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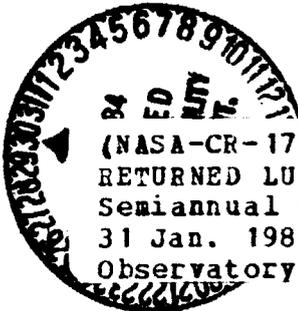
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**RADIOACTIVITIES IN RETURNED LUNAR MATERIALS  
AND IN METEORITES**

**Semiannual Progress Report No. 2  
For the period 1 August 1983 to 31 January 1984**

**Grant NAG 9-42**

**Principal Investigator  
Dr. Edward L. Fireman**



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Smithsonian Institution  
Astrophysical Observatory  
Cambridge, Massachusetts 02138

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The NASA Technical Officer for this grant is Dr. John Dietrich, Code SN2, Lyndon  
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# RADIOACTIVITIES IN RETURNED LUNAR MATERIALS AND IN METEORITES

Grant NAG 9-42

Semiannual Progress Report No. 2

For the period 1 August 1983 to 31 January 1984

We continued making  $^{14}\text{C}$  measurements in Antarctic meteorites and developing techniques for accelerator mass-spectrometer  $^{14}\text{C}$  measurements on small samples in collaboration with the University of Arizona. We also collaborated with the University of Bern, Switzerland on  $^{10}\text{Be}$  measurements on Antarctic ice samples. Attached are two abstracts<sup>1,2</sup> submitted to the XV Lunar and Planetary Science Conference, March 12-16, 1984 and an article<sup>3</sup> submitted to Earth and Planetary Science Letters during the 1 August 1983 to 31 January 1984 period.

## Attachments

- <sup>1</sup>E. L. Fireman, Carbon-14 Terrestrial Ages of Yamato and ALHA meteorites. Submitted to Lunar and Planetary Science XV (1984).
- <sup>2</sup>A. J. T. Jull, T. H. Zabel, D. H. Donahue, and E. L. Fireman, Accelerator Measurements of Carbon-14 Ages of Antarctic Meteorites. Submitted to Lunar and Planetary Science XV (1984).
- <sup>3</sup>J. Beer, M. Andréé, H. Oeschger, G. Bonani, M. Suter, W. Wölfli, and E. L. Fireman,  $^{10}\text{Be}$  Concentrations in Byrd Core and Allan Hills Ice. Submitted by Bern University to Earth and Planetary Science Letters (1983).

ATTACHMENT 1

CARBON-14 TERRESTRIAL AGES OF YAMATO AND ALHA METEORITES

Edward L. Fireman

**CARBON-14 TERRESTRIAL AGES OF YAMATO AND ALHA METEORITES**

Edward L. Fireman, Smithsonian Astrophysical Observatory, Cambridge,  
Massachusetts 02138

Carbon-14 terrestrial ages have been determined with low-level minicounters and accelerator mass spectrometry for one Yamato and eighteen Allan Hills and nearby-sited meteorites (1-6). The Yamato sample, Y7403, with an age of  $(7.0 \pm 0.7) \times 10^3$  yr was the youngest Antarctic meteorite (5, 6). Carbon-14 terrestrial ages of more Yamato meteorites are needed;  $^{14}\text{C}$  ages for additional ALHA meteorites are also desirable. We report low-level minicounter  $^{14}\text{C}$  results for three additional Yamato and five additional ALHA meteorites.

The  $^{14}\text{C}$  terrestrial age is determined from the activity per gram sample in the carbon extracted at high temperature (above melting) subsequent to a low-temperature extraction (500°C). The high-temperature extraction gives the cosmic-ray-produced  $^{14}\text{C}$  from the sample. The low-temperature extraction gives the atmospheric  $^{14}\text{C}$  and terrestrial carbon introduced by weathering (1-4). The Bruderheim meteorite, a March 4, 1960 fall, is used as the comparison reference. Table 1 gives the  $^{14}\text{C}$  activities (dpm/kg) in the high-temperature extraction and the corresponding terrestrial ages.

Table 1. Melt extraction carbon-14 counting results.

Sample (Type)	$^{14}\text{C}$ (dpm/kg)*	$^{14}\text{C}$ Terrestrial Age ( $10^3$ yr)
Bruderheim (L6)	$57 \pm 3$	Fell March 4, 1960
Yamato 75102 (L6)	$34.1 \pm 2.7$	$4.3 \pm 1.0$
Yamato 74013 (Di)	$4.8 \pm 0.7$	$19 \pm 2$
Yamato 74459 (H6)	$3.0 \pm 0.6$	$24 \pm 2$
ALHA 77208 (H4)	$\leq 0.4$	$\geq 40$
ALHA 77232 (H4)	$\leq 0.9$	$\geq 34$
ALHA 77269 (L6)	$0.4 \pm 0.2$	$\sim 40$
ALHA 80101 (L6)	$\leq 0.3$	$\geq 43$
ALHA 79025 (H5)	$\leq 0.4$	$\geq 40$

\* Errors are  $1\sigma$  errors in the counting.

The three Yamato meteorites have young  $^{14}\text{C}$  ages. Y75102, the youngest with a  $4.3 \times 10^3$  yr age, is even younger than the Yamato meteorite previously measured (5, 6). The others, Y74013 and Y74459 with  $19 \times 10^3$  and  $24 \times 10^3$  yr ages, are older but are within the measuring capacity of the minicounter method. It appears that most Yamato meteorites are amenable to minicounter  $^{14}\text{C}$  dating. On the other hand, the five ALHA meteorites have ages beyond the capability of the minicounters.

These results indicate that the Yamato site is collecting recent falls more rapidly than the ALHA site. Both sites have similar areas ( $\sim 100 \text{ km}^2$ ). Either ice from a larger region has fed meteorites into the Yamato site than into the Allan Hills site during the past  $25 \times 10^3$  yr or most of the recent falls ( $< 25 \times 10^3$  yr) have been deposited upstream from the Allan Hills site.

The carbon compounds extracted from the meteorites are converted to  $\text{CO}_2$  before counting. After the  $\text{CO}_2$  is counted, the  $\text{CO}_2$  is converted to amorphous carbon for accelerator mass spectrometry measurements.

Fireman, E.L.

We thank J.C. DeFelice for his help in all phases of this work. This research was supported in part by NASA Grant 09-015-145 and NSF Grant DPP80-2534.

References

- (1) Fireman, E.L. (1979) Proc. Lunar Sci. Conf. 10th, 1053.
- (2) Fireman, E.L., Rancitelli, L., and Kirsten, T. (1979) Science 203, 453.
- (3) Fireman, E.L. (1980) Proc. Lunar Sci. Conf. 11th, 1215.
- (4) Fireman, E.L. and Norris, T. (1981) Proc. Lunar Sci. Conf. 12th, 1019.
- (5) Fireman, E.L., Andrews, H.R., Ball, G.C., Brown, R.M., and Milton, J.C. D. (1982) Lunar and Planetary Science XIII, 219.
- (6) Fireman, E.L. (1983) Lunar and Planetary Science XIV, 195.

ATTACHMENT 2

ACCELERATOR MEASUREMENTS OF CARBON-14 AGES OF ANTARCTIC METEORITES

A.J.T. Jull, T.H. Zabel, D.J. Donahue, and E.L. Fireman

## ACCELERATOR MEASUREMENTS OF CARBON-14 AGES OF ANTARCTIC METEORITES

A. J. T. Jull, T. H. Zabel and D. J. Donahue, NSF Accelerator Facility for Radioisotope Analysis, University of Arizona, Tucson, Arizona 85721, and E. L. Fireman, Smithsonian Astrophysical Observatory, Cambridge, Mass. 02138

Radionuclide measurements using tandem accelerator mass spectrometry (TAMS) have been reported by several groups (1-4). The isotopes  $^{10}\text{Be}$ ,  $^{14}\text{C}$ ,  $^{26}\text{Al}$  and  $^{36}\text{Cl}$  have been detected in meteorites and other extraterrestrial material using this technique. The shorter lived nuclides  $^{14}\text{C}$  and  $^{36}\text{Cl}$ , with half-lives of 5,730 and 300,000 years respectively, are most suited to determination of terrestrial residence ages, as they reach saturation under cosmic-ray bombardment in space in a short period of time, relative to the longer-lived nuclides, and also cover the most useful time span for terrestrial age measurements. Characteristically, Antarctic meteorites have longer residence times on the earth's surface than other meteorites. About half the samples for which  $^{36}\text{Cl}$  ages have been determined (1) have finite ages of more than 100,000 years. For  $^{14}\text{C}$  ages determined to date, 11 have ages greater than 30,000 years, and four are greater than 25,000 years. Only 2 samples, ALHA 77256 (11,000 yrs) and Yamato 7304 (7,500 yrs) have lower values (4,5). In our method, carbon from the samples is extracted at two or more temperature steps, a low (500C), intermediate (1000C), and a melt fraction. The carbon from the melt fraction contains the spallogenic  $^{14}\text{C}$ , released only at high temperatures, normally >1000C (4). Lower temperatures release  $^{14}\text{C}$  bound in carbonates or organic material. The latter materials contain  $^{14}\text{C}$  of a presumed terrestrial origin in ordinary chondrites. At SAO,  $\text{CO}_2$  produced by combustion in an RF furnace is reduced over hot Mg contained in an Mo boat. The amorphous carbon produced is cleaned in HCl, dried, and sent to Tucson, where targets made by dissolution of carbon in molten iron are produced. Typical sample sizes are about 1 mg carbon. Procedures are similar to those described previously (4,6).  $^{14}\text{C}/^{13}\text{C}$  ratios are measured by TAMS, and compared to a known standard AD1890 wood (7). Terrestrial ages are calculated by comparison of the amount of  $^{14}\text{C}$  per gram meteorite with the  $^{14}\text{C}$  content of a recent fall, usually Bruderheim. This sample has been measured previously by TAMS (4,8) to have a  $^{14}\text{C}$  content of  $2.13 \pm 0.04 \times 10^8$   $^{14}\text{C}/\text{g}$  (or  $49 \pm 1$  dpm/(kg) meteorite. This value is slightly lower than the counter measured value  $57 \pm 3$  dpm/kg (9). Terrestrial ages for 6 samples are reported in table 1. There is a clear difference between the older Allan Hills and Mt. Baldr samples, and the three Yamato meteorites studied. Two of the Yamato samples have ages of 19 and 17 Kyr, the third, Yamato 75102 represents the youngest age recorded for an Antarctic meteorite so far. Our data indicate it is less than one thousand years old. This may represent a meteorite that actually fell in the locality where it was collected, rather than being transported by the ice sheet. The Yamato site appears, on the basis of this and earlier data (4) to have meteorites of lower terrestrial age than other localities. This may be indicative of a different time-scale for the ice concentration mechanism for meteorites at this site. "Weathering ages" for 8 meteorites are reported in table 2. These data can be interpreted as an age since incorporation of terrestrial atmospheric carbon. The weathering age of Yamato 75102, ~5000 yrs, is older than its measured terrestrial age of <1000 yrs. This suggests, that for this sample at least, terrestrial carbon has been incorporated which was already a few thousand years old, that is, the carbon did not come directly from atmospheric  $\text{CO}_2$ . Perhaps  $\text{CO}_2$  from ice is a more likely source for the weathering carbon. The 500C fraction is most likely due to breakdown of low-temperature carbonates and bicarbonates, though organic material cannot be

# Carbon-14 Ages of Antarctic Meteorites

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excluded (10). In conclusion, our data show that for the samples measured, Yamato meteorites appear to be more recent falls than other Antarctic samples meteorites. Clearly, data for many more samples are necessary to build up a systematic picture of age distributions.

References: (1) Nishiizumi, K. et al., Earth Planet. Sci. Lett. 62, 407. (2) Raisbeck, G. M., et al. (1983), Nature 301, 690. (3) Pal, D. K. et al. (1983), Lunar and Planetary Science XIV, 588. (4) Fireman, E. L. et al. (1983), Lunar and Planetary Science XIV, 195. (5) Fireman, E. L. et al. (1981), Proc. Lunar Planet. Sci. 11th, 1215. (6) Jull, A. J. T. et al. (1984), Nuclear. Instrum. Methods, in press. (7) Donahue, D. J. et al. (1983), Radiocarbon 25, 719. (8) Jull, A. J. T. et al. (1983), Lunar and Planet. Sci. XIV, 359. (9) Fireman, E. L. et al. (1979), Proc. Lunar Planet. Sci. 10th, 1053. (10) Swart, P. K. et al. (1983), Meteoritics 18, 137.

Table 1: Melt Extraction Results and Terrestrial Ages

Sample (wt., class)	CO <sub>2</sub> (cm <sup>3</sup> STP)	F <sub>m</sub> ( <sup>14</sup> C) <sup>1</sup>	Dilution and Blank-corrected F <sub>m</sub> ( <sup>14</sup> C)	<sup>14</sup> C x 10 <sup>6</sup> atoms/g	<sup>14</sup> C dpm/Kg	Terrestrial Age x 10 <sup>3</sup> yrs
Yamato 75102 5.0g; L6	7.6	4.49±0.13	4.21±0.13	2.01±0.06	46.3±1.4	0.8
Yamato 74459 4.85g; H6	3.6	1.23±0.04	0.95±0.05	0.22±0.01	5.06±0.27	19±1
Yamato 74013 5.7g; Oloqenite	2.82	1.25±0.06	1.74±0.11 <sup>2</sup>	0.27±0.02	6.21±0.37	17±1
ALHA 77232 10.0g; H4	3.05	0.355±0.016	0.075	< 0.007	< 0.16	> 47
MBRA 76001 10.2g; H6	3.85	0.464±0.016	0.17±0.03	0.020±0.004	0.44±0.08	39±2
ALHA 80101 10.1g; L6	1.44	0.298±0.018	0.16 <sup>1</sup>	< 0.007	< 0.16	> 47

<sup>1</sup>F<sub>m</sub> = Fraction of modern 1950AD carbon, (<sup>14</sup>C/<sup>13</sup>C sample)/(<sup>14</sup>C/<sup>13</sup>C 1950AD)

<sup>2</sup>CO<sub>2</sub>: gas diluted by 1.79 <sup>13</sup>CO<sub>2</sub>; gas diluted by 2.0

Blank correction 0.28±0.02

Table 2: Low Temperature <sup>14</sup>C Results

Sample (wt., class)	Fractionator temperature (°C)	Blank-corrected F <sub>m</sub> ( <sup>14</sup> C)	<sup>14</sup> C Reservoir Age 10 <sup>3</sup> yrs
Yamato 75102 (5.0g; L6)	500	0.84±0.03	5.1±0.5
Yamato 74459 (4.85g; H6)	500	0.26±0.03	11.8±1.0
Yamato 74013 (5.7g; Oloqenite)	500	0.13±0.06 <sup>1</sup>	17±4
ALHA 77232 (9.3g; H4)	500	< 0.03	> 29
ALHA 76001 (10.1g; H6)	500	0.46±0.03	7.0±0.5
MBRA 76001 (10.2g; H6)	500	0.11±0.01 <sup>1</sup>	18±1
	1000	0.08±0.04 <sup>1</sup>	21±5
ALHA 80101 (10.1g; L6)	500	0.25±0.05 <sup>1</sup>	11.5±1.3
ALHA 77232 (10.4g; L6)	500	< 0.26 <sup>1</sup>	> 11

Dilution of CO<sub>2</sub> gas indicated by superscript:

dilution factors: (1) 2.6, (2) 1.1, (3) 1.31, (4), 1.33, (5) 4.14

ATTACHMENT 3

<sup>10</sup>BE CONCENTRATIONS IN BYRD CORE AND ALLAN HILLS ICE

J. Beer, M. Andrée, H. Oeschger, G. Bonani, M. Suter,  
W. Wolfli, and E.L. Fireman

2<sup>nd</sup> Draft

$^{10}\text{Be}$  CONCENTRATIONS IN BYRD CORE AND ALLAN HILLS ICE

J. Beer, M. Andrée, and H. Oeschger

Physics Institute, University of Bern,  
Sidlerstrasse 5, 3012 Bern, Switzerland

G. Bonani, M. Suter, and W. Wölfli

IMP, Swiss Federal Institute of Technology ETHZ,  
8093 Zürich, Switzerland

and

E.L. Fireman

Smithsonian Astrophysical Observatory,  
Cambridge, MA 02138, U.S.A.

The  $^{10}\text{Be}$  concentrations are measured in Byrd core and Allan Hills ice samples of which  $^{18}\text{O}/^{16}\text{O}$  ratios ( $\delta^{18}\text{O}$ ) had been previously determined. For Byrd core an inverse correlation with  $\delta^{18}\text{O}$  is found. During Holocene, <sup>period, < 10<sup>4</sup> years before the present</sup> the  $^{10}\text{Be}$  concentrations range from  $2.3 \times 10^4$  to  $2.7 \times 10^4$  atoms/g and the  $\delta^{18}\text{O}$  values from -36.0 ‰ to -37.7 ‰. At the end of the last glaciation, <sup>and 14 x 10<sup>3</sup> years ago</sup> a  $^{10}\text{Be}$  concentration of  $3.8 \times 10^4$  atoms/g and a  $\delta^{18}\text{O}$  value of -42.7 ‰ is found. The Byrd core results are compared to those measured for Dome C and Dye 3 cores and can be simply explained by the relative precipitation rates. It seems that the precipitation rates at all three sites were reduced by about a factor of 2 <sup>about</sup> 15,000 years ago. The  $^{10}\text{Be}$  contents in the ablation region of Allan Hills are higher than would be anticipated from the  $\delta^{18}\text{O}$  values.  $^{10}\text{Be}$  is enriched at the surface indicating that the main ablation mechanism <sup>at some Allan Hills sites</sup> is evaporation and sublimation. The highest  $^{10}\text{Be}$  surface contents are found at sites with high meteorite concentrations.

1. Introduction

$^{10}\text{Be}$  ( $T_{1/2} = 1.5 \times 10^6$  y) is produced in the upper atmosphere by cosmic ray spallation reactions on nitrogen and oxygen and is deposited within a short time ( $\leq 2$  years) by precipitation. With the development of accelerator mass spectrometry the detection sensitivity for  $^{10}\text{Be}$  has been increased by several orders of magnitude.  $^{10}\text{Be}$  measurements in polar ice sheets contain the precipitation of the last  $\sim 10^5$  yrs in a stratigraphically and chemically undisturbed way.

Raisbeck et al. (1) measured the  $^{10}\text{Be}$  concentrations in the Antarctic Dome C core ( $74^{\circ}39'S$ ,  $124^{\circ}10'E$ ) and found an inverse correlation with the  $^{18}\text{O}/^{16}\text{O}$  ratios in the ice. During the last glaciation (indicated by low  $\delta^{18}\text{O}$  values) the  $^{10}\text{Be}$  concentrations were approximately twice those in recent times. Beer et al. (2, 3) confirmed the correlation between  $^{10}\text{Be}$  and  $\delta^{18}\text{O}$  in the Greenland Dye 3 core ( $65^{\circ}11'N$ ,  $43^{\circ}50'W$ ) and found a similar increase of the  $^{10}\text{Be}$  concentrations during the last glaciation (3). The inverse correlation of  $^{10}\text{Be}$  and  $\delta^{18}\text{O}$  during and at the end of the last glaciation suggests the explanation, that during colder periods the precipitation rates were reduced and therefore the  $^{10}\text{Be}$  concentration increased. This explanation is in good agreement with measurements of anions in Greenland which also indicate smaller snow accumulation rates at the end of the last glaciation compared to present times (4). Nishiizumi et al. (5) measured the  $^{10}\text{Be}$  and  $^{36}\text{Cl}$  concentrations but not the  $\delta^{18}\text{O}$  values in several Allan Hills samples (Antarctica,  $75^{\circ}45'S$ ,  $159^{\circ}00'E$ ).

Fireman and Norris (6) studied the elemental and isotopic compositions of the gas and the  $^{18}\text{O}/^{16}\text{O}$  ratios in melt water from Byrd core ( $80^{\circ}01'S$ ,  $119^{\circ}31'N$ ) and Allan Hills ice. Most of the water from these samples was preserved.

We deemed it desirable to measure the  $^{10}\text{Be}$  concentrations in aliquots of these water samples. The  $^{18}\text{O}/^{16}\text{O}$  ratios in the Byrd core had been studied in great detail earlier (7, 8).

The Dome C, Byrd and Dye 3 ice cores represent polar regions with remarkably different precipitation rates, namely  $\sim 4$  cm ice/year at Dome C (9),  $\sim 13$  cm ice/year at Byrd (10) and  $\sim 50$  cm ice/year at Dye 3 (3). Allan Hills (Antarctica) is an ice ablation region where large numbers of meteorites are found (11). Approximately 2000 meteorites have been recovered from an area of less than  $100 \text{ km}^2$ . On the basis of glaciological evidence (ice movement), the source of the Allan Hills ice is the Taylor glacier (12) where the precipitation rate is higher than at Dome C but lower than at Byrd Station. Fig. 1 is a map (13) of the Allan Hills region illustrating the distribution of recovered meteorites; also shown is a numbered stake network and the Cul de Sac and Strain Flower locations. The meteorites are highly concentrated in a narrow strip ( $\sim 2$  km wide) that extends from  $\sim 2$  km north of the Strain Flower location to the Cul de Sac site and passes through the stake network between stakes 9 and 14. The terrestrial ages of the meteorites range from  $11 \times 10^3$  to  $700 \times 10^3$  years (14, 15, 16, 17) in agreement with ice ages based on flow models assuming constant meteorite influx and glacial flow (18). Cul de Sac is the location of the most stagnant ice (priv. comm. W.A. Cassidy, 1982) and there a  $500 \times 10^3$  year old meteorite and several other old ones were found. It is of interest to see whether the  $^{10}\text{Be}$  contents of Allan Hills ice can be related to the meteorite distribution.

2.  $^{10}\text{Be}$  sample preparation and experimental procedures

The procedures for the cleaning of the Byrd core and Allan Hills ice samples and the He purging of the melt water have been described elsewhere (6). The melt water had been acidified to  $\text{pH} = 1$ , so that the  $^{10}\text{Be}$  should be retained in the water. Be carrier ( $\sim 5$  mg) was added to the melt water of 10 - 15 kg. 3.0 kg aliquots of the water were evaporated to 10 g using heat lamps.

Beryllium acetylacetonate in the presence of EDTA was extracted into  $\text{CHCl}_3$  and evaporated after adding HCl. The organic material was oxidized with aqua-regia. Be  $(\text{OH})_2$  was precipitated with  $\text{NH}_4\text{OH}$  and converted to BeO by ignition at  $950^\circ\text{C}$  in a quartz crucible.

The  $^{10}\text{Be}$  concentrations were measured using the EN-tandem accelerator mass spectrometer of the ETH Zurich (19). The Cs sputter ion source produced BeO currents of up to 1  $\mu\text{A}$  leading to count rates of up to  $10^3$  cph for a typical  $^{10}\text{Be}/^9\text{Be}$  ratio of  $5 \cdot 10^{-13}$ . The background is of the order of  $10^{-14}$  depending on the boron content of the sample. The 1 $\sigma$  errors of the  $^{10}\text{Be}$  measurements are 3 - 5 % relative to our standard. The absolute  $^{10}\text{Be}/^9\text{Be}$  ratio of the standard however is only known to about 10 %.

3. Results and discussion

Table 1 gives the  $^{10}\text{Be}$  concentrations, the depths with age estimates based on ice flow models, and the  $\delta^{18}\text{O}$  values for the measured Byrd core samples. The Byrd samples averaged the precipitation over at least several decades, thus fine scale fluctuations in  $^{10}\text{Be}$  contents and  $\delta^{18}\text{O}$  values are averaged out. Also given in Table 1 for comparison are

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$^{10}\text{Be}$  and  $\delta^{18}\text{O}$  values (1, 3) for Dome C and Dye 3 cores.

The Dome C samples were selected to approximately correspond in age to the Byrd samples; the Dye 3 values are averages of many measurements at depths which span the ages for the samples from the other cores. A comparison of the three sets of data reveals the following results:

- At all three sites, the  $^{10}\text{Be}$  concentration and the  $\delta^{18}\text{O}$  were relatively stable during the last ca 10'000 y. Before this time, during the last glaciation, the  $^{10}\text{Be}$  concentration rose by a factor of  $\sim 2$  while the  $\delta^{18}\text{O}$  value fell by  $\sim 5$  ‰. This indicates that the climatic change accompanying the last glaciation evidently reduced the precipitation rate of all three sites by a factor of  $\sim 2$ .
- The  $^{10}\text{Be}$  concentrations for Byrd core are intermediate to those for Dome C and Dye 3 cores. This can be anticipated assuming that the relative precipitation rates at these three locations had been the same in the past and taking into account that the cosmic ray flux over the polar region is essentially uniform.

Table 2 gives the  $^{10}\text{Be}$  concentrations and  $\delta^{18}\text{O}$  values for the Allan Hills samples. For comparison the  $^{10}\text{Be}$  measurements of Nishiizumi et al. (5) are also given. The data reveal the following results:

- The  $^{10}\text{Be}$  contents for all Allan Hills samples are higher than would be anticipated from their  $\delta^{18}\text{O}$  values. Evidently the simple negative correlation between the  $^{10}\text{Be}$  contents and the  $\delta^{18}\text{O}$  values, which holds quite well for the cores in snow accumulation regions (Table 1) is disturbed in an ice ablation region by processes which enrich the  $^{10}\text{Be}$  contents.

- At all sites except stake 14, the  $^{10}\text{Be}$  concentration in the surface (0 - 20 cm) samples is higher than in deeper samples, while the  $\delta^{18}\text{O}$  values do not show much variation with depth. The most marked  $^{10}\text{Be}$  enrichment was found near the surface of the Cul de Sac site. Here the  $^{10}\text{Be}$  concentration of  $(13.7 \pm 0.6) \times 10^4$  atoms/g is the highest ever observed. Its  $\delta^{18}\text{O}$  value of  $(-40.7 \pm 0.1) \text{‰}$  is intermediate to  $\delta^{18}\text{O}$  values obtained from recent ( $\leq 10^4$  y) and old ( $\sim 15 \cdot 10^3$  y) ice in Byrd core, but its  $^{10}\text{Be}$  content is nearly 6 times that of the recent Byrd samples and nearly 4 times that of the old Byrd sample. At a depth 20 - 35 cm, the  $^{10}\text{Be}$  content drops to  $(5.8 \pm 0.3) \times 10^4$  atoms/g, the  $\delta^{18}\text{O}$  change is small. These results cannot be explained by changes of the production or precipitation rates. It is very unlikely that such a high cosmic ray flux or a correspondingly low precipitation rate would only be reflected in the surface layer. In an ablation region, ice can be removed from the surface either by wind ablation or by evaporation and sublimation. Wind ablation blows away fine grains of ice with their  $^{10}\text{Be}$  content; evaporation and sublimation removes ice without its  $^{10}\text{Be}$  content. Thus a reasonable explanation for the observed very high  $^{10}\text{Be}$  content is that the ice at sites with high  $^{10}\text{Be}$  surface concentrations is mainly ablated by evaporation and sublimation. From the observed  $^{10}\text{Be}$  concentrations and from the total ablation rate of approximately 5 cm/y (18) we roughly estimate that at Cul de Sac wind ablation does not contribute more than a few percent.
- It is interesting to compare  $^{10}\text{Be}$  surface concentrations with meteorite concentrations. In the strip connecting Strain Flower with Cul de Sac (Fig. 1) both  $^{10}\text{Be}$  and meteorite concentrations are high. There seems to be

a trend of decreasing  $^{10}\text{Be}$  and meteorite concentrations as moving along the stake system. At stake 18 which has no meteorites in its vicinity no  $^{10}\text{Be}$  enrichment occurs at the surface. This suggests that both  $^{10}\text{Be}$  and meteorites are concentrated by the same mechanism, probably sublimation. Lower concentrations could simply be explained by lower ablation rates.

- The comparison of our measurements with those of Nishiizumi et al. (5) at stake 14 shows consistency for all data except the deepest one. There the  $^{10}\text{Be}$  concentration is higher by a factor of 1.6 which is similar to the variations observed during the last glaciation (2) and could be attributed to changes of the precipitation rate.

The presented data clearly show that  $^{10}\text{Be}$  is a powerful tool to study glacial parameters like accumulation and ablation rates and processes like evaporation, sublimation, <sup>freezing out of</sup> ~~precipitation~~ and wind erosion. For further insight into the involved processes, more samples, especially with better depth resolution, are needed.

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References

1. G.M. Raisbeck, F. Yiou, M. Franeau, J.M. Loiseaux, M. Lieuvin, J.C. Ravel, and C. Lorius, Cosmogenic  $^{10}\text{Be}$  concentrations in Antarctic ice during the past 30,000 years. *Nature* 292 (1981) 825-826.
2. J. Beer, H. Oeschger, M. Andrée, G. Bonani, M. Suter, W. Wölfli, and C.C. Langway, Temporal variations in the  $^{10}\text{Be}$  concentration levels found in the Dye 3 ice core, Greenland, Proc. Symp. Ice and Climate Modeling, Evanston, Ill., USA, June 1983. To be published in *Annals of Glaciology*, 5, 1984.
3. J. Beer, M. Andrée, H. Oeschger, B. Stauffer, R. Balzer, G. Bonani, C. Stoller, M. Suter, W. Wölfli, and R.C. Finkel, Temporal  $^{10}\text{Be}$  variations in ice. *Radiocarbon* 25 (1983) 269-278.
4. M. Herron and C.C. Langway, Chloride, Nitrate and Sulfate in the Dye 3 and Camp Century, Greenland, ice cores, AGU, Proceedings of the spring meeting 1982, Philadelphia, Union Session: Greenland Ice Sheet Program, 1983, in press.
5. K. Nishiizumi, J.R. Arnold, D. Elmore, X. Ma, D. Newman, and H.E. Gove,  $^{36}\text{Cl}$  and  $^{53}\text{Mn}$  in Antarctic meteorites and  $^{10}\text{Be}$ - $^{36}\text{Cl}$  dating of Antarctic ice. *Earth and Planet. Sci. Lett.* 62 (1983) 407-417.
6. E.L. Fireman and T.L. Norris, Ages and composition of gas trapped in Allan Hills and Byrd core ice. *Earth and Planet. Sci. Lett.* 60 (1982) 339-350.

7. S. Epstein, R.P. Sharp, and A.J. Gow, Antarctic ice sheet: stable isotope analyses of Byrd station core and inter-hemispheric climatic implications. *Science* 168 (1970) 1570-1572.
8. S.J. Johnson, W. Dansgaard, H.B. Clausen, and C.C. Langway, Oxygen isotope profiles through the Antarctic and Greenland ice sheets. *Nature* 235 (1972) 429-434.
9. C. Lorius, L. Merlivat, J. Jouzel, and M. Pourchet, A 30,000 yr isotope climate record from Antarctic ice. *Nature* 280 (1979) 644-647.
10. C.R. Bentley, R.L. Cameron, C. Bull, K. Koime, and A.J. Gow, Physical characteristics of Antarctic ice sheet. *Am. Geogr. Soc. Antarct. Map Folio Ser., Folio 2* (1964).
11. W.A. Cassidy, E. Olsen, and K. Yanai, Antarctica: a deep-freeze storehouse of meteorites. *Science* 198 (1977) 727-731.
12. D.J. Drewry, Pleistocene bimodal response of Antarctic ice. *Nature* 287 (1980) 204-216.
13. F. Nishio and J.O. Annexstad, Studies on the ice flow in the bare ice area near the Allan Hills in Victoria Land. *Antarctica, Proc. 5th Symp. on Antarctic Meteors* (National Institute of Polar Studies, Tokyo, 1980) 1-13.
14. E.L. Fireman, Carbon-14 and argon-39 in ALHA meteorites. *Proc. 11th Lunar Planet, Sci. Conf.* (1980) 1215-1221.

15. E.L. Fireman, H.R. Andrews, G.C. Ball, R.M. Brown, and J.C.D. Milton,  $^{14}\text{C}$  terrestrial ages of Antarctic meteorites with counters and with a Van de Graaff accelerator, in: Lunar and Planetary Science XIII (Lunar and Planetary Institute, Houston, Texas, 1982) 219-221 (abstract).
16. K. Nishiizumi and J.R. Arnold, Ages of Antarctic meteorites, in: Lunar and Planetary Science XI (Lunar and Planetary Institute Houston, Texas, 1980) 815-817 (abstract).
17. K. Nishiizumi, M.T. Murrell, J.R. Arnold, D. Elmore, R.D. Ferraro, H.E. Gove and R.C. Finkel, Cosmic-ray-produced  $^{36}\text{Cl}$  and  $^{53}\text{Mn}$  in Allan Hills-77 meteorites. Earth Planet. Sci. Lett. 52 (1981) 31-38.
18. I.M. Whillans and W.A. Cassidy, Catch a Falling Star: Meteorites and Old Ice. Science 222 (1983) 55-57.
19. W. Wölfli, G. Bonani, M. Suter, R. Balzer, M. Nessi, and Ch. Stoller, Radioisotope dating with the ETHZ-EN-Tandem accelerator. Radiocarbon 25 (1983) 745-753.

Table 1.  $^{10}\text{Be}$  contents versus depth.

Depth (m)	Est. Age ( $10^3$ yr)*	$\delta^{18}\text{O}$ (‰)*	$^{10}\text{Be}$ ( $10^4$ atom/g)
Byrd Core ( $80^\circ 01'S$ , $119^\circ 31'W$ )			
270	~2	$-36.0 \pm 0.4$	$2.4 \pm 0.3$
360	~3	$-36.4 \pm 0.5$	$2.3 \pm 0.1$
1068	~10	$-37.7 \pm 0.5$	$2.7 \pm 0.1$
1071	~10	$-37.7 \pm 0.3$	$2.7 \pm 0.1$
1468	~15	$-42.7 \pm 0.4$	$3.8 \pm 0.2$

\* Fireman and Norris (1982).

Dome C Core** ( $74^\circ 39'S$ , $124^\circ 10'E$ )			
100	~2	-50	$3.8 \pm 0.5$
150	~3	-50	$4.0 \pm 0.5$
300	~9	-50	$4.0 \pm 0.5$
320	~9	-50	$4.0 \pm 0.5$
500	~15	-55	$10.0 \pm 1.0$

\*\* Raisbeck et al. (1981).

Dye 3 Core*** ( $65^\circ 11'N$ , $124^\circ 10'E$ )			
0-70†	0-0.1	-29	$0.97 \pm 0.25$
1300-1780†	4-10	-29	$0.93 \pm 0.22$
1833-1930†	~15	-34	$2.1 \pm 0.2$

\*\*\* Beer et al. (1983).

† Average of many values.

Table 2.  $^{10}\text{Be}$  versus depth and location at Allan Hills ( $76^{\circ}45'\text{S}$ ,  $159^{\circ}00'\text{E}$ )

Location	Depth (cm)	$\delta^{18}\text{O}$ (‰) <sup>a</sup>	$^{10}\text{Be}$ ( $10^4$ atom/g)
Cul de Sac	5-20	$-40.74 \pm 0.10$	$13.7 \pm 0.6$
Cul de Sac	20-35	$-41.80 \pm 0.60$	$5.3 \pm 0.3$
Strain Flower	5-25	$-42.1 \pm 0.5$	$9.8 \pm 0.5$
Stake 12	5-20	$-39.2 \pm 0.3$	$9.7 \pm 0.5$
Stake 10-11	5-20	$-43.5 \pm 0.4$	$8.1 \pm 0.3$
Stake 18	0-15	$-40.1 \pm 0.2$	$5.4 \pm 0.3$
Stake 14	5-20	$-41.4 \pm 0.4$	$8.9 \pm 0.4$
Stake 14	20-35	$-40.5 \pm 0.5$	$5.1 \pm 0.3$
Stake 14 <sup>b</sup>	65-100	—	$4.9 \pm 1.1$
Stake 14 <sup>b</sup>	270-313	—	$5.0 \pm 0.4$
Stake 14 <sup>b</sup>	675-713	—	$8.1 \pm 0.7$
Stake 16 <sup>b</sup>	0-12	—	$6.7 \pm 0.4$
Stake 16 <sup>b</sup>	12-24	—	$7.4 \pm 0.4$

(a) Fireman and Norris, *EPSL* 60 (1982) 339-350.

(b) Nishiizumi *et al.*, *EPSL* 62 (1983) 407-417.

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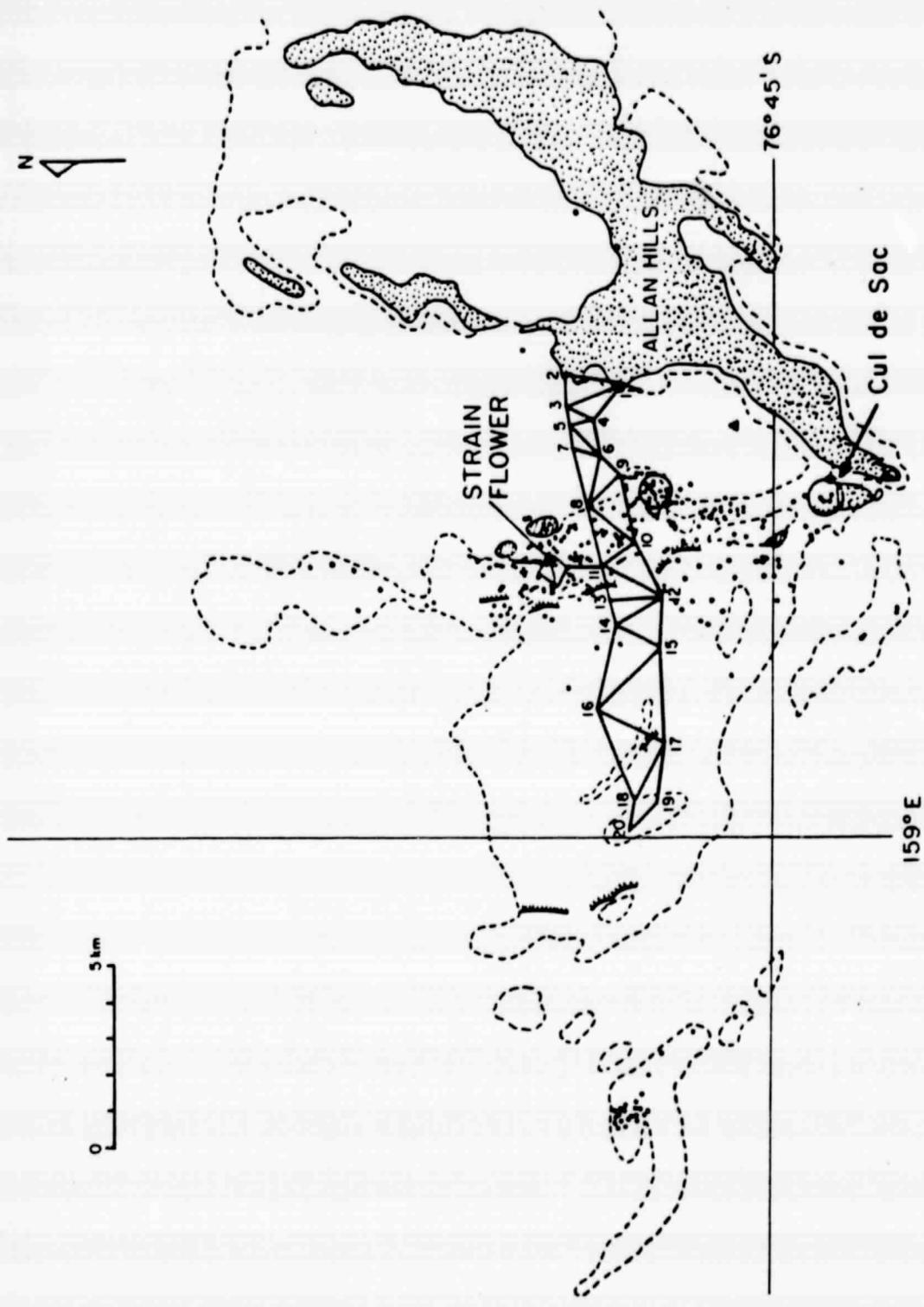


Fig. 1. Map of Allan Hills region. Dots give meteorite locations.