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CORE DRILLING ON VERNAGTFERNER (OETZTAL ALPS, AUSTRIA) IN 1979: DEUTERIUM AND OXYGEN-18 CONTENTS

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With 8 figures

ABSTRACT

In March, 1979, core drillings were made on Vernagtferner (Oetztal Alps, Austria). The entire core I (81 m) was divided into 2.5 cm sections, from which ^{2}H and ^{18}O measurements were made. The measurements on core II (45 m) were made only along selected sections. A summary is given of the changes which occur in the deuterium excess d due to evaporation or melting in a snow cover. The resulting oscillations in excess d values are then used for dating the ice in core I. These oscillations in excess d resolve the yearly firn and ice layers better than the corresponding oscillations in the ^{2}H or ^{18}O content. An age of between 75 and 83 years, and a corresponding average yearly accumulation rate of between 0.85 and 0.77 m water equivalent was calculated for the core. Although a comparison of the isotope contents in core I with temperature data from Vent (Oetztal) yields a discrepancy of four years, the rise in temperature in the second half of the 1940's is clearly reflected by a corresponding rise in isotope content along the core. The results of these isotope analyses are also compared to results from an earlier core drilling on the Vernagtferner, as well as from a core drilling on the cold Grenzgletscher, Switzerland.

KERNBOHRUNGEN AM VERNAGTFERNER (ÖTZTALER ALPEN, ÖSTERREICH) IM JAHR 1979: ERGEBNISSE DER DEUTERIUM- UND SAUERSTOFF-18-GEHALTSBESTIMMUNG

ZUSAMMENFASSUNG

Im März 1979 wurden auf dem Vernagtferner (Ötztaler Alpen, Österreich) Kernbohrungen niedergebracht. Am gesamten Bohrkern I (81 m) wurden der ^{2}H- und ^{18}O-Gehalt an jeweils 2,5 cm langen Probenstücken gemessen; am Bohrkern II (45 m) nur an ausgewählten Kernabschnitten. Einleitend werden die Veränderungen beschrieben, die der Deuteriumexzeß d erfährt, wenn an der Oberfläche einer Schneedecke Verdunstung oder Schmelzung auftritt. Zur Datierung des Bohrkerns I werden die Schwankungen des Deuteriumexzesses herangezogen, die ein klareres Bild der jährlichen Schichtenfolge erkennen lassen, als die jahreszeitlichen Schwankungen des ^{2}H- oder ^{18}O-Gehalts. Es ergab sich für den Bohrkern ein Alter zwischen 75 und 83 Jahren und dementsprechend eine mittlere Akkumulationsrate zwischen 0.85 und 0.77 m Wasseräquivalent pro Jahr. Ein Vergleich der Isotopengehalte im Bohrkern mit den Temperaturdaten von Vent (Ötztal) ergibt zwar eine Diskrepanz von vier Jahren, aber die Temperaturerhöhung in der zweiten Hälfte der vierziger Jahre ist durch eine Erhöhung des Isotopengehalts im Bohrkern markiert. Die Ergebnisse der Isotopenanalysen werden auch mit den Ergebnissen einer früheren Bohrung auf dem Vernagtferner und mit einer Bohrung auf einem kalten Gletscher (Grenzgletscher, Schweiz) verglichen.

1. INTRODUCTION

In the natural water cycle the ratios of the stable isotopes of hydrogen ($^2H/^1H$) and oxygen ($^{18}O/^{16}O$) do not remain constant. Precipitation exhibits seasonal variations of its ^2H and ^{18}O contents which depend essentially on the origin of the water vapour and on the condensation temperature. Many measurements and calculations reveal that it is possible to establish a relation between isotope content and temperature in such small regions for which the meteorological conditions are rather uniform (e. g. Aldaz and Deutsch, 1967; Stichler and Herrmann, 1978). Figure 1 a shows the seasonal variation of monthly means, averaged over an observation period of 5 years, of temperature and ^2H content for precipitation in Vent (Oetztal, Austria), and fig 1 b shows the correlation between them. This annual variation of the isotope content of precipitation usually remains detectable in snow covers (Moser and Stichler, 1975).

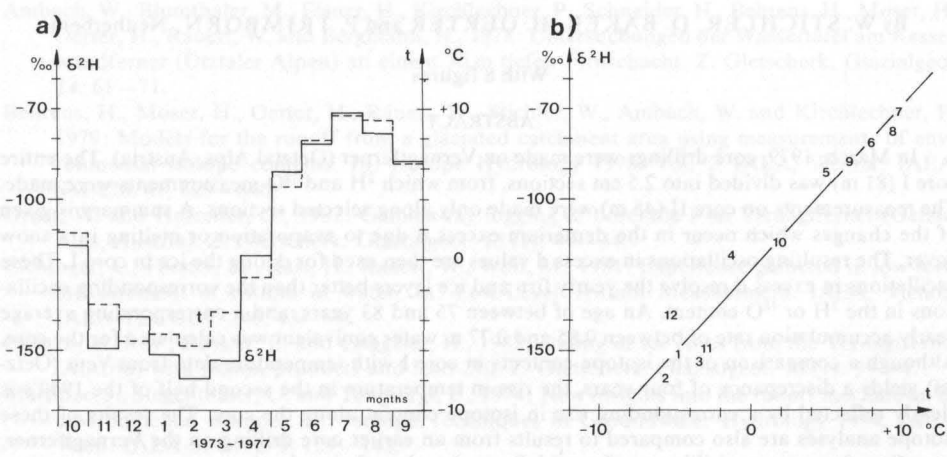

Fig. 1: Meteorological station Vent (1900 m a. s. l.: Oetztal, Austria):
a) 5-year means of monthly air temperatures (t) and of monthly means of the ^2H content in precipitation (δ^2H).
b) Relationship between air temperature (t) and ^2H content in precipitation (δ^2H) for the monthly mean values shown in fig. 1 a. The numbers are assigned to the months January (1) through December (12). The ^2H content shows an increase of approximately 5 ‰ per 1° C.

In studies on cold glaciers of the Greenland and Antarctic ice shields, measurements of stable isotopes have been used as indicators for dating and computing accumulation rates (e. g. Reeh et al., 1978; Reinwarth et al., 1982). The precipitation there falls only in solid phase and melting of the deposited snow is practically negligible.

For temperate Alpine glaciers only a few measurements of stable isotopes in firn and ice samples are available (Deutsch et al., 1966; Behrens et al., 1979). The isotope variations found here appear to be much more complicated then in cold glaciers. In the firn areas of temperate glaciers the annual precipitation is not normally made up entirely of snow. Very important are also the effects of melting and evaporating processes, as well as the influence of meltwater seepage through snow and firn. The following considerations, which are based on results of cold chamber experiments and field measurements, should demonstrate the possibility of using stable isotope measurements for dating temperate Alpine glaciers.

2. EXPERIMENTAL

In natural water the concentration of ^2H varies between 220 and 340 ppm (parts per million), and that of ^{18}O between 1920 and 2010 ppm. These small concentrations are determined using sensitive mass spectrometers with special preceding preparations. Usually the isotope contents are indicated in terms of relative deviations δ^2H and $\delta^{18}O$, respectively, from an international standard (V-SMOW). These δ values are defined by the relation

$$\delta^2H \text{ or } \delta^{18}O = \left(\frac{R_{sample}}{R_{standard}} - 1\right) 1000 \text{ (‰)}$$

R_{sample} and $R_{standard}$ are the isotope ratios of hydrogen $^2H/^1H$ and oxygen $^{18}O/^{16}O$, respectively, in the sample and in standard water. The measuring accuracy is ± 1 ‰ for deuterium and ± 0.15 ‰ for oxygen-18.

2.1 THE DEUTERIUM EXCESS d

Normally it does not seem possible to date ice cores from temperate glaciers by means of ^2H and ^{18}O isotope analysis using only the mentioned seasonal variation of the ^2H and ^{18}O content in the precipitation. We checked the feasibility of obtaining additional dating information from the relationship between both isotopes, which is generally given by the equation

$$\delta^2H = 8\,\delta^{18}O + d,$$

where d is the so-called deuterium excess which depends on climatic conditions. After the snow is deposited the deuterium excess of the snow cover will be changed by isotope fractionation processes at the surface. These effects probably can be used as a further tool to date firn and ice layers of a temperate glacier. The possible changes of the deuterium excess are demonstrated by the examples given in fig. 2.

Isotopic effects due to evaporation on the snow surface, and due to condensation of atmospheric moisture at the snow surface still remain for the large part uninvestigated. Preliminary tests with respect to the relationship between variations in isotope contents and evaporation losses of snow samples have been performed in a cold chamber keeping temperature ($-10°$ C) and humidity (85 %) fairly constant during the time of experiment (Moser and Stichler, 1975). The observed relative mass losses of the snow samples were accompanied by a decrease of the deuterium excess calculated from the δ^2H and $\delta^{18}O$ values of the remaining snow samples (fig. 2a).

Figure 2b shows that in a natural snow cover, the increase in the δ^2H values of the snow surface (the topmost 1—2 cm of the snow cover), caused by evaporation during day time, is compensated by condensation of air moisture during night time (Moser and Stichler, 1983). The same is reflected in the fluctuations of the deuterium excess. Whereas the absolute level of the ^2H content increased when new air masses (indicated by the change of humidity) were transported into the investigation area, the values of the deuterium excess d did not show any significant change.

Isotopic effects occuring during melting processes also cause changes in the deuterium excess values. Melting experiments with 35 cm long snow columns were carried out in a cold chamber with constant temperature a few tenths of a degree below 0° C, and at a relative air humidity of about 60 % (Herrmann et al., 1981). In fig. 2c the deu-

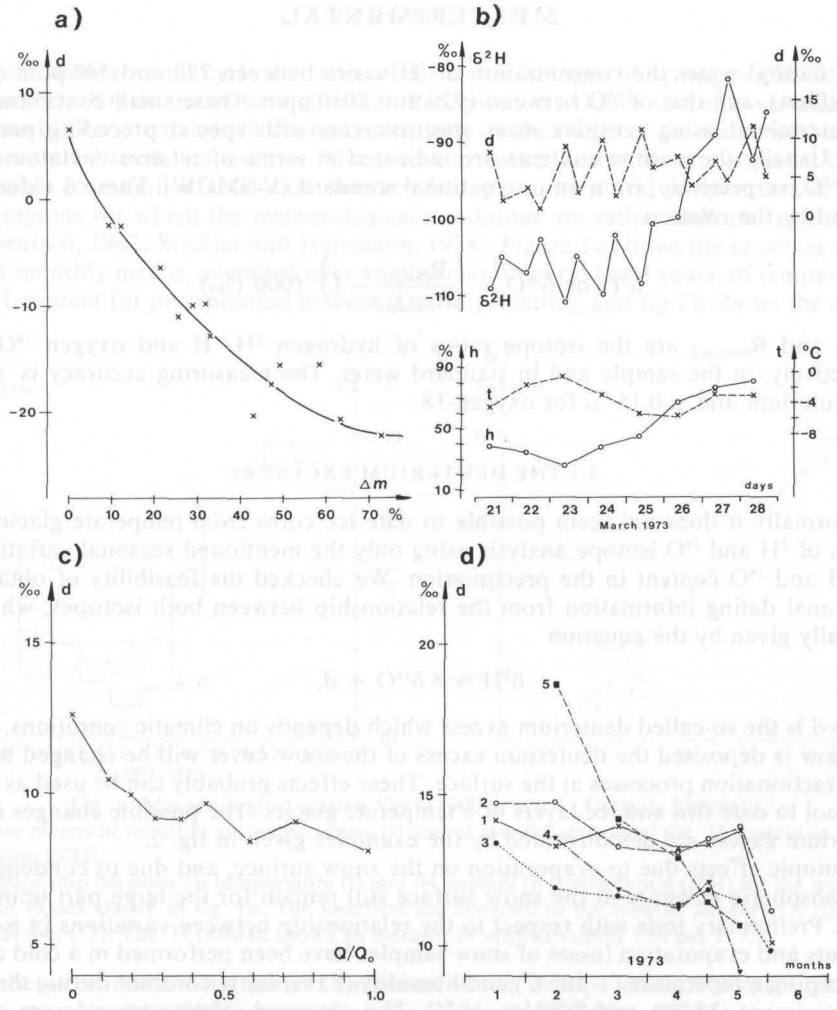

Fig. 2: Variations of the deuterium excess d due to evaporation and melting processes in snow samples from cold chamber experiments (a and c) and in natural snow covers (b and d).

a) Relationship between deuterium excess d and the mass losses Δm of a snow sample due to evaporation. Δm is the ratio of the evaporated amount of snow to the original mass of the snow sample (after Moser and Stichler, 1975).

b) Diurnal variation of the ^2H content and the deuterium excess d in a natural snow cover surface (topmost 1—2 cm) due to evaporation during day time and condensation during night time. Air temperature t and humidity h during the time of observation are also shown (from Moser and Stichler, 1983).

c) Relationship between deuterium excess d and the relative runoff of meltwater Q/Q_0 in a snow column due to melting. Q/Q_0 is the ratio of the meltwater amount to the total amount of snow during the time of experiment (after Herrmann et al., 1981).

d) Variations of deuterium excess d in different layers (numbers 1—5) of a natural snow cover at Weißfluhjoch/Davos (2540 m a. s. l.; Switzerland) in the time period January—June, 1973 (after Martinec et al., 1977).

terium excess, calculated from the δ^2H and $\delta^{18}O$ values of the total remaining snow, is plotted against the relative runoff of snow meltwater. During the experiment the deuterium excess decreased by about 5‰, or one third of the initial value.

Other measurements were carried out on the snow cover at Weißfluhjoch, Davos (Switzerland) at an altitude of 2540 m a. s. l. (Martinec et al., 1977). Snow samples were taken out of previously labelled snow layers, starting in January, and ending in June when the snow cover had completely melted. The changes in the deuterium excess of these snow layers are illustrated in fig. 2d. Except for one layer, the deuterium excess is more or less constant during the winter season. At the beginning of the ablation period, at the end of April, the d values start to decrease. In layer no. 5, which belongs to the surface, there is a decrease of the d value during the whole observation period.

These results indicate that besides the general enrichment of the stable isotopes ^2H and ^{18}O during ablation (melting and evaporation), the deuterium excess d decreases. These effects can be used to identify those snow layers exposed at the glacier surface during summer time.

2.2 THE DRILLING OPERATION

Core drillings were performed in March 1979 on Vernagtferner (Oetztal Alps, Austria). The drilling operation and the location of the boreholes as well as stratigraphical features of the recovered cores are described by Oerter et al. (1982). Investigations of the ^2H and the ^{18}O content were carried out on the whole of core I (total length 81.35 m), and on selected sections of core II (45.85 m). The cores were drilled 160 m apart from each other. They were cut parallel to their axes into four parts. One part with a cross section of about 14 cm^2 was further cut perpendicular to the axis into pieces 2.5 cm (core I) or 3 cm (core II) long. These small pieces were carefully melted and poured into glass bottles. The meltwater was used for ^2H, ^{18}O and ^3H measurements (Oerter and Rauert, 1982).

3. RESULTS

Figure 3 shows the results of the measurements: single values of the ^2H and ^{18}O content and the corresponding values of the calculated deuterium excess d. The δ^2H and $\delta^{18}O$ curves are very similar. They show a lot of non-periodic variations which are especially pronounced in the layers from the top of the core down to 15 m, and from 28 to 40 m. Below 40 m the variations are more regular and more similar to the annual variations as they are known for cold ice cores. A long wave variation with its maximum around 35 m and its minimum towards the bottom of the core seems to be superposed on the short wave variations. One pronounced minimum appears in both curves at 15.4 m. The δ^2H values vary within the range between -154.6 ‰ and -73.3 ‰, with an overall mean of -108.4 ‰. The $\delta^{18}O$ values vary in the range between -20.49 ‰ and -8.31 ‰, with an overall mean of -14.56 ‰. The single values of the computed deuterium excess d show much stronger variations than the original isotope contents. Without further statistic analysis no regular variations are recognizable apart from the fact that below 40 m the excess d varies around the normal value (according to precipitation of that area) of 10 ‰, whereas above 40 m the values are almost

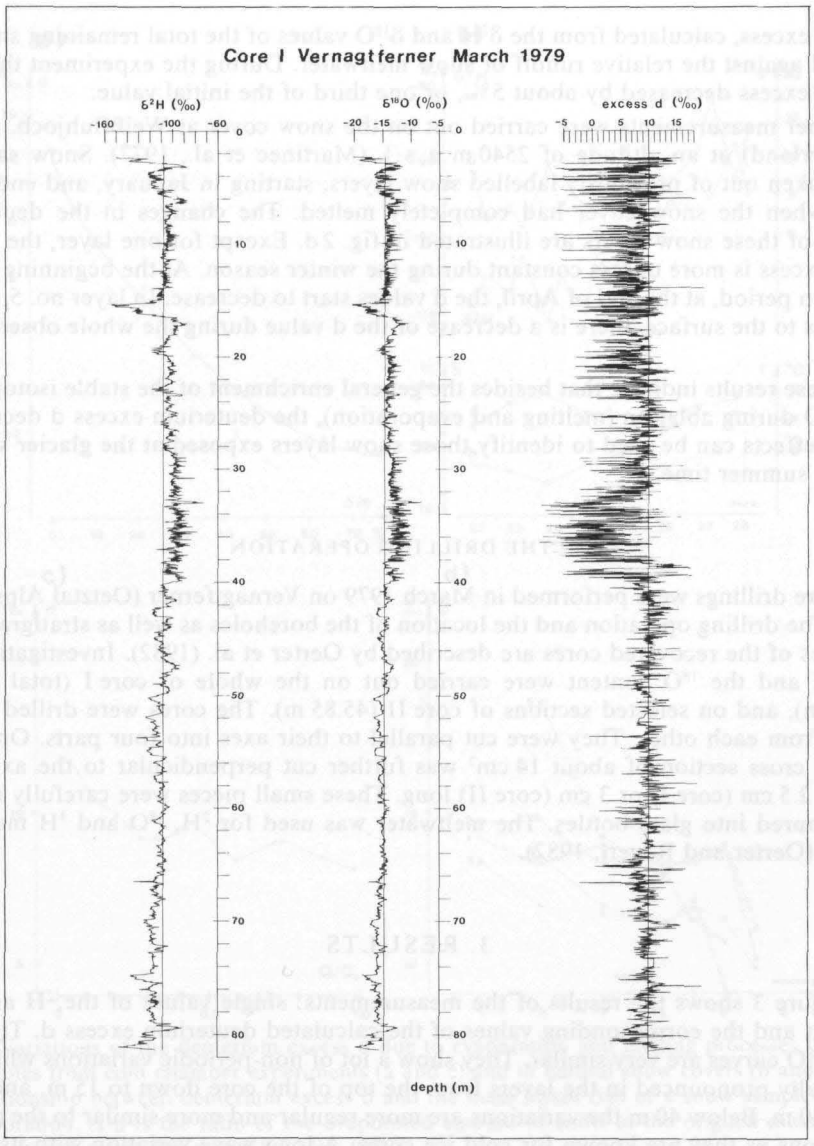

Fig. 3: Core I Vernagtferner, March 1979: ^{2}H and ^{18}O content and corresponding values of the deuterium excess d. The mean values of the ^{2}H content (-180.4 ‰) and the ^{18}O content (-14.56 ‰) are also shown

always smaller. The variation limits of the single d values are -9.3 ‰ and $+20.0$ ‰, with an overall mean of 8.1 ‰.

The chosen high resolution pattern of 2.5 cm core length for each isotope content measurement reveals a picture with too much irregular variation and the data in this form are poorly suited for dating purposes. These variations are not surprising considering the variations of the isotope content which are observed in single precipitation

events (cf. Stichler and Herrmann, 1977), and the data show that the isotope content in the snow and firn is not completely blurred by melting and seepage processes. However, some sort of averaging process is called for, in order to reveal the regularity hidden under these variations.

A first step in this direction was the computation of different weighted mean val-

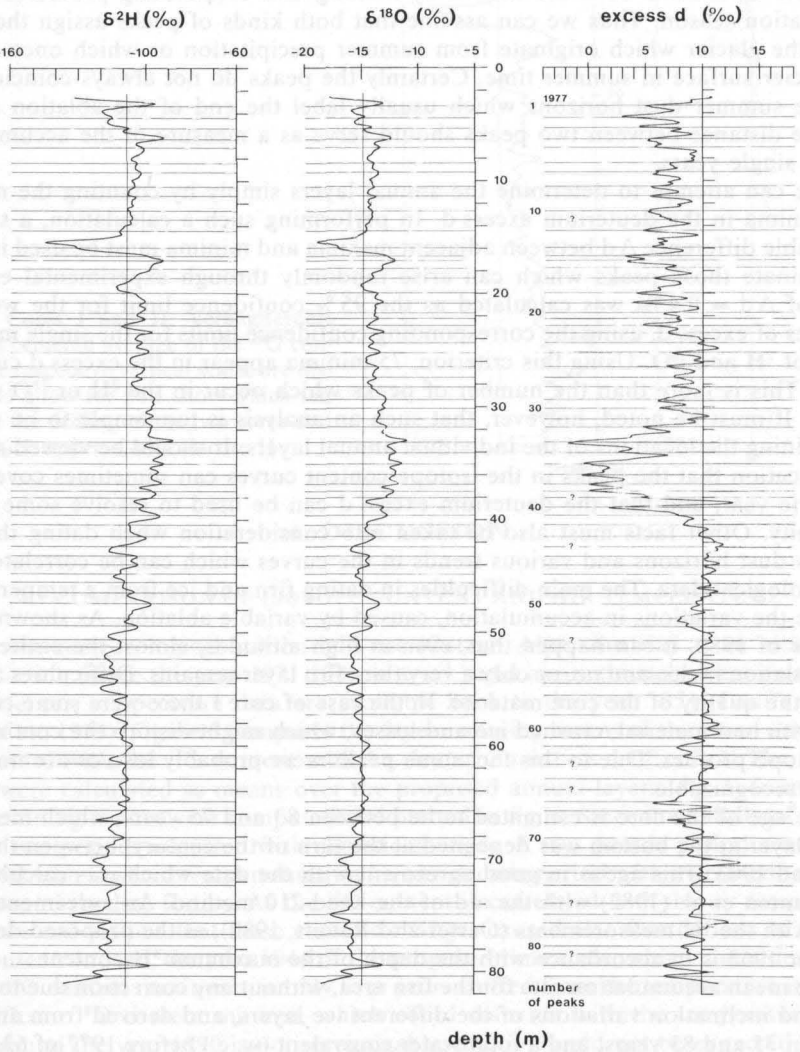

Fig. 4: Core I Vernagtferner, March 1979: Weighted mean values (10-point centered average of 10-point averages of raw data) of ^{2}H and ^{18}O content as well as deuterium excess d. The horizontal lines are assigned to the proposed location of summer snow layers. The question marks indicate uncertain horizons. The over all means of the ^{2}H and ^{18}O content are also shown

ues. The best results were obtained from a weighted average which was constructed as a 10-point centered average of 10-point averages of raw data. This method yields the curve shown in fig. 4, which displays much clearer trends than the plot of the single values (fig. 3). One can recognize that the maxima of the ^{2}H and the ^{18}O contents usually correspond to a minimum of the deuterium excess d. The maxima of the isotope contents are correlated with summer precipitation (fig. 1). As discussed in chapter 2, minima of d are caused by melting and evaporating processes during the ablation season. Thus we can assume that both kinds of peaks assign those layers in the glacier which originate from summer precipitation or which once formed the glacier surface in summer time. Certainly the peaks do not always coincide with the late summer dust horizons which usually label the end of the ablation season. Still the distance between two peaks should serve as a measure of the accumulation rate of single years.

One can attempt to determine the annual layers simply by counting the maxima and minima in the deuterium excess d. In performing such a calculation, a smallest acceptable difference Δd between adjacent maxima and minima must be used in order to eliminate those peaks which can arise randomly through experimental error. A value of $\Delta d = 0.4$ ‰ was calculated as the 95 % confidence limit for the weighted averages of excess d, using the corresponding confidence limits for the single measurements of ^{2}H and ^{18}O. Using this criterion, 75 minima appear in the excess d curve for core I. This is more than the number of peaks which occur in the ^{2}H or ^{18}O content curves. It must be noted, however, that such an analysis is too simple to be used in determining the locations of the individual annual layers. It should be viewed more as an indication that the peaks in the isotope content curves can sometimes cover more than one year, and that the deuterium excess d can be used to resolve some of this ambiguity. Other facts must also be taken into consideration when dating the core, such as dust horizons and various trends in the curves which can be correlated with meteorological data. The main difficulties in dating firn and ice from a temperate glacier are the variations in accumulation, caused by variable ablation. As shown by the summer of 1982, it can happen that, even at high altitudes, almost the entire winter accumulation melts, and no, or only a very thin, firn layer remains. Difficulties are also due to the quality of the core material. In the case of core I there were some core sections with bad material, crushed ice and losses, which might disturb the continuity of the isotope profiles. Due to this fact some peaks were probably lost, or are no longer clearly recognizable.

The age of the core is estimated to be between 83 and 75 years, which means the oldest layer at the bottom was deposited at the turn of the century, between the years 1895 and 1903. This age is in good agreement with the date which was calculated by von Gunten et al. (1982) with the aid of the Lead-210 method. An agreement is also given with the ^{3}H measurements (Oerter and Rauert, 1982), as the proposed depth for the year 1963 is in accordance with the depth of the maximum ^{3}H content.

The mean accumulation rate for the firn area, without any correction due to glacier flow and inclination variations of the different ice layers, and derived from an age of between 75 and 83 years, and a total water equivalent (w. e.) before 1977 of 63.85 m is 0.85 m or 0.77 m w. e. per year, respectively.

In view of the limited facilities available the ^{18}O measurements on core II were taken only in those sections where the ^{18}O content of core I displayed unusual variations (fig. 5). In particular, the large oscillation in ^{18}O values occurring at 15—17 m in core I was not found in core II. An analogous disagreement between the two cores was

also observed in the ^{3}H data (Oerter and Rauert, 1982). We are not able at this time to provide a satisfactory explanation for this fact.

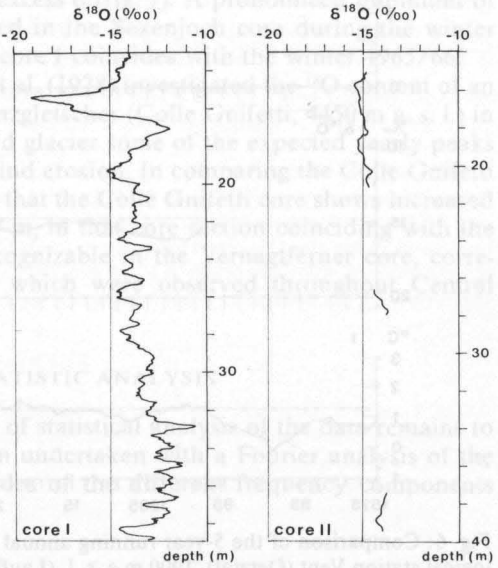

Fig. 5: Cores I and II, Vernagtferner: 10-point centered average of the ^{18}O content. The respective vertical scales are displaced to allow for new snow which fell between the drilling of the two cores and which appears only in core II

4. DISCUSSION

4.1 COMPARISON OF ISOTOPE CONTENT AND AIR TEMPERATURE

For the meteorological station at Vent (Oetztal Alps, Austria) at an altitude of 1893 m a. s. l. (since the year 1971 1906 m a. s. l.) and approximately 8 km away from Vernagtferner, temperature data are available back to the year 1851 (Lauffer, 1966; Kuhn et al., 1979). Figure 6 compares the 5-year running means of the mean annual air temperature with the ^{18}O content and the deuterium excess d of core I. The isotope values were calculated as means over the proposed annual layers (fig. 3) from which 5-year running means were computed and plotted in fig. 6. Since the middle of the last century two periods occurred with climatic changes. A two decade period around the year 1890 with lowered temperatures and a one decade period with increased temperatures around the late forties. As the ^{18}O content is correlated with the air temperature (fig. 1) we can assume that these climatic changes caused also fluctuations of the isotope content. Indeed, the year 1944 of the proposed time scale, which coincides with a ^{2}H and ^{18}O content maximum, is only four years shifted from the temperature maxima. A significant ^{18}O content minima, which could coincide with the temperature minimum around the year 1890 is not recognizable, and it should not be expected in view of the proposed age of 75—83 years for the core. Thus the temperature and ^{18}O correlation confirm the dating of the ice core, and at the same time show a possible error of at least one year in ten. A minimum of the deuterium excess d coincides with the ^{18}O content maximum. One can assume that these low d values are due to a period with higher temperatures and thus increased melting and evaporation.

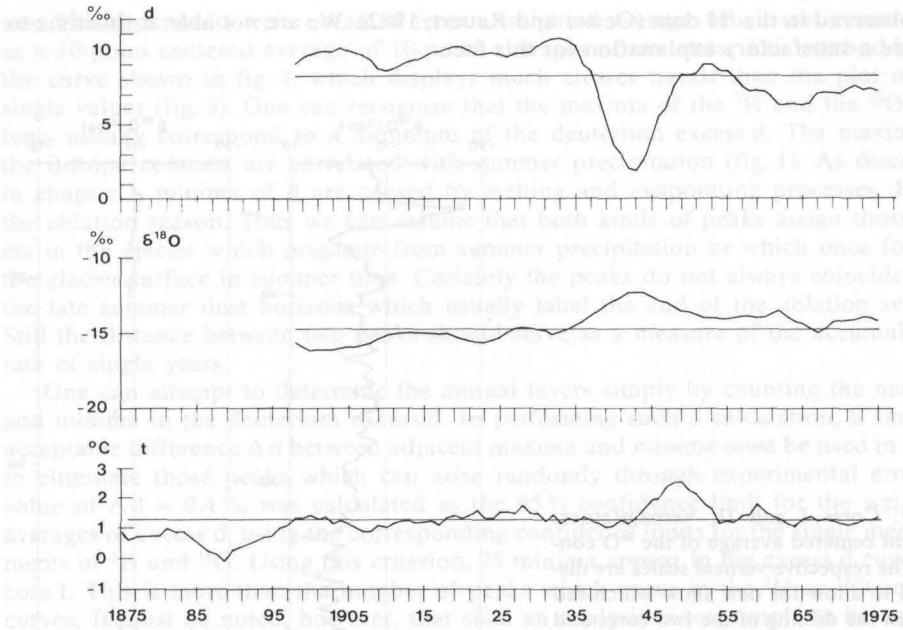

Fig. 6: Comparison of the 5-year running annual mean values of air temperature at the meteorological station Vent (Oetztal), 1900 m a. s. l. (Lauffer, 1966, Kuhn et al., 1979) with corresponding means of ^{18}O content and deuterium excess d. The isotope mean values were computed as 5-year running means for the proposed annual firn and ice layers (see fig. 4)

4.2 COMPARISON WITH OTHER INVESTIGATIONS

A firn core at Vernagtferner had already been drilled in 1976 (Behrens et al., 1979). The drilling site was situated beneath Sexenjoch (for location cf. the map of Vernagtferner 1979, Rentsch, 1982), approximately at a 50 m higher elevation then core I and 1.2 km away from it, a place with less accumulation. The dating of the ice core was attempted with the aid of stratigraphic features, total-beta-activity and ^{3}H content. The fluctuations of ^{2}H or ^{18}O content seemed not to be very suitable for this purpose. The

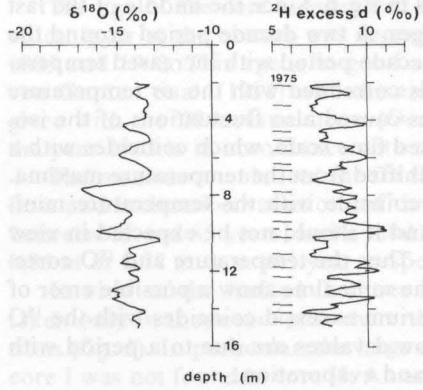

Fig. 7: Core Sexenjoch, Vernagtferner, May 1976: ^{18}O content and deuterium excess d. The short horizontal lines are assigned to the summer snow layers as they are indicated by the excess minima (after Behrens et al., 1979)

15 m core was assumed to cover the time period between 1975 and 1953. If we now try to use also the deuterium excess, we see that the isotopes ^{2}H and ^{18}O also reveal annual fluctuations, with 20 yearly peaks of the excess d (fig. 7). A pronounced minimum of the ^{2}H as well as the ^{18}O content occurred in the Sexenjoch core during the winter 1966/67. A comparable minimum within core I coincides with the winter 1965/66.

Oeschger et al. (1977) and Schotterer et al. (1978) investigated the ^{18}O content of an ice core of the uppermost part of the Grenzgletscher (Colle Gnifetti, 4450 m a. s. l.) in Switzerland. Since Grenzgletscher is a cold glacier some of the expected yearly peaks do not appear in this core due to strong wind erosion. In comparing the Colle Gnifetti core and the Vernagtferner core one notes that the Colle Gnifetti core shows increased $\delta^{18}O$ values in a depth between 14 and 17 m, in that core section coinciding with the late forties. A comparable increase is recognizable in the Vernagtferner core, corresponding to the increased temperatures which were observed throughout Central Europe at that time.

4.3 FURTHER STATISTIC ANALYSIS

At this point it seems that a great deal of statistical analysis of the data remains to be done. A start in this direction has been undertaken with a Fourier analysis of the isotope curves. Fig. 8 shows the amplitudes of the different frequency components

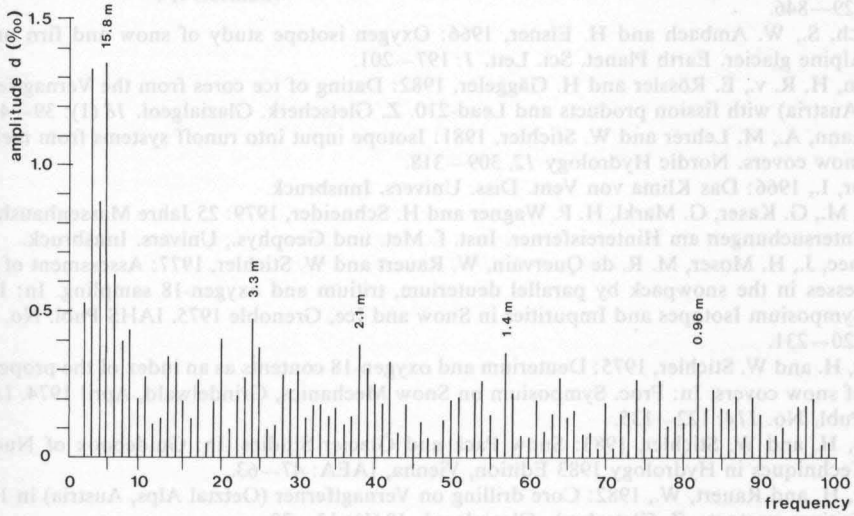

Fig. 8: Amplitudes of the frequency components in the Fourier analysis of the deuterium excess d for core I. The frequency is in cycles per 78.73 m, the length of the core. The wave lengths of the most prominent frequencies are also given

which occur in the analysis of the deuterium excess d for core I. The results of such a straight forward analysis are difficult to interpret, in spite of the temptation to try to find marked frequencies which would correspond to yearly oscillations. The problem here is that the phenomena being considered are periodic only in a very rough sense of the word. Different accumulation rates and temperature fluctuations during different

years, and a downward mixing due to seepage disturb the picture substantially. A more reasonable approach would be to attempt to correlate the isotope data with the time series of air temperature and precipitation amounts which exist for the area in question. Such a correlation also poses problems, because it presupposes a knowledge of the times corresponding to given depths along the ice cores. Work in this direction is in progress, and a more detailed discussion is planned for the future.

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