AGES OF ANTARCTIC METEORITES, K. Nishiizumi and J. R. Arnold, Dept. of Chem., B-017, Univ. of Calif., San Diego, La Jolla, Calif. 92093.

The discovery of large numbers of meteorites on the surface of Antarctic "blue ice" areas has been a major event in meteoritics (1). Their study promises to increase our knowledge of the history of meteoritic infall and of the history of the ice sheet, over periods up to millions of years. This paper deals with chronology on this time scale.

The tools available for chronological studies include radioactive and stable nuclides produced by cosmic rays, nuclear tracks, and thermoluminescence. For various reasons much more data exist for cosmogenic nuclides. The reader is referred elsewhere for discussion of the last two methods and their results (2).

Two time intervals are of special interest. The exposure age is the length of time a meteorite spent in space as a small enough object to be penetrated by cosmic rays. The terrestrial age is the period between the end of bombardment (fall on the earth) and the present. In principle the exposure age can be determined from one stable rare gas nuclide (^{21}Ne or ^{38}Ar, for example), and a known production rate for small meteorites. However, the use of a suitable radioactive-stable nuclide pair (^{81}Kr-Kr, ^{36}Cl-^{36}Ar, etc.) is preferable. To define both time intervals, one needs at least two radioactive nuclides of substantially different half-life, and one stable rare gas nuclide.

Table 1 is a compilation of published and unpublished data available to us, for those Antarctic meteorites for which measurements of more than one nuclide are available. These include objects from the Yamato and Allan Hills sites. The most abundant data are for ^{53}Mn ($t_{1/2}$ = 3.7x10^6 yrs), determined by neutron activation (3, 4, 5, 6), ^{26}Al ($t_{1/2}$ = 7.2x10^5 yrs), determined by non-destructive γ-ray counting (4, 7, 8), and stable ^{21}Ne determined by mass spectrometry (9, 10, 11, 12, 13). The nuclide ^{36}Cl (3.0x10^5 yrs) was measured by the new method of high energy ion counting using a Van de Graaff accelerator (6, 14); ^{10}Be (1.6x10^6 yrs) has so far been measured by beta counting (4). Fireman determined limits on ^{14}C (5700 years) by beta counting (15); no activity has been observed. The few ^{40}K measurements reported were done by mass spectrometry (16).

One problem which is obvious in examining Antarctic meteorites is weathering. Many or most of these objects show visible stains or deposits of Fe(III) oxides and hydroxides, showing oxidation in the presence of air and H_2O.

To check on weathering effects ^{53}Mn was measured in a separated metal phase and in a heavily weathered silicate phase of Yamato-7301 and ALHA-76008 (5). The results in disintegrations/minute per kilogram iron target (dpm/kg Fe) were the same. As is customary ^{36}Cl was determined in a separated metal fraction. We do not believe any of the radionuclide data reported here are affected by weathering; this may be a little less certain for rare gas data (10), but again a purified metal phase should give reliable results.

It is possible by high energy ion counting to measure the radionuclides also in the ice surrounding or adjacent to a meteorite. Five such measurements of ^{36}Cl have been made (14, 17). This ^{36}Cl was presumably produced in the earth's atmosphere by bombardment of Ar. Unfortunately, the meteorite samples associated with these have not yet been made available.

Ages of Antarctic Meteorites.

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The exposure age and the terrestrial age can be estimated, though rare gas data was not available, using the radionuclides ^{36}Cl, ^{26}Al and ^{53}Mn in the same meteorite. The three Yamato diogenites seem to be a single fall (1). Several Antarctic meteorites have terrestrial ages in the range $0.3\text{-}2\times10^5$ yrs, based on ^{14}C and ^{36}Cl. ALHA-77002 and -77272 seem to have longer terrestrial ages, about $6\text{-}7\times10^5$ yrs, and ALHA-77257 and -77278 seem to be in the range $\sim4\times10^5$ yrs. The long terrestrial age for ALHA-77002 is also supported by its unusually low metallic content (only 1% of the meteorite), presumably due to weathering. Outside Antarctica only iron meteorites have shown such long terrestrial ages. Presumably weathering processes on land are effective in removing old stone meteorites.

Two Antarctic meteorites, Yamato-7301 and ALHA-76008, have experienced two-stage irradiations in space (3, 4, 14). Both have large discrepancies between low radioactivity levels and long rare gas expsoure ages. Almost all the cosmogenic stable nuclides were apparently produced during the first stage, when the meteorite was irradiated in a heavily shielded position in the parent body. After breakup, forming a small object, the second-stage irradiation was initiated. Its duration was too short to saturate the radionuclide concentration.

The conclusions to date can be summarized as follows: (1) The terrestrial ages of Antarctic meteorites studied so far are in the range $10^5\text{-}10^6$ years. (2) The ages vary, even at the same site. (3) Weathering and terrestrial age are only roughly correlated. It may be that weathering is mainly dependent on surface exposure time, and on meteorite structure. (4) The distribution of exposure ages is comparable to that of recent falls. However, the presence in a small sample of two objects showing clear evidence for two-stage irradiation is unexpected.

There are many possibilities for further study. The correlation of cosmogenic nuclides in meteorites with those in associated ice is perhaps the most interesting. The measurement, by high-energy ion counting, of nuclides of half-life $\sim10^5$ years (^{59}Ni, ^{60}Fe, ^{41}Ca), is another promising area.

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TABLE 1.

	Class	recovered mass (kg)	dpm/kg meteorite* ^{53}Mn $t_{1/2}$=3.7x10^{6}y	^{10}Be 1.6x10^{6}y	^{26}Al 7.2x10^{5}y	^{36}Cl 3.0x10^{5}y	exposure age(10^{6}y) ^{21}Ne	^{40}K 1.28x10^{9}y	References
Yamato-692	D	0.14	429±17				31		5,9
-7301	H4	0.65	101±6	9±1	29±2	17.8±1.9	13	11±1	3,4,11,14,16
-7304	L5	0.50	412±21	19±2	62±3	24.2±2.5	18	21±3	3,4,11,14,16
-7305	L5	0.90	352±18	15±5	48±3		22		3,4,8,11
-74013	D	2.06	401±37				32		4,12
-74097	D	2.19	421±38				35		4,12
-74155	H4	3.07	255±15	9±3	35±3				4,8
-74190	L5-6	3.24	436±16				25		5,13
-74191	L3	1.09	449±23		71±4		6.4		4,8,12
-74640	H6-5	1.07	494±17				11		5,13
ALHA-76001	L6	20.15	443±33				28,33		4,10,12
-76002	Iron	1.51	556±21					340	5,16
-76003	L6	10.50	431±25				34		4,10
-76004	LL3	0.31			58±2		17		7,10
-76005	Eu	1.44	390±36		89±2		8		4,7,10
-76006	H6	1.14	453±33		51±1		19		4,7,10
-76007	L6	0.41	332±26		45±1		21		4,7,10
-76008	H6	1.15	22±3		11.2±0.4	9.4±1.0	1.4,1.6		4,7,10,12,14
-76009	L6	407.0	477±34				13	19±3	4,10,16
-77001	L6	0.25	419			20			6
-77002	L5	0.24	244		30±3	4.6±1.1			6,7,14
-77003	L3	0.78	315		45±5	18			6,7
-77214	LLorL	2.10	150		56±6	17			6,7
-77257	U	2.00	168			11			6
-77272	L6	0.67	212		35±4	6.5			6,7
-77278	L3	0.31	262			11			6
-77299	H3	0.26	315		43±4	19			6,7
Mt. Baldr #1	H	4.11	394±34				4.9,4.5		4,10,12
#2	H	13.78	355±26				4.5		4,10

* ^{53}Mn: dpm/kg (Fe+1/3 Ni), ^{36}Cl: dpm/kg (Fe+Ni+6Ca)