CARBON-14 TERRESTRIAL AGES OF ANTARCTIC METEORITES

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Abstract: The carbon-14(^{14}C) terrestirial ages of four Yamato meteorites are measured and compared with the ^{14}C terrestrial ages of eighteen meteorites from Victoria Land. The youngest Yamato meteorite, Y-75102, is $(4.3\pm1.0)\times10^3$ yr; the oldest, Y-74459, is $(24\pm2)\times10^3$ yr. The Yamato meteorite site is collecting recent falls, less than 25×10^3 yr, at a more rapid rate than the Victoria Land sites.

1. Introduction

The terrestrial ages of meteorites are determined by their content of cosmic ray produced radio-nuclides, mainly ^{26}Al ($t_{1/2}=7.2\times10^5$ yr), ^{36}Cl ($t_{1/2}=3.1\times10^5$ yr), and ^{14}C ($t_{1/2}=5730$ yr). These nuclides are produced by cosmic rays in small bodies (less than 1-m diameter) in space. After fall, the earth's atmosphere protects the meteorite from cosmic rays and the radio-nuclides decay with their characteristic half-lives.

Although the terrestrial ages of meteorite finds have been determined by the cosmic ray radio-nuclide method for three decades, only during the past few years has this method been applied to Antarctic meteorites. ^{26}Al has been measured in 129 Victoria Land meterorites and in a few Yamato meteorites by EVANS *et al.* (1979) and EVANS and REEVES (1983) using nondestructive gamma-ray counting. Because of its long half-life, ^{26}Al is useful for terrestrial age determinations only when the age is greater than $\sim200\times10^3$ yr. It is necessary for the meteoroid to be exposed to cosmic rays in a relatively unshielded condition in space for more than two half-lives of a radioactivity for it to become saturated and have its full complement of the radioactivity at fall. On the basis of associated cosmogenic nuclide studies, approximately 15% of the meteorites did not attain saturated ^{26}Al values because of multiple collisions in space. This underexposure necessitates the measurement of cosmogenic radioactivities with shorter half-lives than ^{26}Al for terrestrial age determination. Nevertheless the ^{26}Al has been very useful for the terrestrial age studies of Antarctic meteorites. When ^{26}Al is near its saturation value, two conclusions can be drawn: (1) The meteorite was exposed in a relatively unshielded condition to cosmic rays for more than 1.4×10^6 yr. (2) The terrestrial age is less than $\sim200\times10^3$ yr. However, when ^{26}Al is less than its saturation value, it is uncertain whether the meteorite was underexposed in space or its terrestrial age is older than $\sim200\times10^3$ yr. One interesting aspect of the ^{26}Al studies in Antarctic meteorites is that all of the stony meteorites have significant amounts of ^{26}Al. The Antarctic ice sheet is supposed to have existed for more than 10 Ma; the ^{26}Al in meteorites which landed more than 3 Ma ago would be unmeasurable. The ^{26}Al results indicate that no stony meteorite older than ~1 Ma has been recovered in Antarctica.

^{36}Cl has been measured in approximately 50 Victoria Land meteorites and four Yamato meteorites by NISHIIZUMI *et al.* (1979, 1981, 1982a, b) with accelerator mass spectrometry. Cosmic rays produce ^{36}Cl from Fe, Ni, and Ca but not from lighter elements. In order to be useful for terrestrial age dating, ^{36}Cl must be measured in the metal phase because ^{36}Cl from Ca is highly variable even in small bodies. Not all stony meteorites have metal. The ^{36}Cl content of the metal at saturation is 22 ± 4 dpm (disintegrations per minute) per kg. Because of its long half-life, ^{36}Cl is useful for terrestrial age determinations only when the age is greater than $\sim 100 \times 10^3$ yr. All four Yamato meteorites studied by ^{36}Cl measurements indicate ages less than $\sim 100 \times 10^3$ yr. Approximately half of the Victoria Land meteorites studied by ^{36}Cl measurements have less than the saturated value; the oldest has one-fourth of the saturation value, which translates to an age of $(700 \pm 160) \times 10^3$ yr. The ^{36}Cl method assumes that all meteorites had the saturation activity of 22 ± 4 dpm per kg of metal at fall. Since it is known that some meteorites ($\sim 15\%$) do not have their ^{26}Al activity saturated at fall, a few meteorites (perhaps $\sim 10\%$) should not have their ^{36}Cl activity saturated at fall. Therefore, a few Antarctic meteorites, which are quoted to have old ^{36}Cl ages, may be young because of undersaturation due to multiple collisions in space.

Because of its short half-life, undersaturated ^{14}C activity is extremely unlikely and has never been observed. On the other hand, ^{14}C can only be measured when the terrestrial age is less than $\sim 45 \times 10^3$ yr. In the near future, ^{14}C terrestrial ages determined by accelerator mass spectrometry may extend to 55×10^3 yr. For Antarctic meteorites collected at high elevations, ~ 2000 m, the likelihood of going beyond 55×10^3 yr ^{14}C terrestrial ages is small because of the cosmic ray ^{14}C production in the specimen at the high elevation.

^{14}C measurements in Antarctic meteorites have been done both by low-level counting (FIREMAN, 1979, 1980, 1983) and by accelerator mass spectrometry (ANDREWS *et al.*, 1982). The two methods are in accord, however, the precision of the accelerator mass spectrometric method is higher. Twenty-two Antarctic meteorites have been dated by the ^{14}C method.

2. Carbon-14 Terrestrial Ages

The ^{14}C terrestrial age is determined from the activity in the carbon extracted above melting temperature subsequent to lower temperature extractions as discussed by FIREMAN (1979, 1980, 1983). Bruderheim, a 1960 fall, is used as a comparison reference. The low-temperature extractions give information about terrestrial carbon incorporated into the meteorite by weathering, which will not be discussed here.

Table 1 gives ^{14}C activities and the terrestrial ages obtained with low-level counting by FIREMAN (1979, 1980, 1983) and FIREMAN and NORRIS (1981). Tabulated are results for three meteorites from the Yamato site and twelve meteorites and two field rocks from Victoria Land and Bruderheim. Table 2 gives similar results obtained by accelerator mass spectrometry by ANDREWS *et al.* (1982). Listed in Table 2 are one Yamato meteorite, six meteorites from Victoria Land, and the dated falls–Bruderheim and Farmington, and Estacado–a meteorite find.

The four Yamato meteorites have relatively young ^{14}C terrestrial ages. The young-

Table 1. Melt extraction carbon-14 counting results.

Sample (type)	^{14}C (dpm/kg)*	^{14}C Terrestrial age (10^3 yr)	^{36}Cl** Terrestrial age (10^3 yr)
Bruderheim (L6)	57 ±3	Fell March 4, 1960	—
Yamato-75102 (L6)	34.1 ±2.7	4.3±1.0	—
Yamato-74013 (Di)	4.8 ±0.7	19 ±2	—
Yamato-74459 (H6)	3.0 ±0.6	24 ±2	—
ALHA76005 (Eu)	<1.0	>33	—
ALHA76006 (H6)	<1.7	>29	—
ALHA76007 (L6)	<1.2	>32	—
ALHA76008 (H6)	<1.7	>29	100±70
ALHA77256 (Di)	14.7 ±1.3	11 ±1	—
ALHA77272 (L6)	<0.5	>39	530±70
ALHA77282 (L6)	1.1 ±0.3	33 ±3	270±70
ALHA77295 (H5)	1.6 ±0.3	29.5±2.5	<100
ALHA77297 (L6)	<0.6	>36	<100
ALHA78084 (H3)	1.41±0.24	30.6±2.5	140±70
EETA79002 (Di)	<0.4	>41	—
MBRA76001 (L6)	1.19±0.30	32 ±3	—
Field Rock 1294 (—)	<0.2	(≥46)***	--
Field Rock 1391 (—)	<0.3	(≥44)***	—

* These errors are 1σ errors in the counting.
** NISHIIZUMI *et al.* (1979, 1981, 1982a, b).
*** Ages calculated similarly to meteorite terrestrial ages to illustrate that cosmic rays at the Allan Hills site produce less activity than measured in meteorites.

Table 2. Melt extraction carbon-14 accelerator (Chalk River) results.

Sample (type)	CO_2 cm^3 (STP)	$^{14}C/^{12}C$ / $^{14}C/^{12}C$ ox. acid*	^{14}C (min^{-1} kg^{-1})	^{14}C Terr. age (10^3 yr)**	^{36}Cl Terr. age (10^3 yr)‡
Bruderheim (L6)	6.7	19.4 ±0.70	49.8 ±1.8	Fell March 4, 1960	—
Farmington (L5)	34.0	3.34 ±0.22	48.2 ±3.2	Fell June 25, 1890	—
Estacado (H6)	33.0	0.64 ±0.021	12.3 ±0.4	11.6±0.4	—
Yamato-7304 (L6)	6.6	2.41 ±0.17	20.9 ±1.5	7.2±0.6	<100
ALHA77003 (C3)	3.4	0.184±0.011	0.67±0.04	35.6±0.5	110±70
ALHA77004 (H4)	8.9	0.096±0.005	0.65±0.03	35.9±0.4	170±70
ALHA77214 (L3)	12.3	0.030±0.002	0.50±0.03	38.0±0.5	120±80
META78028 (L6)	0.97	1.37 ±0.07	0.95±0.05	32.7±0.5	<100
RKPA79001 (L6)	7.6	0.085±0.005	0.46±0.03	38.7±0.5	—
EETA79003 (L6)	1.33	0.231±0.021	0.35±0.03	41.0±0.8	—

* NBS Oxalic Acid Standard No. SRM 4990: 7.65×10^{-3} ^{14}C min^{-1} cm^{-3} CO_2. Measurements errors are 1 standard deviation.
** These errors are lower limits based on the experimental errors in the ^{14}C determinations; they do not reflect possible systematic errors in the interpretation of the ^{14}C content.
‡ NISHIIZUMI *et al.* (1979, 1981, 1982a, b).

est is Y-75102, $(4.3 \pm 1.0) \times 10^3$ yr; Y-7304 is the next youngest $(7.2 \pm 0.6) \times 10^3$ yr; and Y-74013 and Y-74459 are $(19 \pm 2) \times 10^3$ and $(24 \pm 2) \times 10^3$ yr, respectively. Only one of the Victoria Land meteorites, ALHA77256, is $(11 \pm 1) \times 10^3$ yr old; ten have ages between 29×10^3 and 41×10^3 yr; the other seven have ^{14}C activities below our detection limit. In eleven of the meteorites for which we measured ^{14}C ages, NISHIIZUMI *et al.* (1979, 1981, 1982a, b) measured ^{36}Cl ages, which are also listed in Tables 1 and 2. The ^{14}C and ^{36}Cl ages for nine of the eleven meteorites are consistent, being essentially within the error range; however, ALHA77282 and ALHA77004 have younger ^{14}C than ^{36}Cl ages. If the ^{14}C and ^{36}Cl measurements are correct, then two of the eleven meteorites had undersaturated ^{36}Cl activities at fall, requiring multiple collisions of an unusual type in space with the most recent collision less than $1/2 \times 10^6$ yr ago.

The conclusion from the ^{14}C results is that the Yamato meteorites are younger than the Victoria Land meteorites. The Yamato site is collecting recent falls at a more rapid rate than the other site. Since the meteorite fall rate is independent of geographic location, a larger collection area must have fed meteorites into the Yamato site than into the other site during the past 25×10^3 yr. The high percentage of Allan Hills meteorites with ^{14}C ages between 29×10^3 and 41×10^3 yr indicates that meteorites were collected more rapidly during this time than in more recent or more ancient times.

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