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Gas Enclosures in a Temperate Glacier[1]

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Abstract

Techniques are described for separating gas from glacier ice and analyzing for oxygen, nitrogen, and carbon dioxide. A systematic survey of a temperate glacier for enclosed gas showed 1) no general loss of gas from the glacier, but a specific loss of oxygen from the gas from the upper to the lower part of the glacier, and 2) the gas pressure and ice density increased from the upper to the lower part of the glacier. Present evidence indicates that a chemical reduction is responsible for the oxygen loss. The various data are discussed in relation to glacier mechanics.

Introduction

A prominent characteristic of glacier ice is the inclusion in the ice of gas bubbles or cavities. These gas enclosures may originate in two different ways (cp. SCHOLANDER, et al., 1956). In high-arctic glaciers where melting does not occur in the ice formation area, glacier ice is formed by snow compaction. The gas enclosed in such ice is simply atmospheric air trapped between the fused snow crystals, and hence of complete uniformity in composition. The atmosphere is 20.94 % O_2 and 0.03 % CO_2 and the rest nitrogen including noble gases (cp. HOCK, et al., 1952).

However, if the freezing of water plays a role in the ice formation, one would expect the gas to have a composition other than atmospheric air. Water fully saturated with air at 0° C and at 760 mm. Hg contains 2.9 % by volume of dissolved gases of which 34.9 % is O_2 and 1.75 % is CO_2 (Handbook of Chemistry and Physics, 1952 ed.). As the solubility of gases in ice is at least 1000 times less than in water, probably zero, these gases will separate from the ice when the water freezes (SCHOLANDER, et. al., 1956). Hence when air-equilibrated meltwater percolates down through snow on a glacier and freezes to ice it will enrich the enclosed gas with oxygen and carbon dioxide, and one would expect considerable local as well as seasonal variations.

Laboratory experiments have indicated that CO_2 diffusion through pure ice is some 40,000 to 70,000 times slower than through water and O_2 is even slower (SCHOLANDER, et al., 1953). Considering the enormous distances in a glacier and the relatively large amounts of trapped gas it seems likely that diffusion losses would be extremely small even over long periods of time. If there are no gas changes through oxidation, it is possible that very ancient atmosphere will be preserved in the depths of the high-arctic inland ice.

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Several workers have determined the composition of this gas in isolated pieces of glacier ice (STEENSTRUP 1883, HAMBURG 1895, BERNARD 1922, BARNES 1927). Though in general the techniques employed for separating the gas from the ice do not yield accurate data, these indicated that the composition of the gas was more or less close to air.

Mire recently BADER (1950) investigated the pressure and amount of gas in the bubbles of the terminus of the Malaspina Glacier, Alaska. The pressure varied between $1^1/_2 - 2^1/_2$ atmospheres and the gas quantity between 3.8 – 4.8 % of bulk volume.

SCHOLANDER, KANWISHER, and NUTT (1956) measured the gas composition (O_2 and N_2), quantity, and pressure in pieces of glacier ice taken from icebergs along the Labrador coast. They concluded that the gas in four out of six icebergs examined was indistinguishable from present day atmosphere, but that the other two had a composition significantly lower in oxygen (20.0%). They suggested that this could possibly signify a low atmospheric O_2 at the time the snow compacted to form the ice, and he sp eculation was made that this might be due to a lowered photosynthetic activity during a period of climatic decline and advanced glaciation. In these determinations the ice was melted under mercury, the gas phase and the dissolved gases were analyzed separately and the results totalled. This method had an accuracy of ±0.2 %. The pressure was found to vary between 1.0 – 6.2 atmospheres.

Many questions arise with regard to the gas enclosures, such as: to what extent is the atmosphere trapped in the ice preserved since the formation of the ice? to what extent do the bubbles reflect the pressures in the ice? to what extent is the ancient precipitation forming the ice preserved in its original composition? Only by systematic studies can one hope to answer these questions.

In the present study we have undertaken such a systematic investigation on a temperate glacier, Storbreen, in the Jotunheimen district of Norway. This was selected for study because it is readily accessible from a log cabin well enough constructed to serve as a field laboratory, and because it is being examined in other respects by the Norsk Polarinstitutt. The field investigation took place in the month of March.

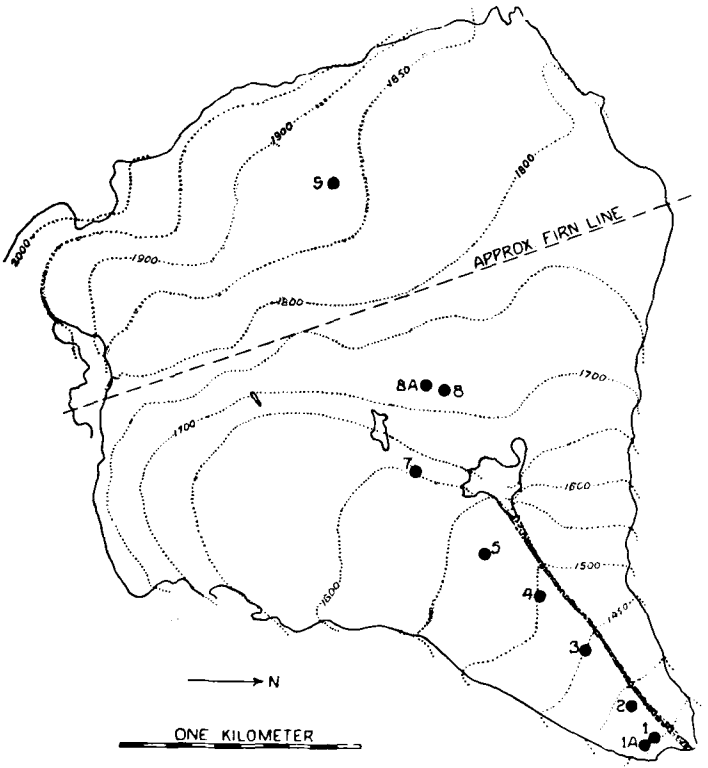

Fig. 1. Map of Storbreen, from surveys by the Norsk Polarinstitutt. The dark circles are sample locations, and the elevations are in meters,

Sampling of Ice

Samples were taken one-half meter below the surface of Storbreen ice in a line from the terminus to well above the firn line (Fig. 1). The glacier topography determined the position of the line, but except possibly for the upper stations (8 – 9) the samples are from more or less the same line of flow. Samples 1A and 8A were taken 30—40 meters laterally distant from 1 and 8 respectively for duplication of the upper and lower ice.

The samples were brought to the field laboratory for analysis. Duplicate samples were brought to the cold room at the Institute of Zoophysiology, Oslo, where studies were made on single bubbles and various chemical tests conducted.

Methods

1. Bulk determination of gas bubbles in ice

In this method the gas is separated from the ice by shaving the ice in high vacuum and in cold. The gas thus released by the opening of the bubbles is collected over mercury and analyzed. Data obtained give gas quantity, pressure, and composition, and ice density.

Apparatus. A piece of ice is rough-hewn, placed in a small specially constructed lathe, and turned to a cylinder. The ice is transferred to a jig and the ends are carefully sheared flat and perpendicular with a wide-bladed knife. Dimensions and weight of the piece are accurately taken. The ice cylinder is inserted in the barrel of an ice shaving box (Fig. 2) where it occupies 75 % of the volume to allow room for the shavings. The top and bottom of the shaving box are vacuum sealed with standard O-rings.

Inserted in the box is a stainless steel rotary knife designed like a wood drill of the German "forstner" type which cuts a hole with a flat bottom. The drill shaft extends through a bearing in the top of the box fitted with four O-ring vacuum seals, and is turned by an

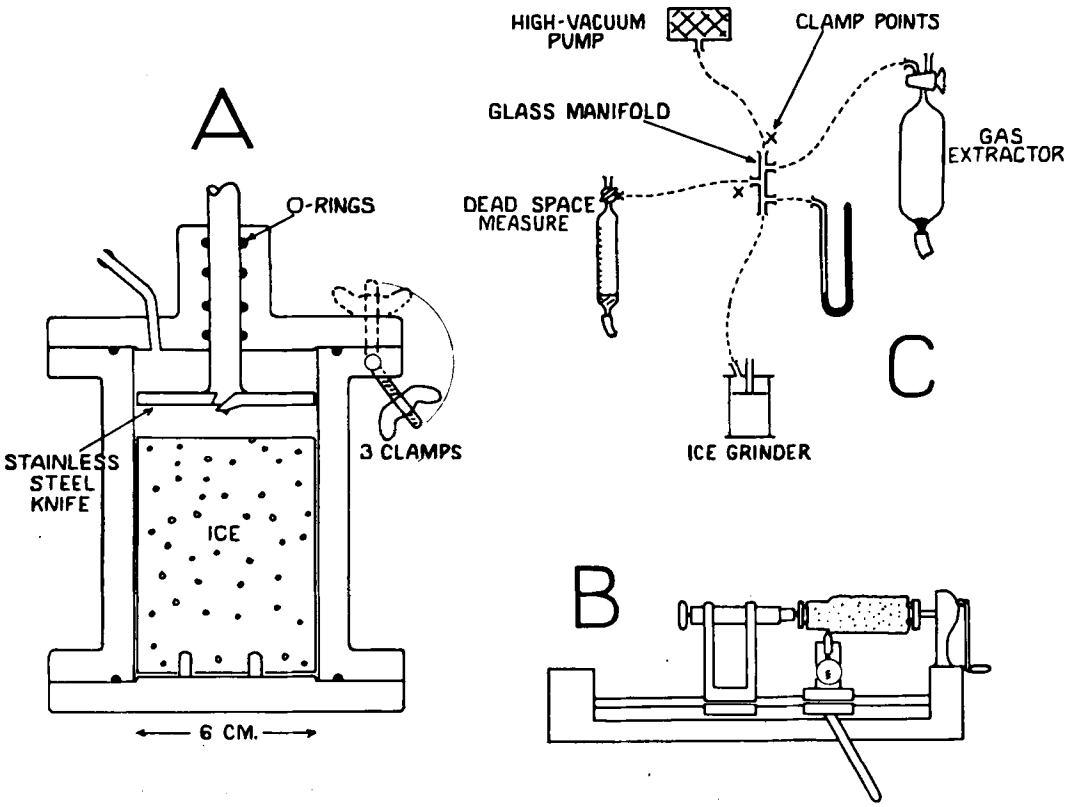

Fig. 2. Sketches of the apparatus. *A* is a section through the ice shaving box, *B* a sketch of the ice lathe, and *C* a schematic diagram of the vacuum system.

ordinary hand brace. The rotary shaving can proceed until the shavings fill the space above the knife, leaving an intact piece of ice at the bottom.

The shaving box is connected to a high vacuum pump through a glass manifold. Also connected on the manifold are 1) a U-tube mercury manometer, 2) a measuring cylinder and leveling bulb filled with ethylene glycol, and 3) a 500 cc. gas extraction flask and leveling bulb filled with mercury (Fig. 2).

Procedure. The shaving box containing the prepared piece of ice is connected to the manifold and the system evacuated until the vapor pressure of ice is obtained (1.7 mm Hg at −10° C.). Air at ambient pressure is introduced from the measuring cylinder, giving a measure of the space evacuated before the ice is shaved[1]. After shaving the gas pressure in the system is read on the manometer. Part of the liberated gas is transferred to the gas extractor and from there to a 5 cc. gas pipette where it is stored under overpressure, and later analyzed. The last step is measuring by caliper the unshaved piece of ice. All these proceedings are conducted at temperatures below freezing.

Gas analysis. The gas was analyzed in a $^1/_2$ cc. volumetric analyzer for O_2, CO_2, and N_2,[2] with an accuracy of ± 0.015 % (SCHOLANDER, 1947). Accurate analyses can only be made in a well thermo-regulated room and not below 20° C., which was accomplished by means of accessory stoves. Checks on atmospheric air were run ahead of all ice gas determinations to insure that full accuracy was attained.

Calculations. The volume of the cylindrical ice sample is calculated from the measurements, then divided by the weight to obtain the density (r). The amount of gas space (s) in the ice is

$$s = \frac{(.917 - r)}{.917} v$$

where .917 is the density of pure ice (Handbook of Chemistry and Physics, 1952 ed.), and v the volume of ice shaved.

The quantity of gas (Q) at STP is

$$Q = (V_s + s - F)\left(\frac{P - vp}{760}\right)$$

where V_s is the volume of the evacuated system, F the volume of the shaft introduced on shaving, P the pressure of the gas, vp the vapor pressure of ice and 760 atmospheric pressure in mm Hg. The pressure (P_g) exerted by the gas in the ice is then

$$P_g = \frac{Q}{s}$$

Checks 1) Diffusion tightness of the system. Introduction of gas mixtures other than air into the system revealed a very slight diffusion leak of air through the vacuum tubing and joints. By reducing the amount of vacuum tubing to the least possible this error was reduced to an insignificant amount.

2) Shaving ice in the presence of gas.

It was thought that adsorption of gas on the enormous surfaces of the shavings might significantly affect the gas composition. To test this 5 cc. of air were introduced into the evacuated system containing nearly bubble-free lake ice, the ice was shaved, and the gas removed and analyzed. The O_2 remained unchanged (±0.015 %) but there was a slight increase of CO_2 (to 0.09 %) which might have come from the few tiny bubbles visible in the ice, or perhaps was present dissolved in intercrystalline brine films (SCHOLANDER, et al., 1953). The same procedure was followed using a gas mixture of 15 % O_2 and 5 % CO_2, and there was a slight loss of CO_2 and a slight gain of O_2 corresponding to the above mentioned diffusion leaks of air. It may be concluded that ice shavings do not measurably alter the gas composition.

3) Gas tightness of the ice cylinder.

Determination of the bulk gas content of the ice requires that the gas bubbles are discrete and that the enclosing ice structure is vacuum tight. To test this pieces of the samples were evacuated for five minutes in kerosene dyed with Sudan III. The volumes of the melted samples and the oil were then taken to determine the amount of oil that had entered the cylinder. In most cases the oil entered only those bubbles that were cut open at the surface, and in these cases the gas pressure estimation had a maximum error of −9 %. In samp-

[1] This can only be used in ice where the gas cavities do not interconnect (cp. check 3).

[2] N_2 as used herein contains the other non-absorable gases.

les 1, 7, 8A, and 9 due to many channels interconnecting the bubbles, the oil penetrated into the pieces, and the pressure measurements on these samples are considered invalid.

2. Micro determination of composition of single gas bubbles

In this method the gas bubbles are opened anaerobically, the gas removed in gas pipettes and transferred directly to composition analyzers.

A well is carefully shaved over a gas bubble with a spoon-shaped chisel. Concentrated acid citrate and then mercury are placed in the well. A 0.8 mm drill, cut off and resharpened so that only 2 mm of spiral grove remain, is inserted through the mercury and citrate and a hole drilled into the bubble. The gas is removed in a mercury micropipette inserted through the fluids, and either 1) transferred directly to a syringe analyzer, and analyzed for O_2, CO_2, and N_2 with ±0.2 % accuracy in 40 mm³ samples (SCHOLANDER, et al., 1955), or 2) stored behind mercury in a cup for analysis by a micrometer micro-analyzer with ±0.2 % accuracy in 1 mm³ samples (SCHOLANDER and EVANS, 1947).

Results

The results of the various measurements on Storbreen ice are presented in Figures 3 and 4, all plotted against the sample locations.

Pressure (Fig. 3). The gas pressure in the ice may be seen to increase more or less regularly from atmospheric pressure in the upper part of the glacier to over 2 atmospheres near the terminus.

Density (Fig. 3). The ice density fluctuates widely throughout the glacier (.854—.904 gm/cc) and in samples from the same location. However there appears to be a trend of increase of ice density from the upper part to the lower part of the glacier.

Gas Quantity (Fig. 3). The amount of gas varies widely throughout the glacier (1.8—7.8 volume-percent) with no relation to location, i.e. there is no general loss of gas going down the glacier.

Oxygen (Fig. 4). The O_2 composition of the gas in the upper part of the glacier (8, 8A, 9) is approximately equivalent to air, and the values vary from bubble to bubble about 2 %

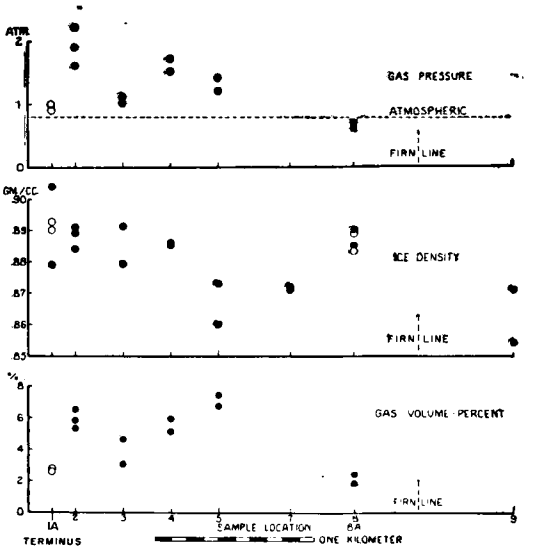

Fig. 3. Plots of the gas pressure, ice density, and gas quantity against sample location. The open circles are samples 1 A and 8 A.

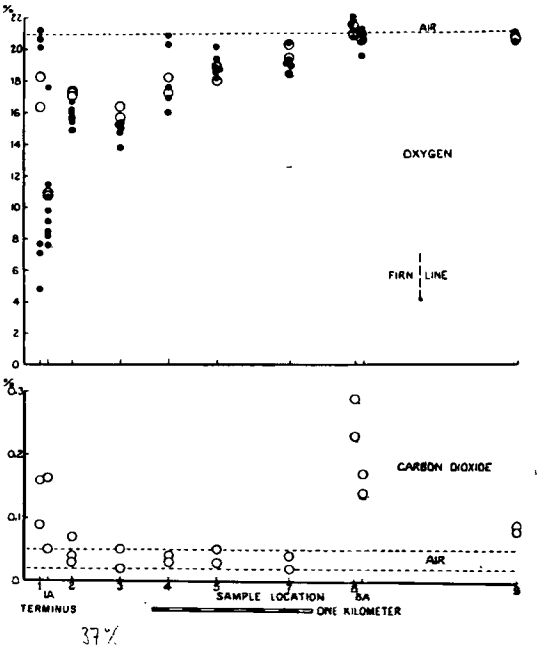

Fig. 4. Plots of the volume-percent of oxygen and carbon dioxide by sample location. The open circles are bulk determinations, and the closed circles are single bubble values.

(19.5—21.9 %). Going toward the terminus there is a general decrease of O_2 to values as low as 4.8 %, and the bubble to bubble variations appear to increase. The terminal values are in two groups, the average of the lower group (5—12 %) continuing the curve of O_2 decrease down the glacier. The higher group of values (16—21 %) suggests that perhaps recently the thin terminal ice may have cracked and allowed air or meltwater to enter and contaminate the original ice.

Carbon Dioxide (Fig. 4). The CO_2 in the samples near the firn line and at the terminus varies from air to values ten times greater than air (0.05—0.29 %). All the remaining samples have atmospheric CO_2 in the bubbles. There is no inverse correlation with the O_2 values.

Chemical Tests of Ice Purity

The amount of dry matter, including particulate matter, in the ice was determined by evaporating samples 1 A, 4, and 8 A to dryness. The residue of these samples weighed 0.6, 0.7, and 0.5 mg. per 100 cc. ice respectively.

The glacier ice is essentially frozen precipitation, and it is of interest to compare it with present day precipitation. The salt content would also give an idea of the amount of brine that may be present as intercrystalline films (cp. DORSEY, 1940, SCHOLANDER, et. al., 1953). The specific conductivity and pH of the melted samples were measured by standard methods. The conductivity was found to be very uniform between 7.0–11.5 $ohms^{-1}cm^{-1} \times \times 10^{-6}$, and the pH ranged 6.08—6.44.

Discussion

A quantitative study of the gas enclosures in Storbreen has given the following main results: that there is a loss of oxygen from near atmospheric in the upper part of the glacier to well below atmospheric in the lower; that the O_2 varies from bubble to bubble, and this variation increases from the upper to the lower part of the glacier; that the O_2 decreases without an increase in CO_2; and that the gas pressure increases from the upper part of the glacier towards the terminus. We shall below discuss these findings in relation to each other and to known data on glacier mechanics.

Oxygen loss. There are two processes that present themselves as possible causes for the O_2 loss: 1) diffusion loss through the ice to the atmosphere, and 2) oxygen loss by chemical action.

If there is a diffusion loss it would most likely take place through intercrystalline brine films, and would then be a function of salt content[1] and temperature. If there is a positive total pressure gradient from the bubble to the air, oxygen would be preferentially lost because of its higher diffusion rate relative to nitrogen.

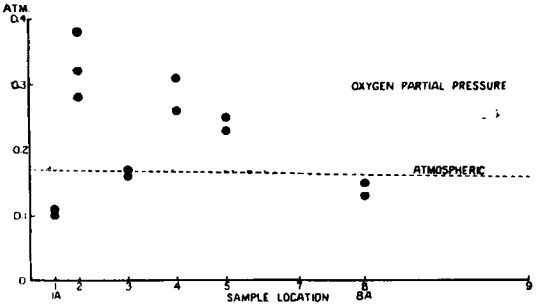

Fig. 5. Plot of oxygen tension by sample location.

The O_2 tension in the bubbles, calculated from content and pressure, are given in Figure 5. It may be seen that in most cases there exists a positive pressure gradient which could be responsible for a preferential diffusion loss of oxygen. However in sample 1A the O_2 loss has proceeded to a tension below that of the ambient atmosphere, and this clearly is not due to diffusion loss to the atmosphere. We must therefore look for other causes for the oxygen loss.

The increasing spread of individual bubble O_2 values going down the glacier suggests that the reduction is not uniform from bubble to bubble and is another indication of the considerable diffusion tightness of ice. This agrees with the finding of gas bubbles containing 40 % CO_2 and 60 % N_2 3 cm below the surface of 6 months old pond ice (SCHOLANDER, et al., 1953).

If the O_2 loss were caused by bacteriul decomposition of organic matter one woald expect a concurrent increase in CO_2. This

[1] 100 cc. meltwater with a conductivity of 10 $ohms^{-1} cm^{-1} \times 10^{-6}$ would leave about 10 mm^3 unfrozen brine at —10° C and 50 mm^3 at —2° C.

intriguing possibility is unlikely, as most of the samples with reduced O_2 had CO_2 values equivalent to air, in fact the highest CO_2 encountered in any sample amounted to only a few tenths of one percent.

In dissolved salts and acidity Storbreen ice compares well with present day precipitation. The range of conductivity and pH of precipitation taken from measurements published for four inland Swedish stations (EGNER and ERIKSSON, 1955) are presented in Table 1.

Table 1. Range of Conductivity and pH in Precipitation. Four Inland Swedish Stations.

Station	Conductivity $ohms^{-1}\,cm^{-1}\cdot 10^{-6}$	pH
Riksgränsen ..	6—54	5.6—6.3
Kiruna	9—19	5.2—6.2
Mora	19—90	6.8—7.3
Åre.....	9—16	6.1—6.3
Storbreen Ice	7—12	6.1—6.4

It may be concluded that the evidence so far points to a chemical oxidation of dust taking place within the individual bubbles, and that the precipitation preserved in Storbreen is essentially the same as today's.

Carbon Dioxide. Slightly elevated CO_2 values occurred in the samples taken near the firn line (8, 8A, 9) and near the terminus (1, 1A). All samples in between had a CO_2 content equivalent to air. Although the analytical accuracy is poor for such low values it seems clear that the CO_2 tension in most of these intermediate samples is higher than in air, and that diffusion equilibrium has not been attained.

Firnification Process. A fresh fallen snow mass has low density and is permeable to air and water. Through various processes the snow crystals become polygonal granules and the snow density may increase to .4—.5 in one year, and in succeeding years these granules compact to ice by the addition of load, the spaces between the granules becoming sealed from each other and from the atmosphere at about density .8 (cp. BADER 1939, 1950, MATTHES 1942).

Examination of the firn at three meters' depth at location 9 showed alternating layers of coarse-grained snow and bubbly ice. Sample 9 was of this ice and although the oxygen was not elevated there was a slight elevation of carbon dioxide indicating gas separated from water on freezing. However most other samples had CO_2 values corresponding to air, and it appears therefore that simple trapping of air by compaction of ice granules outweighs by far gas formed by freezing of meltwater.

Relation to Glacier Mechanics. In Figure 6 is given a schematic sketch of the lines of flow of a temperate glacier (KOECHLIN, 1944). In this concept the ice moves through the glacier along specific levels and is thereby subjected to different loads, the ice nearest the terminus having been subjected to the greatest load. It would appear that the gradient found in gas pressure agrees with this concept, and the surface samples reflect the compaction in the glacier interior. However the pressures are not equal to the theoretical ice load, and as Bader concluded, some of the pressure appears to be lost as the ice surfaces from inside the glacier.

It is also evident from this concept that surface sampling down the glacier would sample ice of increasing age, and the gradient in oxygen content found in Storbreen also agrees with this. If the oxygen reduction proceeds at a uniform rate and the rate were known, the ages of the samples could be estimated. For example, the O_2 in sample 9, estimated by other criteria as some 15 years old (Liestøl, personal communication), was about 0.3 % below air, corresponding to a reduction of 0.02 % per year. In the terminal samples the oxygen averages about 12 % below air and hence the age of this ice might possibly be some 600 years.

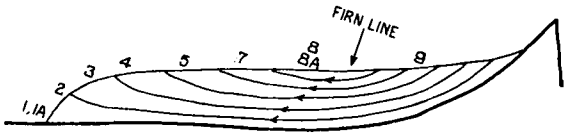

Fig. 6. Schematic diagram of a longitudinal section through a temperate glacier, after KOECHLIN, 1944. The arrows indicate the lines of flow.

Summary

A systematic investigation of the gas enclosures in a temperate glacier has been undertaken. The apparatus and method are described

for separating the gas from the ice in bulk and analyzing it for oxygen, nitrogen, and carbon dioxide with ±0.015 % accuracy. This method gives data on gas composition, quantity, and pressure, and ice density. A technique is also described for extracting and analyzing the gas in individual bubbles with ±0.2 % accuracy.

Samples were taken from the surface of the glacier in a longitudinal line from above the firn line to the terminus. It was found that: 1) the gas pressure increased from atmospheric near the firn line to three times atmospheric near the terminus, 2) there was a trend of increasing ice density from the upper to the lower part of the glacier, 3) there was no general loss of gas from the glacier, 4) the oxygen content was equivalent to air in the upper part of the glacier, but there was a loss of oxygen going toward the terminus, 5) the oxygen content varied from bubble to bubble, and this variation increased going down the glacier, and 6) the oxygen was lost without an increase in carbon dioxide.

The possible causes for the oxygen loss are discussed. Loss by diffusion through the ice appears unlikely, and the present evidence points to dust oxidation within the individual bubbles. The glacier ice was tested chemically, and compares well with present day precipitation.

The various gas parameters are discussed in relation to glacier mechanics. It appears that simple trapping of atmospheric air is responsible for most of the gas in the glacier, and that gas frozen out of meltwater is of minor occurrence. The various data support the current concept of glacier movement.

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