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# Ages and ablation and accumulation rates from $^{14}C$ measurements on Antarctic ice

J. J. VAN ROIJEN, K. VAN DER BORG, A. F. M. DE JONG,
*Valxgroep Subatomaire Physica, Universiteit Utrecht, 3508 TA Utrecht, The Netherlands*

J. OERLEMANS
*Instituut voor Marien en Atmosferisch Onderzoek, Universiteit Utrecht, 3508 TA Utrecht, The Netherlands*

ABSTRACT. Shallow ice cores from an Antarctic blue-ice area at Scharffenbergbotnen were $^{14}C$-analyzed using a dry-extraction technique and accelerator mass spectrometry. The in situ production was determined from the $^{14}CO$ component and used to deduce the natural $^{14}CO_2$ component. The ages were measured at $10\,000 \pm 3000$ BP. The accumulation and ablation rates determined from the in situ production are 7–20 and 10 cm a$^{-1}$, respectively, showing agreement with field observations. The derived ages and air-yield data show a nearby origin for the surface ice.

## INTRODUCTION

Numerical models have been developed to describe the ice flow in temperate glaciers and ice sheets. Dating of ice is an important tool for validating these models. A reliable time-scale is also required in order to interpret the palaeoclimatic records derived from ice cores. The $CO_2$ component of the enclosed air contains a radioactive $^{14}C$ clock which starts when snow is transformed into ice and when air is sealed off from the atmosphere. Measurement of the residual $^{14}C$ activity reveals the date of the ice. Unlike methods that count the annual varying parameters, such as $\delta^{18}O$ or conductivity, $^{14}C$ dating does not depend on the observability of layers. This may be useful, particularly for dating ice from ablation zones.

The $^{14}C$ activity in ice originates, however, not only from the trapping of atmospheric $CO_2$, but also from the in situ production of $^{14}C$ in the ice due to nuclear reactions by cosmic rays (Fireman and Norris, 1982). After their formation, hot $^{14}C$ atoms become oxidized as they slow down. During this process, $^{14}CO_2$ and $^{14}CO$ may be formed at a constant ratio (Roessler, 1988). Because the atmospheric $^{14}CO$ concentration is negligible, $^{14}CO$ in ice is ascribed exclusively to in situ production and can be used to determine the amount of in situ $^{14}CO_2$ on the basis of a known production ratio of in situ $^{14}CO_2$ and $^{14}CO$ (Van Roijen and others, 1994). After correcting the amount of $^{14}CO_2$ in ice for the amount of in situ $^{14}CO_2$ the ice can be dated.

The production of $^{14}C$ decreases exponentially with depth due to the attenuation of cosmic rays in ice. Since surface ice is generally exposed to erosion, production depends not only on the intensity of cosmic rays but also on the exposure time and thus the ablation rate. The ablation rate can thus be determined from the total amount of in situ products in the ice (Lal and others, 1990). A similar relation is expected between in situ production and the accumulation rate at the time of ice formation (Lal and Jull, 1990; Van Roijen and others, 1994).

In this report we analyze shallow ice cores obtained from an Antarctic blue-ice area in Dronning Maud Land Both $^{14}CO_2$ and $^{14}CO$ measurements will be presented. After correction for the in situ $^{14}C$ component the ages of the ice cores will be deduced. In addition we will discuss how the in situ $^{14}C$ can provide a better understanding of ablation and accumulation rates.

## FIELD DESCRIPTION

Figure 1 shows schematically the blue-ice area at Scharffenbergbotnen (74°34′ S, 11°03′ W). The coring locations are indicated. Cores 5, 6 and 15, with lengths of 3, 3 and 10 m, respectively, were used in this investigation. The cirque-like basin is downstream from the Heimefrontfjella nunataks, western Dronning Maud Land, East Antarctica. Inside the valley a depression has formed, where ablation occurs. The elevation here is about 1150 m, but the westerly ice divides are located 80–100 m higher. In addition to the ice that enters Scharffenbergbotnen from the ice divides, there is a small ice flow which enters the valley along a 400 m icefall in the east (Jonsson, 1992). The mean annual temperature in the centre of the depression is estimated at −18°C for the year 1988 (personal communication from R. Bintanja and S. Jonsson, 1994). Melt features have been observed only around the eastern part of the blue-ice area, at the bottom of the depression (Jonsson, 1992). The drilling locations

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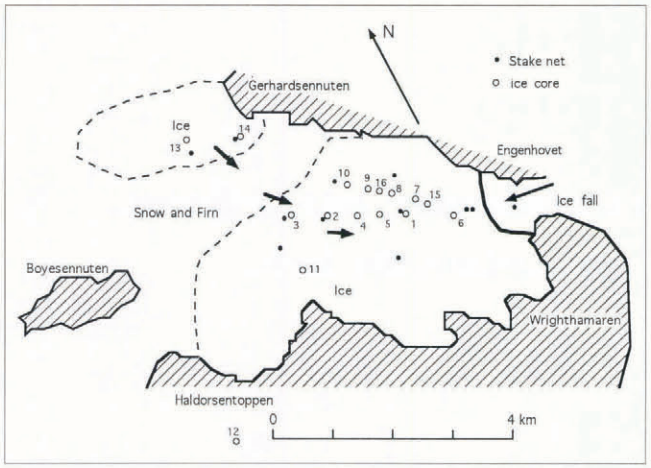


*Fig. 1. View of the Scharffenbergbotnen basin. Indicated are the coring sites, from which cores 5, 6 and 15 are used in this work. For comparison, part of the Swedish stake net is marked.*

chosen were outside this area. In accordance with the Swedish Antarctic Research Programme (SWEDARP), a number of stakes were planted by Swedish scientists both inside and outside the basin for mass-balance and ice-movement studies. Measurements have been carried out since the field season 1988, and ablation rates have been reported over a 4 a period (Näslund, 1992).

## METHOD

### Ice sampling

The ice samples were handled carefully to prevent any contamination. No drilling fluids were used, and immediately after drilling the ice samples were sealed in polythene bags. The ice cores were kept below –12°C during transport by sledge, boat and truck. The ice samples were transported immediately in order to prevent the risk of post-core in situ contamination.

Before extraction, about 1 cm of the outer parts of the ice samples and a number of cracks in the samples were removed with a band-saw in a cold room at –25°C. Before the sample was loaded in the extraction vessel the outer parts were removed once more with a sharp knife under an argon atmosphere.

### Experimental

A dry-extraction technique was chosen for extracting the gases from the ice (Van Roijen, 1995). Dry extraction prevents dissolution of particulates or salts and minimises contamination from outgassing (Moor and Stauffer 1984). We expect in our set-up an efficiency comparable to that of the similar systems of Moor and Stauffer (1984) and Nakazawa and others (1993), which was found to be 90% and 98%, respectively.

After loading, the outer parts of the ice sample were evaporated for at least 5 h at –30°C. Under vacuum conditions, rotating razor blades driven by an external motor milled samples weighing approximately 3 kg for 20 min. The ice samples were chipped into small particles approximately 2 mm long and 0.2 mm in diameter. The stainless-steel walls of the 34 l volume were kept at –30°C during operation to minimise outgassing. The total desorption of $CO_2$ was measured and found to be less than 0.5 $\mu l h^{-1}$ (STP).

About 80 $\mu$l (STP) of $^{14}C$-free CO was added to the extraction vessel before milling, as a carrier for the extraction of $^{14}CO$ from the ice. After milling, the released air was extracted with a molecular sieve at $T = 70$ K for 45 min. The $H_2O$ and $CO_2$ were removed in traps cooled with a dry-ice–alcohol mixture and liquid nitrogen. The CO was oxidized to $CO_2$ by flushing it over CuO at 620°C. Air and $CO_2$ yields were measured with an uncertainty of about 1% using a capacitance manometer.

The $CO_2$ samples were converted into graphite samples weighing about 20–50 $\mu$g and analyzed with the Utrecht AMS facility (Van der Borg and others, 1987). A mean contamination-level value of $1.4 \pm 0.5$ pMC (percentage of modern carbon) was obtained for CO and $CO_2$ samples of 70–140 $\mu$l (Van Roijen and others, 1994).

## RESULTS AND INTERPRETATION

### $^{14}C$ depth profiles

Table 1 describes the samples from cores 5, 6 and 15, the $CO_2$ yield and the CO carrier used. The size of each ice sample is about 2.5 kg, a compromise between the sample size and the depth resolution. The $CO_2$ concentrations obtained are 14–18 $\mu g\,kg^{-1}$ and are shown in Table 1. Air extracted from core 15 decreases from $106 \pm 1$ ml $kg^{-1}$ at 10 m depth, to $93 \pm 1$ ml $kg^{-1}$ at 1 m depth. Table 2 summarises the results of the $^{14}C$ analysis. Figures 2 and 3 show the $^{14}CO_2$ and $^{14}CO$ profiles (in atoms $g^{-1}$ of ice) vs depth for the 3 m cores 5 and 6, and Figure 4 for the 10 m core 15.

The presence of $^{14}CO$ clearly indicates in situ production of $^{14}C$. The exponential decrease is according to the attenuation length of cosmic rays in ice. The equation $C(x) = C_0 \exp(-x/\Lambda) + C_1$ is fitted to the $^{14}CO$ data, where $C(x)$ is the concentration (atoms $g^{-1}$) as a function of depth $x$ (cm), $\Lambda$ is the attenuation length of cosmic rays in ice (170 cm), $C_0$ is the production coefficient (atoms $g^{-1}$) and $C_1$ is a constant (asymptotic) level (atoms $g^{-1}$) (Van Roijen and others, 1994). A similar fit is made to the $CO_2$ data from which the coefficients $C_0'$ and $C_1'$ are derived. Table 3 shows the results for cores 5, 6 and 15. Also listed is the ratio $C_0'/C_0$, which represents the $^{14}CO_2/^{14}CO$ ratio for in situ production. The deduced values of 3.5, 3.1 and 4.1, respectively, agree within error limit. The fits are drawn in Figures 2–4 to illustrate the results.

Clearly the $^{14}CO$ constant level differs from zero, which indicates the presence of another in situ component. Such a component is to be expected for $^{14}CO_2$ as well. Assuming an equal ratio for in situ production of these components, the in situ $^{14}CO_2$ at the constant level is obtained from the $^{14}CO$ value by applying the deduced ratio. Subtraction of the in situ $^{14}CO_2$, thus obtained, from the constant-level $^{14}CO_2$ results in the remaining natural $^{14}CO_2$.

### Calculation of ages, ablation and accumulation rates

The deduced natural $^{14}CO_2$ concentrations are compared


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*Table 1. Ice samples used for analysis*

| *Sample* | *Depth* cm | *Weight* g | *$CO_2$ yield* $\mu g\,C$ | *$CO_2$ concentration* $\mu g\,kg^{-1}$ | *CO carrier* $\mu g\,C$ |
|---|---|---|---|---|---|
| c-05/01 | 3–27 | 1250 ± 14 | 17.7 ± 0.2 | 14.2 ± 0.2 | 39 ± 1 |
| c-05/02 | 30–95 | 2680 ± 30 | 40 ± 1 | 14.9 ± 0.4 | 33 ± 1 |
| c-05/04 | 95–155 | 2450 ± 30 | 34 ± 1 | 13.9 ± 0.4 | 36 ± 1 |
| c-05/06 | 155–224 | 2700 ± 30 | 40 ± 1 | 14.8 ± 0.4 | 41 ± 1 |
| c-05/08 | 228–294 | 2620 ± 30 | 39 ± 1 | 14.9 ± 0.4 | 41 ± 1 |
| c-06/02 | 26–70 | 2020 ± 20 | 32 ± 1 | 15.8 ± 0.5 | 40 ± 1 |
| c-06/04 | 74–135 | 2540 ± 20 | 38.9 ± 0.4 | 15.3 ± 0.2 | 41 ± 1 |
| c-06/09 | 236–303 | 2860 ± 20 | 44 ± 1 | 15.4 ± 0.4 | 41 ± 1 |
| c-15/02 | 18–83 | 2760 ± 20 | 42 ± 1 | 15.2 ± 0.4 | 37 ± 1 |
| c-15/04 | 88–152 | 2970 ± 20 | 48.1 ± 0.5 | 16.2 ± 0.2 | 39 ± 1 |
| c-15/08 | 238–300 | 2710 ± 20 | 49.3 ± 0.5 | 18.2 ± 0.2 | 38 ± 1 |
| c-15/14 | 442–499 | 2490 ± 20 | 44.8 ± 0.5 | 18.0 ± 0.2 | 40 ± 1 |
| c-15/24/A | 721–793 | 1300 ± 30 | 22 ± 1 | 16.9 ± 0.9 | 42 ± 1 |
| c-15/24/B | 721–793 | 2380 ± 30 | 40 ± 1 | 16.8 ± 0.5 | 49 ± 1 |
| c-15/32 | 944–1010 | 2940 ± 20 | 52.1 ± 0.5 | 17.7 ± 0.2 | 43 ± 1 |

with the 100 pMC for modern $CO_2$ in ice (Table 2). The $^{14}C$ ages obtained are 10 000 ± 3000 BP (Table 3). Only the decrease by radioactive decay ($^{14}C$ half-life of 5570 a) is taken into account in this calculation. The ages obtained in this way do not depend on the efficiency of dry extraction of in situ products, as the correction takes this into account (Van Roijen and others, 1994).

For a constant ablation rate $C_0 = P_0/(\lambda + a/\Lambda)$ (Lal and others, 1990), where $P_0$ is the production rate of the total in situ $^{14}C$ in the ablation zone (atoms $g^{-1}$ $a^{-1}$), $a$ is the ablation rate (cm $a^{-1}$), and $\lambda$ is the decay constant ($\lambda = 1.25 \times 10^{-4}\,a^{-1}$). Using the total production rate $P_0 = 45$ atoms $g^{-1}\,a^{-1}$ (Lal and others, 1990) for Scharffenbergbotnen, the ablation rates calculated are about 10 cm $a^{-1}$ (Table 3).

The ratio of the total in situ $^{14}C$ and the natural component as found in the asymptotic values of the ice in the ablation region may still be equal to the ratio in the region of origin, as the decay does not affect the ratio. We calculate this ratio $R$ for the three cores (Table 3). We use this value to obtain the accumulation rate $s$ in the relation $R = 0.176\ P_0/s$, where $s$ (cm w.e. $a^{-1}$) is the accumulation rate, and $P_0$ (atoms $g^{-1}\,a^{-1}$) is the production rate of in situ $^{14}C$ in the accumulation zone (Lal and

*Table 2. $^{14}CO$ and $^{14}CO_2$ concentrations in Antarctic ice*

| | $^{14}CO$ | | | $^{14}CO_2$ | | | |
|---|---|---|---|---|---|---|---|
| *Sample* | *UtC- Nr.** | *Activity†* pMC | *Conc.‡* atoms $g^{-1}$ | *UtC- Nr.** | *Activity†* pMC | *Conc.†* atoms $g^{-1}$ | *Conc-"100"§* atoms $g^{-1}$ |
| c-05/01 | 3220 | 5.0 ± 0.8 | 92 ± 15 | 3219 | 143 ± 3 | 1200 ± 30 | 840 ± 30 |
| c-05/02 | 2868 | 26.3 ± 1.3 | 192 ± 11 | 2867 | 114 ± 3 | 1000 ± 40 | 880 ± 30 |
| c-05/04 | 2990 | 17.7 ± 1.3 | 154 ± 12 | 2989 | 96 ± 3 | 790 ± 40 | 820 ± 30 |
| c-05/06 | 2998 | 14.3 ± 0.9 | 129 ± 8 | 2997 | 83.8 ± 1.6 | 740 ± 20 | 880 ± 30 |
| c-05/08 | 2992 | 12.1 ± 1.2 | 112 ± 11 | 2991 | 81 ± 3 | 710 ± 30 | 880 ± 30 |
| c-06/02 | 3017 | 14.6 ± 1.4 | 171 ± 16 | 3016 | 83 ± 3 | 780 ± 40 | 940 ± 50 |
| c-06/04 | 3231 | 11.4 ± 0.9 | 109 ± 9 | 3230 | 69.0 ± 1.3 | 626 ± 14 | 910 ± 20 |
| c-06/09 | 3011 | 7.5 ± 0.9 | 64 ± 8 | 3010 | 50.1 ± 1.2 | 456 ± 15 | 910 ± 30 |
| c-15/02 | 3020 | 19.3 ± 1.3 | 153 ± 11 | 3018/3019 | 91.4 ± 1.9 | 820 ± 30 | 900 ± 30 |
| c-15/04 | 3222 | 15.6 ± 1.1 | 117 ± 9 | 3221 | 75.4 ± 1.5 | 724 ± 17 | 960 ± 20 |
| c-15/08 | 3224 | 11.1 ± 0.7 | 92 ± 6 | 3223 | 53.9 ± 1.2 | 580 ± 15 | 1080 ± 30 |
| c-15/14 | 3227 | 6.5 ± 0.7 | 62 ± 7 | 3226 | 54.8 ± 1.1 | 584 ± 14 | 1070 ± 30 |
| c-15/24/a | 2939 | 3.4 ± 0.7 | 65 ± 13 | 2938 | 42 ± 1 | 420 ± 20 | 1000 ± 50 |
| c-15/24/b | 2941 | 4.2 ± 0.7 | 51 ± 9 | 2940 | 42 ± 1 | 420 ± 16 | 1000 ± 30 |
| c-15/32 | 3229 | 6.2 ± 0.7 | 54 ± 6 | 3228 | 39.4 ± 1.1 | 413 ± 13 | 1050 ± 30 |

* Laboratory code.
† $^{14}C$ activity in percentage modern carbon (pMC).
‡ $^{14}CO$, or $^{14}CO_2$ concentration in atoms $g^{-1}$ ice.
§ $^{14}CO_2$ concentration in atoms $g^{-1}$ ice normalized to 100 pMC.

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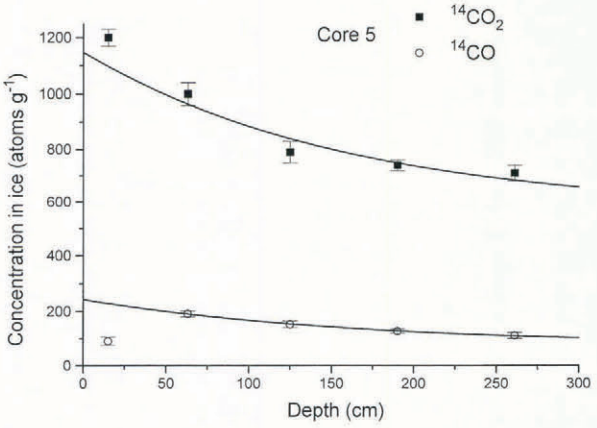


*Fig. 2. Result of the $^{14}C$ measurements of core 5. The fitted equation $C_0 \exp(-x/\Lambda) + C_1$ is shown for $^{14}CO$ and $^{14}CO_2$. Note the low value in the $^{14}CO$ concentration of the surface sample, which is not included in the fits.*

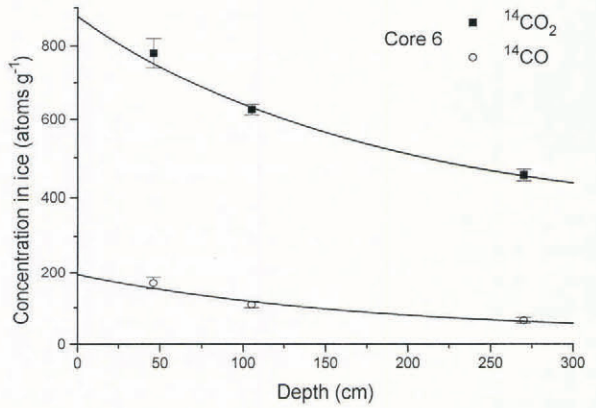


*Fig. 3. Result of the $^{14}C$ measurements of core 6.*

Tull, 1990). Likely accumulation zones are the westerly ice divides (altitude 1240 m), the Bremnesflaket plateau (2000 m) or the area in between, for which production

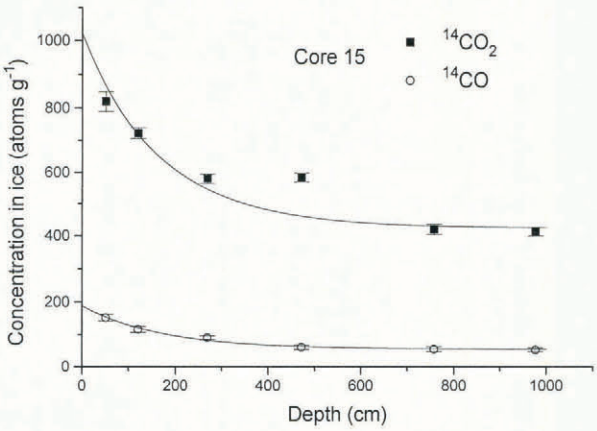


*Fig. 4. Result of the $^{14}C$ measurements of core 15.*

rates varying from 45 to 85 atoms g$^{-1}$ a$^{-1}$ can be derived. Calculated accumulation rates for cores 5, 6 and 15 are 7–20 cm w.e. a$^{-1}$ for $P_0 = 45$ atoms g$^{-1}$a$^{-1}$ (Table 3).

## DISCUSSION

Calculated ages are independent of the $^{14}C$ extraction efficiency because the correction method used in this work takes the efficiency into account (Van Roijen and others, 1994). Calculation of the ages depends on the fixed relation between the in situ production of $^{14}CO_2$ and that of $^{14}CO$. The obtained values of 3.5, 3.1 and 4.1 agree with a reported value of $6 \pm 3$ (Roessler, 1988). The ages obtained are supported by the $CO_2$ concentrations of the ice samples. Concentrations of about 16 $\mu$g kg$^{-1}$ have been reported for Interglacials whereas at glacial stages concentrations were only 10 $\mu$g kg$^{-1}$ (Van de Wal and others, 1994). The $CO_2$ yields for cores 5, 6 and 15 show values of about 14–18 $\mu$g kg$^{-1}$, indicating a Holocene age. The almost Pleistocene age for core 15 indicates that any slow oxidation of CO to $CO_2$ in the long duration between accumulation and ablation is negligible. But

*Table 3. Calculated $^{14}C$ concentrations (which result from the fit), deduced ages and surface mass-balance data. For comparison the ablation rates obtained from stake readings (Näslund, 1992) are added. For the accumulation rates it is assumed that the altitude of ice formation is 1240 m a.s.l.*

| | *Core 5* | *Core 6* | *Core 15* |
|---|---|---|---|
| $C_0$ "$^{14}CO$" (atoms g$^{-1}$) | 170 ± 30 | 170 ± 30 | 135 ± 14 |
| $C_1$ "$^{14}CO$" (atoms g$^{-1}$) | 74 ± 13 | 27 ± 12 | 55 ± 4 |
| $C_0$ "$^{14}CO_2$" (atoms g$^{-1}$) | 590 ± 100 | 530 ± 50 | 550 ± 130 |
| $C_1$ "$^{14}CO_2$" (atoms g$^{-1}$) | 550 ± 40 | 340 ± 20 | 450 ± 30 |
| Production ratio $^{14}CO_2/^{14}CO$ | 3.5 ± 0.9 | 3.1 ± 0.6 | 4.1 ± 1.1 |
| Corrected $^{14}CO_2$ conc. (atoms g$^{-1}$) | 290 ± 120 | 260 ± 60 | 220 ± 80 |
| Age (ka) | 9 ± 3 | 10 ± 2 | 13 ± 3 |
| Ablation rate (cm a$^{-1}$) | 10.1 ± 1.4 | 10.9 ± 0.9 | 11 ± 2 |
| Ablation rate (cm a$^{-1}$) from stake readings | 10 | 13–16 | 13–16 |
| Ratio $^{14}C$ (in situ)/$^{14}C$ (natural) | 1.1 ± 0.5 | 0.4 ± 0.2 | 1.2 ± 0.7 |
| Accumulation rate (cm w.e. a$^{-1}$) | 7 ± 3 | 20 ± 10 | 7 ± 4 |


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even if oxidation of $^{14}CO$ occurred, the derived ratio would be too small and this would result only in an *under*-estimate of the ages.

The calculated ages indicate that the surface ice at Scharffenbergbotnen is relatively young. From ice-flow considerations, "zero-age" ice is expected to be found on the equilibrium line between accumulation and ablation zones, and the oldest ice is expected to be near the boundary formed by the two opposite flow regimes. The oldest ice is still of Holocene age. The increasing age along the transect formed by cores 5, 15 and 6 is not contradicted by the $^{14}C$ data.

The ablation rates obtained are in agreement with field observations of about 10 cm $a^{-1}$ (Näslund, 1992). It has been pointed out that the ablation rate is related to the total amount of in situ $^{14}C$ in ice. Although dry extraction is known to be nearly 100% efficient when applied to gases, its efficiency when applied to in situ $^{14}CO_2$ and $^{14}CO$ is still unknown. The similarity of ablation rates obtained from field observations and from $^{14}C$ measurements indicates that in situ products have been extracted almost completely. In fact, $^{14}C$ ablation rates tend to be even lower than those from field observations, possibly due to the 4 a average of the stake readings, which is shorter than the 20 a period average of the $^{14}C$ data. This shows that a precise determination of the extraction efficiency should make it possible to determine mean ablation rates.

Although some loss of in situ $^{14}C$ from the firn cannot be ruled out, Jull and others (1994) recently reported on high concentrations of $^{14}C$ in two Antarctic ice cores, and their data support the approximately total retention of in situ $^{14}C$. In our calculation of accumulation rates we assume total retention.

The calculated accumulation rates are proportional to the production rates, which in turn are a function of the altitude at the ice origin. Calculation of accumulation rates requires knowledge of the altitude of the area where the ice was formed. The calculated ages indicate a nearby origin, since reported surface velocities in Scharffenbergbotnen are only about 1 m $a^{-1}$ (Jonsson, 1992). The accumulation zone may be located on the westerly ice divides (altitude 1240 m). This view is supported by the air content data of core 15. Using the empirical relation between total gas content and altitude of the area where the ice is formed (Raynaud and Lebel, 1979), a maximum altitude of 1900 m can be derived assuming a 100% gas-extraction efficiency. The obtained accumulation rates of approximately 7–20 cm w.e. $a^{-1}$ are in the same range as the value at the equilibrium line and a present-day value found 5 km from the valley, 20 cm w.e. $a^{-1}$ (Jonsson, 1992). It would be valuable to compare the information obtained about ages and ablation and accumulation rates with results obtained with an ice-flow model. This model should focus on the local flow around Scharffenbergbotnen. Of course, this would mean extension of the measurements to parts of the blue-ice area that have lower ablation rates and younger ages.

## CONCLUSIONS

It is shown that $^{14}C$ ages can be determined in surface ice samples using the dry-extraction method. However, the correction that has to be made for the in situ component in $^{14}CO_2$ exceeds the natural value. This means significant errors of about 25% in the final ages. Calculated ages are $10\,000 \pm 3000$ BP; these values are supported by the $CO_2$ concentrations of the ice samples and indicate that most of the surface ice of Scharffenbergbotnen is of Holocene age. The deduced ablation rates are in agreement with field observations, indicating an almost complete extraction for in situ produced $^{14}C$. The deduced ages, and measurements of the air yield, support a nearby accumulation zone as the area where the ice was formed. The area is presumably at the westerly ice divides.

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