COSMIC RAY EXPOSURE AGES OF FEATURES AND EVENTS AT THE APOLLO LANDING SITES

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Abstract. Cosmic ray exposure ages of lunar samples have been used to date surface features related to impact cratering and downslope movement of material. Only when multiple samples related to a feature have the same rare gas exposure age, or when a single sample has the same ^{81}Kr–Kr and track exposure age can a feature be considered reliably dated. Because any single lunar sample is likely to have had a complex exposure history, assignment of ages to features based upon only one determination by any method should be avoided. Based on the above criteria, there are only five well-dated lunar features: Cone Crater (Apollo 14) 26 m.y., North Ray Crater (Apollo 16) 50 m.y., South Ray Crater (Apollo 16) 2 m.y., the emplacement of the Station 6 boulders (Apollo 17) 22 m.y., and the emplacement of the Station 7 boulder (Apollo 17) 28 m.y. Other features are tentatively dated or have limits set on their ages: Bench Crater (Apollo 12) $\leqslant$99 m.y., Baby Ray Crater (Apollo 16) $\leqslant$2 m.y., Shorty Crater (Apollo 17) $\approx$30 m.y., Camelot Crater (Apollo 17) $\leqslant$140 m.y., the emplacement of the Station 2 boulder 1 (Apollo 17) 45–55 m.y., and the slide which generated the light mantle (Apollo 17) $\geqslant$50 m.y.

1. Introduction

The two dominant processes that shape the lunar surface appear to be impact cratering and downslope mass wasting of material. Impact cratering is likely more important and, in fact, downslope mass movements may be largely triggered by impact events. Cosmic ray exposure histories of lunar samples provide contraints on the rates of both these processes (Drozd *et al.*, 1974) and on events associated with them (Arvidson *et al.*, 1975).

This paper summarizes the present understanding of cosmic ray exposure ages of craters at the Apollo landing sites and also certain samples not related to craters. The latter include samples associated with Hadley Rille (Apollo 15) and with boulders that rolled or bounded down the slopes of the massifs bordering the Taurus-Littrow Valley (Apollo 17). A companion paper (Arvidson *et al.*, 1975) utilizes these age estimates to derive constraints on the rates of vertical and horizontal redistribution of lunar material.

Exposure ages have been measured by several techniques. The first involves measurement of rare gas isotopes. High-energy galactic cosmic-ray protons and their secondaries interact with target elements in lunar samples, producing ‘spallogenic’ or ‘cosmogenic’ rare gases. Such particles have effective ranges of over 300 g cm^{-2} ($\sim$1 m of rock or $\sim$1.5 m of regolith).

There are two types of rare gas ages. The first type is based only upon measurements of the accumulated quantity of spallogenic rare gas isotopes, usually ^{21}Ne, ^{38}Ar, and ^{126}Xe. Ages based on ^{38}Ar are the most numerous; ^{126}Xe ages are unavailable for many samples and ^{21}Ne ages are complicated by possible diffusive losses of neon

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(Drozd *et al.*, 1974). Therefore, among the ages calculated from accumulated rare gas isotopes, those based upon ^{38}Ar were preferentially selected for use in this work unless only ^{21}Ne ages were available. All such accumulation ages require prior knowledge of the absolute production rate for a rare gas isotope in atoms/gram-year or equivalent unit.

Knowing the production rate, the absolute amount of spallogenic gases is a function of sample orientation and shielding during the entire exposure history, as well as the concentration of target elements. Target chemistry can be measured in a returned sample but accurate production rates require knowledge of the exposure conditions as well. Since it is often difficult or impossible to reconstruct this with certainty, some average production rate is generally assumed, and ages are therefore subject to potentially large systematic errors (Drozd *et al.*, 1974). Recently, improved production rates which take into account some shielding effects have been proposed by Pepin *et al.* (1974), which should improve the quality of exposure ages measured by the accumulated isotope method.

The other rare gas method for obtaining cosmic ray exposure ages, the ^{81}Kr–Kr method (Marti, 1967), avoids much of the uncertainty of an unknown production rate. Measurement of radioactive ^{81}Kr (half-life, 0.2 m.y.) provides self-normalization of production rates for each individual sample. Details of the method have been described elsewhere (Lugmair and Marti, 1971, 1972; Drozd *et al.*, 1974). It is important to stress that the ^{81}Kr–Kr method derives exposure ages from krypton isotopic information alone and not from the absolute quantity of cosmogenic gases. This makes the ^{81}Kr–Kr method inherently more precise than the previous method. Because ^{81}Kr has a short half-life, recent dramatic changes in sample shielding can alter the value of the apparent ^{81}Kr–Kr age; however, such an effect, if it can be detected, can be of use in understanding complexities of sample exposure histories.

Another method for obtaining exposure ages is based on cosmic ray particle tracks produced by iron group nuclei in the cosmic rays. Such particles have ranges on the order of 30 g cm^{-2} and, further, are rapidly absorbed by nuclear collisions. The best track ages are calculated from a profile of track density versus depth in a sample; the shape of the profile yields the exposure information. Accurate knowledge of geometry and orientation of the sample on the lunar surface is required to determine the expected profile for a given age. The detailed theory of this method has been described by Walker and Yuhas (1973), Yuhas (1974), and Fleischer *et al.* (1974).

Micrometeoroid impact features on fresh surfaces of lunar samples and the undersaturation of various cosmic ray produced radionuclides have also been used to obtain surface residence times for certain samples (see Clark and Keith, 1973; Eldridge *et al.*, 1973; Morrison *et al.*, 1973; Neukum *et al.*, 1973; Rancitelli *et al.*, 1973). Unfortunately, for exposure times of the order of several million years or less, microcrater populations and radionuclides reach saturation and can no longer provide age information. Therefore, tracks and rare gases are the primary tools used for exposure age dating.

2. Criteria for Dating a Lunar Feature or Event

If a lunar event exposes material for the first time to cosmic rays, then spallogenic rare gases and tracks would, in principle, date the event. However, most lunar samples have had complex exposure histories which make interpretation of an 'exposure age' difficult (Drozd *et al.*, 1974). Because of such difficulties, we have previously proposed (Crozaz *et al.*, 1974; Drozd *et al.*, 1974) that a feature or event can be dated in one of two ways. First, if a number of samples thought to be associated with a particular feature or event give the same rare gas exposure age, that age can be assigned to the event with some certainty. Due to uncertainties in production rates, conventional rare gas exposure ages may not cluster as tightly as ^{81}Kr–Kr ages. They may even cluster about different values as production rates can be systematically in error by up to a factor of two (Drozd *et al.*, 1974). Nevertheless, all such clusterings should be examined because they may be related to a lunar event or feature.

The other way of dating a lunar feature is to make use of concordant ^{81}Kr–Kr ages and track ages based upon profiles of track density versus depth. Due to the large difference in ranges of the particles producing the effect ($\lesssim 300$ g cm^{-2} for protons and $\lesssim 30$ g cm^{-2} for iron nuclei), when both methods agree, it demonstrates a simple exposure history for the sample and therefore a meaningful exposure age. A single age determination whether by rare gas or track techniques does not reliably date a lunar feature; one must have multiple rare gas ages or concordant rare gas and track ages. For reasons developed above, we will use all rare gas ages to establish age clusterings but *only* ^{81}Kr–Kr ages to establish the absolute value of the age.

3. Apollo 11 Landing Site

Table I lists ^{38}Ar accumulation ages and ^{81}Kr–Kr ages for some Apollo 11 samples, all of which were larger than 100 g in mass. Figure 1 illustrates these data in histogram

TABLE I

Apollo 11 samples

Sample	Exposure age (m.y.)	Method	Reference
10003	129	Kr	Schwaller (1971)
	140	Ar	Hintenberger *et al.* (1971)
10017	480	Kr	Eberhardt *et al.* (1974)
	510	Ar	Hintenberger *et al.* (1971)
10044	70	Kr	Hohenberg *et al.* (1970)
	93	Ar	Hintenberger *et al.* (1971)
10047	84	Kr	Schwaller (1971)
10049	36	Ar	Hintenberger *et al.* (1971)
10057	52.5	Kr	Schwaller (1971)
	58	Ar	Hintenberger *et al.* (1971)
10069	42.5	Kr	Schwaller (1971)
10071	350	Kr	Eberhardt *et al.* (1974)

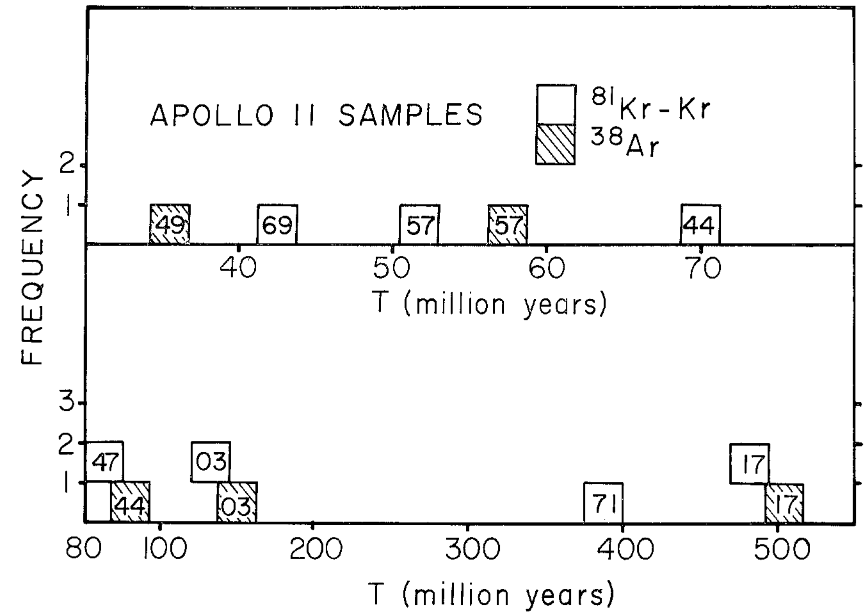

Fig. 1. Histogram of rare gas exposure ages of Apollo 11 samples. ^{81}Kr–Kr ages (open squares) and ^{38}Ar ages (hatched squares) are presented; ^{21}Ne ages have been omitted because they tend to duplicate ^{38}Ar ages. Numbers within the squares are the last two digits of the Apollo 11 lunar sample number, 100xx.

form. There are no groupings of ages, nor are there concordant track and krypton ages. These samples span a range of exposure histories and illustrate more than anything else the complexity of the lunar regolith. The Apollo 11 mission landed in a relatively featureless region between blocky rays of the 180 m diam West crater. Apparently, no craters within the sampled site are sufficiently large and young enough to supply an input of fresh material with simple exposure histories. The only reliable correlation that can be made is that 10017, the sample with the largest exposure age, also appears to be the most rounded and smoothed by micrometeoroid bombardment (Apollo 11 Preliminary Science Report).

4. Apollo 12 Landing Site

Results for the Apollo 12 site are given in Table II and Figure 2 for samples greater than 50 g in mass. Samples collected from the rim of Bench Crater span ages from 99 m.y. to 225 m.y. Most likely, pre-irradiated (burial $\gtrsim 1$ m for some fraction of lifetime) material was excavated during the Bench cratering event and is now exposed at the crater rim. Assuming that the youngest sample age (99 m.y. for 12053) is least affected by pre-irradiation, we assign a tentative age for Bench Crater of $\leqslant 99$ m.y. The clustering of sample ages around 50 m.y. may also be related to Bench Crater, being blocks that were excavated and thrown far from the crater during the impact event. If this were true, then an age of 50 m.y. could be assigned to Bench Crater just

TABLE II

Apollo 12 samples

Sample	Exposure age (m.y.)	Method	Feature	Reference
12002	94	Kr	Bench (?)	Marti and Lugmair (1971)
12004	58.5	Kr		Schwaller (1971)
	45	Ar		Hintenberger *et al* (1971)
12008	50	Ar		Stettler *et al.* (1973)
12009	136	Kr	Head (?)	Marti and Lugmair (1971)
12010	80–100	Ar		Bogard *et al.* (1971)
12011	80–100	Ar		Bogard *et al.* (1971)
12012	40–60	Ar		Bogard *et al.* (1971)
12014	40–60	Ar		Bogard *et al.* (1971)
12015	120–140	Ar		Bogard *et al.* (1971)
12018	195	Kr		Marti and Lugmair (1971)
12020	56	Ar		Hintenberger *et al.* (1971)
12021	303	Kr		Marti and Lugmair (1971)
12027	120–140	Ar		Bogard *et al.* (1971)
12040	225	Kr		Schwaller (1971)
12051	205	Kr		Schwaller (1971)
	205	Ar		Stettler *et al.* (1971)
12052	129	Kr	Head	Marti and Lugmair (1971)
12053	99	Kr	Bench	Lugmair and Marti (1971)
12063	95	Kr	Bench (?)	Marti and Lugmair (1971)

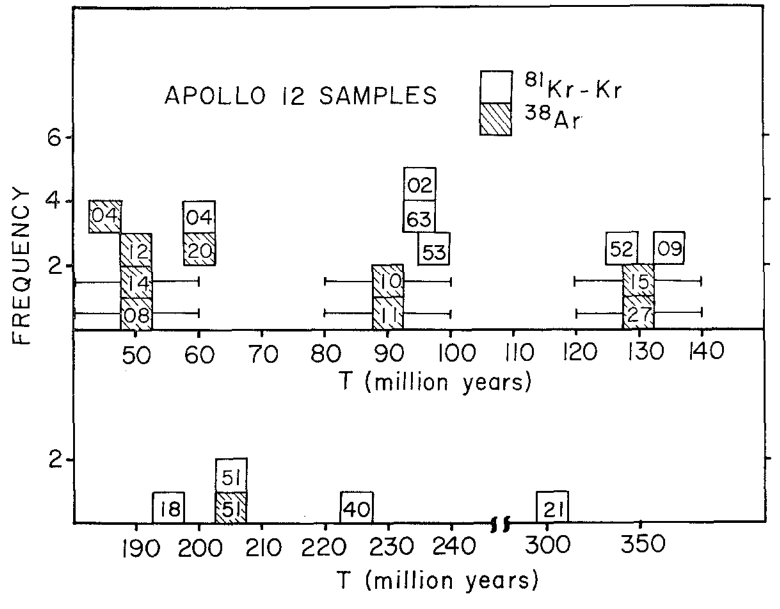

Fig. 2. Histogram of rare gas exposure ages for the Apollo 12 samples. Error bars are given on some ages because of the large spread in reported values. Numbers within squares refer to the last two digits of the Apollo 12 lunar sample number, 120xx.

as, later in this paper, an age of 2 m.y. is assigned to South Ray Crater from rocks scattered over the Apollo 16 site (Drozd *et al.*, 1974). Discussion of the Apollo 12 site is tentative since a complex stratigraphy and re-excavation sequence probably exists and dominates the site. It is interesting to note that one 58 m.y. old sample (12004) also has a low spallogenic $^{131}Xe/^{126}Xe$ ratio (Schwaller, 1971), indicating that it probably spent its entire irradiation history exposed on the lunar surface. Further work in this area is underway which may prove useful in further deciphering the history of the Apollo 12 site (Burnett *et al.*, 1975, in preparation).

5. Apollo 14 Landing Site

Data for Apollo 14 samples are reported in Table III and Figure 3. Data for some coarse fragments have been included in the Apollo 14 compilation of ages because they aid in interpreting the history of the site, hence some sample numbers are multiply reported in Figure 3. A clustering of ages is observed in the region 24 to 28 m.y., corresponding to rocks collected throughout the Apollo 14 site. The region is dominated by Cone Crater, a young 340-m-diam crater. Five samples collected near the rim of the crater yield ages of 24 to 28 m.y. Based upon seven ^{81}Kr–Kr ages from six different samples, we assign a mean age of (26.0±0.8) m.y. to the Cone Crater event. There is good agreement between the ^{38}Ar and ^{81}Kr–Kr ages on four rocks believed to have been excavated from Cone Crater. This indicates that the average production

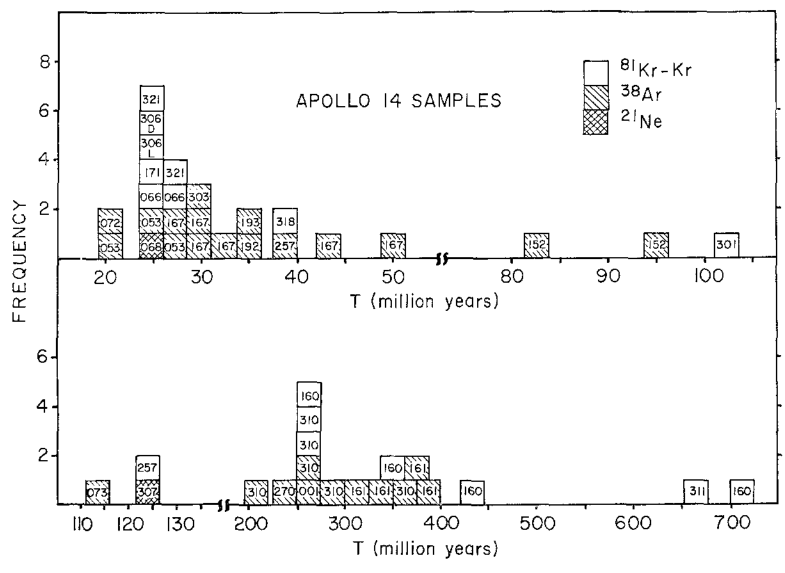

Fig. 3. Histogram of rare gas exposure ages for the Apollo 14 samples. ^{21}Ne ages have been included when no ^{38}Ar ages or ^{81}Kr–Kr ages exist. Numbers within squares refer to the last three digits of the Apollo 14 lunar sample number, 14xxx. Some samples are multiply reported. A few (e.g., 14152 and 14168) are coarse fines and each age represents a different fragment. Others (e.g., 14310) are ages determined in different laboratories (see Table III). The clustering of ages at 26 m.y. is identified with Cone Crater.

TABLE III

Apollo 14 samples

Sample	Exposure age (m.y.)	Method	Feature	Reference
14001	260	Ar		Turner *et al.* (1971
14053	24	Ar	Cone	Stettler *et al.* (1973)
	26	Ar	Cone	Turner *et al.* (1971)
	21	Ar	Cone	Husain *et al.* (1972)
14066	24	Kr	Cone	Kaiser (1972)
	27	Kr	Cone	Srinivasan (1974)
14068	25	Ne	Cone	Bogard and Nyquist (1971)
14072	21	Ar	Cone	York *et al.* (1972)
14073	113	Ar		York *et al.* (1972)
14152	82	Ar		Husain *et al.* (1972)
	95	Ar		Husain *et al.* (1972)
14160	700	Kr		Lugmair and Marti (1972)
	351	Kr		Lugmair and Marti (1972)
	264	Kr		Lugmair and Marti (1972)
	421	Kr		Lugmair and Marti (1972)
14161	300	Ar		Kirsten *et al.* (1972)
	320	Ar		Kirsten *et al.* (1972)
	360	Ar		Kirsten *et al.* (1972)
	380	Ar		Kirsten *et al.* (1972)
14167	27	Ar	Cone	York *et al.* (1972)
	29	Ar	Cone	Turner *et al.* (1971)
	29	Ar	Cone	Husain *et al.* (1972)
	32	Ar	Cone	Husain *et al.* (1972)
	43	Ar		Husain *et al.* (1972)
	50	Ar		Husain *et al.* (1972)
14171	24.5	Kr	Cone	Drozd *et al.* (1974)
14192	35	Ar	Cone (?)	Husain *et al.* (1972)
14193	35	Ar	Cone (?)	Husain *et al.* (1972)
14257	124	Kr		Lugmair and Marti (1972)
	40	Ar		Husain *et al.* (1972)
14270	240	Ar		Alexander and Kahl (1974)
14301	102	Kr		Drozd *et al.* (1974)
14303	29	Ar	Cone	Kirsten *et al.* (1972)
14306L	24.6	Kr	Cone	Crozaz *et al.* (1972)
14306D	24.5	Kr	Cone	Crozaz *et al.* (1972)
14307	125	Ne		Bogard and Nyquist (1972)
14310	265	Kr		Drozd *et al.* (1974)
	259	Kr		Lugmair and Marti (1972)
	210	Ar		Husain *et al.* (1972)
	250	Ar		Stettler *et al.* (1973)
	280	Ar		Turner *et al.* (1972)
	340	Ar		York *et al.* (1972)
14311	661	Kr		Drozd *et al.* (1974)
14318	38.8	Kr		Drozd *et al.* (1974)
14321				
FM1 & 2	23.8	Kr	Cone	Lugmair and Marti (1972)
FM5	27.2	Kr	Cone	Lugmair and Marti (1972)

rate used for the ^{38}Ar ages are probably suitable for the majority of Apollo 14 samples, provided that any unusual shielding effects are considered.

The clustering of ages in Figure 3 in the region of 250 to 300 m.y. does not seem to represent a known lunar surface event. With the exception of 14310, all data were obtained on small rock fragments. The value of $\approx$260 m.y. may rather represent an average exposure lifetime for coarse fragments in the Fra Mauro area. In addition, rock 14310 appears to have experienced a complex irradiation history as evidenced by its high neutron dose (Burnett *et al.*, 1972), its nuclear particle track record (Yuhas *et al.*, 1972), and its spallogenic krypton record (Lugmair and Marti, 1972; Drozd *et al.*, 1974).

At this time no other feature has been dated at the Apollo 14 site. However, ejecta from large craters in the valley such as Doublet and Triplet, which penetrated through the regolith are probably represented in the sample collection. However, the complexity of the individual exposure histories may have broadened any exposure age clusters. With further work it may be possible that the ages of these features can be determined.

6. Apollo 15 Landing Site

Apollo 15 exposure ages are shown in Table IV and Figure 4. Dates on coarse frag-

TABLE IV

Apollo 15 samples

Sample	Exposure age (m.y.)	Method	Reference
15016	285	Ar	Kirsten *et al.* (1973b)
15076	280	Ar	Kirsten *et al.* (1973b)
15263	216	Ar	Husain (1972)
15382	230	Ar	Stettler *et al.* (1973)
15385	270	Ar	Husain *et al.* (1972)
15415	90	Ar	Husain *et al.* (1972)
	100	Ar	Stettler *et al.* (1973)
	112	Ar	Turner (1972)
15418	250	Ar	Stettler *et al.* (1973)
15426	350	Ar	Lakatos and Heymann (1972)
15459	520	Ar	Stettler *et al.* (1973)
15473	656	Ar	Husain (1972)
15475	473	Kr	Drozd *et al.* (1974)
15535	110	Kr	Alexander *et al.* (1973)
15555	81	Kr	Marti and Lightner (1972)
	80	Ar	Husain *et al.* (1972)
	75	Ar	York *et al.* (1972)
	90	Ar	Podosek *et al.* (1972)
15556	490	Ar	Kirsten *et al.* (1972)
15595	110	Kr	Behrmann *et al.* (1972)
15597	210	Ar	Kirsten *et al.* (1973b)
15668	510	Ar	Husain *et al.* (1972)
15678	150	Ar	Husain *et al.* (1972)
15683	290	Ar	Husain *et al.* (1972)

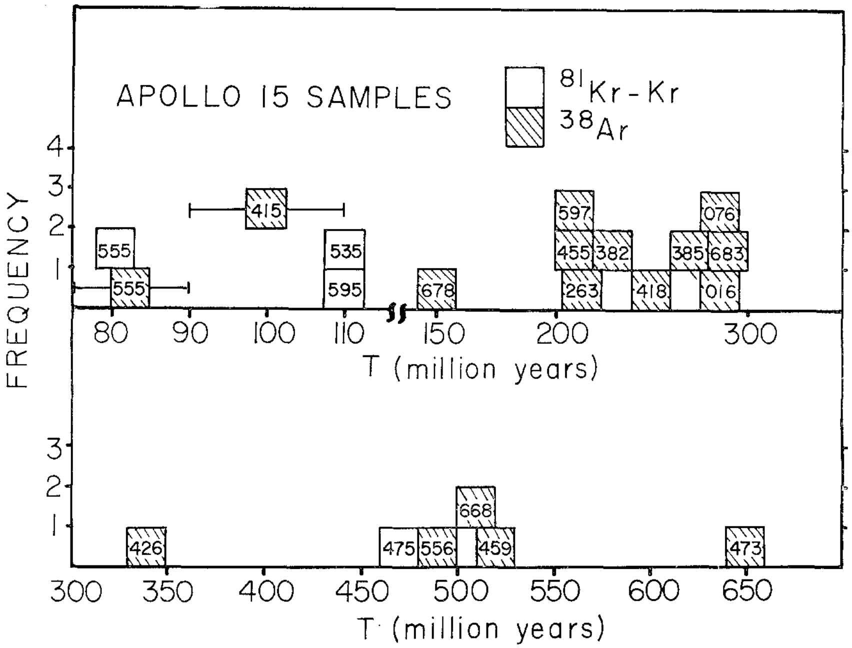

Fig. 4. Histogram of rare gas exposure ages for Apollo 15 samples. Numbers within squares are the last three digits of the Apollo 15 sample number, 15xxx.

ments have been omitted because of the large number of them and in an attempt to restrict the data to samples whose history is probably less complicated, i.e., large rocks and boulders (see Husain (1974) for a summary of fragment ages from Apollo 15).

Clustering of ages are not apparent in Figure 4, leading to the conclusion that no major surface event has recently sprayed fresh material into the Apollo 15 area. However, the presence of as yet undated glass-coated rocks in the LEM area (Hörz, 1975) indicates that some fresh material may have been recently added in that region. The best-sampled crater, Spur (100 m diam) located on the lower slopes of Hadley Delta, excavated a range of rock types (Apollo 15 Sample Catalog); the spread in exposure ages suggests that Spur may also have excavated a complex set of partially pre-irradiated material, making an assignment of an age for this crater difficult. An additional complicating factor is that Spur, by morphological criteria, seems to be degraded enough that a significant fraction of present rim material may have been added from other sources after the Spur event.

The two bedrock samples collected at Station 9A (15535, 15595) on the rim of Hadley Rille, both have identical krypton ages of 110 m.y. Material is being removed from the rim and placed down into the rille as talus debris. The 110 m.y. age does not date an event, but rather places a constraint on the rate of bedrock removal on the upper rim of the Hadley Rille. This point is expanded further in Arvidson *et al.* (1975).

7. Apollo 16 Landing Site

Cosmic ray exposure ages are presented in Table V and Figure 5. Ages for fragments and fines have been included when they aid in dating a feature. Two clusterings of ages are obvious in Figure 5; the most prominent is that at 50 m.y. for samples from

TABLE V

Apollo 16 samples

Sample	Exposure age (m.y.)	Method	Feature	Reference
60015	1.8	Ar	South Ray	Reynolds (1974)
60025	1.9	Kr	South Ray	Marti (1974)
60315	4.5	Ar	South Ray	Kirsten *et al.* (1973b)
62235	153	Kr		Drozd *et al.* (1974)
	162	Kr		Marti (1974)
62255	1.9	Kr	South Ray	Marti (1974)
62295	235	Kr		Marti (1974)
	310	Ar		Turner *et al.* (1973)
63502	285	Ar		Kirsten *et al.* (1973b)
	390	Ar		Kirsten *et al.* (1973b)
63503	55	Ar		Schaeffer and Husain (1973)
	155	Ar		Schaeffer and Husain (1973)
64435	2	Ar	South Ray	Bogard *et al.* (1973)
64455	2	Ar	South Ray	Bogard *et al.* (1973)
65015	365	Ar		Kirsten *et al.* (1973b)
66043	490	Ar		Schaeffer and Husain (1973)
66095	1	Ne	South Ray	Heymann and Hubner (1974)
67015	51.1	Kr	North Ray	Marti *et al.* (1973)
67075	48.5	Kr	North Ray	Marti *et al.* (1973)
	46	Ar	North Ray	Turner *et al.* (1973)
67095	50.2	Kr	North Ray	Drozd *et al.* (1974)
67455	50.3	Kr	North Ray	Drozd *et al.* (1974)
	33	Ar		Kirsten *et al.* (1973b)
	31	Ar		Kirsten *et al.* (1973b)
67601	55	Ne	North Ray	Kirsten *et al.* (1973b)
67701	49	Ne	North Ray	Walton *et al.* (1973)
67915	50.6	Kr	North Ray	Drozd *et al.* (1974)
	49.7	Kr	North Ray	Marti *et al.* (1973)
	48.6	Kr	North Ray	Marti *et al.* (1973)
	32	Ar		Kirsten *et al.* (1973b)
	27	Ar		Kirsten *et al.* (1973b)
	28	Ar		Kirsten *et al.* (1973b)
	28	Ar		Kirsten *et al.* (1973b)
67955	50.1	Kr	North Ray	Drozd *et al.* (1974)
68115	2.08	Kr	South Ray	Drozd *et al.* (1974)
68415	92.5	Kr		Drozd *et al.* (1974)
	90	Ar		Stettler *et al.* (1973)
68416	89	Ar		Kirsten *et al.* (1973b)
68503	122–169	Ar		Schaeffer and Husain (1973)
68815	2.04	Kr	South Ray	Drozd *et al.* (1974)
69935	1.99	Kr	South Ray	Drozd *et al.* (1974)
69955	4.23	Kr	South Ray	Drozd *et al.* (1974)

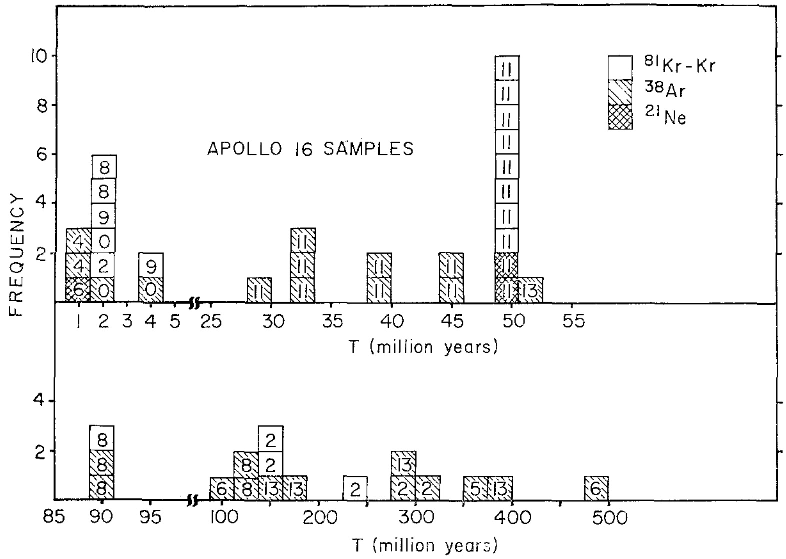

Fig. 5. Histogram for rare gas exposure ages for Apollo 16 samples. ^{38}Ar were preferentially selected over ^{21}Ne ages except where only ^{21}Ne ages were available. Numbers within squares refer to station numbers at which the samples were collected; for sample numbers, see Table V. The grouping of ages at 2 m.y. dates South Ray Crater, that at 50 m.y. dates North Ray Crater.

Station 11, which is on the rim of North Ray Crater. The eight ^{81}Kr–Kr ages based upon six different samples taken from large boulders yield a mean value of (50.0 ± 1.4) m.y. for the age of North Ray Crater. If we assume an erosion rate of 1 mm/m.y., a concordant track age has also been derived for 67915 (Behrmann *et al.*, 1973), a sample from one of these boulders. Thus the age of North Ray Crater can be firmly fixed at (50.0 ± 1.4) m.y. based upon multiple krypton ages and a concordant track age.

If only argon ages were utilized, however, the picture would be less clear. The argon ages plotted in Figure 5 which span the region 30 to 50 m.y. were obtained by analysis of the same samples which give krypton ages of 50 m.y. Some of the spread in argon ages arises because different laboratories use different average production rates for spallogenic ^{38}Ar (see Bogard *et al.*, 1971; Turner *et al.*, 1971; Stettler *et al.*, 1974). Even if the argon ages are adjusted for this effect, they still do not cluster as well or give the same mean age as those derived by the krypton method. The difference is due to erroneous production rates for samples taken from large boulders with restricted geometry and substantial shielding effects.

The second clustering of ages in Figure 5 is at 2 m.y., an age we identify with the South Ray cratering event. Five rocks from Stations 0, 2, 8, and 9 have ^{81}Kr–Kr ages of 2 m.y. In addition, there is a concordant track age for sample 68815 (Behrmann *et al.*, 1973). Table V shows further that five accumulation gas ages are also close to 2 m.y. Micrometeorite impact pits on fresh surfaces of a few rock samples also suggest young ($\sim$2 m.y.) ages (Morrison *et al.*, 1973; Neukum *et al.*, 1973) although this conclusion has been criticized by Hartung *et al.* (1973). Although none of these samples were collected from the continuous ejecta blanket, South Ray is the only crater in the region large enough and fresh-looking enough to populate these widely scattered stations with such material. Because of its small size (100 m), Baby Ray, although younger than South Ray as indicated by the superimposed ray pattern, is not a viable source for that quantity of 2 m.y. old ejecta at that ($\sim$2 km) distance (Drozd *et al.*, 1974). On the basis of this evidence, we suggest that samples with 2 m.y. exposure ages are related to the South Ray cratering event. This freshly exposed material, however, does not dominate material in the regolith as evidenced by the old apparent exposure ages for soils and coarse fines in the region (Schaeffer and Husain, 1973; Walton *et al.*, 1973).

Measurements on a Station 9 boulder support the 2 m.y. age assignment for South Ray and give further information on the nature of secondary crater ejecta. This boulder was sampled both on the top (69935) and on the bottom (69955). Analysis of the apparent krypton ages, spallation isotopic spectra, and tracks suggests the following exposure history (Drozd *et al.*, 1974). For some time (2 ± 0.4 m.y.), the boulder was buried in the regolith inverted from its present position; 69935 was shielded by about (350 ± 100) gm cm^{-2} or $\sim$180 cm of regolith, which implies a burial of $\sim$170 gm cm^{-2} or $\sim$90 cm for 69955. It was subsequently transported to the surface, to its present orientation, 2 m.y. ago, by the South Ray event. Pepin *et al.* (1974) using Drozd *et al.*'s (1974) light rare gas data, together with improved production rates, that explicitly involve shielding effects, derived a similar pre-surface irradiation. The apparent 180 deg flip that occurred upon ejection seems to be a common feature of cratering dynamics (Shoemaker, 1963). The boulder from which 69935 and 69955 were taken is meter-sized and is located well off ($\sim$8 crater diam) the South Ray continuous ejecta blanket. Excavation at this distance implies that a projectile excavated from South Ray landed near the sample site and then excavated local material. This lends support to models which invoke significant regolith stirring and mixing by secondary projectiles hitting at considerabe distance from the main cratering event (see for example Oberbeck *et al.*, 1974).

8. Apollo 17 Landing Site

Figure 6 and Table VI presents ages for Apollo 17 samples. Some ages for fragments and fines have been included when they are of importance in determining the age of a feature. Ages that can be associated directly with lunar processes include both cratering events in the Taurus-Littrow Valley and times of downslope movements on the bordering massifs.

8.1. BOULDER EMPLACEMENTS

Based on concordant ^{81}Kr–Kr and track from sample 76315, taken from the side of a boulder at Station 6 near the base of the North Massif, we have been able to date when the boulder rolled or tumbled to its present position (Crozaz *et al.*, 1974). Accumulation rare gas ages average at about 11 m.y. (Heiken *et al.*, 1973), while con-

TABLE VI

Apollo 17 samples

Sample	Exposure age (m.y.)	Method	Feature	Reference
70017	126	Ar		Reynolds (1974)
70030	116	Kr		Marti (1974)
70035	95–100	Ar		Stettler *et al.* (1973)
70215	100	Ar		Kirsten and Horn (1974)
72255	45	Kr	South Massif slide	Leich *et al.* (1974)
72275	55	Kr	South Massif slide	Leich *et al.* (1974)
73235	111	Ar		Reynolds (1974)
73275	139	Kr		Crozaz *et al.* (1974)
74220	30	Ar	Shorty (?)	Huneke *et al.* (1973)
74241	300	Ar		Huneke *et al.* (1973)
74243	315	Ar		Kirsten and Horn
	57.5	Ar		Kirsten and Horn (1974)
74275	25	Ar	Shorty (?)	Eberhardt *et al.* (1974)
75035	72	Kr		Crozaz *et al.* (1974)
75055	95	Ar		Huneke *et al.* (1973)
	90	Ar		Turner *et al.* (1973)
	85	Ar		Kirsten *et al.* (1973a)
75075	143	Kr		Marti (1974)
75083	310	Ar		Huneke *et al.* (1973)
76010	14.8	Kr	Station 6 boulder	Marti (1974)
76015	17.5	Kr	Station 6 boulder	Crozaz *et al.* (1974)
76055	140	Ar		Huneke *et al.* (1973)
76315	21	Kr	Station 6 boulder	Crozaz *et al.* (1974)
76535	195	Kr		Crozaz *et al.* (1974)
	200	Ar		Bogard and Nyquist (1974)
77017	128	Ar		Reynolds (1974)
77075	25.5	Ar	Station 7 boulder	Stettler *et al.* (1974)
77135	28.6	Kr	Station 7 boulder	Crozaz *et al.* (1974)
,51	28.5	Ar	Station 7 boulder	Stettler *et al.* (1974)
,71	29.6	Ar	Station 7 boulder	Stettler *et al.* (1974)
77215	27.2	Ar	Station 7 boulder	Stettler *et al.* (1974)

cordant krypton and track ages are 22 m.y. This apparent discrepancy, however, disappears when one realizes that the samples, which were taken from the side of the boulder, were restricted by geometry to a π exposure. Heiken *et al.* (1973) incorrectly used production rates calculated on the basis of a 2π exposure. The 22 m.y. age thus dates the time when the boulder moved into its present position. We discount the possibility that some of the exposure could have occurred before the boulder rolled down the massif because only a few centimeters of shielding change would disrupt track-rare gas concordancy. The track of the boulder is littered with debris, apparently shed by the boulder as it tumbled down the slope (Muehlberger, 1974, private communication), indicating that similar shielding and exposure geometry before and after the descent are unlikely.

Sample 76015 was taken from another of the Station 6 boulders. It has a krypton age of 17.5 m.y. (Crozaz *et al.*, 1974) and chips from it have ≈15 m.y. exposure ages (Marti, 1974). This is an interesting sample because it was lying loose on the top of one of the boulders before being sampled. Both track and rare gas data suggest that a change in shielding for this sample occurred ≈1 m.y. ago (Crozaz *et al.*, 1974), perhaps caused by a meteoroid impact on the boulder.

The time of emplacement of the Station 7 boulder can also be derived. This boulder, also at the base of the North Massif, presumably tumbled downslope from high on the massif, but has no visible track. One sample from this boulder has been ^{81}Kr–Kr dated, yielding an exposure age of 28.6 m.y. (Crozaz *et al.*, 1974). Four samples have been dated by the accumulation methods using spallation-produced argon. When the argon production rates are corrected for restricted exposure geometry for the samples, a mean age of (27.5±2.5) m.y. is obtained (Stettler *et al.*, 1974), in excellent agreement with the krypton exposure age. Although the track surface exposure age is only (5.4±0.8) m.y. for the sample dated at 27.5 m.y. by the krypton method and although there is no second ^{81}Kr–Kr age, the rare gas data strongly suggest that the Station 7

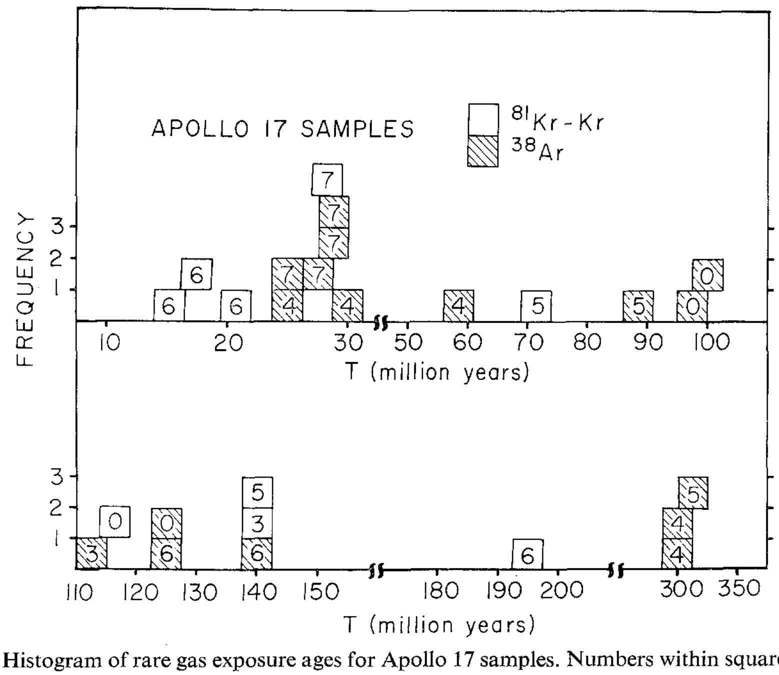

Fig. 6. Histogram of rare gas exposure ages for Apollo 17 samples. Numbers within squares refer to station numbers at which the samples were collected; for sample numbers, see Table VI. Station 6 boulders are dated at 22 m.y. and the Station 7 boulder at 28 m.y.

boulder was emplaced ~28 m.y. ago. The discrepancy between Kr and track exposure ages can easily be accounted for if a small amount of material (few centimeters) was spalled from the boulder 5 m.y. ago.

Boulders sampled at Station 2 on the bright mantle at the base of the South Massif are also potentially datable as to time of emplacement. Two ages of 45 and 55 m.y. have been reported for boulder 1 by Leich *et al.* (1974). They attribute the age difference to shielding differences when the boulder was still in position on the top of the South Massif. Thus, the date of emplacement for the boulder must be ⩽50 m.y. Alternatively, the younger sample may have experienced a change in shielding geometry like that of 76015 indicating boulder emplacement ≈50 m.y. ago. The work of Hutcheon (1974), who suggests a shielding change ≈20 m.y. ago, is consistent with either viewpoint, although more supportive of the latter.

Shorty Crater, which penetrated the light mantle material at Station 4, is dated by two argon ages at 25 to 30 m.y. (see Figure 6). When further ages become available, it should be a simple matter to assign a more precise age to Shorty.

The bright mantle has been interpreted as a landslide initiated by the impact of projectiles at the top of South Massif (Howard, 1973). Secondary material from Tycho has been suggested as a source of the projectiles, leading to the intriguing speculation that more precise dating of the landslide event may date the Tycho cratering event (Howard, 1973). Since Shorty penetrated the light mantle material and the Station 2 boulder rests on it, the exposure ages of each of these set firm lower limits for the landslide; ⩾30 m.y. from Shorty and ⩾50 m.y. from the boulder.

Camelot Crater (≈700 m diam) has proved to be difficult to date. Three samples collected from the rim of Camelot, 75035, 75055, and 75075, have ages of 72 m.y., 90 m.y., and 140 m.y., respectively. Such a large spread in ages from the rim of a crater as large as Camelot is unusual, since depths of excavation and overturned stratigraphy should expose a great deal of un-irradiated material. Sample 75055, with an exposure age of ~90 m.y., is fairly fresh and angular, while sample 75075 (140 m.y.) appears to be relatively smoothed and mostly buried (Apollo 17 Preliminary Science Report). We do not believe, as stated by Kirsten and Horn (1974), that the similar exposure ages (~95 m.y.) they observe on three rocks, of which only one was collected on the rim of Camelot Crater, provides a sufficient basis to date this event. A complicating factor in dating Camelot may be the presence of ejecta material from Central Cluster, a cluster of large craters that lie mostly to the east of Camelot (Apollo 17 Preliminary Science Report).

The Central Cluster craters may have formed simultaneously, after formation of Camelot Crater, by impact of a large swarm of secondary projectiles (Apollo 17 Preliminary Science Report). The Apollo 17 deep drill core was taken between Camelot and the Central Cluster Craters. Track analysis seems to indicate that the upper one meter coarse-grained layer of the core was emplaced ~10 m.y. as a single event (Crozaz *et al.*, 1974). The coarse-grained layer may either be a local event or part of a lens of material associated with Central Cluster, in which case the Apollo 17 site was subjected to a major cratering only ~10 m.y. ago. However, if the Central Cluster were so young a feature as suggested by the latter possibility, then there should be a large amount of fresh young bedrock excavated by the large craters. There are no young exposure ages for any samples from the entire Apollo 17 site (Table VI). Work delineating the source of the coarse-grained layer is continuing. A possible relationship between the landslide and emplacement of the Central Cluster Craters, now linked by some circumstantial evidence (roughly parallel lineations and textural similarities of the crater field at the top of the massif with those of the Central Cluster) is being explored. Exposure ages of samples collected from Station 1 (Central Cluster site) may help delineate further the age of emplacement of the Central Cluster Craters and, in addition, rule on the possibilities of association of the Central Cluster feature with either the landslide or the coarse-grained layer of the deep drill.

9. Summary and Implications

By our criteria, there are only five well-dated events: Cone Crater (26 m.y.), North Ray Crater (50 m.y.), South Ray Crater (2 m.y.), and the emplacement of the Apollo 17 Station 6 (22 m.y.) and Station 7 (28 m.y.) boulders. These features have multiple concordant rare gas exposure ages and, except for Cone Crater and the Station 7 boulder, concordant track ages. Shorty Crater (25–30 m.y.), and the emplacement of Apollo 17 Station 2 boulders (44–45 m.y.) are tentatively dated; further work may more precisely delineate these ages. Bench Crater ($\leqslant$99 m.y.), Baby Ray Crater ($\leqslant$2 m.y.), Camelot Crater ($<$140 m.y.), and the Apollo 17 bright mantle ($>$50 m.y.) can be tentatively bracketed as to time of formation. The Central Cluster Craters are potentially datable when more rare gas data from the Apollo 17 mission is obtained and if exposure age concordancy is attained with some Station 1 material. It is hoped that a more complete history of the Apollo site will be delineated. Among the likely new results should be (1) the origin of the Apollo 17 deep drill coarse-grained layer, (2) the relationship, if any, between the Central Cluster and the South Massif landslide, (3) possible association between Tycho and prominent features at the Apollo 17 site, and (4) possibly an age for Tycho.

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