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AGES OF CA-RICH ACHONDRITES

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INTRODUCTION

In the past decade statistically significant numbers of ages have been established for meteorites of various classes, owing to the work of several investigators. However, our knowledge of the ages of the Ca-rich achondrites has remained rather sketchy. The present work was therefore undertaken to settle this matter more firmly. We have measured the inert gas contents of 27 of the 30 meteorites classified as eucrites and shergottites by HEY [1] . With the additional

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re-interpretation of literature data on 9 eucrites and 4 howardites, all of the known eucrites are thus covered, except Adalia.

CLASSIFICATION

We have generally followed the classifications of PRIOR [2], HEY [1], and MASON [3], [4]. A few adjustments were necessary, however, and it is quite possible that future studies of achondrites may lead to a few more reassignments. Mässing and Medanitos, although listed as eucrites by HEY appear to be howardites because of their bulk compositions (R. A. SCHMITT, private communication) and iron content of the pyroxene (M. B. DUKE, private communication). Bialystok appears to be a eucrite (MASON, [4]). Padvirninkai and Brient were taken to be eucrites. Finally, we found it useful to treat the unbrecciated eucrites, Moore County and Serra de Magé, as a separate subclass, following the suggestion of DUKE and SILVER [5].

PROCEDURES

The inert gases were measured by mass-spectrometry in bulk samples as well as in separated mineral fractions by techniques described in a previous publication (HEYMANN and MAZOR [6]). The approximate mineralogical compositions of the separates of five meteorites are shown in Table I. Separations were also attempted for Béréba and Brient, but these were not satisfactory, hence different sieve fractions were measured in these two cases. A pyroxene fraction from Nuevo Laredo was kindly provided by Dr. M. B. DUKE; it has been described by DUKE and SILVER [5].

The reason that magnetic separations were not attempted in more cases is that the amounts of material available to us were often only about 0.1 g. or less.

RESULTS

The inert-gas data are presented in Table II. Our results confirm the important observation made by MEGRUE [7], namely that the feldspar in achondrites is strongly deficient in cosmogenic He and Ne. For example, the feldspar (non-magnetic) fraction of Chervony Kut contains 5.1 x 10^{-8} cc $STPg^{-1}$ of ^{3}He and 2.17 x 10^{-8} cc $STPg^{-1}$ of ^{21}Ne, whereas the pyroxene fraction (strongly magnetic) contains 61 x 10^{-8} cc $STPg^{-1}$ of ^{3}He and 7.60 x 10^{-8} $ccSTPg^{-1}$ of ^{21}Ne. The bulk sample, as expected, has inert gas contents in-between these two extremes. Similar relations are seen in Moore County, Petersburg, and Sioux County. The ^{4}He values of these measurements show that radiogenic ^{4}He was also lost from feldspar, although apparently to a lesser extent than cosmogenic ^{3}He.

It is noteworthy that not one of the eucrites studied by us contains detectable amounts of trapped He or Ne; in fact, the available literature data on the remaining eucrites strengthen the conclusion that meteorites in this class do not seem to contain any trapped He or Ne. Eucrites, therefore present an interesting contrast with the howardites, at least two of which, Jodzie and Kapoeta, are known to be gas-rich [8], [9].

HELIUM-3/ARGON-38 AGES

We have attempted to obtain radiation ages on the basis of stable, inert-gas isotopes alone in the following way. Among chondrites, the degree of shielding seems to be constant within ± 10% in most cases, judging from ^{26}Al measurements ([10] [11], but ROWE ET AL [12] find larger variations). Four eucrites investigated to date show ^{26}Al levels constant to within less than ± 10% (FUSE and ANDERS, unpublished work). Hence it would seem that the assumption of a constant degree of shielding may be permissible for most eucrites. This in turn allows the use of constant production rates for meteorites of similar chemical composition.

On the basis of MEGRUE's data and our own results we assume that ^{3}He is quantitatively lost from feldspar, but is quantitatively retained by the remaining minerals (largely pyroxene). Thus, the gas-data themselves contain information on the feldspar content of the sample, because:

$$\frac{^{3}\mathrm{He}}{^{38}\mathrm{Ar}} = \frac{^{3}\underline{\mathrm{He}}_{p}\ (1-\alpha)}{^{38}\underline{\mathrm{Ar}}_{f}\ \alpha + {}^{38}\underline{\mathrm{Ar}}_{p}\ (1-\alpha)} \qquad (1)$$

, where

α = weight fraction of feldspar

^{3}He/^{38}Ar = ratio as measured in the sample

$^{3}\underline{He}_{p}$, $^{38}\underline{Ar}_{p}$ = production rates of ^{3}He and ^{38}Ar in pyroxene

$^{38}\underline{Ar}_{f}$ = production rate of ^{38}Ar in feldspar

We have adopted $^{3}\underline{He}_{p} = 2.10 \times 10^{-8}$ cc STPg^{-1} Myr^{-1} for eucrites and 2.14×10^{-8} cc STPg^{-1} Myr^{-1} for howarditic meteorites. These values are slightly greater than the generally adopted value in chondrites of 2.0×10^{-8} cc STPg^{-1} Myr^{-1} to account for the greater oxygen contents of the achondrites. $^{38}\underline{Ar}$ production rates were calculated with the average compositions of feldspar and "pyroxene" (i.e. the entire non-feldspar fraction, including pyroxene, quartz, or tridymite, ilmenite, chromite, troilite, and Ni-Fe), as listed in Table III, using: a) $^{38}\underline{Ar}_{Ca}/^{38}\underline{Ar}_{Fe} = 16.5 \pm 2.7$ [13], and b) $^{38}\underline{Ar}$ (hypersthene chondrites) = 0.526×10^{-8} cc STPg^{-1}Myr^{-1}. Note that Moore County, Serra de Magé, and Shergotty (Zagami) were treated individually.

The relationship ^{3}He/^{38}Ar vs. $(1 - \alpha)$ is shown by the curves in Figure 1. Plotted in the same figure are data points obtained from MEGRUE's [7] and our own magnetic separates (Table II), for which the "pyroxene" fractions were estimated by the simple assumption:

$$(1 - \alpha)_{i} = {}^{3}He_{i}/{}^{3}He_{S} \qquad (2)$$

$^{3}He_{i}$ = ^{3}He content of a given sample of the meteorite, either bulk, non-magnetic, intermediate, or strongly magnetic.

^3He_S = ^3He content of the "pyroxene" fraction of the same meteorite.

It is seen that the experimental points agree reasonably well with the calculated curves. The differences seem to indicate that the strongly magnetic fractions still contained some feldspar. On the other hand, the $^3He/^{38}Ar$ ratio depends not only on the feldspar impurity, but also on the Ca-content of the pyroxene itself, such that the differences may be in part due to real compositional variations.

Table IV lists the average ^3He-radiation ages obtained from all the bulk samples, strongly magnetic and intermediate fractions, or sieve fractions listed in Table II, supplemented with previously published literature data which were re-evaluated by the method outlined here. Because of space limitations, a detailed version of this Table will be published elsewhere.

When several age-determinations are available for one meteorite, the ages tend to agree rather well, i.e. the differences between the highest and lowest values are seldomly greater than 10%. This is especially gratifying, because ^3He-contents vary by as much as a factor 2 (e.g. Chervony Kut, Table II).

The following meteorites are special cases. The $^3He/^{38}Ar$ ratios for Zagami and Shergotty, 12.7, 14.2, and 12.0 are higher than the maximum value of 11.0 expected with complete

^{3}He loss from feldspar. We have therefore calculated ^{3}He-ages on the assumption of no diffusion loss from feldspar. In the case of Serra de Magé it was not possible to obtain reliable ages from ^{3}He/^{38}Ar ratios, but it seemed permissible to calculate ^{21}Ne ages using the bulk ^{21}Ne production rate listed in Table III. The mean age of Serra de Magé, 1.9 Myr is lowest of any eucrite. However, an ^{26}Al measurement (FUSE and ANDERS, unpublished work) suggests an even shorter age, because the ^{26}Al content of this meteorite is less than 10% of the saturation value. Since Serra de Magé seems to have been a rather small meteorite, the low ^{26}Al content indicates a low radiation age ($\leq$ 0.1 Myr.) rather than heavy shielding. The juxtaposition of a short ^{26}Al age and the older inert-gas age indicates a somewhat unusual history, such as a very recent, secondary breakup of a large meteorite [14], or "pre-irradiation" a few meters below the surface of the parent body [15], [16]. Apparently the transit time to Earth since the last collision must have been shorter than 0.1 Myr. The two samples of Nuevo Laredo give discordant ages. The pyroxene separate gives 16.0 Myr. The bulk sample has an abnormally low ^{3}He/^{38}Ar ratio, which cannot be explained by high ($\gtrsim$85%) feldspar content (this was ruled out by petrographic examination), hence one suspects ^{3}He loss from the pyroxene as well as from the feldspar. We have calculated a "^{3}He$_{max}$-age" for this sample of 11.8 Myr by correcting ^{3}He/^{21}Ne upwards to 8.5, the value expected in the pyroxene in eucrites. It is puzzling that the pyroxene separate still gives a distinctly higher age. Pending clarification of this matter, we have used only the radiation age of the pyroxene separate, which probably represents the fraction with complete ^{3}He retention.

GAS-RETENTION AGES

Because of the lack of U, Th, and K values and because of ^{4}He-losses from feldspar, no accurate gas-retention ages can be calculated at this time. On the basis of published U and Th data ([17], [18], [19], [20], [21]) we have adopted a constant U content of 130 ppb and Th/U = 3.6 for all the brecciated eucrites. Among the unbrecciated eucrites, data are available only for Moore County [20]. We have refrained from calculating any U-He ages of howardites or shergottites. All ^{4}He data were corrected for diffusion loss from feldspar using the $(1 - \alpha)$ values from Table IV. Such a correction is undoubtedly needed, but its magnitude is debatable. A correction for cosmogenic ^{4}He was made by assuming $(^4\text{He}/^3\text{He})_c = 5.0$.

Potassium data are likewise incomplete, however, Na contents are known for 27 meteorites in Table IV, and since the Na/K is fairly constant at 9.0, the K content can be estimated from the Na content.

DISCUSSION

Figure 2 shows the radiation ages on linear and logarithmic scales. The linear scale accentuates the rate of meteorite production, while the logarithmic one favors recognition of age-clusters by keeping the relative scatter of the points constant, regardless of age. Interestingly, the overall distribution resembles that of chondrites rather than that of Ca-poor achondrites such as aubrites [16]: a fairly even distribution up to ~ 30 Myr. with a few "stragglers" up to ~ 70 Myr. A further similarity to the chondrites is the presence of one age shorter than 1 Myr (Serra de Magé). Such a short age seems to imply an origin from an Earth-crossing starting orbit such as the Moon or the Apollo asteroids ([22], [23], [11]).

The logarithmic scale shows some evidence for age clusters, the two most distinct ones occurring at ~ 5 and ~ 11 Myr. It is interesting to note that all three meteorites in the 5 Myr. cluster have high K-Ar ages. Some additional clusters may be present at about 18 Myr and in the 26-46 Myr. interval, but recognition of clusters becomes, obviously, more difficult with increasing age.

Figure 3 shows a plot of (U, Th) - He age vs K-Ar age. Most points follow a smooth trend, short U-He ages being correlated with short K-Ar ages. With only few exceptions, the U-He age is always shorter than the K-Ar age, and there are apparently no concordant short ages (< 1 Gyr.)

among the eucrites. The principal feature of Figure 3 is thus ^{4}He loss. In principle, such loss could have occurred before or after the meteorite's departure from its parent body. The latter possibility can be ruled out, however. According to MEGRUE [7], radiogenic ^{4}He is almost as evenly distributed as is cosmogenic ^{3}He. The substantial (50-99%) ^{4}He losses seen in Figure 3 would imply substantial ^{3}He losses during the exposure era, hence one would expect many abnormally low ^{3}He/^{21}Ne ratios (0.1 - 4.0). Since this is not the case, radiogenic ^{4}He was obviously lost in the parent body.

There are three alternatives for such loss: (1) origin in a deep and relatively warm region of an asteroid [24], (2 origin in a subsurface layer of the Moon, and (3) reheating by shock [25]. The first possibility has fallen into disfavor for chondrites, because there seems to be no self-consistent radius and burial depth that will permit ^{40}Ar retention to commence 3-4 Gyr. ago, but ^{4}He retention only several Gyr. later [25]. However, until more reliable diffusion parameters become available for Ca-rich achondrites, this possibility cannot be firmly ruled out. The second possibility is more attractive, but seems to require that material was brought from some 20-40 Km depth to the surface in an impact or tectonic event to permit ^{4}He retention to commence some 0.1 - 2 Gyr ago. The third possibility has been shown to apply to the hypersthene chondrites ([25], [26]). The eucrites and howardites show a similar, though less conclusive picture. Their U-He ages seem to approach a minimum value of 0.1-0.2 Gyr and the three meteorites with the shortest ages happen to be the ones that show distinct shock effects (Cachari, Emmaville, and Padvarninkai). The case for this model would be strengthened if meteorites with short, concordant ages were found. No such cases are known at present.

ORIGIN

Two origins have been proposed for the Ca-roch achondrites: the Moon (DUKE and SILVER [5] and the asteroids (various authors, see [25] for references). The case for a lunar origin has recently received strong impetus from the discovery by TURKEVICH ET AL [27], [28] that two lunar mare areas resemble Ca-rich achondrites in composition. The present work has the following implications.

1 The observed radiation-age distribution (Figure 2) is rather flat to ~ 30 Myr. As in the case of most other classes of stony meteorites, no ages above 70 Myr. are found. This distribution can be compared with two predicted distributions calculated by ARNOLD's program (ARNOLD [23], ANDERS and ARNOLD [29]), shown in Figure 4. The lunar distribution is rather too steep, having 81% of its ages in the 0-10 Myr interval, compared to 38% for the Apollo distribution. However, this is not a strong argument against a lunar origin if one assumes that only a few minor impacts occurred on the Moon in the last 10 Myr.

2 The gas-retention ages seem to imply either burial at some tens of kilometers beneath the surface of the Moon to allow for the loss of ^{4}He; transport to the surface mainly in the last 2 Gyr; ejection in another impact. The asteroidal model would require reheating by impact followed by relatively slow cooling; ejection in another, more recent impact.

Even with the evidence of the ages now before us, it is still difficult to speak out in favor of either one of the two basic hypotheses on the origin of the Ca-rich achondrites. The lunar evidence is in good accord with the predominance of morning falls among eucrites and can be reconciled with the radiation age distribution. Real difficulties arise only from the existence of mesosiderites and unbrecciated eucrites, which would seem to favor an asteroidal origin.

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Table I

Approximate Mineralogical Composition of Magnetic Separates

Meteorite	Fraction and Weight* (mg)	Plagioclase %	Pyroxene %	Quartz or Tridymite %	Opaques %
Chervony Kut	S(165)	2	90		8
Chervony Kut	I(952)	55	40		5
Chervony Kut	N(242)	85	12		3
Moore Co.	S(701)	15	85		2
Moore Co.	N(150)	96	~ 2	~ 2	
Petersburg	S(472)	5	90		5
Petersburg	N(34)	90	8	~ 2	
Serra de Magé†	N2(1684)	95	5		
Serra de Magé†	S2(1426)	10	88		~ 2
Sioux Co.	S(236)	5	90		5
Sioux Co.	N(180)	95	5		

[*] S = strongly magnetic fraction, I = intermediate fraction, N = non-magnetic fraction.

[†] Serra de Magé N1 was a hand-picked single crystal of feldspar, weighing 41.9 mg. Serra de Magé S1 likewise was a hand-picked fraction, consisting largely of yellow and brown pyroxene crystals. It weighed 19.4 mg.

Table II.

He, Ne, and Ar in Calcium-rich Achondrites

				Noble-Gas Content, 10^{-8} ccSTP/g[d]							
Meteorite[a]	Series[b]	Source[c]	#	^{3}He	^{4}He	^{20}Ne	^{21}Ne	^{22}Ne	^{36}Ar	^{38}Ar	^{40}Ar
Béréba 100/200	IV	PM	1297	28.8 ±1.5	1130±100	4.8±0.3	4.71±0.25	5.4 ±0.3	2.72±0.15	2.76±0.12	1130± 60
Béréba +100	II			32.0 ±1.6	1200± 60		5.16±0.26	5.9 ±0.3	1.80±0.10	2.49±0.15	840± 50
Béréba -200	II			31.1 ±1.6	1300± 70	6.1±0.3	4.91±0.25	5.9 ±0.3	1.29±0.09	2.57±0.18	840± 50
Bialystok	III	U	332	27.7 ±1.5	3500±200	3.8±0.3	3.37±0.16	4.5 ±0.2	1.85±0.10	2.12±0.10	700± 50
Brient	I	CM	718	12.0 ±0.6	720± 40		2.0 ±0.1		5.12±0.26	2.57±0.13	1130± 60
Brient	I			10.7 ±0.6	610± 30		2.1 ±0.1		5.93±0.30	2.50±0.13	1040± 50
Brient +100	II			14.8 ±0.7	1290± 80		2.32±0.12	2.6 ±0.14	3.75	2.18	1190
Brient -200	II			15.4 ±0.7	910± 50		2.31±0.12	2.6 ±0.15	3.04	2.05	1440
Cachari	III	PM		12.2 ±0.6	320± 30	2.7±0.2	2.39±0.14	2.9 ±0.15	1.29±0.07	1.87±0.09	1240± 70
Chervony Kut	I	CM	1290	35.7 ±1.8	1370± 70		4.7 ±0.3		3.3 ±0.1	4.6 ±0.3	910± 50
Chervony Kut S	II			61 ±3	1840± 90		8.40±0.45	8.9 ±0.5	2.25±0.12	3.12±0.16	305± 20
Chervony Kut S	IV			62 ±3	2120±100	7.3±0.4	7.60±0.39	8.1 ±0.4	3.12±0.15	2.89±0.15	290± 20
Chervony Kut I	IV			43 ±3	1930±100	6.6±0.4	5.9 ±0.4	6.9 ±0.4	2.89±0.20	4.04±0.20	780± 40
Chervony Kut N	II			8.6 ±0.4	420± 20		2.33±0.12	2.5 ±0.1	4.24±0.22	5.89±0.30	1570± 80
Chervony Kut N	IV			5.1 ±0.3	480± 25	3.0±0.2	2.17±0.12	2.7 ±0.15	3.9 ±0.2	5.2 ±0.3	1170± 60
Constantinople	III	VM	A163	47 ±2	7450±350	7.4±0.6	6.44±0.35	7.5 ±0.4	5.20±0.25	7.58±0.40	2240±130
Emmaville	IV	A		24.8 ±1.2	360± 50	5.5±0.5	4.55±0.25	5.3 ±0.2	2.61±0.14	2.95±0.15	1220± 90
Haraiya	IV	AS	637.1	34.7 ±2.0	4500±250	5.9±0.4	5.24±0.30	6.0 ±0.4	3.48±0.18	5.15±0.27	1260± 80
Haraiya	IV	CA		40 ±2	6500±350	6.2±0.3	6.1 ±0.3	6.4 ±0.3	4.4 ±0.2	5.7 ±0.3	1130± 60
Ibitira	IV	MP	110/1	15.6 ±0.7	3660±180	3.5±0.5	2.48±0.14	3.3 ±0.3	1.63±0.08	1.79±0.09	1230± 70
Jonzac	I	F		37.1 ±1.8	7300±400		5.00±0.25		3.82±0.20	5.29±0.27	2360±120
Jonzac	I			36.8 ±1.8	9500±500		4.94±0.25		4.11±0.20	5.67±0.30	2780±140
Kirbyville	IV	M		22.1 ±1.2	13,300±700	3.4±0.3	2.78±0.15	3.3 ±0.2	2.61±0.14	2.95±0.15	1220±100
Lakangaon	III	B	1915,142	37.2 ±1.8	11,000±500	6.3±0.7	5.70±0.30	7.0 ±0.4	3.21±0.15	4.44±0.20	2560±140
Luotolax	III	F	1613	100 ±5	5900±350	18.3±0.9	17.8 ±0.9	20.4 ±1.0	11.4 ±0.5	9.89±0.5	1400± 70
Mässing	III	H		65 ±3	6630±400	12.0±0.8	12.0 ±0.6	13.4 ±0.7	2.81±0.15	3.82±0.18	990± 60
Medanitos	III	V		40 ±2	550± 30	6.6±0.6	5.72±0.25	7.0 ±0.4	2.54±0.13	3.53±0.18	610± 40
Moore County	III	AS	294ax	13.4 ±0.6	3890±250	1.7±0.2	1.99±0.10	2.3 ±0.1	0.62±0.04	0.73±0.05	970± 80
Moore County S	III			15.3 ±0.5	8110±250	1.6±0.2	1.80±0.09	2.1 ±0.1	0.43±0.03	0.63±0.04	700± 40
Moore County S	II			13.0 ±0.6	7280±400	2.2±0.1	1.64±0.10	1.9 ±0.1	0.68	0.69	740
Moore County N	II			0.3	336± 20	2.4±0.12	1.47±0.10	1.8 ±0.1	1.09	1.25	3490
Nagaria	II	F	1574	22.6 ±1.2	1400± 75	6.3±0.3	3.29±0.17	4.3 ±0.3	2.52±0.14	2.07±0.1	740± 40
Nagaria	III			24.0 ±1.2	1080± 60	3.8±0.2	3.42±0.15	4.4 ±0.3	1.36±0.07	1.74±0.09	700± 40
Nobleborough	III	F	1370	8.6 ±0.4	8180±400	1.8±0.3	0.90±0.04	1.5 ±0.06	1.27±0.06	0.88±0.04	2380±140
Nuevo Laredo S	III	MD	P150,R200	27.1 ±1.5	4920±250	4.4±0.3	3.56±0.16	4.2 ±0.2	1.62±0.08	2.15±0.11	380± 20
Nuevo Laredo	IV	LS		2.20±0.12	670± 60	2.3±0.2	2.10±0.10	2.4 ±0.13	1.39±0.08	1.87±0.10	1680±100
Padvarninkai	III	P	312	18.1 ±0.9	210± 30	4.1±0.4	3.90±0.20	4.7 ±0.3	2.37±0.12	2.76±0.15	920± 60
Pasamonte L	IV	AS	197g	6.9 ±0.4	5290±250	1.2±0.6	1.13±0.50	1.2 ±0.6	0.74±0.04	0.90±0.04	1440± 60
Pasamonte D	IV			5.9 ±0.4	2750±150	1.3±0.6	1.24±0.50	1.4 ±0.7	0.86±0.04	0.78±0.04	1110± 60
Peramiho	III	VM	H982	30.0 ±1.5	2970±160	3.5±0.5	3.39±0.17	3.9 ±0.2	2.39±0.11	3.31±0.16	1250± 70
Petersburg	III	AM	334.3	32.1 ±1.5	2540±150	6.7±0.6	4.86±0.25	6.0 ±0.4	4.35±0.20	3.16±0.20	
Petersburg S	III			37.9 ±1.5	2630±130	5.7±0.6	4.94±0.2	5.9 ±0.3	1.69±0.05	2.09±0.06	1080± 70
Petersburg S	II			33.6 ±1.5	2430±150	5.2±0.3	4.46±0.2	5.3 ±0.3	1.88	2.01	910
Petersburg N	II			3.4 ±0.2	750± 40	6.7±0.4	4.31±0.25	5.4 ±0.3	3.72	3.72	4120
Serra de Magé	III	U	839	0.88±0.09	700± 60		0.38±0.02	0.57±0.04	3.2 ±0.2	1.0 ±0.1	1290± 70
Serra de Magé S1	IV	C		4.3 ±0.2	1350± 70		0.84±0.04	0.63±0.04	2.2 ±0.2	0.70±0.05	480± 50
Serra de Magé S2	IV	C		2.13±0.12	1480± 90		0.51±0.03	0.79±0.04	0.36±0.03	0.34±0.02	190± 15
Serra de Magé N1	IV	C		2.5 ±0.1	1100± 50		0.55±0.03	0.74±0.04	1.5 ±0.1	0.61±0.05	370± 20
Serra de Magé N2	IV	C		1.14±0.08	500± 30		0.55±0.04	0.90±0.06	0.57±0.04	0.66±0.04	1380± 80
Shergotty	III	U	817	5.2 ±0.3	70± 20		0.58±0.04	0.87±0.05	0.37±0.03	0.42±0.03	300± 20
Sioux County	IV	AM		27.8 ±1.5	5110±250	4.5±0.3	4.73±0.23	5.3 ±0.3	5.40±0.28	3.45±0.20	990± 60
Sioux County S	III	AM		41 ±2	7800±400	5.2±0.3	5.55±0.28	6.3 ±0.3	1.90±0.10	2.63±0.15	560± 30
Sioux County S	II	AM		34.7 ±1.5	6420±350	5.2±0.3	5.12±0.25	5.5 ±0.3	8.15	3.67	430
Sioux County N	II	AM		6.8 ±0.4	2230±100	5.5±0.3	4.13±0.20	5.5 ±0.3	3.82	4.60	2740
Stannern	IV	GM		47 ±3	12,700±600	8.5±0.45	7.2 ±0.35	7.8 ±0.4	4.6 ±0.25	5.9 ±0.3	2640±150
Zagami	IV	B	1966,54	5.2 ±0.2	260± 10	1.0±0.05	0.69±0.03	0.86±0.03	1.00±0.05	0.54±0.03	460± 25

Notes on Table II.

[a] Symbols: D = dark lithic fragment; L = light, fine-grained groundmass ; N = non-magnetic fraction; I = intermediate fraction; S = strongly magnetic fraction; +100 = >100 mesh sieve fraction; -200 = <200 mesh; 100/200 = 100-200 mesh.

[b] Series I, II, and III are measurements done in 1964, 1966, and 1967 respectively at the University of Chicago. Series IV are measurements done in 1967 at Rice University. The two mass spectrometers are very similar in construction. However, different calibration standards were used for each of the series.

[c] The abbreviations stand for the following institutions and donors, to whom we express our sincere gratitude.

A - Australian Museum, Sydney (Drs. R. O. Chalmers and R. A. Binns).

AM - American Meteorite Museum, Sedona, Arizona (Dr. H. H. Nininger and G. I Huss).

AS - Arizona State University (Dr. C. B. Moore and C. F. Lewis).

B - British Museum, London (Drs. M. H. Hey and M. J. Frost).

C - Dr. Walter da Silva Curvello, Rio de Janeiro, Brazil.

CA - Geological Survey of India, Calcutta.

CM - Committee on Meteorites, Acad. Sci. USSR, Moscow. (Drs. E. L. Krinov and L. G. Kvasha).

F - Field Museum of Natural History, Chicago (Dr. E. Olsen).

GM - Dr. George Megrue, Smithsonian Astrophysical Observatory. This sample (Stannern) had originally been obtained from Dr. Brian Mason at the American Museum of Natural History in New York (MEGRUE [7]).

H - Humboldt-Universität, Berlin, GDR (Dr. G. Wappler).

LS - Dr. Leon T. Silver, California Institute of Technology, Pasadena.

M - Mr. Oscar E. Monnig, Fort Worth, Texas.

MD - Dr. M. B. Duke, U. S. Geological Survey, Washington, D. C.

MP - Max-Planck-Institut für Chemie, Mainz (Dr. H. Wänke).

P - National Museum, Prague (Dr. K. Tuček).

PM - Musée d'Histoire Naturelle, Paris (Dr. J. Orcel).

U - U. S. National Museum, Washington (Drs. R. Clarke and K. Fredriksson).

V - Vatican Collection of Meteorites (Father E. Salpeter).

VM - Naturhistorisches Museum, Vienna (Dr. G. Kurat).

[d] No entry: sample was lost, or blank correction >50%. Errors were calculated from standard deviations of repeated peak measurements and estimated errors of blank corrections, calibration standards, and instrument instability.

Italicized argon values for Brient, Moore Co., Petersburg, and Sioux Co. were corrected upward by a factor of 1.35. In these runs, some Ar was apparently lost because of discharge in the furnace during the melting. The factor 1.35 was obtained by duplicate measurements on other samples which were also low in Ar.

Table III

Protduction Rates of ^{3}He, ^{21}Ne, and ^{38}Ar in Calcium-Rich Achondrites

Meteorite and Fraction	%	Si %	Mg %	Fe %	Al %	Ca %	P %	Na %	K ppm	Ref.	Production Rates 10^{-8} ccSTP g^{-1} m.y.$^{-1}$		
											^{3}He	^{21}Ne	^{38}Ar
Eucrites		22.9	4.14	15.1	6.68	7.37	0.05	0.32	360	1			
Feldspar	36.5	21.3			18.3	13.0	0.13					0.3211	0.256
"Pyroxene"	63.5	23.7	6.52	23.7		4.12					2.10	0.2607	0.110
Howardites		23.0	9.06	14.25	4.80	4.94	0.03	0.16	150	2			
Feldspar	25.8	21.0			18.6	13.4	0.12					0.3223	0.265
"Pyroxene"	74.2	23.7	12.2	19.2		1.98					2.14	0.3411	0.0620
Moore Co.		23.0	5.07	12.2	8.24	7.92		0.31	200	3			
Feldspar	44.2	21.2			18.6	13.2						0.3233	0.260
"Pyroxene"	55.8	24.5	9.09	21.8		3.73					2.10	0.3031	0.100
Serra de Magé		20.8	1.96	5.29	14.7	10.6	0.34			3			
Feldspar	78.9	21.2			18.7	13.2						0.3243	0.261
"Pyroxene"	21.1	19.3	9.31	25.1		0.82					2.00	0.2688	0.0462
Shergotty		23.5	6.03	16.7	3.12	7.43		1.34	1510	3			
Feldspar	23.8	28.3			13.1	4.51						0.3115	0.101
"Pyroxene"	76.2	22.0	7.92	22.3		8.35					2.10	0.2746	0.191
Hypersthene Chondrites		18.7	15.2	21.6	1.27	1.36	0.12	0.71	830	5	2.00	0.3774	0.0526

References.

1. Average of 6 analyses from DUKE and SILVER [5] and 8 analyses (Béréba, Cachari, Chervony Kut, Jonzac, Juvinas, Pasamonte, Peramiho, and Petersburg) from UREY and CRAIG [30].
2. Average of Binda, Pavlovka, Yurtuk, and Le Teilleul (UREY and CRAIG, [30], Kapoeta (MASON and WIIK, [31] and Bununu (MASON, [4]).
3. UREY and CRAIG [30].
4. MASON and WIIK [31].
5. MASON [32].

Table IV

Ages of Calcium-rich Achondrites

Meteorite$^{a)}$	Class$^{b)}$		^{3}He-^{38}Ar Age, m.y.$^{c)}$	U-He age, Gyr	K-Ar Age, Gyr$^{d)}$	Ref.$^{e)}$
Béréba (4)	E	E	18.1	0.46	2.8	*, [33]
Bialystok (1)	E	H	15.5	1.3	2.4	*
Brient (4)	E	E	10.1	0.44	3.2	*
Cachari (1)	E	E	10.6	0.17	2.9	*
Chervony Kut (4)	E	E	28	0.63	3.0	*
Constantinople (1)	E	E	42	3.5	4.2	*
Emmaville (1)	E	E	17.9	0.12	3.2	*
Haraiya (5)	E	E	31	2.4	4.0	*, [7]
Ibitira (1)	E	E	10.9	1.6	3.2	*
Jonzac (2)	E	E	31	3.6	4.4	*
Juvinas (3)	E	E	11.4	2.0	3.98	[7]
Kirbyville (1)	E	E	14.9	4.5	3.2	*
Lakagaon (1)	E	H ?	27	3.9	4.2	*
Luotolax (1)	E	H	62	2.1	3.8	*
Macibini (1)	E	E	46	1.4	3.6	[34]
Moore County (3)	U	U	6.7	5.0	3.5	*
Nagaria (2)	E	E	13.2	0.46	2.4	*
Nobleborough (1)	E	H?	5.2	2.9	4.2	*
Nuevo Laredo (1)	E	E	16.0	1.6	3.7	*
Padvarninkai (1)	E	E	15.2	0.08	3.0	*
Pasamonte (3)	E	E	5.1	2.4	3.5	* [13], [35],[36]
Peramiho (1)	E	E	21.0	1.3	3.4	*
Petersburg (3)	E	H	18.0	0.98	3.12	*
Serra de Magé (5)	U	U	1.9		2.7	*
Shergotty (2)	S	E	2.4		0.52	*, [13], [35],[36]
Sioux County (4)	E	E	18.9	2.0	3.2	*, [34]
Stannern (5)	E	E	37	3.9	3.8	*,[7],[37]
Zagami (1)	S	E	2.5		0.61	*
Bholghati (2)	H	H	11.7		2.56	[33],[37]
Jodzie (1)	H	H	11.3		2.8	[8]
Kapoeta (1)	H	H	3.0		4.48	[9]
Mässing (1)	H	H	36		3.7	*
Medanitos (1)	H	H	26		2.8	*
Pavlovka (1)	H	H	4.7		4.0	[13]

Notes to Table IV

a) Number between parantheses shows number of samples used in the average age-values.

b) The first entry gives MASON'S [4] classification, the second that of DUKE and SILVER [5]. E = (brecciated) eucrite; H = howardite; S = shergottite; U = unbrecciated eucrite. For modifications see text.

c) The ages of Shergotty and Zagami calculated with assumption of no ^{3}He loss from feldspar. Age of Serra de Magé calculated from ^{21}Ne content (see text).

d) K contents were either taken from the literature or estimated from Na-measurements. References will be published elsewhere.

e) An asterisk indicates that the radiation ages are based either wholly or in part (when reference follows) on the data listed in Table II.

FIGURE CAPTIONS

Fig. 1. $^3He/^{38}Ar$ ratios calculated on the assumption that ^3He is lost from feldspar but not from "pyroxene." Data on Haraiya, Juvinas, and Stannern from MEGRUE [7]; all others from this work.

Fig. 2. Radiation ages of Ca-rich achondrites on linear (top) and logarithmic (bottom) scales. The distribution of ages is similar to that of chondrites, i.e. flat from 0 to 30 Myr; declining rapidly beyond that limit and terminating at ~70 Myr.

Fig. 3. Gas-retention ages of eucrites. Most of the ages are based on assumed U, Th and K-contents, thus are somewhat uncertain. Most of the ages are discordant and appreciably shorter than 4.5 Gyr.

Fig. 4. Observed cosmic-ray age distribution for chondrites compared with theoretical distributions calculated by Arnold's Monte Carlo method. Taken from HEYMANN and ANDERS [11].

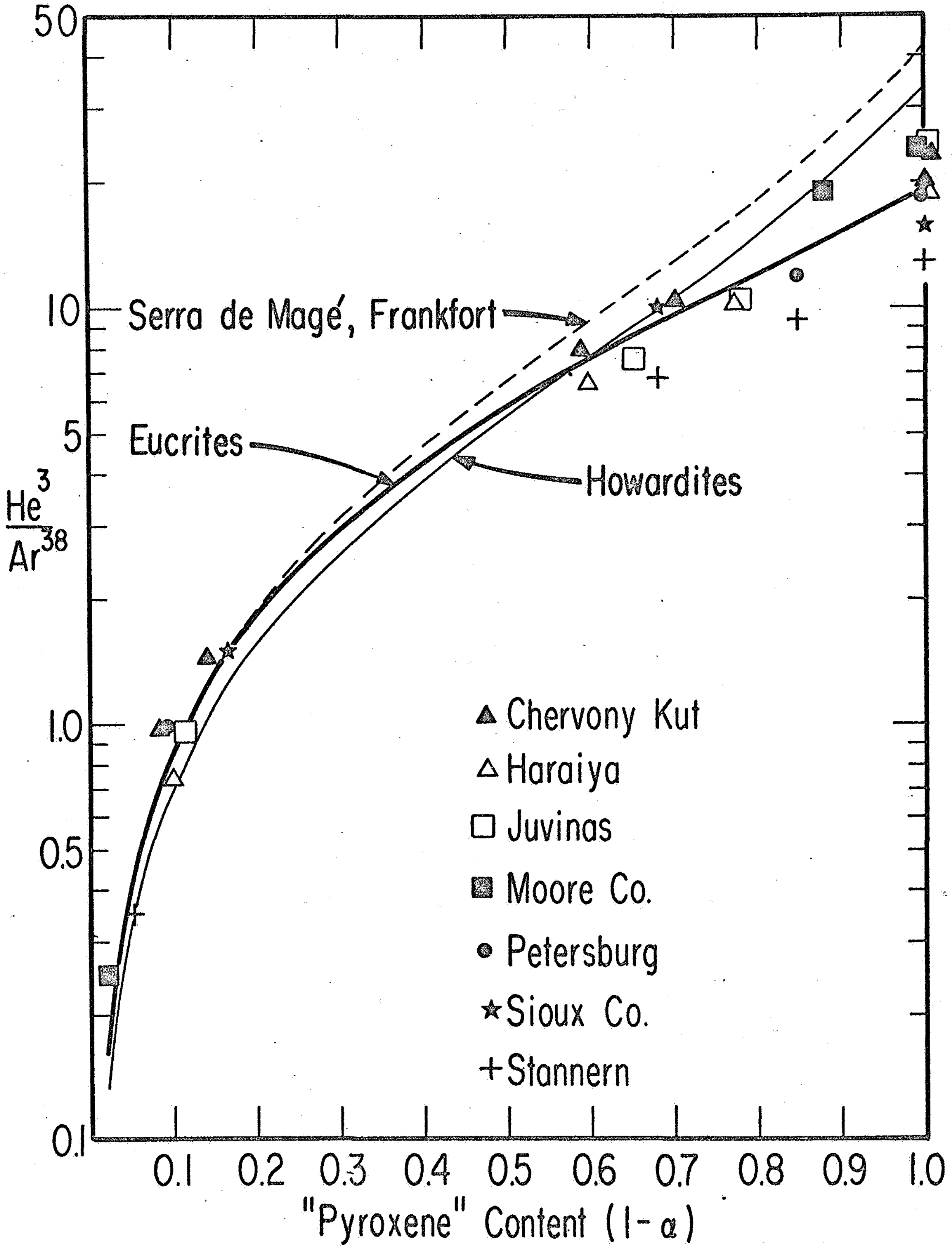

50
10
5
1.0
0.5
0.1
$\frac{He^3}{Ar^{38}}$
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
"Pyroxene" Content (1- α)
Serra de Magé, Frankfort
Eucrites
Howardites
▲ Chervony Kut
△ Haraiya
□ Juvinas
■ Moore Co.
● Petersburg
★ Sioux Co.
+ Stannern

Fig. 1

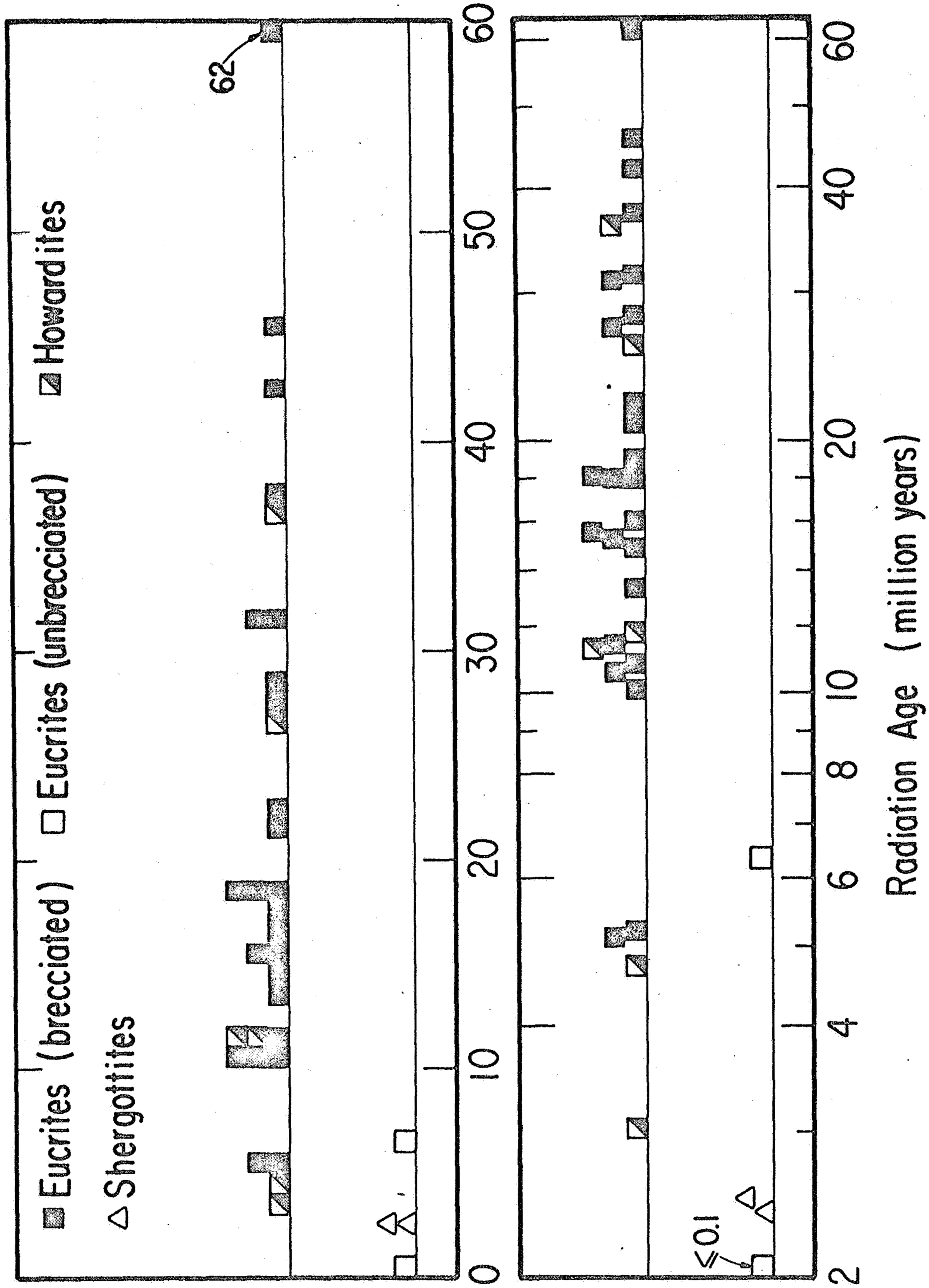

■ Eucrites (brecciated)
□ Eucrites (unbrecciated)
◪ Howardites
△ Shergottites
62
0
10
20
30
40
50
60
≤0.1
2
4
6
8
10
20
40
60
Radiation Age (million years)

Fig. 2

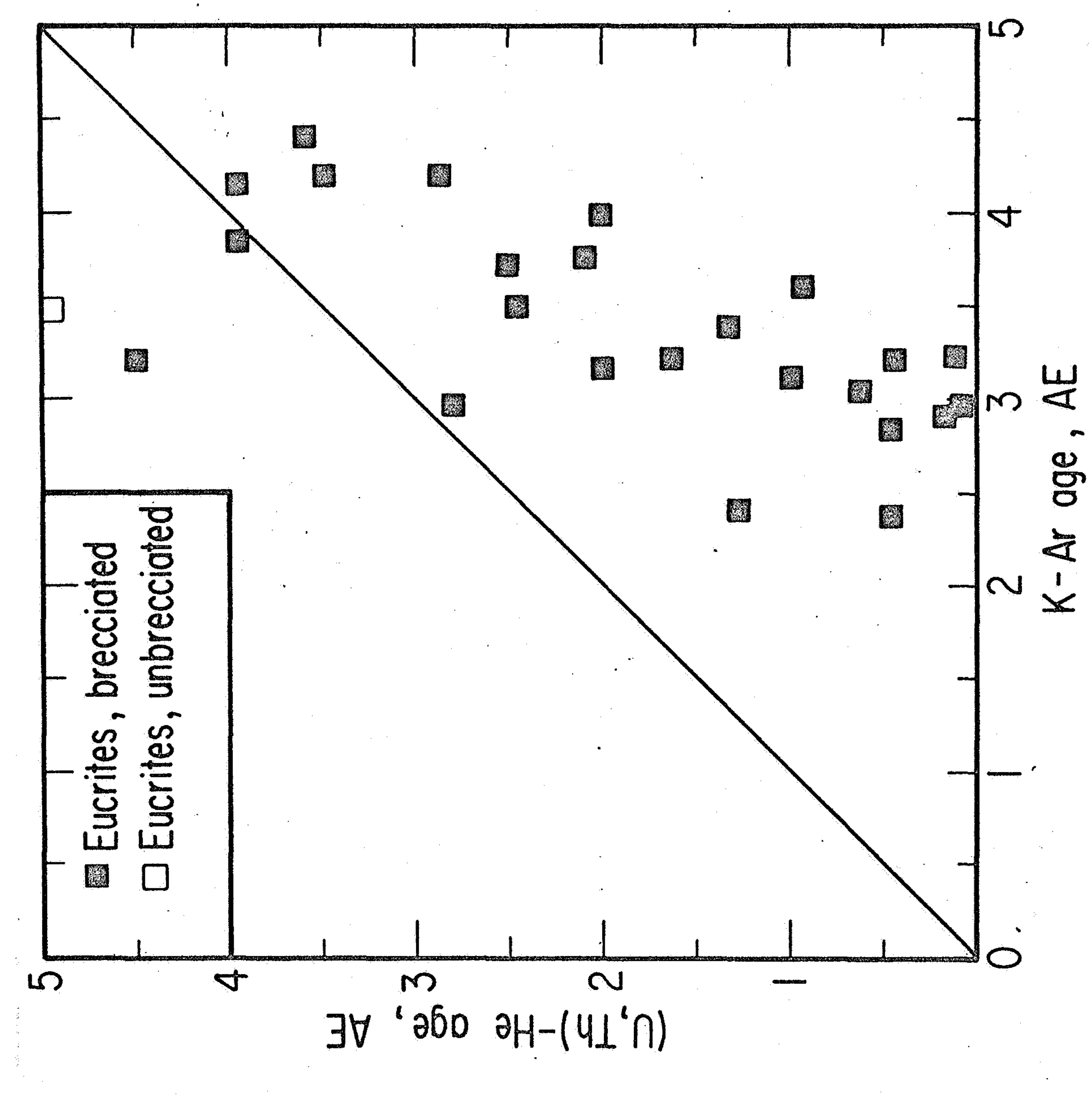
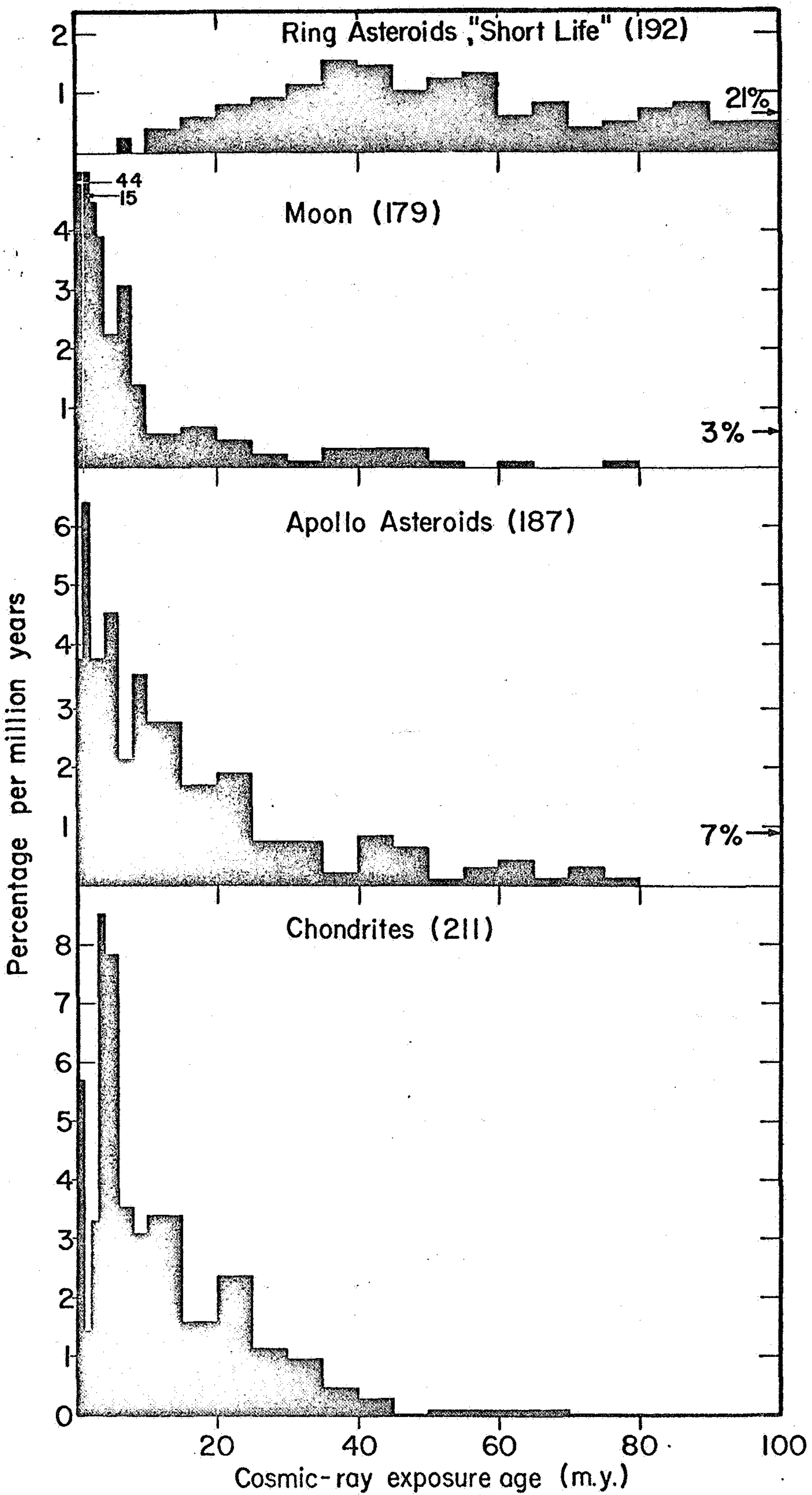

▨ Eucrites, brecciated
☐ Eucrites, unbrecciated
0
1
2
3
4
5
K-Ar age, AE
(U,Th)-He age, AE

Fig. 3



Ring Asteroids ,"Short Life" (192)
21%
44
15
Moon (179)
3%
Apollo Asteroids (187)
7%
Chondrites (211)
Percentage per million years
Cosmic-ray exposure age (m.y.)
0
1
2
3
4
5
6
7
8
20
40
60
80
100

Fig. 4