mare Imbrium are lower, 3.1–3.4 Ga. There is, however, evidence that high-Ti basalts with lower ages and low-Ti basalts with higher ages occur on the Moon. The observed age spread of rocks even in limited areas suggests that lava flow activity in a basin lasted for several 100 Ma. The age variability of Apollo 11 basalts is particularly well documented: there are at least three different times of rock formation, two for the low-K and one for the high-K rocks. The ages of the oldest mare basalts 10003 (high-Ti, low-K rock) and 14053 (an igneous rock with low-Ti, low-K, high-Al mare basalt composition) of 3.91 ± 0.03 Ga and 3.95 ± 0.03 Ga respectively, suggest that mafic basalt flows had already begun to invade the older basins when the last basin-forming impacts occurred.

Introduction

There are two principal stages in the history of a lunar mare. The first is the impact event which excavates the basin. The second is the subsequent filling of this basin with mafic basalts, debris from craters and other maria, and possibly also by isostatic adjustment and 'mass wasting'. While the relative sequence of the large basin forming impacts has been established with some certainty (Stuart-Alexander & Howard 1970), the absolute time scale is still the subject of ongoing research and discussion. At present, there are two ways of interpreting the existing radiometric data, principally Rb-Sr internal isochrons and ^{39}Ar–^{40}Ar ages. The first view (Schaeffer & Husain 1974, 1975; Nunes *et al.* 1974; cf. Baldwin 1974) holds that the ^{39}Ar–^{40}Ar ages of 4.2–4.3 Ga, determined for several lithic fragments from Apollo 16 and two rocks and one fragment from Apollo 17 (Kirsten & Horn 1974, Husain & Schaeffer 1975; Turner & Cadogan 1975) are associated with significant ejecta blankets at these sites, i.e. with the Nectaris and Serenitatis impacts. The difficulty with this view is that ages below 4 Ga are dominant even at the Apollo 16 and 17 sites. In the other view (Jessberger *et al.* 1974; Turner & Cadogan 1975) Serenitatis and all later basins were produced in a rather short interval (the cataclysm of Tera *et al.* 1973) between approximately 3.85 and 4.0 Ga. This interpretation is based on the widespread occurrence of Rb–Sr and ^{39}Ar–^{40}Ar ages in this time interval at all highland sites (cf. figure 1). Recrystallization at ~3.9 Ga, affecting all highland sites, is also evident in the U–Pb system (Tera *et al.* 1974). The difficulty here is to account for the occurrence of the ^{39}Ar–^{40}Ar high temperature plateau ages of 4.2–4.3 Ga at Apollo 16 and 17. Blankets from basins older than Serenitatis are probably rather thin and deeply buried at these highland sites (McGetchin *et al.* 1973). On the other hand, there is no unequivocal evidence for magmatic activity during the time interval in question (Papanastassiou & Wasserburg

1975). A possible relation of the 4.2–4.3 Ga ages to large craters was mentioned by Turner & Cadogan (1975). Detailed radiometric studies on the many subunits of the Apollo 17 boulders are in progress in several laboratories, and it is hoped that these investigations will help in deciding this issue.

Later in this paper we shall be mainly concerned with western Tranquillitatis. This is one of the oldest basins (cf. Stuart-Alexander & Howard 1970). It is not associated with a strong positive gravity anomaly, and in many respects is different from the younger circular maria. Thus, this basin ought to be considerably older than 4 Ga (cf. the arguments of Baldwin 1974).

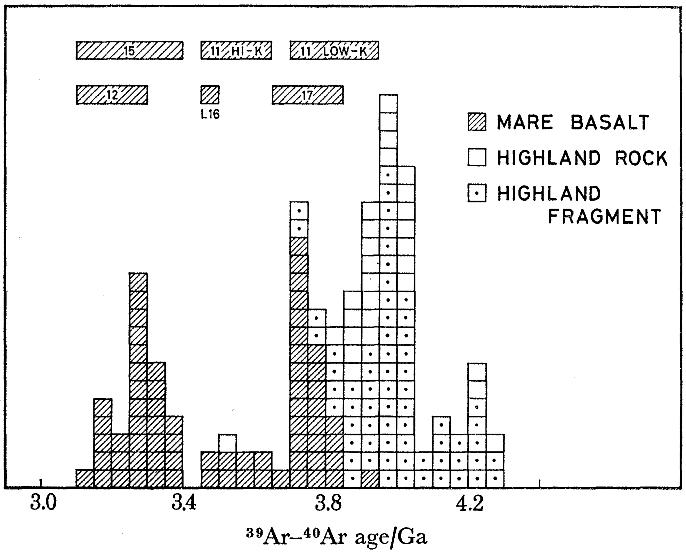

Figure 1. Histogram of ^{39}Ar–^{40}Ar ages of lunar rocks including 2–4 mm coarse fines. Data from Turner *et al.* (1973), Stettler *et al.* (1973), Huneke *et al.* (1973), Husain (1974), Kirsten & Horn (1974), Alexander & Kahl (1974), and references quoted in these publications. High temperature and intermediate temperature ages as given by these authors were used.

The absolute time scale of mare filling by mafic basalts has been established in general terms, for some time (cf. figure 1). The high-Ti basalts in the maria Tranquillitatis and Serenitatis are older (chiefly 3.6–3.4 Ga) than the low-Ti basalts in Mare Imbrium and Oceanus Procellarum (3.1–3.4 Ga). A basaltic fragment brought back from Mare Fecunditatis by Luna 16 is somewhat intermediate, both in Ti-content and age (Huneke *et al.* 1972). However, within the Apollo 11 high-Ti group, already Turner (1970) reported differences of a few hundred million years between the ^{39}Ar–^{40}Ar ages of low-K and high-K basalts. We have embarked on a detailed ^{39}Ar–^{40}Ar investigation of the Apollo 11 basalts in an attempt to establish good statistics for this age distribution and to gain a better understanding of the significance of the observed differences. For two rocks we have also measured plagioclase concentrates using a substantially increased number of temperature steps. Detailed investigations, even if restricted to rocks from a limited area such as that sampled by the Apollo 11 astronauts, appear to us worth while for the following reasons:

(1) Among all the major materials sampled on the Moon, the mare basalts are derived from the deepest lunar layers according to most investigators (Gast 1972; Brown, this volume; Ringwood & Green 1975). Thus, ages of mare basalts are relevant for models of the thermal history and differentiation processes of the lunar mantle.

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(2) Onset time and duration of filling of basins are among the key elements for the understanding of the formation of mascons.

(3) There are vast mare areas which have not been sampled. The only source of information on these areas are photography and remote sensing. Crater counts and indices are being used to establish a time scale of mare surfaces, and this scale has to be anchored to absolute times at the five mare sites which have been sampled. Two of these (Apollo 15 and 17) are in small bays at the edge of large basins, and for one (Luna 16) the sampling is very limited. Crater count ages represent integrals over several hundred square kilometres, whereas the absolute time scale is based on ages of rocks which come from a limited area, as indicated by the observed sharp boundary between mare and highland rock areas at the Apollo 15 and 17 sites. Obviously, the spread in ages of the rocks from one location as well as their possible relation to local stratigraphy should be known before an absolute time can be assigned to a surface age inferred from photogeology. In this way it might be possible to answer some open questions concerning the evolution of the Moon such as: Was there any significant lava flow activity in the western parts of Mare Imbrium and Oceanus Procellarum after 3.2 Ga (the age of the Apollo 12 basalts), as indicated by crater erosion studies (Boyce *et al.* 1974)? Are there young Ti-rich basalt formations in northern Procellarum as indicated by γ-ray sensing (Metzger *et al.* 1974; cf. Boyce *et al.* 1974)?

In this paper we shall report some of the new data we have obtained on Apollo 11 rocks and mineral concentrates prepared from them, and shall discuss them together with previously reported results.

EXPERIMENTAL RESULTS

We have recently obtained ^{39}Ar–^{40}Ar ages of several Apollo 11 rocks, some of them dated previously. The results are summarized in table 1, detailed data will be published elsewhere (Stettler *et al.* 1976). In the case of rocks 10050 and 10072, mineral concentrates were investigated in addition to a whole rock sample. Since these data enter specifically into our discussion, the release curves are given in figures 2 and 3. The error bars include the 3σ-error of

TABLE 1. ^{39}Ar–^{40}Ar AGES AND Ca AND K CONCENTRATIONS INFERRED FROM NEUTRON ACTIVATED APOLLO 11 ROCKS AND PLAGIOCLASE CONCENTRATES.

(Values in brackets: intermediate temperature plateaus only. Constants used: $\lambda = 5.305 \times 10^{-10}\,\mathrm{a}^{-1}$, $\lambda_e = 0.585 \times 10^{-10}\,\mathrm{a}^{-1}$, and $\mathrm{K}^{40}/\mathrm{K} = 0.019$ mol percent. Errors for the Ca and K data are estimated to be better than 10%.)

sample	plateau age/Ga	Ca (%)	K (g/10^6 g)
10062,64	(3.80 ± 0.04)	7.75	630
10020,138	(3.77 ± 0.03)	8.05	440
10045,23	(3.75 ± 0.03)	7.75	480
10044,27	(3.71 ± 0.03)	—	—
10058,136	(3.71 ± 0.03)	8.55	620
10050,40 whole rock	$(\geqslant 3.70 \pm 0.03)$	8.70	580
plagioclase	3.75 ± 0.03	11.3	790
10049,23	(3.45 ± 0.04)	6.00	2410
10069,28	$(\geqslant 3.48 \pm 0.04)$	7.70	2600
10022,78	3.58 ± 0.04	6.95	2350
10057,47	$(\geqslant 3.39 \pm 0.04)$	7.20	2340
10072,99 whole rock	3.57 ± 0.04	6.70	2440
plagioclase	3.62 ± 0.04	9.00	3780

the $^{40}Ar^{*}/^{39}Ar^{*}$ ratio and the uncertainty of the fluence inhomogeneity correction. They do not include uncertainties in the age of our standard and in the decay constants of ^{40}K. Our results from ^{39}Ar–^{40}Ar investigations on mineral concentrates of rocks 10003 and 10071 have been published earlier (Stettler *et al.* 1973, 1974).

The whole rock sample of 10050 gives a relatively poor release curve, whereas the hand-picked feldspar sample (150 to 600 μm) gives a long, undisturbed plateau at 3.75 ± 0.03 Ga. We conclude from our measurements (cf. figure 4) that there is a significant difference of (160 ± 50) Ma between the ages of the two low-K rocks 10003 and 10050.

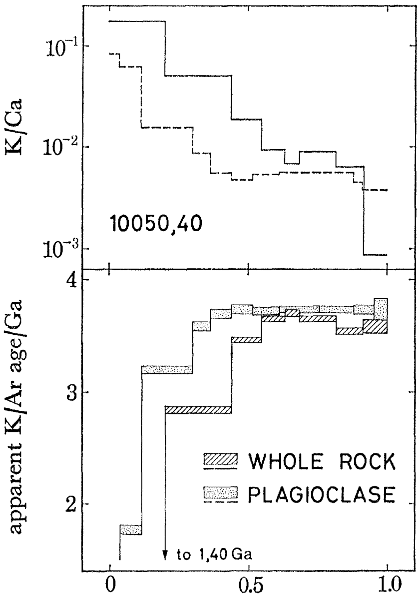

FIGURE 2

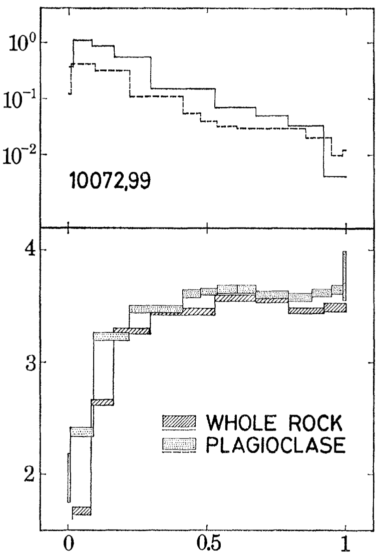

FIGURE 3

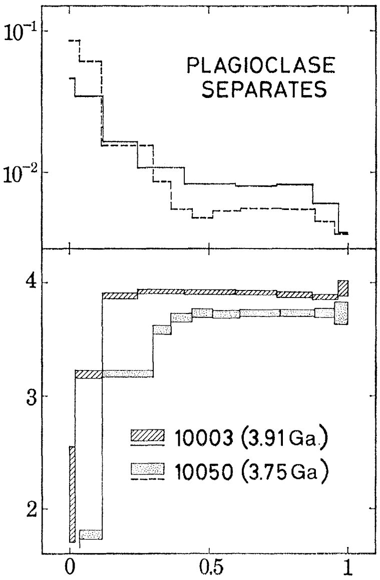

FIGURE 4

FIGURE 2. ^{39}Ar–^{40}Ar age curves and K/Ca patterns of a whole rock sample and a plagioclase concentrate of low-K basalt 10050. A plateau age of 3.75 ± 0.03 Ga is obtained from the plagioclase.

FIGURE 3. ^{39}Ar–^{40}Ar age curves and K/Ca patterns of a whole rock sample and a plagioclase concentrate of high-K basalt 10072. From the last 9 temperature steps of the plagioclase release curve an age of 3.62 ± 0.04 Ga is inferred for this rock.

FIGURE 4. Comparison of the ^{39}Ar–^{40}Ar plateau ages and K/Ca patterns of feldspar samples of the two Apollo 11 low-K rocks 10003 and 10050 (data for 10003 from Stettler *et al.* 1974).

The apparent K/Ca ratio for the 10050 feldspar is fairly constant over the temperature range associated to the age plateau. This indicates that the corresponding potassium is closely associated with the feldspar, i.e. most of it is not interstitial. We cannot yet decide whether this K resides in solid solution in the plagioclase, in K-feldspar or in glassy inclusions whose argon release is controlled by diffusion through the plagioclase. Since virtually all the calcium in this sample is in the feldspar, we take its Ca concentration of 11.3 % and calculate K = 550 $g/10^{6}g$ for the plateau. Such a low concentration might well be in solid solution (Deer *et al.* 1967). In any case, the simultaneous occurrence of plateaus in the K/Ca and age curves underlines the validity of the age obtained.

The residual glass content of rock 10003 is 0.1 % (by volume) (James & Jackson 1970). An average K content of 4 % for this phase (cf. Roedder & Weiblen 1970) gives only 40 $g/10^{6}g$

for the whole rock, as compared to the measured total concentration of 430 g/10^6 g (cf. Stettler *et al.* 1974; Papanastassiou & Wasserburg 1975). These estimates would seem to rule out that much of the potassium in the 10003 feldspar sample resides in residual glass. A possible explanation for the decrease in the K/Ca ratio (figure 4) is that K is enriched at the rims of the plagioclase crystals (cf. Roedder & Weiblen 1970).

In the high-K basalts collected at Tranquillity Base, most of the potassium resides in the mesostasis, and caution has to be exercised in interpreting ^{39}Ar–^{40}Ar data of this rock type. Results of investigation on mineral concentrates of high-K rock 10071 were previously reported (Stettler *et al.* 1973). New results on a whole rock sample and a feldspar concentrate of high-K basalt 10072 are given in figure 3. For both rocks, the feldspar fraction shows an improved plateau as compared to the whole rock sample. However, even these plateaus are not entirely satisfactory. In the case of the 10072 feldspar concentrate, the apparent ages of the last nine temperature steps agree within the limits of the given errors with a value of 3.62 Ga. If we consider, however, that relative errors (2σ; fluence error excluded) for most of these data points are only about ± 0.015 Ga, and that the ^{40}Ar*/^{39}Ar* ratio is low for two consecutive temperatures, we conclude that the dip in the plateau indicated in figure 3 is most probably real. A dip of this kind, often much deeper, is frequently observed for lunar rocks. Therefore, we use increased error limits and adopt an ^{39}Ar–^{40}Ar age of 3.62 ± 0.04 Ga (the weighted average of the last nine temperature steps of the feldspar sample) for rock 10072 on the basis of the data obtained so far.

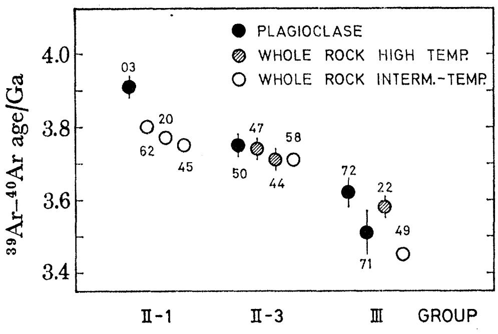

FIGURE 5

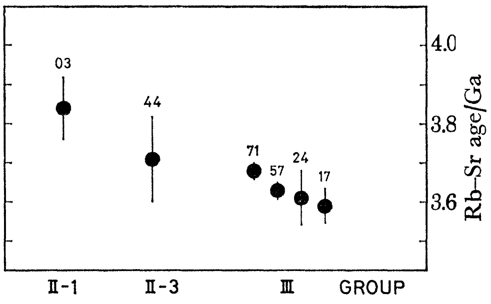

FIGURE 6

FIGURE 5. Summary of our ^{39}Ar–^{40}Ar results of Apollo 11 basalts (data for 10003, 10047, 10071 from Stettler *et al.* 1973, 1974). Warner's (1971) petrologic groups are given at the bottom. Wherever a comparison is possible, there is good agreement with Turner's (1970) data. The plagioclase ages are considered to be the most reliable, followed by the high temperature plateau ages of whole rock samples. The intermediate temperature plateaus are the least reliable and therefore no error limits are given. Nevertheless, in many cases they should provide a fair approximation to the age of the rocks.

FIGURE 6. Rb–Sr internal isochron ages of Apollo 11 basalts (Papanastassiou & Wasserburg 1971 *a*, 1975). Warner's (1971) petrologic groups are given at the bottom. For the purpose of our discussion of age differences in these rocks, only data with error limits smaller than 0.12 Ga for low-K rocks and 0.08 Ga for high-K rocks were included. Apollo 11 rock numbers are indicated.

DISCUSSION

Figure 5 shows the ^{39}Ar–^{40}Ar ages of all Apollo 11 basalts for which either a high or intermediate temperature plateau has been determined. The data are plotted according to Warner's (1971) classification of mare basalts. Group III was not subdivided because of the small number of ages available. In figure 6 the Rb–Sr internal isochron ages of the Apollo 11 rocks are given.

There is good agreement between the ages obtained by the two methods, except for rock 10071. This is actually the only case of a lunar rock where there is a significant difference between a Rb–Sr and ^{39}Ar–^{40}Ar age. We intend to re-study rock 10071 in order to determine if this deviation is due to the imperfections still observed in the plateau of the 10071 feldspar concentrates (Stettler *et al.* 1973).

Figures 4 and 5 show clearly that there are at least three different age groups in the Apollo 11 basalts. If we consider the ^{39}Ar–^{40}Ar results of the feldspar concentrates only, we have a significant age difference between the low-K rocks 10003 and 10050, and again between 10050 and the high-K rocks (10072 and 10071). This conclusion is compatible with the Rb–Sr ages (Papanastassiou & Wasserburg 1975; cf. figure 6). The age differences among the low-K rocks have not been resolved by the Rb–Sr method, but the Rb–Sr age of 10003 is significantly different from those of the high-K rocks. Any further reservations regarding the ^{39}Ar–^{40}Ar data of the high-K rocks can be removed by establishing the difference between some rocks of the low-K group II-3, and some of the high-K group III rocks by comparing the ^{39}Ar–^{40}Ar age of 10050 with the Rb–Sr ages of 10017 and 10057. Such a comparison is valid because there is no evidence for a systematic deviation between the two methods (cf. Tera *et al.* 1974; Stettler *et al.* 1974; Kirsten & Horn 1974).

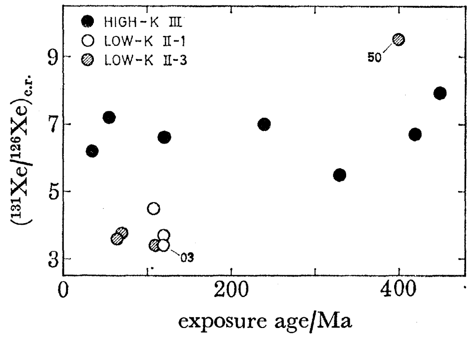

Figure 7. Irradiation history of Apollo 11 rocks (Eberhardt *et al.* 1970 and references given by these authors: Bogard *et al.* 1971; Schwaller 1971). The $(^{131}Xe/^{126}Xe)_{c.r.}$ ratio, as produced by galactic cosmic rays, is a function of the depth of irradiation. Indicated are the data points of rocks 10003 and 10050, which are discussed in the text. The $(^{131}Xe/^{126}Xe)_{c.r.}$ value for 10050 is very uncertain, the high value is, however, concordant with the high Gd isotope anomaly observed by Eugster *et al.* (1970).

The large spread in the radiometric ages of the Apollo 11 basalts indicates that the lava flow activity in Mare Tranquillitatis lasted at least 300 million years. This period may have been considerably longer, since the Apollo 11 rocks represent only the near-surface material of a small area. Crater statistics appear to support the radiometric evidence. From an anomalous crater size distribution Neukum *et al.* (1975) have concluded that there are two or more surface ages in a region of Mare Tranquillitatis not far from the Apollo 11 site.

Large differences of basalt ages, i.e. extended periods of flooding, in a single basin are probably a rather common feature as suggested by crater observations (Boyce *et al.* 1974). Thus the age data indicate that the mafic basalts in a basin were formed in successive and rather thin lava flows. This conclusion is not only supported by surface features in the maria which are interpreted as lava flow fronts, but also by the observation that the Apollo 11 high-K and low-K rocks have different exposure histories (Eberhardt *et al.* 1970). This is shown in figure 7, where $^{131}Xe/^{126}Xe$ from cosmic rays is plotted against exposure age. Since ^{131}Xe is also produced by slow neutrons, the $^{131}Xe/^{126}Xe$ ratio increases with the depth of irradiation. Figure 7 shows that there is a significant difference between the irradiation histories of low-K and high-K rocks. The low-K rocks were irradiated at or close to the surface, whereas the high-K rocks received a substantial fraction of their irradiation at some depth ($1\text{ m} \lesssim d \lesssim 5\text{ m}$). Several possible models have been discussed by Eberhardt *et al.* (1970). Both, the exposure age distribution and the $^{131}Xe/^{126}Xe$ ratios would be consistent with the hypothesis that in the neighbourhood of the Apollo 11 site the high-K material resides close to the surface whereas the low-K rocks come from greater depth and are excavated by relatively rare impacts (model B of Eberhardt *et al.* 1970).

So far the high age of rock 10003 is an isolated case. Since the other three group II-1 rocks investigated gave only short age plateaus at intermediate temperatures (cf. table 1 and figure 5), we should not entirely exclude the possibility that their true ages come close to the age of 10003. Studies on feldspar separates would be likely to answer this question. In terms of chemistry and petrology, rock 10003 does not seem to constitute a separate group, it rather appears as an end member of the low-K basalts (cf. its low potassium and residual glass contents, James & Jackson 1970). Also, stratigraphically there is no obvious difference to the other low-K rocks (cf. figure 7). The age of 10003 basalt is very close to the time of the Imbrian impact. Thus it is likely that mare basalt lavas had begun to invade the Tranquillitatis basin when the Imbrian ejecta fell onto it. If the cataclysmic time scale (Jessberger *et al.* 1974) is essentially correct, and if the onset of basalt flows predated 10003 by approximately 80 Ma or more, then the Tranquillitatis basin should be filled with several alternating layers of basalts and debris, including the thick Nectaris and Serenitatis ejecta. An early onset of lava flows in the older basins is not in contradiction with evidence on the geochemical age of the reservoirs from which these rocks were derived. Lead isotope data on mare basalts, when interpreted in a two stage model, show such reservoir ages to be *ca.* 4.4 Ga (Tera & Wasserburg 1974; Nunes *et al.* 1974; Tera & Wasserburg 1975). The initial $^{87}Sr/^{86}Sr$ values of low-K mare basalts also indicate early times for rubidium-strontium fractionations. However, comparison between Rb/Sr and initial $^{87}Sr/^{86}Sr$ ratios of the Apollo 11 high-K rocks shows that the chemical fractionation leading to the relatively high Rb/Sr ratios of these rocks occurred as late as *ca.* 3.9 Ga (Papanastassiou & Wasserburg 1971*a*).

As mentioned above, the high-Ti basalts from Apollo 11 and 17 clearly predate the low-Ti basalts collected at the Apollo 12 and 15 sites (cf. figure 1). There is, however, evidence of early formation of low-Ti basalts and late extrusion of high-Ti basalts. The Fra Mauro rock 14053 has a composition similar to low-Ti mare basalts (Reid & Jakeš 1974), with a somewhat enhanced Al-content. Its age is very well established at 3.95 Ga (cf. Papanastassiou & Wasserburg 1971*b*; Stettler *et al.* 1973), i.e. it is as old or older than 10003. This material was transported to the Fra Mauro region by either the Humorum (Jessberger *et al.* 1974) or Imbrium impact, and thus it provides evidence that lavas with a composition similar to low-Ti mare basalts had risen into the lunar crust at the time of one of these impacts (cf. Stettler *et al.* 1973). Metzger *et al.* (1974) found surface concentrations of titanium in northern Oceanus Procellarum and in the Aristarchus region to be nearly as high as in Mare Serenitatis. Crater erosion studies in the Aristarchus area indicate surface ages as low as those near the Apollo 12 site, i.e. it seems that there exist relatively young formations of high-Ti mare basalts in the western part of the lunar frontside (cf. Boyce *et al.* 1974).

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