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TERRESTRIAL AGES AND EXPOSURE AGES OF ANTARCTIC H-CHONDRITES FROM FRONTIER MOUNTAIN, NORTH VICTORIA LAND

Kees C. WELTEN[1], Kunihiko NISHIIZUMI[1], Marc W. CAFFEE[2],
Joerg SCHÄFER[3] and Rainer WIELER[3]

[1] *Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450, U.S.A.*
[2] *Geosciences and Environmental Technologies and Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, Livermore, CA 94551, U.S.A.*
[3] *ETH Zürich, Isotope Geochemistry, NO C61, CH-8092, Zürich, Switzerland*

***Abstract*:** We measured the isotopic compositions and concentrations of He, Ne and Ar as well as the concentrations of cosmogenic ^{10}Be, ^{26}Al and ^{36}Cl in 26 H-chondrites and 1 L-chondrite from a meteorite stranding area near the Frontier Mountain Range, East Antarctica. Based on the radionuclide concentrations and the noble gas signatures we conclude the 26 H-chondrite samples represent at least 13 different falls. The exposure ages of most H-chondrites are in the range of 4–10 million years (My). This age range encompasses the well-established exposure age peak at ~7 My and an additional feature at ~4 My. We determined the terrestrial ages on the basis of the ^{36}Cl concentration as well as using the relation between the ^{36}Cl/^{10}Be ratio and the ^{10}Be concentration. This relation also corrects for shielding effects and reduces the uncertainty in the age by ~25% compared to simple ^{36}Cl terrestrial ages. About 40% of the meteorites are older than 100 thousand years (ky), but none are older than 200 ky. The relatively short terrestrial ages suggest that Frontier Mountain is a young meteorite stranding area. This seems to be supported by the bedrock exposure history, which shows a recent surface exposure ≤70 ky.

1. Introduction

In the past three decades about 20,000 meteorites have been found in less than 40 different locations on the Antarctic ice sheet. With a total of 385 meteorites recovered during one GANOVEX and three EUROMET expeditions, the Frontier Mountain (FRO) location in North Victoria Land has become a significant source of meteorites. For other major stranding areas, such as the Yamato Mountains, Allan Hills, Elephant Moraine and Lewis Cliff Icefields, extensive studies have been published on the terrestrial ages of these meteorites (NISHIIZUMI *et al.*, 1989a; NISHIIZUMI, 1995; WELTEN *et al.*, 1998). Each stranding area shows a different terrestrial age distribution, thus providing insight into the local accumulation mechanisms. For example, meteorites found on Yamato Mountains Icefields have ages up to 0.2 My, whereas Lewis Cliff and Allan Hills specimens have ages up to 0.5 and 1.0 My, respectively. Recently, two meteorites with exceptional ages of about 2 My were reported from Allan Hills (SCHERER *et al.*, 1997) and Lewis Cliff (WELTEN *et al.*, 1997), indicating that the process of meteorite accumulation into present-day stranding areas started at least 2 million years ago.

In order to understand exposure and terrestrial histories of FRO meteorites, we measured the cosmogenic radionuclides ^{10}Be (half-life$=1.5\times10^6$ y), ^{26}Al (7.05×10^5 y) and ^{36}Cl (3.01×10^5 y) and noble gases He, Ne, and Ar in 26 H-chondrites and one L chondrite. Noble gases were measured in bulk samples, whereas radionuclides were measured in metal fractions separated from chips adjacent to those used for noble gas analysis. Preliminary results were previously published (WIELER *et al.,* 1995, 1998). Prior to this work, only a few terrestrial ages of FRO meteorites have been determined. Based on the concentration of cosmogenic ^{26}Al in conjunction with ^{22}Ne/^{21}Ne ratios, ages of 0.3–0.7 My were reported for three out of five FRO meteorites (DELISLE *et al.,* 1989). However, NISHIIZUMI *et al.* (1989a) reported a ^{36}Cl terrestrial age of 0.12 ± 0.10 My for FRO 8403, almost a factor of six lower than the ^{26}Al age given by DELISLE *et al.* (1989). In this study we focus on the use of ^{36}Cl for terrestrial age determinations. The half-life of ^{36}Cl is well suited for the determination of terrestrial ages between 0.1–1.0 My and its production rate in the metal phase is well known and relatively insensitive to shielding (NISHIIZUMI *et al.,* 1989a; NISHIIZUMI, 1995). However, the assumption of an average saturation value of 22.1 ± 2.8 dpm/kg (2σ) introduces an uncertainty of 55 ky in the terrestrial ages. To reduce this uncertainty, we will obtain shielding-corrected terrestrial ages utilizing the empirical relation between the ^{36}Cl/^{10}Be ratio and the ^{10}Be concentration in the metal phase (NISHIIZUMI *et al.,* 1997).

A general problem in the statistical interpretation of Antarctic meteorites is the possible bias due to unrecognized meteorite showers and the breakup of meteorites on the ice. The FRO meteorite population is unusual in that H-chondrites are three times more abundant than L-chondrites, whereas the H/L-chondrite ratio among non-Antarctic meteorite falls is approximately one (DELISLE *et al.,* 1993). In fact, extensive pairing was suggested for many of the H3 and H4 chondrites recovered during the 1984 field season on the basis of their similar, brecciated texture (DELISLE *et al.,* 1989). However, the recognition of paired fragments is more difficult for equilibrated ordinary chondrites, which show only minor differences in chemical and mineralogical composition. We will use the cosmogenic, radiogenic and trapped noble gas components as well as the cosmogenic radionuclide concentrations to identify paired fragments.

2. Experimental

Meteorite samples: The Frontier Mountain meteorite trap is described by DELISLE *et al.* (1989, 1993), CASSIDY *et al.* (1992) and FOLCO (1997). Briefly, perennial fall winds on the leeward side of Frontier Mountain (72° 59′S, 160° 20′E) formed a ~ 40 km^2 blue-ice field. The ablation of ice is 3–9 cm per year (FOLCO, 1997). This loss of ice is compensated by ice flowing around the Mountain, thereby concentrating meteorites in the area. Meteorites are mainly found in two places, on the northern end of the blue ice and on a moraine in one of several valleys embayed in the Frontier Mountain rock barrier. The first site contains mostly small meteorites, typically <32 g, that were windblown over the blue ice until they were stopped by snow and crevasses. In addition, a few relatively large specimens were found on different locations on the blue ice. The largest of these is FRO 8401 (942 g), the only L-chondrite measured in this work. All other specimens are H5 or H6 chondrites, mainly from the 1990/91 season. FRO 8401 and 8403 were selected for this study in order to check long terrestrial ages reported by DELISLE *et al.* (1989).

Noble gas analyses: Samples consisted of one or several chips (100–150 mg) of bulk meteorite free of fusion crust, wrapped in aluminium foil. Prior to analysis, they had been preheated for about a day at ~130°C to desorb loosely bound atmospheric noble gases. Helium, neon and argon were determined as described by WIELER *et al.* (1989) and GRAF *et al.* (1990a). Gas concentrations are accurate to ~5%, Ne isotopic ratios and ^{36}Ar/^{38}Ar to ~1%.

Radionuclides: Bulk samples of 1–2 g were crushed in an agate mortar and separated into a magnetic and a non-magnetic fraction. The magnetic fraction was cleaned several times in an ultrasonic bath with 0.2 N HCl and once with concentrated HF to dissolve attached troilite and silicates. Carrier solutions (containing ~2 mg of Be and Al and ~5 mg of Cl and Ca) were added to the purified metal samples (50–100 mg). The samples were dissolved in 20 m*l* 1.5 N HNO_3 at ~80°C. After taking an aliquot for chemical analysis by atomic absorption spectroscopy (AAS), Cl was isolated as AgCl. Be and Al were separated by anion exchange chromatography, acetylacetone solvent extraction, and cation exchange chromatography. The Be, Al, and Cl fractions were further purified and converted to BeO, Al_2O_3, and AgCl, respectively, for AMS measurements.

The ^{10}Be, ^{26}Al, and ^{36}Cl concentrations were determined using the Lawrence Livermore National Laboratory tandem accelerator (DAVIS *et al.*, 1990). The measured ^{10}Be/^{9}Be ratios ranged from 5×10^{-13} to 5×10^{-12}, the measured ^{26}Al/^{27}Al ratios from 6×10^{-13} to 5×10^{-12}, and the measured ^{36}Cl/Cl ratios from 8×10^{-13} to 6×10^{-12}. After making corrections for isobaric interferences (^{10}B for ^{10}Be and ^{36}S for ^{36}Cl), and for chemical blanks (3×10^{-14} for ^{10}Be/Be, ~2×10^{-15} for ^{26}Al/Al, and ~3×10^{-15} for ^{36}Cl/Cl), the measured ratios were normalized to ICN ^{10}Be, NBS ^{26}Al and ^{36}Cl standards prepared by one of the authors (NISHIIZUMI *et al.*, 1989b; SHARMA *et al.*, 1990). The ^{10}Be, ^{26}Al, and ^{36}Cl concentrations are shown in Table 1. The uncertainties include all known AMS errors (1σ) but not the uncertainties of the AMS standards.

3. Results and Discussion

3.1. *Identification of paired specimens*

We used the cosmogenic radionuclide concentrations and the cosmogenic, radiogenic and trapped noble gas components to identify paired specimens. The petrographic type was not used as a pairing criterion, since the differences between ordinary chondrites of type 5 and 6 are minor and the classification is somewhat subjective. Also the location of find was not used as a pairing criterion, because the wind is known to move meteorites up to ~170 g (FOLCO, 1997). The proposed groups of paired meteorites, a–e, are shown in Table 1.

For eight H-chondrite samples, pairing with any of the other samples can be excluded. Although it remains difficult to identify paired samples with absolute certainty, the confidence level increases with the number of parameters they have in common and the uniqueness of their values. For example, the four samples of pairing

Table 1. *Noble gas and radionuclides concentrations of Frontier Mountain meteorites.*

FRO	Type/ Loc.	Rec. mass	Pair- ings	^{3}He	^{4}He	^{20}Ne	^{21}Ne	^{22}Ne	^{36}Ar	^{38}Ar	^{40}Ar	^{21}Ne$_c$	$\frac{^{22}Ne_c}{^{21}Ne_c}$	^{10}Be	^{26}Al	^{36}Cl
8401	L6 I	942.3		16.0	170	5.91	5.86	6.97	1.04	0.94	560	5.86	1.18	6.04±0.15	4.20±0.13	23.1±0.40
8403	H6 M	19.4	d	6.50	1050	1.47	1.58	1.73	0.84	0.34	5360	1.58	1.09	3.72±0.11	-	17.1±1.49
90001	H6 I	76.1	a	3.26	386	1.63	1.75	1.84	0.52	0.25	3070	1.75	1.06	3.54±0.08	3.06±0.09	21.4±0.24
90002	H5-6 I	22.1	b	8.78	10900	36.7	1.38	4.45	2.46	0.60	4650	1.29	-	4.11±0.13	3.22±0.19	19.9±0.23
90012	H5 M	6.9		18.2	47200	95.8	2.37	10.53	4.65	1.16	4600	2.12	-	3.57±0.09	2.37±0.07	15.8±0.16
90024	H5 M	16.5		4.13	1930	2.17	1.92	2.14	0.56	0.37	51	1.92	1.09	4.23±0.10	3.14±0.19	14.1±0.26
90025	H6 I	11.8	e?	4.79	199	0.90	0.66	0.88	0.36	0.16	1270	0.66	1.28	5.14±0.13	3.55±0.11	18.3±0.28
90037	H5 I	13.1		9.11	1200	1.17	1.05	1.41	0.65	0.32	4810	1.05	1.32	6.09±0.37	3.80±0.12	19.4±0.19
90043	H6 I	38.4	b	14.1	27800	125.6	1.85	11.80	7.27	1.52	4920	1.54	-	3.66±0.08	2.97±0.09	18.9±0.21
90048	H6 I	20.3		45.8	1780	6.37	6.08	7.62	0.98	1.02	5410	6.06	1.24	5.86±0.12	3.83±0.11	20.8±0.72
90050	H5 I	15.8	a	3.96	458	1.52	1.52	1.65	0.91	0.25	3950	1.52	1.075	3.51±0.12	2.99±0.11	20.3±0.22
90059	H5 I	30.4		5.72	1090	1.09	1.14	1.28	0.74	0.26	4620	1.14	1.12	4.15±0.09	3.16±0.16	19.6±0.24
90069	H6 I	17.7	c	9.70	1430	1.79	1.90	2.13	0.60	0.33	5310	1.90	1.12	5.11±0.11	3.80±0.14	23.7±0.34
90072	H5 I	108.1		12.6	1605	1.84	1.84	2.22	0.84	0.39	4970	1.84	1.20	5.66±0.13	4.07±0.15	22.9±0.32
90073	H6 I	20.6	a	3.03	338	1.51	1.64	1.72	0.43	0.22	2790	1.64	1.05	3.09±0.07	2.70±0.10	20.6±0.29
90082	H5 M	60.5		13.7	1390	1.96	1.89	2.33	0.61	0.34	4820	1.89	1.22	5.77±0.12	3.52±0.16	17.3±0.28
90087	H5 M	8.3	d	7.22	1290	1.75	1.93	2.06	0.67	0.32	5110	1.93	1.07	3.19±0.08	2.25±0.10	14.2±0.15
90104	H6 I	10.9		5.35	152	3.26	3.42	3.71	1.28	0.53	926	3.42	1.08	4.29±0.16	3.68±0.11	23.2±0.20
90107	H5 M	10.3	d	7.02	1310	1.68	1.70	1.88	2.78	0.72	5860	1.70	1.10	3.78±0.15	2.73±0.16	14.9±0.23
90150	H6 I	16.7	c	9.27	1430	1.63	1.55	1.83	1.52	0.50	5830	1.55	1.16	5.41±0.27	4.08±0.16	23.0±0.27
90151	H5 I	33.6	e?	4.16	283	1.54	0.58	0.83	0.43	0.19	4120	0.58	(1.27)	4.97±0.15	3.74±0.11	18.1±0.39
90152	H5 I	18.3	a	3.54	352	1.67	1.78	1.89	0.39	0.24	2240	1.78	1.06	3.50±0.07	2.99±0.20	20.7±0.37
90174	H5 M	12.7	d	6.51	1320	3.99	1.81	2.18	0.93	0.35	4720	1.80	(1.07)	3.50±0.07	2.61±0.09	14.9±0.24
90203	H6 I	11.3	d	6.73	1270	1.94	1.96	2.11	0.70	0.31	5100	1.96	1.07	2.61±0.07	1.87±0.07	12.5±0.20
90204	H6 M	12.6	d	6.72	1440	1.74	1.81	1.95	0.64	0.28	5670	1.81	1.07	2.93±0.06	2.27±0.12	13.9±0.23
90207	H5 M	4.0	d?	8.48	1390	2.44	2.61	2.79	0.91	0.41	5400	2.61	1.07	2.60±0.06	1.88±0.06	12.2±0.13
90211	H5 I	11.9	d	6.62	1320	1.72	1.90	2.03	1.33	0.39	5240	1.90	1.07	2.83±0.06	2.00±0.09	13.0±0.15

Location of find: I = Blue Ice, M = Moraine; Recovered mass in [g]; Noble gas concentrations in [10^{-8} cm^{3}STP/g], radionuclide activities in [dpm/kg metal]. Corrections for ^{10}Be and ^{26}Al due to silicate contamination (0.02-0.22 wt%) were made on the basis of the Mg concentration measured by AAS. Uncertainties of noble gas concentrations ~5%, uncertainties of the ^{22}Ne/^{21}Ne ratio of the cosmogenic component ~1% (~2% for values in parentheses). Cosmogenic Ne calculated by subtracting trapped Ne of solar composition for 90002, 90012 and 90043, and of atmospheric composition otherwise. Noble gas concentrations of FRO 8403 from Delisle *et al.* (1989). Uncertainties in radionuclide concentrations are 1σ. Pairing assignments are based on noble gas and radionuclide concentrations.

group (a) are strongly suspected to be fragments of a common fall, because of their unusually high ^{36}Cl/^{10}Be ratios, low concentrations of radiogenic ^{4}He and low ^{3}He/^{21}Ne and ^{22}Ne/^{21}Ne ratios. Another pairing group (d) consists of at least six fragments with low ^{10}Be, ^{26}Al and ^{36}Cl concentrations and low ^{22}Ne/^{21}Ne ratios. FRO 8403 and FRO 90207 may also belong to pairing group (d); this is quite likely for FRO 8403, although it has a somewhat higher ^{36}Cl concentration, but is more uncertain for FRO 90207, because it has significantly higher ^{3}He and ^{21}Ne concentrations than the other samples. Assuming that our 26 samples are representative for the whole FRO collection, we conclude that up to 40–45% of all H5/6 chondrite specimens at Frontier Mountain belong to two large showers.

Two other probable pairings are the solar-gas rich meteorites FRO 90002/90043 (group b) and FRO 90069/90150 (group c). Although FRO 90025 and 90151 (group e) might be paired on the basis of their small ^{3}He deficiencies and similarly low ^{4}He contents, we do not consider them as a pair, because they show a factor of 3.2 difference in radiogenic ^{40}Ar (Table 1).

In short, besides the eight unpaired specimens, the remaining eighteen samples represent between five and eight different falls (Table 1), reducing the 26 H-chondrite specimens to a total of 13–16 distinct falls. In this paper, we will assume a total of 15 distinct H-chondrite falls. This suggests that the true number of H-chondrite falls at Frontier Mountain is probably considerably higher than estimated by FOLCO and BLAND (1994) and that paring studies based on petrographic criteria alone generally tend to underestimate the number of distinct meteorite falls.

3.2. *Neon-21 exposure ages*

The cosmic-ray exposure ages are determined from the measured concentrations of ^{21}Ne and calculated production rates (P_{21}) according to EUGSTER (1988) and GRAF *et al.* (1990b), in both cases using the ^{22}Ne/^{21}Ne ratio as a shielding indicator. For samples with a ^{22}Ne/^{21}Ne ratio$\geq$1.08, the ^{21}Ne exposure ages derived with the two methods agree well (WIELER *et al.,* 1995) and are estimated to be accurate to within 20%. However, for more heavily shielded samples, the ages derived with the model of GRAF *et al.* (1990b) are systematically higher than those derived with production rates proposed by EUGSTER (1988). The difference in the two methods is that EUGSTER assumes that P_{21} always increases with increasing shielding, whereas the GRAF *et al.* model takes into account that in very large meteorites P_{21} eventually decreases with increasing size or depth. Although it is known that the correlation used by EUGSTER overestimates the production rates for ^{22}Ne/^{21}Ne ratios less than 1.08, it is not clear how well the GRAF *et al.* model extrapolates toward heavy shielding. For samples with a ^{22}Ne/^{21}Ne ratio higher than 1.08 we use the production rates of EUGSTER (1988), for more heavily shielded samples we use the maximum production rates given by GRAF *et al.* (1990b), corresponding to meteoroid radii of 40–60 cm, *i.e.* the largest bodies commonly expected. Since it is possible that the GRAF *et al.* (1990b) model underestimates production rates at very high shielding, we adopt for the samples of pairing group (a), the exposure age of FRO 90050, the sample with the highest (^{22}Ne/^{21}Ne)$_{cos}$ ratio of this group.

Figure 1 shows the exposure age distribution of the Frontier Mountain H

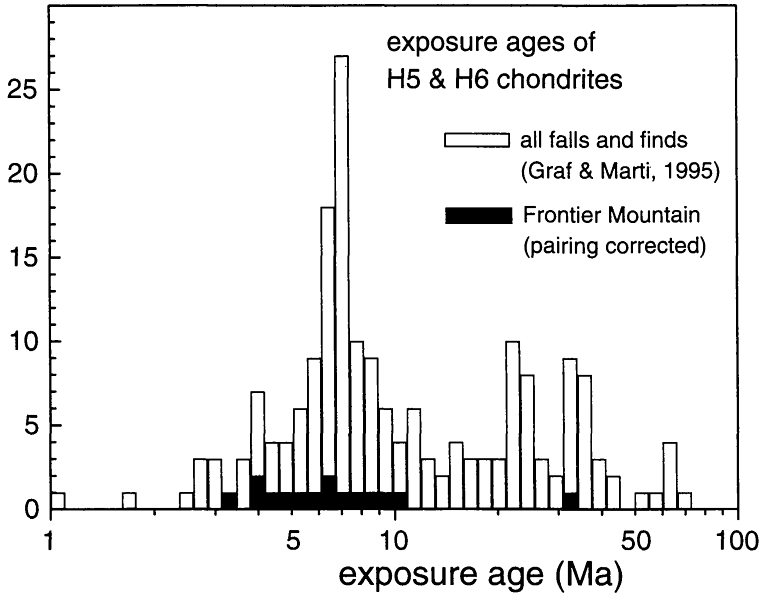

Fig. 1. Exposure ages of Frontier Mountain H5/6 chondrites compared with those of non-Antarctic falls and finds (Graf and Marti, 1995). The exposure age distribution of FRO samples has been corrected for pairing.

chondrites studied here, corrected for the pairings shown in Table 1. Except for group (a) –see previous paragraph– the average exposure age is adopted for paired specimens. The figure also shows the cumulative distribution of H5 and H6 chondrite finds and falls compiled by Graf and Marti (1995). Most Frontier Mountain meteorites have exposure ages between 4 and 10 My. This age range encompasses the well-known peak at 7 My, which contains about 45% of all H chondrites and also the exposure age peak for H5 chondrites around 3–4 My, reported by Graf and Marti (1991).

It is rather puzzling that only one out of 15 individual FRO H-chondrites has an exposure age above 10 My, whereas ~40% of all H5/6 chondrites belong to the > 10 My group. Notably, the exposure age of 31 My of FRO 90048 coincides with the second major peak at ~33 My (Graf and Marti, 1995). The probability that only one out of fifteen meteorites randomly selected from a population in which 40% of its members are older than 10 My, actually belongs to this old age group, is only ~0.5%. For one out of thirteen meteorites, *i.e.* the minimum number of individual falls deduced above, this probability would still only be ~1.1%. Similar age distributions having deficits of long exposure ages are not observed for other Antarctic H-chondrite populations, such as those from Allan Hills (Schultz *et al.*, 1991) or Yamato (Loeken and Schultz, 1998). This suggests that the lack of long exposure ages in our Frontier Mountain samples, even though statistically unlikely, is probably only a matter of poor statistics, especially since we have studied only 13–16 distinct meteorites.

3.3. *Terrestrial ages*

In the past two decades, terrestrial ages of a few hundred Antarctic meteorites were determined, mostly on the basis of the ^{36}Cl or ^{14}C concentration. Chlorine-36 has a

Table 2. Exposure ages, terrestrial ages and saturation activities of ^{36}Cl and ^{10}Be for Frontier Mountain meteorites.

Sample	$(^{22}Ne/^{21}Ne)_c$	T_{exp}	$T(^{36}Cl)$	T(36/10)	$A_0(^{36}Cl)$	$A_0(^{10}Be)$
FRO	ratio	My	ky	ky	dpm/kg	dpm/kg
8401 (L6)	1.18	24.9	-19±57	19±37	24.1	6.1
group-a						
90001	1.06	6.1	14±56	-46±47	19.3	4.0
90050	1.075	4.5	37±56	-22±49	19.3	4.0
90073	1.05	8.6	30±56	-78±47	17.2	3.4
90152	1.06	6.4	29±57	-33±48	19.2	3.9
Average (a)	1.06	4.5	28±55	-45±55	18.7	3.8
group-b						
90002	-	(4.2)	45±56	35±48	21.6	4.7
90043	-	(5.0)	68±56	26±46	20.1	4.2
Average (b)	-	(4.6)	57±55	30±55	20.8	4.5
group-c						
90069	1.12	6.3	-30±56	-12±40	23.0	5.4
90150	1.16	6.2	-18±56	13±46	23.7	5.8
Average (c)	1.14	6.3	-24±55	0±55	23.4	5.6
group-d						
8403	1.09	4.7	111±94	65±64	19.9	4.2
90087	1.07	5.9	193±56	106±43	18.1	3.6
90107	1.10	5.3	171±57	141±46	20.6	4.4
90174	1.07	5.6	172±57	116±43	19.4	4.0
90203	1.07	6.0	246±57	89±43	15.4	3.0
90204	1.07	5.5	201±57	83±43	16.8	3.3
90211	1.07	5.8	230±56	104±42	16.5	3.2
Average (d)	1.08	5.5	189±44	101±25	18.1	3.7
90012	-	(6.9)	145±56	78±39	19.0	3.9
90024	1.09	5.7	194±57	195±42	22.2	5.0
90025	1.28	3.8	82±57	127±53	24.5	6.6
90037	1.32	6.6	57±56	103±49	24.6	6.7
90048	1.24	31.1	27±63	64±39	24.0	6.0
90059	1.12	3.9	52±56	60±51	22.5	5.1
90072	1.20	8.2	-15±56	17±37	23.8	5.8
90082	1.22	9.1	106±57	147±36	24.3	6.3
90104	1.08	10.0	-21±56	-63±39	20.1	4.2
90151	1.27	3.2	86±58	133±58	24.6	6.8
90207	1.07	7.9	257±55	77±37	14.6	2.8

Neon-21 exposure ages calculated with shielding correction according to Eugster (1988), except for samples with $(^{22}Ne/^{21}Ne)_c < 1.08$. Here the maximum ^{21}Ne production rate for heavily shielded samples according to Graf et al. (1990b) was assumed. Exposure ages in parentheses assume $(^{22}Ne/^{21}Ne)_c = 1.11$. Exposure age of FRO 8403 from Delisle *et al.* (1989). Terrestrial ages $T(^{36}Cl)$ and T(36/10) calculated as explained in text. Errors include 2σ-uncertainties of radionuclide analyses and production rates as well as 20% uncertainty of the exposure age. Saturation activities (A_0) of ^{10}Be and ^{36}Cl were calculated on the basis of the measured ^{10}Be and ^{36}Cl activities (Table 1), corrected for the ^{21}Ne exposure ages and $^{36}Cl/^{10}Be$ terrestrial ages.

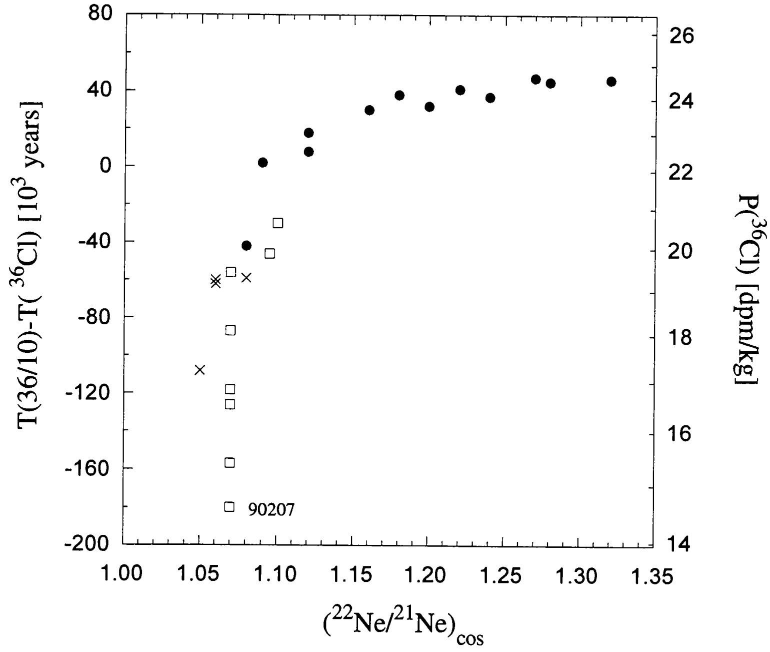

Fig. 2. Difference between simple ^{36}Cl terrestrial age and shielding-corrected ^{36}Cl/^{10}Be age as a function of the cosmogenic ^{22}Ne/^{21}Ne ratio, which serves as a measure of shielding conditions. The difference in age for each sample corresponds to different ^{36}Cl saturation values (right-hand axis), as derived from the measured ^{36}Cl concentration and the shielding-corrected terrestrial age. Open squares correspond to members of pairing group (d), crosses to members of pairing group (a), closed symbols to other samples. Note the logarithmic scale of the right-hand axis.

half-life well suited to determine ages between 0.1–1.0 My and its production rate in the metal phase is relatively independent of shielding effects. Terrestrial ages that are calculated on the basis of a ^{36}Cl saturation value of 22.1 ± 2.8 dpm/kg ($\pm 2\sigma$) have a systematic uncertainty of 55 ky, provided that the meteorite did not experience unusually high shielding. The ^{36}Cl terrestrial ages listed in Table 2 range up to 250–300 ky, with 60% of the meteorites being younger than 100 ky.

Recent measurements of ^{36}Cl in large (iron and stony-iron) meteorites have shown that under very high shielding the ^{36}Cl production rate is significantly lower (Nishiizumi *et al.*, 1996, 1997). This implies that for some of the meteorites with low ^{22}Ne/^{21}Ne ratios, the terrestrial age may have been overestimated. We therefore use the relation between the ^{36}Cl/^{10}Be ratio and the ^{10}Be concentration, as found by Nishiizumi *et al.* (1997), to calculate shielding-corrected terrestrial ages. In order to do so, the exposure age has to be known, so corrections can be made (if necessary) for undersaturation of ^{36}Cl and ^{10}Be at the time of fall. The estimated uncertainty of 20% in the exposure age introduces an additional error to the shielding-corrected terrestrial ages, but for meteorites with exposure ages >6 My its effect is negligible compared to other errors. For these samples typical uncertainties are 35–40 ky, mainly due to the 6% uncertainty (2σ) in the ^{36}Cl/^{10}Be production ratio, whereas meteorites with exposure ages of 3–6 My generally show uncertainties in the 40–60 ky range.

The shielding-corrected ^{36}Cl/^{10}Be ages generally agree within 50–60 ky of the simple

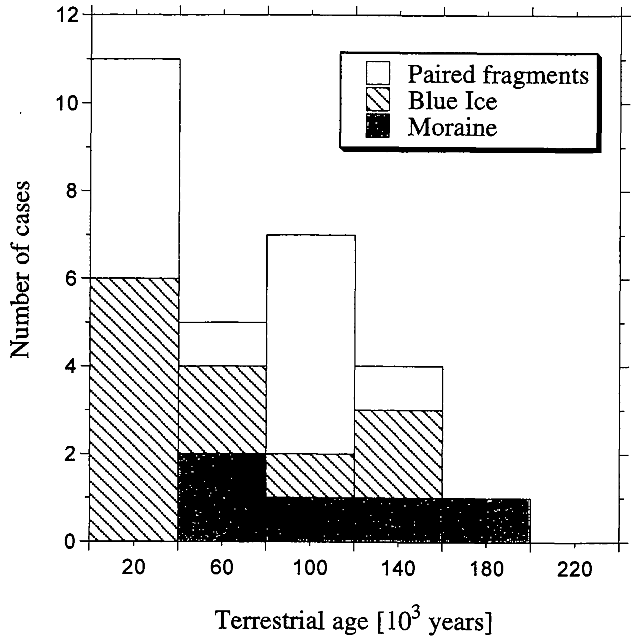

Fig. 3. Shielding corrected terrestrial ages of ordinary chondrites from Frontier Mountain. The cumulate histogram represent the age distribution uncorrected for pairing, whereas the shaded and striped bars represent the distribution after correction for pairing, for samples found in the moraine and on the blue ice, respectively. Average ages are used for paired Frontier Mountain samples. Pairing group (d) is considered to be found in the moraine, although two members were found on blue ice.

^{36}Cl ages (Table 2), except for some of the members of pairing group (d) including FRO 90207. Figure 2 shows that differences between the two ages are mainly a function of shielding conditions. For instance, for meteorites with ^{22}Ne/^{21}Ne ratios $>$1.15 the shielding-corrected ages are systematically 25–50 ky higher than the simple ^{36}Cl ages. Figure 2 shows that under these low shielding conditions the actual ^{36}Cl saturation activities in metal are 23–25 dpm/kg, *i.e.* somewhat higher than the average of 22.1 dpm/kg. On the other hand, for samples which experienced high shielding, the shielding-corrected ages are up to ~180 ky lower than the simple ^{36}Cl ages. Figure 2 shows that for FRO 90207 and members of shower (d) the actual ^{36}Cl saturation values range from 15 to 21 dpm/kg. These values are significantly lower than those in Knyahinya (21–22 dpm/kg, REEDY *et al.*, 1993), but higher than those in Chico (10–17 dpm/kg, BOGARD *et al.*, 1995), two ordinary chondrites with pre-atmospheric radii of 45 cm and 60 cm, respectively. This implies that the fragments of shower (d), including FRO 90207, are derived from an object between 45 and 60 cm in radius.

Some of the other samples which show major differences between the two ages are associated with negative ^{36}Cl/^{10}Be ages (FRO 90104 and the members of shower a). All these samples have relatively high ^{36}Cl/^{10}Be ratios that plot above the ^{10}Be-^{36}Cl/^{10}Be correlation curve of NISHIIZUMI *et al.* (1997). These high ^{36}Cl/^{10}Be ratios are the result of ^{10}Be undersaturation due to short exposure ages. By assuming zero terrestrial ages and using the ^{10}Be-^{36}Cl/^{10}Be correlation, we find exposure ages of ~3.4 My for FRO

90104 and of 2.6–3.7 My for the members of shower (a). These ages are much lower than the corresponding ^{21}Ne ages of 10 My and 4.5–8.6 My, respectively (Table 2), which suggests that these meteorites most likely experienced a two-stage exposure history. Since the ^{36}Cl concentrations are close to the average saturation level, we simply adopted the ^{36}Cl terrestrial ages of 28 ± 55 ky for group (a) and of < 35 ky for FRO 90104.

Figure 3 shows the terrestrial ages of Frontier Mountain chondrites, corrected for pairing. All meteorites investigated are younger than 200 ky, which suggests that the stranding area at Frontier Mountain is much younger than the Allan Hills or Lewis Cliff stranding areas. Delisle *et al.* (1989) reported long terrestrial ages of FRO meteorites, including FRO 8401 (380 ± 130 ky) and FRO 8403 (710 ± 130 ky) based on their ^{26}Al measurements. However, we found short terrestrial ages for these meteorites, based on ^{36}Cl and ^{10}Be measurements. The young age of the Frontier Mountain trap might be due to a recent drop in the ice level, which follows from the short surface exposure age of the local bedrock at Frontier Mountain, as discussed in the next section. On the average, meteorites found in the Moraine seem somewhat younger than those found on the blue ice, but statistics are still too poor to draw firm conclusions.

3.4. *Surface exposure age of bedrock sample*

A granitic bedrock sample was collected from Frontier Mountain (72°20′S, 161°00′E, 2300 m above sea level) for the measurement of *in situ* produced ^{10}Be and ^{26}Al and Ne in quartz. The sample was taken from a rather smooth, near flat surface located about 100-m above the present ice level, near the moraine where part of the meteorite samples for this study were collected. After clean quartz grains were chemically isolated from the granite, the concentrations of ^{10}Be and ^{26}Al in quartz were measured by AMS (Kohl and Nishiizumi, 1992). Neon isotopes in the quartz were analyzed in three temperature steps. Results are given in Table 3. Excess ^{21}Ne was released in the 400°C fraction, whereas the two high temperature steps showed a nearly atmospheric Ne composition. Since nucleogenic Ne is released from quartz at >400°C (Niedermann *et al.*, 1994), we assume that the entire ^{21}Ne excess in the low temperature step is cosmogenic even though the ratio $(^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_{\mathrm{exc}}$ of 1.03 ± 0.12 is somewhat lower than values of ~1.27 usually observed in terrestrial quartz (Schäfer *et al.*, 1998). The ^{10}Be surface exposure age of ~150 ky is much lower than the minimum surface exposure age of 3.2 My reported by Delisle *et al.* (1989) based on their ^{10}Be measurement in quartz. However, since the ^{26}Al concentration in their sample ($\leq 21 \times 10^6$ atom/g) is in agreement with ours, their high ^{10}Be concentration is most likely due to a meteoric ^{10}Be

Table 3. Cosmogenic nuclides in quartz from Frontier Mountain bedrock (2300 m a.s.l.).

Temp	^{20}Ne	^{21}Ne/^{20}Ne	^{22}Ne/^{20}Ne	^{21}Ne$_{cos}$	^{10}Be	^{26}Al	T(^{21}Ne)	T(^{10}Be)	T(^{26}Al)
400	12.62±0.45	.0625±.0039	.1562±.0069	.752±.057					
610	9.85±0.36	.0083±.0017	.1040±.0070	-					
1800	18.67±0.45	.0045±.0008	.1047±.0058	-					
Total	41.14±0.73	.0232±.0015	.1203±.0049	.752±.057	5.35±0.20	17.3±1.2	510±39	147±6	79±6

Ne concentrations in [10^8 atoms/g], radionuclide concentrations in [10^6 atoms/g], temperature in [°C], exposure ages in [ky]. Errors are 2σ. Production rates used (sea level, high latitude): P(^{10}Be)=6.03 atoms/(g SiO_2.y), P(^{26}Al)=36.8 atoms/(g SiO_2.y) (Nishiizumi *et al.*, 1989b) and P(^{21}Ne)=0.65*P(^{26}Al) (Niedermann *et al.*, 1994), altitude scaling according to Lal (1991).

contamination.

The disagreement between the three surface exposure ages in Table 3 indicates that the Frontier Mountain bedrock experienced a complex exposure history, as is also shown by the low ^{26}Al/^{10}Be ratio (3.23±0.13) and the high ^{21}Ne/^{26}Al ratio (4.35±0.36). The concentrations of the three nuclides are consistent with two scenarios: (i) a first-stage exposure of 400–500 ky, followed by a long burial time (3–4 My) and a final exposure of ~70 ky or (ii) a first-stage exposure of 5–6 My, followed by a burial time of about 1 My, removal of the top ~425 g/cm^2 and a final surface exposure of ~50 ky. No matter which scenario is closer to the real exposure history, the ^{26}Al concentration constrains the final exposure to <70 ky. At first sight, this relatively short exposure age of Frontier Mountain—compared to million years exposure for Allan Hills bedrock (NISHIIZUMI *et al.*, 1991)—seems consistent with the shorter terrestrial ages of the FRO meteorites. However, the terrestrial ages up to 200 ky require some special circumstances, *i.e.* either some of the meteorites traveled for more than 100 ky in the ice or the stranding area started to accumulate meteorites when the ice-level was more than 100 meter higher than the present level.

3.5. *The H-chondrite/L-chondrite ratio at Frontier Mountain*

Out of 377 meteorites from Frontier Mountain classified so far, 227 are H chondrites and 73 are L-chondrites (A.S. SEXTON, personal comm., FOLCO and BLAND, 1994). The ratio of H- to L-chondrite specimens at Frontier Mountain is thus 3.1, substantially higher than the values of 0.87 and 1.2 for observed falls and non-Antarctic finds, respectively (HUSS, 1991). A considerable overabundance of H- relative to L-chondrites in the Antarctic meteorite collection has already been pointed out by DENNISON *et al.* (1986), who used this observation, together with trace element data, to suggest that Antarctic meteorites are from a different population than modern falls and non-Antarctic finds. HUSS (1991) pointed out, however, that not all find locations in Antarctica show such an excess of H-chondrites and suggested that an unrecognized H5 shower over the Allan Hills Main and Near Western Ice fields caused the overabundance of H chondrites noted by DENNISON *et al.* (1986). According to HUSS (1991) the observed different H/L ratios do not favor the DENNISON *et al.* (1986) hypothesis. The question now arises whether the high H/L ratio at Frontier Mountain could also be due to one or a few large H chondrite showers. We note above that the 26 H-chondrite specimens studied here represent at least 13 distinct falls. On the other hand, Table 1 shows that up to 12 out of the 26 samples belong to only two distinct falls (a, d). Hence, it is indeed possible that a few large showers can in part explain the relatively high proportion of H chondrites. It seems improbable, however, that this is the only explanation of the overabundance of H-chondrites at Frontier Mountain (unfortunately, no noble gas or radionuclide data on a significant number of FRO L-chondrites are available yet to rule on the pairing of L-chondrites). We therefore also doubt whether stochastic effects alone can explain the high H/L ratio in Antarctica as a whole. The most likely explanation for this circumstance is a higher occurrence of fragmentation among H-chondrites found in Antarctica. This hypothesis is bolstered by the observation that at Frontier Mountain the total recovered mass of 179 H-chondrites is similar to that of 59 L-chondrites, *i.e.* 1831 *vs.* 1810 g (A. SEXTON, pers. comm.).

4. Summary

Summarizing the discussion above we can draw the following conclusions:

1) The 26 H-chondrite samples represent between 13 and 16 distinct falls. The two largest pairing groups contain a total of 10-12 specimens, accounting for almost half of the samples. This suggests that the high H- to L-chondrite ratio at Frontier Mountain can be explained in part by the presence of several large H-chondrite showers, although other factors of terrestrial or pre-terrestrial origin may play a role as well.

2) Exposure ages of Frontier Mountain H-chondrites are in the same range as those of non-Antarctic specimens. The apparent lack of ages older than 10 My for Frontier Mountain samples deserves further attention, but may simply be a result of poor statistics.

3) The shielding-corrected terrestrial ages, based on the relation between ^{36}Cl/^{10}Be and ^{10}Be, improve the accuracy for meteorites with high-shielding conditions, where the ^{36}Cl concentration in the metal phase can be much lower than the average saturation value of ~22 dpm/kg.

4) The terrestrial ages of 16 Frontier Mountain chondrites are all younger than 200,000 years, which indicates that this stranding area is much younger than others, such as Allan Hills or Lewis Cliff. The young age of the Frontier Mountain stranding area is supported by the surface exposure age of less than 70,000 years, determined for a granitic bedrock sample collected 100 meters above the present ice level.

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