

Apollo 14 mineral ages and the thermal history of the Fra Mauro formation

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Abstract—Rb–Sr mineral isochrons for two basalt clasts from the partially annealed breccia 14321 (4.06 b.y.) are detectably older than 14310 (3.93 b.y.). Less precise ages for a troctolite clast from 14321 and the igneous chip 14072 can agree with either of these. A directionally consistent thermoremanent magnetism in 14321 reported by Pearce *et al.* shows that the temperature of this breccia was at least 800°C after final assembly. If the annealing of the breccia occurred within the Fra Mauro formation after deposition, temperatures may have remained above 600°C for as long as $\sim 10^2$ yr owing to thermal blanketing. During such a thermal event, the estimated diffusion ranges of Rb and Sr in glass (mesostasis), plagioclase, and possibly pyroxene would exceed the basalt grain size and probably produce local equilibration of Sr isotopes between minerals. The age of the 14321 clasts would therefore represent the age of the Imbrium impact on this model, and 14310 would be a post-Fra Mauro rock rather than a Fra Mauro breccia clast. On the other hand, if the Fra Mauro formation was deposited at low temperatures, the ages of the clasts and their magnetization would represent pre-Imbrian events, and only a limiting age of younger than 3.9 b.y. can be set for the Imbrium impact.

INTRODUCTION

IN THIS PAPER we document and give multiple interpretations of the isotopic ages of Apollo 14 igneous rocks cited previously at the Third Lunar Science Conference (Compston *et al.*, 1972). Our major-element analyses for the latter were given at the same conference, and major- and trace-element analyses on these and of the remainder of our allocation, various Apollo 14 fines, will be reported and discussed later.

Analytical methods

The complete fragment received for each of the crystalline rocks, 14310 and 14072, was crushed and representative aliquots of 0.9 g and 0.3 g were taken, for trace-element and major-element analysis by x-ray fluorescence, respectively, using standard methods (Compston *et al.*, 1970). Part of the remainder was used for mineral separations with the aid of heavy liquids, and hand picking gave final concentrates of plagioclase free from ilmenite (low Rb/Sr) and ilmenite and pyroxene free from plagioclase (high Rb/Sr owing to included alkali-rich mesostasis). Representative Rb–Sr total rock samples were also prepared. All handling and mineral separations

were done in a clean-air work station. Three igneous clasts were extracted from faces of the breccia 14321,88 and mineral concentrates made, as described for one of them (basalt 4A) by Compston *et al.* (1971a). Representative total-rock aliquots of two of these, basalt 6A and troctolite 8A, and minerals from 8A were analyzed for trace-elements (Taylor *et al.*, 1972a), and the troctolite for major-elements (Compston *et al.*, 1972). Electron-microprobe analysis of minerals from all three clasts will be reported by Ware and Green (in preparation).

Some details of the mineral concentrates and the Rb, Sr, and $^{87}\text{Sr}/^{86}\text{Sr}$ analytical results are given for all samples in Table 1. The chemical procedures and mass-spectrometer used were the same as those described by Compston *et al.* (1971a).

CALIBRATION OF MASS SPECTROMETERS

Our previous measurements of $^{87}\text{Sr}/^{86}\text{Sr}$ in lunar samples (Compston *et al.*, 1971b), using a Nuclide 12-60-SU machine with Faraday-cup collector and Cary

Table 1. Isotope dilution analyses of Apollo 14 igneous rocks and minerals. Concentrates prepared solely by hand-picking are denoted (H) and purity is given in percent.

	Weight (mg)	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}^*$	$^{87}\text{Sr}/^{86}\text{Sr}^*$
<i>14310,118, basalt</i>					
Plagioclase 1, (H), ~100%	10.6	2.47	287.2	0.0248 ± 2	0.70190 ± 4
Plagioclase 2, 98%, ~2% mesostasis	19.4	7.00	309.1	0.1312 ± 6	0.70782 ± 6
Plagioclase-rich mesostasis A	13.4	22.35	304.3	0.2122 ± 11	0.71258 ± 5
Plagioclase-rich mesostasis B	14.9	16.75	232.2	0.2084 ± 10	0.71231 ± 5
Total-rock A	22.3	12.96	192.3	0.1948 ± 10	0.71144 ± 3
Total-rock B	12.2	12.83	190.6	0.1946 ± 10	0.71157 ± 3
Pyroxene 3, (H), ~100%	9.8	1.38	46.13	0.0866 ± 3	0.70540 ± 9
Pyroxene 2, with ilmenite	9.5	5.46	50.8	0.3105 ± 15	0.71848 ± 4
Pyroxene 1, 98%, 2% mesostasis	41.3	4.54	31.1	0.4212 ± 21	0.72484 ± 7
<i>14072,2, basalt</i>					
Plagioclase 1, (H), ~100%	13.0	0.66	210.7	0.0090 ± 1	0.69980 ± 8
Plagioclase 2, 98%, ~2% mesostasis	15.8	1.69	227.0	0.0215 ± 2	0.70049 ± 3
Pyroxene, pigeonite/augite, 99%	51.6	0.95	10.2	0.0270 ± 1	0.70069 ± 5
Total-rock	20.5	1.21	81.6	0.0428 ± 4	0.70183 ± 3
Ilmenite 1, (H), ~100%	8.1	1.80	19.5	0.265 ± 3	0.71480 ± 2
Ilmenite 2, ~90%, 10% pyroxene	4.8	1.62	20.8	0.223 ± 3	0.71205 ± 5
<i>14321,88,basalt 6A</i>					
Plagioclase 1, (H), ~100%	1.8	2.08	279.6	0.0215 ± 7	0.70062 ± 6
2.6 < ρ < 2.9, plagioclase + plagioclase mesostasis	3.1	5.40	197.0	0.0791 ± 9	0.70392 ± 5
ρ < 2.6, plagioclase + trace K-feldspar	1.4	4.83	162.5	0.0857 ± 18	0.70427 ± 6
Plagioclase-rich mesostasis	9.2	5.79	129.2	0.1294 ± 1	0.70689 ± 5
ρ > 3.3, pyroxene, ~95%	15.4	2.19	29.35	0.2154 ± 17	0.71200 ± 5
Ilmenite, 35%, + pyroxene + olivine	1.7	7.16	71.4	0.290 ± 4	0.7170 ± 1
<i>14321,88, troctolite 8A</i>					
Plagioclase, ~94% + olivine	31.4	1.39	220.4	0.0183 ± 1	0.70047 ± 7
Total-rock 2	29.6	1.22	162.8	0.0217 ± 2	0.7006 ± 1
Total-rock 1	22.4	0.85	161.3	0.0152 ± 2	0.70042 ± 4
K-feldspar + plagioclase A	11.4	3.34	205.5	0.0466 ± 2	0.70209 ± 2
K-feldspar + plagioclase B	12.2	3.06	191.2	0.0463 ± 2	0.70222 ± 6
Olivine, ~98%	46.7	0.16	3.93	0.114 ± 2	0.7056 ± 1

* Uncertainties refer to the last digits and represent the standard error for precision. In addition, all values for $^{87}\text{Rb}/^{86}\text{Sr}$ should be increased by 1.8% according to recalibration of spikes by De Laeter *et al.* (1972).

model 31 electrometer (serial number 1588), have been systematically ~ 0.0002 higher (0.03%) than Papanastassiou and Wasserburg (1971a) and ~ 0.0001 higher than Murthy *et al.* (1971). The only reasonable source of such biases appears to be nonlinearity in the measurement system: for example, if our $^{88}\text{Sr}/^{86}\text{Sr}$ were erroneously low by 0.06% owing to the system characteristic, then the operation of normalizing $^{88}\text{Sr}/^{86}\text{Sr}$ to a standard value will introduce a fixed error of 0.03% in $^{87}\text{Sr}/^{86}\text{Sr}$ because the $^{88}\text{Sr}/^{86}\text{Sr}$ error will be treated as isotopic fractionation. We have previously monitored nonlinearity by injecting highly accurate voltage ratios (from 0.02 to 1) into the feedback loop of the electrometer. The corresponding output ratios as registered via a digital system have consistently agreed to better than 0.01%. However this procedure does not completely simulate the measurement of input ion-currents: It is necessary instead to feed voltage ramps in accurately known ratios to the electrometer input via a stable capacitor. A satisfactory ramp-generator has now been constructed and is being applied to the calibration of a number of Cary electrometers. Figures 1 and 2 show the characteristics obtained for two Cary 31 electrometers, over the range in ion currents used in measuring $^{88}\text{Sr}/^{86}\text{Sr}$ and $^{87}\text{Sr}/^{86}\text{Sr}$. For electrometer #1588, a nonlinearity of 0.06% for a ratio of $\sim 10:1$ is strikingly revealed, in contrast to #1565 that has no detectable nonlinearity, at least for the 3 V output range. The

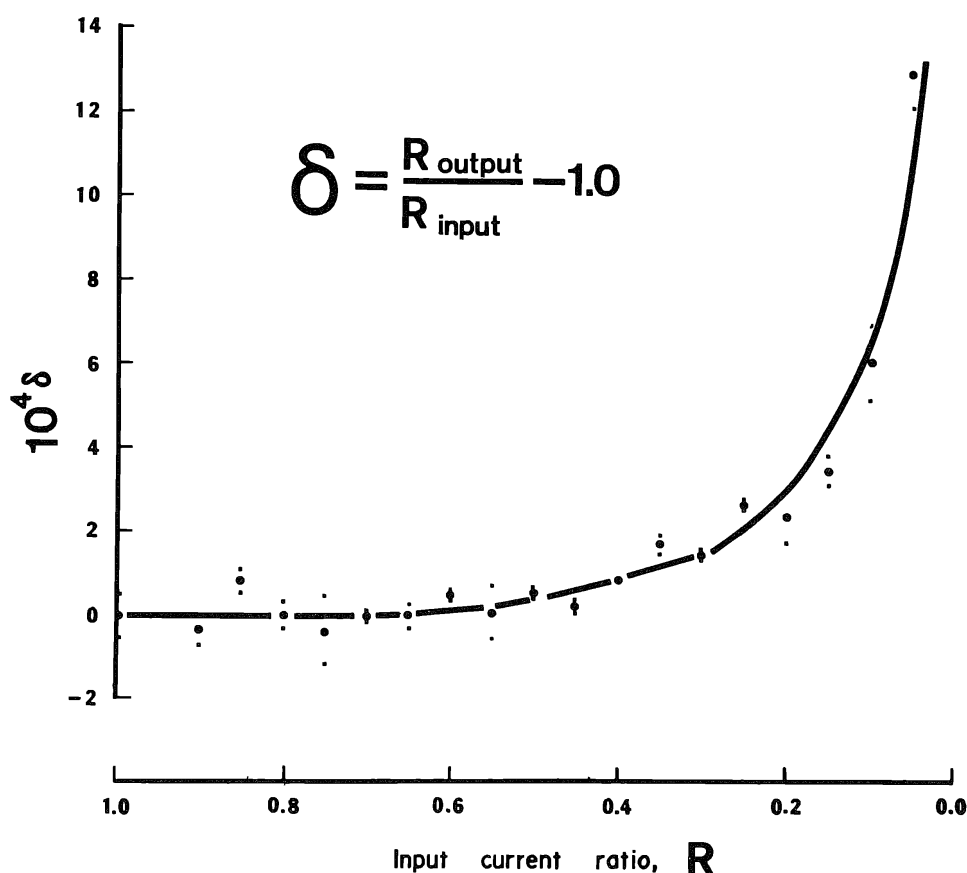


Fig. 1. Nonlinearity detected in Cary model 31 electrometer #1588 using a ramp generator. The input resistor was $2 \times 10^{10} \Omega$ (Victoreen Hi-meg) and electrometer output voltage 1.6 V on the 3V range for the reference input current. Input ratios are the fractions shown of the reference input current, of accuracy about 10 ppm.

$$\delta = \frac{R_{\text{output}}}{R_{\text{input}}} - 1.0$$

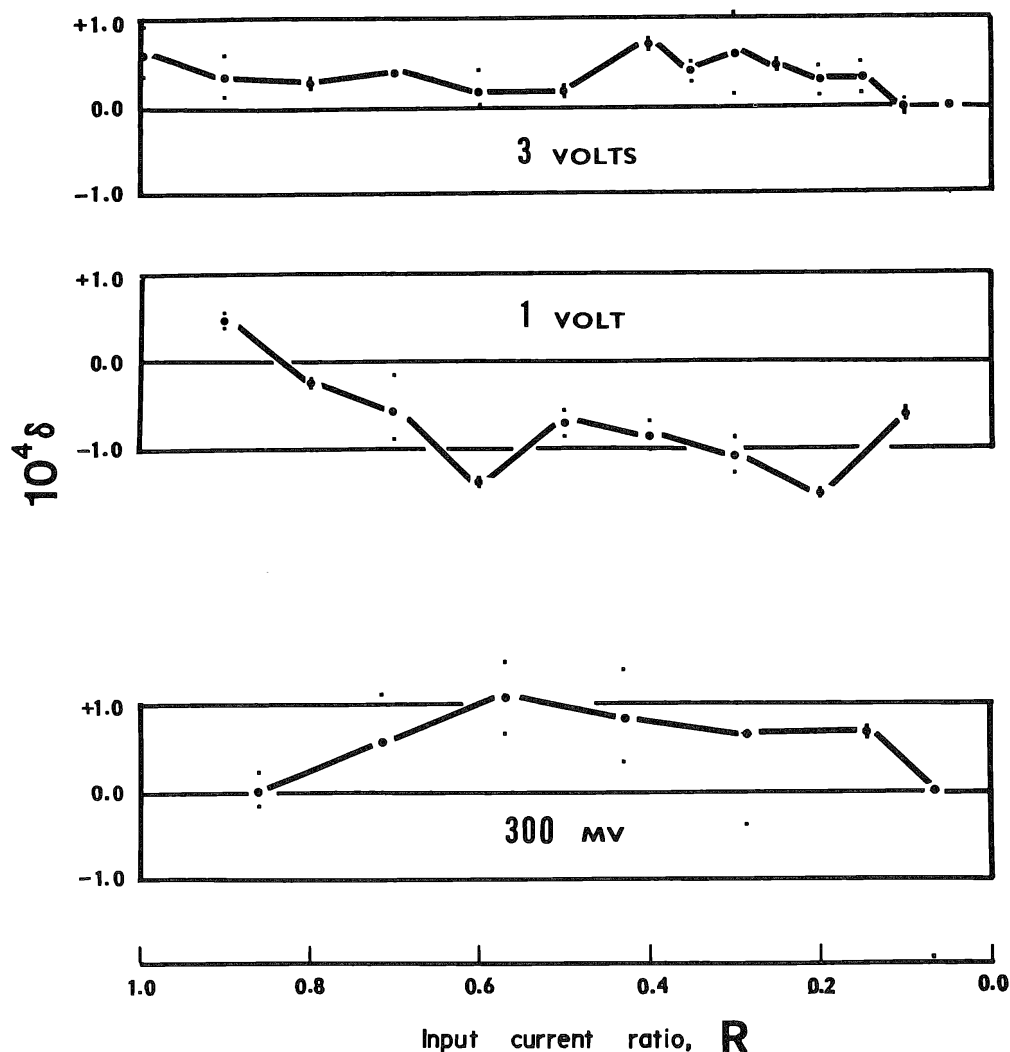


Fig. 2. Limits to non-linearity of Cary model 31 electrometer #1565 employed for Apollo 14 analyses, for three different output ranges. The input resistor was Victoreen $2 \times 10^{10} \Omega$.

interlaboratory bias in $^{87}\text{Sr}/^{86}\text{Sr}$ is thus located as originating within our electrometer (which nevertheless is working to within manufacturers' specifications) rather than within Papanastassiou and Wasserburg's. The cause of the nonlinearity will be examined later: It is not simple polarization of the input resistor, as it is present no matter which particular resistor is used.

We do not know yet whether the apparently systematic variations in Fig. 2 within the 1 V and 300 mV ranges of electrometer #1565 are real. If they are, then the $^{87}\text{Sr}/^{86}\text{Sr}$ measurements reported here and by us previously for 14321,88,4A (Compston *et al.*, 1971a), will be high by approximately 0.01%.

A small number of measurements for the C.I.T. seawater standard made so far on #1565 give 0.70918 ± 6 (without correction for the above possible bias of about 0.01%). More adequate data for the same standard on #1588 give 0.70931 ± 4 , which becomes 0.70910 after correction for the known nonlinearity of this electrometer on the 3 V range. As we have not yet checked the 300 mV and 1 V ranges of #1588 (on which $^{87}\text{Sr}/^{86}\text{Sr}$ was measured) with the ramp generator, a further correction for nonlinearity may be needed. However, it is clear that our results for $^{87}\text{Sr}/^{86}\text{Sr}$ in the Apollo 11 and 12 samples, which were obtained solely with electrometer #1588, should be reduced by 0.00021 for direct comparison with those of Papanastassiou and Wasserburg (1971a).

THERMAL HISTORY OF THE FRA MAURO FORMATION

The crystallinity of the Apollo 14 fragmental rocks that constitute the Fra Mauro formation has been described as “compatible with a single very large impact event in which annealing took place within a thick, hot ejecta blanket” (LSPET, 1971). This view is disputed by Chao *et al.* (1972), who believe that the Fra Mauro formation was deposited at low temperatures. Quantitative information on the thermal history of such an ejecta blanket is vital to the interpretation of the mineral ages of the basaltic clasts in breccia 14321, and probably also of 14072 and 14310 which may be fragments of bigger clasts. If the clasts had a large enough temperature-time integral during and after final deposition, their original pre-Fra Mauro mineral ages could have been reset. On the other hand, if the Imbrium debris had cooled sufficiently by the time it eroded and deposited the igneous clasts, the original ages of the latter may be completely unchanged.

Petrographic evidence for recrystallization of lithic fragments and glass in Apollo 14 soils and breccias has been given by Anderson *et al.* (1972), Chao *et al.* (1972), Grieve *et al.* (1972), Kurat *et al.* (1972), Lindsay (1972), Quaide (1972), Taylor *et al.* (1972b), Warner (1972), and Wilshire and Jackson (1972). Warner (1972) describes a range in metamorphic grade within the breccias. From the distribution of ejecta around Cone Crater, Wilshire and Jackson (1972) and Quaide (1972) suggest that this range is associated with the depth of particular samples within the Fra Mauro formation, due at least in part to differences in their thermal blanketing during post-depositional cooling of the (hot) debris flow. Taylor *et al.* (1972b) refer to noritic fragments and to matrices of clasts in the Apollo 14 soils that have been remelted: They believe that this occurred after the deposition of the Fra Mauro formation. Anderson *et al.* (1972) infer that temperatures of some breccia components were as high as 900°C during at least the early part of the Imbrium impact, and suggest the presence of vapor during compaction (of the Fra Mauro formation). The growth of crystals in vuggy recrystallized breccias (McKay *et al.*, 1972) is compelling evidence for high postdepositional temperatures and vapor transport. The origin of the Fra Mauro formation as a single, very hot debris-flow has been detailed by Williams (1972), who integrates petrographic with diverse physical and chemical properties of the breccias.

Grieve *et al.* (1972) in a detailed analysis of textural ordering in breccia 14321, see

different degrees of metamorphism in its different components. In their view, norites and other lithic fragments were subjected to an early period of severe thermal metamorphism; brecciation followed, accompanied by a second less-severe thermal metamorphism; final assembly of the sample occurred with the incorporation of basaltic and other clasts in an unrecrystallized light matrix. Multiple periods of heating and brecciation are also seen by Chao *et al.* (1972), who in addition use the sample distribution to infer the co-existence of unannealed with highly annealed breccias, and to conclude that the Fra Mauro formation was deposited at low temperatures with little or no subsequent annealing. They see the annealed breccias as pre-Fra Mauro clasts and adduce support for their interpretation from the high porosity of the Fra Mauro formation found by Kovachs *et al.* (1971). Dence *et al.* (1972), Hörz, and Chao (personal communication) believe that a low temperature of deposition for the Fra Mauro formation must be expected by analogy with annealing evidence found in terrestrial ejecta blankets.

Independent and quantitative evidence for elevated postassembly temperatures for breccia 14321 is available from studies of the remanent magnetization of lunar samples. Pearce *et al.* (1972) have discovered that three adjacent fragments of breccia 14321 have the same stable and directionally consistent magnetization component, which they regard as a thermoremanent magnetization carried by metallic iron. Hargraves and Dorety (1972) find the same TRM orientation for a more distant fourth fragment of 14321 (Gose, personal communication). This implies that the temperature of this particular breccia, which contains both annealed and unannealed components, was above the Curie point, $\sim 780^{\circ}\text{C}$, *during or after its final assembly*. Either the TRM was acquired before deposition in the Fra Mauro formation and the entire rock 14321 is a single clast, or the final assembly of 14321 occurred, and its TRM was acquired, within the deposited Fra Mauro formation, and the temperature of the latter was at least 780°C .

The thermal inertia of the Fra Mauro formation limits its rate of cooling. If we assume that the formation is 100 m thick at the Apollo 14 site (Offield, 1970), and for simplicity, that its temperature was uniform throughout at the time of emplacement, we may use the calculations of Jaeger (1961) for the cooling of an extrusive sheet to estimate the time required for its central temperature to drop by 10%. This time is approximately 45 yr, using the Horai *et al.* (1970) measurement of thermal diffusivity for lunar breccias. For a 90% temperature drop, the time will be about 200 yr. Even though the assumption of a uniform emplacement temperature may be only a poor approximation, and the Fra Mauro formation may be a factor of 2 less in thickness (Kovach *et al.*, 1971), the order of magnitude of the above cooling times will be correct, and applicable to breccia 14321, believed to be excavated from a depth of ~ 30 m (dark clast-dominated group, Wilshire and Jackson, 1972).

DIFFUSION OF Rb AND Sr WITHIN LUNAR BASALT

During contact metamorphism, biotite rapidly loses its Rb–Sr age above 300°C and other minerals, including K-feldspar, lose their ages at temperatures less than 600°C (Hanson and Gast, 1967). If the temperature within the Fra Mauro formation was 780°C or more immediately after its final deposition at the Apollo 14 site, then

at least its central portion must have remained *above* 600°C for a period of the order of 10² yr. Whether the minerals of the basaltic clasts lost their pre-Fra Mauro ages during this time depends critically on the rate at which Rb and Sr diffuse within and between the minerals at the raised temperature.

Table 2 lists some measurements for the diffusion coefficients *D* of alkalis in glass and in albite. The composition of the mesostasis glass (Gancarz *et al.*, 1971) is not matched by any of the experimentally determined glasses. However the range in *D* observed is quite small for large changes in glass composition, and the values for Na, K, and Rb are similar. The *D* for Sr in alkali glasses will be smaller but probably comparable; *D* for Ar also is within the range observed for alkalis.

The time *t* required for effectively complete diffusion (≥98%) into or out of a sphere of radius *L* can be calculated using the relationship $\sqrt{Dt}/L = 0.75$ (Kingery, 1960).

Taking 10⁻⁶ as the mean *D* for alkalis in glass above 600°C, and 0.01 cm for *L* as the order of magnitude of the mesostasis grain size, we find that this time is only 56 sec. Obviously the diffusion of alkalis in the mesostasis is extremely rapid, and even if *D* for Sr in glass is taken as several orders of magnitude lower, Sr diffusion also will be rapid over the time scale available (10² yr). A flux of Rb and Sr must be expected across the glass boundaries owing to intergranular diffusion, which is usually faster than volume diffusion. Thus the K-rich mesostasis can hardly be viewed as chemically closed during the Fra Mauro thermal event.

To change the mesostasis age, there must be a decrease (or increase) in its ratio radiogenic Sr⁸⁷/Sr⁸⁷. By analogy with terrestrial metamorphism, a decrease can be expected, owing to Sr isotopic exchange between radiogenic Sr⁸⁷ and common Sr diffusing from adjacent Sr-rich minerals, which may result in Sr isotopic equilibration within small volumes of the rock. Such equilibration will be limited for the lunar basalts by the diffusion coefficients of Sr in plagioclase and pyroxene, which are not known. However an upper limit for plagioclase can be taken from the diffusion of Na in albite and a lower limit for the pyroxene from the diffusion of Ca in CaO and Ca₃Si₂O₇ (Table 2).

Calculating as before the time required for complete diffusion, only a short time is required for plagioclase (≤6 days) if the mean *D*^{Sr} above 600°C is taken as 10⁻¹² cm² sec⁻¹, equal to the value for Na in albite at 600°C. For 45 yr above 700°C, as required for breccia 14321 from the Curie point datum and the cooling rate, diffusion would be complete for *D*^{Sr} as small as 4 × 10⁻¹⁶ cm² sec⁻¹, which is unreasonably

Table 2. Some typical measured values for diffusion coefficients of alkalis in glass.

Phase*	Species	log <i>D</i>			Reference
		800°C	700°C	600°C	
Glass, 19 % Na ₂ O, 6 % Rb ₂ O	Rb	-6.2	-6.8	-8.1	McVay and Day (1970)
Glass, 19 % Na ₂ O, 6 % Rb ₂ O	Na	-5.4	-5.8	-6.8	McVay and Day (1970)
Glass, 20 % K ₂ O	K	-7.0	-7.3	-7.9	Doremus (1962)
Glass, 26 % K ₂ O, 5 % CaO, 5 % Al ₂ O ₃	Ar	-6.6	-7.1	-8.4	Reynolds (1957)
Albite	Na	-10.5	-11.0	-12.2	Sippel (1963)
CaO, Ca ₃ Si ₂ O ₇	Ca	-17.0			Kingery (1960)

* Balance is SiO₂ for glasses.

low. Thus it seems certain that the Sr of the plagioclase would equilibrate with that in adjacent mesostasis during the time available. We can be much less sure about equilibration of the pyroxene. However as only a small fraction of the total Sr in the Apollo 14 basalts is located in the pyroxene, this is less important.

To summarize, local Sr isotope equilibration must be expected between minerals in igneous clasts deeply buried within a thick, hot ejecta blanket. It is likely also that small clasts would be open systems, especially for alkali diffusion. For the basalts within breccia 14321, internal Rb–Sr isochrons should be completely reset to the age of the Fra Mauro formation *provided the final assembly of this breccia took place at high temperatures deep within the formation*. On the other hand, if its final assembly occurred elsewhere, very little can be said of the cooling time for 14321 and the interpretation of the ages of its clasts becomes ambiguous.

MINERAL AGES

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The isotopic data for this rock and its various mineral separates (Table 1) are plotted in Fig. 3. The points cover a wide range in $^{87}\text{Rb}/^{86}\text{Sr}$ and all fit the regression

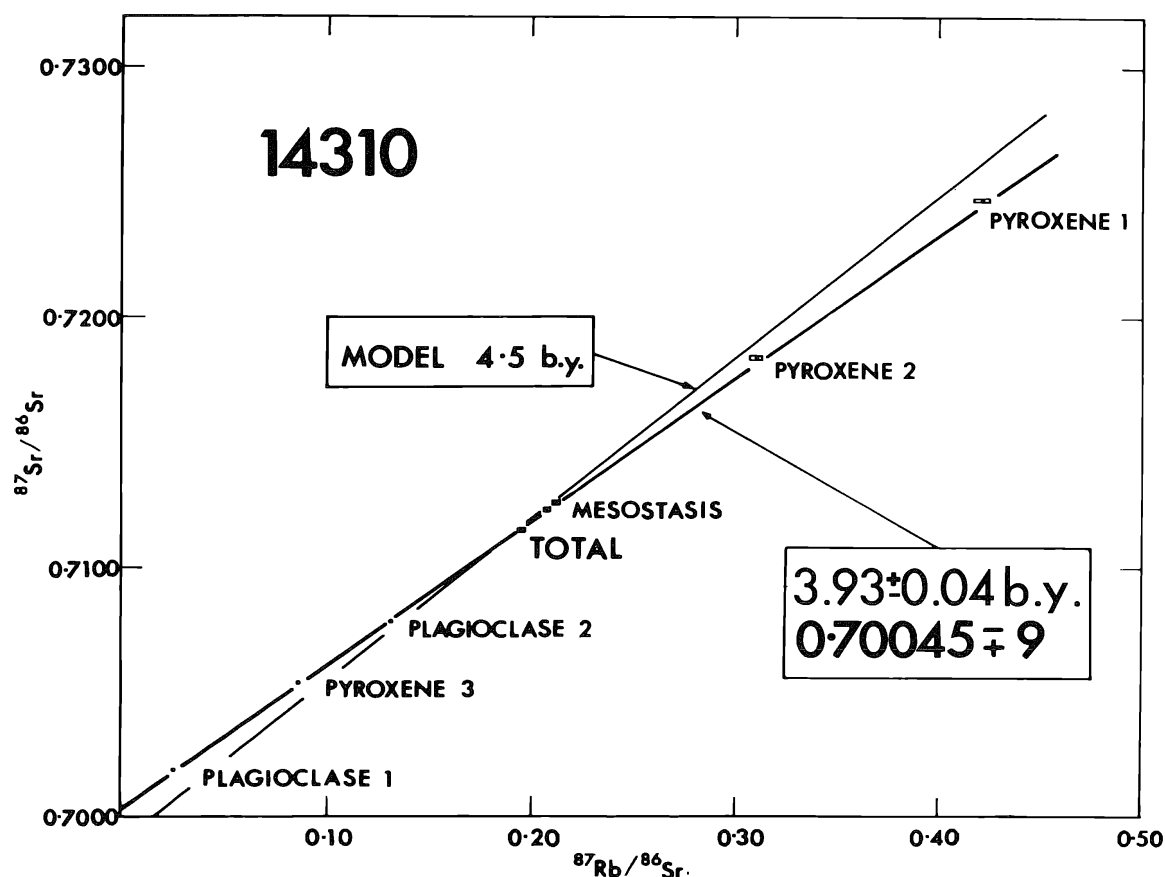


Fig. 3. Isochron diagram for igneous rock 14310. The fit of points in this and other isochron diagrams is within experimental precision, which is shown as 95% confidence limits. The "Model 4.5 b.y." isochron shown for comparison is drawn through initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.6990. The ^{87}Rb decay constant is taken as 0.0139 b.y.^{-1} . Errors in isochron parameters are 95% limits.

line to within experimental error, so that the slope of the line is precisely measured ($\pm 1\%$, at 95% confidence limits). The mineral age is 3.93 ± 0.04 b.y., in agreement with the results of Papanastassiou and Wasserburg (1971b), Murthy *et al.* (1972), and Tatsumoto *et al.* (1972) for the same rock. (We have reduced our previous values for lunar ages by 1.8% following recalibration of spikes using the National Bureau of Standards stoichiometric Rb and Sr salts, as reported by De Laeter *et al.*, 1972.)

The variation in $^{87}\text{Rb}/^{86}\text{Sr}$ for the pyroxene concentrates in Fig. 3 is plainly due to variation in their content of the alkali-rich mesostasis, which has $^{87}\text{Rb}/^{86}\text{Sr}$ of at least 2.4 (Papanastassiou and Wasserburg, 1971b). However the mesostasis does not wholly control the slope of the isochron. The total rock-plagioclase tieline is also well-defined at 3.88 b.y., with limits as small as ± 0.08 b.y., so that if the mesostasis has lost any radiogenic ^{87}Sr by postcrystallization diffusion, the plagioclase has absorbed it. The good fit of all samples to the regression line favors an isochron interpretation either as the original age of crystallization or as a later thermal event involving complete isotopic equilibration. However this is not a compelling argument. Partial isotopic equilibration might have occurred, making the plagioclase and mesostasis each internally heterogeneous in $^{87}\text{Sr}/^{86}\text{Sr}$, but a good “isochron” alignment could still be produced by adequate mixing and representative sampling of the plagioclase and mesostasis during the operations of mineral separation. The high value for “initial” $^{87}\text{Sr}/^{86}\text{Sr}$ of 14310 compared with mare basalts is likewise suggestive of metamorphic equilibration of isotopes but not compelling, as mare basalts themselves have a range in initial $^{87}\text{Sr}/^{86}\text{Sr}$.

14321,88, basalt clast 6A

This was a ~ 0.5 cm diameter, rounded clast within the light grey matrix that Grieve *et al.* (1972) describe as the youngest textural element of breccia 14321. The clast weighed ~ 150 mg after cleaning, and was then crushed and divided into two equal and representative portions, one for mineral separation and Rb–Sr dating (Table 1) and the other for determination of trace-elements by spark-source mass spectrometry (Taylor, 1972a).

Figure 4 shows that the data for six different mineral separates give well-defined values for isochron slope, 4.05 b.y., and intercept. They are not distinguishable from our (revised) result for the basalt clast 4A (4.08 ± 0.1 b.y., Compston *et al.*, 1971a), which is from the opposite face of the breccia slab within the same light grey matrix. However both basalts are significantly older than 14310 and lower in initial $^{87}\text{Sr}/^{86}\text{Sr}$, the difference between the pooled basalt age and 14310 being 0.13 ± 0.08 b.y. for 95% confidence limits. Papanastassiou and Wasserburg (1971b) detect a similar difference, 0.08 ± 0.06 b.y., between the mineral ages of 14310 and several igneous chips of similar type, and a basalt clast (191 X1) extracted from 14321. Turner *et al.* (1971) likewise detect a difference in the ^{40}Ar – ^{39}Ar ages of these groups.

Interpretation of the isochron as a geological process is again ambiguous: The good alignment suggests either the original crystallization or complete postcrystallization resetting, although the data also allow an interpretation as partial resetting if the making and sampling of mineral concentrates were representative.

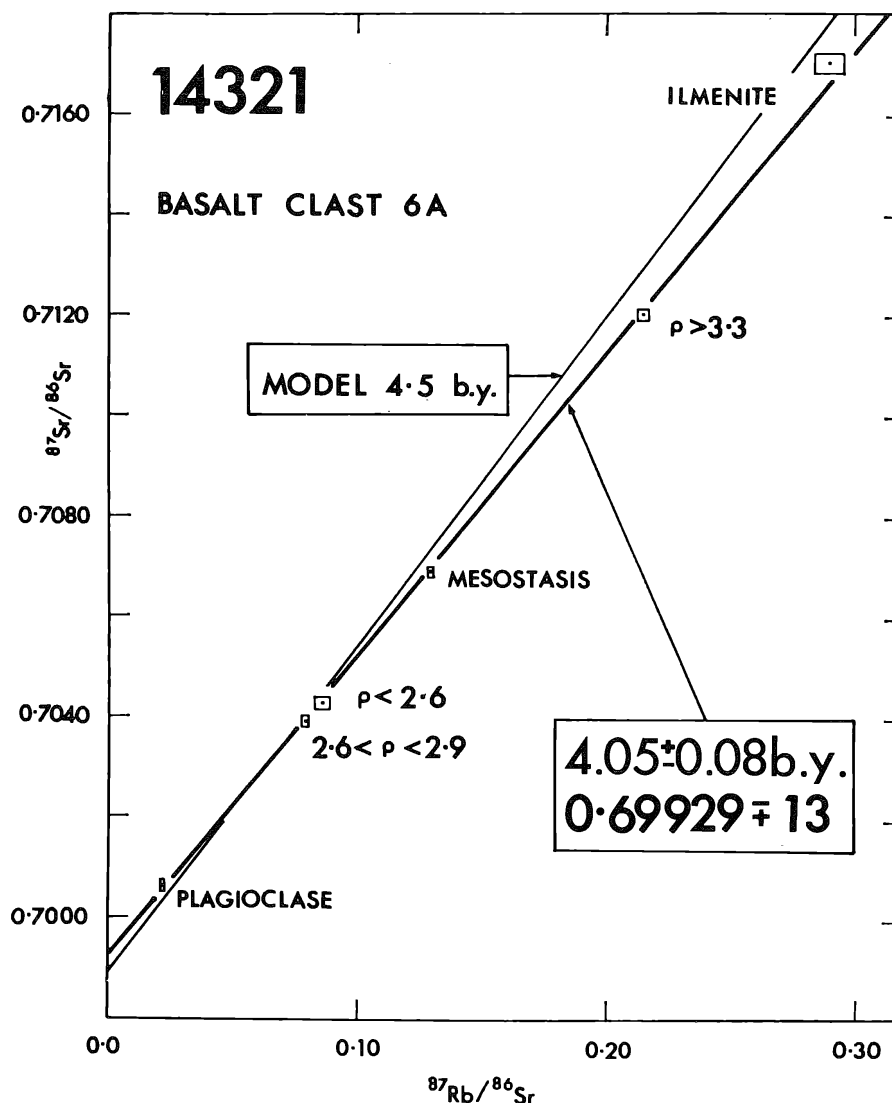


Fig. 4. Isochron diagram for basalt 6A, a clast from breccia 14321,88.

14072

The apparent age and initial $^{87}\text{Sr}/^{86}\text{Sr}$ of this basalt (Fig. 5) are not detectably different to those given by our analyses of basalt clasts 4A and 6A, but the initial $^{87}\text{Sr}/^{86}\text{Sr}$ for clast 191 X1 and rock 14053 by Papanastassiou and Wasserburg (1971b) is slightly higher. Our age is in good agreement with the ^{39}Ar - ^{40}Ar result of York *et al.* (1972) for the same rock.

14321,88 troctolite clast 8A

Like the basalts 4A and 6A, this clast also occurs within the (youngest) light grey matrix of the breccia. Its apparent age (Fig. 6) is less precisely determined because a satisfactory separation of the traces of K-feldspar within this sample from Sr-rich plagioclase could not be achieved, with the result that the dispersion in Rb/Sr between the mineral concentrates was comparatively small. Furthermore, the Rb and Sr

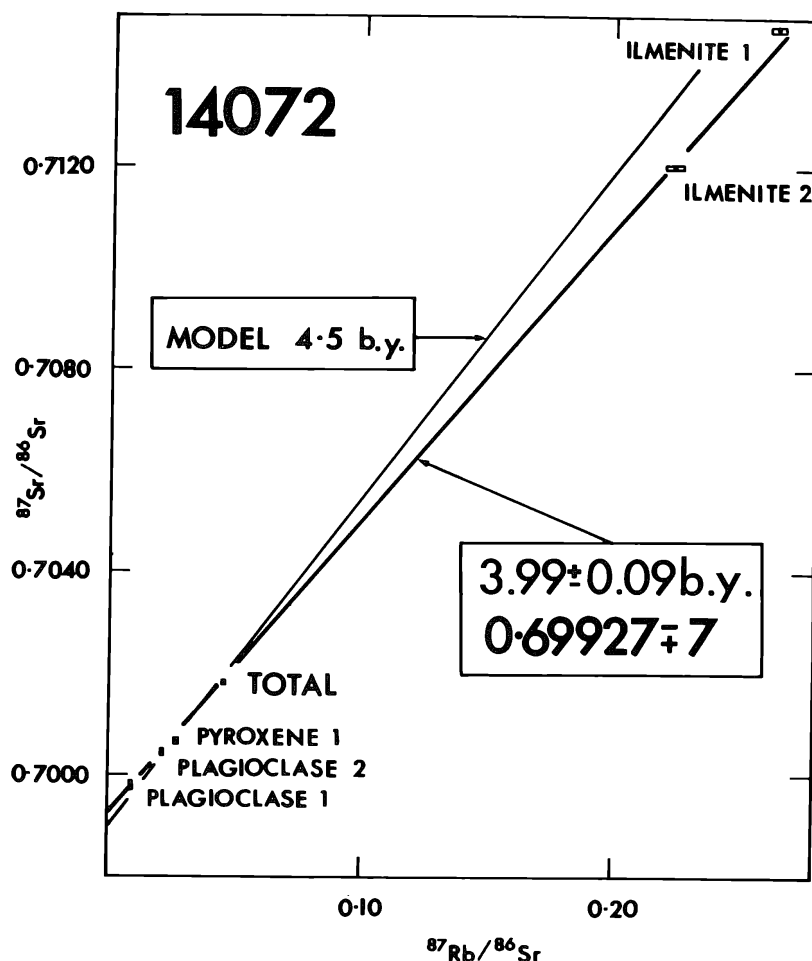


Fig. 5. Isochron diagram for basalt chip 14072.

contents of the highest $^{87}\text{Rb}/^{86}\text{Sr}$ sample, the olivine, were so low that the normal variation in the Rb blank and short-term Sr beam noise limited the precision of the analysis. Nevertheless, the mineral age is in good agreement with the overall Fra Mauro formation results, and the initial $^{87}\text{Sr}/^{86}\text{Sr}$ of the troctolite is clearly placed with the “mare” type basalts rather than rock 14310 type. A mineral age of 3.9 ± 0.3 b.y. is given by the K-feldspar and total-rock samples alone. This clast could belong either to the 14310 age group or to the 14053, 4A, 6A, and 191 X1 clast group.

DISCUSSION

A good quality fit of Rb–Sr mineral points to a regression line is necessary to interpret the line as an isochron. But no event thus identified can be equated to a particular geological process without additional information. Previously we used the well-preserved igneous mineralogy of clast 4A from 14321 and lack of shock effects as evidence that the dated event was the pre-Imbrian crystallization of an original lava flow. Papanastassiou and Wasserburg (1971b) cited the good agreement of their Rb–Sr ages with the ^{40}Ar – ^{39}Ar ages of Turner *et al.* (1971) as additional evidence to support the same conclusion. However, neither preservation of petrography nor age

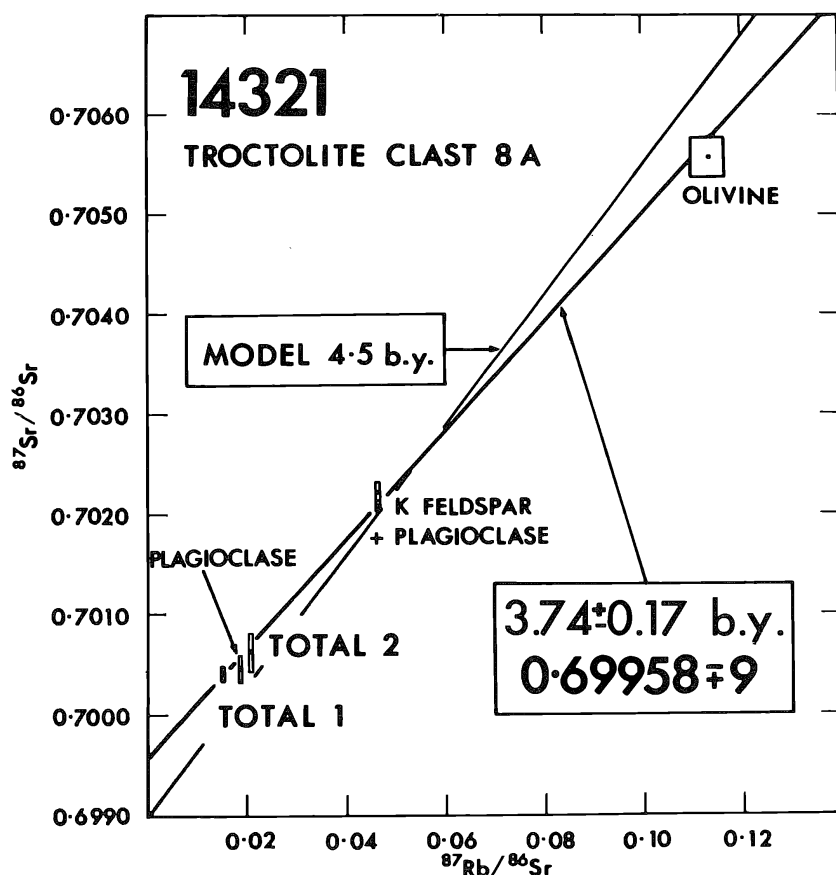


Fig. 6. Isochron diagram for troctolite clast 8A, from breccia 14321,88.

concordance are conclusive arguments. Instead we must now recognize the possibility of high and prolonged temperatures within the (deposited) Fra Mauro formation and the consequent diffusion of trace-elements within the basalt clasts which this would imply. For such a model, the good quality isochron fits are best interpreted as evidence for total re-equilibration of Sr isotopes between the minerals of each clast during the thermal event, and the concordance with K–Ar ages as due to complete Ar degassing at the same time. All clasts would be expected to give identical mineral ages; for the group of known basaltic clasts (4A, 6A, 191 X1) and probable clasts (14053) dated so far, this appears to be so. All have ages close to 4 b.y. In addition, Cliff *et al.* (1972) find the same value for the Rb–Sr mineral age of igneous fragments within a clast of older breccia included in the highly annealed breccia 14066, which is in close agreement with the result of these authors for another basalt clast from 14321. Thus, for the model of high-temperature deposition for the Fra Mauro formation, the age of deposition, i.e., the Imbrian event, is directly registered as 4 b.y. Schaeffer *et al.* (1972) have given this interpretation for their ^{40}Ar – ^{39}Ar results.

It also follows that the slightly younger group of basalts that also show perfectly fitted mineral isochrons (14310, 14073, and 14001,7,3) cannot be regarded on this model as clasts belonging to the Fra Mauro formation. Their present mineral ages must have formed slightly later, and probably elsewhere. There is no geological evidence to preclude this: Rock 14310 for example, is a large isolated boulder completely free of adhering breccia-type matrix. Schaeffer *et al.* (1972) report still younger “non-

mare" type basaltic fragments in Apollo 14 soils, between 3.5 and 3.6 b.y., that they also interpret as post-Fra Mauro formation.

In contrast to the above, if the Fra Mauro formation was deposited at low temperature, then the age of the Imbrian event is much less well determined. If the 14310 type rocks are assumed to be clasts, then the Imbrian event can be taken as 3.9 b.y. or younger. The significance of the 4 b.y. ages in the mare-type basalt clasts is now unknown: They could be unreset crystallization ages if the pre-Imbrian magnetization and annealing of the breccias occurred in a very short heating and cooling pulse, or they could be partially or completely reset mineral ages associated with a sufficiently long period of pre-Imbrian metamorphism.

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