AIR CONTENT OF THE BYRD CORE AND

PAST CHANGES IN THE WEST ANTARCTIC ICE SHEET

by

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ABSTRACT

Analyses of ice cores taken from the Antarctic ice sheet can provide information on the environmental conditions under which the ice was formed. New results from measurements of gas content and stable isotope ratios in the Byrd station ice core are discussed and interpreted in terms of past ice-flow changes.

165 selected ice samples from 32 different depth levels along the core were processed for total gas content V and stable isotope ratios. This large data-set is used to discuss the variability and significance of the values of V at different depths. The short term variations of V are mainly explained by heterogeneities of the pore volume when the firn pores close off.

The general trends in the values of V with depth are then used to investigate the possibility of past changes in the ice sheet. They suggest near-steady flow during the past few tens of thousands of years and that a thickening of about 200 to 250 m occurred in this area of the ice sheet at the end of the last ice age. This thickening could be due to a change in the accumulation rate.

1. INTRODUCTION

Measurements of the volume of air trapped in ice have been performed along ice cores taken in Greenland and East Antarctica. The results provide unique information about the surface elevation of the ice sheets during the past (e.g. Raynaud and others 1979, Raynaud and Whillans 1981).

It has been suggested that the West Antarctic ice sheet is particularly vulnerable to climatic change. Measurements of the total gas content V along cores recovered from the ice sheet can reveal surface changes associated with ice-flow modifications during past periods involving important climatic changes. The core obtained to the bedrock at Byrd station (Ueda and Garfield 1969) provides the opportunity to perform this research for a central part of the ice sheet and a large time interval of the last ice age and the Holocene, a time interval which includes the important glacial-interglacial climatic change. Previous V measurements along the core (Gow and Williamson 1975, Raynaud and Lorius 1977) suggest no dramatic changes in surface elevation. In their

extensive and useful study of the physical properties of gas inclusions in the Byrd station core, Gow and Williamson report little systematic variation of V, except possibly for slightly reduced values which would correspond with the termination and culmination of the last ice age in Antarctica. They add that the correlation is too tenuous to link the observed variations with thickening or thinning of the ice sheet. The maximum error of their analytical technique was estimated not to exceed 7%. On the other hand, Raynaud and Lorius used a more accurate analytical method, but they pointed out that the small number of measurements they performed precludes a detailed interpretation in terms of elevation.

This paper presents a new set of V measurements. The large data-set obtained is used to discuss the variability and significance of the measured values at different depths. The general trends in the V values are then used to investigate the possibility of past major changes in the glacier. We begin with a discussion of the significance of the volume of air trapped in ice formed by dry sintering of snow.

2. SIGNIFICANCE OF THE VOLUME OF AIR TRAPPED IN ICE

When firn turns into ice near the surface of an ice sheet, a sample of air is sealed inside the ice. This process occurs continuously with time and the trapped air moves as the ice moves. The cores recovered from ice sheets can be studied for air content and the results used to deduce conditions at the time and place that the ice was formed.

The volume of air trapped when the ice forms by dry sintering of snow depends on two kinds of conditions when the firn pores close off from the surrounding atmosphere: pressure P_c and temperature T_c of the air, and pore volume of the firn at close-off V_c. It can be expressed as:

$$V = V_c \frac{P_c}{T_c(^\circ K)} \frac{T_0(^\circ K)}{P_0} , \qquad (1)$$

in which V is reduced to standard temperature T_0 and pressure P_0.

Since P_c and T_c are primarily linked with the atmospheric pressure and temperature prevailing at the snow surface, V depends on the elevation E and average climatic conditions of the surface, and on

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the pore volume at close-off in the firn. The V-E relation and the variations of V_c with the origin site of the ice have been investigated under present-day conditions (Raynaud and Lebel 1979). V decreases empirically with elevation according to:

$$V(cm^3 \ g^{-1} \ of \ ice) = -1.66 \times 10^{-5} \ E(m) + 0.138. \quad (2)$$

Equation (2) corresponds to a consistent dependence of V_c on T_c which can be expressed by:

$$V_c(cm^3 \ g^{-1} \ of \ ice) = 7.4 \times 10^{-4} \ T_c(°K) - 0.057. \quad (3)$$

Equations (1) and (3) lead to the following relation between V, P_c, and T_c:

$$V(cm^3 \ g^{-1} \ of \ ice) =$$

$$= \left[7.4 \times 10^{-4} \ P_c - 0.057 \ \frac{P_c}{T_c(°K)} \right] \frac{T_0(°K)}{P_0} . \quad (4)$$

Equations (2) and (4) allow us to estimate the variations of V due to changes in the elevation and average climatic conditions of the surface.

The influence of temperature on pore volume at close-off is also indicated by the occurrence of significant short-term variations of V in ice formed under near-constant elevation and climatic conditions. These V variations must be due to changes in V_c. They were found to be correlated with the seasonal variations of the isotope composition δ of the ice (Berner and others 1978, Raynaud and Lebel 1979) and show that ice formed from snow deposited in warmer conditions (high δ values) contains a higher pore volume (high V values) than ice formed from snow deposited in colder conditions (low δ). The deposition temperature influences the structure of the firn grains (size and shape distribution), which, in turn, must affect significantly V_c.

3. SAMPLING AND EXPERIMENTAL PROCEDURE

32 core sections were selected for measurements of total gas content and stable isotope ratios of ice along the ice column recovered at Byrd station. These sections were taken at depths ranging from about 100 to about 2 140 m. Unfortunately, it was not possible to process samples for V measurement in the 450 to 900 m depth interval because this part of the core is very brittle and fractured.

Each core section analysed represents an ice thickness in the glacier which is generally of the order of 10 to 15 cm and corresponds (except for the 440.25 m depth level) to at least one year of snow accumulation at the surface, according to the variations of the annual ice-layer thickness with depth obtained by modeling the ice flow in the Byrd area (Whillans 1979). A longer piece (50 cm) was processed at a depth of about 102.5 m for a detailed study of short-term variations. At each depth level, the piece was cut in slices 2.5 to 3 cm thick (in the vertical direction) and each slice measured for total gas content and stable isotope ratio δ. 165 slices were processed and each measurement of V was generally performed on 20 to 25 g of ice. Samples for total gas content were carefully selected and visibly fractured ice was excluded.

The experimental procedure used for V determinations is the same as in Raynaud and Lebel (1979) and is described in detail by Raynaud and others (1982). The procedure includes gas extraction by melting the ice and refreezing the melt water under vacuum. The gas is then dried and collected in a volumetric gas burette using a Toepler pump. Results are given in cm^3 of air at STP per gram of ice. The relative precision of the experimental procedure has been analysed from repetitive measurements performed

on natural ice sampled from the same slices of 2.5 to 3.5 cm thickness and is of the order of 10^{-3} cm^3 g^{-1} of ice. There are differences between the V results presented here and previous preliminary results published for the same core by Raynaud (1977) and Raynaud and Lorius (1977). There is, first, a systematic difference due to the use of different extraction methods that does not affect the relative variations (Raynaud and Lebel 1979). Furthermore the trends of V versus depth are partly different here. In the case of the Byrd core the trends are small and the differences are due to the increased number and length of samples which makes the new data-set more reliable than the preliminary one.

4. SHORT-TERM VARIATIONS OF THE AIR CONTENT IN THE BYRD CORE

The most detailed information is provided by the analysis of the 50 cm long core section taken at about 102.5 m depth. The ice represents several years of snow accumulation deposited at the surface about 700 a BP. Due to the time required for the pore close-off, air trapping was completed at about 60 m depth, approximately 300 a after the deposition time (roughly 400 a BP).

The measured variations of V at this depth are shown in Figure 1. The amplitude of these variations is generally much larger than the experimental errors (± 0.001 cm^3 g^{-1} of ice) and may reflect fluctuations
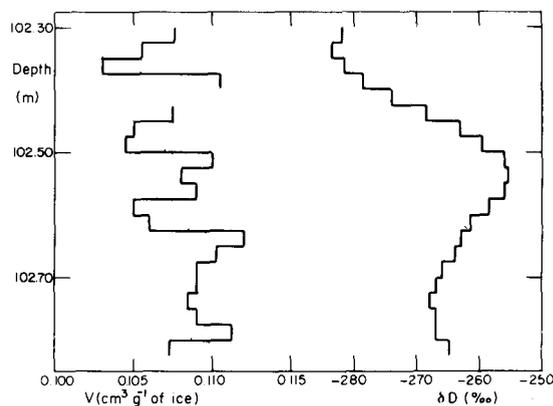
Fig.1. Byrd station. Variations of the total gas content V and the isotopic ratio (in δD°/oo) of the ice at about 102.5 m depth.

of P_c, T_c, and V_c. Taking into account the meteorological observations made in several representative stations (including Byrd station) on the Antarctic ice sheet, Raynaud (1977) estimates that the natural fluctuations of both P_c and T_c can produce a maximum variability of 3% on the total gas-content measurements performed on ice formed under present-day conditions in a given site. Thus, experimental errors and fluctuations in P_c and T_c can account for only about half of the maximum amplitude (0.009 cm^3 g^{-1} of ice) of the V variations observed. These variations probably reflect significant short-term variations in V_c, as deduced previously for other sites (see section 2). Figure 1 can be interpreted in terms of seasonal fluctuations. The distances between the four higher values, which could correspond to snow deposited during warm seasons according to Raynaud and Lebel (1979), are respectively 12.5, 12.5, and 15 cm. They are in good agreement with the annual accumulation-rate pattern observed in the Byrd station area. As pointed out in section 2, these seasonal fluctuations of V_c must be due to the stratigraphic structure of the firn which is well preserved with depth in the Byrd area (Gow 1968). Figure 1 also shows the δ variations. It is interesting to note that these variations are not compatible with

the accumulation rates measured stratigraphically. This is probably due to the fast isotopic homogenization in the firn at Byrd (Dansgaard and others 1973).

The amplitude of the short-term variations of V measured within other sections further down the core (Fig.2) is smaller and decreases on the average by a factor of 2 between 170 and 2 140 m depth. The thinning of the ice layers with depth probably smooths the heterogeneities of V_C due to the seasonal changes of the firn structure. Thus, if an ice layer 3 cm thick at 100 m depth at Byrd corresponds to only a few months of snow accumulation, a layer of the same thickness at 1 400 m depth will correspond to about one year of accumulation according to Whillans (1979).
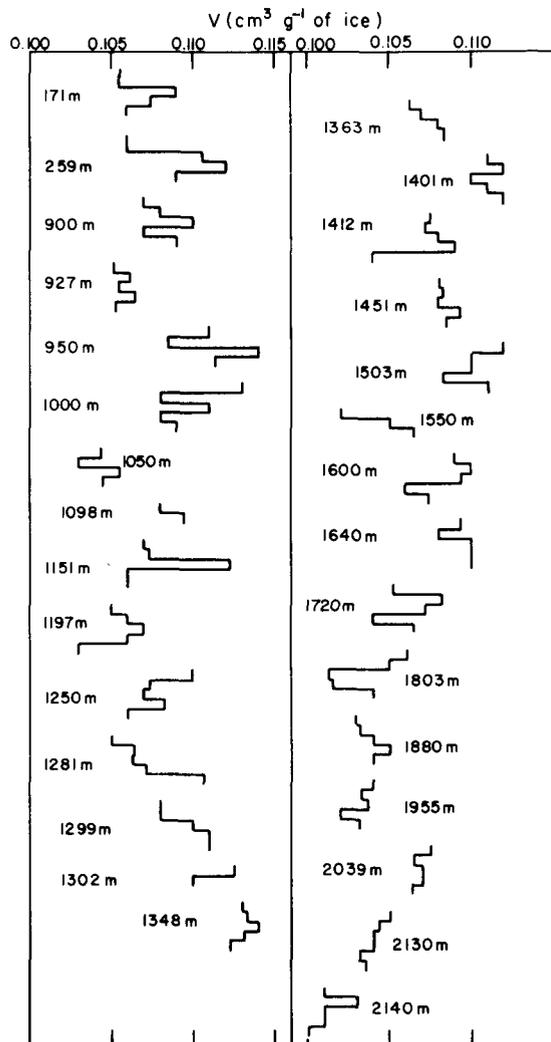
Fig.2. Byrd station. Short-term variations of the total gas content V of ice measured every 2.5 to 3 cm at different depth levels.

On the other hand, the effect of the fluctuations of P_C and T_C on the short-term variations of V observed within the core sections probably does not decrease significantly with depth. This is because these fluctuations *cover longer time periods*, due to the fact that the pores close off at different depths in the firn and over a relatively long time interval as the firn turns into ice (Raynaud 1977). In fact, below about 1 400 m depth the amplitude of these variations never exceeds 0.005 cm³ g⁻¹ of ice, which is the maximum variability expected from experimental errors and fluctuations in P_C and T_C.

In conclusion, the short-term variations of V observed within core sections less than 50 cm long along the Byrd core can be explained both by short-term fluctuations of the air pressure and temperature in the firn and by heterogeneities of V_C due to the stratigraphic seasonal structure of the firn. The variations between core sections are discussed next.

5. AIR CONTENT WITH DEPTH ALONG THE BYRD CORE AND PAST CHANGES IN THE WEST ANTARCTIC ICE SHEET

The V values in each section have been averaged and are shown versus depth in Figure 3. Part of the scattering observed cannot be explained only by short-term fluctuations of P_C and T_C and "seasonal" changes of V_C. This dispersion in the mean V values must also reflect longer-term variations in the conditions prevailing at the pore close-off.
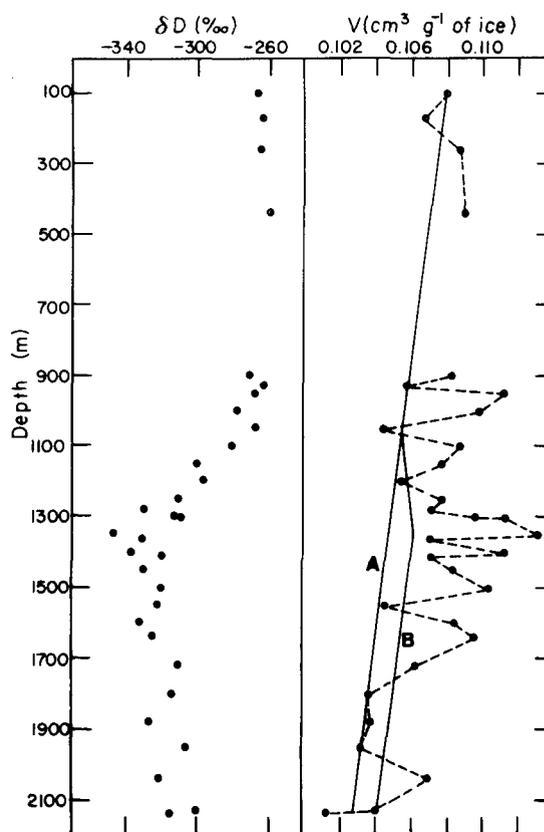
Fig.3. Byrd station. Variations of the mean total gas content V and isotope ratio δ with depth. Mean V values measured at different depth levels are compared with the change of V to be expected by ice flow according to the present flow pattern under constant temperature (line A) and corrected for colder temperatures during the ice age (curve B).

The general trends of V with depth, as indicated by Figures 2 and 3, do not show dramatic changes in contrast with the observations made on the Camp Century, Greenland, and D 10, East Antarctica, cores (Raynaud and Lorius 1977, Raynaud and others 1979). Nevertheless significant trends appear. V increases progressively between 2 140 and about 1 350 to 1 300 m depth *and then decreases more rapidly until* about 1 200 m depth.

Due to the dependence of the total gas content on the elevation of ice origin, lower V values with depth are to be expected because the ice has flowed downhill according to its surface slope and deeper, older ice was formed at more distant higher elevations. Any residual long-term changes in V could be

due to changes in atmospheric pressure, temperature, and ice-surface elevation with time.

We begin by evaluating the gas-content change expected by flow according to the present pattern. For realistic thickness gradients, accumulation-rate gradients, and strain-rate-depth variations according to Whillans (1979), the elevation of origin/depth relationship is nearly linear. Under present-day conditions, the empirical V-elevation of origin relation is also linear (Equation (2) in section 2). Consequently it is possible to calculate a V-depth relation describing the change of V to be expected by the ice flow according to the present pattern (Fig.3, line A). As indicated by isotope measurements (Epstein and others 1970, Johnsen and others 1972, see also Fig.3) the Byrd core records the important climatic change at the end of the last ice age and part of the ice was formed under glacial temperature conditions. The total gas content depends also on the temperature, and the changes in V expected by the ice flow can be corrected for climatic changes. In Figure 3, curve B corresponds to the corrected curve A taking into account ice-age temperatures 7°C colder than today (Lorius and others 1979) and a V-temperature gradient deduced from Equation (4) (given in section 2).

Figure 3 shows a significant deviation between the overall trend of the mean measured data and curve B in the 1 300 to 1 500 m depth interval where the V values observed are systematically higher than expected. This depth interval corresponds to ice formed during the last part of the last ice age, as indicated by isotopic measurements. The higher V values observed may be due to an increase in the mean atmospheric pressure at this time. However, the difference between the V measurements and curve B, which is on the average about 3.5 to 4 x 10^{-3} cm^3 g^{-1} of ice, would correspond to a very large pressure increase in the atmosphere of about 25 to 30 mbar (calculated from Equation (4)).

On the other hand, the difference can be explained if the ice in this area was thinner than now by about 200 to 250 m. Our results suggest consequently a thickening with time of the ice starting at the end end of the last ice age. The timing and magnitude of this thickening are consistent with a 50% increase in the accumulation rate at the end of the ice age according to the theory proposed by Whillans (1981). Such an increase in accumulation rate was suggested by Robin (1977) to have been associated with the start of warmer air temperatures and greater moisture-carrying capacity of the atmosphere.

An ice-thickness change of 200 to 250 m in a time interval of the order of 10 ka is relatively small. Consequently the gas-content results suggest no dramatic variations in the elevation of origin and we conclude that the region has not changed greatly over the past few tens of thousands of years. Such a result is consistent with earlier work on other data from Byrd station and its vicinity. Whillans (1976) studied the form of internal radio-reflecting layers and found no great change over approximately the past 30 ka*. According to Robin (1977), analysis of the temperature profile measured in the Byrd bore hole indicates no important past changes in ice thickness. Finally, all these results confirm that the variation of stable isotope ratio with depth is due mainly to climatic changes.

6. CONCLUSION

The V variations observed along the Byrd core show an important seasonal component near 100 m depth. This component probably reflects seasonal changes in

the size and shape distribution of the firn grains when the pores close.

Due to the thinning of the ice layers, the seasonal variations are smoothed with depth and disappear below approximately 1 400 m depth. The remainder of the observed variations are mainly caused by elevation, atmospheric pressure, and temperature conditions prevailing at the site of ice formation.

Systematic deviation between the V values measured and the air content of ice expected by steady-state flow occurs between 1 300 to 1 500 m depth. This deviation suggests that the ice sheet in the Byrd area was thinner during the last part of the recent ice age and that a thickening of approximately 200 to 250 m occurred between the end of the glacial period and now. This thickening could be explained by an increase of about 50% in the accumulation rate.

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