Isotope measurements and firn stratigraphy on ice caps surrounding the North Water polynya

F. Müller, B. Stauffer and G. Schriber

Abstract. With the aim of assessing the effect of the North Water polynya on the accumulation rates and the thermal regime of the ice masses on the surrounding land, firn samples were collected for ^{18}O and T analyses and firn stratigraphy carried out in pits and on cores to depths of up to 25.6 m at six sites. The preliminary findings indicate that a combined application of the two techniques produces useful results in spite of the homogenizing effect of percolating meltwater in the lower accumulation zones.

Mesures des isotopes et la stratigraphie du névé sur des calottes glaciaires autour de la polynya du 'North Water'

Résumé. Dans le but d'évaluer l'effet de la polynya du 'North Water' sur le degré d'accumulation et le régime thermique des masses de glace sur la terre autour du 'North Water', des échantillons de névé ont été pris pour les analyses de ^{18}O et T, et la stratigraphie du névé a été faite dans des puits et avec des carottes de névé obtenues par forage jusqu'à une profondeur de 25.6 m à six endroits. La conclusion peut en être tirée que l'application jointe des deux techniques puisse donner des résultats utiles, malgré l'effet homogénéisant de l'eau de fonte s'infiltrant dans les zones inférieures d'accumulation.

INTRODUCTION

For some twenty years the measurement of isotopes in snow and ice samples from the polar regions has been used to determine age and net accumulation rates (Benson, 1962; Epstein *et al.*, 1963; Picciotto *et al.*, 1964; Aegerter *et al.*, 1969; Merlivat *et al.*, 1973; Prantl *et al.*, 1974). In recent years more and more efforts have been made to also deduce climatic information—mainly temperature

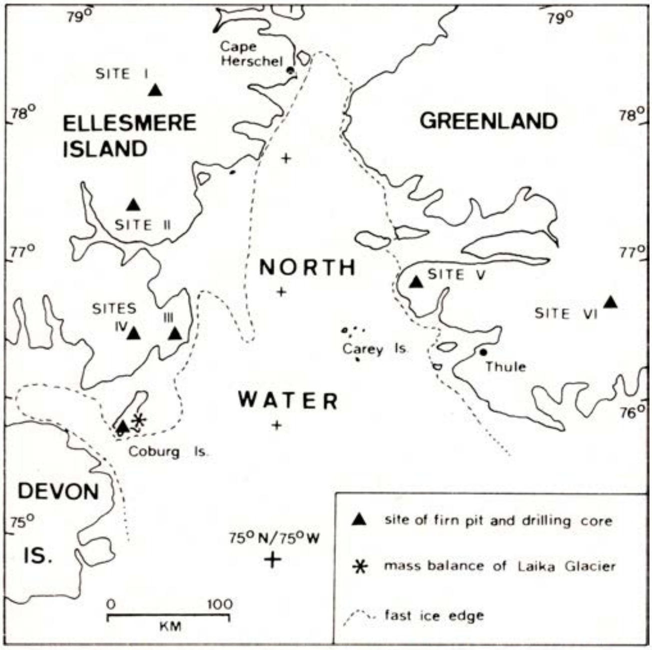

FIGURE 1. Location map.

—from the isotope content of the snow, firn and ice of these areas (Dansgaard *et al.*, 1969, 1973; Ambach and Dansgaard, 1970).

The present isotope investigation carried out in conjunction with firn stratigraphic work was part of an attempt to assess the extent and magnitude of the influence of the North Water polynya (an area of open water and reduced sea ice thickness) in northern Baffin Bay, between northwest Greenland and Ellesmere Island (Fig. 1) (Müller *et al.*, 1973). Moisture and heat is being transferred from the polynya to the surrounding glaciers and ice caps; with accumulation and temperature data the lateral and altitudinal extent of these effects may be estimated.

The present paper concentrates on the problems and results of $^{18}O/^{16}O$ ratio measurements and tritium analyses used together with classical snow and firn stratigraphy. Total β-activity will be discussed in a separate paper when more samples from the lower accumulation zones are obtained and analysed. There was uncertainty as to whether the radioactive layers and $\delta(^{18}O)$ variations could be found in the Lower Percolation Zone and below (for zonation scheme see Müller, 1962). The intense melting occurring in these zones during the summer may obliterate the isotopic peaks. This would be unfortunate, as it is evident from the climatic data that the North Water influence is strongest in the immediate surroundings of the polynya, i.e. on the low-lying nearby glaciers and ice caps. From radiosonde measurements in the area it was found that the vertical extent of the heating effect reaches at most the 850 mb level (Müller *et al.*, 1976).

FIELD WORK AND DATA COMPILATION

In April and May 1974 firn pits were dug and cores taken at three sites on Ellesmere Island (Fig. 1. nos. I, II, III) and at two sites on the Thule Peninsula, Greenland (nos. V, VI). In addition, Dr R. M. Koerner (Canadian Polar Continental Shelf Project) provided part of a core towards this programme (no. IV). In mid-June 1974 a shaft was dug down to superimposed ice on the

TABLE 1. Site description and sampling programme

Position + elevation	Accumulation zone	Depth reached	$\delta(^{18}O)$ samples	T and β-samples (depth)
Site I (1390 m) 78°25′N, 80°W	upper end of Lower Percolation Z.	pit 5.6 m	120 × 5 cm	—
		core 25.6 m	200 × 10 cm	33 (5.6 to 10.2 m)
Site II (1350 m) 77°33′N, 80°20′W	middle part of Lower Percolation Z.	pit 5.2 m	100 × 5 cm	—
		core 22.2 m		28 (6.2 to 10.1 m)
Site III (660 m) 76°38′N, 78°22′W	lower end of Lower Percolation Z.	pit 1.7 m	100 × 5 cm	—
		core 10.0 m		22 (7 to 10 m)
Site IV (900 m) 76°35′N, 79°30′W	Lower Percolation to Slush Zone	core 3.9 m	72 × 5 cm	—
Laika I.C. (490 m) 75°55′N, 79°15′W	Slush and Superimposed Ice Z.	pit 1.6 m	43 × 2–6 cm	—
		core 10.0 m		
Site V (1100 m) 77°04′N, 70°25′W	upper end of Slush Zone	pit 1.7 m	100 × 5 cm	—
		core 7.0 m		12 (4.7 to 6.1 m)
Site VI (1560 m) 76°46′N, 64°35′W	lower end of Upper Percolation Z.	pit 3.4 m	100 × 5 cm	—
		core 22.1 m		146 (5 to 21 m)

Laika Ice Cap on Coburg Island. Particulars of all these sites are given in Table 1. The drilling was performed with a Teflon coated 3-in. SIPRE auger and the cores dissected in the field. The samples were dispatched to the University of Bern for analysis for ^{18}O in 20 ml air-tight glass jars, and for tritium and β-activity in 500 ml sealed tin cans and plastic bottles.

The firn stratigraphy of the pits (density, grain size and type, hardness, melt and metamorphic features and temperature profiles) was done in great detail so as to establish the main patterns of accumulation and to aid in the assessment of the cores. The ^{18}O-measurements are made with a mass spectrometer. The technique for T-measurements used at the Low Level Counting Laboratory, Bern, is described by Siegenthaler *et al.* (1975). The compilation of the isotopic data for this study was made by Schriber (1974).

DISCUSSION OF RESULTS

$\delta(^{18}O)$ variations and firn stratigraphy (Fig. 2 and unpublished data)
At sites I and VI seasonal variations of the $\delta(^{18}O)$-values are well preserved. Observed irregularities in the isotopic patterns can in most cases be explained in terms of summer melt and snow drifting and scouring. The good agreement in the general trend and in the detail of these patterns testifies to the usefulness of stable isotope studies not only in the Dry Snow Zone but also in the transition area of the Upper to the Lower Percolation Zone. For example the agreement in the increase of the size of the winter minima 1969–1970 to 1972–1973

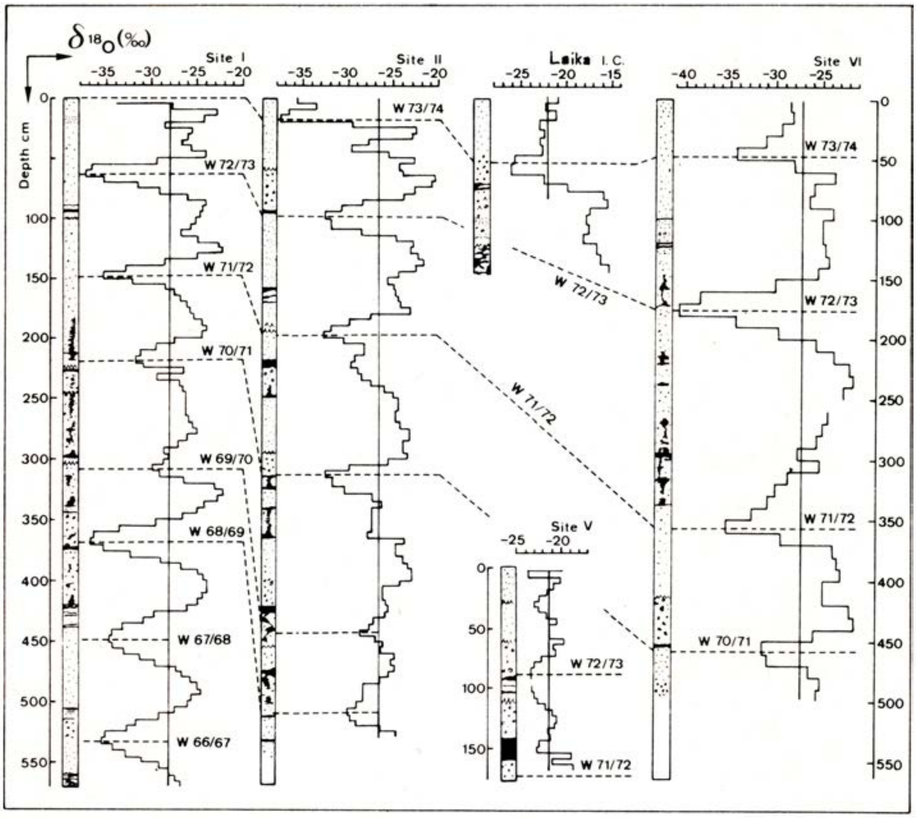

FIGURE 2. $\delta(^{18}O)$ variations and melt features at five sites.

observed at sites I and VI is paralleled in the D/H profile on the Devon Ice Cap at a site located 1800 m a.s.l. (Prantl *et al.*, 1974, p. 635). This shift of winter values probably does not result from temperature lowering; the pit stratigraphy clearly suggests that a slightly more than usual amount of melting during the summers 1970, 1971 and 1972 caused the isotopically heavy percolation water to penetrate into the previous winter layers. At site I this homogenization process was particularly strong during the summers from 1956 to 1962, a period in which increasingly heavy summer melting was also observed elsewhere in the Canadian High Arctic (e.g. Koerner, 1970). On the other hand, during the period 1963–1969 and the decade prior to 1956, when less summer melting took place, well developed seasonal fluctuations of $\delta(^{18}O)$ values were observed.

At site II, situated at a slightly lower elevation and in orographically more irregular terrain, the influence of percolation water would have reduced the effectiveness of both the isotope and the snow stratigraphic technique if there had not been a one-third increase in the annual accumulation rate here as compared with site I.

At sites III, V and Laika Ice Cap where heavy summer melt dominated the profiles, seasonal $\delta(^{18}O)$ fluctuations could only be followed for the last few annual cycles. On the Laika Ice Cap only one annual cycle was well developed. At site III—because of large accumulation rates—the firn stratigraphic method still permitted analysis of the core. Unfortunately, this was not possible for the lower portion of the site V core.

Mean annual air temperatures ($\bar{T}_a$) from $\delta(^{18}O)$ data and 10 m firn temperatures ($\bar{T}_f$) (Table 2, part A)

The 10-m firn temperatures measured in any of the accumulation zones situated below the Dry Snow Limit are affected by meltwater percolation, particularly in the Lower Percolation Zone and are therefore often several degrees higher than the corresponding air temperatures (Müller, 1976). On the other hand, mean annual air temperatures calculated from $\delta(^{18}O)$ profiles in firn, being based on a different physical process, should provide alternative and independent data. However, there are also several uncertainties involved in this approach (latitude and inland effects, admixture of local moisture). As suggested by Dansgaard *et al.* (1973, fig. 2), the equation

$$\delta(^{18}O) = 0.62\bar{T}_a - 15.6‰$$

was used for the ice cap stations situated above 1000 m elevation (sites I, II, V, VI), while the equation

$$\delta(^{18}O) = \bar{T}_a - 6.6‰$$

was applied for the lower lying stations and again for site V. The latter equation, meant for sea level stations, assumes local moisture admixture. As the mean $\delta(^{18}O)$ values do not cover the same time spans and because of the uncertainties mentioned above, the resulting temperatures are not strictly comparable. Especially the $\bar{T}_a$ values obtained for the lower stations are no more than approximations. Nevertheless, the following tentative conclusions can be drawn:

(1) The unexpectedly high $\bar{T}_a$ values obtained for site V with both the 'ice cap' and the 'sea level' equations indicate a strong North Water warming effect in this area. This finding is supported by the heavy melt metamorphism observed at this site.

(2) The almost identical and generally high mean $\delta(^{18}O)$ values for the sites III, Laika Ice Cap and V suggest approximately isothermal and relatively warm conditions for the first 1000 m of elevation in the North Water surroundings.

TABLE 2. Mean annual air temperature ($\bar{T}_a$) as calculated from $\delta(^{18}O)$ values and mean net balance (b_n) prior to 1974 at six ice cap locations around North Water

		A. Mean annual temperatures				B. Mean net balance b_n		
Location	Depth [m]	Period	$\delta(^{18}O)$ [‰]	$\bar{T}_a$ [°C]	$\bar{T}_f$ 10 m [°C]	Depth [m]	N (years)	b_n [cm water equiv.]
Site I	0–5.7	Su '66–Apr. '74	−28.1	$-20.0^{(a)}$	−19 ± 1	25.6	27 (1946–)	42.7 ± 13.6
	6–16	Su '54–Su '66	−27.7	$-19.6^{(a)}$				
Site II	0–5.3	Su '68–Apr. '74	−26.8	$-18.0^{(a)}$	−17 ± 1	22.2	17 (1956–)	57.2 ± 14.6
Site III	0–2.7	Su '71–Apr. '74	−21.1	$-14.5^{(b)}$	−11 ± 1	10.0	6 (1967–)	71.3 ± 22.2?
Laika I.C.	0–1	Su '73–Su '74	−21.1	$-14.5^{(b)}$	−11.2 ± 0.2		2 (1973–)	26
Site V	0–1.7	Su '72–Apr. '74	−21.4	$(-14.8^{(b)})$ $(-9.3^{(a)})$	−12 ± 1	4.5	5 (1968–)	46.3 ± 26.6?
Site VI	0–5	Wi '70/1–Apr. '74	−27.1	$-18.5^{(a)}$	−19 ± 1	22.1	16 (1957–)	71.3 ± 13.9

(a) calculated using $\delta(^{18}O) = 0.62\,\bar{T}_a - 15.6‰$.
(b) calculated using $\delta(^{18}O) = \bar{T}_a - 6.6‰$.

The radiosonde data from the Coburg Island meteorological station (in horizontal distance only a few kilometres from the Laika Ice Cap snow pit) gives a mean air temperature at the 500 m level of −12.5°C for the same time span as covered by the $\delta(^{18}O)$ profile, thus indicating that the equation

$$\delta(^{18}O) = \bar{T}_a - 6.6^{0}/_{00}$$

produces slightly too low $\bar{T}_a$ values for the North Water area.

(3) North Water warming seems to have little effect on the 'isotopic' $\bar{T}_a$ values of sites I, II, VI and 1a–20 (a site investigated by Benson, 1962, situated 100 m higher and some 40 km further east than site VI, with a mean $\delta(^{18}O) \simeq -27^{0}/_{00}$). This conclusion is supported by the large environmental lapse rate existing above about 1000 m elevation, and by the good fit of these $\bar{T}_a$ values with the surface temperature patterns calculated for the Thule Peninsula by Mock and Weeks (1965, fig. 15).

Tritium measurements and accumulation rates

In 1954 and again in 1959 and 1963, the tritium concentration in the precipitation of the Northern Hemisphere was drastically raised as a result of nuclear bomb tests in the atmosphere. These events form 'Leithorizonte' in the arctic accumulation. It was decided to concentrate the search for an absolute

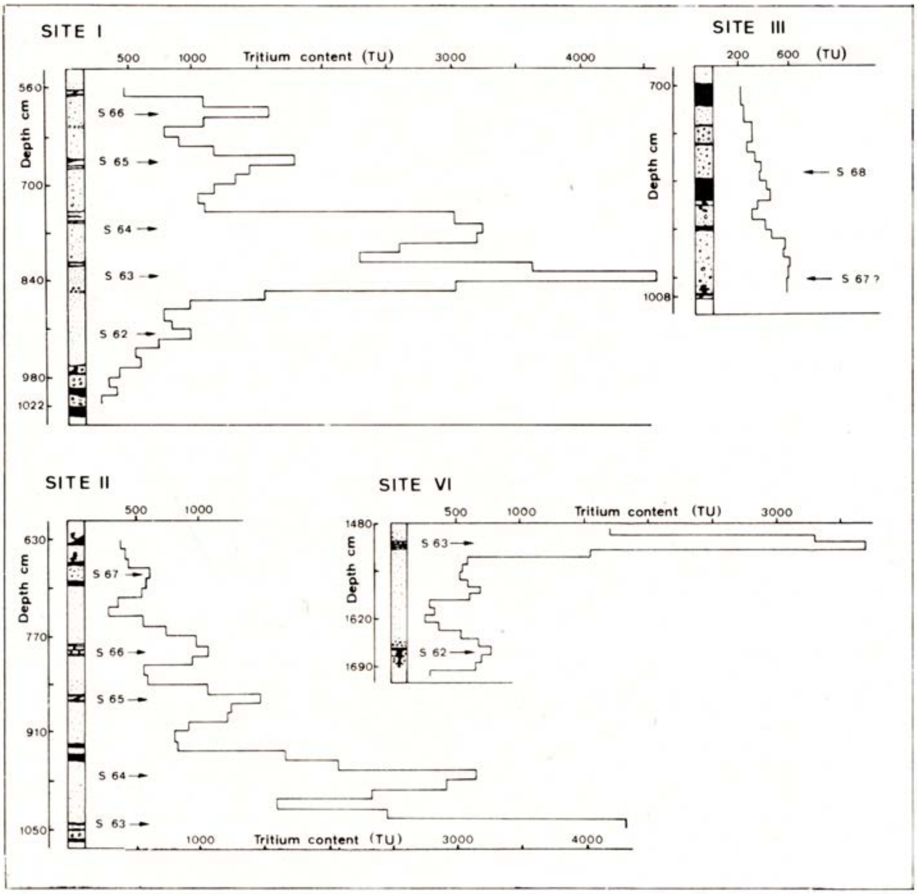

FIGURE 3. Tritium measurements in four cores.

dating horizon on the 1963 level which could also be expected to be better preserved than the older ones, especially as experience elsewhere in the Canadian Arctic had shown that the summers 1963–1965 (inclusive) had produced relatively little melt.

Figure 3, showing the tritium profiles obtained from four of the cores, demonstrates that this technique produces excellent results in all the accumulation zones situated above the middle of the Lower Percolation Zone. Even if the core of site III had reached the desired depth of some 16 m there would not have been much hope of finding a clear reference horizon, as the lower portion of this T-profile would have been strongly homogenized by meltwater percolation. In this context the finding by Ambach and Dansgaard (1970) and Prantl *et al.* (1974) that total β-activity of fission products from nuclear bomb tests deposited in the snow and firn may be less affected by melting and percolation processes than the tritium content is of great interest.

Tritium reference horizons, firn stratigraphic work and $\delta(^{18}O)$ variation profiles together permitted calculation of the accumulation rates listed in Table 2, part B. On the Ellesmere side of the polynya an increase in net balance values from north to south and from high to low altitude is noticed. Koerner's (personal communication) b_n values for site IV, averaging 46.8 cm water equivalent, support this pattern. The low net balance for the Laika Ice Cap is due to strong runoff and snow drifting, a fact made obvious by the large winter accumulations in 1973–1974 and 1974–1975, found to average 54 cm water equivalent.

On the Greenland side North Water moisture seems to have increased accumulation rates of sites V and VI Higher on the Thule Peninsula, Mock (1968) attributes the large accumulation observed there to Melville Bay influence. At site VI, the two influences may be combined.

CONCLUSION

The combined application of isotope measurement and snow stratigraphy provides a useful tool to assess the environmental influences of a large polynya on its surroundings. The results are better for higher elevations. For low-lying areas total β-activity measurements may still improve the results obtained so far.

Acknowledgements. The project was supported financially by the Government of Canada (contract no. OSX4-0098), by the US National Science Foundation (contract no. GV-40404A1) and by the Schweizerischer Nationalfonds (contracts no. 2.383.70 and no. 2.596.71). Logistic support in the field was generously made available by the Polar Continental Shelf Project, Department of Energy, Mines and Resourses of Canada and by the Canadian Coast Guard, Ministry of Transport. The efforts of many in the field, in the office and in the laboratory are gratefully acknowledged.

REFERENCES

Ambach, W. and Dansgaard, W. (1970) Fall out and climate studies on firn cores from Carrefour, Greenland. *Earth Planet. Sci. Lett.* **8**, 311–316.

Aegerter, S., Oeschger, H., Renaud, A. and Schumacher, E. (1969) Tritium studies on firn samples collected by E.G.I.G. in Greenland. *Medd. Grønland* **177**, no. 2, 76–88.

Benson, C. S. (1962) Stratigraphic studies in the snow and firn of the Greenland ice sheet. *S.I.P.R.E. Research Report, no. 70*, 93 pp.

Dansgaard, W. (1964) Stable isotopes in precipitation. *Tellus* **16**, no. 4, 436–468.

Dansgaard, W., Johnsen, S. J., Møller, J. and Langway, C. C. Jr (1969) One thousand centuries of climatic record from Camp Century on the Greenland ice sheet. *Science* **166**, 377–381.

Dansgaard, W., Johnsen, S. J., Clausen, H. B. and Gundestrup, N. (1973) Stable isotope glaciology. *Medd. Grønland* **197**, no. 2, 53 pp.

Epstein, S., Sharp, R. P. and Goddard, I. (1963) Oxygen isotope ratios in Antarctic snow, firn and ice. *J. Geol.* **71**, no. 6, 698–720.

Koerner, R. M. (1970) The mass balance of the Devon Island Ice Cap, Northwest Territories, Canada, 1961–1966. *J. Glaciol.* **9**, no. 57, 325–336.

Merlivat, L., Ravoire, J., Vergnaud, J. P. and Lorius, C. (1973) Tritium and deuterium content of the snow in Greenland. *Earth Planet. Sci. Lett.* **19**, 235–240.

Mock, S. J. (1968) Snow accumulation on the Thule Peninsula, Greenland. *J. Glaciol.* **7**, no. 49, 59–76.

Mock, S. J. and Weeks, W. F. (1965) The distribution of 10 m snow temperatures on the Greenland Ice Sheet. *CRREL Research Report 170*, 44 pp.

Müller, F. (1962) Zonation in the accumulation area of the glaciers of Axel Heiberg Island, N.W.T., Canada. *J. Glaciol.* **4**, no. 33, 302–311.

Müller, F. (1976) On the thermal regime of a high Arctic valley glacier. Proceedings of Symposium on the Thermal Regime of Glaciers and Ice Sheets, Canada, April 1975. *J. Glaciol.* **16**, no. 74, 119–133.

Müller, F., Ohmura, A. and Braithwaite, R. J. (1973) Das North Water Projekt (kanadisch-grönländische Hocharktis). *Geographica Helvetica* **28**, Jahrgang, Heft 2, 111–117.

Müller, F., Ohmura, A. and Braithewaite, R. J. (1976) On the climatic influence of North Water. *Proceedings of International Geographical Union Congress, Moscow, July/August 1976.*

Picciotto, E., Crozaz, G. and de Breuck, W. (1964) Rate of accumulation of snow at the South Pole as determined by radioactive measurements. *Nature* **203**, 3931–3934.

Prantl, F., Koerner, R. M. and Robertson, E. (1974) Nuclear techniques for snow and ice studies in Canadian subpolar regions (Devon Island). *Proceedings of a Symposium on Advanced Concepts and Techniques in the Study of Snow and Ice Resources*, pp. 632–641: National Academy of Sciences, Washington DC, USA.

Schriber, G. (1974) Isotopenuntersuchungen im Rahmen des North Water Projektes. Diploma Thesis, University of Bern, 78 pp.

Schriber, G., Stauffer, B. and Müller, F. (1977) $^{18}O/^{16}O$, $^{2}H/^{1}H$ and ^{3}H measurements on precipitation and air moisture samples from the North Water area. In *Isotopes and Impurities in Snow and Ice* (Proceedings of the Grenoble Symposium, August–September 1975), pp. 182–187: IAHS Publ. no. 118.

Siegenthaler, U., Oeschger, H., Schotterer, U. and Hänni, K. (1975) Conversion of water to a counting gas for low-level tritium measurements by means of aluminium carbide. *Int. J. Appl. Radiation and Isotopes* **26**, 459–464.

DISCUSSION

Fisher:
At the place where you took pit samples how many pits did you make in each area?

Müller:
Usually only one pit was dug. However, a separate investigation of the stable isotope variability was carried out during the occupancy of the Coburg base station between 1972 and 1974 when samples were taken of the developing snow cover at different times and at a variety of sites. This study is not completed yet.

Fisher:
You remarked on the discrepancies observed between the maxima respectively minima of the $\delta(^{18}O)$ values and those of tritium.

Müller:
The difference between $\delta(^{18}O)$ and tritium peaks seems to be frequent and systematic. Professor Oeschger has put forward an explanation for this phenomenon.

Oeschger:
For the $\delta(^{18}O)$ and tritium maxima independent mechanisms are responsible. $\delta(^{18}O)$ maxima represent snow which fell during the warm part of the accumulation period, whereas high tritium values are observed in periods of high mixing through the tropopause in spring and early summer. The two phenomena therefore are not necessarily in phase. (Oeschger and Siegenthaler, 1972)

Fisher:
$\delta(^{18}O)$-time series taken from pits or cores close together seem to have correlation coefficients that lie between 0.4 and 0.7. Reeh's paper (Reeh *et al.*, 1977) takes up part of this question.

REFERENCES TO DISCUSSION

Oeschger, H. and Siegenthaler, U. (1972) Umgebungsisotope im Dienste der Hydrologie und Ausblick auf neue Methoden, GWF. *Das Gas- und Wasserfach, Wasser, Abwasser* **113**. Jahrgang, Heft 11, 501–552.

Reeh, N., Clausen, H. B., Gundestrup, N., Johnsen, S. J. and Stauffer, B. (1977) $\delta(^{18}O)$ and accumulation rate distributions in the Dye-3 area, south Greenland. In *Isotopes and Impurities in Snow and Ice* (Proceedings of the Grenoble Symposium, August–September 1975), pp. 171–181: IAHS Publ. no. 118.