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RADIO-CARBON AGE AND OXYGEN-18  
CONTENT OF GREENLAND ICEBERGS

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### **Abstract.**

The main objective of the Arctic Institute Greenland Expedition 1958 was (a) to determine the composition and age of ancient atmosphere trapped in glacier ice, and (b) to seek information regarding age and origin of the icebergs. All operations were performed on board a Norwegian sealing vessel equipped with deck laboratory, machine shop, and vacuum boilers for processing large quantities of ice. By melting 6 to 16 tons of the iceberg ice, sufficient  $\text{CO}_2$  from the gas enclosures was vacuum extracted and collected for one radio-carbon dating. Melt water was sampled at the same time for oxygen-18 determinations. Ice with perfectly homogeneous composition was never encountered, however, so some process, like melting and possibly organic contamination, must have slightly changed the entrapped air. The age of the ice ranged from recent to over 3000 years, with the oldest ice having the least oxygen-18; i.e., it was formed at the lowest temperatures, thus highest up and furthest inland. Most samples had originated relatively near the coast, and only three out of our eleven samples were formed 200 km or more inland. The overall rate of movement of the ice, calculated from age and distance, ranged between 110 and 270 m/year, which is in reasonable agreement with estimates by other authors in regard to icebergs formed not too far from the coast. Our data from separate flow systems indicate that simultaneous carbon-14 and oxygen-18 determinations may yield valuable flow information, especially so if applied to single drainage systems.



## Preface.

This study of Greenland icebergs was supported by the Arctic Institute of North America with primary funds provided under contract with the U. S. Office of Naval Research. The development of the instrumentation was carried out at the University of Oslo. The  $C^{14}$  determinations were made in the Physical Laboratory at the University of Groningen, and the  $O^{18}$  determinations in the Biophysical Laboratory at the University of Copenhagen. Dr. S. EPSTEIN kindly made the  $C^{13}/C^{12}$  determinations at the California Institute of Technology. Other collaborating organizations included Dartmouth College, Scripps Institution of Oceanography, and the U. S. Air Force Cambridge Research Center. The Ministry for Greenland of the Danish Government granted permission for and greatly aided in the planning of the field work. The sealer "RUNDØY" was owned by A/S Koppernæs & Sønner of Ålesund and under the able command of Captain HARALD MOLTU. Chief Engineer JOHN HELLE designed and constructed the special steam knife which proved so effective in cutting up large pieces of ice. Norsk Tindeklub, Oslo, provided us with valuable ice equipment. Appreciation is expressed to the above organizations and individuals for their wholehearted cooperation, to all scientific and technical colleagues who participated in the various phases of the study and field operations, to the late Professors C.-G. ROSSBY and H. U. SVERDRUP, who greatly inspired the early stages of the work, and particularly to Professor H. W. SON AHLMANN and Rear Admiral LEO COLBERT for their continuing interest and encouragement.



## INTRODUCTION

One of the main objectives of the Arctic Institute Greenland Expedition of 1958 was a search for ancient atmosphere through a study of the gas enclosures in glacier ice. That such atmosphere could be found trapped in high polar ice under ideal conditions seemed a fair possibility, for it had been shown that cold ice is practically impervious to gases (SCHOLANDER, FLAGG, HOCK and IRVING, 1953; HEMMINGSEN, 1959). Provided such ice were clean and dust free, only warming and resultant melt water could seemingly alter the original gas composition, because it dissolves the atmospheric gases in different proportions from that found in the air. If melt water were to seep down into the snow and refreeze, it would enrich the trapped air with oxygen, argon and  $\text{CO}_2$ . And conversely, if the glacier ice on its way to the ocean is being heated to near melting, water will be extruded from the ice because of the bubble pressure, and will carry with it preferentially the same gases. Such a sequence could naturally explain the loss of oxygen and argon which was found in the Norwegian temperate glacier, Storbreen (COACHMAN, ENNS and SCHOLANDER 1958).

Only in high polar glaciers where melting had never taken place could one therefore hope to find undisturbed atmospheric air such as existed perhaps millennia back. This possibility was even more tempting to pursue, since the enclosed air could lend itself for radio-carbon dating because of its content of atmospheric  $\text{CO}_2$ . If the  $\text{CO}_2$  concentration were found to vary in time, one would have the means for testing the well-known "greenhouse theory" of climatic changes (ARRHENIUS, 1903). As discussed separately, completely undisturbed ancient atmosphere was never found, although our analyses showed that the gas composition was close to that of present day air (SCHOLANDER, HEMMINGSEN, COACHMAN and NUTT, 1961).

That dating of ice was technically feasible was demonstrated on the temperate glacier, Storbreen, in the Jotunheim district of Norway in 1957, where it was found necessary to process some five tons of ice for one dating sample. The ice was melted in a 100-liter vacuum pot by means of gasoline torches, and the water brought to boiling. The water vapor was reflux condensed, and the gases were pumped through a solution of barium

hydroxide to trap the  $\text{CO}_2$ . Enough  $\text{CO}_2$  was collected to give a total of a little more than 0.2 gram of carbon, which was dated at the Physical Laboratory at the University of Groningen. The age of this glacier ice, that is, the time it took for the ice to pass through this glacier, was shown to be some 700 years, which seemed a reasonable figure from estimates which have been arrived at by other means (COACHMAN, HEMMINGSEN, SCHOLANDER, ENNS and DEVRIES, 1958).

Another intriguing aspect of the dating derives from the stable isotope content of the ice. DANSGAARD (1954, 1961), EPSTEIN (1956), and GONFIANTINI and PICCIOTTO (1959), have shown the  $\text{H}_2\text{O}^{18}$  content of fresh water to reflect the temperature at which the precipitation fell. This relation seems also to hold for the HDO content (FRIEDMAN, 1953, and DANSGAARD, NIEF and ROTH, 1960).

If the relation between temperature and  $\text{H}_2\text{O}^{18}$  content is known,  $\text{O}^{18}$  analysis makes possible an estimate of the temperature of formation of the ice. If, furthermore, we assume the present temperature distribution on the glacier to be approximately the same as when the ice was formed, we have, in principle, a method for determining the region of formation of the ice and its distance from the glacier front. If we add to this the age determination by the radio-carbon method, we would have the means of estimating also the rate of ice movement.

The stage was now set for applying our analysis and dating techniques to high polar ice. The most promising, and by far the easiest of access, were the West Greenland outlet glaciers, from which we might hope to find old ice extruded from the depths of the inland ice. Thus, on the Arctic Institute Greenland Expedition of 1958 we planned to make a survey of West Greenland glaciers from southern Greenland northward, if possible to the ice fronts of Melville Bugt.

## ICE SAMPLING

### Technique.

The gas entrapped in the Storbreen ice had several times higher  $\text{CO}_2$  content than our present atmosphere, and it was therefore necessary to process only some five tons of ice. But if the high polar ice were to contain air of present day  $\text{CO}_2$  content, such as we expected to find, we would have to prepare for processing of thirty tons or more of ice in order to obtain one single dating sample of 0.2 gram carbon. This and other considerations of equipment and the need for a laboratory at each site made it necessary to perform the operations in Greenland from shipboard and to use glacier fronts or newly discharged icebergs as sources of ice.

From our operations at Storbreen many improvements in technique suggested themselves. Instead of gasoline torches spewing out highly concentrated CO<sub>2</sub> around the melting pots, it would be cleaner and safer to use an internal steam coil for the melting and boiling. It was likewise highly desirable to avoid the use of oil lubricated vacuum pumps, which might possibly contaminate the samples. The processing time could also be halved by alternating between two units. Throughout the spring of 1958, the new instrumentation was built in the shop of the Institute of Zoophysiology at the University of Oslo, and several tests were run on lake ice. Various ice drills and ice saws were also tested for possible use in obtaining ice.

A Norwegian sealer, the 114-foot M/S RUNDØY, was chartered in Ålesund, Norway. Like all sealers, it had excellent ice-working capabilities, a large deck upon which we could erect our laboratory and store the ice, and it had good quarters and mess facilities for a party of ten in addition to the crew of ten. The vessel was equipped with a heavy duty commercial steam generator, such as is commonly used on board ship for processing fish and shark livers. This unit had ample capacity for our work, and functioned perfectly day and night throughout the entire two months' operation in Greenland. It was likewise useful in furnishing steam for a special cutting tool which was used for dismembering the large pieces of ice which had been towed to the ship's side.

During the period of planning in Oslo the question always arising was how to get the ice for our melting pots. Naturally, either working at a glacier front or on large icebergs would involve too great a risk for ship and men. Mining ice with chain saws from small and apparently safe bergs turned out to be too slow and contaminated the ice surface with oil and exhaust smoke. In the field it soon became clear that the only practical and safe way was to handle relatively small pieces alongside the vessel. The most generally successful method was to lie at a safe distance off a glacier front or iceberg and wait for a calving to take place. When the pieces had drifted clear of the calving area they were herded alongside by the motor launch. The larger ones, some 100 tons or more, were cut up by steam knife and wooden wedges into pieces of a suitable size for hoisting aboard by cargo net.

In all some thirty to forty tons of ice were required for one dating, and this quantity was hoisted aboard in several lots, forming large heaps on the deck (Fig. 4). The ice was kept protected against direct sunlight by tarpaulins. Throughout the summer's operation a total of some 150 to 200 tons were processed, requiring almost double this amount to be hoisted aboard.

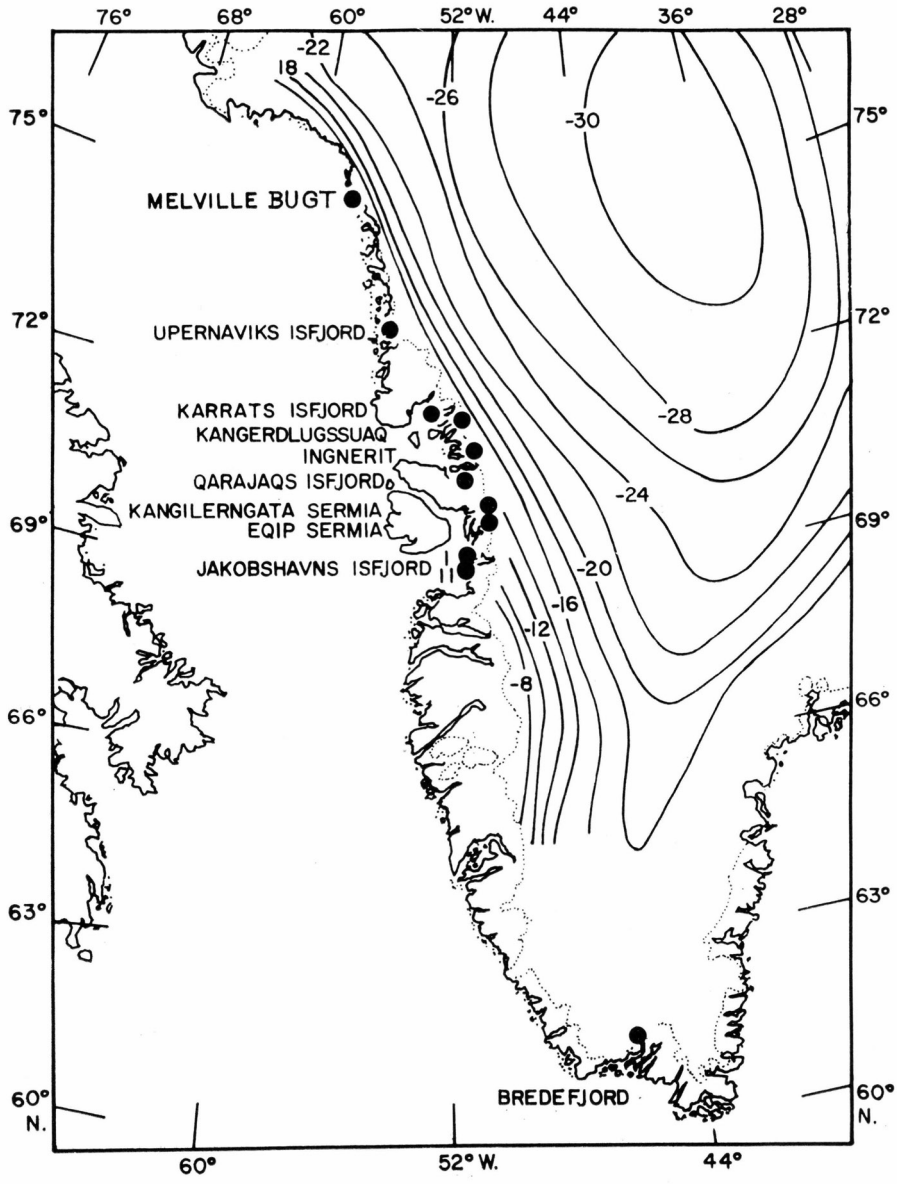


Fig. 1. Sample locations in West Greenland and approximate location of average yearly isotherms, measured at 10 meters depth in the ice, based on DIAMOND's map, 1960.

### Sample Locations.

On the map (Fig. 1) are shown the various areas where dating samples were obtained. Below the localities, dates, and sample sources are listed in order from north to south:

1. Melville Bugt: latitude  $75.0^{\circ}\text{N.}$ , July 27—30, iceberg from Kjaers Bræ or vicinity, large tabular berg.
2. Upernaviks Isfjord: latitude  $73.0^{\circ}\text{N.}$ , July 21—26, small iceberg from the icefjord.
3. Karrats Isfjord: latitude  $71.8^{\circ}\text{N.}$ , July 11—16, large grounded iceberg.
4. Kangerdlugssuaq: latitude  $71.4^{\circ}\text{N.}$ , July 8—10, calvings from the glacier front.
5. Ingnerit: latitude  $70.9^{\circ}\text{N.}$ , July 17—20, calvings from the glacier front.
6. Qarajaqs Isfjord: latitude  $70.3^{\circ}\text{N.}$ , July 5—7, single calving from an iceberg.
7. Kangilerngata sermia: latitude  $69.9^{\circ}\text{N.}$ , July 1—3, calving from the ice front.
8. Eqip sermia: latitude  $69.8^{\circ}\text{N.}$ , June 27—30, calvings from the ice front.
9. Jakobshavns Isfjord I: latitude  $69.3^{\circ}\text{N.}$ , June 20—23, two icebergs and a few extra pieces mixed together from the mouth of the icefjord. This was the first dating attempted.
10. Jakobshavns Isfjord II: latitude  $69.2^{\circ}\text{N.}$ , June 24—26, single small berg from the mouth of the icefjord.
11. Bredefjord: latitude  $61.5^{\circ}\text{N.}$ , August 11—13, NE. glacier, calvings from glacier front.

Further observations on these icebergs are given in DANSGAARD (1961, pp. 104-105).

### EXTRACTION OF $\text{CO}_2$ FROM GLACIER ICE FOR CARBON-14 DATING

#### Principle.

Glacier ice is melted under vacuum and the water boiled; the steam is held back by a reflux condenser while the extracted gas is pumped through an alkali solution where the  $\text{CO}_2$  is absorbed.

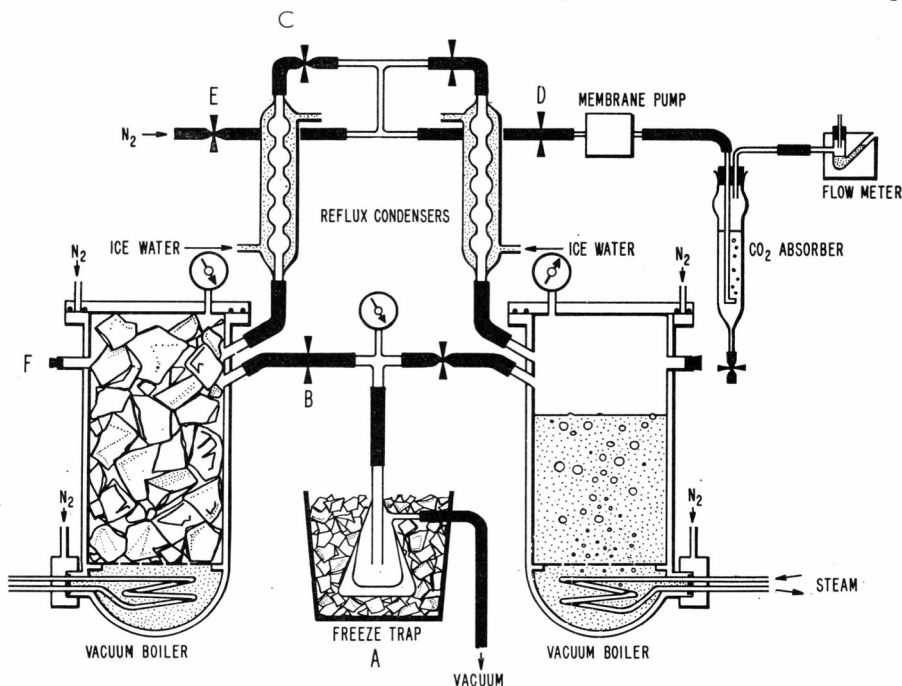


Fig. 2. Apparatus assembly for collection of  $\text{CO}_2$  from glacier ice. The membrane pump,  $\text{CO}_2$  absorber and flow meter were located inside deck laboratory, the rest on the outside.

### Apparatus.

The principal parts of the apparatus may be seen in Figs. 2 and 3. There were two vacuum boilers, each carrying a reflux condenser. Both of these units were serviced by a single evacuation unit and a  $\text{CO}_2$  absorption unit. The vacuum boilers (melting pots) were of stainless steel with a capacity of 150 liters each. These pots were closed vacuum tight by means of a lid furnished with a double O-ring seal. At the bottom entered, vacuum tight, a steam coil connected with a pressure hose from the steam generator. The ice was supported by a grid above the steam coil. The upper end of the boiler connected through one wide tube with a glass reflux condenser which was cooled by running ice water. Another wide tube went from the kettle to the evacuation unit. The space between the O-rings on the lid was supplied with  $\text{CO}_2$ -free nitrogen gas at slight over-pressure, and a similar nitrogen gas seal protected the vacuum tight glands where the steampipe entered the bottom compartment of the pot. The steam coils were made of tinned copper tubing.

The evacuation unit consisted of a heavy duty vacuum pump protected by a freeze trap chilled in an ice-brine mixture.





Fig. 3. Vacuum boilers with reflux condensers outside deck laboratory. CO<sub>2</sub> absorber located inside laboratory could be observed through window.

The CO<sub>2</sub> absorption unit was connected with the condensers and consisted of a "paint spray" type membrane pump capable of pulling a vacuum down to water vapor tension. This pumped the evolved gas from the boilers through a sinter glass absorption flask charged with 50 cc. 10 % CO<sub>2</sub>-free NaOH, i.e., about twice the amount necessary to bind all CO<sub>2</sub>. From the bubbler the gas went through a flow meter and out.

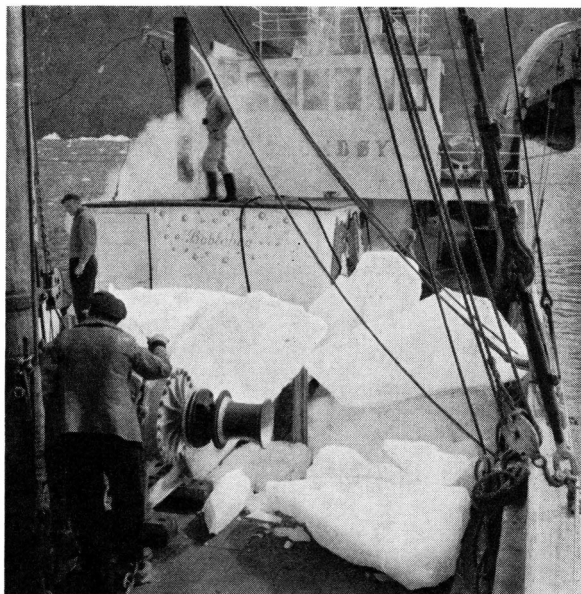


Fig. 4. A load of iceberg ice is on deck. Smoke pipe (left) belongs to steam generator operating vacuum boilers and steam cutting knife.

### Procedure.

By means of an ice ax, the melting surface of the ice blocks was trimmed off. These were then split into smaller pieces which were placed into the boiler until filled. The lid, with lightly greased O-rings, was put in place and clamped on with three screw clamps. The boiler, with condenser, was evacuated down to water vapor tension through A. Steam was admitted for a few seconds through the heating coil so as to melt the surface of the ice pieces and produce an excess of vapor, which was pumped out through A. By this procedure the system was flushed out by a great excess of water vapor, carrying with it any last minute surface melt and some liberated ice gases which were discarded. The connection to the vacuum system was now closed at B and steam admitted to the coil until the pressure in the kettle had risen to about one-quarter of an atmosphere. With the membrane pump running continuously, the connections to the absorption unit, C, D, were now carefully opened, while the flow through the bubbler was watched. By regulating the steam admission and adjusting D, one could control the melting and gas evolution in the boiler so that the gas flow through the bubbler was maintained at some 300—400 cc per minute.

When all ice had melted in the pot, the gas bubbling in the absorber would rather suddenly cease, and much water would appear in the

condenser. D was closed momentarily and this water was flushed back by a brief release of nitrogen through E. After a while, this gas would have passed through the absorption bubbler and water would again appear in the condenser, which was flushed down with a second release of nitrogen. The boiler unit was then closed off from the bubbler at C, air was admitted through F, and the lid opened and the water pumped out. The unit was recharged with ice and the process repeated. By filling one boiler while the other was being extracted, it was possible to process some twenty tons of ice in the course of two to three days and nights of continuous running, which was necessary in order to get the 0.2 gm of carbon needed for a dating. The alkali containing the precious dating  $\text{CO}_2$  was sealed off in glass ampules for storage.

### Checks on the technique.

Two potential sources of error needed special attention. One was contamination with air from the outside, either by simple leaks or by diffusion; the other was the possibility of fractionation of the  $\text{CO}_2$  gas.

Because it took from 80 to 230 pots to give one sample in an operation extending continuously over 2 to 3 days, any leak would be serious. In order to minimize the possibility of leaks, heavy duty vacuum tubing was used throughout the system, and the most critical places in the system, such as the lid seal and the seal for the introduction of the steam coil, were protected by  $\text{CO}_2$ -free nitrogen gas under slight over-pressure.

**Diffusion tightness.** A closed circuit was formed by the membrane pump, the  $\text{CO}_2$  absorber, and a length of neoprene tubing. After 24 hours of pumping, no  $\text{CO}_2$  had accumulated in the alkali, which proved that the plastic membrane in the pump and the tubing had no significant diffusivity for atmospheric  $\text{CO}_2$ . Neither were significant amounts of  $\text{CO}_2$  given off from any part of the interior system.

**Absorption efficiency.** Inasmuch as all  $\text{CO}_2$  was extracted from the ice, the only possible fractionation error would rest with incomplete absorption of the  $\text{CO}_2$  in the alkali solution. In order to test this possibility, outdoor air was forced by the membrane pump through the bubbler and into a large spirometer. The flow rate was adjusted to about 500 cc per minute, and 310 liters were collected in the spirometer. The amount of  $\text{CO}_2$  which accumulated in the alkali was measured and gave an air concentration of 0.036 %, that is, the absorption was satisfactorily completed. Whatever fractionation might have occurred to affect the  $\text{C}^{14}$  measurements must have been small, and in any event it has been accounted for by the  $\text{C}^{13}/\text{C}^{12}$  normalization.

In each field run, the amount of  $\text{CO}_2$  accumulating in the alkali was checked at intervals by withdrawing some 50 mm<sup>3</sup> of the alkali solution and injecting it into a volumetric respirometer containing a slight amount of acid. The  $\text{CO}_2$  evolution could then be directly measured. (KINOSHITA, BUNKER and SCHOLANDER, 1952).

**Pre-evacuation of boilers.** Because of the very small amounts of  $\text{CO}_2$  yielded by each cooking, it was essential that every trace of atmospheric air be pumped out of the pots prior to the gas collecting. This was accomplished by pumping down to water vapor pressure ( $4.5 \pm 0.1$  mm), which presumably would completely exhaust the air. If, nevertheless, 0.1–0.2 mm (= 10–20 cc) air remained, a shot of steam was routinely admitted to the coil, raising the pressure by 1–2 mm by releasing 100–200 cc gas from the ice. The pressure was again pumped down to water vapor. The amount of ice collecting in the freeze trap by these evacuations was measured and corresponded to 1000 liters of water vapor per pot, but as the ratio of vapor tension before and after the trap would be no smaller than  $1/2$ , it follows that the flushing volume of water vapor was at least 2000 liters per pot. The total amount of gas to be released from the ice after the pre-evacuation was 4–6 liters, and it is concluded that no significant errors are due to incomplete exhaustion of the initial air in the pot.

**Sea water contamination.** Although most samples were from recent calvings, the possibility of contamination by sea water penetration into the ice lattice was checked by frequent conductivity measurements of the melted ice. 55 measurements from 10 locations were made on ice which had been exposed to sea water. 50 of these were within the natural variations for glacier ice not exposed to sea water; 5 were slightly higher. Even if these values had been caused by sea water, the  $\text{CO}_2$  contributed from this source would be insignificant.

## RESULTS OF RADIO-CARBON DATING

The results are given in Table I, listed from north to south. These datings were performed in the physical laboratory of the University of Groningen. The samples were counted as  $\text{CO}_2$  gas and contained at the final analysis about 0.14 gm of carbon. The ages given in the last column of the Table include a correction for fractionation and a correction of 240 years for Suess effect.

It will be seen that in the random sampling from different glaciers over a great range of latitude, most ages are surprisingly low. The oldest

Table I.

Location	Latitude	Age uncorrected years	(C <sup>13</sup> )* ‰	Age**** corrected years
Melville Bugt.....	75.0°	−570 ± 150	+ 13.7	−110 ± 150
Upernaviks Isfjord .....	73.0°	2610 ± 150	+ 15.5	3100 ± 150
Karrats Isfjord .....	71.8°	−620 ± 150	+ 15.3	−130 ± 150
Kangerdlugssuaq.....	71.4°	300 ± 150	+ 16.1	800 ± 150
Ingnerit.....	70.9°	80 ± 150	+ 14.0	560 ± 150
Qarajaqs Isfjord .....	70.3°	470 ± 150	+ 14.5	940 ± 150
Kangilerngata sermia.....	69.9°	1020 ± 200	+ 15.6	1510 ± 200
Eqip sermia .....	69.8°	510 ± 150	+ 12.6	950 ± 150
Jakobshavns Isfjord I .....	69.3°	135 ± 200	+ 12.5	580 ± 200
Jakobshavns Isfjord II .....	69.2°	−380 ± 160	+ 14.9	100 ± 160
Bredefjord .....	61.5°	−170 ± 130	+ 13.9	290 ± 130
P** .....		Standard	0.00	
Ox*** .....		+ 8.1 ‰ C <sup>14</sup>	+ 6.60	

\* C<sup>13</sup>/C<sup>12</sup> ratio difference in per mille, from P.  
Measured by Dr. S. EPSTEIN, California Institute of Technology.  
Precision about 0.1 per mille.  
Relative to the P.D.B. standard, P was −26.7 ± 0.5 per mille.

\*\* P stands for the Groningen recent C<sup>14</sup> standard (peanut shells).

\*\*\* Ox stands for the oxalic acid C<sup>14</sup> standard (N.B.S., Washington).

\*\*\*\* Final age corrected for fractionation and Suess effect (240 years for the Groningen standard).

ice sample was 3100 years old. Only two exceeded an age of 1000 years, and three were very young. The standard deviation on the C<sup>14</sup> countings was approximately 150 years, i. e., the probability that the true ages were within the given limits is 68‰. Thus, the measurements on the samples from Melville Bugt and Karrats Isfjord are not necessarily wrong.

Contamination by recent CO<sub>2</sub> might be considered as a possible source of error. The extraction and analysis techniques, together with the precautions and checks, have been discussed above. Gas composition analyses from our samples gave CO<sub>2</sub> values from 0.04 to 0.10 volume percent, i.e., higher than atmospheric, and oxygen values from 20.2 to 21.0 volume percent, averaging generally lower than atmospheric. The variations of composition within the same block of ice show that ancient atmosphere as such was not found. Contamination at the site of formation of the ice would not affect the dating results. Only the addition of new CO<sub>2</sub> at a later date would cause an error and give too low ages,

but even if all  $\text{CO}_2$  above normal air composition were recent, none of the dated ice could be more than 4700 years old, and 8 of the samples would still be younger than 2000 years.

However, evidence argues against the possibility of addition of new  $\text{CO}_2$ . Cold ice has been shown to be virtually diffusion-tight, and the warming of the temperate Storbreen glacier towards the terminus resulted in loss of  $\text{CO}_2$  rather than enrichment. All of our Greenland dating samples had high bubble pressure which, upon warming, would tend to expel water and with it dissolved  $\text{CO}_2$  (SCHOLANDER and NUTT, 1960).

One possibility is that dust oxidation could have caused the elevated  $\text{CO}_2$  and generally low oxygen content in the bubbles. The contaminant could be organic dust, bacteria, pollen, etc., which had fallen at the site of formation. Even so, this material would have so nearly the same  $\text{C}^{14}$  content as the included atmospheric  $\text{CO}_2$  that it would cause no significant error in the age determination<sup>1)</sup>.

With due regard to the possibility of error in technique and in the integrity of the gas inclusions, all of which would tend to increase the  $\text{C}^{14}$  content of the ice, the generally low ages do stand out significantly and indicate that old ice, such as must occur deep within the central ice cap mass, was not found in the icebergs we examined.

## THE $\text{O}^{18}$ CONTENT OF GREENLAND ICEBERGS

The isotopic composition of precipitation with its climatic implications has been the subject of a general treatment by DANSGAARD (1961). From the relationships established, it seems possible to estimate the region of formation of the icebergs discharged from the West Greenland glaciers; and by application of the measured ages, one may also estimate the velocities of ice movement.

### 1. Measurement of $\text{O}^{18}$ content of the iceberg<sup>2)</sup>.

Seasonal and random variations of the isotopic composition of the ice are preserved during many hundred years (FRIEDMAN, 1953; EPSTEIN and BENSON, 1959; DANSGAARD, 1961). Therefore, only if an ice sample contained many years' precipitation would its average  $\text{O}^{18}$  content equal

<sup>1)</sup> The  $\text{C}^{13}/\text{C}^{12}$  ratio was less in our samples than found in  $\text{CO}_2$  of present day air. Organic contamination could produce such an effect.

<sup>2)</sup> The  $\text{O}^{18}$  content of a water sample is given here as the difference ( $\Delta a$ ) between the true  $\text{O}^{18}$  occurrence (in ppm of all oxygen atoms) in the water and that in a standard, whose  $\text{O}^{18}$  content is 39.1 ppm less than that of ocean water.

the mean annual  $O^{18}$  content of the precipitation at the site and time of formation of the ice. In this respect the dating samples were ideal, since many tons of ice were needed for each dating. The procedure was to take 50 cc of melt water from every second pot and mix them all together. No significant amount of water vapor could escape through the reflux condensers, and consequently there is no significant fractionation error in this sampling technique.

In Table II the values for the sampled icebergs are recorded in column 3.

Table II.

1	2	3	4	5	6	7	8
Location	Latitude	$\Delta a$ (weighted mean)	$t'$	Distance from coast	Age	Velocity	$\Delta a_c$
	°N	ppm	°C	km	years	m/year	ppm
Melville Bugt . . . . .	75.0	−19.8	−22.0	$80 \pm 20$	$-110 \pm 150$		−15.1
Upernavik . . . . .	73.0	−34.4	−30.6	$460 \pm 80$	$3100 \pm 150$	150	−31.6
Karrat . . . . .	71.8	−17.1	−20.5	$60 \pm 20$	$-130 \pm 150$		−15.4
Kangerdlugssuaq . . .	71.4	−19.4	−21.8	$90 \pm 20$	$800 \pm 150$	110	−18.1
Ingnerit . . . . .	70.9	−17.4	−20.6	$90 \pm 20$	$560 \pm 150$	160	−16.6
Qarajaq . . . . .	70.3	−22.7	−23.8	$190 \pm 30$	$940 \pm 150$	200	−22.4
Kangilerngata sermia	69.9	−24.5	−24.8	$260 \pm 40$	$1510 \pm 200$	170	−24.6
Eqip sermia . . . . .	69.8	−18.0	−21.0	$150 \pm 30$	$950 \pm 150$	160	−18.2
Jakobshavns Isfjord I	69.3	−15.1	−19.3	$140 \pm 20$	$580 \pm 200$	240	−15.8
Jakobshavns Isfjord II	69.2	−15.7	−19.6	$150 \pm 20$	$100 \pm 160$		−16.4
Bredefjord . . . . .	61.5	− 6.2	−14.0	$80 \pm 20$	$290 \pm 130$	270	−14.1

## 2. Determination of the temperature 10 meters below the surface at the place and time of formation of the ice.

It has recently been shown that a close correlation exists between the annual mean  $O^{18}$  content of the precipitation and the temperature,  $t'$ , 10 m below the surface.  $t'$  is equal to the mean annual air temperature in regions with no or little melting. The correlation was shown to be linear for a number of Greenland ice cap stations located at various altitudes and latitudes. The relation is given by the following equation (DANS-GAARD, 1961):

$$t' = 0.58_s \Delta a - 10.4 \quad (1)$$

The temperature range for  $t'$  extends from  $-14^\circ\text{C}$  to  $-30^\circ\text{C}$ . The mean deviation of the observed  $t'$  from the curve is less than  $1^\circ\text{C}$ .

Using equation (1) and the  $\Delta a$  values in Table II, column 3, the corresponding temperatures,  $t'$ , in column 4 were calculated.



### 3. Finding the region of origin of the ice on the Greenland ice cap.

The distribution of the  $t'$  isotherms on the Greenland ice cap is fairly well known, and is given in Fig. 1 (DIAMOND, 1960). Each of the distances recorded in Table II, column 5 (except that for the Bredefjord ice), is found by measuring on the map the distance from the particular outlet glacier to the nearest point of the  $t'$  isotherm. Since the South Greenland part of the map is considered unreliable, the Bredefjord value is obtained by considering the data from the South Greenland ice cap stations (DANSGAARD, 1961).

Isotherms shown in Fig. 1 may, of course, be affected by possible changes in the climate, or in the altitude of the ice cap since the time of formation of the ice. An altitude change of 130 m is equivalent to a change of near  $1^{\circ}\text{C}$  in  $t'$ . Errors of this kind may cause some further uncertainty, but will not alter the basic conclusions which may be drawn. The distances are seen to vary from some 60 to 460 km. Two of the icebergs (the oldest ones) seem to have come from more than 200 km inland. Each distance given in column 5 represents, naturally, a lower limit for the length of path passed by the particular iceberg, since the path could easily have had a component parallel to the isotherms.

### 4. Overall velocity of the ice flow.

Except for the three youngest icebergs for which the relative uncertainty of the age determination is very large, the data in Table II, columns 5 and 6, give the overall velocities throughout the lifetime of the ice shown in column 7. These velocities are seen to be rather similar, ranging from some 110 to 270 m/year.

### 5. Relation between $\text{C}^{14}$ and $\text{O}^{18}$ data.

If two icebergs formed at the same elevation and distance inland but at different latitudes are assumed to flow westwards toward the coastal outlets at the same velocity, they will be the same age when extruded from the glaciers. However, the  $\text{O}^{18}$  content of the northern iceberg will be less than that of the southern one, since the mean annual temperature and hence the  $\text{O}^{18}$  content of the ice decreases from south to north. In order to compare the  $\text{O}^{18}$  content and age at different latitudes, it is necessary to reduce the  $\text{O}^{18}$  values to a common latitude. Available data (DANSGAARD, 1961) suggest that the latitude effect amounts to a decrease of near 0.9 ppm per degree latitude going north.



The  $\Delta a_c$  values in column 8 have thus been reduced to latitude  $70^\circ\text{N}$ . In Fig. 5 are plotted the standardized  $\text{O}^{18}$  values against ages, and it will be seen that the  $\text{O}^{18}$  in general decreases with age, which simply means that the oldest ice originated in the coldest regions, i.e., higher up and further inland.

## DISCUSSION

It was pointed out in the introduction that the primary objective of the present study was a search for ancient atmosphere entrapped in Greenland icebergs. In this our efforts were thwarted, however, because even small pieces of ice showed slight variability in the gas composition, which of course is incompatible with undisturbed air. Whatever processes may have brought about these changes could hardly affect the radio-carbon dating of the entrapped gas, however, nor could they disturb the isotopic composition of the ice itself. However, from knowledge of the age of the ice and its  $\text{O}^{18}$  content, certain parameters of the ice flow may be deduced. These are discussed below.

We shall first make a few observations regarding the age concept of icebergs. Our dating samples of 6–16 tons each may seem very big samples, but constitute in fact only an infinitesimal part of a large berg and span only a few decennia of its total life history. Most of our dated icebergs were very large, 100 meters or more in thickness, and since the annual precipitation in the source area is only some 20 to 60 cm per year (BENSON, 1960), it follows that the oldest parts of any large berg must be at least several centuries old. It is also clear (excepting superimposed ice and ice from crack fills) that the age of the youngest ice in a berg cannot as a rule be less than the time it takes the berg to descend from the firn area to the sea level. The time spent during the latter path can vary greatly according to topography, from short and steep glaciers to long major outlets from the ice cap. But however long a life history the berg may thus have had, comparatively recent surface layers from the firn area may still be preserved on it.

Thus samples from the same glacier or large iceberg can vary substantially in age and only in exceptional cases can the actual location of the sample block within the discharging glacier be estimated. The Melville Bugt sample came from pieces falling off the upper part of a 25 to 30 meter vertical wall. With this height above water the berg would be some 200–250 meters thick which is equivalent to several centuries of precipitation. The great horizontal extent of this berg evidently had kept it from capsizing and our sample therefore dated merely young upper layers.

Evidently also the sample from Karrats Isfjord came from the upper layers of a berg discharged from the rapidly moving Rinks Isbræ. Both of these were among the youngest samples. In another case (Kangilerngata sermia) there was a massive calving in the central part of the glacier front with ice blocks discharged from above and below the water level. Evidently in this case our sample which was 1500 years old must have come from deep within the glacier front. We may discuss, therefore, the age and origin of a small piece of ice rather than of a whole iceberg. In the latter, the various layers are different with respect to both age and place of origin, and have in common only that they belong to the same flow system.

The carbon dating indicated that the age of the various samples ranged from very young to some 3000 years. There was a prevalence of relatively young ice in our samples. Thus 9 out of 11 samples were less than 1000 years old. This may be fortuitous, but such a distribution would be expected considering that the bulk of the precipitation in West Greenland falls in the coastal rather than in the inland locations (BENSON, 1960). The rate of flow of our dated ice was found between 110 and 270 m/year as an average over the entire course.

Various authors have estimated the age and rate of ice flows. HESS (1904) calculated the mean age of the icebergs by dividing the total volume of the ice cap by the total accumulation under the assumption of (1) mass balance of the ice cap and (2) all parts of the inland ice being exchanged with the same frequency. On this basis he found the mean age of the icebergs to be no more than 2000–3000 years. According to BAUER (1960b) the recent measurements of mass and balance of the ice cap made by the Expeditions Polaires Francaises give:

$$\frac{2.35 \times 10^6 \text{ km}^3}{446 \text{ km}^3/\text{year}} = 5300 \text{ years}$$

as the mean age of all icebergs, when using Hess's procedure.

A simple comparison between the total thickness of the ice cap and the annual accumulation shows that the ice close to the bedrock in central Greenland must be thousands of years old; HAEFELI (1960) estimated 30,000 to 100,000 years. However, it might well be that the oldest ice melts before reaching the outlet glaciers, because of friction and heat flux from the earth (HAEFELI, 1961). The above calculations would not hold if the deeper layers of the inland ice were essentially stagnant as is suggested by the general bowl shape of the bottom topography. There is presently little or no knowledge of the heights of the rocky thresholds over which the ice must flow near the coast. In any case, it seems that the oldest ice rarely, if ever, finds its way to the sea.

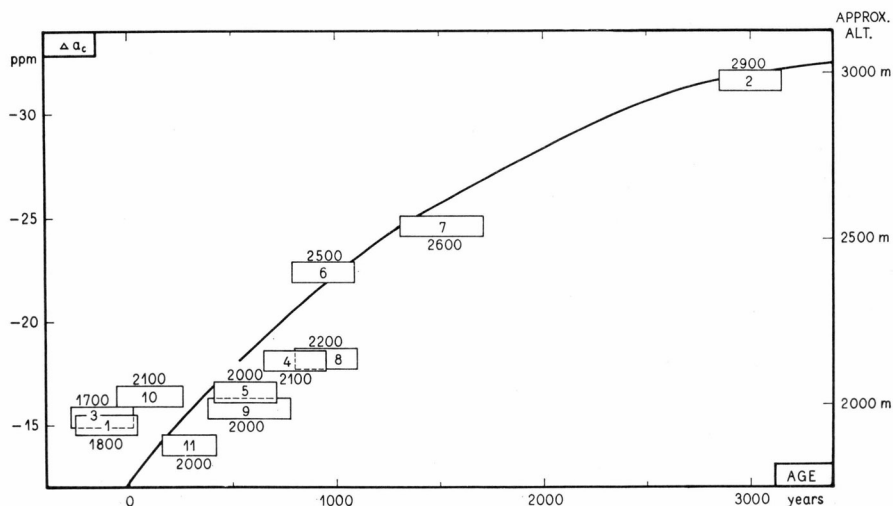


Fig. 5. Oxygen<sup>18</sup> of ice (and corresponding altitude) *versus* C<sup>14</sup> age. The scale to the right is based on an O<sup>18</sup> altitude effect of  $-1.26$  ppm/100 m increasing altitude. The numbers under or above the rectangles refer to the altitudes of the estimated sites of ice formation. The numbers within the rectangles designate the sample locations, p. 11. The dimensions of the rectangles correspond to the uncertainty of measurements.

The horizontal velocity of the surface of the ice cap varies from zero at the ice divide to several kilometers per year in the ice streams up to e.g. 10 km/year in the Jakobshavns Isbræ (BAUER, 1960b). The rate has also been measured in various Antarctic ice streams, and was found to be mostly between 110 and 1100 m/year, with an estimated average of some 360 m/year. These measurements were all taken near the coast and are undoubtedly considerably higher than the average flow rate over the entire life history of the ice, which is what we measured. Ice shelves were found to move 400 to 500 m/year, and high altitude ice sheets moved at an average of only 15 m/year (MELLOR, 1959).

Assuming a more or less steady state situation in the mass balance of the ice cap, BAUER (1960a) calculates the velocity distribution in the drainage area of the Jakobshavns Isbræ. A numerical integration gives us 700 and 5000 years as the time needed for the ice to traverse 40 and 80 %, respectively, of the assumed length of the accumulation area. This corresponds respectively to 50 and 175 m/year as a mean velocity for the entire movement, which latter figure fits rather well with our estimates.

Our O<sup>18</sup> data give information as to the temperature of ice formation and hence the altitude, and we may thus correlate age with altitude (Fig. 5). It will be seen that the few data available indicate a curve which flattens with increasing age, which is to say that the vertical component

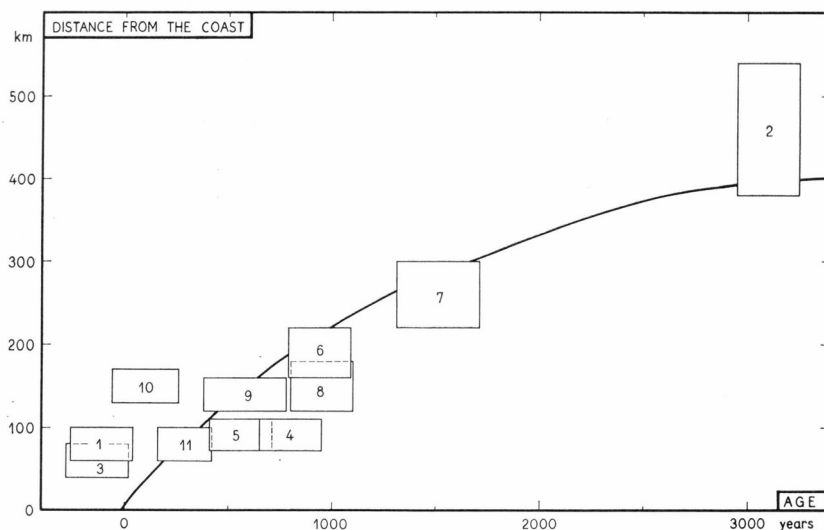


Fig. 6. Distance from coast of our ice samples *versus*  $C^{14}$  age. Solid line: possible interpretation. The numbers within the rectangles designate the sample locations, p. 11. The dimensions of the rectangles correspond to the uncertainty of measurements.

of the descent rate of the ice is slower at high altitudes than at the firn line; this, of course, would be expected<sup>1)</sup>.

By considering the altitude profile of the ice cap it is possible to arrive at an estimate of the rate of flow in the horizontal or surface projection (Fig. 6). The accuracy of this statement depends upon how well we can define the geographical position of the isotherms  $t'$ . Although the vertical lapse rate of  $t'$  (and  $O^{18}$ ) is rather well defined, it is much more difficult to fix the corresponding distance in the horizontal projection, for above the firn line the ice cap slopes very gently and merges imperceptibly into the level central plateau. Our oldest and coldest sample, Upernavik, evidently originated at near summit altitude, and its distance from the coast is therefore subject to considerable uncertainty. With due allowance for this, it may be said that our data are not in conflict with the notion of a slow flow at the summit which accelerates toward the firn line (Fig. 6). Presumably, these and other relations would have been more strikingly displayed had we sampled one single drainage area, rather than separate flow systems.

<sup>1)</sup> The very existence of a correlation between the two mutually independent parameters,  $O^{18}$  and  $C^{14}$  contents, would seem to support the general validity of our datings, and it suggests the possibility of a rough dating of ice from discharging glaciers by  $O^{18}$  measurements alone.

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