TERRESTRIAL ^{81}Kr-AGES OF FOUR YAMATO METEORITES

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Abstract: The terrestrial ages of four Yamato achondrites have been determined from ^{81}Kr-Kr-exposure ages and cosmogenic ^{38}Ar concentrations. A comparison of terrestrial ages and exposure ages shows that Y-74450 and Y-790007 are paired. The terrestrial age is less than 4×10^4 y and the exposure age is about 70×10^6 y. This group of polymict eucrites is different from Y-790122, Y-790260 and Y-790266. The diogenite Y-75032 has an exposure age of 17×10^6 y and a terrestrial age of less than 7×10^4 y. The howardite Y-790727 contains large amounts of trapped gases. The exposure age is about 20×10^6 y. The terrestrial ages of Yamato meteorites are younger than those from the Allan Hills region. This is possibly due to a young age of the Yamato ice field. The relatively short terrestrial ages also exclude a longer time of transportation within the ice and a special concentration mechanism due to ice flow.

1. Introduction

The terrestrial age of a meteorite is defined as the length of time the specimen has spent on Earth. It is an important parameter for the discussion of concentration mechanisms of Antarctic meteorites. For stone meteorites the terrestrial "half-life" for disintegration by weathering under the climatic conditions of the Western United States is about 3600 y (BOECKL, 1972). A number of Antarctic meteorites, on the other hand, have terrestrial ages longer than 10^5 y (*e.g.* NISHIIZUMI, 1984) because of the dry and cold climate at the polar plateau. The terrestrial ages of Antarctic meteorites are furthermore important time markers for the history of Antarctic ice (FIREMAN *et al.*, 1979).

The terrestrial ages of meteorites are determined from their content of cosmic-ray-produced radionuclides. If the activity of such a nuclide is known at the time of fall of the meteorite, the terrestrial age can be calculated from the fraction of the activity still present at the time of collection of the meteorite. However, terrestrial age and halflife of the radionuclide must be of the same order of magnitude. Hence ^{14}C ($t_{1/2}$=5730 y) can be utilized for terrestrial ages less than about 4×10^4 y (FIREMAN, 1978, 1979, 1980, 1984; FIREMAN and NORRIS, 1981; BROWN *et al.*, 1984; JULL *et al.*, 1984) while ^{26}Al ($t_{1/2}=7.05\times10^5$ y) is only useful for ages older than about 3×10^5 y and younger than a few million years. In both cases the saturation activities needed for the calculation of the terrestrial age are dependent on the chemical composition of the meteorite and the shielding conditions of the sample.

The gap between ^{14}C and ^{26}Al is bridged by ^{36}Cl ($t_{1/2}=3.0\times10^5$ y; NISHIIZUMI *et al.*, 1979, 1981, 1983). Preferably, this isotope should be measured in the metal phase of meteorites because its production in silicate phases is highly variable which prevents the prediction of saturation values in such samples. Therefore, terrestrial ages of non-metal containing meteorites like achondrites can be determined via ^{36}Cl with smaller accuracy only. About the same range of ages is covered by ^{81}Kr with a half-life of 2.1×10^{5} y (FREUNDEL, 1983; FREUNDEL *et al.*, 1983; SCHULTZ and FREUNDEL, 1984). However, since ^{81}Kr is produced from targets which are present in trace amounts, its concentration in chondrites is only of the order of 10^{-14} ccSTP/g. Furthermore in chondrites the cosmogenic component is masked by trapped noble gases and neutron-produced Kr-isotopes from bromine. In achondrites, however, the interfering noble gas components are smaller in concentration and the cosmogenic component is more abundant due to higher target element concentrations.

MARTI (1967) and EUGSTER *et al.* (1967a) have demonstrated that the exposure age of meteorites can be measured reliably using cosmogenic Kr isotopes. This method avoids many of the uncertainties which are due to unknown production rates because it provides a self-normalization of production rates for each individual sample since the exposure age T is calculated from the Kr-*isotopic ratios* only and not from concentrations of cosmogenic nuclides which can only be determined with larger uncertainties (MARTI, 1967):

$$T=\frac{0.425}{\lambda_{81}}\cdot[^{80}\mathrm{Kr}/^{83}\mathrm{Kr}+^{82}\mathrm{Kr}/^{83}\mathrm{Kr}]\cdot\frac{^{83}\mathrm{Kr}}{^{81}\mathrm{Kr}};\quad \lambda_{81}\text{: decay constant of }^{81}\mathrm{Kr}\,. \quad (1)$$

While the terrestrial age of a meteorite increases, the ^{83}Kr/^{81}Kr ratio increases because of the decay of ^{81}Kr. Therefore, in case of a longer terrestrial age eq. (1) yields an apparent exposure age T_a which is larger than the true exposure age T. The terrestrial age T_t is calculated from the true and the apparent exposure age by

$$T_t=\frac{1}{\lambda_{81}}\cdot\ln(T_a/T)\,. \quad (2)$$

The true exposure age can be calculated from other cosmogenic nuclides if their production rates are known. FREUNDEL (1983) and FREUNDEL *et al.* (1983) have shown that ^{38}Ar can be used to determine T. The production rate $P(38)$ of this isotope as a function of chemical composition was determined from the ^{81}Kr-exposure ages of 4 eucrite falls, their ^{38}Ar concentration and their chemical composition:

$$P(38)=1.5\underset{8}{8}[\mathrm{Ca}]+0.08\underset{15}{6}[\mathrm{Fe+Ni}]+0.3\underset{10}{3}[\mathrm{Ti+Cr+Mn}]+1\underset{7}{1}[\mathrm{K}]\,. \quad (3)$$

[X]=concentration of element X as weight fraction.
No correction for shielding effects is applied. The uncertainties given might be too small for extreme shielding conditions.

In this paper the measurements of concentration and isotopic composition of 4 Yamato achondrites are reported and their terrestrial and exposure age calculated. Also discussed are the data of 3 Yamato eucrites (FREUNDEL *et al.*, 1983). Their ages are recalculated using the chemical composition of these samples which is now known.

3. Experimental Procedures and Results

Bulk samples were wrapped in Ni foil and preheated at about 120°C for at least

12 hours in vacuum. They were then dropped into the Ta crucible of a resistance heated double-vacuum-oven and vaporized at about 1700°C. The gases were purified by exposure to Ti sponge and SAES getters. Elemental fractions of Ar and Kr were received from the sample gas mixture by means of a temperature controlled charcoal trap. The Kr fraction contained less than 0.1% of the total Ar which reduced the background between mass 78 and 82 as well as the memory effect. The isotopic composition of each fraction was measured in an all-metal mass spectrometer. It is equipped with a Faraday cup for argon and an electron multiplier for Kr measurements. The mass resolution is 230 but can be increased to 1300 for the multiplier. The sensitivity for Ar was about 1.2×10^{-4} A/Torr. Total extraction blanks were less than 5×10^{-9} and 2×10^{-12} ccSTP for ^{40}Ar and ^{84}Kr, respectively. They are negligible for all measurements reported here. The background at mass ^{81}Kr corresponds to about 3×10^{-14} ccSTP and was correlated with the peak height at mass 79.

Concentrations of Ar were determined by isotope dilution using air argon as spike. Amounts of Kr were determined by comparing the peak hights with those of calibrated standard samples of comparable size. A detailed description of the apparatus and the experimental procedures are given by FREUNDEL (1983).

The Kr in achondrites is a mixture of cosmogenic and trapped gas. To calculate the cosmogenic component the following assumptions are made:

— Cosmogenic $^{86}Kr/^{83}Kr=0.015$ (MARTI and LUGMAIR, 1971).
— Besides this cosmogenic component all ^{86}Kr is trapped.
— The trapped component has the isotopic composition of atmospheric Kr (using AVCC-Kr or solar Kr isotopic compositions instead the terrestrial ages will vary within the limits of errors).

Cosmogenic ^{38}Ar is calculated assuming trapped $^{36}Ar/^{38}Ar=5.32$ and cosmogenic $^{36}Ar/^{38}Ar=0.67$.

The experimental results are shown in Table 1. The uncertainties given are the sum of the statistical errors of the measurement, blank corrections and mass fractionation. For eucrites the cosmogenic component is more than 98% of the total ^{38}Ar and about 80% of the ^{83}Kr. Also the diogenite Y-75032 contains large percentages of cosmogenic ^{38}Ar and ^{83}Kr. The howardite Y-790727, however, has large quantities of trapped gases. Only about 15% of the ^{38}Ar and about 11% of the ^{83}Kr are of cosmogenic origin. This introduces large errors for the calculated ages.

Table 2 contains chemical analyses of pertinent elements used for the calculation of the production rate of ^{38}Ar. Included are the apparent ^{81}Kr-exposure age, the ^{38}Ar-exposure age and the terrestrial age. The ages of three polymict eucrites Y-790122, Y-790260 and Y-790266 are from FREUNDEL *et al.* (1983). However, these preliminary results have been recalculated using the chemical composition of these samples which became recently available (B. SPETTEL, private communication).

A direct comparison of the terrestrial ages reported here with other terrestrial age determinations of the same meteorites is not possible. The diogenite Y-75032 is presumably not paired with the diogenite group Y-74013 (TAKEDA *et al.*, 1978). Thus, the terrestrial age given from ^{14}C measurements of Y-74013 (*e.g.* JULL *et al.*, 1984) cannot be compared with the age of Y-75032 reported here.

For Y-790727 a preliminary terrestrial age of $(2.2\pm0.6)\times10^{5}$ y was given

(SCHULTZ, 1985b). Considering the large corrections for trapped Kr this value is changed to $(1.5\pm1.3)\times10^5$ y.

Table 1. Concentration and isotopic composition of Ar and Kr in four Yamato achondrites. The cosmogenic component is calculated for each sample and the isotopic composition of air is included for comparison.

Name and class	Weight (mg)	^{36}Ar*	$^{38}Ar/^{36}Ar$	$^{40}Ar/^{36}Ar$	$^{38}Ar_c$*	^{86}Kr#	^{78}Kr
Y-74450 Euc	672.8	6.39 ±.30	1.497 ±.002	425.9 ±1.0		26.8 ±1.4	443 ±14
Cosmogenic					9.56 ±.47		17.2 ±.6
Y-790007 Euc	980.0	6.44 ±.60	1.492 ±.005	420.5 ±1.0		20.3 ±1.9	519 ±21
Cosmogenic					9.61 ±.84		17.1 ±.8
Y-75032 Dio	1039.0	.66 ±.04	1.450 ±.10	188.0 ±1.0		7.2 ±.7	108.2 ±4.4
Cosmogenic					.95 ±.05		18.2 ±1.1
Y-790727 How	1022.0	4.38 ±.12	.381 ±.001	187.2 ±.5		87.0 ±7.4	3.31 ±.07
Cosmogenic					.97 ±.03		15.9 ±2.3
Air (NIER, 1950; EUGSTER *et al.*, 1967a, b)			.1880 ±.0004	296.0 ±.5			1.995 ±.008

Name and class	^{80}Kr	^{81}Kr	^{82}Kr	^{83}Kr	^{84}Kr	^{86}Kr	^{83}Kr#
Y-74450 Euc	135.3 ±4.1	.70 ±.08	255.6 ±7.2	309.5 ±5.8	407 ±10	≡100	
Cosmogenic	49.9 ±1.9	.284 ±.032	78.1 ±3.2	≡100	38.7 ±4.1	≡1.5	66.0 ±3.4
Y-790007 Euc	165.1 ±5.6	.81 ±.04	278.1 ±5.6	354.4 ±5.3	442.9 ±4.4	≡100	
Cosmogenic	52.3 ±2.1	.276 ±.013	73.7 ±2.3	≡100	45.6 ±1.7	≡1.5	59.3 ±5.7
Y-75032 Dio	37.9 ±1.3	.48 ±.07	101.3 ±1.9	114.1 ±1.7	365.2 ±2.4	≡100	
Cosmogenic	51.5 ±3.1	.99 ±.14	73.3 ±4.7	≡100	83.5 ±6.0	≡1.5	3.5 ±1.5
Y-790727 How	16.8 ±.4	.075 ±.004	72.6 ±4.0	74.2 ±1.1	331.0 ±3.0	≡100	
Cosmogenic	46.6 ±7.8	.90 ±.13	79 ±49	≡100	49 ±33	≡1.5	7.2 ±1.3
Air (NIER, 1950; EUGSTER *et al.*, 1967a, b)	12.96 ±.04	—	66.17 ±.16	66.00 ±.14	327.3 ±.7	≡100	

* 10^{-8} ccSTPg^{-1}. # 10^{-12} ccSTPg^{-1}.

Table 2. Chemical composition, production rate of ^{38}Ar, P(38), true exposure age T, as calculated from cosmogenic ^{38}Ar, the apparent ^{81}Kr-exposure age and the terrestrial age of 7 Yamato achondrites. Chemical data for Y-74450 are the mean of 3 analysis (WÄNKE et al., 1977; TAKEDA et al., 1978; JOCHUM et al., 1980). All other chemical data from B. SPETTEL (private communication). Y-790122, Y-790260 and Y-790266 are recalculated from FREUNDEL et al. (1983).

	Ca (wt%)	Fe (wt%)	Ti+Cr +Mn (wt%)	K (ppm)	P (38)*	T (10^6 y)	T_a (10^6 y)	T_t (10^3 y)
Y-74450	6.97 ±.16	14.2 ±.3	1.2 ±.2	453 ±45	.131 ±.007	73.0 ±6.4	65.8 ±7.7	−32 ±44
Y-790007	6.99 ±.28	14.9 ±.5	1.1 ±.2	420 ±20	.131 ±.008	73.3 ±7.2	66.6 ±3.6	−29 ±34
Y-75032	2.43 ±.29	14.55 ±.44	1.0 ±.2	49 ±10	.055 ±.006	17.2 ±1.6	18.5 ±2.9	22 ±56
Y-790727	3.77 ±.45	13.7 ±.4	1.2 ±.2	157 ±9	.077 ±.008	12.7 ±1.2	20.3 ±8.5	150 ±130
Y-790122	6.52 ±.28	14.80 ±.44	1.2 ±.2	630 ±25	.126 ±.008	24.4 ±1.7	35.1 ±2.5	110 ±31
Y-790260	6.26 ±.25	14.79 ±.44	1.2 ±.2	488 ±15	.120 ±.008	21.6 ±1.7	34.1 ±2.4	140 ±32
Y-790266	7.14 ±.36	15.25 ±.46	1.2 ±.2	383 ±16	.133 ±.008	21.9 ±1.6	35.8 ±2.8	150 ± 33

* 10^{-8} ccSTPg^{-1} 10^{-6} y^{-1}.

4. Discussion

4.1. Pairing

Many of the Antarctic meteorites are not single falls but parts of a meteorite shower. Estimations for the number of individual meteorites represented by the 299 specimens collected from the Allan Hills area in the 1977/78 season range from 20–50 (YANAI *et al.*, 1978) to 50–150 (SCOTT, 1985). Criteria for the possibility that two meteorites are paired are obtained from chemical and petrological similarities, proximity of discovery locations and effects of ablation and weathering. These criteria and similarities in the concentration of cosmogenic nuclides have also been used to describe meteorite showers at the Yamato site (HONDA, 1981). Since meteorites from paired or multiple falls must have the same cosmic-ray exposure age as well as the same terrestrial age these two parameters can be used to detect paired falls. The concentration of other noble gas isotopes can be used also for this purpose (WEBER and SCHULTZ, 1980; WEBER *et al.*, 1983).

DELANEY *et al.* (1983, 1984) have discussed the Antarctic polymict eucrites. They conclude that only 3 independent falls contribute to the Yamato eucrite collection.

Y-74450 and Y-790007 have very similar exposure and terrestrial age. Their exposure age of 73×10^6 y is the highest value so far found for an eucrite. It is concluded that these two eucrites belong to the same fall. This is in contrast to DELANEY *et al.* (1983) but agrees with a recent study by DELANEY *et al.* (1984). Concentration of cosmogenic ^{38}Ar in Y-74159 (KANEOKA *et al.*, 1979) and Y-75015 (NAGAO *et al.*, 1983) are very similar to those of Y-74450 and Y-790007; all these eucrites should belong to the same fall. Y-790122, Y-790260 and Y-790266 have also similar exposure and terrestrial ages which are different, however, from the Y-74450 group. These polymict eucrites are from a different fall. This is different from suggested pairings given by DELANEY *et al.* (1983).

4.2. Terrestrial ages

Attempts to measure the terrestrial ages of Yamato meteorites from their ^{26}Al content failed because the half-life of ^{26}Al is much longer than the terrestrial ages (EVANS *et al.*, 1979; EVANS and REEVES, 1984; KOMURA *et al.*, 1982). Also all Yamato meteorites analysed for ^{36}Cl indicated terrestrial ages less than 10^5 y (NISHIIZUMI *et al.*, 1979, 1983). However, four Yamato stone meteorites yielded reliable ^{14}C terrestrial ages, all less than 22×10^3 y (FIREMAN, 1984; JULL *et al.*, 1984; MATSUDA and KIGOSHI, 1985). The ^{81}Kr measurements gave only for the eucrite group Y-790122, Y-790260 and Y-790266 a terrestrial age of about 10^5 y. This is the oldest age for Yamato meteorites reported so far if Y-790727 is not taken into account because of its large experimental uncertainties. However, it seems to be a safe conclusion that most of the Yamato meteorites have terrestrial ages less than 10^5 y.

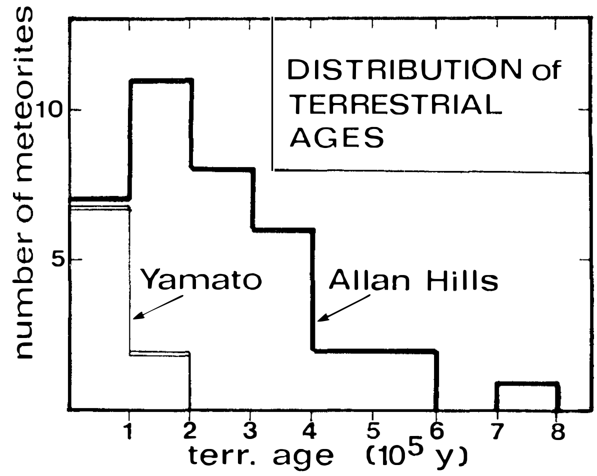

Fig. 1. Distribution of terrestrial ages of Yamato and Allan Hills meteorites. The sources of the ages are given in the text.

Terrestrial ages are important parameters for a test of theories which try to explain the concentration of meteorites on some bare ice fields in the Antarctic. CASSIDY *et al.* (1977) noted that most of the meteorites are concentrated in zones of high ice ablation where strong winds strip away the snow cover and promote ablation by sublimation of the ice. If the ablating ice is replaced by other ice, emerging from below, entrapped meteorites could become concentrated on these ice fields. NAGATA (1978) refined this concentration hypothesis, and it was further developed by WHILLANS and CASSIDY (1983) and VAN HEESWIJK (1984). All these models assume that meteorites fallen in the accumulation zone of Antarctic ice will be entrapped and transported with the ice. Blocking mountain chains or heights in the submerged massifs are the cause for ablation zones and, thus, icefields with high meteorite concentrations. The meteorites collected on the ablating surface are joined by direct meteorite falls. Compressive ice flow can further concentrate these meteorites. Such a collecting mechanism produces a special distribution of terrestrial ages of these meteorites. It has been shown that the distribution of terrestrial ages of Allan Hills meteorites can be explained if direct falls and transported meteorites are present with about equal abundances (FREUNDEL, 1983; SCHULTZ, 1985a). The transport time of the meteorites within the ice is about 1.5×10^5 y. Weathering and destruction takes place while the meteorites are on the surface of the ice. If this is the only sink for meteorites the half-life of destruction by weathering is about 1.6×10^5 y. This is considerably longer than that under normal climatic conditions of about 4×10^3 y (BOECKL, 1972).

A comparison of terrestrial ages of Antarctic meteorites from the Allan Hills area and those from the Yamato Mountains is given in Fig. 1. Most Allan Hills meteorites have terrestrial ages larger than 10^5 y but Yamato meteorite ages are mainly less than 10^5 y. This difference has been noted earlier by HONDA (1981), NISHIIZUMI *et al.* (1983), FIREMAN (1984), and JULL *et al.* (1984). The latter authors explain the absence of Yamato meteorites with longer terrestrial ages by their removal through the blocking system of the Yamato barrier. Ice flow in passages through the Yamato Mountains carries away most of the ancient falls. This picture should also apply to meteorites found on ice fields which are not directly connected with blocking mountains. This is the case for the Western Ice Fields of the Allan Hills, the Elephant Moraine and the Reckling Peak Moraine. The polymict eucrites from Elephant Moraine have terrestrial ages in excess of 10^5 y (FREUNDEL *et al.*, 1983) which could be due to the time of transport within the ice.

The Allan Hills ice field seems to be stagnant for a much longer time than those ice fields which are not directly connected with blocking mountains. This is also seen in the density of meteorites which is less in the Yamato area compared to the Allan Hills (HONDA, 1981). This lower density and the relatively young ages show that the Yamato ice field is not stagnant for longer than a few 10^4 y. A possible concentration mechanism for the Yamato site as described by NAGATA (1978) is not acting long enough to build-up high meteorite concentrations. Furthermore, the terrestrial ages of Yamato meteorites are too short to allow for a transport time comparable with that of Allan Hills meteorites.

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References

BOECKL, R. (1972): Terrestrial age of nineteen stony meteorites derived from their radiocarbon content. Nature, **236**, 25–26.

BROWN, R. M., ANDREWS, H. R., BALL, G. C., BURN, N., IMAHORI, Y., MILTON, J. C. D. and FIREMAN, E. L. (1984): ^{14}C content of ten meteorites measured by Tandem Accelerator Mass Spectrometry. Earth Planet. Sci. Lett., **67**, 1–8.

CASSIDY, W. A., OLSEN, E. and YANAI, K. (1977): Antarctica; A deep-freeze storehouse for meteorites. Science, **198**, 727–731.

DELANEY, J. S., TAKEDA, H. and PRINZ, M. (1983): Modal comparison of Yamato and Allan Hills polymict eucrites. Mem. Natl Inst. Polar Res., Spec. Issue, **30**, 206–223.

DELANEY, J. S., PRINZ, M. and TAKEDA, H. (1984): The polymict eucrites. Proc. Lunar Planet. Sci. Conf. 15th, Pt. 1, C251–C288 (J. Geophys. Res., **89**, Suppl.).

EUGSTER, O., EBERHARDT, P. and GEISS, J. (1967a): ^{81}Kr in meteorites and ^{81}Kr radiation ages. Earth Planet. Sci. Lett., **2**, 77–82.

EUGSTER, O., EBERHARDT, P. and GEISS, J. (1967b): The isotopic composition of krypton in unequilibrated and gas rich chondrites. Earth Planet. Sci. Lett., **2**, 385–393.

EVANS, J. C. and REEVES, J. H. (1984): Aluminum-26 measurements on Antarctic meteorites (abstract). Lunar and Planetary Science, XV. Houston, Lunar Planet. Inst., 260–261.

EVANS, J. C., RANCITELLI, L. A. and REEVES, J. H. (1979): ^{26}Al content of Antarctic meteorites; Implications for terrestrial ages and bombardment history. Proc. Lunar Planet. Sci. Conf., 10th, 1061–1072.

FIREMAN, E. L. (1978): Carbon-14 in lunar soil and in meteorites. Proc. Lunar Planet. Sci. Conf., 9th, 1647–1654.

FIREMAN, E. L. (1979): ^{14}C and ^{39}Ar in Allan Hills meteorites. Proc. Lunar Planet. Sci. Conf., 10th, 1053–1060.

FIREMAN, E. L. (1980): Carbon-14 and argon-39 in ALHA meteorites. Proc. Lunar Planet. Sci. Conf., 11th, 1215–1221.

FIREMAN, E. L. (1984): Carbon-14 terrestrial ages of Antarctic meteorites. Mem. Natl Inst. Polar Res., Spec. Issue, **30**, 246–250.

FIREMAN, E. L. and NORRIS, T. L. (1981): Carbon-14 ages of Allan Hills meteorites and ice. Proc. Lunar Planet. Sci., 12B, 1019–1025.

FIREMAN, E. L., RANCITELLI, L. A. and KIRSTEN, T. (1979): Terrestrial ages of four Allan Hills meteorites; Consequences for Antarctic ice. Science, **203**, 453–455.

FREUNDEL, M. (1983): Massenspektrometrischer Nachweis von ^{81}Kr in Meteoriten und das terrestrische Alter antarktischer Eukrite. Ph. D. thesis. University of Mainz.

FREUNDEL, M., CRABB, J. and SCHULTZ, L. (1983): ^{81}Kr terrestrial ages of Antarctic eucrites. Meteoritics, **18**, 299–300.

HONDA, M. (1981): Terrestrial history of Antarctic meteorites recorded in the cosmogenic nuclides. Geochem. J., **15**, 163–181.

JOCHUM, K. P., GRAIS, K. I. and HINTENBERGER, H. (1980): Chemical composition and classification of 19 Yamato meteorites. Meteoritics, **15**, 31–39.

JULL, A. J. T., DONAHUE, D. J., ZABEL, T. H. and FIREMAN, E. L. (1984): Carbon-14 ages of Antarctic meteorites with accelerator and small-volume counting techniques. Proc. Lunar Planet. Sci. Conf., 15th, Pt. 1, C329–C335 (J. Geophys. Res., **89** Suppl.).

KANEOKA, I., OZIMA, M. and YANAGISAWA, M. (1979): ^{40}Ar–^{39}Ar age studies of four Yamato-74 meteorites. Mem. Natl Inst. Polar Res., Spec. Issue, **12**, 186–206.

KOMURA, K., TSUKAMOTO, M. and SAKANOUE, M. (1982): Non-destructive measurements of cosmogenic ^{26}Al, natural ^{40}K and fallout ^{137}Cs in Antarctic meteorites. Mem. Natl Inst. Polar Res., Spec. Issue, **25**, 178–187.

MARTI, K. (1967): Mass spectrometric detection of cosmic-ray-produced Kr^{81} in meteorites and the possibility of Kr-Kr dating. Phys. Rev. Lett., **18**, 264–266.

MARTI, K. and LUGMAIR, G. W. (1971): Kr^{81}-Kr and K-Ar^{40} ages, cosmic-ray spallation products, and neutron effects in lunar samples from Oceanus Procellarum. Proc. Lunar Sci. Conf., 2nd, 1591–1605.

MATSUDA, E. and KIGOSHI, K. (1985): Carbon-14 terrestrial ages of Antarctic meteorites. Papers presented to the Tenth Symposium on Antarctic Meteorites, 25–27 March 1985. Tokyo. Natl Inst. Polar Res., 165.

NAGAO, K., OGATA, K., TAKAOKA, N. and SAITO, K. (1983): Rare gas studies of sixteen stony meteorites from Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **30**, 349–361.

NAGATA, T. (1978): A possible mechanism of concentration of meteorites within the meteorite ice field in Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **8**, 70–92.

NIER, A. O. (1950): A redetermination of the relative abundances of the isotopes of carbon, nitrogen, oxygen, argon and potassium. Phys. Rev., **77**, 789–793.

NISHIIZUMI, K. (1984): Cosmic-ray-produced nuclides in Victoria Land meteorites. Smithson. Contrib. Earth Sci., **26**, 105–109.

NISHIIZUMI, K., ARNOLD, J. R., ELMORE, D., FERRARO, R. D., GOVE, H. E., FINKEL, R. C., BEUKENS, R. P., CHANG, K. H. and KILIUS, L. R. (1979): Measurements of ^{36}Cl in Antarctic meteorites and Antarctic ice using a Van de Graaff accelerator. Earth Planet. Sci. Lett., **45**, 285–292.

NISHIIZUMI, K., MURRELL, M. T., ARNOLD, J. R., ELMORE, D., FERRARO, R. D., GOVE, H. E. and FINKEL, R. C. (1981): Cosmic ray produced ^{36}Cl and ^{53}Mn in Allan Hills-77 meteorites. Earth Planet. Sci. Lett., **52**, 31–38.

NISHIIZUMI, K., ARNOLD, J. R., ELMORE, D., MA, X., NEWMAN, D. and GOVE, H. E. (1983): ^{36}Cl and ^{53}Mn in Antarctic meteorites and ^{10}Be-^{36}Cl dating of Antarctic ice. Earth Planet. Sci. Lett., **62**, 407–417.

SCHULTZ, L. (1985a): Terrestrial ages of Antarctic meteorites; Implications for concentration mechanisms (abstract). Workshop on Antarctic Meteorites (Abstracts), Mainz.

SCHULTZ, L. (1985b): Terrestrial ages of four Yamato achondrites. Papers presented to the Tenth Symposium on Antarctic Meteorites, 25–27 March 1985. Tokyo, Natl Inst. Polar Res., 158–159.

SCHULTZ, L. and FREUNDEL, M. (1984): Terrestrial ages of Antarctic meteorites. Meteoritics, **19**, 310.

SCOTT, E. R. D. (1985): Pairing of meteorites found in Victoria Land, Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **35**, 102–125.

TAKEDA, H., MIYAMOTO, M., YANAI, K. and HARAMURA, H. (1978): A preliminary mineralogical examination of the Yamato-74 achondrites. Mem. Natl Inst. Polar Res., Spec. Issue, **8**, 170–184.

VAN HEESWIJK, M. (1984): Meteorite concentration by ice flow. Inst. Polar Stud., Rep. **83**, 67 p.

WÄNKE, H., BADDENHAUSEN, H., BLUM, K., CENDALES, M., DREIBUS, G., HOFMEISTER, H., KRUSE, H., JAGOUTZ, E., PALME, C., SPETTEL, B., THACKER, R. and VILCSEK, E. (1977): On the chemistry of lunar samples and achondrites. Primary matter in lunar highlands; A re-evaluation. Proc. Lunar Sci. Conf., 8th, 2191–2213.

WEBER, H. W. and SCHULTZ, L. (1980): Noble gases in ten stone meteorites from Antarctica. Z. Naturforsch., **35a**, 44–49.

WEBER, H. W., BRAUN, O., SCHULTZ, L. and BEGEMANN, F. (1983): The noble gas record in Antarctic and other meteorites. Z. Naturforsch., **38a**, 267–272.

WHILLANS, I. M. and CASSIDY, W. A. (1983): Catch a falling star; Meteorites and old ice. Science, **222**, 55–57.

YANAI, K., CASSIDY, W. A., FUNAKI, M. and GLASS, B. P. (1978): Meteorite recoveries in Antarctica during field season 1977–1978. Proc. Lunar Planet. Sci. Conf., 9th, 977–987.

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