Willi Dansgaard

Frozen Annals

Greenland Ice Sheet Research

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AAGE V. JENSENS FONDE

Dedicated to

The Glaciological Group at the Niels Bohr Institute

CONTENT

PREFACE

This book does not pretend to be a strict scientific review. It rather aims to be a readable story primarily about some Danish contributions to the exploration of the Greenland ice cap.

Prior to World War II most ice cap research rested on relatively simple techniques applied by daring Polar explorers. The civilian post-war research was marked by international co-operation and logistical progress (reliable surface and air transport), as well as new analytical and drilling techniques. For example, in the 1950'es some seeds of stable isotope meteorology were sowed at the University of Copenhagen, and from the late 1960'es they developed into extensive studies of Greenland ice cores, originally in co-operation with USA CRREL (Cold Regions Research and Engineering Laboratories).

The enthusiasm and versatility of all my Danish colleagues, scientists and technicians, in the laboratory and in the field, made our group an attractive partner for major foreign institutions, American, European and Japanese.

Most of our Greenland research has been executed as joint efforts by up to 11 nations, and, we are deeply indebted to many "external" scientists, who contributed materially to our common achievements. This applies particularly to Chester C. Langway Jr., Lyle B. Hansen, and Jim W.C. White (U.S.A.), Hans Oeschger, Bernhard Stauffer, Jacob Schwander, and Henry Rufli (Switzerland), Jean Jouzel and Laurent Augustin (France), David Fisher (Canada), Margareta Hansson (Sweden), Okitsugu Watanabe and Hitoshi Shoji (Japan), Heinz Miller and J. Kipfstuhl (Germany), David Peel and Eric Wolff (Great Britain), Preben Gudmandsen and through half a century, Henrik Tauber (Copenhagen), who recently improved this manuscript considerably.

Throughout the years we enjoyed a close, competent and fair logistic co-operation with The Royal Danish Air Force and The US Air Force, New York National Guard, 109' TAG (Tactical Air Group).

Some of the figures in this book are reproduced from dias kindly put at my disposal by Lars Berg Larsen, Ivars Silis, J.P. Steffensen, and The Danish Polar Center.

Financially, the Danish part of the work was supported by former Minister of Research Bertel Haarder, by The University of Copenhagen, and by several foundations, particularly The Carlsberg Foundation, The Commission for Scientific Research in Greenland, and The Danish Natural Science Research Council. I thank them all sincerely.

In the text, references to the list of selected background papers p. 120-122 are indicated by chapter and number in angular parentheses.

Annotations (passing remarks on techniques, digressions, definitions, and a few complex topics of secondary importance) are put in blue "boxes" that may be skipped without disturbing the principal line in the text.

January 2004,
Willi Dansgaard

1. APPROACHING GREENLAND

In the far northwesterly corner of the Atlantic Ocean lies Kalaallit Nunaat, the land of man, as Greenland is called by the Inuits. From a distance this largest island in the world looks like a white jewel set in dark mountains. And behind the mountains lies the inland ice, barren and wide, cold and white, a temptation to the adventurer, a challenge to the searcher, ruthless to the rash, generous to the seeking. Deep silence inland, interrupted by howling blizzards over the endless monotony of the snow-sheet, and roaring drama along the edges, when icebergs calve from the glaciers, or foaming rivers plunge into the sea.

This is the impression of the Greenland nature that emerges from Knud Rasmussen's legendary research among the Eskimoes, reports on explorer's struggle for life in the wilderness of Northeast Greenland, and Peter Freuchen's wonderful polar stories. Personally, I had no ambition of being a polar hero, neither did I become one. But I did experience the heroes' wonderful world, and I managed to contribute a bit to its exploration.

Some memorable years in Greenland

Greenland has been inhabited by Inuits (Eskimoes) intermittently through the last more than 4000 years, and permanently since about 500 A.D. The first European settlement was founded by Erik the Red in 985 A.D. and lasted till some time in the 15'th century, when the Norsemen society died out for unknown reasons.

Only 300 years later, in 1721 A.D., the Danish-Norwegian priest Hans Egede, founded Godthåb (now Nuuk). Until 1950 A.D., an agency under the Danish Government administered Greenland with the chief aims of (1) providing the Greenlanders with goods needed to sustain a primitive life based on local sealing, whaling and fishing, and (2) protecting the Greenlanders against the "destructive trends" in the modern world.

However, during the Second World War supplies of goods were imported from U.S.A. and paid in cryolite, a mineral of great importance for the production of aluminum. This opened the Greenland gate ajar to the outside world. Eventually, the gate was fully opened to a completely new life implying education on all levels and build-up of trades and industries supplementing the traditional hunting and fishing, a social quantum leap unmatched in depth, extent and pace anywhere in the world.

Since 1979, Greenland has had local autonomy executed by a Home Rule within the framework of the Kingdom of Denmark.

Fig. 1.1 *Greenland and its ice cap*

The Greenland ice cap

50 % of all fresh water on Earth outside Antarctica is bound as ice in Greenland. The ice cap covers 85 % of the total 2.2 mill. km^2 area of Greenland (Fig.1.1). It measures 2500 km from north to south and about 750 km from west to east in Mid Greenland. The surface reaches 3250 m a.s.l. at Summit and 2850 m on a minor dome in South Greenland. These two locations and station NGRIP lie on the main ice divide that separates two ice masses moving toward the West Coast and the East coast, respectively. The longitudinal surface velocities range from zero along the ice divide to several metres per day in the coastal glaciers. The thickness of the ice is well over 3000 m in Central Greenland.

Unlike the American and Scandinavian ice sheets built up during each glaciation in the past, most of the Greenland ice cap survived the intervening warm periods for two reasons: Firstly, the high surface elevation (at present 2/3 of its area lies more than 2000 m a.s.l.) is associated with low surface temperatures (present annual mean values down to -32 °C at Summit), and melting with run-off only in the marginal areas. Secondly, ample supply of precipitation from the Atlantic Ocean is given off by low-pressures moving northward along the coasts, sometimes even crossing the ice sheet.

The annual accumulation ranges from 13 cm of water equivalent in the central part of northeast Greenland to more than 100 cm along the southeastern coast, a total supply of about 500 km^3 of water equivalent per year. The total annual loss of material is approximately of the same magnitude, of which 50 % is given off as melt water by mainly coastal surface and bottom melting and an equal amount as icebergs.

Early ice cap studies

The first to winter on the inland ice was the Danish officer J.P. Koch and the German meteorologist Alfred Wegener (who later became famous for his theory on continental drift). In 1912 they built a hut on the ice in Northeast Greenland and a stable for the Icelandic horses that next summer should enable them to cross the ice cap at its broadest, 750 km.

Wegener studied the weather conditions throughout the winter, and inside the hut they drilled to a depth of 25 metres by an auger not unlike an oversized corkscrew. They measured the temperature at various depths and its variation throughout the winter.

Koch plunged into a 30 m deep crevasse, but fortunately he remained hanging on a ledge 12 m down, with a broken leg though and losing their only theodolite. During his subsequent three months sickbed Koch constructed a so-called Jacob stick for observation of the altitude of the sun, a primitive instrument known already by the Vikings 1000 years earlier. It enabled them to navigate across the inland ice in the summer 1913 thereby confirming Nansen's (1888) and de Quervain's (1912) observation farther south that the idea of an ice free area in central Greenland was just a myth. The horses were put down one by one and used as food for dogs and people, the last one when they reached the crevassed zone along the west coast.

16 years later Wegener set out for his famous expedition 1929-30, the crux of which became the wintering station Eismitte in Central Greenland 500 km from the west coast. The start was marked by misfortunes, however. The supply ship was delayed two months due to unusually bad sea ice conditions, and the motorized sledges failed. In stead, Greenlanders with dog sledges brought supplies to Eismitte in late summer. Tragically, Wegener and his faithful Greenlandic travelling companion Rasmus Willumsen died of cold and overexertion on their way out from Eismitte in November.

But scientifically the Wegener expedition was a great success. At Eismitte

1. the myth about a permanent central Greenland high pressure was disproved,
2. An elegant method was developed for measuring annual accumulation of snow by driving a stick into the firn (snow pack) with well defined strokes.
3. The ice thickness was measured at c. 2500 m by bursting dynamite on the surface and picking up the echoes from the bedrock.
4. Bursting experiments performed next summer in the marginal zone showed that Green-

land is like a bowl filled with ice, which slowly flows through chips in the edge ending up as icebergs or meltwater plunging into the sea.

A beginning

The first step toward my own lifelong engagement in Greenland science was taken in 1947, when the Danish Meteorological Institute sent me to the Geomagnetic Observatory in Godhavn (now Qreqertarssuak) on the Disko Island. The one year stay in Northwest Greenland became a great experience to my wife and myself, with deep impressions of the course of Greenland nature, its forces, its bounty, its cruelty, and above all its beauty. We were both bitten with Greenland for life, but after a year the need for further education forced us to turn homeward to the parish pump.

After some time I was transferred to the Danish weather service. The war had intensified the demands for reliable weather forecasts, and during the years that followed the international observation and weather forecast service made rapid progress. New radio communication techniques were developed, and small radiosondes, lifted to 10 to 15 km altitudes by balloons, reported about temperature, humidity, and wind speed and direction during ascent. Meteorology had become 3-dimensional – and international as no other field during the cold war that followed the hot one. In addition, Denmark felt obliged to build up and operate a net of observation stations along the extensive coast lines of Greenland placed close to the weather systems that dominate Europe and the entire North Atlantic region.

Meteorology was a more exciting field than geomagnetism, I felt, but the working climate was less attractive in the weather service than at the Biophysical Laboratory of the University of Copenhagen, where I was educated. Therefore, when a door opened in 1951 for a return to my original field I left for the sake of free university research and teaching.

My first job was to install a new mass spectrometer and introduce the application of heavy stable isotopes in biology and medicine. The heavy stable isotopes of oxygen and nitrogen seemed to be of particular interest in biological research, because radioactive oxygen and nitrogen have too short half-lives to allow long-lasting experiments. Stable isotopes used as tracers offered both advantages and disadvantages, and in the first run I did my best to inform scientists about their need for the new technique. Unfortunately, they did not have much need, and it only led to a few minor applications.

Box 1.1 A trans-Atlantic experiment. *The hyper-active Niels A. Lassen, MD, asked for my assistance in some physiological experiments aiming at measuring the oxygen exchange in the lungs by using the heavy oxygen-18 isotope as a tracer.*

The project was carried out extremely fast and rationally: Niels did the experiments during a stay at a hospital in New York. Every night he drove to the airport and handed the samples of the day to the pilot on the SAS night-flight at Copenhagen, where I picked them up next morning, Danish time. I measured the samples in the day hours, and in the afternoon I gave Niels the results by phone. By then he had just shown up at the hospital in the morning, New York time, and could continue the experiments without delay. The difference of time used twice. Voila.

Box 1.2 A Swedish physicist. *Shortly after the mass spectrometer was installed I was contacted by a young physicist, Lennart Lundberg, from the Swedish Atomic Energy, Inc., in Stockholm, a great concern owned by the Swedish state and with the aim of preparing the way for peaceful development of atomic energy. Lennart asked if he might use my instrument for measuring the content of the heavy hydrogen isotope deuterium (D) in some water samples. In retrospect, I should have wondered why a financially and scientifically strong organization like Atomic Energy Inc. was unable to buy or build a suitable instrument itself, or have the job done at other Swedish institutes. But at that time I did not think along those lines, so after consulting my boss we wished Lennart welcome.*

He showed to be an excellent physicist, and besides an elegant and pleasant man to be associated with, so before long we had established close relations, professionally and personally. I learned a great deal from him, although direct introduction of water vapour into a mass spectrometer is not a recommendable procedure. There was no risk of permanent damage, however, and no other task ahead.

↓

↑

But here is the most exciting part of the story: After his return to Stockholm, Lennart sent me a letter in May 1952, in which he wrote: "My new workplace is the Research Institution of the Defence, and my field of activity is secret". A few years later I read in the press that Lennart Lundberg was found killed under mysterious circumstances. He was put in connection with circles within the Swedish national defence, who had worked for developing a Swedish atomic bomb in contravention of the politics of the Swedish government.

That raises a few interesting questions: Was he killed by Soviet agents? Was his water samples a step on the road toward non-peaceful atomic energy? Did he only go to Copenhagen with his samples, because no laboratory in Sweden should, or wanted to be involved? If so, we were taken in and abused for purposes we disagreed with.

Isotope meteorology

Ordinary water consists of slightly different kinds of so-called isotopic water molecules of equal chemical properties but different masses: a light one (H_2O^{16}), which occurs most frequently by far in natural waters, and quite a few heavier ones, of which the H_2O^{18} and the HDO^{16} components occur in concentrations of approximately 2000 and 320 ppm (parts per million) water molecules, respectively. Due to slightly different vapour pressures and rates of reaction, the concentrations of the isotopic components change somewhat during phase-shifts in the natural water cycle, and that is informative. The mass spectrometer was able to separate molecules by weight and measure the relative concentration of a heavy component in a given water sample.

Box 1.3 The δ scale. *The concentrations of the heavy water components H_2O^{18} and HDO in water samples were originally expressed in ppm (parts per million). However, in practice the isotopic composition of natural waters is now given as the per mille (‰) deviations delta (δ) of the concentrations of its heavy components from the composition of an international standard called SMOW (Standard Mean Ocean Water). Below, δ indicates $\delta(H_2O^{18})$, whereas δ(HDO) is always specified as δ(D). Both of the δ values of SMOW are thus zero per definition. On request, samples of SMOW are available at IAEA (International Atomic Energy Agency) in Vienna.*

Fig. 1.2 *A sophisticated experimental set-up in the lawn became the beginning of a new field in geophysics.*

Box 1.4 Miracles. *The Danish painter Axel P. Jensen once denied being superstitious, because, as he said: "quacks, ghosts and miracles are facts one meets frequently. We knew a needlewoman in Firenze. She ran to all church weddings, wanted to get married by all her heart. She had a wooden figure of the holy Antonio standing in front of her next to the sewing machine, and she prayed to him all the time, because he is the patron saint of all girls, and he provides a husband if they are just pious enough. One evening she lost patience. She felt that all the piety made her an old maid and flung the holy Antonio out of the window. Shortly after, a man came up complaining of being hit on the head by Antonio. That man became her husband."*

Wonders never cease. Here I shall report on a minor, but to me fateful miracle:

On Saturday the 21'st of June 1952 the weather was cool and showers portended a wet weekend. I pondered about the isotopic composition of rain water. Did it change from one shower to the next? Now when I had an instrument that ought to be able to measure it, there was no harm in trying. I placed an empty beer bottle with a funnel on the lawn and let it rain.

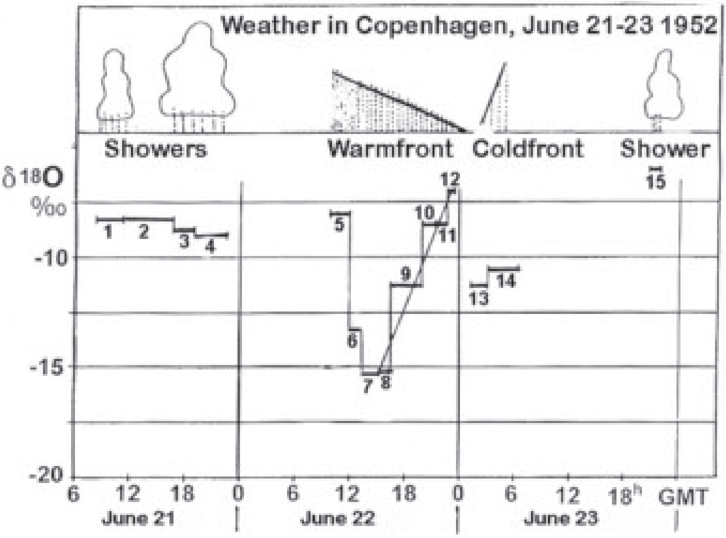

Fig. 1.3 *Changing H_2O^{18} concentration δ in rain during passage of showers and a front system.*

Once in a while I emptied the bottle into sealed containers, and next day it started raining again, now constantly till midnight, while a low pressure system passed just over Denmark. Without knowing the meteorological development, I continued collecting rain in new bottles throughout the day and the following night, when the cold front passed.

It turned out to be an unusually well developed front system. When the rain began in western Jutland, it had not stopped raining in Wales 1000 km to the west. I have never seen anything like it, at no time before or after. The miracle consisted in my starting the collection accidentally under these unusually favourable conditions.

As time went on I ran out of suitable containers for the rain water, and finally I had to use pots and pitchers. The collection looked far from scientific when I transported the whole lot to the laboratory Monday morning. At first, the samples were transferred into sealed and numbered containers and subsequently measured in the mass spectrometer by a technique that didn't require passing water directly into the instrument. In fact, the water was isotopically equilibrated with CO_2, which was dried in a cold trap and passed into the mass spectrometer.

The results of the rain water analyses were remarkable, even though I tended to oversimplify the interpretation in the beginning. Fig.1.3 shows the δ values in rain collected In Copenhagen from June 21 to June 23, 1952. The first samples (1-4) had δ values about -9 ‰ in the rain falling as showers before the arrival of the warm front.

The very first front rain (sample 5) was formed at the highest and therefore coldest part of the precipitating front cloud, and yet its δ-value was relatively high due to evaporation from the rain drops falling through the still dry air below the cloud. As time went on, the rain was formed at steadily decreasing altitudes and therefore at steadily increasing temperatures. From a minimum below -15 ‰(sample 7), δ increased with the temperature of formation of the rain till -7 ‰ (sample 12) in rain formed at a very low altitude. High altitude rain was formed once more, when the cold front arrived the following night (sample 13 and 14).

Disregarding the complicating evaporation effects on samples 5 and 6, the δ-values of warm front rain reflect its temperature of formation in the cloud – the lower the temperature, the lower the δ-value of the rain [ref.1.1].

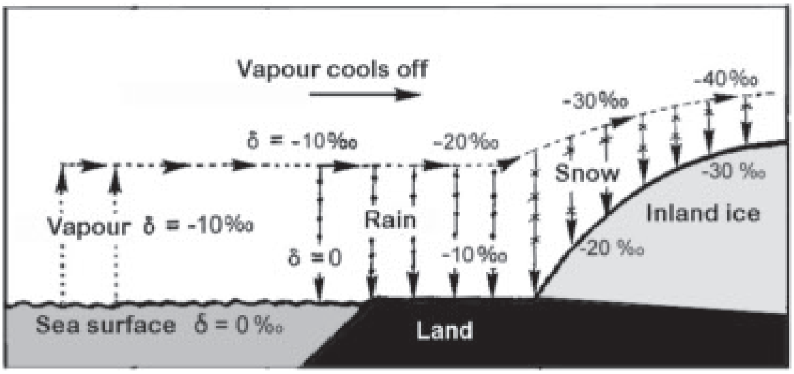

Fig. 1.4 *δ-changes (isotopic fractionation, cf. Box 1.5) in vapour and precipitation by evaporation from the sea (to the left) and by formation of precipitation from a cooling air mass during its move towards higher latitudes and/or higher altitudes, e.g. along a warm front or over the inland ice (to the right).*

Box 1.5 δ-changes. *The main reason why δ varies in the water cycle is that the heavy* H_2O^{18} *molecules have a 10 ‰ lower tendency to evaporate from a water surface than the light* H_2O^{16} *molecules, and a 10 ‰ higher tendency to condensate from water vapour – or in physical terms: The vapour pressure of* H_2O^{18} *is 10 ‰ lower than that of* H_2O^{16}*. Hence, vapour in equilibrium with sea water (SMOW) has a δ-value of -10 ‰. (cf.* Fig. *1.4) and, conversely, when the vapour cools off droplets are formed with a δ-value 10 ‰ higher than that of the vapour, at first therefore 0 ‰.*

When a cloud gives off rain, it loses more H_2O^{18} *than corresponding to the concentration in the vapour. The remaining vapour thereby gets a lower δ-value. This decrease in δ will continue by further cooling, and so will the δ of the rain as the precipitation process proceeds. If the air mass does not take up new vapour on the way, the δ-value of the precipitation decreases approximately by 0.7 ‰ per °C cooling.*

In Fig. 1.4 the primary evaporation takes place from a sub-tropical ocean surface to the left, and the horizontal arrows follow the humid air mass toward north while cooling to the dew point, when the first rain is formed (with δ = 0 ‰). During the proceeding cooling, when the air mass crosses a continent, or flows over the inland ice (to the right in the figure), or ascent along a warm front, it gives off precipitation and acquires steadily decreasing δ's for both the vapour and the precipitation. This explains i.a. the generally very low δ values in rain from the top part of the warm front, cf. Fig. 1.4.

Heaven and sea

The warm front success sharpened the appetite. I philosophized that cumulus clouds, beyond being one of the most beautiful and fascinating phenomena in nature, must function almost like the condensation part of a distillation apparatus in the laboratory: Warm and humid air ascents under cooling, whereby the water vapour, and particularly its heavy isotopic components, condensate into drops that fall as rain. During the ascent the remaining vapour becomes steadily poorer in heavy water components, and finally it shoots out from the top of the cloud with presumably very low δ values.

This model ought to be verifiable, and the efficiency of the natural distillation apparatus should be measurable, if water vapour could be collected under the cloud, in the middle of it, and above it, for comparison with the rain from the cloud. But how do you get into a cloud in an affordable way?

One of my colleagues had useful connections to the Research Council of the Defence, and he cleared the way for an experiment by means of an Oxford training aircraft of the Royal Danish Air Force. It was assigned the task of flying through and around a big cumulus cloud, while I sat in the cabin collecting vapour and cloud droplets in cold traps cooled by dry ice.

My wife Inge took part in the flights, because, as she said: *"I don't want to become a young widow."* We were both dressed with parachutes and got careful instructions that if we had to jump we should wait 10 seconds before pulling the string that releases the parachute. After landing gently we should disengage ourselves from the parachute by pressing a button on the front. When the whole game had come to a happy ending, Inge repeated: *"How was it? First you jump. Then wait a little. And then you press the button on the front."* Happily, God takes care of his children.

Box 1.6 Deep sea samples. *My only investigation on ocean water did not bring any dramatic news either. The Danish Galathea Expedition going around the world (1950-52) returned with numerous water samples, i.a. some from great depths reaching 10,500 m in the Philippine Trench in the Pacific Ocean. The head of the expedition, the zoologist Dr. Anton Bruun, asked if I thought their isotopic composition deviated from normal.*

I made some calculations and concluded that if the water masses in the Philippine Trench had been stagnant through a long period of time the gravitation would have sedimented the heavy water components causing measurably elevated δ's in the samples from the greatest depths – just as the gravitation in the stable stratosphere results in the highest concentration of the heavy gases in the lowest strata.

I measured the water samples carefully, remeasured, checked and controlled, but I could not find the slightest sign of elevated δ's. Bruun reacted this way: "That is an important result, because it shows that the water masses are exchanged even at the greatest depths. As a matter of fact, that is what we expected."

It was not a sensational result, to put it mildly, and the small article about it in "Deep Sea Research" is probably consigned to oblivion long ago.

Going through a magnificent cumulus cloud caused an extremely violent tossing. At last we circulated above the cloud collecting a few tidy samples of water vapour. Apparently, the pilot was not aware that the westerly wind blew the cloud, and thereby us, over the Swedish border. But at least he was informed about it when we came back, because the Swedish air defence had raised the alarm having observed an "unidentified, invading aircraft" that did not react to warnings (we were in the middle of one of the hot phases of the cold war, Korean war etc.). The Swedes were in the process of sending fighter planes after us, when a signal from our air field averted veritable acts of war!

The isotopic composition of the samples confirmed the distillation model, but the samples were too scarce for a quantitative description of the phenomenon. My next paper also presented some indication of a seasonal δ-variation, but again the material was too scarce.

What about the Climate?

Next step was to check if the relationship between δ values and condensation temperatures demonstrated for warm front rain held true also for average values of rain over extended periods of time and under varying climatic conditions.

In a global context, the climatic influence on the δ values was an even harder problem to tackle. I myself would not be able to collect rain water, much less vapour, from different parts of the Earth throughout extended periods of time. Such a project implied a worldwide network organized through international co-operation (this was actually implemented 7 years later, cf. chapter 4, p. 38), but maybe river water would do, as it often represents the average precipitation in the drainage area. However, even river water would be too expensive, yet exciting, to collect if I had to travel around the world and do it myself.

I put the problem before Dr. Bruun, who immediately suggested a solution. Through the Galathea Expedition he had good contacts to the worldwide Danish East Asiatic Company and its director HRH Prince Axel. Bruun was convinced that the Prince would endorse a request for all branches of the Company to send samples of river water or just tap water.

And that's what happened. A few months later I was in the possession of a nice collection of fresh water samples taken directly from rivers or indirectly just from faucets. Together with snow and ice samples provided by my Greenland friends, they ranged from the tropics to the Arctic region. In warm climates the δ-values were considerably scattered and could not be related to the mean air temperature, but under temperate and particularly polar climate conditions the samples had lower δ values the colder the climate.

I explained this observation by calculating the isotopic turn-over in the water circulation in nature assuming (somewhat simplified as in Fig 1.4) that the precipitating water vapour originates essentially from the subtropical oceans. 35 years later, it was shown [ref.11.12] that this assumption is valid only for precipitation at high altitudes in the Arctic (Box 11.3, p. 93). Fortunately, it was just there a close δ to temperature correlation was important to us. Epstein and Mayeda had suggested a more complicated, qualitative model, in which uptake of new vapour en route was mentioned [ref.1.4]. But at that time, in 1953/54, my calculation [ref. 1.5] was at least a first approximation to reality.

Climate archives

The most important aspect was implied in an "internal reasoning" that the present δ to temperature relationship for cold regions might also be valid when going back in time. In other words, δ in old water might reflect the climate at the time of formation of the water. Now, where do you find old water? In glacier ice. And where do you find old glacier ice? In Greenland.

This is how my interest in Greenland was revived, now in a new context. I was sure it was a good idea, maybe the only really good one I ever got. Anyway, I have been nursing it for the rest of my life. I was also sure, however, that the idea would be "stolen" from me, if I let the cat out of the bag too soon. In my paper [ref.1.5] therefore I just put my fingerprint on the idea in the form of some cryptic phrases about local glaciers that might contain climatic information about "the past several hundred years". This was before the ice core deep drilling technique was developed, so I just imagined measuring the isotopic composition of the old ice flowing from the marginal glaciers.

The manuscript was completed the night before May 24, 1954. In manic condition I cycled at 4 o'clock in the morning through the quiet, dawn-illuminated streets to the central post office with an enormous envelope containing the full-sized drawings, franked with 35 available 1 penny stamps and addressed to the Scandinavian editor of the English Geophysica et Geochemica Acta, Prof. Wickman at the University of Stockholm.

A week later Prof. Wickman informed me that he found the manuscript interesting and that he would forward it to the editorial office in England, *"if I find an envelope that large"*.

U.S.A.

In early 1954 the OEEC (Organisation for European Economic Co-operation) granted me a one year scholarship that obliged me to study ways of transferring the American interaction of science and industry to Europe. I never understood how my boss Prof. H.M. Hansen managed to convince the grant committee that I was able to make a noticeable contribution in that field. I only wanted and committed myself to continue my isotope-meteorological studies

Northwestern University lies in the fashionable Evanston north of Chicago. It was much too expensive for our budget, so my family and I remained living on the Chicago South side, where we were first installed. That cost me 3 hours of train ride per day, until we bought a car later on. A drivers licence was acquired by driving around a block without putting additional cratches on my vehicle.

In Evanston, my boss Prof. Dole proved to be a nice and well-meaning man. His institute was not ideal for my field of work, but completely free. Mile-long rows of parked cars narrowed down the roadways to a degree that made the authorities forbid bicycling. Prof. Dole refused to obey the ban. He had already been fined, but he refused to pay referring to the American Constitution of 1776 that ensures the citizens full freedom of movement. The case ended high up in the system of justice, and as far as I know he won at last.

In the following months I continued working on the isotopic composition of rain and vapour samples, and I spent quite a few weeks studying the daily weather maps at the U.S. Weather Bureau. For each of the samples I estimated the percentage contribution of vapour originating from four groups of air masses, i.e. air containing vapour from the Caribbean, the Atlantic, the Pacific Ocean, and the Polar regions.

As expected, the warm and humid air from the Caribbean Sea had the highest, Polar air the lowest, and Atlantic air intermediate δ-values. As an interesting feature, the δ-values in Pacific air were just as low as those in Polar air. When passing the Rocky Mountains the Pacific air had lost so much of the heavy water components that the vapour reaching Chicago in the middle of the continent had very low δ-values. It was also interesting that the winter minimum in δ was mainly due to extremely

Box 1.7 Chicago. *On the Chicago South Side revolver shots and hooting police sirens sometimes formed part of the general disorder of the night. Personally, I was once in contact with both a policeman and a criminal, even in one and the same person:*

A policeman stopped me at a corner of a controlled crossing, where I used to turn left as prescribed by arrows on the asphalt. On that day, however, a tiny sign temporarily changed the mandatory into a prohibition, which I had overlooked.

The policeman took me severely to task, impressed on me the gravity of my offence, and I confessed immediately my guilt. He continued, however, referring to my jeopardizing of my family and other road-users etc. etc. He just kept laying down the law, despite my repeated admission. At long last I got enough and asked him to give me the fine and let me go ahead – after which he just waved me on.

Some friends of mine laughed at my naivety and interpreted the incident to mean that the policeman had placed his private small sign himself and was just standing on the opposite corner catching the fishes when they entered the trap. "You were supposed to give him 5 $ to be released. The Chicago police is so ill-payed that they have to do some private business late in the month." An object lesson in creative traffic regulation.

low winter δ's in Polar air, whereas the isotopic composition of the other air masses was less dependant on the season.

All taken together some results that were worth publishing. Not sensational, but valuable enough as a basis of the talk, which Prof. Dole reasonably enough asked me to give at the Gordon Conference in New Hampshire in July. After the conference, I planned for a round-trip in the U.S.A. collecting water samples all over the continent and visiting colleagues at several Universities.

Before leaving Chicago, I was supposed to submit a report to OEEC on my thoughts about the future interaction between science and industry in Europe! Not exactly my cup of tea, but by several intricate avenues, e.g. via the Scandinavian Club, I collected material enough to make the report look quite reasonable, at least to myself. My main conclusion was a recommendation that the European countries should establish really powerful common research institutions where the industry could buy advanced analyses or even research without having to invest in expensive instrumentation or specially trained scientists.

In retrospect the thought was perhaps a bit naive, but the basic idea was not completely different from what later became part of the European Union. I remained an amateur in politics, however, so my hard-won pearls scarcely made anybody raise an eyebrow in OEEC. Nevertheless, the report was okayed. The OEEC agreed to pay the trip to New Hampshire, and moreover considered the succeeding sampling tour around in U.S.A. as part of my scholarship – quite generous considering the main purpose of OEEC.

The grand tour around the States became a great experience. I visited several well-known scientists, i.a. Nier in Minneapolis and Sam Epstein in Los Angeles, and of course I collected water samples throughout the States for subsequent analysis.

Soon after, the Greenland ice sheet and its kids, the icebergs, should re-entered my sphere of interest as objects of the isotope-meteorological tool.

2. THE BUBBLE EXPEDITION 1958

One day in late 1956, a most fascinating man turned up at the laboratory: Per Scholander, Professor of Zoophysiology at the University of Oslo, world famous inventive experimentalist with micro-analysis of gases as a speciality. He had explained how whales reduce the loss of heat to their cold environment; how deep-sea fish establish great pressures in their swim-bladder; why Arctic animals do not get snow-blind; and how Polar insects survive extremely cold winters. Now he had got a new idea with no connection to either zoo or physiology: The air in the micro-bubbles entrapped in glacier ice are samples of the atmosphere of the past. By extracting the air from the ice, one should be able to measure the composition of past atmospheres and, in addition, determine the age of the ice by applying the recently established carbon-14 dating method on the CO_2 content in the bubbles.

Scholander (among friends called Pete) had heard about my interest in glacier ice, and I mentioned the possibility of estimating the temperature of formation of the ice and maybe past climates by stable isotope measurements on old ice. He was not immediately interested in the latter point. At least, his only comment was: *"The best climate is the one you find under the duvet"*, and I could not help answering: *"Yes, if you keep your head outside"*. Obviously, however, our two ideas complemented each other as falling off a log, so Pete invited me to participate in a dating experiment on a Norwegian glacier next spring and, if positive, in a Greenland expedition in 1958. I accepted the invitation on the spot.

Fig. 2.1 *Per Scholander*

In May 1957 I joined Pete's staff in Oslo, i.a. the technically talented biologist Edvard Hemmingsen, the instrument maker Iversen, and the student Harald Steen. We all drove to the Jothunheimen massif, and in six weeks we mined two big samples of glacier ice, 5 tons each, one from the young top and one from the terminus of Store Breen (The Great Glacier). The ice was melted in an evacuated steel container, and the released air was led through a CO_2 absorber. Subsequent carbon-14 dating by de Vries in Holland indicated that the oldest ice was 700 years old, which agreed with an estimate by Norwegian glaciologists. Hence, carbon-14 dating of glacier ice proved feasible.

However, analyses of the bubble air showed reduced contents of the most soluble gases that were more or less washed out by meltwater. Old atmospheric air had to be looked for in cold glacier ice, i.e. ice in Greenland or Antarctica.

In early May 1958 I went to the fishing port Ålesund in northern Norway for being enrolled on the fishing and sealing boat Rundøy chartered as an expedition ship by Pete. Ålesund had been made totally dry, but never in my life have I seen so many people being plastered at the same time. On board Rundøy only the cook was drunk, as he was most of the summer, which once gave rise to a minor fire in the galley. I shook hands with all of my 19 fellow travellers, including skipper Moltu's crew of 9 men.

I was installed chock forward at the bow just under deck with 5 others. Fortunately, my upper berth was just so narrow that I could wedge myself tight in a seaway. However, it implied being squeezed up against the ship's side, which resulted in my sleeping bag being

Fig. 2.2 *Rundøy dancing across the Atlantic Ocean*

soaked with seeping sea water. Alternatively, I could give myself up to the rolling, which implied the advantage that the seeping water ran directly down to the poor fellow in the lower berth.

Pete and his old friend Skjelten shared a cabin midships. In his memoirs [ref.2.1] Pete tells the story about his lost suitcase: "*When I undressed the first night on board, I simply could not find my suitcase – and concluded that I must have left it ashore. Skjelten, realizing my hopeless predicament, generously suggested that I accept his bounty – so from then on I used everything of his underwear, shirts, pyjamas, toothbrushes, shaving equipment etc. I have no idea how it ever got washed –", cf. Skjelten's report, Box 2.1 p. 21.*

Playing dolphins

On the way over the Atlantic we enjoyed watching the dolphins (or was it guinea pigs?) following us curiously. When swimming alongside the ship they had to work hard to keep the pace, but the few that found room just in front of the bow

Fig. 2.3 *Catching ice*

Fig. 2.4 *Splitting ice by a steam knife*

Fig. 2.5 *Cooking ice. My dress is a protection against the mosquitoes, not the coldness.*

Box 2.1 Skjelten's report: *Skjelten refreshed Pete's memory about the entire course of events: "One day after three weeks of travelling, you sat cursing and talking about fleas and lice and other pests that can eat up our bodies, and then at last,* ***"I am frightfully lousy, I can't find my suitcase. It is just gone",*** *whereupon I answered that I had plenty and we would keep the lice in check. The same evening you washed what you had taken off, and hung it up behind the ship's smokestack to dry. Next morning it all looked as if the devil had wiped his claws on it, and it had to be thrown away, whereupon your short comment:* ***"Let it go! I am clean as an angel and without a louse on my body".*** *When we unloaded the boat three months later, one of the crew told you that in the port lifeboat lay a suitcase with your name on it. We were interested as to what you had thought to smuggle, and what was so well hidden. There was your sought-after suitcase with underclothes, well packed by a loving woman's hand, and it hadn't been opened since Susan closed it for you. It was suggested by joking tongues that you had placed it in the lifeboat during the storm at Cape Farewell, to be sure to have it along if we had to take to the boats.*

did not move at all, apparently. Was it because we could not see them moving their tails up and down the whale-way, or had they hit on "surfing" down the bow-wave, that is gliding down the front wave like certain sportsmen? That had to be checked, of course, and an experiment was soon initiated based on a flexible model of a whale tale that was lowered into the front wave.

After homecoming, Pete published a paper on the whales' surfing in the journal Science. The end of the paper hinted that some of his colleagues disagreed: "*This is the way I think the dolphins do it. And if not, they should try.*"

Butting and cooking icebergs

South of Cape Farewell (Fig. 1.1, p. 9) we ran into the traditional gale and we lay hove-to a couple of days. Rundøy performed a war dance that reminded me of an old refrain: You cannot see what is up and what is down.

But everything comes to an end, and as soon as we came to leeward with Greenland on the starboard side we started changing Rundøy. A big shanty house was erected as a laboratory on the foredeck and called Boblebua (home of bubbles). It did not make the craft look very seaworthy, and the skipper crossed himself. While sailing along the West Greenland coast we installed the laboratory inside and the melting jar etc. outside Boblebua. So when we reached Jakobshavn (now Illulisat) in the Disko Bay (Fig. 1.1, p. 9) we were ready to cook ice.

The big question was, however, how we got hold of suitable amounts of ice, preferably from the same ice mass. Innumerable small ice chunks floated around, but they could have different origins, which would complicate the matter. Attacking great icebergs of millions of tons was out of the question, but medium sized ice chunks of some hundred, perhaps a few thousand tons might be cut up in lumps manageable by the winch. Simple souls tried to make unstable looking ice bergs disintegrate by rifle-shots, in vain of course.

In stead, we allied ourselves with Nature in some cases by going close to a glacier front and simply wait till it calved with an ice chunk of suitable size. In other cases, Multu rammed Rundøy full speed into minor icebergs (no ship-owner around, happily). During the collision everybody held on to hats and glasses, and those in Boblebua tried to save most of the glassware. After some training the technique proved quite efficient.

The lumps breaking off were often too large for being hoisted directly on deck, so they had to be further divided by a steam-knife, a long copper tubing put around the ice chunk and connected to a steam generator (Fig. 2.3 – 2.5). It might take 10 minutes for the "knife" to eat itself through the lump, and the poor fellow holding the end of the hot tubing had trouble avoiding burns.

When the ice was on deck, it went through the same procedure as used at Store Breen the year before. The ice-melting went on around the clock. The total outcome of the summer was 11 samples of carbon dioxide from icebergs ranging from the Melville Bay in north to Brede Fiord in the south. Each sample contained a minimum of ½ gram of carbon and represented 6 to 15 tons of ice, depending on the carbon dioxide concentration in the ice. In addition, many minor ice samples were prepared for gas analysis done by Pete himself in Boblebua.

Abreast Klaushavn, just south of Jakobshavn, we started working on a nicely looking ice chunk of some 1000 tons. Rundøy went alongside, and Harald Steen and a few others entered the chunk and drilled a hole to a depth of two metres, where they measured a temperature of -14 °C. It was blowing hard, so Rundøy went to leeward of a point.

This caused a dramatic event that nearly cost three lives, including mine, cf. Box 2.2.

In retrospect, the reason for the accident was probably that the drill hole had been filled with meltwater that refroze during the night creating great mechanical stresses in the ice. As a physical glaciologists I should have been aware of that, but I doubt if awareness would have changed the course of events.

Pete felt partly responsible for the horrible event, but with his long experience in sea ice skipper Moltu came to Pete's defence saying; *"Men, there is one rule in the ice: Use your dammed wits."* Later, this remark hit Multu as a boomerang:

Grounding

On the way northward we sailed in sheltered waters due to rough weather in the Melville Bay, where the charts are not reliable. Icebergs of all sizes were constantly in our way, which made the navigation pretty scrolled. At long last a large ice-free area opened up, and the impatient Moltu ordered "full speed ahead". It worked nicely for some time, but suddenly the ship crashed to a complete stop – and remained standing.

The reason for the ice-free area was obviously that low waters kept icebergs out. Moltu lowered the anchor into the motor boat and sailed it to an island nearby. A strong steel wire connected it to the winch on Rundøy, which pulled at all its might – in vain. Only after four hours we came afloat, when the high tide had lifted Rundøy by 1 metre. Had the grounding happened six hours later, when low tide was coming on, we had not got afloat unaided. "*Use your dammed wits.*"

After the swim I got toothache in both the upper and the lower jar. Every travelling dentist we came across was ordered to check fillings here and there by boring out and refilling. They used a drill of torture driven by the dentist's left foot as in old-fashioned sewing machines. Electricity had not yet come to the small villages.

Meeting Greenlanders

Our northernmost destination was Kraulshavn, the last habitation before Thule. When approaching we observed intense activity ashore. Women and children disappeared, and the men dispersed around the harbour seeking cover and aiming at us with rifles, when Rundøy anchor ed in the harbour. As the only Danish speaking member of the crew I sailed ashore with Pete and two seamen. We looked up the Greenlandic manager of the trading station, and as soon as I had explained our peaceful intentions the defence alarm was called off. I felt it would have been practical and considerate if Rundøy had sent a telegram in advance with reference to the Ministry's accept of our activity.

It was not the last instance of Pete's and Moltu's lack of understanding of Greenland custom. When later we operated in the Umanak Bay, we anchored at Ikerasaq, my old friend Lars Postbox's village (Fig. 2.7). Lars was part of the old Greenland. The absolute ruler of his kingdom, loved by his subjects. A legendary figure in West Greenland. For many years he lived with Dorthe, who was so beautiful that she got eight children. "*But she cheats me*", he told me in 1948, *"they are not all mine"*. Finally he married her: *"I decided to make her a decent woman"*.

Unfortunately, when we arrived Lars was on leave in Copenhagen, where he created a stir by walking around in the summer-hot city arrayed in his Greenland fur boots (kamiks). Had he been home, I am sure he had invited all hands on Rundøy to a mighty party *"knocking down a hen and snapping off the head of a pig"*.

Lars' Greenland substitute rowed out to Rundøy in his kayak to welcome us (Fig. 2.8, p. 25). I asked Pete to invite him on board, but Pete refused: *"We are here to work, not to practice social activities"*. I saw that the poor vice-manager was just about to loose face in front of the observing crowd ashore – a great defeat for a Greenlander.

Fig. 2.6 *Icebergs stranded on the bank at the mouth of Jakobshavn Icefiord*

Fig. 2.7 *Lars' kingdom., Ikerasaq.*
Insert*: Lars with beautiful Dorthe. No wonder she got 8 children. Photo: Arctic Institute*

He could have demanded admission to get aboard, so I asked him up for a cigar and a glass of wine, which we enjoyed on deck, visible to everybody. Then I showed him around on the ship and of course he invited me for a return visit to his home. His honour was satisfied, but my anger against Pete culminated.

At this point, Pete's assistant Edvard Hemmingsen told me details about Pete's life pointing out how Pete never spared himself, either in highly dangerous experiments or when other people needed his help, whether in peace or at war. In 1942, for example, he was close to dying when testing the vacuum tightness of pilots' spacesuit. And next year he saved three people crash-landed on a high-altitude Alaskan glacier by his first parachute jump, defying a military ban in time of war. Pete only escaped being court-martialed by the intervention of influential friends. In stead he received a military cross and an American citizenship.

That made me perceive that we must evaluate people as the complex beings we all are. One should never set oneself up in negative judgement of others based on one or a few instances of tact- or thoughtlessness. Neither should one idolize a man for his charisma or heroic deeds. Therefore, Pete and I remained friends for the rest of the life.

Box 2.2 Swimming. *Next morning, Pete encouraged me to go back on the chunk with two seamen, Kåre and Tore, collecting samples for isotope analysis before we started ramming and ice cutting. I did not like the job with Rundøy out of sight, but we entered the motor boat bringing life jackets and some plastic bottles for samples of ice. When rounding the point we agreed that Kåre and I should work on the chunk, while Tore should remain in the boat. I asked the two seamen to follow my example putting on their life jackets. Although they could not swim, they rejected smilingly. They did not need life jackets, as they were used to jump around on the ice floes in East Greenland when hunting seals.*

Kåre was first man on the ice. He moored the boat at a bar put into the hole drilled the day before. When I came over I realized having good foothold on the rifled surface of the ice. But then Tore jumped over contrary to our agreement. With an almighty crash the ice split right between my feet and a 300 ton block broke off.

Fortunately, I fell to the main part of the chunk, but now it started turning around so I ended in the water. I was unable to inflate my life vest, but using a few of the plastic bottles I began swimming around the chunk hoping to find a point of access to the ice. There was none. Kåre was still on the chunk and had a hold of Tore in the water.

I was not afraid of being so close to drowning, but I felt having deserted Inge and our two kids, and I was furious at having accepted to do the job without proper surveillance.

At that moment a true miracle occurred. A rowboat sent out from Klaushavn by manager Fritz Fencker, came just in time to save all three of us. A true miracle, because apart from Ikerasaq this was the only time we worked close to an inhabited area.

Back on Rundøy, Tore and I were shaking so violently from cold that we had to be assisted on board and to our berths. The content of a bottle of sherry disappeared gradually along with the shaking and the cold leaving me in deep sleep.

The home voyage

On our way southward we put in at Godthåb for bunkering oil and water – not food, unfortunately. Old potatoes are not a delicacy. The same holds for the girls who jumped aboard quickly as lightning. Two of the seamen became busy in the adjacent cabins. They were renamed Casanova and Don Juan, respectively.

The end of the Bubble-expedition was now in sight, and it was high time for Pete to realize his plan (a new one!) to measure the pressure in the microscopic air bubbles in the ice, Box 2.3.

This is a fine example of Pete's ability to solve a difficult experimental problem by simple means. However, all that could be concluded was that the diffusivity of air in cold ice is close to zero, which Pete had shown already. The bubble pressure in floating ice chunks ranges from 1 to 15 atmospheres, but it is influenced on several independent and incalculable physical conditions during the travel of the ice from its site of formation on the ice sheet to the open water.

The last carbon-14 sample was prepared in the very south, in Brede Fiord, near the old settlement of Erik the Red, Brattahlid. The end of the field work was celebrated by a mighty drinking bout styled a bit too coarsely for me.

Fig. 2.8 *The substitute manager at Ikerasaq*

Fig. 2.9 *Alfred Wegener's Peninsula*

I shall never become a true sailor. As soon as everybody became sober we started emptying and removing Boblebua and making Rundøy fit for the waves.

The prospect of going through a new storm south of Cape Farewell was not attractive. Therefore, everybody appreciated Moltu's plan of going through Prince Christian Sound, a narrow strait connecting East and West Greenland just north of the southernmost tip of Greenland. It became a memorable experience. Even the discriminating Norwegians were impressed by the Alpine peaks and the glaciers that here and there reach all the way down to the fiord. Only few people have experienced this fantastic scenery, because usually there is fog or low clouds in this area (Fig. 2.11).

At summertime the eastern, sometimes also the western mouth of the sound are blocked by great masses of sea-ice brought down from the Arctic Ocean by the East Greenland Current, so large ships prefer the rocking trip south of Cape Farewell. In August 1958, however, the way was open for the last voyage to Ålesund.

A whole summer among Norwegian speaking companions had of course enabled me to speak perfect Norwegian. However, Pete's student, Harald Steen, brought me down to earth again, when he took leave with the kindly meant words: *"Good by, Dansgaard. You are the first Dane I have met, who speaks an understandable Danish."* Sic.

When I left Copenhagen in early May, I told my four year old boy, Finn, that I would be back when the leaves on the trees turned yellow. At the homecoming already in August I was met by this greeting: *"It is fine that you are home, but the leaves have not turned yellow yet."* The little fellow had watched the colour of the leaves all summer long.

Results

I brought back thousands of melted ice samples in plastic bottles, and the mass spectrometer was soon running with a data production of twenty δ values a day, a quite unusual performance at that time. The first series of samples were cut along a line perpendicular to visible melt layers in an ice chunk from the Ingnerit glacier. The δ's oscillated with maxima in the visible meltwater layers, i.e. in the summer layers [ref.2.2]. Hence, the original seasonal δ variations in the snow were preserved in the old ice.

As time went on, the entire sample collection became measured in δ (oxygen -18), and de Vries in Holland had completed the carbon-14 datings on the CO_2 samples. We could summerize the most important results to imply [ref. 2.3] that

1. only two of the 11 dated icebergs were more than 1000 years old (1500 and 3100 years, cf. Fig. 2.12 p. 29), and three had ages that did not deviate significantly from zero. The surprisingly young ages gave rise to long discussions on the theme: Could the carbon-14 samples have been contaminated by modern carbon dioxide in the preparation process? Nobody could point at any probable source of error.
2. The oldest icebergs had the lowest oxygen-18 concentration and therefore the lowest temperature of formation, which should also be expected, since the oldest ones – other things being equal – are supposed to be formed at the greatest distance from the coast and therefore at the greatest altitude, i.e. in the coldest areas. The correlation between age and δ supported the validity of the datings – unless all the samples were contaminated with modern carbon dioxide, which might make all of them e.g. 1000 years older than indicated by carbon-14.
3. With this reservation we concluded in an article in the journal Meddelelser om Grønland [ref. 2.3] that generally icebergs reach the coast by moving in superficial ice streams. In the light of subsequent research it would have been wiser to conclude that most of the icebergs reaching the sea have moved in fast ice streams from not too far inland, whereas the major part of ice from Central Greenland moves so close to the bedrock that it melts on the way out and arrives at the coast in the form of meltwater.

Fig. 2.10 *Pete and student Steen with the bubble pressure instrument*

Box 2.3 Measuring bubble pressures. *This implied production of a new instrument based on a brilliant idea of his, but mechanic Iversen lay seasick in his berth. Also Pete was seasick. Deathly pale he stood for hours at the lathe on the rocking deck making a pressure chamber of brass shaped like a thick-walled cup. Two metal tubes were put through holes in the cup-side. One was connected to a pressure gauge, the other one was provided with a tight-fitting piston that could be screwed forth and back, thereby changing the pressure in the chamber, when it was covered by a close-fitting lid of thick-walled glass, Fig. 2.10.*

But where do you get a thick plate of glass at sea? Quite simply: You remove a porthole, cut out a suitable piece of glass, and cover the empty porthole by plywood. Skipper Moltu crossed himself once again.

The pressure chamber was then filled with glycerine, a piece of ice was flopped in, and its melting surface was watched by a microscope through the glass cover. As long as the pressure in the chamber was lower than that in the bubbles, they "exploded" when passed by the melting surface. But if the chamber pressure exceeded the bubble pressure, they "imploded" as indicated by a water membrane being "sucked" into the exposed bubble. It was quite easy to establish the same pressure as in the bubbles. That pressure could then be read on the manometer.

The results of the Bubble Expedition hardly satisfied Pete's expectations. We knew from the Store Breen project that glacier ice can be dated by carbon-14, and the apparently young ages of icebergs were exciting enough, but also so surprising that, in spite of extreme care, we did not feel completely sure having excluded all possible sources of error. As hinted above under item 2, however, a general error of the order of a 1000 years would make the results acceptable.

It must have been a great disappointment to Pete that the air analyses unambiguously showed that the air in the bubbles did not represent past atmospheres. Even ice without visible signs of melting had too high contents of the most soluble gases showing that at least part of the original summer snow had been wet enough to dissolve these gasses making them overrepresented in the ice (which did not invalidate the carbon-14 datings, though). The conclusion was that it may only be possible to find old undisturbed air in Antarctic ice.

Of positive results Pete had only the bubble pressure measurements and the dolphin's

Fig. 2.11 *Rundøy en route Prince Christian Sound. The pointed tops of the mountains show that this area was not completely covered by ice during the glaciation.*

surfing. In both cases the validity of the results was questioned. As far as I know, however, the development has shown that he was right about the dolphins.

After all, I was perhaps the one who benefited most from the Bubble Expedition, i.a. a good deal of material which resulted in a Ph.D. degree in 1961 and a professorship at the University of Copenhagen in 1962. Pete's idea of dating icebergs was not exhausted, however, so the Bubble Expedition was repeated on a new basis ten years later, cf chapter 5, p. 53.

La Jolla

Pete's days as professor at University of Oslo were numbered. His teaching activities by seminars, colloquies and individual tutorials did not satisfy the Faculty, and on the other hand he could not live with conventionally scheduled lectures, exercises etc. "I am not receptive enough for that". But he enjoyed lecturing about the unknown, which he found "infinitely more exiting". And he never ceased stressing the importance of finding experimental evidence of "scientific dogmas". Already prior to the departure for Greenland he

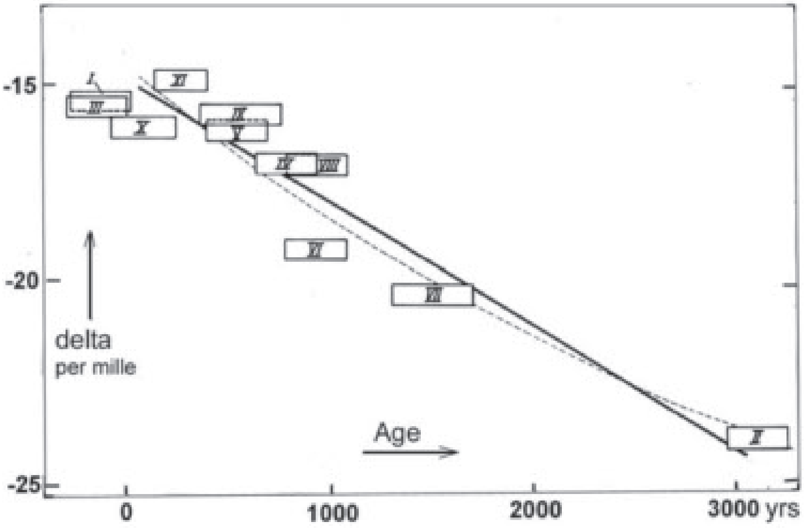

Fig. 2.12 *Relationship between the carbon-14 ages of the icebergs and their δ-values corrected for latitude effect.*

had accepted an offer of a position as a leader of the physiological laboratory at Scripps Institution of Oceanography at La Jolla, South California.

This job was entirely concentrated about science and that was just his element – in the employment contract he was even warned against getting too much "*involved in scholar activities*". He and Susan settled in a beautiful house in a palm grove on the beach of La Jolla. I visited them there twice and enjoyed the society of both of them and the humming birds.

In 1980 Pete died of a cardiac infarct, 73 years old. A college at Scripps is called after him: Scholander Hall. He almost completed his autobiography from which I quote extracts of Susan's epilogue:

"Pete's aversion against teaching disappeared over the years. He enjoyed his students as sparring partners, from which they benefited just as much as he, and they often became his coauthors – the year before he died Pete received the award of the Nansen Prize from the University of Oslo – I know that he valued this recognition more even than the honorary degrees from Alaska and Uppsala. – If in 1939 Pete left with no qualms about breaking his ties with the Old World; in 1977 he was equally glad to renew them".

My personal benefit from the contact with Pete was primarily the inspiration from his fiery soul. That influenced the rest of my working life – for better or for worse.

3. E.G.I.G. 1959-67

In 1957 it was rumoured that a big European expedition to Greenland had long been under way, Expedition Glaciologique International au Groenlande (EGIG). After the usual lengthy quarrels about getting the highest possible scientific output for the lowest possible financial input, five European countries agreed to join in a really big project in Mid Greenland. The five contributing countries were France, Germany, Switzerland, Austria and, as a deadhead, Denmark as the "host country", whose "contribution" was little more than permitting the project and requiring all scientific papers be published in the old Danish periodical Meddelelser om Grønland – at the author's own expense!

The main objectives of EGIG was (1) to carry out a geodetic and seismic survey along a traverse in Mid Greenland and repeat the survey at a later occasion with a view to determining the mass balance and the surface velocity of the ice; (2) to auger snow and firn cores en route to 10-20 metre depths aiming at physical-chemical analyses: and (3) to establish a wintering station in central Greenland for meteorological and glaciological studies in continuation of those of the Alfred Wegener expedition 27 years earlier.

The French Arctic traveller Paul-Emile Victor and his Expéditions Polaires Françaises (EPF) assumed the responsibility for the logistics (transport, supplies, equipment, accommodation etc.) and staked on transport by a combination of belt vehicles and aircraft. EPF got considerable resources, but not enough to enable France to conduct a real big project like EGIG on its own. This led to the first large scale European co-operation in the Polar regions – long before the European Union became a reality.

I contacted the Danish representative in the EGIG Steering Committee, Børge Fristrup, and asked him if anybody had plans for stable isotope analysis of the cores to be recovered on the inland ice. Since this was not the case I announced my interest on the spot pointing out that such analyses might allow determining the sites of formation of West Greenland icebergs. If the icebergs were carbon-14 dated, which Per Scholander's work on Norwegian glacier ice had proved feasible, one would immediately have a measure of the mean velocity of the ice on its way towards the coast.

On my behalf, Fristrup asked that samples of the ice cores be placed at my disposal, and

Fig. 3.1 *Prior to the era of big air freighters, deployment of heavy equipment for inland ice expeditions was often hampered by difficult access to the marginal zone. In case of an active moving ice front, even passing the edge could be a problem. Photo: Lars Berg Larsen.*

Fig. 3.2. *Easier access exists in places with "dead" ice, but the marginal zone is often cut by dangerous crevasses. Photo: Ivars Silis.*

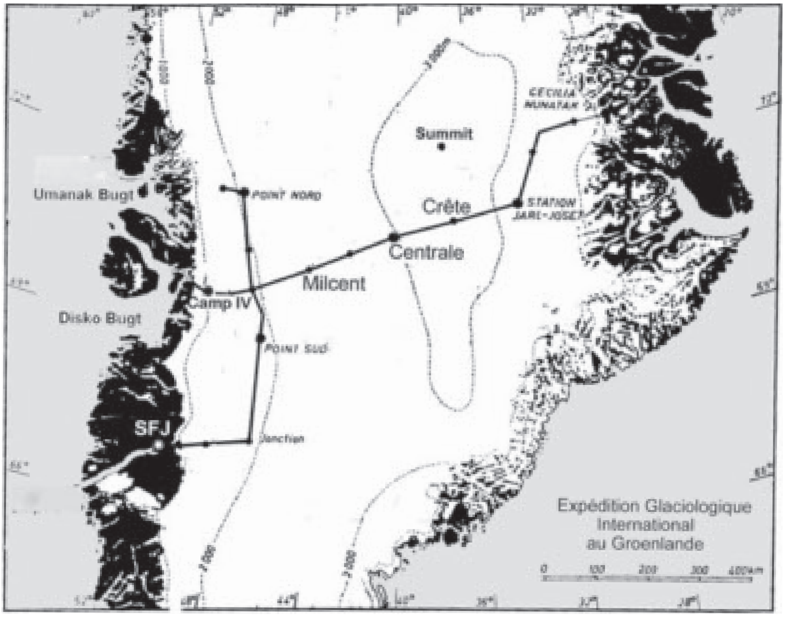

Fig. 3.3. *EGIG's area of operation in mid Greenland. The ramp to the inland ice started from the head of Sdr. Strømfjord (SFJ, now Kangerlugssuak). The wintering camp Station Centrale was not far from Alfred Wegener's station Eismitte. The highest point of the EGIG profile was called Crête. Station Jarl-Joset was named after two participants who were killed by falling into a crevasse.*

the Steering Committee complied with the request knowing that any foreign expedition to Greenland is obliged to hand over part of its collected material to Danish scientists if need be. Similar rules probably exist in other countries.

The samples arrived in 1959, but not as detailed as planned for, actually only a few samples from each core, because the EPF cold house caught fire shortly after the cores arrived in Paris. They all melted, but fortunately it was possible to save a representative sample from

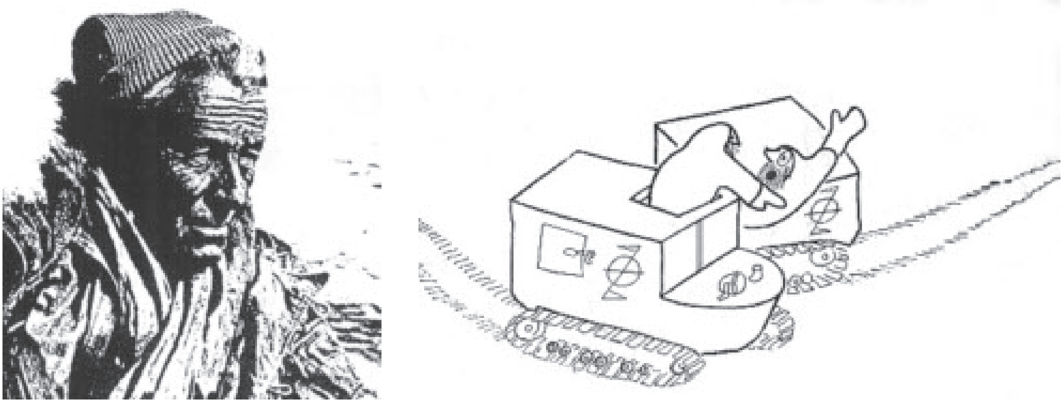

Fig. 3.4 *Paul-Émile Victor – and one of his Christmas greetings.*

each of the containers. As expected, the δ's decreased inland like the surface temperatures, which gave a good basis for comparison with the iceberg δ values.

Disregarding the tragic loss of two lives in 1955 (the Danish Jarl and the French Joset, who fell into a crevasse), the EGIG field work 1959-60 was a success. Victor's leadership was marked by his sense of the general lines, and his close relations to the French aircraft industry: Several small Aluette helicopters brought supplies to EGIG's moving and stationary units on the inland ice. He was a skilful PR-man, but the Steering Committee turned down his request for having all publications marked "Mission Paul-Emile Victor" on the front page.

He was also an artist with humorous drawings as a speciality. Every year he sent out a Christmas card with a motif from his expeditions. While listening at the meetings, he was always drawing abstract motifs in Indian ink. I often tried laying hands on one of the works of art – in vain. In the mid 1960's he married a young beauty with whom he settled in Tahiti. At the following EGIG meeting I encouraged him to arrange the next meeting there pointing out to the PR-man the chance of a dramatic newspaper headline: "Polar expedition meeting under the tropical sun". Unfortunately, he did not swallow the bait.

Steering Committee meetings

Throughout the 1960'es I joined several EGIG Steering Committee meetings in the participating countries. They were all arranged by the extremely dynamic and stubborn French secretary general, Prof. Albert Bauer, who spoke perfect French and German, and quite good English. The Danish participants were former head of the Ministry of Greenland Eske Brun, Børge Fristrup, chief inspector Helge Larsen, and usually my humble self with my recently acquired assistant, chemical engineer Henrik Clausen.

When the meetings were held in Paris, Helge Larsen was an expert guide. For example, he knew precisely where on the left bank of River Seine they served the world's best frog legs, so the whole Danish delegation marched in a body to the sanctuary and threw themselves upon the delicacies. The night became gruesome, however. Each of us got ill to a degree proportional to the number of frog legs consumed. Henrik and I shared a room, and we spent most of the night alternately in the bathroom and the room outside impatiently knocking the door in order to hasten the next shift.

The presidentship of EGIG was undertaken by the member states in rotation, from 1966 persistently by Eske Brun, permanent under-secretary of the Ministry of Greenland. Despite his limited knowledge of glaciology, Eske Brun was highly esteemed by EGIG, due to his strong personality and close relations to both Danish and American

Fig. 3.5 *EGIG's belt vehicles going through the crevassed marginal zone. Photo: EPF.*

Fig. 3.6 *Disko Bay 1968.*

authorities. At one occasion, insuperable logistic difficulties piled up already on the first day of the meeting. Brun asked EGIG's vice president to take the chair and declared that with the Steering Committee's accept he would fly to Washington already the same afternoon for negotiation with U.S. Air Force about the air support in the field that would solve the problem. He got the accept, and next day EGIG got the support.

Another reason for Brun's high esteem was that nobody could bamboozle him, not even a crafty tactician like Bauer. For example, Bauer once presented a French intention to measure the water depth in front of EGIG's favourite glacier Eqip Sermia. As a chairman Eske Brun declared that according to the rules EGIG should stick to the inland ice, and that hydrographic measurements rested with the Danish marine. Bauer protested, explained that special equipment had been purchased and worked in with a view to solving the outflow problem, and he questioned if the Danish marine was equal to the task. He continued for some time, energetic as he was, but at long last Brun lost patience and declared, quite unscientifically, but most impressively: *"Gentlemen. You can be sure that if the Royal Danish Navy undertakes a task, it will be accomplished satisfactorily. And now, let us turn to the next item on the agenda".* Tableau

The EGIG poles

In 1968, EGIG measured the new positions of the poles set out along the mid Green- land traverse 9 years earlier. This showed how far the poles had moved since then and thereby the surface velocities of the ice. The project was accomplished, not without serious difficulties, though. Victor's belt vehicles were originally bought as "used cars" from the American surplus stocks after the Korean war in 1952, and they were now worn out using more oil than gasoline. In the meantime, U.S.A. had developed a new technique of transport on the inland ice based on long trains of cargo sledges and personnel carriers pulled by enormous tractors, the so-called Swings, supplied by aircraft landing on skies. EGIG's transport system had become outdated. The small French helicopters were still operative and very useful, however.

As late as 1994 most of the old EGIG poles were found by metal detectors by a German group from the Alfred Wegener Institute connected to a new consortium, GReenland Icecore Project (GRIP, cf. chapter 12). Now covered by many metres of snow, the poles were lengthened to above the surface, and their new positions were measured precisely by modern satellite navigation system equipment. Thereby EGIG entered the computer-age after all.

Eqip Sermia

One of the sub-projects entirely based on helicopter support was a Danish-Swiss attempt to date the old ice at the edge of the inland ice close to Eqip Sermia (cover photo). This became the first one of pleasant co-operative efforts through many years with the Swiss group at the Institute of Physics of the University of Bern under the leadership of Prof. Hans Oeschger.

The Swiss idea was to drill a hole in the uncovered ice; lower an electric heater into the hole; melt a considerable amount of ice; and pump the liberated air up through a carbon dioxide absorber. The brilliant idea failed, unfortunately, due to difficulties with keeping the hole tight. As a better-than-nothing experiment, several tons of meltwater was pumped up for chemical treatment by Henrik Clausen in the hope that an alternative dating method based on radioactive silicon-32 might work.

When the water was pumped away, a large hole was left in the ice, and the temptation of going down for inspection was irresistible. Henrik and Bernhard Stauffer were first in the blue ice hall, followed by another colleague of ours, who had no trouble getting down, assisted by the gravitation. This force cannot be reversed, however, so the retreat caused troubles.

Actually our poor friend was firmly fixed in the borehole, and thereby the tightness problem was solved, but for obvious reasons it was replaced by a few others. However, by unified efforts everybody came afloat ready for being moved by helicopter to a new camp site 25 km from the edge.

Fig. 3.7 *These photos are reproduced from 8 mm narrow-gauge films.* ***Left****: Henrik Clausen pulling his plastic jars toward Camp III. On the port side one senses Hans Oeschger's bright top. He is not trying to overturn the load, but rather to right it, which perhaps had been more efficient on the starboard side.* ***Right:*** *When the end of the field season was drawing near, everybody aimed at looking civilized again. Here Henrik is making an honest attempt. Photos: Bernhard Stauffer.*

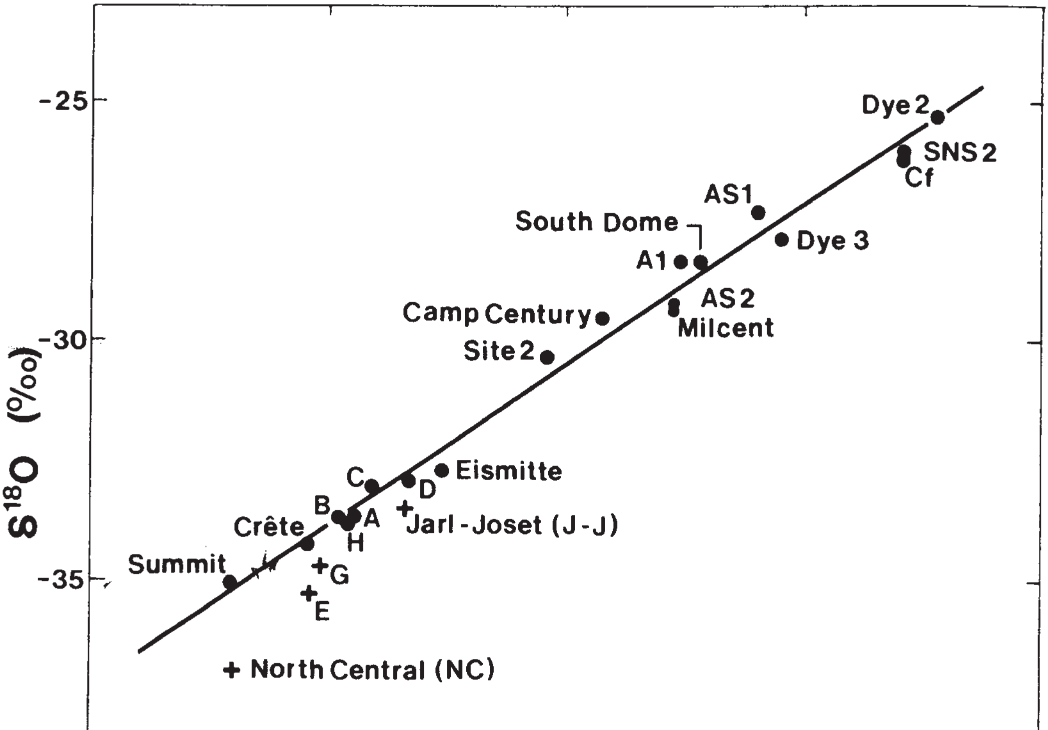

Fig. 3.8 *Mean annual δ of snow versus temperature at EGIG and other stations visited later.*

Here they lay detained by stormy weather for a couple of weeks. Once in a while, their small tents had to be freed for the burden of snow, a tough job in a howling snow storm. Under such circumstances people either start hating each other, or they become friends for life. Fortunately, the latter became the case, in spite of Henrik's unintended attack on Swiss vitals, when he provided his companions with sleeping-bag "convenience" bottles that previously contained concentrated ammonia.

The first isotope climate record

Although melted, EGIG's firn cores gave an important spin-off. The annual accumulation at the drill sites enabled us to calculate a time scale along each core and for example estimate how far back in time a given core reached, the longest ones to the beginning of the century. Each melt water sample represented several years of accumulation, and its δ value was used as a measure of the mean temperature at the drill site in the relevant period.

Fig. 3.8 shows how the mean δ of snow is correlated with the local mean annual air temperature measured 10 or 20 m below surface. Disregarding some stations on the eastern slope of the ice cap indicated by crosses, 1 centigrade lower temperature corresponds to 0.7 ‰ lower δ-value. The deviation of the stations on the eastern slope is probably due to these stations receiving some snow from western directions, i.e. from air-masses that have passed the high ice-ridge thereby losing considerable amounts of the isotopically heavy components of the water vapour, whereas the temperature is determined by adiabatic ascent from the east.

For lack of a temporal δ to temperature relationship, the present geographic correlation demonstrated by Fig. 3.8 was used to transform the temporal δ-profiles along EGIG cores into the temperature variations shown in Fig. 3.9. They may therefore need some correction, but the trends are undoubtedly correct.

There was only 32 EGIG samples from the interior of Greenland, but the sparse data reflected clearly the well-known global warming from 1920 to 1945. From then on there was a sign of Arctic cooling, however. This reversed tendency had been noticed in Alaska, but nobody really believed in it, partly because the observations at the Greenland coast stations did not indicate any cooling, perhaps due to still favourable ocean currents.

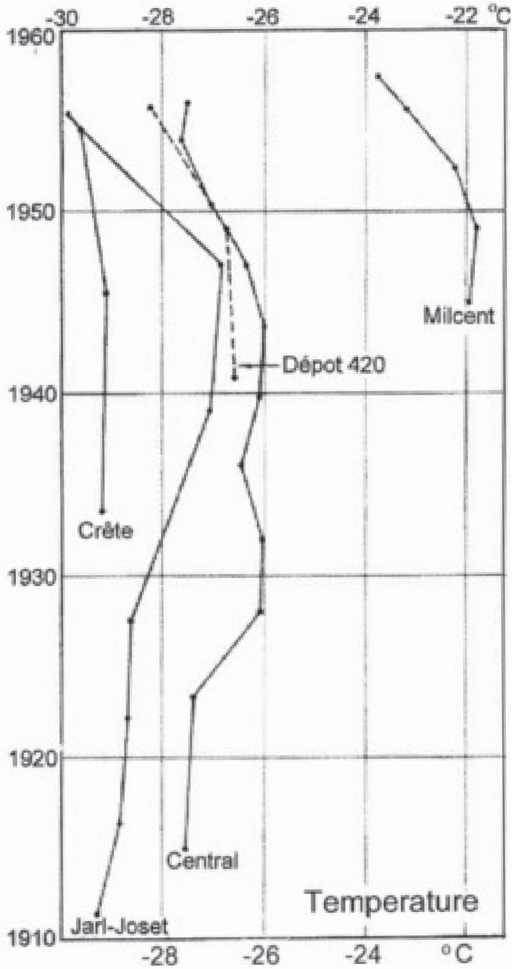

Fig. 3.9 *Climate records based on the H_2O^{18} concentration (δ) in snow and firn layers deposited at five EGIG stations on the inland ice (cf. Fig.3.3, p. 31). Two of the records reach more than 50 years back showing the warming trend in the first half of the 20'th century, and they all suggest a subsequent cooling.*

This was an issue full of political dynamite. It should be born in mind that during the first 20 years after the war Greenland waters were thick of cod. Foreign fishermen, particularly Portuguese, shovelled rich catchings aboard big mother-ships that served as factories and headquarters for a swarm of small one-man fishing boats. Unfortunately, neither Greenland nor Danish fisher-men had resources for profiting by the sumptuousness.

Only in the late 1950'es the Ministry of Greenland began investing considerable means in building up a Greenland fishing industry, and at the same time we presented sign of an approaching Arctic cooling, which might make an end to the Greenland cod. The Greenland fishery has always balanced on the edge of a degree Celsius, e.g. the one that was gained 1920-40.

In 1965 Anker Weidick and I published a paper entitled: "Climate deterioration in Greenland?" in the Danish language periodical "Grønland". Unfortunately, the prophecy came true. Ten years later the cod had almost disappeared and so far it has not come back, in spite of the recent global warming. One reason may be unfavourable ocean currents, but the most important one is probably greedy overfishing in the waters, from where the cod finds its way to Greenland.

4. THE IAEA-WMO NETWORK 1960-73

The stable isotope research got a lift of decisive importance thanks to the intervention of Hans Henrik Koch, permanent secretary of the Danish Ministry of Social Affairs. During the war he was a member of the oligarchy of permanent ministerial secretaries that virtually led, more or less illegally, the Danish administration after the Danish rejection of German exactions and till the end of the war. By hidden ways H.H.Koch directed big money from the Treasury to the Resistance, and he arranged shippings of foodstuffs to Danish prisoners in German concentration camps.

In 1961, Koch had become President of the Danish Atomic Energy Commission with close relations to the United Nations' International Atomic Energy Agency (IAEA) in Vienna. The purpose of the latter institution was, firstly, controlling the measures of precaution in connection with nuclear power stations; secondly, assisting the developing countries by word and deed concerning nuclear energy and, thirdly, monitoring the global pollution by radioactive substances after nuclear bomb-tests and unintentional leakages at nuclear power plants.

An important part of the pollution control was the formation of a global network of stations that should systematically collect monthly samples of atmospheric air and precipitation. This project was organized jointly with the World Meteorological Organization and called The IAEA – WMO Global Precipitation Network.

This was the project H.H.Koch saw must be a scoop for me. It was simply the perfect solution of my problem eight years earlier, when I only got limited access to non-recurrent collection of river water or just tap water from the East Asiatic Company branches around the world. Now the prospect was not only global coverage, including the important ocean areas, but also a possibility to follow temporal variations by samples collected systematically and treated equally according to a standard procedure.

Via the director of IAEA, Koch connected me to the head of the Section of Isotope Hydrology, the British Dr. Bryan Payne. During my visit to Vienna – the first of many – we met in the stately headquarters of IAEA on the fashionable

Fig. 4.1 *The WMO-IAEA global Precipitation Network 1962 before the Antarctic stations were included. Note the uncovered Asian and East European area.*

Kärntner Ring in Vienna. Payne's main task was to organize the collection of large samples of precipitation for measuring the fall-out of the radioactive hydrogen isotope tritium, a by-product at hydrogen bomb explosions. The tritium content of the large samples was measured at IAEA's own laboratory at Seibersdorf just outside Vienna, and since additional measurements of the stable oxygen and hydrogen isotopes only called for a spot of sample, they obviously ought to be included in the project.

Therefore we prepared instructions on the collection procedures for the responsible persons at those weather stations around the world we chose as participants in the project. Payne's main interest lay in tropical and subtropical areas, mine in the temperate and Arctic ones, but we found a useable compromise. I had brought a small 20 ml water and air tight plastic bottle of a type that had served well for years. It was accepted as a standard, purchased in large numbers, and distributed to the weather stations along with the instructions.

Complications

In spite of extensive diplomatic activity by IAEA, we never succeeded involving the Soviet Union and its allied in the project, obviously due to their suspicion of sinister intentions laying behind it. Soviet and China claimed doing these measurements themselves, but we never saw any data, and that was bad because the territories of the then Soviet and Chinese dominated countries covered a large part of the Eurasian continent (cf. Fig. 4.1).

I only succeeded collecting one sample from the Soviet Union. In 1967, I was on my way home from a conference in Japan. After Bangkok we stopped over in Tashkent, Utsbekistan. All passengers must leave the aircraft during refuelling, and at the exit door everybody had to give up their passport. Don't ask me why. It is difficult to imagine that anybody wanted to escape to the eastern paradise. Perhaps the aircraft crew simply wanted to avoid possible confiscation of passports in the airport?

Just when the stewardess got my passport at the exit it struck me: Holy Moses! Here is the chance of getting one of the water sample I have sighed for. But where do you get a tight container in that situation? Quickly I asked the stewardess for a Martini. *"Now?"* she asked confused. *"Yes, please, right now!"* I got my Martini mini-bottle, emptied it on the spot, and put the emptied bottle in my pocket.

In the air terminal there was no water faucet available, however, not even in the lavatory. But there was water flushing in the toilet, indeed, and using this technical wonder my Martini bottle got filled with a sample of the river water flowing slowly outside the barbed wires enclosing the airport.

The isotopic composition of the water sample proved to be quite interesting – very low δ-value, almost like Polar water. This is because most of the precipitation in this dry area is given off from air masses that have passed a high mountain range thereby losing considerable amounts of the heavy water components, just like moist air masses do when moving towards the Polar regions under cooling.

Based on the prospect of getting the worldwide IAEA material at disposal I got means from the Carlsberg Foundation for purchasing a new French mass spectrometer specially designed for measuring the concentration of the heavy hydrogen isotope deuterium (δD ‰) in water. The old, but updated instrument from 1951 should then take care of the oxygen isotope measurements ($\delta(H_2O^{18})$ ‰) as usual.

The samples now began surging into the laboratory, 100 per month, one from each station. Beyond the samples, IAEA placed considerable means at my disposal from 1961 for running the two instruments, including wages for increased working capacity. In addition to two laboratory assistants, highly qualified drafted graduates were on hand. Paid by the hour they were ready to work late on the samples prepared in the day hours. The instruments were usually in operation each evening, often till far on the night.

Expensive accommodation

Each year I went to Vienna for negotiation on renewal of the contract with IAEA, which became the basis of the activities of my group throughout the 1960'es. I was independent, did not need to fight with others in the laboratory about my share of the common annual grant.

One of my visits to Vienna elapsed really in accordance with my rank! In my hurry, I had just asked a travel agency to make reservation for a room in some hotel not too far from IAEA. The Taxi stopped at the entrance portal of Hotel Imperial vis a vis IAEA. A field marshal arrayed in a royal blue uniform with white gloves and plastered with gold and medals stalked dignified out and opened the Taxi door for me with heel-smack and stiff salute. By a flourish he invoked another general, who took possession of my only luggage, my handgrip, and together we stalked in procession through the swing door into the palace.

Box 4.1 Distillation columns. *In* Fig. *4.2 the Atlantic IAEA stations are divided into groups of ocean, coast and continental stations. Further grouping in a tropical-subtropical (red), a temperate (green) and a polar (violet) category shows linear relationships between annual* δ *versus temperature within each category, which suggests (1) the influence of re-evaporated fresh water from the continents, and (2) the existence of at least two more or less separate distillation columns in the Atlantic Ocean, a tropical-subtropical and a temperate one, perhaps even a polar one. This is an effect of the air taking up new vapour during its travel toward higher latitudes, i.e. a precipitation pattern more complicated than that considered in Fig.1.4.*

My "room" turned out to be a hall, by all accounts just the one occupied by a certain Mr. Adolf Hitler during his stay in Vienna after "Anschluss" in 1938. The walls were decorated by silk tapestries and the ceiling by numerous small fat cherubs cut out of wood and playing Mozart's minuet for flute, trumpet and harp down to elegant rococo furniture tastefully distributed in groups.

On a raised platform in the background a big altar stood under a baldachin with hanging and indirectly floodlighted semi-transparent white draperies. My attending general retreated to a dream of a bathroom in marble, and a plashing sound proclaimed that my bath would soon be ready. After having drained me for a minor fortune in tips he disappeared bowing and leaving me little man in the centre of all the splendour of the world, of which the altar showed to be a magnificent four poster bed, large enough for a whole family.

Unfortunately there was nobody with whom I could share the state, but an extra treat was waiting next day, when I told Brian Payne and his co-workers about my adventure. They laughed so heartily at me and my expensive mistake that I did not have the heart to tell them that the heavy bill would be payed by themselves via my IAEA account.

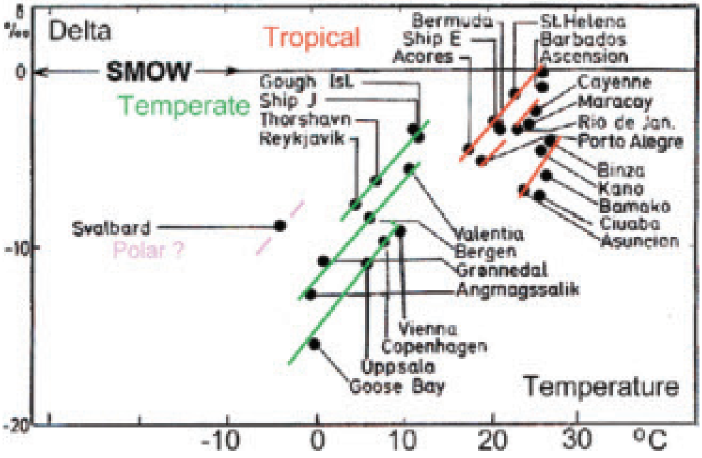

Fig. 4.2 *Mean annual δ versus temperature at Atlantic island, coast and continental stations suggest (1) a separate tropical-subtropical, a temperate and perhaps a Polar distillation column, and (2) the influence of re-evaporated freshwater on δ at coastal and particularly continental stations.*

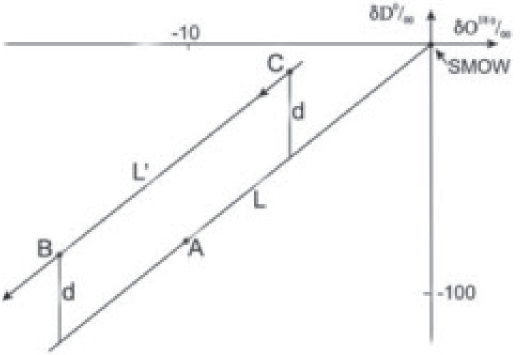

Fig. 4.3. *δD versus δO*^{18} *diagram. Point A marks the isotopic composition of vapour in equilibrium with SMOW. Line L has a slope of 8. B is the initial composition of normal atmospheric vapour in the source area of the moisture. Its deuterium excess is denoted by d. The first stage of a condensation process under equilibrium gives precipitation of the isotopic composition C with unchanged d. Progressive condensation makes the compositions of the remaining vapour and new precipitation move down along line L' from points B and C, respectively, i.e. with unchanged deuterium excess.*

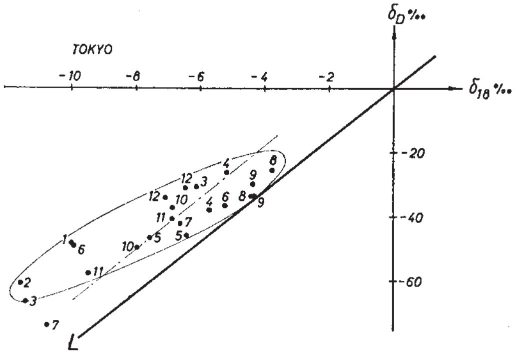

Fig. 4.4. *δD versus δ(O*^{18}*) diagram with numbered monthly samples from Tokyo (1 = Jan, 12 = Dec.). Winter precipitation has deuterium excesses higher than 14 ‰ due to fast evaporation from the surface of the Sea of Japan.*

Box 4.2 Deuterium excess. *In a δD versus δ(O*^{18}*) diagram (*Fig. *4.3) the "zero point" is SMOW. Vapour in equilibrium with SMOW has an isotopic composition A on a line L with a slope of 8. Depending on the humidity and temperature in the source area of the moisture, however, the isotopic composition B of atmospheric vapour usually lie on a line L': δD = 8 δ(O*^{18}*) + 10 ‰ [ref.4.2] showing that the evaporation from ocean water is a non-equilibrium process influenced by a kinetic effect due to the deuterium component HDO having a higher rate of reaction than the* H_2O^{18} *component. First stage condensation of atmospheric vapour results in precipitation (composition C in* Fig. *4.3) of the same deuterium excess d = δD – 8δ(O*^{18}*) ‰ as atmospheric vapour (10 ‰), indicating equilibrium conditions. Since equilibrium processes only displace the state of a system along a line of slope = 8 (i.e. with unchanged deuterium excess d), progressing condensation makes both the vapour point B and the condensation point C move downslope the line L'.*

Evaporation from falling rain drops is a complicating factor that causes a decrease of the deuterium excess in the precipitation, in semi-arid areas even to negative d-values, again due to the above mentioned kinetic effect.

Results

In the period when the network was densest, it comprised more that 100 stations from Station North in northernmost Greenland to Halley Bay in Antarctica. The collection and shipment of the samples did not cost us anything, and the measurements were well payed. I would not have had the slightest chance of establishing anything like that on my own. Under those circumstances it would have been disgraceful not to produce some good science from such a titbit, but I think I did.

I 1963 many of the stations had been in operation for more than a year, and that became the basis of a quite comprehensive paper in the Swedish geophysical journal TELLUS In 1964 entitled "Stable isotopes in precipitation" [ref.4.1]. It described a simplified theory for the turnover of heavy isotopes in the natural water cycle, supported by experimental evidence.

The IAEA ordered extra 1000 reprints of the Tellus paper. They were distributed among the participating meteorological stations as a kind

Box 4.3 Tokyo precipitation. *In Tokyo, northwesterly winds from the Asiatic continent prevail in winter. The dry continental air collects moisture of high d from the Sea of Japan in a fast, non-equilibrium evaporation. Much of this moisture is precipitated with very high d-values on the northeastern slope of the island. The rest is mixed up with Pacific moisture causing precipitation in Tokyo, often with relatively low δ's, but with d-values higher than the 14 ‰ that characterizes the thin line in* Fig. *4.4. In the summer time, the prevailing southeasterly winds bring occasionally heavy rainfall of the monsoon type with lower d-values.*

Furthermore, the IAEA samples demonstrated that the mean δ-value of monthly precipitation at a given station depends not only on the previously mentioned mean temperature t (higher δ for higher t), but also on the amount of precipitation p (higher δ for lower p due to increased evaporation from falling rain drops under dry conditions).

Fig. 4.5 shows the negative correlation between δ and p in Tokyo, except for the winter time, when the monthly mean temperature is only 5 °C, i.e. when the climate on the Japanese Islands is more like that of high latitude regions, where the temperature effect dominates the isotopic variation. The δ curves reflect a seasonal variation due to strongly varying temperature, on which is superimposed a short periodic variation in antiphase with p (except in mid winter).

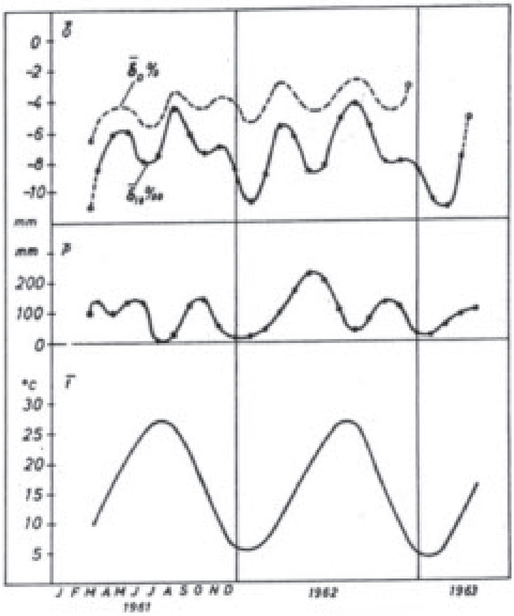

Fig. 4.5 *Combined temperature and amount effect in Tokyo. In the* ***upper section*** *the solid curve shows mean* $\delta(H_2O^{18})$ *values of the precipitation in two successive months, the dashed curve the corresponding δ(deuterium) values.* ***Mid section:*** *The corresponding amounts of precipitation in mm.* ***Lower section****: The corresponding mean air temperatures in °C.*

of acknowledgement of their contribution. It might perhaps have been suitable to choose a more popular description of the project, its purpose and perspective. But it lasted a long time before the paper was superseded. 15 years later I was pleased to observe that it was still used for teaching geophysics at two universities in U.S.A.

The co-operation with IAEA was only broken up in 1973. By that time the scientific value of the network had long been exhausted, at least from my point of view, and I had both hands full of other tasks. IAEA continued the collection of precipitation, and from 1973 the Seibersdorf laboratory took over the δ -measurements.

The data were still published currently in yearbooks. When the computer technique was introduced all data from the beginning of the project were put on an easily accessible form, and now it appeared as if all δ -values, including the many thousand data from the period 1961-72, had been measured at – Seibersdorf!

5. CAMP CENTURY 1964

The doubt about Scholander's young iceberg ages being correct made us search for an alternative to the carbon-14 dating method. The only possible radioactive element seemed to be silicon-32 [ref. 5.1].

Chemical engineer Henrik Clausen developed a preparation technique usable in the field, so in 1962 we went to the only dated ice mass in the world, Store Breen in Norway, accompanied by two laboratory technicians. The Si-32 concentration difference between new snow and the old ice corresponded fairly well with the age difference of 700 years measured previously. It looked good.

However, that summer we did not know that radioactive fall-out from great Soviet nuclear bomb-tests contaminated both of our samples (each 20 tons!) during the preparation. The theorists claimed that the fall-out could not contain Si-32, but a way of checking this would be to compare two relatively young water samples, one quite new and another one from shortly before the first hydrogen bomb test. Such samples could be obtained from a new American installation on the Greenland ice cap.

Camp Century was the name of a subsurface military research station established 1958-59 by U.S.A. on the inland ice 220 km east of Thule (Fig. 5.1). It was a strictly isolated male society set up when the cold war was coldest and it emerged from the American concern about a possible Soviet military attack across the Arctic Ocean. The purpose of Camp Century was to improve the American defence capability in the Arctic, i.a. by developing improved survival and transportation techniques and obtaining better knowledge about the harsh climate and the physical properties of snow and firn (compressed snow).

Camp Century was driven by the U.S. Army CRREL (Cold Regions Research Engineering Laboratories) all year round from 1958 to 66, in summer time manned by up to 250 men. 32 buildings (Fig. 5.2) were dug into the firn and enabled the camp to perform all activities of a modern town comprising power stations, workshops, offices, radio station, garages, dump

Box 5.1 Silicon-32 *is formed high in the atmosphere due to impact by cosmic radiation and scavenged by precipitation. According to the literature, the half-life of Si-32 seemed to be suitable 700 years (it was later shown to be considerably less), but its application called for a rather complex chemical preparation. Si-32 decays into phosphorus-32, a ß-emitter with a half life of 14.2 days. In a given sample radioactive equilibrium is established after a few months, and the amount of P-32 then indicates the Si-32 concentration in the sample.*

Fig. 5.1 *Map of northernmost Greenland*

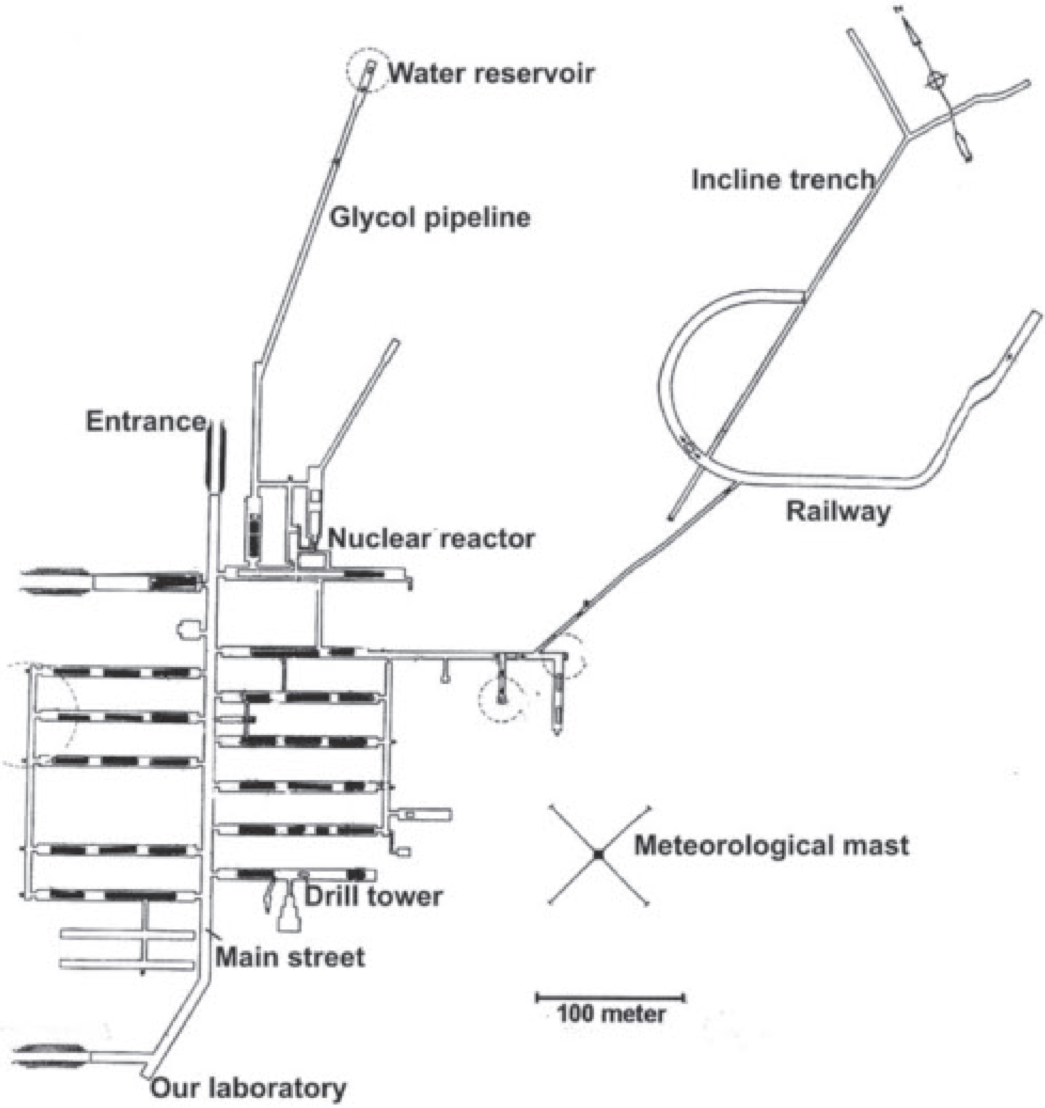

Fig. 5.2 *Map of the sub-surface Camp Century. The fat dashes represent buildings. The distance from the nuclear reactor to the living quarters was only a good hundred metres.*

building, shops, hospital, living quarters, fitness centre, baths, shops, canteens, storerooms, bars, cinema, church, and library. The buildings were connected by galleries leading to a central main street with one-way traffic of various kinds of vehicles.

Swings

Maintaining an enterprise like that called for a hitherto unseen transport capacity. A minor ski-equipped aircraft was the fast connection link with the Thule Air Base, but the nucleus of the logistics was the so-called Swings, long trains of

Fig. 5.3 *The American freight and passenger trains, Swings, defied any weather condition (if the refrigerator functioned!)*

big waggons and sledges pulled out from Thule by enormous tractors (Fig. 5.3). They were slow – you could easily walk beside them – but no weather condition could stop them.

Swings were a certain success regarding safe transport of very large and heavy cargo on the inland ice. As to speed and flexibility they were surpassed by the large aircraft Hercules C-130 that were just being developed and put into Arctic traffic these years. From then on and up to this very day the Hercules aircraft has offered solutions of many logistic problems in Greenland and Antarctica.

The nuclear reactor

The reactor experiment in Camp Century was reported successful. Officially, the purpose of installing the reactor was just to see if it were possible to operate it under extreme climatic conditions. The installation, the function, and after 4 years of operation the removal of a 1.5 MW nuclear reactor passed off without any serious accident.

Its surplus energy was led 100 m below surface, where it created a spherical water reservoir 60 m in diameter. It became a popular exercise to descend in a girdle to the magnificent hall that was almost filled with water.

The reactor was disassembled and removed in 1964, and the energy supply was taken over by diesel generators. The enormous energy consumption in the camp raised its annual mean temperature by a couple of degrees above the normal -24 °C, which speeded up the deformation of the firn walls and ceilings that slowly caved in. Therefore, buildings and galleries frequently had to be cut free by power chain saws.

Visiting Camp Century

In 1964 we got an opportunity to consolidate the Si-32 dating method at Camp Century. In an inclined shaft under excavation pre-bomb snow, or rather firn, could be mined for comparison with new snow that was directly accessible, to put it mildly. So in early June I flew with Henrik Clausen and our laboratory technician John Hessel Jensen to the American Thule Air Base bringing along some chemicals, ten 200 litre plastic vats, and a stainless steel container for melting the snow by a kerosine burner.

Upon arrival to Thule we were told to go to the depot delivering standard Polar equipment and then immediately drive to the waiting Carabu aircraft (its pet name was "the stork" referring to the high "legs", on which the wheels and the skies were mounted). It was important to take advantage of the favourable weather conditions, which did not give us time to get a look at Thule, not even changing to more suitable clothes. After an hour's flight we therefore stepped out in deep snow and -10 ˚C attired in scanty Danish summer costume and ditto shoes. Only when the sacks with the polar clothes were opened we could continue to the sub-surface town.

We were met by unique obligingness from the Americans. In advance, we had asked for two drums of fuel for melting our two 20 tons snow samples. The commanding officer, major Morris, suspected us of modesty (a true misconception), so he doubled up. Down at the Thule air base it was questioned if we meant heavy or light fuel, and consequently they decided to order four drums of each, an order that was doubled once again further up in the hierachi. Therefore, 16 drums of fuel was waiting for us at the end of the subsurface main street, where our preparation was supposed to take place. 14 drums are still available for deserving poor.

Diary notes

Here are some extracts of my diary from July 19 to August 4 1964:

Camp Century, Sunday July 19, 1964

The seventh "heavy Swing" of the year arrived last night. Eight big tractors with 1½ metre wide tracks, each followed by up to eight carriages with 3 metres big wheels, and sledges for freight and supplies of any kind, or housing including sleepers with 24 berths, shower and toilet; mess-carriage with music centre, kitchen and refrigerator; head quarter sledge with office, radio-room and 6 berths for officers; work-shop sledge with lathe, welding equipment etc.

Swings do not move fast, but they defy any kind of weather, and they are an unfailing connection between Camp Century and the field station Tuto (Thule take off) at the foot of the ramp that leads from the Thule-road and up on the inland ice. And yet: Dr Evans told me that this Swing had returned to Tuto the day after departure – because the refrigerator was out of order!

Lieutenant Arthur took us to the inclined trench they are digging, or rather drilling, with a cross section of 4 x 3 metres and inclination 1:3. It will end 100 m below surface, and so far they have reached a depth of 30 m, i.e. to snow that fell in the 1930'es. Just what we need.

On the way we saw the 100 m deep well that ends in an enormous water reservoir of 100,000 m^3. It will take 10 years to refreeze it. No wonder there is no rationing of water here. Sadly, we cannot just pump water up for our experiment, because the water does not have a well defined age. A less fortunate experiment has been the attempt to build a subsurface railway hoping to establish a train connection between North and South Greenland! We saw the skewed remains of the rails. A bit more thought might have saved money and effort.

Our stately laboratory is located in an "appendix" to the main street (Fig. 5.2), 20 m long, 5 m broad and 6 m to the ceiling. Electric light has been put up for us on the walls. Originally, the main street led directly to the surface here, but it is now replaced by a side street in order to prevent fast closing by snow. As soon as the Swing is unloaded we will get our fuel.

In the afternoon we went skiing in wonderful weather. We observed an optical phenomenon: No matter where we were in the absolutely flat landscape we felt being at the bottom of a pot. The refraction in the lowermost stratum of air "lifts" the horizon.

Four Carabu and three helicopter flights today. The Danish scientific liaison officer Børge Fristrup left.

Fig. 5.4 *Main street, Camp Century. Photo: Henrik Clausen*

We were late for dinner tonight. Managed to put quite a few things behind the vest, though, including a jolly good drink in the bar. Any drink costs 25 cents, independent of kind and size, and the bartender is a generous person. On the wall behind him hangs a large photograph of a laying beauty in bathing suit. When a clergyman comes on a visit the picture is simply turned backside out – all you see then is somebody fishing.

The last point on the agenda was a new visit to the movie theatre. New program every night. Henrik's comment hit the nail-head: *"Here are all facilities, but for women"*.

Monday, July 20

Still busy activity unloading the Swing. We waited all forenoon for our kerosene. After lunch we took the matter into our own hand and at dinner time all our gear is ready for snow from the shaft. We have been promised a load tomorrow.

In the mess room is a poster on measures to be taken in case of notice of atom-bomb attack:

1. Open windows and doors.
2. Loosen tie and belt.
3. Sit down on the floor with the head bent down between the legs,
4. And then – kiss your ass goodbye.

A deep sigh in the cinema tonight, when a bad king killed a beautiful woman: *"Oh, isn't it a shame he is killing all that good looking stuff"*.

Tuesday, July 21

Only soup was served for lunch in order to prevent fatness. In all obscurity, however, Henrik and Jensen managed to consume ten extra buns with tooth-butter.

Snowstorm above. No flights today. All vehicles are busy loading the Swing that leaves this afternoon. A 7 m long, 15 tons trailer has been chosen for carrying snow from the shaft to our "laboratory". But there is no tractor to pull it, and it is too big for our purpose anyway. In stead we saw a closed passenger sledge with a suitable volume of 5 m^3, but a brace was broken. It will now be fixed in the workshop.

A ridiculous problem is the lack of tarpaulins for keeping the snow samples separated from new snow during transport and from meltwater dripping from the ceiling during melting.

Late in the afternoon the giant trailer brought the first load of snow, but the trailer blocked the main street, and since we could not store so large an amount of snow due to the lack of tarpaulins, it left with the whole lot as soon as we had filled the melting jar. We started the heaters, warmed 200 litres of meltwater to boiling, and poured it on the floor. The hot water melted a deep, deep hole – at last the splash sounded as coming from hell itself.

We quickly arranged a bet. Henrik bet on a depth of 60 m, Jensen on 25, and I on 12 m. A flashlight in a string was lowered into the hole and stopped at 13 m. Henrik Clausen now has to give a pre-dinner drink of his own composition, called “a Santa Clausen”. Understandably, it has become quite popular, as it consists of two parts of gin and one of Cherry Heering. With ice that kind of drink takes up a beer glass when served by the generous bartender. He increases the price to 30 cent, though.

High spirits, and a new bet on whether or not we are going to start preparing the first sample tomorrow. Henrik and Jensen bet on yes, and in order to have a bet going I had no choice: No. Our patience is threadbare by now.

Wednesday, July 22

Beautiful weather above, but fog at Thule. No flight today.

Hermanson is the handyman here, who directs carpenters, smiths, electricians etc. Quick at repartee and full of contempt for “the whole bunch of civilians” – that must be us. He evaded when asked about the reparation of the damaged sledge. The carpenter meant it might drag out till tomorrow.

“Very well”, I said, *“we will pick up the snow in rucksacks”*. Their pride of being able to cope with any Arctic transport problem must cause some action, I thought, when their guests have to carry snow in rucksacks. They already cross themselves, when we walk on foot from one end of the camp to the other.

We emptied the sacks for our sleeping bags and got hold of a hand sled. While Jensen was sent up for lessons in belt vehicle driving, Henrik and I set out on the old-fashioned Polar way. We reached the inclined trench, picked labouriously 150 kg of clean ice out of a mountain of small pieces of ice contaminated by glycol, and began the retreat pulling the sled over the rugged snow surface. Hard job.

One hour later the big sledge was repaired.

At 2 p.m. Jensen and I left for the first load of snow in an old weasel vehicle followed by the sledge. The weasel was quite asthmatic, could only go in lowest gear. Half-way to the shaft clouds of steam and smoke enveloped the creature. Back to the workshop at snail’s pace and without snow. All other vehicles are busy.

But now we are using a bulldozer which is out of other jobs all night.

Thursday, July 23

By midnight Henrik and Jensen had not returned from the inclined trench, so I went out looking for them. It was calm, clear sky, low red sun. After nearly an hour, I found them. They had still got no snow, this time because the Archimedes-spiral bringing the snow up from the deep had fastened, *“but now it is OK, so within an hour we shall have two loads”*.

Unfortunately, I won the bet of yesterday, but now we are moving ahead -I think.

I went back to our subsurface hutment and went to bed. The others came in at 4 o’clock. Henrik with a frost-bitten ear. These two boys are doing an excellent job.

I got up 8 o’clock, let the others sleep and went to the “lab” for melting snow. They came 10 o’clock, and during the afternoon Jensen and I slaved away at melting 1½ tons of snow, at the same time as Henrik started the chemistry. You make a dense precipitate that drags everything down forming a thick wobbling jelly that includes all Si-32 in the melted snow. The temperature of the water was 10 °C falling half a degree per hour.

In the afternoon Jensen was ready to drop with fatigue, so he was dismissed. Henrik and I decanted till 11 p.m. I have never been so tired in my life. We found Jensen sleeping fully dressed.

Visitors are called “blue birds”, because their blue flashlights are deposited allover as white eggs during the photo race through the gallery. Today loud-speakers gave warning of 13 blue birds coming in. Everybody moans and groans, because you are now supposed to explain everything politely as you have done 100 times before. A feeling of relief spread allover, when the aircraft turned back due to bad weather.

Friday, July 24
Two loads of snow came in today. Jensen and I have got a strong headache – could it be due to poor ventilation in our cave? After all we burn 8 kg kerosene per hour.

Cecil Jacobsen from Risø came today for officially watching the dismantling and removal of the atomic reactor. It was removed a month ago!

Saturday, July 25
Jensen and I had to lie down with headache, dizziness, and deadly tiredness. I am sure we are being poisoned by carbon monoxide. Major Morris has promised to set up a strong ventilator. Late in the afternoon Jensen and I forced ourselves to go on a stroll in the snowy weather. That helped to some degree.

In the bar a sigh from Hermansson who is of Finnish descent: *“Why must there be so many languages in the world? Why can’t everybody speak Finnish?”*

In spite of a many whiskies, not a single obscene story.

Sunday, July 26
Everybody keeps the Sunday, but for us and the snow cutters in the shaft.

In the evening we saw a movie with a chap called Elvis Presley. It was supposed to be the most daring and sexy movie ever shown in America. Good Lord, how Americans must be clean and pious? Beyond some semi-sexy hip-twists amid enthusiastic applause from the crew, it was just whipped cream, candy flush and virtuous bridal veil from beginning to end.

Monday, July 27
No supply of snow yesterday. The tractor was frozen and the crew had kept Sunday. When everything was ready this morning, the hydraulic starting system for the snow cutting machine bursted, a fantastically expensive and sensitive thing, which is responsible for 17 men having spent 3 months on digging down to a depth of 27 m. I resisted the temptation of reporting about the Swiss Dupont who single-handed dug to the same depth in the same length of time using a simple spade under the European EGIG expedition.

Tuesday, July 28
All night there was an infernal noise as if all devils of hell held their annual general meeting on the roof of our hut. The firn walls have collapsed to a degree that necessitates cutting the houses free. Nobody knows why it must be done in the night hours. The roof creaked every time a block fell down. Thank heaven I am sleeping in a lower bunk.

Today we finished the 10 tons of snow we have chemicals to prepare. More chemicals for the next sample of surface snow arrive at Thule tomorrow. Then I can just as well go home.

Wednesday, July 29
Henrik was in great trouble last night. In the middle of the dark he carried on a long and agitated conversation with the people, who cut down ice on our heads yesterday. *“Can’t you get rid of all that snow somewhere else, gentlemen?”*

I put on the light and asked what was the matter.

“They throw a hell of a lot of snow into my bed.

“Do you have snow in your bed?”

“Yes, the bed is full of snow – there is no space for me any more.”

“Perhaps you should lie down quietly and go on sleeping.”

“Jae, perhaps I should, damned it” – and that is what he did.

I spent most of the afternoon on a ladder set up against a 5 m high snow wall (Fig.5.5). It was unpleasantly windy and cold, -22 °C. I cut 48 samples for oxygen-18 analysis along a vertical section that represents the annual layers from

Fig. 5.5 *WD cutting samples from a 5 m high snow wall. The sticks mark summer layers estimated from melt layers. This profile reached back to 1953.*

1959 on top and down to 1953. This is indicated by large melt water features in the second lowest layer from the warm summer 1954.

Bad weather. No flight today, so now I cannot reach the next SAS flight from Thule. That will cost me a whole week extra. We were busy decanting yesterday's production and putting together big boxes for the plastic jars with the precipitate. I bring them to Thule whenever I get a chance and put them on a ship homeward. Henrik and Jensen will bring the rest, when they have completed the second sample.

Thursday, July 30

A big tractor is scraping surface snow to one metre depth for the next sample.

Friday, July 31

Next Swing starts out from Tuto, the last one for a long time, because the entire crew is going on vacation in U.S.A. According to the regulations nobody must serve in Greenland for more than 180 running days.

The weather is still worsening. The barometer is falling. It is blowing up to 30 knots at Tuto and 70 in Thule – that is close to hurricane. Bad weather conditions are characterized as phase 1, 2 or 3. Under phase 1 people are instructed to be careful when moving away from the camp. Under phase 2 people are only permitted to go to the surface two by two, and only on urgent business. Under phase 3 any surface traffic is simply prohibited, but for Swings. Today we have phase 1, Tuto phase 3.

We cannot proceed with the preparation until new chemicals come in from Thule. But the melt water must be kept liquid till then. We have placed the jars close together and covered them with tarpaulin. That makes the temperature decrease only a quarter of a degree per hour, or 6 degrees per 24 hours. Some 25 litres from each jar is therefore warmed up to boiling each day and poured back again.

A derrick is set up in a large side-room. The drilling goes on night and day, but there is no access for unauthorized persons. We were dissuaded to try, because the drill master is a very determined gentleman. Sounds as if some military secrets are involved. What a shame, because the ice core must be very interesting for measuring stable isotopes. What the Americans are going to do with the ice core is unknown. We might have referred to the rule that foreign expeditions collecting material on Danish ground are under an obligation to share it with Danish scientists, if need be. However, the way we got access to the ice core later on made things develop more harmoniously.

Saturday, August 1

Phase 2. Visibility zero. Hermansson's elbow tells him, however, that there will be flights tomorrow. Only a helicopter, though, because the skiway has to be smoothed by the tractor.

Sunday, August 2

Beautiful weather here and in Thule, but 20-24 knots at Tuto, and that is too much for the helicopter. A man fell and broke an ankle today- maybe that improves the interest in flying in from Thule. Major Morris is angry. He lacks nails, beer and Camel cigarettes (and we chemicals). He called Thule over the radio, but neither the supreme nor the second-in-command were available today. They kept Sunday.

Fig. 5.6 *The famous Camp Century deep ice core drill was designed by Lyle B. Hansen and built at U.S. SIPRE (Snow, Ice and Permafrost Research Establishment). In 1966 it penetrated the inland ice to bedrock, and CRREL recovered the first deep ice core in the world. We were not invited to see the drill setup, but the 1390 m long ice core kept us busy for years. Photo: USArmy CRREL*

Late in the afternoon the wind calmed down at Tuto, but it was replaced by fog in Thule!

Monday, August 3

8 a.m. Light breeze everywhere. The helicopter is prepared for take-off, but at 9 a.m. the wind is rising at Tuto.

10 a.m. it is reported that the Carabu will land in 45 minutes.

Packing at top speed. Cordial goodby to near and far. Along to the air strip that is so bumpy that they do not risk loading our three drums with the first sample.

Strong side wind on the skiway. Lowering fog banks near by. We hear him searching for a hole. Just before the fog closes up we see him coming down between very low clouds. Hurray. Now Henrik and Jensen can finish the job quickly. Nails, beer, Camel cigarettes and chemicals are unloaded faster than fast. I and 8 Army people are seated lengthwise in the Carabu, which takes off immediately after some colossal kangaroo jumps over the snow drifts. Wonderful being in the summer heat in Thule – plus 2 °C. At the office of the Danish liaison officer there is not much optimism regarding shipping opportunity for our cargo. The ice situation is disastrous this year. Two Danish ships are locked up by the ice in the Melville Bay. One of them have got ice breaker assistance, but it cannot even follow the ice breaker. 3-4 m of ice, and the frost is coming in a couple of weeks.

I met Fristrup. He has been on the Humbolt glacier setting up a memorial plaque for two men who lost their lives in a hurricane four years ago under glacier studies in relation to EGIG and the international geophysical year.

On a madly muddy road I drove to Tuto for delivery of the loaned U.S. equipment – clothes, boots etc. Passed the early warning radar antenna- its screen is the size of a football field. Changed to civilian clothes. When I came out from the cabin, my loaned sleeping bag was stolen. The depot corporal's only comment was: *"Pinch another one".* Nobody wanted to listen to my explanation, much less control the rest. They even refused receiving the excellent sunglasses. No wonder that the Armed Forces are expensive.

Met captain Gaston, who urged me to go directly to the Army for help next time (U.S. Army Research Support Group) and skip the detour via *"those dammed Air Force people".*

We were quartered at the "North Star Inn", an elegant hotel for higher officers, only after Fristrup and I had documented our high rank, though!

Arrayed in white shirt, tie and clean nails, we had dinner in the officer's club, which is ridiculously elegant in view of the history of this locality. Two years ago, any kind of beard was prohibited. To bed 9 o'clock – the striptease girls appear at Tuto tonight, unfortunately.

Tuesday, August 4

Made reservation for the "Hong-Kong ferry" – that is the nickname of the slightly used American air service from Thule to Sdr. Strømfjord/Kangerlussuak.

Drove with shipping agent Klaussen to his home in the old Thule. Kivfak (maid) in the kitchen, dogs around the house – it reminded me of Godhavn 16 years ago, except that the dogs are chained up here, due to their appetite for kids.

Saw Knud Rasmussen's and Peter Freuchen's old house that is still occupied. There are plans for converting it into a museum – that will probably be in the next century.

The magnificent Thule mountain should be seen from this place in the red midnight sun, surrounded by white pack ice and icebergs.

The Iceworm

Being a small country of great strategic importance, and being located very close to the Soviet Union, Denmark refrained in the 1950'es from having nuclear weapons placed on Danish soil. Therefore, the American request for permission to use Thule for that purpose worked as an elephant in a glassware shop. However, the official Danish reaction has been called a diplomatic masterpiece: *"The Danish government does not want to be asked that kind of question."*

40 years later, source studies revealed that the purpose of Camp Century had a much wider perspective than generally known about 1960, here referred from the periodical "Polarfronten", issued by The Danish Polar Centre.

In 1997, the Institute of Danish Foreign Policy published an 1100 pages historic account, originally aimed at clarifying the role of the Thule Air Base in relation to the U.S. overflying Greenland with nuclear armed aircraft during the cold war.

The search among previously classified documents from the early 1960'es revealed a detailed picture of a large-scale project, *Iceworm*, aiming at making Greenland the centre of the American nuclear strategy: Up to 600 nuclear-armed missiles should be placed in a 4000 km long subsurface tunnel system provided with railway tracks. New tunnels should be excavated every year enabling the operators to move around with the missiles. The project called for 11,000 people working in an area of 140,000 km^2.

The story sounds like the script for a science fiction movie, but it was quite serious. The planning group included top members of the security council of the Kennedy administration. It is likely that Camp Century was meant as a test experiment for Iceworm. The nuclear reactor, the railway, and the heavy Swings, as well as the broad scientific studies of the properties of snow, firn an ice all involved problems that had to be solved before Iceworm could be realized.

We did not know the intended extent of Iceworm in 1964. But our experience of the railway in Camp Century clearly shows why Iceworm had to be abandoned.

One may ask if Iceworm were in accordance with the US-Danish defence agreement of 1951, which only talked about military bases, and if Denmark would have had political will and strength to avoid that essential parts of what later became the world's largest National Park were turned into a military theatre of operations. Fortunately, this is just speculations today.

Silicon-32 dating

Analyses of our two Camp Century samples showed, firstly, an abundance of Si-32 in the new snow, undoubtedly due to fall-out of bomb-debris and, secondly, that its half life was 300 years rather than the 700 years estimated previously.

However, this did not invalidate the Si-32 dating method in relation to icebergs, because the sample from the inclined trench was deposited in the 1930'es, and certainly free from bomb-produced Si-32. Its Si-32 concentration could therefore serve as a reference-level, in particular because the sample represented several years of accumulation at approximately the same latitude as the sites of formation of the icebergs.

In 1967, the Director of the Danish Geodetic Institute offered to place the survey ship Tycho Brahe at our disposal for a new Bubble Expedition aiming at simultaneous ice datings by C-14 and Si-32. A new large melting jar was built of stainless steel and with absolutely no organic material, thereby excluding any risk of contamination with "false" CO_2 during the preparation. A laboratory was arranged in the hold under deck. Ramming Tycho Brahe into icebergs the Rundøy way did not work, she was too small for that, but the steam-knife was just as efficient as nine years earlier. And the melt water was transferred into Henrik Clausen's big plastic jars on deck for extraction of Si-32 [ref. 5.1].

We started out at our favourite glacier Eqip Sermia (Fig. 3.6, p. 33), where we unloaded some Swiss cargo at the old EGIG house and lay wind-bound in a full gale. I noted that this was not the first time natural forces obstructed science, because somebody had bitterly written on the wall: *Die Natur scheisst auf dem Naturwissenschaftler (Nature shits on the natural scientist).*

After a busy summer we came home with a satisfactory number of samples, but something important had happened in the meantime taking up our full attention, so only a few samples went through the entire dating procedure.

6. THE DEEP ICE CORE

As mentioned above, we were not invited to see the scientifically most exciting project going on in Camp Century, namely the deep ice core drilling by USA CRREL under the leadership of Lyle B. Hansen. But a new fantastic task had turned up, a task that simply made iceberg dating inessential, a task that turned the interest from floating icebergs to the inland ice where they were formed, a task that gave rise to a new discipline within glaciology and palaeo-climatology: The analysis of the deep ice core from Camp Century.

The Camp Century ice drilling continued till the summer of 1966, when the drill reached bedrock at a depth of 1390 metres. The deepest 25 metres of ice core consisted of silty ice containing bottom material of increasing coarseness downward from dust to small and larger stones. This indicated that the deepest ice had been in contact with the bedrock farther upstream from Camp Century.

Ice core analyses

The recovery of the world's first deep ice core was a great achievement, and Lyle B. Hansen was met by the glaciological community with all the appreciation he deserved. But other big news were implied in the analysis of the Camp Century ice core.

Box 6.1 Boring into the past. *Information about past environments are filed in chronological order, wherever material is deposited and left unchanged year by year. The inland ice at Camp Century is one example of such deposition. Other examples are peat in bogs, deposits on the ocean floor, and growing trees. Each time a snow flake is deposited on the inland ice, a pollen grain falls into a bog, a shell of a foraminifera sinks to the bottom of the ocean, or a new year-ring is formed in the forests, Nature leaves a message of her physical and/or chemical condition at the time of deposition.*

We can dig up this information by core drilling through the annual layers, and if we can put all the information on a common time scale a comprehensive description emerges on how and why the environment changed through the ages.

This would be an important piece for understanding the complicated puzzle of the climate system, an understanding necessary, though not sufficient, for giving realistic climate scenarios by the so-called climate-models.

Cores drilled through ocean sediments and glacier ice distinguish themselves by containing time series of climate parameters from today and far back in time. They supplement each other, because the ocean sediment cores tell primarily about the marine environment through very long periods of time (millions of years), though not in fine details, whereas ice cores render information primarily on atmospheric conditions through shorter periods of time (hundred thousands of years) but in fine details, in younger ice down to seasonal variations.

Box 6.2 Deep ice core drills. *The upper 400 metres at Camp Century were penetrated by a thermo-drill developed by US SIPRE and previously successfully applied at Site 2 on the Thule peninsula. It was hanging in a cable and functioned by inducing electrical energy through the cable into a metal-ring at the end of the cylindric drill-tube, which melted itself and thereby the whole drill downward, at the same time as the ice core "grew up" into the lower drill section. In order to prevent the meltwater from refreezing, it was dissolved in glycol and hoisted to the surface along with the drill and the disengaged piece of ice core.*

The ice is like a viscous liquid, i.e. the pressure increases downward by 1 atmosphere per 11 m of ice. Therefore, an open drill hole closes faster the deeper you go, cp. that removing a stick from an oatmeal leaves a "drill hole" that closes fast, and first at the bottom. If a drill hole in ice just closes a tenth of a millimetre or two, a thermo-drill may get stuck. In practice, a depth of 400 m is the limit of thermo-drilling.

The only way to prevent hole closure is filling the drill-hole with a liquid of the same density as ice. This creates an increasing pressure down-hole, which balances that of the ice. The technique was used when Lyle Hansen applied an electro-mechanical drill beyond 400 m depth at Camp Century. It was developed at USA CRREL and provided with three knives at the lower end, knives that were fixed to the rotating drill tube thereby cutting a groove around the ice core, which was disengaged by barbs ("core catchers") and a forceful pull in the cable.

Obviously, the Camp Century ice core would be a scientific gold mine for anyone who got access to it. Twelve years earlier I had played with the thought of gaining information on past climates from dated ice in coastal glaciers. Here, such information must lie nicely arranged in the ice core that represented the 1390 m high layer cake of ice – one annual layer on top of the other, each of them with information about the climatic conditions in the year the layer was formed by falling snow. The ice core might turn out to be just as valuable for the study of the Arctic climate backward in time, as the IAEA samples were for the study of the water circulation at present. The two projects supplemented each other in a broad perspective, and it was particularly favourable that they could be treated by the same tool, stable isotope analyses (δ).

American researchers probably queued up for getting hold of this tidbit. Or did they? Could I really have the third stroke of luck following EGIG's firn cores and IAEA's global network samples? It seemed improbable, since an anonymous paper [ref.1.3] indicated that American scientists had found seasonal δ -variations in an ice core like those I found in an ice chunk at the Bubble Expedition. But the climate aspect was not touched upon in the paper.

I submitted a proposal to Dr. Chester C. Langway, Jr., who was responsible for all ice cores recovered by SIPRE and CRREL. I enclosed some reprints documenting, firstly, that I had some experience regarding the transposition of isotopes in the circulation of water in nature and, secondly, that the EGIG cores had already given evidence of past climatic changes being marked by δ -variations in the inland ice. Finally, I offered to measure the whole ice core from top to bottom in any reasonable detail in co-operation with, but without expense to CRREL. Langway and CRREL accepted my proposal, and thereby the basis was laid for many years of trustful and fruitful co-operation with Chester Langway, among friends Chet.

In the following 35 years, European and American scientists proved that ice cores contain a wealth of information on past climates in the form of a great number of parameters, of which some are listed below:

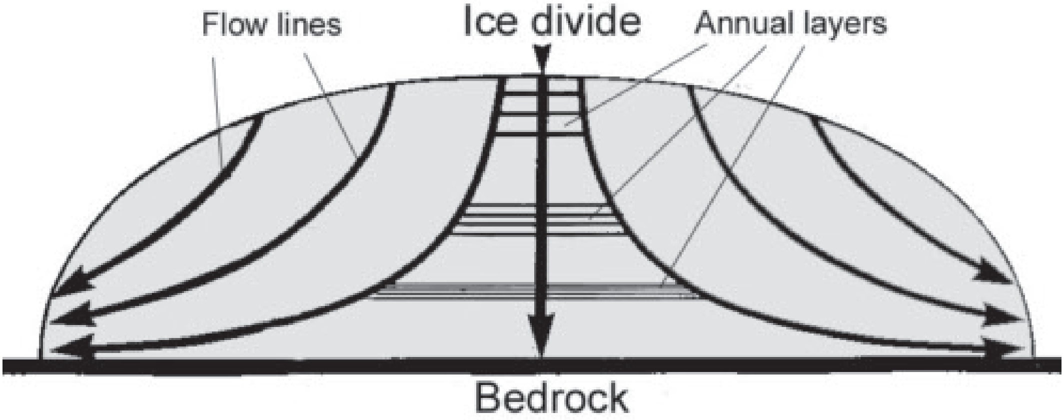

Fig. 6.1 *Ice flow. Vertical West-East section through a simplified model of an ice cap. If the ice is at the pressure melting point all over, the horizontal velocity component is the same along a given vertical line. If the ice is frozen to a horizontal bedrock, however, the heavy arrows from the dome-shaped surface still symbolize the direction (**but not the velocity!**) of the ice movement toward the coasts. The ice moves vertically downward only from the very top. The horizontal lines symbolize annual layers that are stretched and therefore get thinner when sinking. Close to the bedrock their original thickness of perhaps ½ m is reduced to a fraction of a mm (without any change of composition). By far most of the annual layers lie close to the bedrock, and a time scale along a deep ice core is therefore strongly compressed at great depths, cf. Fig. 6.2.*

1. Concentrations of the oxygen-18 and deuterium components of water in the ice give information about the cloud temperature and precipitation at the time of deposition,
2. the content of air in bubbles reveals the altitude of the then ice surface,
3. the concentrations of carbon dioxide and methane in the air bubbles tell about the greenhouse effect in past atmospheres,
4. the chemical composition of the ice itself gives information about other aspects of the chemistry in past atmospheres,
5. dust and calcium concentration tell about the violence and frequency of the storms that carried dust from ice free areas to the inland ice, and
6. the acidity of the ice indicates the fall-out of volcanic acids and thereby past volcanic activity.

The first step of executing the agreement with Chet and CRREL was developing a plan for rational sample cutting. Since the thickness of the inland ice keeps essentially constant in spite of new layers being added year by year, the annual layers must get thinner and thinner as they approach the bedrock – not due to the increasing pressure, but because the layers get gradually stretched horizontally, cf. Fig. 6.1. One metre of core therefore contains more annual layers the closer to the bedrock, and a time scale along the core will look more and more "compressed" downwards. A rational cutting plan must take this into account by operating with a still denser sampling sequence downwards.

Time scales

Furthermore, the reliability of any climatic interpretation depends on the dating of the various sections of the core, on establishing a realistic time scale along the core permitting comparison of the δ-record with other climate records known from carbon-14 dated pollen profiles in bogs, varve countings in glacier deposits, ocean sediment core analyses, etc. Carbon-14 dating of the ice core was not possible, particularly not the deep layers, partly because there was not enough ice available, and partly because this dating technique only reaches 40,000 years back in time, at best.

We needed an ice flow model.

Box 6.3 The sandwich model. *At this point, Sigfus Johnsen entered the scene in earnest, and opened for a close and fruitful co-operation through decades. Our first common paper just dealt with the time scale problem with a view to planning a rational way of cutting samples from the 1390 m long core.*

Our basis was the English physicist John Nye's considerations [ref.6.1] on the movement pattern of the ice in temperate glaciers, i.e. glaciers with ice at the pressure melting point point all over (Fig. 6.1). In such "temperate glaciers" the horizontal velocity component of the ice is the same along a given vertical line – the ice slides along the bedrock with the same horizontal velocity as at the surface just above. That causes a relatively simple ice flow pattern assuming (a) no melting and (b) steady state, i.e. ice sheet thickness and annual surface accumulation independent of age t and distance from the ice divide. Nye's considerations led to a simple formula giving the age t of the ice z metres above the bedrock as a function of the ice sheet thickness H and the annual surface accumulation \ (H). With H = 1390 m and \ (H) = 35 cm of ice per year at Camp Century the age of the ice 20 metres above the bottom was estimated at 16,000 years.

However, the bottom temperature at Camp Century was measured by CRREL at -13°C indicating that the ice is frozen to the bottom, thus moving very slowly down there, if at all, so Nye's formula could not be valid for the deeper parts of "cold glaciers". In stead, we calculated a slightly more complicated formula for the age assuming that the horizontal ice velocity in the bottom 400 metres increases linearly from zero at bedrock to a value equal to the surface velocity all the way up to the surface [ref.6.2].

According to the new calculation ice situated 20 metres above the bottom should be 160,000 years old, i.e. 10 times older than suggested by Nye's formula for temperate glaciers. The new one rests upon an approximation to the real ice flow in cold glaciers frozen to the bedrock. And yet, calculated ages of ice at the greatest depths are not reliable, if only because the bottom 25 metres of ice contains silt, which influences the flow properties considerably.

25 years later, Sigfus Johnsen further improved the time scale, cf. Box 6.4.

A remarkable δ-profile

In 1967, Jørgen Møller went to the headquarters of CRREL in Hanover, New Hampshire, for cutting samples from the Camp Century ice core that was kept as increments in 2 metres long cardboard cylinders. He came back with 86 samples cut with great care at selected depths from top to bottom according to a thoroughly planned distribution.

The result was quite surprising. I cannot recall what we had expected, but indeed we did not dare to hope for a δ-record that apparently reached throughout the last glaciation, and even farther into the past. The ice core opened the possibility of going in finer details than any other long-term continuous layer sequence: Year by year or even finer resolution in the younger part of the core. A fantastic perspective. Fig. 6.2 shows the δ-profile plotted on a depth scale to the left and on a logaritmic time scale in kyr B.P. (thousands of years before present) to the right [ref.6.3]. At a great depth (approximately 1350 m) lies a peak indicating higher temperatures than today through a longer period than Greenland has experienced ever since. We interpreted this peak as corresponding to the preceding warm interglacial period, Eem, known from European pollen studies, and the large grey area as reflecting the last glaciation.

As to post-glacial time (the last 10 kyr), most of the already known climate changes were recognizable in Fig. 6.2: (a) High temperatures until ca. 3000 years B.P.; (b) the "Medieval Warmth" about 1000 years B.P. (AD 900 – 1200); (c) the succeeding "Little Ice Age"; (d) the warm period (AD 1920-40) about 40 years before the recovery of the ice core; and (e) the succeeding cooling that drove the cod away from Greenland waters.

The names close to the low δ values in the shaded area was an attempt to interpret the relatively mild periods during the glaciation in agreement with the then known interstadials found mainly by European pollen studies. According to the time scale in Fig. 6.2 the last glaciation lasted from 70 to 10 kyr B.P., i.e. 60,000 years in fair agreement with the general opinion around AD 1970. The figures (2 to 5e) in the lower part of the figure refer to a subsequent interpretation with a view to the "Marine Isotope Stages" defined by foraminifera profiles along ocean sediment cores [ref.6.4]. Many years later the δ scale was transferred into a temperature scale [Box 6.4 and ref. 6.5], cf. also [ref.6.6].

At the international symposium ISAGE arranged by CRREL in 1968 we presented – with Chet as a co-author – this first version of the Camp Century record [ref.6.3] in a talk that created quite a stir. I was invited on the spot to give a talk next year at the Nobel symposium "Radiocarbon Variations and Absolute Chronology" in Uppsala, and so I did. But by then Sigfus Johnsen and Henrik Clausen had cut 7,500 additional samples altogether covering the entire Camp Century core from top to bottom.

Furthermore, in 1969 we had published the new results with Chet under the title: "One thousand centuries of climate record from Camp Century on the Greenland ice sheet" [ref.6.7] – in other words, 100 kyr of climate record, and even this turned out to be underestimated.

After the talk at the Nobel symposium a colleague praised me for the consistency by having reckoned on unchanged accumulation rate throughout the whole lapse of time without guessing on its value under glacial conditions. I found it difficult to accept the praise, because one of the weaknesses of our sandwich model was just that the accumulation under glacial conditions was obviously lower than in warm periods. By then, however, nobody knew how much lower, so we desisted from guessing. The problem was only solved 25 years later.

Box 6.4 An advanced sandwich model. *Subsequently, the model was extended [ref.6.5] to include several parameters not taken into account in the original sandwich model, e.g. temporal changes of ice thickness and accumulation rate. The heavy line at the bottom to the outer right of* Fig. *6.2 indicates the age 100 kyr B.P. calculated by the new model, which dates the onset of the glaciation already at 115 kyr B.P. and its duration to 105 kyr. The first 50 kyr of this period are now considered initial stages of the glaciation, although it comprises two long periods of relatively mild climate. The first really big advance of continental ice masses only happened 60 – 70 kyr B.P.*

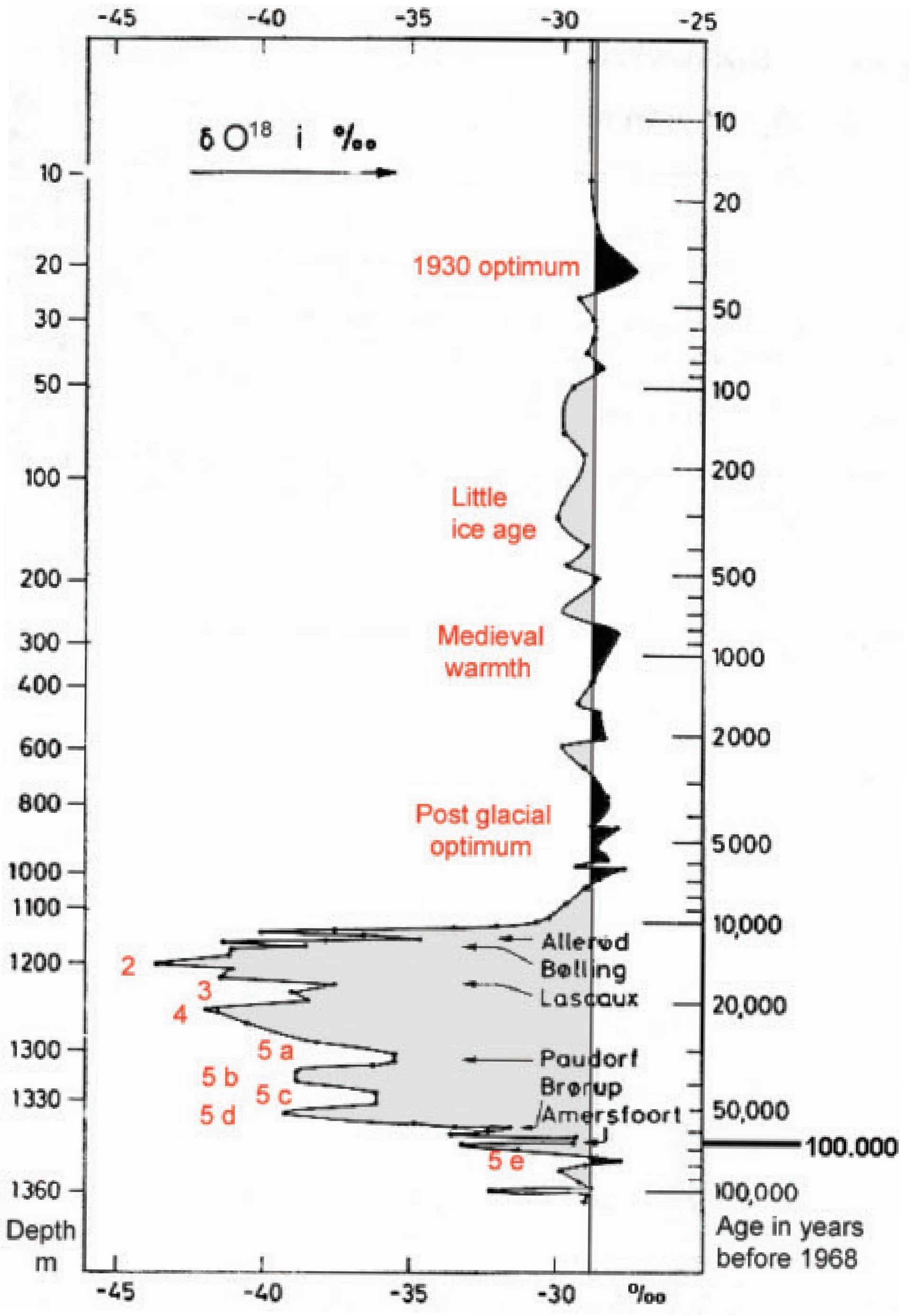

Fig. 6.2 *The δ-profile along the Camp Century ice core plotted on a depth scale to the left and a preliminary logaritmic time scale to the right. The black and grey areas correspond to periods of Greenland temperatures higher and lower than today, respectively. The large grey area reflects the last glaciation. The time scale based on the simple sandwich model is correct, by and large, through the upper 85 % of the core, i.e. back to 14,000 years B.P. (before present). The heavy line in the lower right corner marks an age of 100,000 years according to a more advanced ice flow model [ref.6.4], cf. Box 6.4*

The success of the Camp Century analysis made our co-operation with Chet continuing through many years. An important reason for his respect for our group was the wealth of ideas, the care and the industry shown by my co-workers in the field and in the laboratory. For example, the careful management and measurement of many thousand (up till now hundreds of thousand) samples was the merit of two excellent laboratory technicians Anita Boas and Ellen Chrillesen.

Our next edition of the long Camp Century record came 1971 in a talk I gave at the Yale University at a symposium in honour of the nestor of American quaternary geology Prof. Richard Flint. In order to get round the difficulty of handling great accumulation rate changes in the sandwich model, we had developed a new time scale based on an apparently persisting long-term δ-oscillation, which we simply attributed a constant period of 2,600 years, not far from a similar periodicity of certain processes on the Sun.

The resulting time scale had just as many drawbacks as the one based on the sandwich model. But independent of the time scale, the δ-record oscillated many times more violently during the glaciation than in post glacial time – a feature that was already observed in the very first Camp Century δ-record, cf. Fig. 6.2. Unless this was due to artifacts, such as disturbances in the layer sequence or the like, the abrupt δ-shifts must correspond to very big temperature changes within short periods of time. The old Prof. Flint saw immediately the significance of this interpretation and stressed the importance of having it verified.

Up-stream and down-hole studies

After 1969 the very Camp Century was inaccessible and, apart from the bore hole, it had only historical interest, cf. Box 6.5. On the other hand, the upstream area was still interesting, because the dating of the deep ice core required knowledge of the accumulation rates and the ice velocities in the area where the ice in the deep core was deposited. Furthermore, the deformation and the temperature distribution along the borehole contained information about the heat balance and the movements in the northern part of the inland ice, but it implied access to the borehole. Already in 1976, i.e. after 7 years, the extended top of the bore hole was buried in snow according to our calculation, and it would further sink ½ metre per year relative to the surface.

In the following decades, members of our group visited the Camp Century area four times with American colleagues from CRREL and PICO (Polar Ice Coring Office). Only in 1977 they succeeded to convince the US National Science Foundation (NSF) that the Camp Century bore hole ought to be remeasured. However, this time the Americans failed finding the drill tower. The maps were simply too inexact for locating it relative to the only visible fix-point in the area, "the meteorology

Box 6.5 Camp Century crashed. *In 1969 the American objectives were to find the old Camp Century drill tower, extend the upper part of the casing to ten ft. above the new surface, and to measure the temperature in the drill fluid all the way down to the bedrock. They succeeded after having forced their way through a ventilation shafts down into the remains of former glories.*

The camp was about to be crashed, but much of it was still in unchanged condition – furniture, equipment, and various supplies, i.a. tons of deep-frozen beef and thousands of prepacked rations of delicacies that were particularly delicious in the officer's packages. The Americans knew the codes on the packages, which facilitated the choice.

They photographed for dear life and the results of their efforts in the deformed camp were published as a CRREL report: "Camp Century revisited, a pictorial view", June 1969 (cf. Fig. *6.3-4).*

Box 6.6 Radar sounding. *These years Prof. Preben Gudmandsen of the Technical University of Denmark developed and used airborne radar equipment, primarily for mapping the thickness and the bottom topography of the inland ice (cf.* Fig. *6.5). The radar reflector served as a fix-point during his and Niels Gundestrup's North Greenland flights with American Hercules aircraft. Without easily recognizable fix-points it was difficult to find one's bearings in the flat monotony of the inland ice. After some years of sounding the radar equipment was handed over to CRREL and used in Antarctica.*

mast". According to the map (Fig. 5.2, p. 44) the drill tower should be located some 300 m from the mast, but it was not.

However, the group got the opportunity to auger perfect shallow cores up to 10 km upstream, where they put up a radar reflector, cf. Box 6.6.

Retrieving a vanished bore hole

The next visit to the Camp Century area only took place 9 years later, that is in 1986. The top of the drill tower must be buried 7-8 m below the surface and therefore be very difficult to find, even with correct maps. But the task was still very important, because the drill hole had now been deformed through 20 years, and its new shape must contain information on the ice movements at various depths and about the mechanical properties of the ice.

A Bell 212 helicopter from US Air Force brought the field party out from Thule, but the pilot was, to tell the truth, not a navigational genius. When he landed and declared being at the position of Camp Century, Niels protested since no meteorology mast was in sight, although its actual height above the surface should be 40 m. The pilot claimed that the mast must be

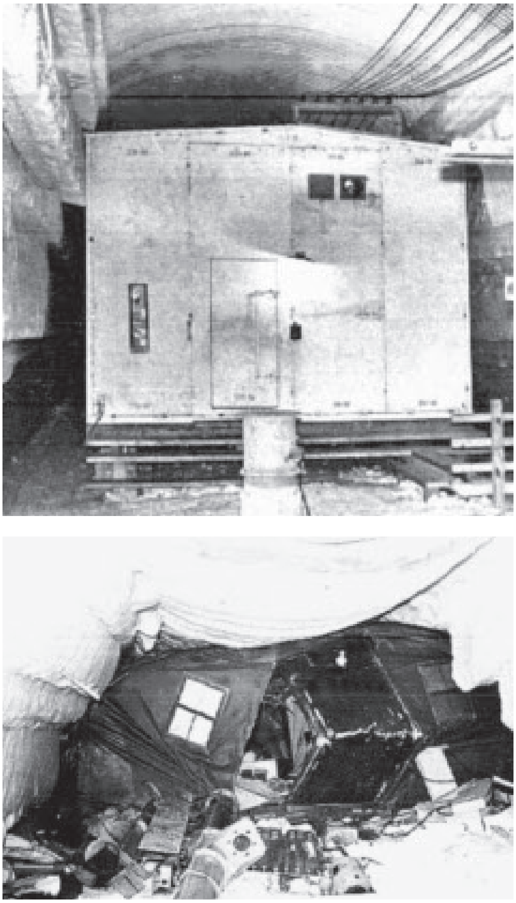

Fig. 6.3 *Our sleeping quarters in 1964 – and 5 years later. Already in 1964, it was difficult to pass the hutments due to hanging ice walls. also called "brain crushers". The high release of energy accelerated the collapse. Photo: USA: CRREL.*

Fig. 6.4 *Sigfus Johnsen visited the closed Camp Century in 1969. Here he is on the way to the water reservoir through the originally 4 m broad galley. The pipes led hot glycol from the nuclear reactor deep into the firn. Photo: USA CRREL.*

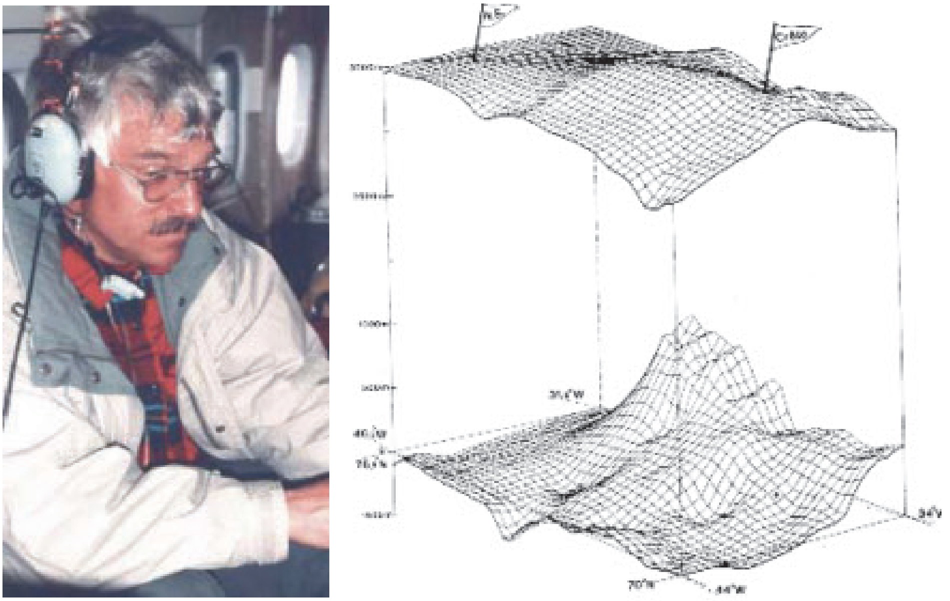

Fig. 6.5 *Niels Gundestrup during a radar flight and the resulting map on surface and bottom topography in a 720x350 km² area of Central Greenland. The ice divide separating the west from the east flowing ice runs on the surface through Crête and North Site that are marked by flags. Between them lies the highest point, Summit, which became the target of GRIP's deep drilling 1989-92. Note that the sub-surface mountains in East Greenland reach far into the area of investigation [ref.6.8-9].*

Fig. 6.6 *When somebody made things too complicated, Niels disentangled himself from the problem by the do-it-yourself method*

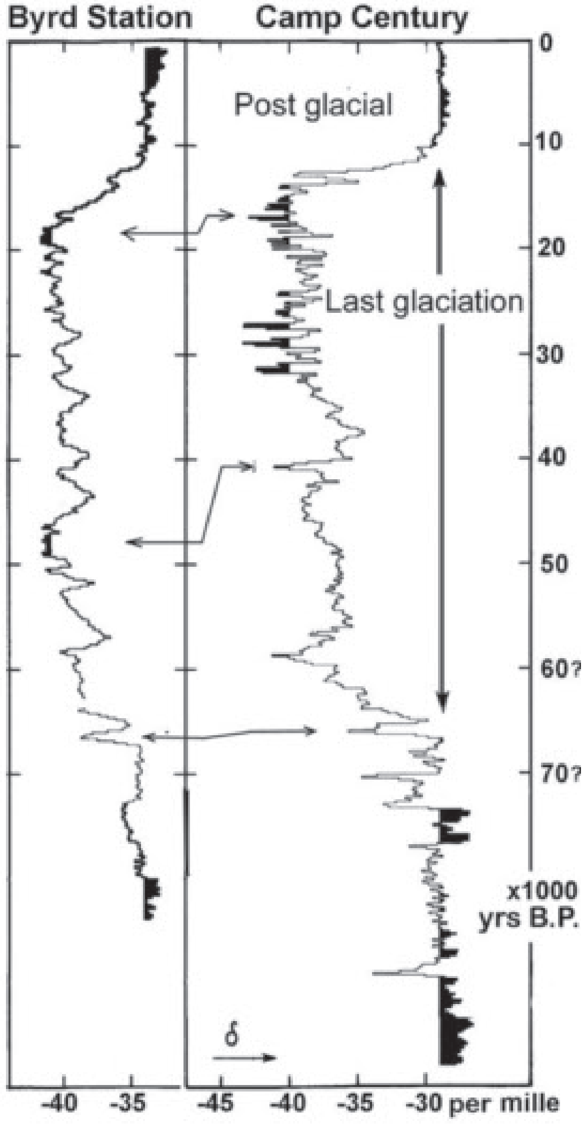

Fig. 6.7 *shows a comparison of the δ profiles at Byrd Station, West Antarctica, and Camp Century, Northwest Greenland. The time scale to the right gives calculated ages in millennia. It has later been changed, particularly beyond 60.000 years. The double arrows show probable simultaneous events. In the coldest part of the glaciation, the climate obviously varied much more violently in Greenland than in Antarctica, probably due to strongly shifting ice cover in the North Atlantic Ocean. Note also the difference at the termination of the glaciation.*

overturned, but fortunately Niels had brought his home-made satellite positioning equipment, a scaled down version of the then available bulky instruments. Including batteries Niels' version was contained in a small suitcase. After a few satellite passages Niels proved that they had landed 30 km from Camp Century, a tremendous error for a 220 km flight.

When they did reach the destination, doubt arose whether the pilot would be able to find them again, a worry that proved to be well-founded. The story repeated itself, and when the pilot found Camp Century at long last, he didn't dare to land due to a black cloud in the horizon, so he turned back to Thule. Here the commander had lost his patience, however. Another pilot was deployed and he hit the target without any trouble.

In the meantime great things had happened at Camp Century. By comparing the old map with areal photos (kindly provided by CRREL) Niels concluded that the map was simply wrong. The drill tower could not be located as indicated on the map. Using a magnetometer he started searching quite a distance from it. As the tower consisted of steel it should reveal itself by a magnetic anomaly on the surface, just like the metal detector techniques.

This may have worked at winter time, but in summer time the geomagnetic disturbances are so high in the polar regions that a minor deviation of the field strength drowns in great and rapid natural variations. That is why the search failed to begin with.

But then Niels made his masterpiece. Using an old-fashioned soldering iron heated over a primus stove in the tent, he changed the electronics of the magnetometer making it measuring the magnetic field *difference* between its ends in stead of the magnetic field strength itself. This difference is independent of the magnetic disturbances, and it is higher the closer to a magnetic piece of metal. And indeed, a new search in the area showed an anomaly – but was it the drill tower or other kinds of metal, for example our 14 drums left in 1964?

The SIPRE hand auger became busy, and after many abortive drillings it suddenly stopped at a depth of 7 m – it hit something solid. Up came a piece of core, the bottom of which bore a clear impression of the top nuts of the drill tower. The tower was retrieved after 17 years. When the place was properly marked, the team went home in well-deserved triumph.

Two years later the group and their American colleagues dug down to the top of the extended casing, which was further extended to well above the new surface. In co-operation with Lyle B. Hansen of CRREL, the group measured the temperature profile and the geometry of the drill hole (inclination, azimuth and diameter as a function of depth). Lyle Hansen's 2 m long instrument was too long, however, and/or too thick to reach through the deepest ice, where the deformation was most pronounced – and therefore most interesting.

Four years later, in 1992, they turned back with a new "logger" of only 50 cm length and 5 cm diameter, and only then the temperature and the geometry of the drill hole was measured down to 30 m above bedrock [ref.6.10].

Greenland – Antarctica

After the completion of the deep drilling in 1966, the Camp Century drill was transferred to Byrd Station, West Antarctica. Two years later Lyle Hansen's drill penetrated the ice sheet at Byrd Station, and 2164 m of ice core was recovered. When the drill hit bedrock, however, bottom melt water entered the bore hole, where it froze and blocked the drill. The famous Camp Century drill was lost for ever, an accident that held up further development of the just commenced deep ice core studies for more than a decade.

The long Byrd Station ice core was intact, however, and in 1970 my previously mentioned colleague Sam Epstein published a paper with a number of δ-values distributed along the core. We felt that a continuous and detailed δ-record could render additional information on possible inter-hemispheric climate relations, e.g. possible phase differences between common characteristic features. Therefore, in a letter to Chester Langway I offered to do such detailed investigation "when Dr. Epstein has terminated his studies on the Byrd core", of course in co-operation with, and without any expense to CRREL. Chet and CRREL accepted, and Fig. 6.7 shows the preliminary results [ref.6.11].

Subsequently, inter-hemispheric time markers harmonized the time scales [ref.6.12]

7. DYE 3 1973

The success of the two deep ice core studies caused an increasing need for a new drilling operation in Greenland. The Camp Century drill was lost, however, and the cost of a new one was estimated at 2 mill. $, prohibitive at that time. But there were other perspectives for ice core drilling, and most of them were tested at the American radar station Dye 3 in South Greenland.

Simultaneously with the excavation of Camp Century in 1959 U.S.A. began establishing their so-called DEW-line, Distant Early Warning Line, a chain of big radar stations extending from Alaska, via South Greenland to Iceland. The aim was to watch over the air space north of U.S.A. 24 hours a day and warn the American defence in case of possible attacking Soviet aircraft en route to U.S.A. The four DEW-line links in South Greenland were the Dye stations, named after the man who got the idea, I think – one on the west coast (Dye 1), two on the inland ice (Dye 2 and 3), and one on the east coast (Dye 4). They were ready as early as 1961, a formidable technical achievement carried out partly by The Danish Arctic Contractors, Inc. (DAC).

The snake pit

The central part of the station could be hot simultaneously with the outer walls being frosted over. The crew suffered from the heat all year long, and visitors were put into "the snake pit", a dormitory with bunks, on which they tossed in 30 °C and a stiff breeze from ventilators. A substantial improvement of the indoor climate

Fig. 7.1 *When building the Dye stations, DAC used prefabricated houses designed to fit precisely into the Hercules aircraft. The houses were fully equipped with sleeping quarters, kitchen and bathroom. They were usable a few minutes after unloading upon the snow. Photo: DAC.*

Fig. 7.2 *The American radar station Dye 3 in South Greenland*

Box 7.1 The Dye buildings. *The six storeys Dye stations are the heaviest buildings ever erected on ice, 7000 tons each. Most materials and supplies had to be flown up from the Sdr. Strømfjord Air Base (BW 8) by the new Hercules aircraft. Equipped with skies they landed on the snow surface and proved robust and safe. To my knowledge only one serious accident with personal damage happened during many years of operation on the inland ice. A man was killed, when a wing hit the snow surface in an "oblique" landing causing a break-off of a propeller that penetrated into the cabin.*

The remarkable achievement behind the erection of the Dye stations may be illustrated by two severe problems that were both solved. Firstly, any object left on the surface has a leeside where drifting snow settles and starts piling up. The object will therefore be buried and disappear from the surface sooner or later. The snow drift only takes place in the lower few metres of the atmosphere, however, and a building may therefore be kept "afloat" if lifted 10 m above the surface allowing the snow to drift away below it.

The second problem was far more serious. It was impossible to establish a firm foundation for the buildings, because it takes roughly 100 years before the surface snow is compressed into solid ice. During this slow process (firnification) a given snow layer sinks to a depth of 80 m below the new surface formed under constant deposition of 1 m of snow per year in South Greenland. In other words, at any time the foundation of the station sinks relative to the actual surface, up to 35 cm per year somewhat depending on the depth of the foundation. The 35 m high station stood on a platform supported by six columns. Each column comprised a 40 m high steel construction, with a 6x6 m cross section, in 1973 founded at the bottom of a 25 m deep shaft. From time to time, the whole building had to be lifted relative to the sinking foundation. This was done by hydraulic jacks.

Originally, the life time of the Dye Stations was estimated at 10 years, but not until 1978, after 17 years of operation, the situation became precarious. The six "legs" followed the main ice stream, but not with exactly the same velocity. As years went by, the heavy steel constructions got twisted to a degree that necessitated strong measures. The 7000 tons stations were moved 200 m to a newly built foundation – again a remarkable engineering achievement by DAC.

The energy supply was delivered by powerful diesel generators. The oil was pumped up from four oil tanks buried in the snow, each containing 450 m^3. In the beginning, the annual consumption was 9.000 m^3, later somewhat less. But the internal regulation of temperature was a problem the engineers had not been able to solve.

was estimated to cost 8 mill. $, but after all formidable wages made it attractive for the crew to resist the tropical heat on the inland ice.

Eventually, the original alarm function was taken over by satellites, but the military wanted to save the stations as an alternative telephone connection between Europe and U.S.A. Therefore, Dye 2 was only abandoned in 1986, Dye 3 in 1990.

Only a couple of years before the close down of Dye 3 it was rumoured that during the erection of the station, 30 years earlier, somebody had blocked a ventilation channel with rags, thereby causing an air circulation in a closed system without intake of fresh air from the outside. It is unclear if the story was spread as a kind of revenge for the sufferings in the snake pit.

Daily life

In the beginning the crew comprised 100 men, no women, later it was reduced to 12, including 6 Danes. They led a humdrum, but comfortable life. From the moment they got off the aircraft and climbed the 10 m high ladder to the entrance of the station most of them never came out in open air for the 9 month duration of their contract. Like Camp Century the station was provided with every imaginable facility, including a sports centre where the most sensible tried to stay in good shape – difficult considering the loneliness, the boredom and the excellent food and drink available. Only seldom the boredom was interrupted by a visiting polar bear led in from the east coast 200 km away by the seductive smell from the exhaust of the station.

The main task of the crew was watching a large radar screen around the clock and observe and take down everything moving in the air space within the range of the radar. Engineers, cooks and handymen ensured trouble-free operation, maintained the 3 km long air strip, took care of the water supply, etc.

The station leader was responsible for everything working properly, including that all military regulations be observed. Ordinarily, the latter point was not taken too seriously, and when controlling officers gave notice of a visit a bad weather report could delay the flight from Sdr. Strømfjord (SFJ) Air Base long enough for making everything look properly on their arrival. In one case they arrived without notice, however, and the station leader was fired on the spot. His successor could not bear the loneliness and the responsibility, so he killed himself. Greenland can be a harsh country.

Throughout the years, Dye 3 became the starting point of several expeditions in South Greenland, and it became kind of a test station for new glaciological techniques, because it offered workshops and accommodation in the field. And up to this very day young U.S. Air Force pilots practice landing and taking off on the Dye 2 skiway instead of being trained in the far more expensive Antarctica.

Intermediate drilling

Dye 3 also became the scene of our first involvement in ice core drilling. After some difficulties, Chester Langway got a U.S. NSF grant to use Lyle Hansen's thermo-drill (Box 6.2, p. 54) with us as partners at the easiest accessible and therefore cheapest location on the inland ice, Dye 3.

The drill was installed 25 m below surface at the bottom of one of the columns supporting the station. The temperature was -20 °C, but the air was absolutely calm, so the work could go on independent of weather conditions. In order to avoid the +30 °C in the snake pit, I slept in -5 °C on a platform in the column trusting that I would not walk in my sleep and tumble 35 m down to the drillers.

The core was split into two parts along the axis, and CRREL and we each got one of the halves. After homecoming we cut 6000 samples from our half, corresponding to an average of 8 samples per year calculated by firnification and ice flow models (cf. Box 6.3, p 56). We counted 740 seasonal δ cycles, so the core reached back to A.D. 1231. The counting was difficult in places, because surface melting often occurs in the summer time. The melt water seeps through the porous snow and refreezes somewhere in the cold firn, which disturbs the layer sequence, of course.

Fig. 7.3 *Lyle Hansen with his thermo drill at the bottom of one of the Dye 3 pillars. In the background his assistant John Rand.*

Fig. 7.4 *Sigfus Johnsen and Chester Langway measuring the density of an ice core increment. The density increases downward from 350 kg/m*^{3} *at surface to 920 kg/m*^{3} *at a depth of c. 100 m, where the snow has been compressed into solid ice.*

Fig. 7.5 *I served as a coolie and a packing master*

Fig. 7.6 *We were called The Three Musketeers. Chester Langway between Hans Oeschger and myself. Chet told a story well, here on how he let himself be lowered into the 80 m deep shaft to the water reservoir at Camp Century. The telephone connection to the crew at surface had broken down, and when he approached the water surface they misunderstood his shout for stopping – or did they?*

The annual layer thickness averaged 53 cm of ice equivalent, but it was particularly high around A.D. 1400. This is interesting in view of reports on frequent landslides in Iceland at that time, and the historic fact that agriculture in Denmark was only possible in the high lying fields, because the low lying ones were flooded. This suggests that the North Atlantic low pressure activity was unusually intensive at that time.

8. POTENTIAL DRILL SITES – GISP

A follow-up of the Camp Century deep drilling at the most favourable location in Greenland had the highest priority in many glaciological circles, and in 1972 an American (CRREL)-Danish (University of Copenhagen)-Swiss (University of Bern) consortium was founded under the name of Greenland Ice Sheet Program (GISP). Deep drilling was its main objective, but no drill was available, neither means to build one. All one could do at that time was to look for the most suitable location. The most important criteria were:

1. There should be no surface melting that could change the chemical composition of the ice by adding soluble gases, e.g. CO_2. This was of special interest to our Swiss colleagues Hans Oeschger and Bernhard Stauffer.
2. The ice flow pattern should be simple ensuring undisturbed stratification at great depths.
3. The seasonal δ-cycles should be preserved with a view to dating by counting annual layers, i.e. high accumulation and little melting.

Obviously, Dye 3 did not fulfill 1. and 2., barely 3. Regarding item 2., Preben Gudmandsen's radar soundings had revealed a wild mountainous landscape under the ice in South Greenland. Therefore, the deep ice under Dye 3 must have followed a very complicated course since it was deposited closer to South Dome some 130 km further south. The transport must have caused considerable disturbances in the deep ice.

All of the three criteria pointed to Central Greenland north of the EGIG line, where the radar soundings revealed a relatively smooth bedrock. But detailed investigations were needed prior to selecting the exact location.

North Site

In 1972, Sigfus Johnsen, Jan Nielsen and our Canadian colleague David Fisher were put down with a SIPRE auger at a location we called North Site, 500 km north of the EGIG line, 2870 m a.s.l. They recovered a nice core to 25 m depth, and over the radio they informed the U.S. Air Force that the snow got rather heavy in the afternoon, so a pick-up in the forenoon might be safest.

The Hercules arrived in the afternoon. As predicted, the take-off was difficult. After several fruitless attempts, jatoes were fired. Same negative result. At last there was only one set of jatoes left, and the pilot ordered everything out: Auger, radio, instruments, tents, ice cores, everything except a few personal belongings. All passengers and dispensable members of the

Fig. 8.1 *The most important drill sites on the inland ice and on two small separate ice caps: Hans Tavsen in Peary Land in the north and Renland in the east.*

Fig. 8.2 *Jan Nielsen and Sigfus Johnsen at North Site in -40 °C and a refreshing wind*

crew were ordered back on the slanting loading hatch. That helped! Well arrived at Sdr. Strømfjord Air Base, David Fisher could please Niels Gundestrup that his precious satellite navigation instrument was saved – built into a small suitcase it looked like a personal belonging!

The equipment and the cores were only picked up in April next year by Sigfus and Jan. The weather was as at Vostok in the summer time: -40 °C and a fresh breeze. But it was quite impressing that the air-crew was able to find their way to the three bamboo sticks marking the location on the infinite, monotonous expanse.

The δ-analyses indicated an accumulation rate of only 16 cm of ice per year, and already at a depth of 6-7 m the diffusion had obliterated some of the seasonal cycles [ref.8.1].

Milcent and Crête

Next GISP-target was Milcent, one of EGIG's stations midway between the highest point Crête and the coast. Lyle Hansen drilled 398 m with his thermo-drill, and a mean accumulation of 56 cm of ice per year left the most beautiful annual δ-cycles we have seen anywhere (Fig. 8.3). It was quite easy to date the entire core back to A.D. 1177 with a ±2 years accuracy. But there was a general tendency toward decreasing δ's downwards in the core, undoubtedly because deeper ice is deposited further inland and therefore at lower temperature.

In 1974, Lyle Hansen's last thermo-drilling took place at Crête in the coldest area of the inland ice (annual mean surface temperature -32 °C). The mean accumulation rate 28 cm of ice per year was marginal for the survival of the annual δ-cycles (Fig. 8.3), but a model was developed for the diffusion re-establishing the almost obliterated cycles – we called the technique for "reversed diffusion" [ref. 8.1]. Annual cycle counting showed that the oldest layer in the 404 m long core was deposited in A.D. 534.

This was the first time an ice core, dated year by year, reached through the Medieval, and it was tempting to interpret a smoothed δ-profile as a climatic record, the more so as the upper part of the δ-profile varied in phase with 100 years of temperature observations in Godthåb/Nuuk

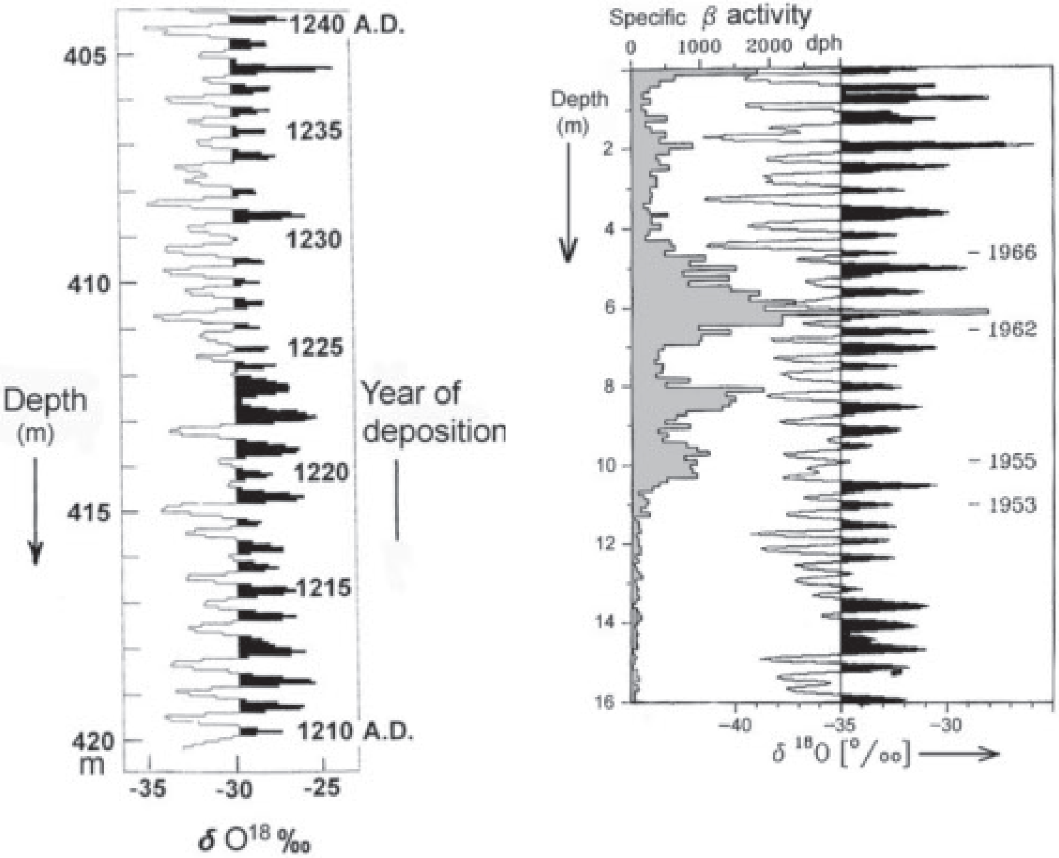

Fig. 8.3 ***On the left***: *Seasonal δ cycles make exact dating possible by counting summer layers downward from surface. This core increment from Milcent was deposited from AD 1210 to 1240. When corrected for thinning, the distance between two minima is a measure of the precipitation in the year of deposition. The decade AD 1225 to 1235 was dryer than the preceding decade, and since the δ mean values was lower it was apparently cooler (assuming unchanged summer to winter precipitation ratio).* ***On the right***: *β and δ measurements along the upper 16 m of the Crête core from 1974. The seasonal cycles in the δ curve to the right have decreasing amplitude downward, because the diffusion in the porous firn tends toward elimination of all δ-gradients. However, the cycles are distinct enough for exact dating back to 1942. The grey shaded curve shows the specific β-radioactivity profile: There is no trace of fall-out from the nuclear bombs in 1945, but the first hydrogen bombs in 1953-55 caused considerable radioactive fall-out on the inland ice, and so did the test series in 1958-59 and in the early 1960'es.*

on the west coast. Furthermore, a climate interpretation was supported by very low δ's in the 1690'es, a period described as extremely cold in the Icelandic annals. In 1695 Iceland was completely surrounded by sea ice, and according to other sources the sea ice reached half way to the Faeroe Islands.

Vostok

At this time a Soviet paper claimed having observed seasonal δ variations in the deep ice core drilled at the Soviet station Vostok, East Antarctica, perhaps the coldest place on Earth (mean annual temperature -52 C°; accumulation rate only a few cm ice equivalent per year). This was in contrast to our experience in Greenland, which indicated that, if existing at all, such variations should be obliterated by diffusion already at very shallow depths. Our colleagues in Leningrad kindly sent us a core increment from Vostok, but we could not find any short-periodic δ variations in it. However, we were interested in seeing, how efficient the diffusion is in an area of extremely low accumulation like Vostok.

Simultaneously, the U.S. National Science Foundation invited our group to participate in the Antarctic Ross Ice Shelf Project (RISP) that aimed at measuring the total annual supply of material to the shelf with a view to its possible gradual disintegration. We were supposed to auger 10 m cores and, by δ and β analyses, measure the distribution of the accumulation rate in a square network of 116 stations covering the enormous ice shelf that has a 900 km long ice barrier along the Antarctic Ocean. Our two exellent instrument makers Jan Nielsen and Steffen Hansen carried out the laborious field job through three consecutive field seasons.

In 1975, NSF kindly invited me to visit the project. It was a great experience visiting the RISP camp, the more so as it opened up for the prospect of visiting the Vostok station. With 20 officers, I was lucky to get reservation of a much-coveted seat on the one and only annual Hercules flight from the American base McMurdo to Vostok. The Soviet guest at McMurdo, the geologist Dr. Barkov, was burning with enthusiasm, when I suggested comparative δ analyses in Leningrad and Copenhagen with the aim of solving the problem of diffusion in the firn at Vostok. He promised that a 2 meter deep pit with vertical sides would be ready for detailed sampling, when my American colleague John Splettstoeser and I arrived.

It had to be a quick operation, maximum stay 2 hours total, as the Hercules had to be left with four roaring engines running full speed for fear of starting problems, if stopped. We were cordially welcomed by our Soviet hosts, and as good guests we were obliged to take part in the welcome ceremony before we could start working,. The mess hall was decorated with pictures of Lenin and other Soviet saints, of course, and the table was set with exotic snacks, even tomatoes grown on the window sills. In addition, Vodka in buckets; speeches and toasts to international co-operation, peace among people etc., all while John and I sipped nervously from the Vodka.

Time was running, however, and at last we insisted on leaving the party to do our job. Armed with a hand sled, a knife, and 150 numbered plastic bags for the samples we went 500 m upwind to the marked pit. A fresh wind of -40 °C is not the best working condition, but the pit was fine, so I jumped down and was partly sheltered from the wind, while poor John sat on the windy edge putting the samples in the bags as I passed them to him.

When the upper 25 samples, each 1 cm thick, were cut, John had to give up. He promised to come out for me in due time and walked back to the station. I realized that alone I could not finish the job as intended, so I cut some big blocks out of the firn, which was very compact. I had only reached down to 1.24 m depth, when John came and helped me up from the hole. Together we pulled the sled with the precious samples toward the air strip.

On the way we were stopped by some people outside the Soviet drill hall: *"Oh, Dr. Dansgaard, where have you been? We have been looking for you allover. You must come in and see our deep ice core drill"*. I told them that nothing in the world was more tempting, except reaching the Hercules that had to take off in five minutes. Disappointed faces. *"We have arranged a party for you, and we have gifts for you"*

How do you handle such a situation? I estimated that it would take me three minutes to run to the airplane and told the nice people that I was very grateful, but I could only spend two minutes with them. In extreme haste I got a look at the drill, consumed a single vodka-toast for peace and co-operation among people, and thanked for the gifts, when an Air Force officer came in and said: *"If you want to stay here for another year, you are welcome, but if not you better* ***run – NOW"*****.**

Holy smoke, how we ran, but the climate and the 3500 m attitude are not suitable for athletic feats, so when I had thrown myself into the aircraft I remained lying on the floor, while the Hercules boomed along the bumpy airstrip. Somebody must have put me on a bench, because when waking up I was lying quite comfortably with an oxygen mask on my face.

Back in McMurdo we used a razor blade to cut 200 samples, each ½ cm thick, from the firn blocks that were so compact that they had survived the harsh transport. As agreed with Barkov, each sample was divided into two parts, one for Leningrad (we never heard about the result of their analyses), and one for Copenhagen. Only the upper 3 or 4 annual layers could be identified by seasonal δ variations. which are obliterated already at a depth of 35 cm. But a high specific β activity identified the 1964-65 layer at 117 cm depth indicating an annual accumulation of 44 mm ice equivalent. This was double as much as expected, but subsequent measurements have shown highly varying accumulation rates in the Vostok area.

The resulting American-Danish-Soviet paper temporarily opened the door for a Danish-Soviet co-operation on ice core analyses. I was asked by the Soviet Academy of Sciences if two glaciologists might come to Copenhagen and measure 50 δ values on the deep ice core from Vostok and on cores drilled through some Soviet glaciers. I wished them welcome, but emphasized that a δ profile along an ice core implied many samples cut in a continuous sequence, so they should rather bring 1000 than 50 samples.

The two men arrived with 50 samples and were lodged in the Soviet Embassy. Only one of them, Felix, knew what it was all about – the other one's task was obviously to prevent Felix from defecting to Danish capitalism. Only a few of the samples were from Vostok, most of them comprised two continuous profiles along cores drilled through glaciers on – Svalbard! This was clearly in defiance of our agreement. Norway has sovereignty over Svalbard, and I anticipated an embarrassment in Norway, if measurements made in Copenhagen were published as being related to "Soviet glaciers on Svalbard". I presented the problem to Tore Gjelsvik, director of The Norwegian Polar Institute, but I added that in my opinion the investigation would hardly give rise to interesting results, because the Svalbard glaciers are unsuitable for stable isotope studies due to the high rate of melting in the summer time. Gjelsvik gave me green light to continue, but as foreseen the result was not worth publishing.

Perhaps the Soviet approach was a feeler aimed at a more far-reaching co-operation on the fantastic deep ice core from Vostok, which at that time exceeded a length of 2500 m. The analyses were finally done as a joint Soviet-French effort with extremely interesting results. I was convinced, however, that Danish glaciology ought to concentrate on Greenland. This was where we had a good co-operation with U.S.A. on promising international projects; this was where we had means, obligations, traditions, and future.

Times change. Today the Danish glaciology group participates in great European projects, also in Antarctica, but Greenland is still our main field of obligation and action.

A few years after his visit to Copenhagen, Felix sent me a letter from Spain, where he had settled with his wife of Spanish birth. Obviously, he had given the guard dog the slip.

Bela Papp

Among the visitors to the laboratory, I remember a Hungarian hydrologist with a special painful pleasure. Bela Papp was a tall, thin, and modest, almost shy man. He had got a 6 months international research scholarship to stay with us in the first half of 1973. For the first time in his life he escaped the control of the Hungarian Communist regime, but only partly as his wife and son were not allowed to join him. Mrs. Papp was paralyzed in the lower part of the body after an unsuccessful parachute jump, and most of Bela's endeavours turned on scraping together enough money to buy her a special handloom in Denmark. His hatred of the Hungarian regime was endless, and our professional discussions often ended in political ones.

In March a message from Budapest revealed that his family in Budapest lived on the starvation line. His salary had been withdrawn, because the authorities considered it unlikely that he would ever come back (his joy of being in Denmark probably appeared in his controlled letters to the family). I recommended Bela to go home on Easter vacation, and the Carlsberg Foundation granted his travelling funds. After a modest assistance from me, Bela went home with the fine handloom. He was convinced of being allowed to return to Copenhagen, because the regime would hardly risk a political scandal.

It was a happy Bela who came back after Easter. The payment of wages was resumed and Mrs. Bela's work with the handloom was well under way. Bela enjoyed his freedom, not least when he participated in an International Glaciological Society meeting in South Greenland.

Our party took up so much of room on the airplane that some of us, including Bela, were requested to adjourn to the first class section. We complied with the request, and after a sumptuous repast Bela said: *"In my country we are always taught that the decadent western world is dying. But I must say, it's a beautiful death"*.

The last night was Midsummer eve, and the students had arranged a big bonfire. In the quiet, light night Scandinavian midsummer songs sounded among the hills. But Bela was missing. I looked around and found him crying behind a rock. Instantly, he composed himself and apologized for his "undignified behaviour", – we sat quietly for some time, – but then he explained: Fire always reminded him of his fellow students who perished in the flames at the University of Budapest during the revolt against Soviet in 1956.

After returning to Copenhagen it was time to part. Bela asked me urgently to visit Budapest, not because he could show me anything of professional interest as he said, but because it would consolidate his position towards the regime. He felt that being visited by "an internationally known scientist" might improve the chances that his son could get a higher education, which was normally reserved for members of the Communist Party and other "trustworthy persons", and at least not for children of participants in the 1956 revolt.

That request could not be declined, of course, so I promised to come in connection with my next journey to Vienna and to send him an early notice. I did so in a most formal letter written on official notepaper and with abundant use of titles and portentous verbiage. Apparently, it worked as intended, because Bela's boss received me as the demigod, I think Bela held me to be. A Government chauffeur dressed up in uniform and gold-braided cap drove us around in a big diplomat automobile, Volga I think it was. Bela showed me the beautiful Budapest, which he loved. We visited his home (all the neighbours hang out of the windows admiring the fashionable vehicle), I greeted Mrs. Bela and the son, whose chemical interests had left multicolored marks on the walls of the garden room.

At Bela's institute I praised him to the director, of course, and I expressed my hope for a continuation of our "highly fruitful co-operation". We spent a whole day sightseeing around the long Lake Balaton southwest of Budapest.

We corresponded a couple of years. Bela was sent as a hydrological expert to Algeria that had close connections to the East European countries. But he was weakened by illness, and in 1978 he died of tuberculosis, 11 years before his dream of a free Hungary came true. He had deserved to see it.

I do not know if my visit to Budapest was beneficial to his son, but in 1993 I received a letter from a biochemist in New York, signed Bela Papp Jr. Something succeeded, obviously.

Up to this very day, a beautiful table-cloth in my home proves that Mrs. Bela became a competent weaver.

9. NEW AIDS, METHODS AND PERSPECTIVES

During the 1970'es our group succeeded in developing several new aids and methods for glaciological research, tools that made us attractive partners for foreign colleagues and, at the same time, ensured the favour of the grant-awarding authorities. The most prominent figures responsible for these achievements were Niels Gundestrup, Sigfus Johnsen, Claus Hammer, Steffen Hansen, Jan Nielsen, and Niels Reeh.

Automatization

Isotope analysis of hundreds of water samples per day was a hitherto unseen performance. Using the water-CO_2 exchange process outlined on p. 13, Sigfus Johnsen built a preparation system for mass spectrometric measurements, which enabled us to prepare up to 256 samples at the same time, including 16 samples of IAEA standard water for reference. The subsequent δ-measurements took only 12 hours thanks to an automatized and computer controlled procedure developed by Niels Gundestrup.

In daily routine, 128 or 256 water samples were transferred to sealed steel bottles that were evacuated and filled with CO_2. From this point, the computer took over the control of the entire process, and nobody needed to be present. After at least 4 hours of shaking for water-CO_2-isotopic exchange, the CO_2 samples were admitted, one by one, into the mass spectrometer. Next morning the instrument had measured, calculated and printed out all of the δ-values.

Having a complicated instrument operating through 12 hours without personal supervision and adjustment calls for extreme stability of all electrical circuits, and Niels had put a lot of effort into solving this problem. Furthermore, as the measuring procedure went on in the night hours, the mains voltage was only slightly disturbed by industry, and the room temperature was particularly constant as there was no coming and going.

Our original goal of measuring many samples with moderate accuracy payed off, and we even got a side benefit: The necessary stability of the electronics resulted in a better accuracy than intended. In the 1970'es our machine measured more δ-values on natural waters than all other machines in the world taken together.

Position-fixing

Geographic positioning has always caused problems for Polar expeditions. Theodolite and chronometer were standard equipment, but difficult to transport and use, particularly under poor weather conditions.

Since 1960 the U.S. Navy had positioning satellites in nearly circular orbit. Every minute they emitted radio signals with information about time and their position. U.S.A. also developed a so-called Geoceiver, an instrument able to combine the signals from several satellites and to calculate the geographic position of the receiver with an accuracy of 50 m, after many satellite passages 5 m.

However, including tripod, antenna, batteries etc. the Geoceiver was heavy and inconvenient to travel around with. But Niels Gundestrup succeeded in boiling the whole lot down to fit into a small suitcase, which gave us a hitherto unseen freedom when operating on the inland ice. For example, it became absolutely safe to leave Dye 3 by oneself on a snow-mobile, if the equipment included Niels' small suitcase and a radio transmitter for reporting one's position to the headquarters.

The new technique was also ideal for measuring very small velocities. For example, the movement of the Dye 3 station measured 12.3 m per year determined by repeated position-fixes with intervals of a few years. In the long run the steel construction of the station strained, because the velocities of the six supporting "legs" were not exactly the same.

The position-fixing technique now rests on a quite different principle. The Global Positioning System (GPS) is based on direct gauging the distances to several satellites. The GPS-instruments are nowadays of the same size and prize as a good mobile telephone.

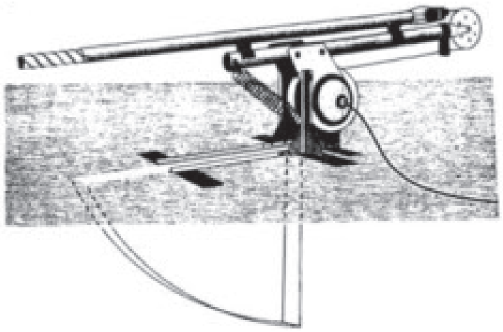

Fig. 9.1 *The "Rolls Royce drill" is based on the same principles as the SIPRE auger. It weighs c. 250 kg, incl. winch, "tower", 200 m cable, electronic control, foundation and generator. The drill can be tilted from horizontal to vertical position, the lower end going into a 1½ m deep trench in the snow. A 100 m long ice core can be drilled and packed in 16 hours by three persons. In the drawing, the inner core barrel has been pulled partly out of the outer one.*

Box 9.1 Previous shallow drills. *Our own shallow drill was based on previous designs, such as the SIPRE hand-auger and a model built by the Swiss mechanical engineer Henry Rufli. His drill was actually a SIPRE auger hanging in a cable and provided with an electromotor that turned the inner core barrel with the knives. There was no winch, however, so the drill was hoisted to the surface by a couple of athletes pulling the cable over the wilds. 60 m of core was impressive if compared to the reach of the SIPRE auger's 20 m.*

The "Rolls Royce drill"

Our group won distinction for the development of a transportable light-weight dril [ref.9.1]. After an unhappy premiere it has served us many years without serious troubles (Fig. 9.1). That is why we have ventured to call it "the Rolls Royce in shallow drilling" (completely unofficial, though). "Shallow drilling" means ice core drilling to a depth of up to 100 m, that is through the youngest 200-500 annual layers of the inland ice. This is much less than offered by a deep drilling, but also much less expensive. The first works of merit in this field were due to American and Swiss engineers

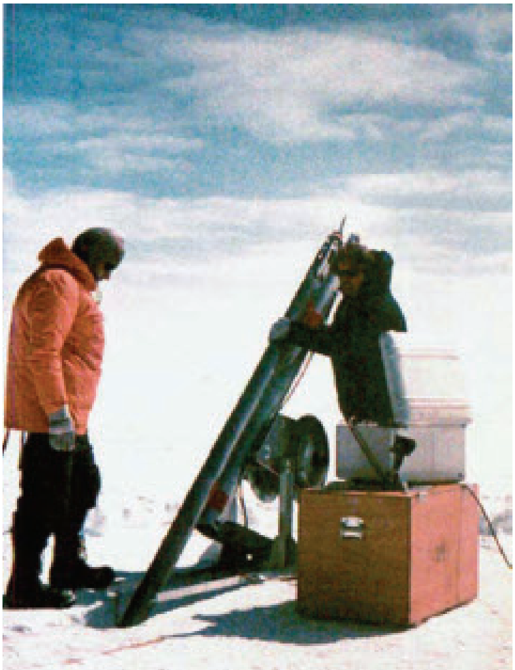

Fig. 9.2 *Sigfus Johnsen and Steffen Hansen tilting the shallow drill into vertical position.*

The Swiss drill was used on the Danish-Swiss expedition 1975 to the Hans Tavsen ice cap in Peary Land, the world's northernmost ice cap (Fig. 8.1). From the very start it was evident that there was considerable surface melting in the summer time, in spite of Hans Tavsen being a neighbour to the North Pole. Nevertheless, the location was interesting, because it lies close to the Arctic Ocean, from where Hans Tavsen undoubtedly receives most of its snow, contrary to more southerly regions of the inland ice.

The Danish drill was completed the following winter. It was provided with a winch fixed to a 3 m high "tower" that could be turned into horizontal position for maintenance and ice core removal. When tilted back to vertical position the lower part of the tower went into a 1.5 m deep trench, cf. Fig. 9.1-3. The very drill had a built-in micro-chip controlling the drill functions on command from the surface.

Fig. 9.3 *Steffen Hansen on a snow mobile pulling two Nansen sledges with the entire drill equipment including fuel, generator packing materials, radio emitter and other emergency accessories.*

Strange to say, the most difficult problem was finding a 2½ m long 10 cm diameter steel tube straight enough for being used as an outer core barrel. Despite persistent efforts searching all over, it turned out that all tubing available in the kingdom were bent a bit – 1 mm deviation from a straight line was enough for disqualification. Then somebody in a stroke of genius proposed to apply "point-heat" making the tube buckle into the right shape. Later, the trick stroke back in a most unpleasant way.

The principal advantages of the "Rolls Royce drill" were (1) the simple technique enabling one person (m/w) to carry out a drilling, and (2) the small dimensions and the low weight (only 300 kg including generator, fuel, winch, cable, control system etc.), which enabled us to ship it by light aircraft or on a sledge pulled by a snowmobile (Fig.9.3).

The Hans Tavsen ice cap

After a test at Dye 2 in early summer 1976, the drill team went back to Hans Tavsen, hoping to go deeper than last year's 60 m.

At that time I had become a member of the Commission for Scientific Research in Greenland that went on a round trip in Greenland by a Danish Hercules. The northernmost location visited was Station Nord in Northeast Greenland, not far from Hans Tavsen. At Station Nord we met members of the Sirius Patrol, a flock of plucky fellows, who exercise the Danish sovereignty over the 2000 km long coast line in northeast Greenland. We even met the Danish Chief of Defence Blixenkrone-Møller, who was quite impressed by the working spirit of our team and the geologists working in the area. He placed a helicopter at our disposal for a flight to the Hans Tavsen camp next day with stop-over at Aftenstjerne søen (Lake of the Evening Star) for congratulating Eigil Knuth to his 70 year birthday. This is how the ageing sculptor and Arctic explorer was fêted with champagne during his lonely stay in a tent in the wilderness.

The visit to the ice cap was less successful. Light new snow was blown up by the helicopter causing a white-out situation. The horizon disappears and you loose the sense of up and

Fig. 9.4 *On the way from Mestersvig to Renland we passed Stauning's Alps.*

down. The pilot simply gave up landing. What a pity.

Next day brought another disappointment. Over the radio, the drill team communicated the sad news that the drill was stuck in the drill hole. It is not too much to say that the Rolls Royce drill was not of noble birth. During the operations, the straightened drill tube had rebended to its original banana shape preventing further drilling. The very drill was lost, but obviously the Commission was less disappointed by the failure of the first attempt, than impressed by our intention to start over again right away. So we did in the following winter supported by the Commission. Steffen Hansen went to a special factory in France and selected a steel tube born absolutely straight.

The Hans Tavsen ice cap in Peary Land was only penetrated ten years later, now by a forerunner of a new deep drill that reached bedrock 325 m below the surface. The separate ice cap became the object of many-sided studies [ref.9.2]. The ice core contained distinct melt layers all the way to bedrock indicating that, contrary to Renland, Hans Tavsen contains no ice from the glaciation. Thus, the world's northernmost ice cap melted away during the post-glacial climatic optimum and was only rebuilt when the climate got colder again some 4000 years ago.

Renland

The final version of "the Rolls Royce drill" was completed in early summer 1977, and at the end of the field season it had produced 800 m of ice core to depths down to 100 m at several localities. The culmination of its performance occurred in 1985, when it penetrated the separate, high-lying Renland ice cap in the Scoresbysund Fiord (cf. Fig.8.1) down to 325 m, world record for this type of drill [ref.9.3].

The δ-profile was extremely interesting, as it proved that the Renland ice cap has always been separated from the inland ice. Since all of the δ-leaps revealed by the Camp Century core recurred in the small Renland ice cap, the Renland peninsula cannot have been overrun by ice streams from the inland ice, not even during the glaciation.

Inclusions in the ice

The only visible inclusions in glacier ice are the air bubbles, which our Swiss colleagues analysed with great success, particularly as far as ^{14}C, ^{10}Be, and the greenhouse gases CO_2 and methane are concerned [ref.9.4-5]. The invisible inclusions, micro particles and chemical impurities, had potential to reveal other interesting facets of the environment of the past [ref.9.6].

Throughout the years, Claus Hammer deserved well of analysing and interpreting invisible inclusions in the ice, especially dust and strong acids that are deposited with the snow. During interglacial time most of the dust comes from spring-dry areas in North America, and most of the strong acids always originate from volcanic eruptions in the northern hemisphere.

At a conference in 1972, I met Dr. Eric Willis, director of the American Advanced Research Programs Agency (ARPA). He had been informed about our activities by Dr. Henrik Tauber, and he asked if somehow ARPA could support our work in Greenland. After a lightning quick brain filtering I mentioned our need of a Coulter counter and a man to operate it. Such an instrument measures the concentration and size distribution of microscopic dust particles in the ice, which render information about the origin of the dust and the frequency and strength of the storms that bring it to Greenland.

On my return I went to the President of the University and asked him if there was anything to prevent me from receiving an American military grant given with the only term that ARPA's name be mentioned in possible resulting publications. Prof. Morten Lange's answer was this: *"If the American military has finally found a sound way of using their money, I think one should not prevent them from doing so"*.

Dust and nitrate

This is how Claus Hammer got an expensive instrument and one year wages paid by ARPA. He threw himself into analysing the Crête core and demonstrated that the fall-out of insoluble dust particles from the continents tops in early summer. Therefore, a continuous profile of the dust concentration along an ice core would allow a year by year dating by counting summer maxima downward from the surface, just like counting δ-maxima. Counting dust maxima may even extend the dating further back in time, because dust does not diffuse like the isotopic components of water [ref.9.7].

One drawback is that Greenland ice deposited through the glaciation contains up to 100 times more dust than post-glacial ice. The summer maxima drown more or less in the high background values that are caused partly by dryer and more stormy climate then, partly by vast areas north of Siberia being drained due to lowering of the sea level, which creates a most efficient source of dust. In contrast, the dust counting method works also on glacial ice in Antarctica, where the air has always contained very little dust. There is simply no large ice-free land areas nearby that may serve as sources of dust.

Claus developed an elegant technique for continuous sampling and chemical analysis that is so fast that dust and nitrate profiles can be established in the field, cf. Box 9.2.

From the Dye 3 core and cores drilled later on, Claus collected myriads of data by these techniques, data that are still not treated in full, but promise information on hitherto unknown facets of the turnover of matter in the atmosphere.

Box 9.2 Dust and nitrate analyses. *Claus melted a groove along a split ice core using a soldering gold in order to ensure purity. The melt water was sucked up into a thin plastic tubing, frequently interrupted by air bubbles separating the water samples from each other. In a long line they wandered slowly into the measuring unit. Via a side tube they entered a short, thick-walled glass capillary closed by a glass plate in both ends and surrounded by a photosensitive counter. A laser beam ran along the axis of the capillary, and the counter recorded a gleam whenever a micro particle came into the beam. The counting was disrupted by the subsequent air bubble and resumed when the next water sample entered the capillary.*

But that was not all. The water samples continued their wandering in the plastic tubing and on the way a solution was added reacting with the nitrate in the samples. This created a dye of a colour density proportional to nitrate concentration, which could subsequently be measured by the degree of weakening of a laser beam sent through the sample.

Nitrate is formed mainly in the atmosphere. The fall-out varies with the seasons and what is more, independently of the fall-out of dust and volcanic acids. As the nitrate diffuses very slowly, its seasonal variations can be used far back in time and in cases of unclear signals from the other parameters.

Acidity and volcanism

The same degree of elegance stamped Claus Hammer's method for detecting great volcanic eruptions in the past. It began with a series of conventional acidity (pH) measurements on ice samples deposited about A.D. 1783, when the Icelandic volcano Laki had a giant eruption. As expected, the 1783 layer was highly acid owing to fall-out of sulphuric acid. The volcano emitted sulphur dioxide (SO_2) into the higher atmosphere, where it was quickly converted into tiny droplets of diluted sulphuric acid. Soon after they have fallen down into the lower atmosphere they are washed out by precipitation, cf. Fig. 9.5-6.

A detailed pH profile along the whole Crête core would be an extremely time consuming task using the conventional technique. However, Claus built a small "hand weapon" of two electrodes with a voltage difference of 1000 volts (Fig 9.7). When pulled along a split core by a speed of 5-10 cm per second, there was an increased current between the electrodes, when they passed a layer of high acidity, and therefore high conductivity. The method is so simple and

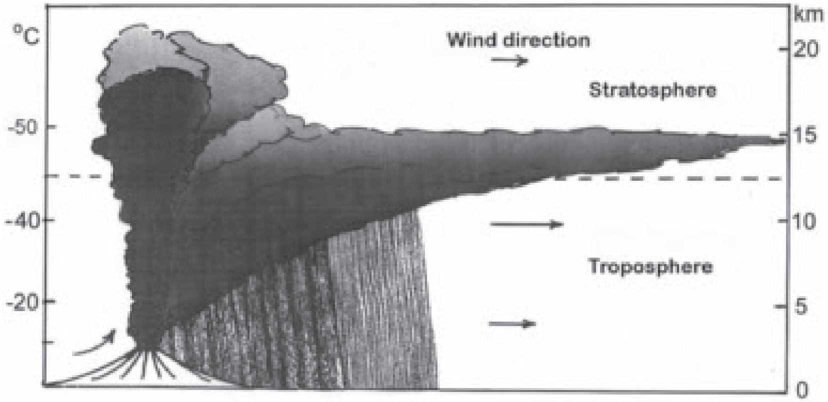

Fig. 9.5 *During a great volcanic eruption (lower left) lava is emitted locally. Depending on the winds in the lower atmosphere, ash and dust are spread widely but without essential influence on the climate. If sulphurous acidic gasses enter the stratosphere, however, they are spread over the entire hemi-sphere being converted into micro droplets of sulphuric acid. They can keep floating for a long time scattering part of the Solar radiation back into space, and thereby cooling the Earth's surface. Finally they fall into the lower atmosphere, where they are washed out as acidic precipitation, on the inland ice as an acidic and electrically conducting layer of snow.*

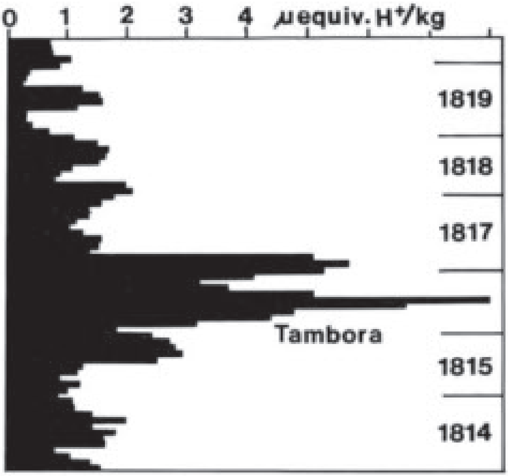

Fig. 9.6 *The giant eruption of Tambora, Indonesia 1815 acidified the atmosphere for more than two years.*

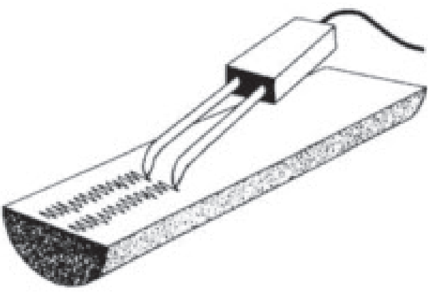

Fig. 9.7 *Claus Hammer's small instrument for fast recording the acidity along a split ice core.*

Box 9.3 Tambora, Indonesia, 1815, *was one of the greatest eruptions in post-glacial time, far greater than Krakatoa's famous explosive eruption in 1883. Their acidity signals in Greenland are relatively weak, because the eruptions happened south of Equator [ref.9.8]. However,* Fig. *9.6 shows that Tambora acidified the atmosphere globally through 3 years, which had a cooling influence on the climate – frost in June 1816 in New England, USA, and freezing the Thames in London the following winter.*

Box 9.4 Hela, Iceland 1104. *According to the Icelandic annals, the greatest Hela eruption in historic time happened in 1104, but in* Fig. *9.8 it appears in the 1105 layer. Originally we found that, despite the small deviation, it was pretty good shooting. But as an Icelander Sigfus Johnsen threw himself into the annals from that time and found the winter 1104-05 mentioned as the "winter of sand-rain". He concluded that the eruption took place so late in 1104 that the ash fell in the winter 1104-05, whereas the acids only fell in Greenland in 1105. Hence, the time scale was correct so far.*

Box 9.5 Elgjá, Iceland, 934. *The Icelandic geologist S. Thorarinson had heard of Claus Hammer's hunting volcanic eruptions. In a letter he asked him if there were any trace of an extremely great eruption of Elgjá that might have happened late in the period of settlement in Iceland according to the very oldest annals. This period ended in 930, so Claus went to the cold-house and analyzed the core backwards from 930. In a letter to Thorarinson he regretted to say that there was no dramatic acidic signal in the period up to 930.*

His letter crossed another one from Thorarinsson saying that incidentally the eruption may have happened shortly after the termination of the settlement. After that, Claus found the greatest acid signal in the whole Crête core in the 934 layer.

Box 9.6 Eruptions in the antiquity. *Vesuvius, Italy, A.D. 79, is only marked by a minor signal. Maybe the eruption was not tremendous in a global context, but it did cause tremendous and famous damages (Pompeii and Herculaneum), because it happened in the heart of ancient Rome.*

The third highest signal, 50 ± 7 BC, may arise from an eruption (probably Etna) that heavily polluted the atmosphere, which was observed in ancient Rome about the assassination of Caesar 44 BC. The contemporary poet Virgil described it this way: "When Caesar died, even the Sun took pity on Rome. It covered its shining face by a dark cloud, and the ungodly race feared an everlasting night."

A high signal 1645 ± 10 years BC is undoubtedly due to the giant eruption of Thera on the Greek island Santorin. This is supported by the dating being in essential agreement with carbon-14 datings of plant residues found in the remains of the Minoan town Acrotiri, which was buried under 60 m of ash. The town was part of the flourishing Minoan kingdom centred on the Island Crete 100 km farther south. The eruption was a catastrophe to the Minoan culture and left a 400 m deep crater 4 times as large as that of Krakatau. Beautifully decorated houses were brought to light at the excavations, but no skeletons or utensils. The population had been warned by earthquakes and fled in due time.

About 360 years BC Platon wrote down an old legend about the island Atlantis, a great and wonderful country that was at war with Athens some time in the past. "But violent earthquakes and floods set in, and in one terrible day and night all able-bodied men sank into the deep".

If Platon's writing is reliable in so far that a geological catastrophe really happened within the circle of knowledge and interest of ancient Athens, Santorin seems to be identical with Atlantis.

quick that it is now adopted as standard in any ice core drilling operation all over the world.

Fig. 9.8 shows the mean acidity of each of the 1440 annual layers in the Crête core identified by the δ-method [ref.9.9]. Many known, and far more unknown volcanic eruptions in the northern hemisphere are revealed in this record. Observe that the acidity does not directly indicate the magnitude of eruptions. Those in low latitudes do not appear so strongly as similar eruption in the nearby Iceland. Some of the recorded eruptions deserve special comments:

For the first time this investigation gave certain proof that series of great eruptions have a cooling effect on the global climate [ref.9.9]. Notice in Fig.9.8 the moderate volcanic activity in the medieval period 850 to 1250 and in the 20'th century, both warm periods, and the intense volcanic activity in "The Little Ice Age" 1350-1700. We treated these data statistically and concluded that 27% of the short periodic climatic variability might be put down to global volcanism (which cannot be predicted!). As to the physical mechanism behind the volcanism to climate correlation, cf. the text to Fig. 9.5.

Next step was to tackle the Camp Century ice core, in which the Elgjá signal is surpassed only by one found in the geologically unstable period shortly after the termination of the glaciation. But in addition to a large number of signals of unknown origin, a few ones appeared of historic interest. Some of the datings in Box 9.6 are from a subsequent counting. Many of the internal reflection layers found by radar sounding turned out to be caused by layers of strongly acid fall-out from great volcanic eruptions [ref.9.10].

The ice from the glaciation contains very few acid layers, hardly because it was a volcanically quiet period, but rather because this ice is generally alkaline. The reason is that during the glaciation enormous amounts of sea water were deposited upon the continents as ice, which low-

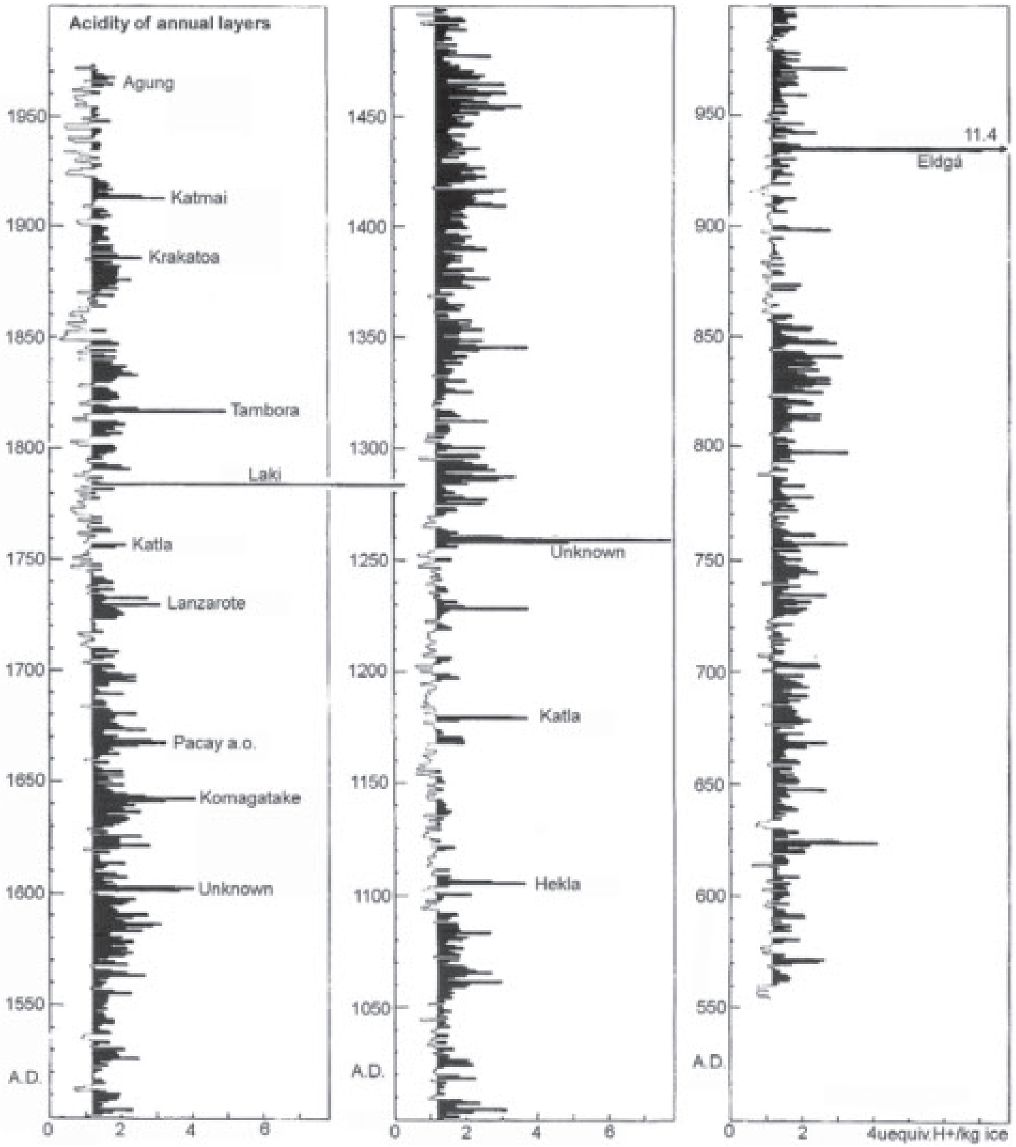

Fig. 9.8 *Great volcanic eruptions in the northern Hemisphere back to AD 553 recorded as the mean acidity of the individual annual layers. Before AD 1600 most identifiable eruptions are Icelandic due to the annals kept carefully from AD 1000. High volcanic activity generally leads to cooling climate.*

ered the sea level until 130 m below the present level. Vast areas of former sea floor were exposed, and fine-grained, chalky bottom material was blown up in the atmosphere, where it neutralized volcanic acids before they were washed out by precipitation [ref.9.7].

This is in contrast to Antarctica, where ice from glacial periods contains numerous acid layers indicative of volcanic activity in the southern hemisphere. There is simply no large nearby areas that might serve as sources of neutralizing aerosols.

10. ISTUK 1978-81

All of the GISP shallow and intermediate drillings mentioned in the previous chapter, as well as Preben Gudmandsen's radar survey from aircraft, aimed at one and the same target: the most suitable location for deep drilling in Greenland. There was no hope for getting a new drill financed, unless we were able to present solid evidence of why and where to use it.

In 1974, the U.S. NSF gave Lyle Hansen a green light for building a new deep drill based on the "wire line" principle, which is used in boring for oil. It was remarkable by allowing continuous drilling without interruptions, thereby saving considerable time: The core increments were hoisted up to surface, while the drilling continued down hole.

Two years later, the wire line drill was quickly tested at Dye 2 and sent to Antarctica for a penetration of the Ross Ice Shelf. NSF had invited the press to witness the final solution of the ice core drilling problem. Regrettably, it became a signal failure. Obviously, Lyle was not given enough time for testing the drill and cure the "children's diseases" that are inseparably linked to any new and complicated system, mechanical, electrical, or whatever. Afterwards, Lyle never had any close contact with NSF. But he did with us, in particular with Niels Gundestrup, with whom he was getting along very well. Together they developed and applied instruments for measuring the deformation and temperature profiles along deep bore holes, cf. e.g. [ref.10.1].

After the loss of the wire-line drill, building a new American deep drill was a very distant possibility. Our group therefore began discussing how to develop a Danish deep drill affordable for Danish funds. During the first half of 1977 the discussions in the haunt room of the laboratory were livelier than ever, sooner or later. Ideas and arguments daily drifted across the table for hours. With Niels Gundestrup, Sigfus Johnsen, Steffen Hansen, Jan Nielsen and Niels Reeh as primary contributors, the result was a draft plan for a construction [ref.10.2], which we named ISTUK of Danish "IS" (ice) and Greenlandic "TUK" (spear, awl or drill).

I presented the draft plan to the Greenland Commission, which agreed to finance the production of the drill, if our GISP partners, in practice the US NSF, would pay the first application in the field. At a GISP meeting in London September 1977 I was supported by our American and Swiss colleagues, and all that remained was persuading US NSF to get involved.

Director of NSF's Division of Polar Programs (DPP) was Edward Todd. At a meeting in Washington he involved his chief scientist, Dr. Duwaine Anderson, in the discussion, a very sharp gentleman who shot series of good, penetrating questions from the hip. Chet had warned me, however, so I was well prepared. Chet also said that one could count on a fair treatment, if one passed the examination, and that showed to be true.

Finally, Duwaine Anderson declared that DPP would support a deep drilling at Dye 3 in south Greenland on condition that our drill tube model passed a test in the ice-filled well at CRREL. I pointed out that from a scientific point of view, Dye 3 was not an ideal drill site, but I got the answer that to begin with it was Dye 3 or nothing. In fact, that was satisfactory because with its workshops Dye 3 was ideal from a technical point of view. Nobody knew if ISTUK needed changes, if and when we reached great depths.

Sigfus and Jan went to New Hampshire with the prototype tube, and with good support from the workshops at CRREL the test was carried through fairly well – we thought! CRREL's report to NSF was scathing, however. "The idea was mistaken, and nothing functioned".

But Chet's prediction of fairness held good. Despite CRREL's report Duwaine Anderson accepted our view that the obvious defects were curable teething troubles. We obliged ourselves to duplicate some vital items as spare parts on NSF's account. This became the only time ever US money has been transferred from NSF to the Danish glaciological group.

Back home the funding of the big task was OK'ed.

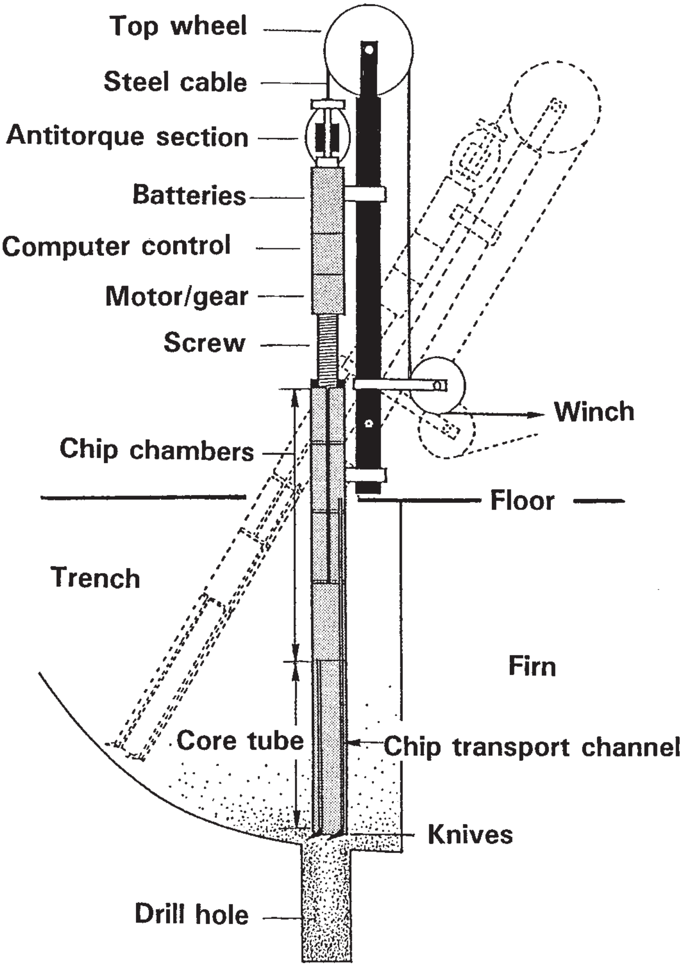

Fig. 10.1 *Principle sketch of ISTUK fixed to the 6.m "tower" (black) after coming up with an ice core increment in the core tube. Like the "Rolls Royce drill", ISTUK can be tilted to horizontal position.*

Box 10.1 The ISTUK components. *We aimed at a lightweight construction based on some quite new principles.*

1. *The drill should generally be smaller and lighter than the former Camp Century drill, which was 26 m long and weighed 70 tons, including tower, winch, cable and some auxiliary equipment. ISTUK was designed to be only 11 m long and weighing a good 1 ton, all included. The longest item was 8 m long, so the whole thing could easily be transported by a Hercules aircraft.*
2. *The very drill should be operated by built-in batteries, charged by weak electric currents through thin wires in the carrying cable, partly when hoisting the drill up and down the bore hole, partly during its maintenance at surface. With this arrangement we only needed a 6 mm cable, 16 times lighter than the Camp Century cable.*
3. *A built-in micro-chip should send information continuously to the operator at surface about the state and functions of the drill: Number and speed of its revolutions, its inclination, the pressure and temperature, the degree of charge of the batteries, the load on the cutter knives, the tightness of the gaskets etc., a total of 24 parameters.*
4. *Through external channels on the drill tube the ice chips cut by the knives should be sucked up into chambers above the drill tube and hoisted to surface with the drill, in stead of being dissolved in glycol down hole.*
5. *The labour-saving tower-tilting arrangement in the "Rolls Royce drill" should be transferred to ISTUK, which could then be operated with a short and light "tower" only 6 m long, cf. Fig. 10.1.*

Fig. 10.2 *The drill hall. ISTUK is being tilted by a hydraulic pump system.*

Fig. 10.3 *An ice core from great depth is released from the core barrel. Note that it is transparent. The air bubbles are dissolved in the crystal lattice at great pressures. When the ice relaxes at normal pressure they re-appear, but now around micro-particles that occur most frequently in summer layers. Thereby these layers become visible and may be used for dating by counting summer layers downward.*

Journeyman's certificate

It became an extremely busy and exciting year after DPP's green light in February 1978. Of course, the task was far beyond the capacity of our small workshop, but the workshops at the H.C.Ørsted Institute and the Niels Bohr Institute assisted readily, and special jobs were undertaken by corporations outside the University. A French special company undertook the production of a 1 m long, 8 cm thick stainless steel screw; a Danish company specialised in trawl-winches for fishing boats produced a winch according to our specifications; our Swiss colleague Henry Rufli at the University of Bern made a drill head with several matching sets of knives for cutting out the core increments; and an American company delivered 2500 m cable to be put on the drum of the winch.

The American Polar Ice Coring Office (PICO) was in charge of all logistics connected to DPP's activities, and we had excellent co-operation with them through many years. In April 1979 PICO began erecting a large building (23x8 m^2) on top of a 4 m deep excavation 600 m from the Dye 3 station. Thus, the effective floor-to-ceiling height was sufficient for raising the 11 m long ISTUK into vertical position.

A buried cable connected the drill house with the radar station enabling us to draw electric energy from the powerful generators at the station.

In early May, ISTUK was ready for transport to Sdr. Strømfjord. The 8 m long box with the drill tube was too long for going into any commercial aircraft, and the first ship could only go through Sdr. Strømfjord from late June. However, the Royal Danish Air Force agreed to send all equipment on a Hercules aircraft. But it was just about to fail, when the first pilot refused to take the 8 m long box with the drill tube for unknown reasons. Since the captain's word is law onboard, the box was left on the airfield.

The prospect of a break-down of our international project made me pour out my troubles to Prof. Isi Foighel, chairman of the Greenland Commission, and miraculously it turned out that another Hercules was put in for bringing a propeller to the first one (!). GISP was saved.

It took a couple of months to install ISTUK and casing the porous upper 90 m of the coming drill hole to prevent leakage of the drill fluid, etc., so we came into July before the first ice core increment was brought to light. As hole fluid we used light jet fuel mixed with a few percent tetra-chlorethylene to match the density of ice. When a core increment was removed from the drill it was carried through a tunnel to a 20 m long sub-surface "science trench". Here it passed a number of stands for logging, splitting along the axis, measurements for conductivity, dust content, crystal structure, chemical composition, and sample cutting, before the core ended up in a repository awaiting transport to the home laboratories.

The set up was arranged by Chester Langway and it set a new standard of efficiency for ice core handling and analyses in the field. Subsequently, the samples were measured for isotopic composition (δ) in Copenhagen, greenhouse gas content in Bern, and chemical and physical properties at the University of New York at Buffalo.

When everything functioned optimally, 45 people were in action. Three drill teams, 3 persons each, worked in turn around the clock, and two teams worked in the science trench from morning to late evening. Frictions among the teams were unavoidable, of course, but they were smoothed out by a board comprising one person from each country plus the field leader. Altogether the project was successful and friendships were formed across frontiers.

As to ISTUK several things had to be changed during the initial stage of the operation, e.g. the soldered chip channels on the drill tube. But we were quite satisfied by having reached a depth of 273 m, when we dismounted the drill in mid August and sent it by American Hercules to Sdr. Strømfjord and by ship to Copenhagen.

Turning point 1980

Next year we met new difficulties. Everybody worked intensively to overcome them, and after some time the situation lightened a bit, still not quite satisfactorily though. One day NSF-DPP's new chief scientist (Duwaine Anderson's successor) turned up accompanied by a project

Fig. 10.4 *Saturday nights were devoted to studies of experimental physics*

Fig. 10.5 ***Top***: *Pálina Kristinsdottir and Claus Hammer working in the science trench.* ***Below***: *Dorthe Dahl-Jensen and Jørgen Peder Steffensen at the drill.*

Fig. 10.6 *The Dye 3 drill house in 1979,*

a year later,

and when we stopped in 1981.

manager. They told me to stop the project immediately, probably terrified by the threat of a new "wireline failure". I asked if they wanted to see the drill in function, which they could not refuse, of course.

So we trudged on to the drill house, where they saw the drill coming up with a core increment, saw the core being carried to the science trench, being carefully logged and split prior to passing a series of benches, where it was studied and measured by teams of well organized and co-operating young people.

The two gentlemen went satisfied back to Washington. But up to this very day I never understood how a funding agency could permit itself to stop an international project without even notifying its contributing partners, The Danish Commission, the Danish and Swiss National Science Foundations etc.

1980 was the year we found two youngsters (and they each other), who should later become prominent participants in our glaciological research: Dorthe Dahl-Jensen and Jørgen Peder Steffensen, both developing very well in teaching and research, she strongest in theory, he in practice and experiment.

At the end of the 1980 field season ISTUK had gnawed itself down to a depth of 901 metres – not bad – and next year, the drilling went on as a hot knife in butter. At a depth of 1785 metres dust and conductivity measurements indicated that we were entering the ice from the last glaciation. On August 7, I sent Preben Gudmandsen a teasing telegram: *"Today we passed 2000 m. How come that your map on ice thicknesses shows only 1950 m here?"*.

He answered by only 5 words: *"Fool. You are drilling askew"*.

On the 11th of August 1981, ISTUK hit bedrock 2038 m below surface. The champagne corks popped, but the champagne had a bit of a tang – ISTUK was stuck, caught by a stone at the bedrock. The inland ice avenged by binding our pride, including 1 million DKK and a lot of hard work.

The drillers increased the density of the drill fluid thus creating an overpressure at the bedrock in the hope that during the coming winter the ice would yield the fraction of a millimetre that might loosen the drill. In addition, the tension in the cable was increased to 75 % of the ultimate strength by hauling in 15 m of cable creating an upward force of one ton on the drill.

Next spring the drillers found ISTUK hanging freely in the cable 15 metres above bedrock.

The three groups published their results separately as agreed upon (American papers were already in the mill before we stopped drilling). Nevertheless, mixed authorships would have given a more realistic impression of the close co-operation among the groups.

11. DYE 3 RESULTS

Papers on some of the investigations were collected in a book published by the American Geophysical Union [ref.11.1]. Some of the topics will be mentioned or shortly summarized below.

Bore hole studies

The deep drilling at Dye 3 resulted in a more than 2 km long ice core that was split up into a European and an American half. But the drilling also left a deep bore hole filled with a fluid of the same density as the ice, which will keep the hole open for measurements in the future. The ice movements at various depths is revealed by the geometry changes of the hole, and the temperature profile along the hole reflects past surface temperatures.

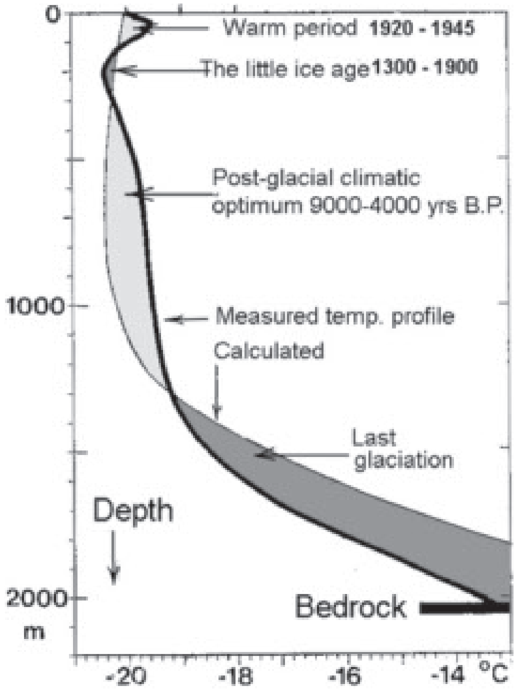

Fig. 11.1 *The heavy curve shows the temperature profile along the Dye 3 bore hole. The thin curve is calculated on the assumption of constant surface temperature through the ages. The light grey deviations reflect warmer, the dark grey ones colder periods in the past.*

The temperature profile was measured with an accuracy of 0.03 °C [ref.10.1 and 11.2] as shown by the heavy curve in Fig. 11.1. By a combined ice-flow / temperature diffusivity model another temperature profile was calculated on the assumption that the surface temperature had always been equal to the mean annual temperature (- 20 °C) in the 1970'es, cf. the thin curve in Fig.11.1. The difference between the two curves reveals the deviation of past temperatures from present values, disregarding past surface altitude changes [ref.11.3].

The measured temperatures are higher than the calculated ones in two depth intervals (about 75 m and 300-1300 m). This reflects the warm period AD 1930-60 and the post-glacial climatic optimum culminating 9000 years B.P., when Greenland was warmer than ever since. Around 200 m depth a trace of The Little Ice Age AD 1300-1900 is found.

And most interesting: Below 1300 m depth lie remains of the long and extremely cold glaciation. The bedrock temperature -13 °C is still no less than 8 °C "too cold" more than 11,000 years after the termination of the glaciation.

A more advanced modelling showed subsequently [ref.13.13] that the 8 °C suggests a mean ice cap surface temperature at the glacial maximum 24 °C below the present one. Ocean sediment cores have shown that the *global* surface temperature was then only 6 °C lower than now.

In the 1990's application of the so-called Monte Carlo method choosing among numerous physically possible temporal temperature trends the one that fits the measured temperature profile best, cp. the dotted curve in Fig. 11.2 [ref.11.4]. The Little Ice Age, the medieval warmth, and the general cooling since 4000 yrs B.P. stand out clearly, but further back in time the decreasing resolution blurs the picture. The method is independent of ice flow and indirect climate parameters (like δ!), but it disregards surface elevation changes.

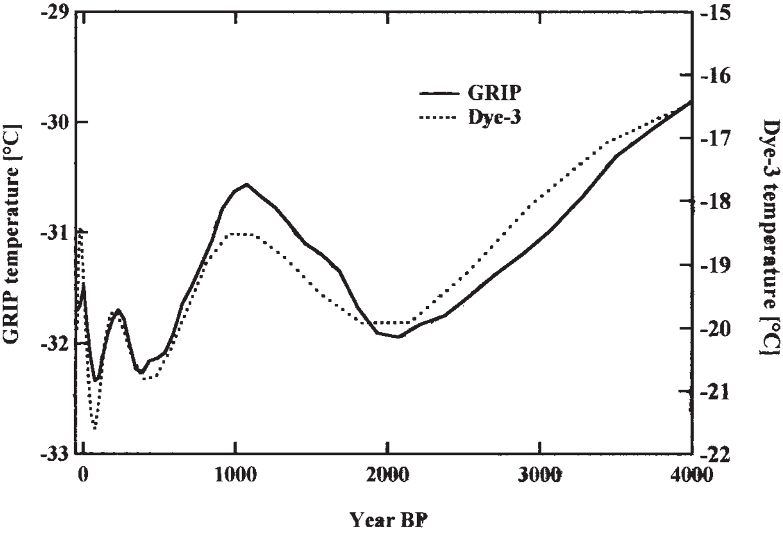

Fig. 11.2 *Surface temperature record for Dye 3 and Summit (GRIP) calculated from the measured temperature profile by the so-called Monte Carlo method The general cooling since 4000 yrs B.P., the medieval warmth, the Little Ice Age, and the warming in the 20'th century stand out clearly. After Dahl-Jensen and Mosegaard.*

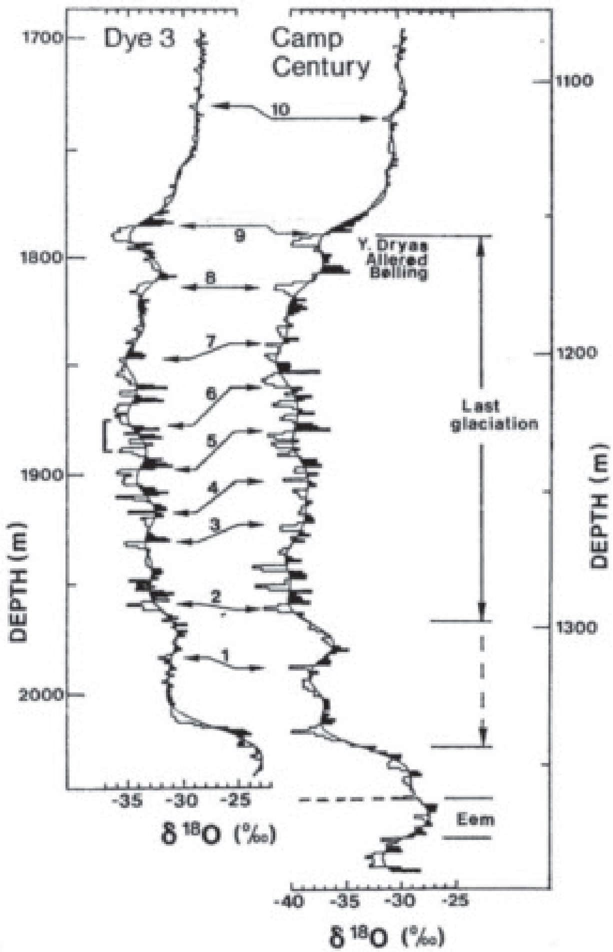

Fig. 11.3 *δ-profiles along the deepest, 300 m, of the surface to bedrock ice cores from Dye*

Ice core analyses

The high activity in the Dye 3 science trench ended in a wealth of data: Continuous profiles of δO^{18} (61,000 samples were cut and packed individually only for this purpose [ref. 11.5]), of electric conductivity, and dust concentration. Our American colleagues studied the chemistry and the crystal structure [ref. 11.6-7]. The Swiss developed a new ice dating method based on the radioactive $^{36}Cl/^{10}Be$ ratio [ref.11.8], and they further demonstrated that the hydrogen peroxide concentration varies seasonally [ref.11.9] and may thus be used as an additional way of annual layer identification, which is not straight forward in this area despite the high annual accumulation. Frequent summer melting causes meltwater seeping down and refreezing at deeper strata.

The mountainous bedrock topography was reflected in a modified undulating surface topography upstream, which complicated the surface accumulation pattern and thereby the medium range δ record. In spite of many supplementary shallow drillings upstream, it was not possible to reproduce the Camp Century δ record over the last few thousand years.

Box 11.1 Is the layer sequence disarranged? *Are the δ leaps e.g. a consequence of two completely different kinds of ice being pushed in between each other? The answer is No considering the complete correspondence between the Dye 3 and Camp Century cores from localities of quite different ice flow pattern, cf. Fig. 11.3.*

Is the time scale discontinuous? *Could it be that the accumulation essentially ceased all over Greenland in very cold periods and was only resumed, when the climate became humid and mild again with high δ-values in the precipitation? If so, one should also find leaps in other climate dependant parameters, for example the fall-out of dust, which is generally high in cold, and low in mild periods.*

On the right hand side of Fig. *11.4 the δ-leap at depth 1867½ m is shown in fine detail along with the dust concentration in the same 2 m of ice core. The dust concentration obviously began decreasing long before the δ-jump occurred, and there is no extremely high dust values suggesting a "hole" in the time scale.*

Fig. 11.3 shows δ-profiles along the deepest c.300 m, of the surface to bedrock ice cores from Dye 3 and Camp Century. The 10 double arrows point at common features suggesting layers of simultaneous deposition. Down to arrow No. 1 the two records are obviously similar indicating that the abrupt δ-shifts during late glacial time are outcomes of events common for the entire ice cap. Below arrow No. 1, however, the two records do not agree in detail. Probably, the Dye 3 core does not reach continuously as far back in time (90,000 years at most) as the Camp Century core, which is not surprising in view of the hilly bedrock upstream. The very deepest part may be of Eemian origin, though, i.e. from the last interglaciation some 125,000 years ago, but the stratigraphy is hardly undisturbed.

What caused the abrupt glacial δ-shifts? Two obvious, but less probable "explanations" are considered in Box 11.1.

The left part of Fig. 11.4 shows two typical δ shifts measured through 11½ m or ca.4000 years of the Dye 3 core deposited some 25,000-30,000 years ago. The two abrupt δ leaps correspond to temperature increases of 10-12 °C in less than a century. However, the subsequent cooling went off stepwise through much longer periods of the order of a millennium. The most plausible explanation of the frequent glacial climatic shifts was given mainly by Hans Oeschger and American scientists, W. Broecker and G. Bond [ref.11.10]. They suggest that somehow the North Atlantic Current (the Gulf Stream) was "switched on-and-off" synchronously with variations in the deep water formation in the North Atlantic Ocean. Sinking surface water (densified by cooling and evaporation) forms a southbound bottom current and drags tropical surface water northwards in the Gulf Stream. However, a layer of light fresh water would stop the sinking of surface water and thereby the Gulf Stream with evident and dramatic consequences for the climate.

Once in a while the great North American ice sheet had grown to a state of instability, and a partial collapse involved extrusion of enormous amounts of icebergs into the ocean, a fantastic natural disaster. The meltwater formed a layer

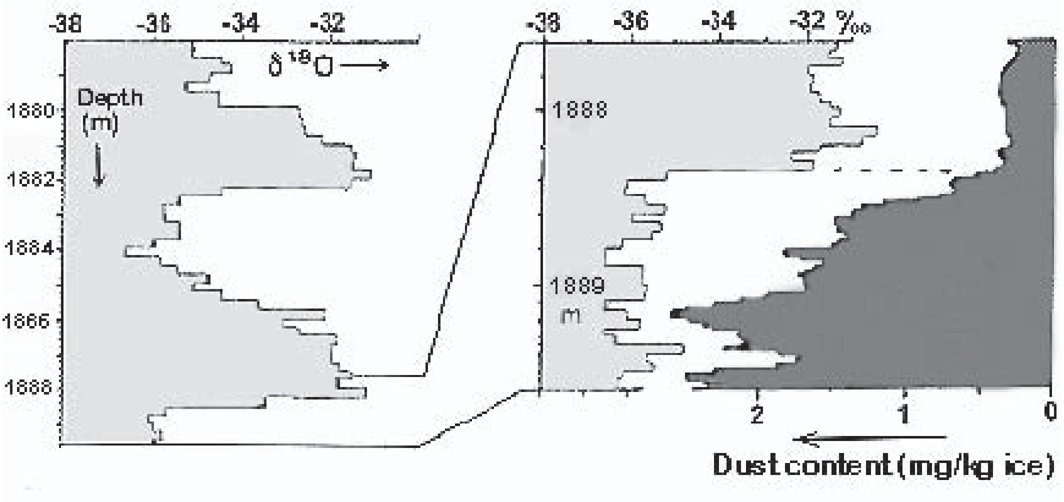

Fig. 11.4 *δ and dust concentration in the ice deposited during some of the great climatic shifts that characterized the coldest part of the glaciation.* ***On the left****: Two violent δ-oscillations measured along 11½ m ice core corresponding to 4000 years around 25 to 30.000 years ago. Each of the two abrupt δ-shifts correspond to 10-12 °C warming within less than a century.* ***On the right****: The eldest of the two is shown in detail and compared with the dust concentration changes in the same two metres of ice.*

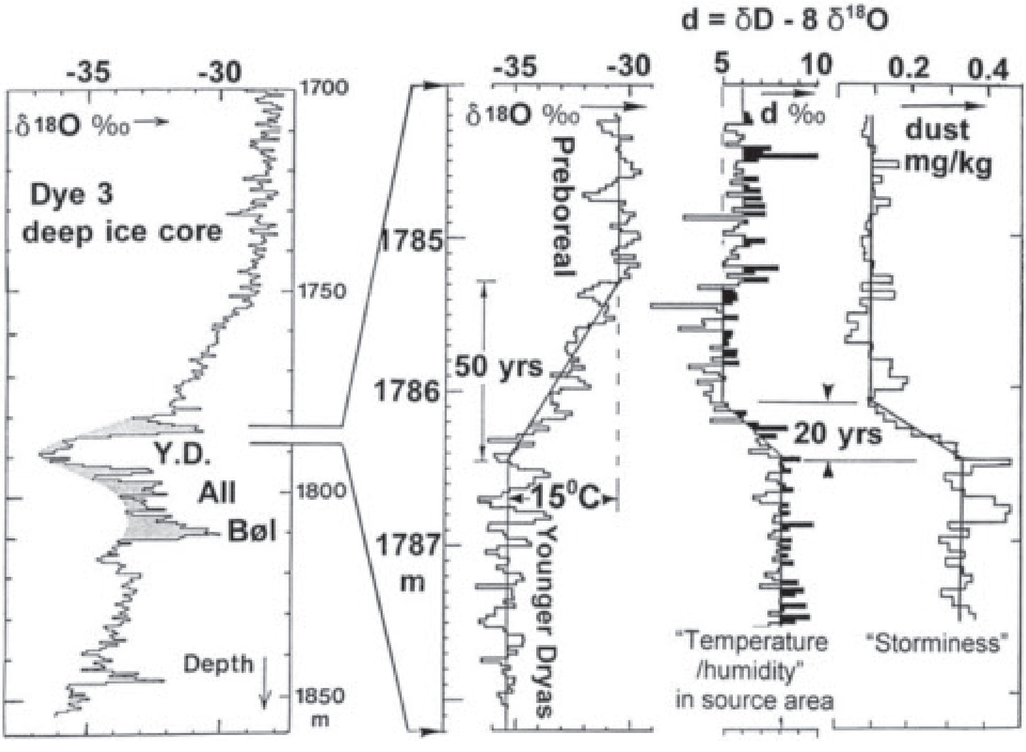

Fig. 11.5 *The section to the left shows the δ-profile along 150 m of the deep ice core from Dye 3. The 1700 to 1850 m depth interval spans most of the Pleistocene to Pre-Boreal transition, including the Bølling/Allerød – Younger Dryas oscillation.* **In the middle:** *Detailed δ-record through the Younger Dryas to Pre-Boreal transition, during which the South Greenland temperature increased by 15 °C in 50 years.* **To the right:** *Deuterium excess and dust concentration shifted to lower levels in less than 20 years.*

of fresh surface water stopping the Gulf Stream, and the silt they carried was deposited on the ocean floor.

The inland ice in Greenland has hardly been exposed to similar collapses. It is fed by high amounts of precipitation and protected against destructive melting by its high elevation (2/3 of the surface lies more than 2000 m above sea level). During the glaciation the edge ran 200 km west of the present coast line. And yet, Greenland was not completely covered by ice. The highest mountain peaks remained as uncovered nunataks (cf. Fig. 2.11), otherwise they had been ground and rounded like Norway's mountains were by the Scandinavian ice cap.

Box 11.2 Ocean sediment cores *contains chalk originating from microorganisms living in the sea water. The percentage of chalk is an index of the biological activity in the ocean at the time of deposition, and it varies in phase with the δ-shifts in the ice cores. Furthermore, several silty layers seem to correspond to δ-leaps in the ice cores, which is a strong support of the general idea behind the explanation [ref. 11.12]. On the face of it, one would expect that export of icebergs was followed by a sudden cooling, but the ice cores clearly register the abrupt events as warmings. Apparently, the build-up of the ice cover in the North Atlantic Ocean was a much slower process than the subsequent break-through of the Gulf Stream into the ice covered areas.*

The deuterium excess in the cold phases (8 ‰) was closer to present ice sheet values than in the mild phases (4 ‰). This indicates that the break-through of the Gulf Stream opened up for a new and cooler contributing source of vapour.

The end of the glaciation

Of the many glacial climatic leaps the last one is the most interesting, not just because it led to our own interglaciation, the Holocene, but also because it has been studied by a great variety of data within geology, biology, and geophysics. For example, the section to the left in Fig.11.5 shows the Dye 3 δ profile through the 1700 to 1850 m depth interval, corresponding to the 8,400 to 18,000 yr B.P. time interval. It comprises most of the termination of the glaciation in Greenland, including the last glacial climatic oscillation, Bølling/Allerød-Younger Dryas [ref.11.11].

During Bølling about 14,000 years ago (in northern Europe also the subsequent Allerød), the climate almost reached present day level. The Scandinavian ice sheet had then already retreated to the great Swedish lakes, and the sea level had risen from 130 to 40 m below present level. Subpolar animals and plants, even trees, invaded the uncovered land.

The subsequent Younger Dryas became really cold, however, a rebound to full glacial severity in Greenland. Only after 1000 years, at 11.5 kyr B.P., the final and great climatic improvement set in, cf. the middle section of Fig.11.5 showing the detailed δ record through the Younger Dryas to Pre-Boreal transition. Within 50 years Greenland became at least 7, perhaps 15 °C warmer.

During the Younger Dryas, the deuterium excess (Box 4.1) value d = 8 ‰ (cf. the right section) suggests a dominating moisture source in the subtropical part of the Atlantic Ocean, but simultaneously with the beginning of the warming the deuterium excess dropped temporarily from 8 to 5 ‰ within 20 years indicating the opening of an additional and colder moisture source, corresponding to an ice-free North Atlantic Ocean. Higher d values of 6 ‰ were gradually restored over the next 30 years as the North Atlantic Ocean warmed up, but the typical Holocene value of 8 ‰ was only reached considerably later.

According to the outer right section of Fig. 11.5 the dust concentration decreased in the same 20 year period by a factor of about 3, reaching values only twice the general Holocene background. This may also be explained by the retreat of the North Atlantic sea-ice cover, which established a wide belt of open sea water of intermediate temperatures in between the tropical and polar water masses. This reduced the latitudinal temperature and pressure gradients, and thereby the storminess, the atmospheric turbidity and the deposition of continental dust on the ice sheet. Later on, vegetation covered the loess areas south of the retreating American ice sheet, thus reducing an important dust source. The last remains of the American ice sheet disappeared about 6000 years ago, the Scandinavian one 2000 years earlier.

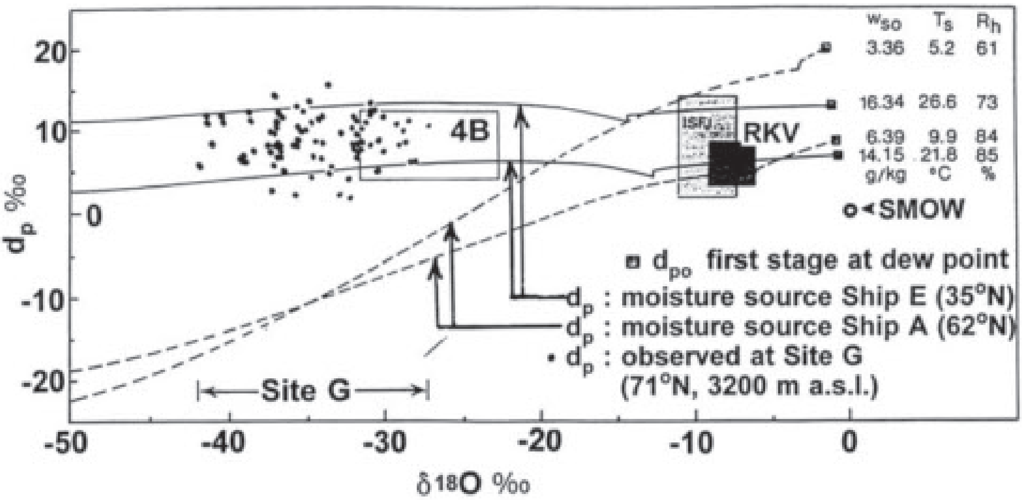

Fig. 11.6 *illustrates the model calculation (cf. Box 11.3) of deuterium excess* $\mathbf{d}_p$ *in precipitation from an air mass travelling from the source region of the vapour towards higher latitudes and altitudes.* $\mathbf{d}_{po}$ *is the deuterium excess in the first amount of condensate.* $\mathbf{w}_{so}$, $\mathbf{T}_s$ *and* $\mathbf{R}_h$ *are the initial mixing ratio (gram vapour per kg dry air) in an air mass giving off precipitation; the surface temperature in the source area of the moisture; and (unconventionally) the humidity of the air relative to air saturated at* T_s *respectively.* **The dashed and the full curves** *show* d_p *in precipitation from vapour evaporated from an Arctic and a subtropical sea surface, respectively.* **The two shaded rectangles** *frame the isotopic compositions of monthly IAEA samples collected from low altitudes at Reykjavik and Isfjord, Svalbard, respectively.* **The open rectangle 4B** *frames samples from station 4B close to Dye 3, 2700 m a.s.l., South Greenland.* **The dots** *refer to samples from Site G, 3100 m a.s.l., in Central Greenland.* **Conclusion:** *Most of Arctic precipitation at high altitudes comes from vapour of subtropical origin, whereas Arctic precipitation at low altitudes may be of local origin.*

The origin of Arctic precipitation

In 1989 we published a paper in Tellus on "The origin of Arctic precipitation under present and glacial conditions" [ref.11.13]. The basic parameter considered was the deuterium excess $d = \delta D - 8\ \delta O^{18}$. Comprehensive model calculations indicated that high altitude Arctic precipitation mainly comes from moisture of subtropical origin, both under present and glacial conditions. Furthermore, it was concluded that present Arctic precipitation at low altitudes may also be of local Arctic origin, cf. Fig. 11.6 and Box 11.3.

The end of GISP

The success of the Dye 3 operation was not followed up by a new GISP deep drilling in Central Greenland as implied in our agreement with Duwayne Anderson. A few years later, a new director of NSF-DPP felt that U.S.A. had gained too little from Dye 3. He claimed cryptically that "the scientific community in the States is not yet ready for a new deep drilling", which had to await "a series of ramp-up projects with the aim of defining exactly where to drill".

Hans Oeschger expressed concern that "ramp-up projects" could very well turn out to be "ramp-down projects", since the present experienced staffs might leave for other tasks, if the big one faded out of sight. I claimed that the radar survey and the shallow and intermediate drillings had already defined the best locality, Summit, with sufficient accuracy. Furthermore, we had proven that ISTUK could do the job.

However, the new DPP director created the myth about the Danes having got "a free ride". He asked for a review of direct Danish and Swiss financial contributions to GISP for comparison

Box 11.3 The deuterium excess model *was developed on the basis of the Rayleigh condensation / sublimation model, which implies immediate removal of condensate from the cloud, and no replacement by new moisture. The latter point presupposes the cloud be isolated from new sources of moisture en route, which may come about when a moist air mass glides up along a warmfront, or is lifted by a warmfront and a coldfront merging as a so-called occlusion at late stages of a low-pressure system.*

Due account was taken of kinetic effects during both evaporation of sea water and sublimation. The model predicts (1) that the initial mixing ratio w_{so} *(gram vapour per kilogram dry air in the air mass at the source area of the moisture) determines the slope of the d versus* δ *relationship at late stages of the precipitation process, and (2) that the sea surface temperature* T_s *in the source area of the moisture only influences the d-level.*

The generally high d-values in ice sheet precipitation are compatible only with high values of w_{so} *and* T_s*,which suggests the subtropical part of the North Atlantic Ocean as a dominating source for ice sheet precipitation. This is supported experimentally: when the model is run with monthly* w_{so} *and* T_s *mean values observed at the subtropical weather ship E (35°N, 48°W), it reproduces the high d-level, the amplitude of the seasonal d variations, and a few months phase difference between d and* δ *on the ice sheet. None of these features can be reproduced with a local, high-latitude moisture source area represented by weather ship A (62°N, 48°W).*

Ice core increments spanning several abrupt climatic shifts under glacial conditions show close to present d-values during the cold phases corresponding to a subtropical moisture source in the Gulf Stream, which was then displaced southward and deflected eastward. On the other hand, the generally 4 ‰ lower d values during the mild glacial phases suggest that a new contributory moisture source opened up by the retreat of the sea ice in the North Atlantic Ocean, cp the remarks on the Younger Dryas to Pre-Boreal transition on p. 95.

with the American ones, and he did not accept "internal means" being included, which simply revealed lack of knowledge about how things work abroad

In Denmark, several heavy expenses, such as wages for most Danish personnel involved; labour and materials in mechanic and electronic workshops; travel to conferences and meetings; overhead to the universities involved etc., were already included in the government's annual block grants to the universities – the so-called internal means.

The annual grant to a given university was distributed among its institutes by the governing body of the university itself, so all what "the winners" needed to seek from various governmental and private foundations was so-called external means covering extra expenses for a given project – in our case transport of personnel and goods to Greenland, purchase of Nansen sledges, snowmobiles, and special items for new drill and instrument developments, wages for student assistants, etc.

We tried to explain to the DPP-director that the internal means had to be included for a fair comparison, because many such items, e.g. "overhead", were included in the American budgets considered by DPP itself, but he did not understand it, or he did not want to.

In the following years a few minor expeditions to Central Greenland studied the surface topography, accumulation rates, etc. One year, Henrik Clausen and Sigfus Johnsen were supposed to drill shallow cores along a West-East line across the ice divide in Central Greenland. NSF-DPP put them in by an American Hercules, unfortunately 35 km too far West due to a navigation error. The snow conditions were unusually bad, so after having struggled through deep, loose snow up to the intended starting point, a good deal of their fuel for the snowmobiles was used, and they were unable to reach the intended end point east of the ice divide.

NSF-DPP did not allow PICO to fly in and drop the drum of fuel that could have saved the project. Without even notifying Copenhagen, NSF-DPP picked up our two men by Hercules. Thus, we were prevented from arranging a fuel drop by a Danish aircraft.

This was the second time DPP acted high-handed without even notifying Copenhagen, in this case even despite it was our team that was in trouble. I sent DPP a very strong letter of protest and was now convinced that we had to seek new partners. With Hans Oeschger's accept I conveyed this message via a program manager.

12. GRIP 1988-92

Our intention of seeking new partners did not affect NSF-DDP, obviously because it was considered infeasible, and indeed tough and protracted negotiations lay ahead of us before a European project was realized.

Box 12.1 Summit characteristics (cf. Fig.8.1, p. 69). *In 1986 we had sufficient information about the highest point of the inland ice, Summit: 72.59 °N, 37.64 °W; 3240 m above sea level; annual mean air temperature -32 °C; essentially never surface melting; annual accumulation 23 cm ice equivalent; ice thickness rather more than 3000 m; bedrock relatively smooth, but slightly sloping; and according to model calculations bedrock temperature well below the pressure melting point of ice (-2.4 °C), i.e. no ice movement at bedrock [ref. 12.1].*

Eurocore

Hans Oeschger had close connections to the French Laboratoire de Glaciologique et Géophysique de l'Environment at the University of Grenoble, but evidently wider European contributions were needed beyond what could be expected from the research councils in our three countries. In order to get going we applied the three national science foundations and the European Union for means for a short-sighted program that included drilling a 300 m ice core ("Eurocore") at Summit by Henry Rufli's intermediate drill and preparation for the deep drilling by ISTUK.

Eurocore was drilled in 1986. We dated it, the French did the chemistry, and the Swiss measured quite interesting profiles of hydrogen peroxide and nitrate. And most important: We demonstrated that we could co-operate.

The GRIP embryo

In parallel, the European Science Foundation (ESF) in Strasbourg worked on finding wide European support for the big project, now called GReenland Icecore Project (GRIP). ESF is an umbrella organisation for the research councils in the member states of the European Council. ESF itself has only got means for arranging meeting, but it does have close connections to the granting authorities in the member states, of course.

In November 1987 the European Council recommended its member states to join GRIP, and eight countries did: Belgium, Denmark, France, Germany, Great Britain, Iceland, Italy, and Switzerland, of which Denmark and Switzerland gave the highest contribution to the GRIP budget, 25 % each. Great Britain put one of British Antarctic Survey's Twin Otter aircraft with pilot and mechanic at our disposal through four field seasons.

When the financial side was agreed upon, people got busy in a couple of places: In Bruxelles the European Union jumped upon the gravy train at the eleventh hour with a fairly large contribution, though smaller that the Danish and the Swiss ones, which did not prevent the Italian manager being offended that the Union did not figure on top of the list of contributors. And in Washington "the scientific community" suddenly became "ready for a new deep drilling". After six long years of dragging out, the NSF-DPP director considered it necessary to quickly develop a new American deep drill.

At a meeting between scientists in Boston, arranged by the oceanographer Wallace Broecker, we agreed to recommend two deep drillings in the Summit area, an American and a European one. If placed close to each other we could do with one common air strip. However, the Americans chose a drill site 30 km west of Summit, where we sat heavily with ISTUK.

The double drilling with considerable distance from each other later proved to be extremely interesting. The American drilling project was called GISP 2.

The GRIP Operation Centre

GRIP's organisation and distribution of responsibilities was mapped out in 1988. Beyond the responsibility for the very drilling, the

Fig. 12.1 *After unloading 10 tons of goods, a chartered US Air Force Hercules takes off using jatoes.*

Danish group undertook the management of transport, communication, supplies, and erection and running the field camp at Summit, in other words all the activities handled by PICO on the American side. Our experience and our close relations to Danish and Greenlandic authorities made it most practical for GRIP that we undertook this colossal effort. But it had been infeasible without the efficient and dynamic Niels Gundestrup, who was made director of The GRIP Operation Centre (GOC) in Copenhagen and Sdr. Strømfjord (SFJ), 800 km SW of Summit.

The Americans called Niels Mr. GRIP, but he was not the only person indispensable to GRIP. Every autumn Niels went to U.S.A. and negotiated with US Air Force 109' TAG (Tactical Air Group) under the New York Air National Guard about Hercules air support for the coming season. We always got a fair deal with "the 109'th", 3500 $ per flight hour, or 14,000 $ for a flight to Summit and return. None of the European Hercules were usable due to lack of the extremely expensive skies.

In SFJ, two "Field Operation Managers" of GOC kept contact with the field camp via radio or satellite telex, they organized transport of cargo and people in and out of SFJ, and they loaded and unloaded aircraft in excellent cooperation with PICO.

The Summit field camp

At Summit, GOC excavated and covered a 30 m long laboratory with side galleries for special investigations. By a tunnel it was connected with a large excavation covered by a two-story hemispherical wooden dome, 7 m diameter. This is where ISTUK was installed. When turned into vertical position the upper part stuck up into the top floor, and the lower end went into a trench dug in the bottom floor like at Dye 3.

The advantage of the hemisphere shape is that the wind runs around it making the drift snow settle 3-4 m from the building. This is not a new invention. The Eskimoes have used it through millennia in their igloes.

Fig. 12.2 *The alley of flags leading from the air strip to the headquarters. The flags of the participating countries were democratically arranged in alphabetic order. In front that of Austria, although this country was not a member of GRIP. We had hired the cook in Austria, however, and it always pays keeping on good terms with a cook. Photo: Ivars Silis.*

Fig. 12.3 *Excavating the drill hall at Summit*

Fig. 12.4 *GRIP's headquarters in windy weather. Photo: Ivars Silis.*

Fig. 12.5 *The GRIP camp with tents, and in the background three domes.*

The other GRIP dome housed the main 65 kW generator. The waste energy was used partly for melting snow for the water supply, partly for heating the kitchen, messroom, toilet and bathroom. The upper floor was used as office, radio-room and sleeping room for a dozen persons. The rest of the crew slept in tents. The manning comprised up to 45 (m/w) scientists, students, technicians, physician, and two cooks. The tents were placed in a row perpendicular to the main wind direction, which minimized the piling up of snow.

At the end of the row of tents an air strip was marked out, 3 km long and 60 m wide. It had to be smoothed frequently for clods that would otherwise be dangerous for landing aircraft.

The science trench was filled up by new and old instruments further developed since the days of the Dye 3 operation.

Fig. 12.6 *Ice core studies on a production line in the sub-surface science trench.*

Fig. 12.7 *Dinner in the main building. Photo: J.P.Steffensen*

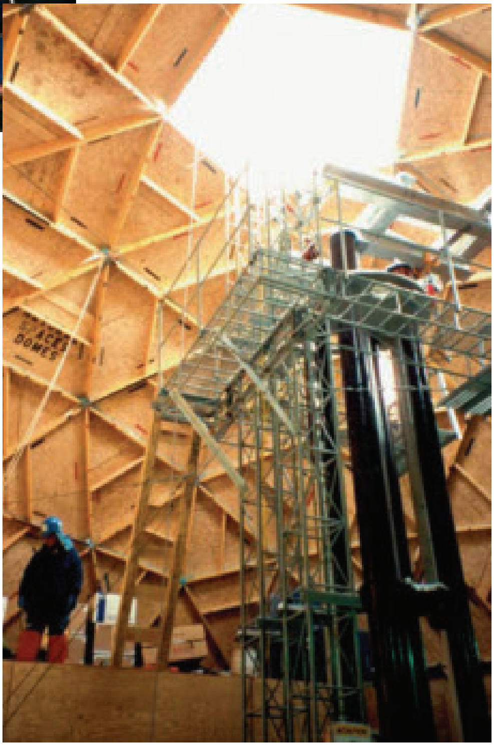

Fig. 12.8 *The American GISP2 drill towered 15 m above a hole in the ceiling of an enormous dome.*

The GRIP economy

Financially, GRIP got so well through the four planned field seasons that we could afford an extra follow-up season within the budget. Firstly, we were lucky that the dollar rate fell considerably, which made the biggest item on the budget, the air support much cheaper than anticipated. Secondly, we were lucky avoiding failing flight missions, where a Hercules had to return to Sdr. Strømfjord ("Sondy"), because the weather at Summit had worsened since departure. And thirdly, the two logistic organizations PICO and GOC both obtained great savings by sharing C-130 capacity. As a spin-off, close personal relations emerged by keeping in touch in hours of need and fun.

The GRIP economy did not pass off completely idyllic, however. From the beginning it was agreed that the due contributions should be payed into GOC's account each January. So they did, but for one, apparently owing to an overwhelming amount of red tape in the country concerned. Of course, we could not pay US Air Force with promises and assurances, so Niels overdrew the GOC account at the University that warned him that he, and ultimately probably I, would be held personally responsible. In spite of numerous written and oral reminders, nothing had happened after 16 months (!). Then we invited the chief of the department concerned to visit the GRIP camp accompanied by the Danish Minister of Research, Bertel Haarder. The lady accepted, and a few days before she arrived in Greenland the due contributions were deposited on our account.

Visitors

By the way, the lady got a lot of excitement for the money, as it became a rather dramatic tour. When landing at the American GISP 2 camp, the visibility was poor, and the pilot asked for a weather report. For unknown reasons he was given a wrong wind direction, so we landed across the skiway, and after an enormous bumping we stopped halfway to the North Pole. At least it took the Hercules 35 minutes taxiing back to the camp. The immediately following Hercules was even more unlucky. It was wrecked and lost a propeller.

In every respect, these VIP visits were successful. HRH Crown Prince Frederik, the French Minister of Research, his German and Danish colleagues, and the chairman of the Greenland Home Rule were all interested in what was going on, and somehow the weather always forced them to stay overnight, which only added to the excitement.

The GISP2 camp

I drove with Minister Bertel Haarder and Mrs. Birgitte by belt vehicle the 30 km westward to the American GISP 2 camp. On long distance we saw the gigantic dome, from the top of which the 30 m high drill tower stood out 15 m [ref.12.2]. We were received very kindly in a mess hall built on pillars that allowed the snow to drift away under the building, just like at Dye 3.

We saw the interesting and well equipped science trench and, dressed in plastic clothes and protective helmets, we entered the big drill hall. We were met by a bad pungent smell from the drill fluid dripping from the 30 m long drill that was just coming up from the drill hole. We were led under a shed just in time to escape a shower of drill fluid coming down from above.

The drill was handled from a two storeys scaffold (Fig.12.8), and the operators wore gas masks protecting them against the toxic fumes from the drill fluid, n-butyl acetate, which is harmful to the lungs. When leaving, we noted that it was also harmful to the plexiglass shield of a snowmobile parked at the exhaust from the drill hall (!). The fine core increment brought up from the deep had a diameter of 25 cm, i.e. a cross section more than 6 times larger than that of our ISTUK core. The whole plant seemed enormous and has certainly cost several times the cost of a new Camp Century drill

I think our Minister was impressed – by how little we needed for doing the same job. Incidentally, the co-operation with our American colleagues passed off quite well. The two teams visited each other occasionally. Sporting matches were arranged, and materials and reports exchanged.

A medivac

In one case the co-operation became a matter of life and death. In the 1991 field season, the GRIP field leader was woken 3 o'clock in the morning by an American colleague, who had driven the 30 km on a snow scooter in bad weather. A man in the GISP 2 camp suffered from the dangerous mountain sickness caused by the low pressure. He had to be evacuated as quickly as possible. The Americans could not call for help themselves due to a radio "black-out". The satellite telex in the GRIP camp was the only connection to the outside world.

A telex was sent to GOC in SFJ, but everybody slept. Niels' next step was sending a telex to Inmarsat in London that operates the satellite system. He explained the situation and asked London to continue calling the phone in the GOC office in SFJ till they got contact. They succeeded, and the initiative lay now with GOC. The problem was finding a ski-equipped aircraft for landing on the snow. An Icelandic Twin Otter stationed in East Greenland had just been provided with skies, but the radio black-out prevented contact. All international airliners were asked to inform the Twin Otter, when they got close enough. This did not help either. Apparently, the Otter crew had turned off the radio for the night. In stead a helicopter was sent off alerting the Twin Otter. After a quick refuelling in the nearest airport the Otter set out on a 560 km journey over the inland ice, in spite of worsening weather and insufficient navigation equipment.

Time was getting close to midday, and the situation in the GISP 2 camp was critical. The patient spitted blood, could hardly breathe, and the stock of oxygen was shrinking. He was put in a belt vehicle bumping along towards the GRIP camp. On the way they ran out of oxygen, at the same time as the Twin Otter could not find the GRIP camp.

Fortunately, there was a small Danish military JetStream aircraft in SFJ. It was sent off with new oxygen containers that were parachuted at the position of the vehicle. Then it guided the

Fig. 12.9 *During the terminal phase of the drilling, people crowded when ISTUK came up from the deep.*

Twin Otter to the GRIP airstrip, where it landed in visibility zero – an extremely dangerous manoeuvre.

But the vehicle with the patient had not yet arrived, so GRIP belt vehicles were sent off searching for it. It had been stuck due to blocking snow in the suction system. This was handled, however, and minutes after the patient arrived in the GRIP camp, the Twin Otter took off. Three hours later, and 24 hours after the alarm was raised the Otter landed in Jakobshavn. The normal air pressure made the patient able to leave the aircraft by himself, and he quickly restored to health at the hospital.

In order to avoid repetitions we bought an airtight plastic bag, big enough to contain a person and provided with a valve for pumping air in to normal pressure.

Events like the described unite people, and undoubtedly it contributed to the fine relations among the two camps. The heroes in the story were the two Icelandic pilots, and I wonder if U.S.A. ever honoured them with a medal for their deed.

Triumph

Otherwise, everything went on very well in the GRIP camp, an undramatic everyday life, including the primary task, the drilling. As a hole fluid we used again light jet-fuel, this time densified by the absolutely non-toxic freon. By far most of the freon will remain in the borehole for hundreds of thousand years. Nevertheless, we were not happy applying freon, because it destroys the ozone layer in the atmosphere. But careful considerations and experiments had proved that no other usable, non-toxic additive existed.

Fig. 12.10 *Drill master Sigfus Johnsen with the last ice core increment from a depth of 3029 m.*

In 1990 ISTUK started on July 1, and six weeks later it had drilled 710 m. In 1991 we reached 40,000 years old ice at a depth of 2320 m, and July 12, 1992, the drilling was brought to a full stop, when the cutters hit gravel and pebbles at bedrock 3029 m below surface – world record in ice core drilling.

Our American friends came up to congratulate us. It became a memorable party, outdoor dancing in a beautiful night, circling around a bonfire singing “Auld Lang Syne”.

13. GRIP RESULTS

Maybe I should have stopped telling the story at my retirement in 1992 and let my successors tell about the continuation, because they should be given full credit for the further accomplishments and therefore first right to tell about them. However, retirement brings plenty of time, and my curiosity made me follow the activities from the sidelines.

The results of GRIP were published in scientific and popular journals written by authors from all the GRIP member states. The subjects were multifarious: Logistics, temperature- and δ-profiles, firnification; stratification, physics and chemistry of the ice core; weather and temporal climate changes in the Summit area; shape of the bore hole, and detailed radar surveys. No less than 47 GRIP and GISP2 papers from the period 1989-1993 were collected in a book published by the American Geophysical Union [ref.13.1]. It comprises e.g. ice sheet development [13.2] chemistry [13.3], visual stratigraphy [13.4] textures and fabrics [13.5], air content [13.6], radioactive elements [13.7-9], aerosols [13.10], and biogenic species [13.11]. Several additional papers will be mentioned or summarized below.

The Danish main tasks were concerned with measuring and interpreting continuous profiles of δ, nitrate, acidity, and dust content along the ice core, and temperature along the borehole, as well as development of computer models of the mass balance back in time and the associated time scale along the ice core.

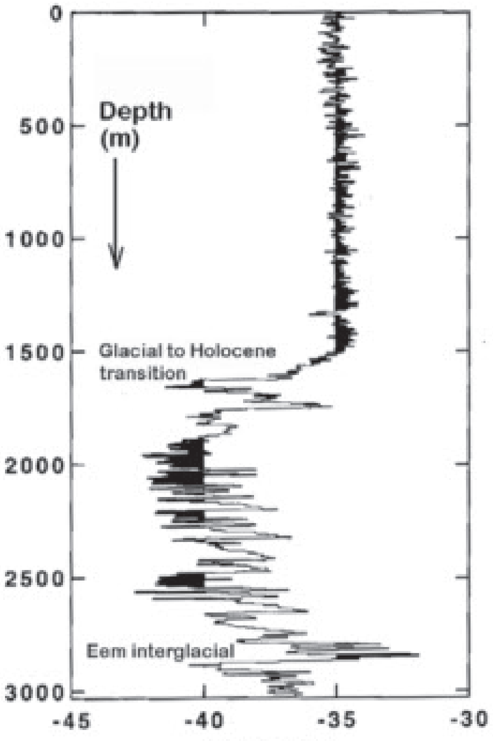

Fig. 13.1. *δ-profile along the GRIP ice core core. The wildly oscillating record from 1500 to c.2750 m depth reflects the turbulent glacial climate.*

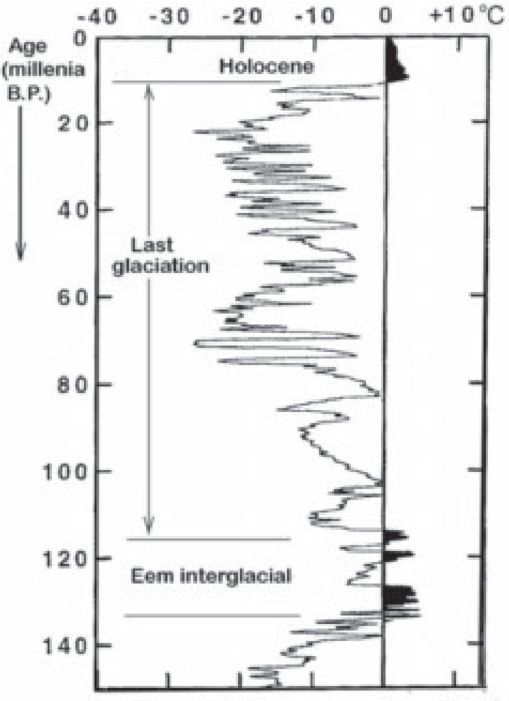

Fig. 13.2. *Calculated Greenland temperature deviations from present values through the last 150,000 years.*

Most of the δ profile (Fig. 13.1) broadly confirmed previous findings. Some of the conclusions may be summarized as follows:

1. The ice core probably reaches more than 150,000 years back in time, i.e. well into the second last glaciation (cf. Box 13.1 and Fig. 13.2).
2. Most of the last glaciation in Greenland (117 kyr to 11.5 kyr B.P.) carries stamp of great and abrupt climate changes, much more violent than in Europe and Antarctica. It was extremely cold about 22 and 70 kyr ago, when Greenland was 25 °C colder than now. In post-glacial time, i.e. the last 11.5 kyr the climate has been relatively stable disregarding a short lasting drastic cooling 8250 yrs ago. Roughly, the temperature in Greenland culminated about 9000 yrs ago with mean air temperatures 4 °C higher than at present, cf. Fig. 13.3.
3. According to our calculated time scale the interglaciation prior to the present one, the Eem period, lasted from 131 to 117 kyr B.P.
4. The climate record describes the Eem period as climatically unstable in Greenland with temperatures varying from 5 °C warmer to 5 °C colder than now, but there is strong evidence that the layer sequence in the deepest 10% of the ice core is disturbed. However, foraminifera records in sediment cores from the western part of the Norwegian Sea show similar trends.

All of the 24 violent glacial δ shifts appear in all of the long Greenland records. This shows that the mechanism behind them affected at least the entire northwestern part of the North Atlantic Ocean, as would be expected if they were caused by repeated surging of the North American ice sheet, cf. p. 93.

Note the controversially split Eemian period, the predecessor of our own warm period about 125,000 years ago. Did the Eem climate in Greenland really oscillate between 5° warmer and 5° colder than now? In Europe the climatic variability was less than in Greenland, during the glaciation as well as in the Eemian period. This schism is further discussed p. 108-110.

Box 13.1 The long-term climate record. *Fig. 13.1 shows the δ-profile plotted on a linear depth scale [ref.13.12]. In the upper half, i.e. down to a depth of 1500 m, our own interglaciation ("post-glacial" or Holocene) appears as a long sequence of nearly constant δ-values. In contrast, the lower half of the profile presents violently varying δ's.*

Before considering the climatic relevance of this δ-profile, the depth scale should be converted into a time scale, and the δ-scale into a temperature scale. Regarding the first problem, the GRIP time scale back to 14.5 kyr B.P. was established by counting annual layers downward from the surface, layers that were identified by seasonal variations of δ and/or acidity, nitrate, and dust concentrations. Beyond 14.5 kyr B.P. the time scale was based on an ice flow model accounting for snow accumulation changes in the past [ref.13.13].

The second task (converting δ to surface temperature) was carried through by a combined ice flow and heat transport model [ref.13.13]. The model was tuned so as to reproduce the measured temperature profile to a mean deviation of ± 0.03 °C from top to bedrock {ref.13.14]. Thereby some important, but non-measurable parameters were fixed, and the δ to surface temperature conversion was established by an equation that accounted for temporal changes of most other parameters that might influence the δ-values, e.g. changing ice thickness, sea level, isotopic composition of sea water, etc, cf. [ref.13.15-17].

The post-glacial period

Fig.13.3 depicts the last 20,000 years climate, including the termination of the glaciation in Greenland with the last glacial climatic oscillation, the Bølling/Allerød-Younger Dryas, which has already been discussed on p. 95.

About 9000 years ago the temperature in Greenland culminated at 4 °C warmer than today. Since then it has become slowly cooler with only one dramatic change of climate. This happened 8250 years ago as shown in detail to the left of the main record in Fig 13.3. In an otherwise warm period the temperature fell 7 °C within a decade, and it took 300 years to re-establish the warm climate. This event has also been demonstrated in European wooden ring series and in European bogs.

It should be noted that the whole change elapsed just opposite the course of events that characterized the great glacial oscillations with

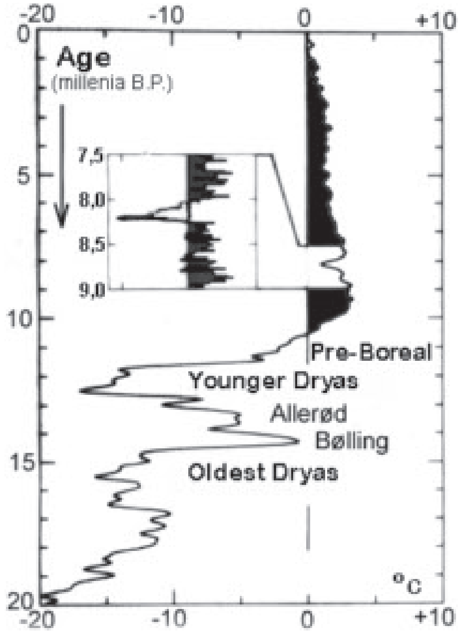

Fig. 13.3 *Calculated Greenland temperatures through the last 20,000 years smoothed by a 200 yr filter. The inserted part of the curve is not smoothed.*

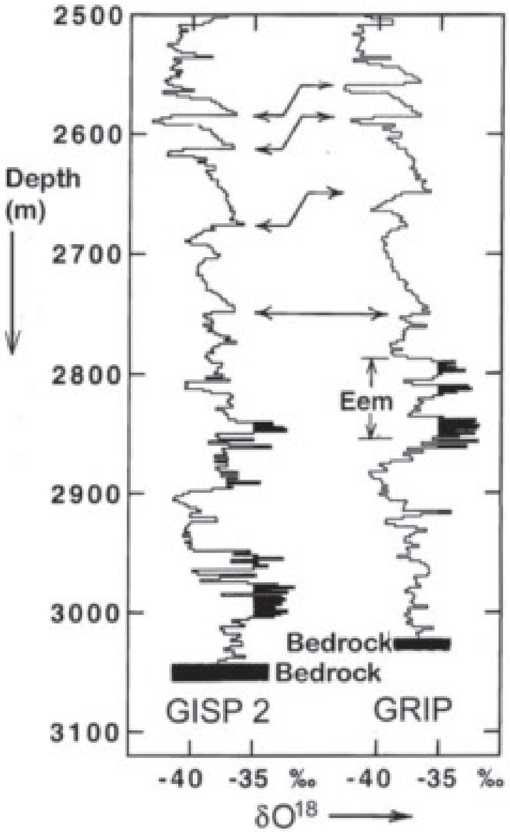

Fig. 13.4 *δ profiles along the deepest parts of the GRIP ice core (to the right) and the American GISP2 core (to the left). Down to a depth of 2750 m the two profiles are essentially identical, but they are different in ice from the Eem period. The layer sequence is disturbed in the GISP2 core. Is this also the case for the GRIP core?*

sudden warming followed by slow cooling. Therefore, the two phenomena hardly have the same cause.

Most probably, the temperature drop 8250 years ago was caused by a release of enormous amounts of dammed meltwater from the retreating American ice sheet. In no time the light fresh water spread over large parts of the North Atlantic Ocean without being able to sink. Thereby the influx of warm water with the Gulf Stream stopped causing a sudden cooling of large oceanic and adjacent continental areas.

Although no other dramatic climate events appears in post-glacial time, it should be born in mind that much smaller changes may have perceptible and even dramatic consequences for the environment and for human activity, particularly at high latitudes. Just think of the warming in the first half of the 20'th century, which brought great fish stocks to Greenland waters, and.the subsequent cooling that reversed the situation.

A tripartite Eem?

The Eem interglaciation is usually described as a warm and climatically stable period. It lasted from 131 to 117 kyr B.P. on our time scale. The sea level was 6-8 m higher than today, and a subtropical fauna invaded parts of Europe.

However, was the Eemian climate as unstable as suggested in Fig. 13.2? Or is the tripartition in the δ-record an artifact caused by the deep layers being disturbed by ice movements, for example by folding? The problem is important, because the course and termination of the Eem period are often used as a model for what might happen to our own interglaciation.

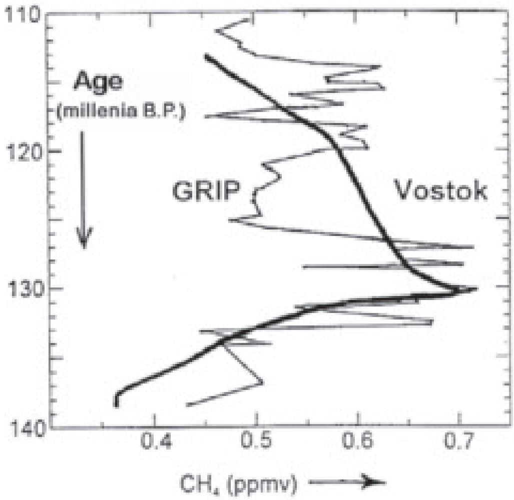

Fig. 13.5 *The atmospheric concentration of methane during the Eem period measured on the ice cores from Vostok, East Antarctica (heavy curve) and GRIP, Central Greenland (the thin, strongly varying curve). The two curves "ought to have" the same trends, because the atmosphere is well mixed any time.*

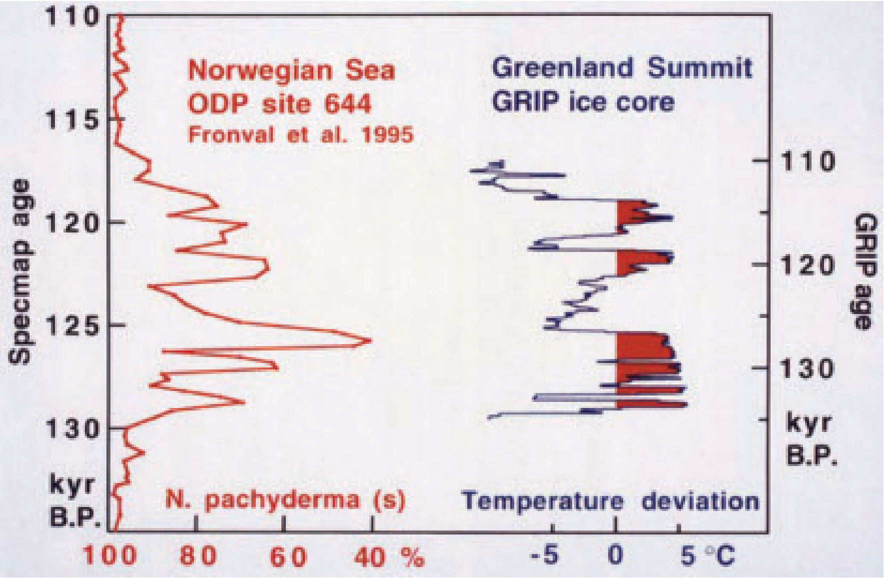

Fig. 13.6 ***On the left****: An ocean sediment core from the western part of the Norwegian Sea outlines the Eem as an unstable period, cf. the per cent occurrence of a foraminifera species (N pachyderma (s)) that thrives best in cold water. Note the reversed scale at the bottom (after Fronval et al.,1999)* ***On the right****: Greenland temperature deviations from present values calculated from the GRIP ice core δ record. Both of the time scales are given in millennia before present.*

The first doubt about the climatic relevance of the Eemian δ record arose when the Americans completed their GISP 2 drilling in 1993 and published their δ-profile the same year [ref.13.18]. It is shown to the left in Fig.13.4 for depth greater than 2700 m and compared with the GRIP profile to the right. 90 % of the two records are essentially identical. But the deepest 10 % are different.

It is generally agreed that the order of the strata are disturbed in the GISP2 core. But that does not necessarily mean that it is also disturbed in the GRIP core, which was drilled on the very Summit where no horizontal ice movement takes place, at least today. Furthermore, in the GRIP core the Eemian ice lies considerably higher above the bedrock than in the GISP2 core. And finally, large scale folding seems excluded, because it has not been possible to find the same layer occurring at two or more levels in the GRIP core, i.e. two layers of the same isotopic and chemical composition.

Nevertheless, incontestable indications of deep layer disturbances in the GRIP core emerged from a French comparison of the methane (CH_4) content in the GRIP and Vostok ice cores measured on the atmospheric air trapped in the bubbles [ref.13.19]. As shown in Fig.13.5 the methane content in Emian ice in the Antarctic Vostok core changes quite smoothly, whereas it changes in phase with the tripartite δ-record at Summit. Since the atmosphere is quite well mixed at any time, its methane content cannot have varied so differently at the two poles. Thus the high δ Eemian ice at Summit must have been exposed to a couple of inserts of low δ ice from a cold period with low methane content in the atmosphere [ref.13.20].

This conclusion does not make it easier to understand the evidence of instability of Emian "ocean climate"in the Norwegian Sea [ref.13.21]. Ocean sediment cores from this region exhibit a split Emian almost like δ in the Summit ice core (Fig. 13.6).

14. NORTH GRIP 1996-2003

The question was now: Is it possible to find a drill site where a deep ice core reveals undisturbed details of the course of climatic events through the entire Emian interglaciation? An apparently favourable location 320 km NNW of Summit, not far from North Site (Fig. 8.1, p. 69), was found on the basis of a detailed radar sounding carried out by the University of Kansas using a special NASA aircraft. The ice movement is very slow and the bedrock flat and horizontal.

Most of the internal reflection layers were recognizable all the way from Summit suggesting undisturbed stratification down to near the bedrock (Fig. 14.1). Furthermore, according to model calculations the glacial ice should lie approximately 100 m higher up from the bottom than at Summit [ref.14.1]. Apparently, it was the most favourable drill site in the northern Hemisphere.

In October 1995, a new consortium was established under the name of NorthGRIP (NGRIP) with Denmark as the main financial contributor. Considerable input was also provided mainly by Germany, but also Belgium, France, Great Britain, Iceland, Japan, Sweden, Switzerland, and U.S.A. contributed.

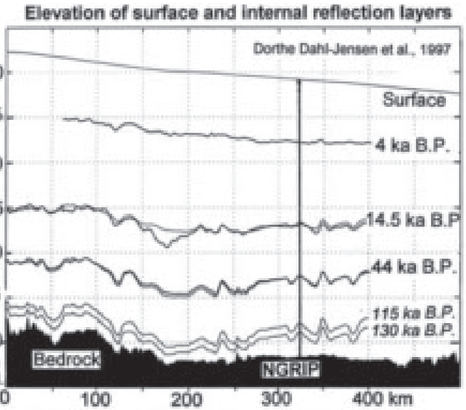

Fig. 14.1. *Vertical radar profile along a flight track closest possible along the ice ridge from Summit to the selected NGRIP drill site. The curves are internal reflection layers created by fall-out of acid volcanic debris, i.e. former surfaces and therefore isochrones. Detailed studies suggested undisturbed stratification in the entire ice mass. The Eemian ice seemed to lie 240 m above bedrock. After D. Dahl-Jensen et al.*

NGRIP got a muddled start, however, due to uncertainty as to where the future Greenland head quarters of the US Air Force would be.

The DEW line (the Dye stations) was closed already in 1988, but the US Air Force was still interested in operating out of Sdr. Strømfjord (SFJ) that offers easy access to the Dy 2 area for training purposes. An agreement, favourable for all parties, obliged GRIP and GISP2 to maintain the Dye 2 skiway in return for free "ferry flights" between USA and SFJ.

Late in 1992 the U.S. Air Force closed the SFJ Air Base, however. All buildings were handed over to the Greenland Home Rule, and in 1995 the Air Force transferred training activities to Thule Air Base and a new skiway prepared at Camp Century.

In view of the intended start of the NGRIP deep drilling early next year, Niels Gundestrup reacted quickly by sending many heavy items by ship to Thule. Late in 1995, however, the Air Force dropped Thule in favour of SFJ, so the rest of the NGRIP equipment was sent from Copenhagen to SFJ, which completed the confusion.

In May 1996, Dorthe Dahl-Jensen went to Thule, where the NGRIP cargo lay under a collapsed garage. Dorthe managed to dig it out by Herculean efforts, and in two days she sent 7 Hercules flights off with 70 tons to the selected NGRIP drill site. At the same time, an 8'th Hercules brought the GRIP bulldozer from the GISP2 camp, and three weeks later 6 Hercules flights with 64 tons from SFJ completed the deployment. Thereby, the tracks were laid out for a true international co-operation through several years. As in the previous GRIP projects at Dye 3 and Summit, the Danish group assumed the responsibility of the NorthGRIP drilling and the logistics organized and managed from offices in Copenhagen and SFJ. The financial matters and the scientific activities were discussed and coordinated by an international NGRIP Steering Committee.

Fig. 14.2 *The NorthGRIP camp August1996. Photo: J. P. Steffensen*

Each field season lasted scarcely three months, and during maximum activity the crew numbered up to 48 people, drillers, scientists, students, two cooks, a mechanic and a doctor. Some exchange took place when supplies were brought in by US Hercules aircraft. The pleasant atmosphere among the representatives of many nations was fed by social events like Saturday night parties with intensive dancing. As a field leader Niels Gundestrup always opened the dance by repeating his old favourite rock-and-roll melody ("One, two, three o'clock, rock –"), which the more advanced youngsters could not stand. Consequently the CD was stolen from him. But Niels would not be Niels, if he had failed making a copy!

At dinner time everybody joined in, except the drillers. In order to get silence for his speech on information and daily news Niels used a colossal squeeze-bulb horn. One evening some knave had put flour in the bulb, and the squeeze created a few indoor snowmen.

Several associated programs were operated in parallel to the drilling and they were all completed successfully, e.g. two radar programs run by the Alfred Wegener Institute, Bremerhaven, and the University of Kansas, respectively, a French meteorite study program, and a seismic observation program run by The Geological Survey of Denmark and Greenland (GEUS)

Myriads of data

In the year 2000, our old friend, Prof. Bernhard Stauffer, University of Bern, generously sent a newly developed multi-analysis instrument [ref.14.2] with operators to the NGRIP camp. With a resolution of c. 1 cm, it continuously measured nine different parameters, i.e. concentrations of ammonium, calcium, sodium, nitrate, sulphate, formaldehyde, hydrogen peroxide, and dust. A total of c. 150,000 such sets of data were obtained. To this should be added more than a million data sets of optical properties and acidity indicated by the electric surface conductivity.

The impressive yield of data was a result of up to 35 people working steadily in the science trench and their co-operation organized by Jørgen Peder Steffensen. Furthermore, a flood of samples were collected for subsequent investigations: 3500 filters for tephra analysis, and 60,000 ice samples for O^{18} (δ) measurements. This enormous number of data are still being treated, of course.

The NGRIP drilling

The main activity was the deep drilling, however, and in the years following 1995 it became a tough test on the patience, the generosity, and the wealth of ideas among the NGRIP partners, in particular the international drill team. The course of events is briefly described in Box 14.1, and further information may be looked for in the annual field reports issued by the Glaciological Department of the Niels Bohr Institute at the University of Copenhagen.

The year 2002 ended with a great loss, the grievous death of Niels Gundestrup, "Mr. GRIP". Through 32 years his good fellowship, his energy, commitment, negotiating skill and versatile inventiveness contributed considerably to the progress of Danish and international glaciology.

2003

This last field season was obviously fateful to NGRIP, in fact to European drilling in Greenland in a foreseeable future. In the light of previous drilling successes, the task was "just" to recover the remaining 80 m, but drilling in "warm" ice called for a new technique and a lot of dogged perseverance. The 2003 field season became a true thriller, because all sorts of jinx seemed to have conspired against NGRIP.

The camp was opened on May 16 by a crew of 14 pioneers (5 DK, 2 IS, 1 CH, 1 UK, 1 D, and a logging/radar team of 4 US). The air temperature was – 29 °C, but they were soon able to keep warm, because their first job was to manually move considerable amounts of snow that

Fig. 14.3

To the left: *The garage with the snow blower and the belt vehicles was buried under 4 m of snow.* ***Above***: *When free of snow the garage was moved to the top of an artificial hill. Photos: J.P. Steffensen.*

Box 14.1 Seven years of strain. *Several drills and hole fluids were applied with varying degree of success [ref.14.3].*

1996 *The "Rolls Royce" drilled to 100 m for casing and preparation of deep drilling. An 11 m long drill provided with an Archimedes spiral as a booster showed to be inefficient though. Total depth only 300 m.*

1997 *A new 11 m long drill developed by Sigfus Johnsen and Steffen Hansen was able to travel as fast as 1.4 m per second up and down the hole, and to recover 3.7 m long core increments. The spiral was replaced by a pump that removed the ice chips from the drill head. A depth of 1370 m was reached, but there the drill got stuck.*

Already in October the same year, an attempt was done to recover it. A "torpedo" filled with ice-dissolving glycol and with a bottom stopper of ice was sent downhole. The idea was that the glycol should only dissolve the stopper and thereby release the glycol, when the torpedo had reached the drill. Unfortunately, it did not work. The drill was lost.

The reason was probably that in stead of freon CFC, which was now internationally banned for its attack on atmospheric ozone, the less harmful Forane 141b was used as a densifier. It appeared, however, that it had a tendency to stick to the ice chips making them heavier than the hole fluid. Thus they stayed at the bottom and blocked the drill.

1999 *A full-sized copy of the 1997 drill, was installed. The Forane 141b densifier was replaced by a new one, Sukane 123, claimed to be free of sticking tendency. It was terribly expensive, however (Niels called it the "cognac densifier"), and at great depths it showed to behave like the old densifier.*

Therefore, all the hole fluid was exchanged by a fluid densified by Forane 141b as in 1997. But as a new procedure, every night was devoted to rinsing the hole for chips, and that worked. At the end of the season the drill had gone from 110 m to 1750 m below surface, world record for a three months field season.

2000 *As described below, this became the big science year. However, on the 12'th of July the drill got stuck at a depth of 2930 m, c. 150 m above bedrock. Niels Gundestrup ordered a couple of drums of chemically pure glycol from Copenhagen. It was sent by air via Sdr. Strømfjord and arrived at NGRIP after a good 24 hours.*

The freezing point of this glycol is -17 °C, and the idea was that frozen pieces of heavy "glycol-candy" should be dropped into the hole. As they sank, they would stay frozen and therefore inactive on the way downward, until they reached temperatures above -17 °C at c. 2600 m. From this depth they began to melt, and when they reached the wedged drill they were active dissolving ice close to and around it.

The splendid idea payed off. The drill got free, and it is being used these years in the highly successful European EPICA deep drilling projects at Dome C and Station Kohnen in East Antarctica.

2001 *At NGRIP, the big question was now: How do we continue the drilling from the greatly expanded bottom part of the drill hole? First of all, the considerable amount of glycol was removed by a special bailer. Next, an only 6 m long drill, first developed and used to penetrate the Hans Tavsen ice cap in 1995, was provided with a very large anti-torch section that got a grasp on the expanded hole wall.*

But the efficiency decreased rapidly from 1 m to less than 10 cm per run, probably because the ice was so close to the pressure melting point, -2.4 °C, that water seeping along the crystal boundaries or generated during drilling refroze on the cutter shoes.

The total outcome of the season was modest 70 m obtained by angelic patience. The drill got stuck no less than 5 times, but it was always released by the "candy dropping" method.

The drilling stopped at a depth of 3001.5 m, probably some 80 m above bedrock.

2002 *No drilling this year, but a lot of deliberations on how to core drill the deepest and very important layers. Would they reach into the Eemian interglaciation? And if so, how far? Obviously, future progress was conditional on another drilling technique being applied. Maybe an ethanol-water solution (EWS) should be added to the bottom part of the hole for dissolution of the disturbing water, and perhaps a thermo drill might be able to penetrate to bedrock. Fortunately, there was a general consensus among the NGRIP partners that it was worth while doing an attempt.*

Contact was established with a Russian colleague, Dr. Zavoronov, now guest researcher at the Ohio State University, which kindly offered to produce six specimens of a heating devise previously applied successfully by the Russians at Vostok had piled up since 2001, e.g the garage with the motorized snow blower was buried under 4 m of snow! Fortunately, all overwintering structures were in good condition, but the beams in the roof of the trenches were broken or bended, and later when the processors got tired of banging their heads on the roof in the science trench they simply lowered the floor.

Four days after the arrival of the pioneer crew they were supplemented by 6 people (1 DK, 1 IS, 1 D, 2 F, 1 B), and before long the associated programs were running. The first week of June brought high surface day time temperatures (c. -6 °C) and consequently bad take-off conditions for the aircraft, in one case a Hecules had to refuel at the GISP2 camp.

As soon as the Danish and US logging of the drill hole was completed, the first attempt was done to lower the Hans Tausen drill into the hole.

In the first week of July the drillers adjusted the cutters, the bottom valve of the chip chamber, and the amount and concentration of the EWS bomb in order to improve the performance of the drill. And really, that increased the lengths of the cores and the stability of the drilling sig-

Fig. 14.4. *A German Kässbohrer belt vehicle provided with radar antennas*

Fig. 14.5. *Only in early July, the drill came up with a well sized ice core in the core barrel. The cutter knives, are numbered 1, 2 and 3. Photo: Lars Berg Larsen.*

Box 14.2. The jinx' conspiracy. *The Hans Tausen drill went down to a depth of 2998 m, i.e. a few m above the bottom of the hole. It came up with the chip chamber and the core barrel full of slush refrozen during the hoisting through the upper cold part of the hole. At the same time the drilling was struck by the first case of bad luck: The inner core barrel was disengaged and left at the bottom of the hole, and it only came up after 40 hours of intense fishing with various tools. The total core production that week was – 19 cm!*

Next week a new heated tank brought down 60 litres of ethanol-water solution (EWS). After 8 runs with decreasing core length and increasing amount of slush, the Hans Tausen drill was replaced by the American thermo drill head mounted on the normal drill anti-torque section. However, for unknown reasons an electric short happened, whenever the melt heads entered the EWS at the bottom. The weekly production: 3.75 m.

The shortening in the melt heads could not be eliminated and it was decided to continue with the Hans Tausen drill modified so as to bring down EWS with the drill and dump EWS prior to the drilling.

After the first run it was discovered that one steel wire on the cable shield had broken at the tower during a core break. No excessive force was used, so it was concluded that the cable was simply worn out. It took 36 hours to replace the whole cable by a new one.

Afterwards, 10 runs produced a total of 2.33 m of core, before a new series of break downs occurred: A short in the anti-torque system and a break-down of the load cell electronics were quickly repaired, but it took almost a week to retrieve first a stainless steel screw lost in the hole, then a lost core catcher spring, the last item by a kind of "vacuum cleaner" constructed on the spot.

Fig. 14.6 *Dorthe Dahl-Jensen enjoying the sight of the last "core" of refrozen bottom water that came up in the next run. Photo: Lars Berg Larsen.*

nificantly. Cores longer than 1 m were now obtained routinely, which gave rise to great relief throughout the camp, of course. The production in the first and second week of July was 26.05 and 32.52 m, respectively.

After the break-through in the first half of July, the depth was 3070.5 m, making the core the longest one ever drilled in Greenland, a scientifically unimportant record, which nevertheless created a long overdue elated atmosphere in the camp. It was obvious that the drill was close to bedrock. Bets on the final depth were arranged, and outside the main building a "Bedrock Bar" was built. It soon became busy serving many visitors, including some from distant countries, e.g. New Zealand, Malaysia and Chile.

Wednesday July 16 no less than 12 distinguished visitors (7 DK, 2 GL, 3D, politicians, administrators and scientists) arrived in the camp together with 8 media representatives (3 GL, 2 D, 2 US, 1 NZ). The visit was highly successful, because next day these guests had a great experience.

After a normal run recovering 1.16 m of core a new drill team took over led by Sigfus

Fig. 14.7 *The entire NorthGRIP crew celebrating the big moment in the drill hall*

Johnsen. As soon as the drill came down again all electric circuits shortened, and the team got red faces. However, the drill came up with 30 cm of light brown refrozen water hanging from the drill head (Fig. 14.6). Evidently, the shortage was due to the drill being lowered into bottom water. Thus, bedrock was reached at a depth of 3085.0 m, and Sigfus was lucky being the first person to complete three deep ice core drillings to bedrock. The refrozen water was sawed off and carefully preserved. The rising surface of the hole fluid indicated that some 50 m of bottom water entered the hole.

The happy completion of 7 years of drilling called for a special celebration, of course, which continued Friday when the third flight mission brought another group of 15 visitors.

During this visit, a moment was spent in memory of Niels Gundestrup.

How far back?

A comprehensive joint scientific paper on the aspects of the multi-national accomplishment at NorthGRIP will be published in NATURE. Some important points have been conspicuous for several years, however. For example, it was obvious already in year 2000 that the annual layer thickness did not decrease as fast downward as predicted by ice flow models, showing that the ice core would not reach as far back in time as expected. However, the δ values (c. – 32 to -33 ‰) in the deepest 25 m of the NGRIP core are generally 2 ‰ higher than those characterising the warmest part of the present interglaciation (cp. Fig. 14.8 with Fig. 13.1). This shows that the NGRIP core at least reached into the last interglaciation, but how far?

This problem may be illuminated by comparison with δ analyses of planktonic foraminifera

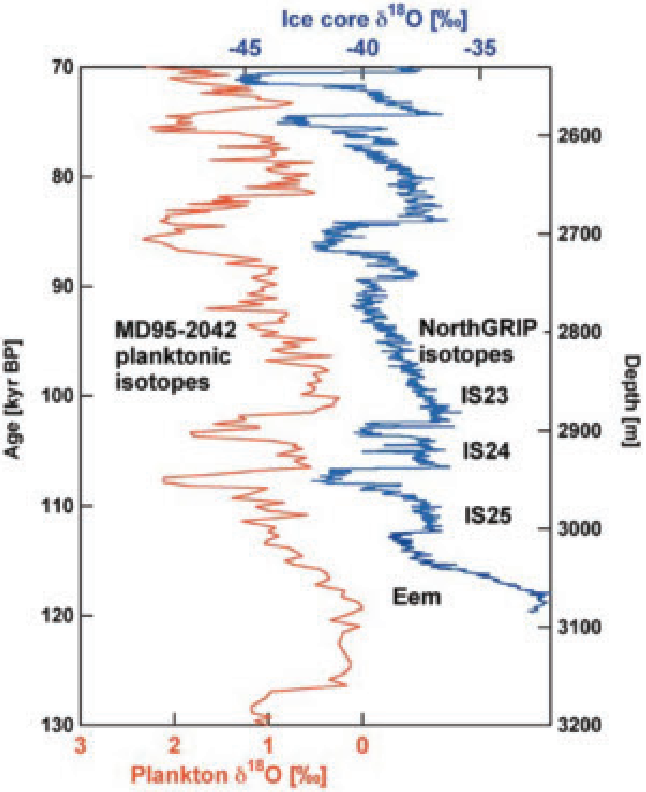

Fig. 14.8 *The NorthGRIP $\delta^{18}O$ profile (blue) over the deepest 550 m [ref.14.4] compared with a radiometrically dated profile of $\delta^{18}O$ (red) in planktonic foraminifera in an ocean sediment core (MD95-2042) from the Northeast Atlantic Ocean off Portugal [ref.14.5].*

along an ocean core off SW Portugal, which reveals a surprisingly close correlation with the glacial NGRIP δ record. In Fig. 14.8 the NGRIP δ record [ref.14.4] through the deepest 454 m is compared with the planktonic δ record through the period 130 to 70 kyrs B.P. dated by radiometric measurements on corals [ref.14.5]. Both of the records are plotted on linear scales (of depth and age, respectively), and the close correlation between them suggests that the ocean time scale may be transferred to the ice core record with some reservations concerning the variability of the accumulation rate at the two drill sites. For example, assuming a constant accumulation rate in the ocean, the relatively narrow minima in the ice core record suggest a lower accumulation rate on the ice sheet in cold periods than under interstadial conditions.

The correlation is astonishing, because it implies that the dramatic climate changes during the first more than 50 kyrs of the glaciation elapsed nearly in parallel on both sides of the North Atlantic Ocean, presumably controlled by varying sea ice cover. Thus, the Gulf Stream was not just deflected toward North Africa in cold periods, it was rather turned off.

The ocean record describes Eem as a non-split interglaciation lasting from c. 127 to 116 kyrs B.P., i.e. somewhat younger than estimates based on astronomical calibration. A comparative interpretation of the two records suggests that the deepest 25 m of the NGRIP core corresponds to the last small maximum in the Eemian part of the ocean record. If so, ice from the onset and the culmination of Eem has melted away, possibly when passing hot spots upstream from, or at the NGRIP position.

The transition from Eem to the first period of full glacial severity (MIS 5e to 5d in Fig. 6.2, p. 57) is described by the discontinuous decrease of δ from 3070 to 2960 m in the NGRIP core. It is tempting to parallel it with the δ decrease from 117 to 108 kyr B.P. in the ocean record, even the small ice core interstadial IS25 has a parallel in the form of a stillstand about 110 kyr B.P. in the ocean record.

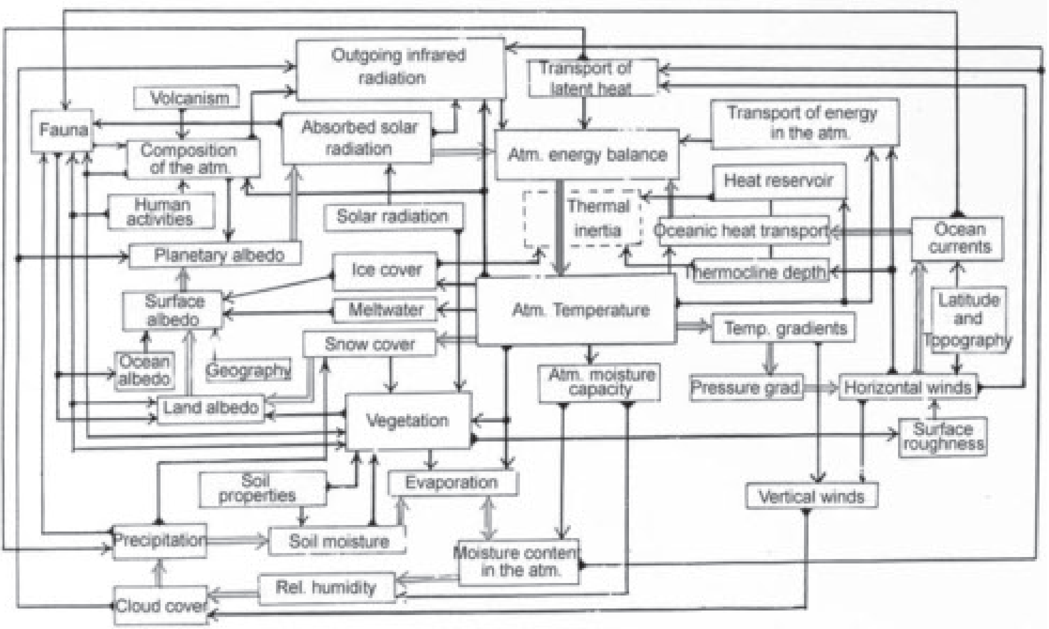

Fig. 14.9. *Block diagram showing the qualitative coherence of some parameters in the climate machine. Two cyclic processes of positive feedback are indicated by heavy arrows in the left hand side of the figure, and one of negative feedback by heavy arrows to the right. Atm. means atmosphere or atmospheric.*

Future climates

It is outside the scope of this book to go deeply into the numerous climate parameters and the processes that connect them, directly or indirectly, often by cyclic processes of positive or negative feedback mechanisms. Coupling all of this into a climate model able to calculate scenarios of the future climate is a task of wide perspectives, but also of overwhelming complexity (Fig. 14.9). Great efforts are being invested into solving the problem, and yet one cannot even be sure that the climate is predictable at all. If climate, like the weather, has a built-in element of chaos, the climate modellers may end up in the same hopeless predicament as a meteorologist trying to predict the weather more than two weeks ahead.

Only one of the climate parameters seems to be predictable, namely the latitudinal distribution of insolation (included, but not specified in Fig 14.9). It changes due to calculable variations of the Earth orbit (eccentricity and obliquity) and precession of the Earth axis. These so-called Milankowich effects are believed to be the main cause of secular climate changes, including the shifts between glacial and interglacial conditions [ref.14.6]. Fortunately, the Milankovich effects do not seem to threaten the stability of the present climate over the next several thousand years. But a profound understanding of the function of the climate machine is an absolute condition for calculating realistic short- and medium-term scenarios based on assumptions about the future release of greenhouse gases.

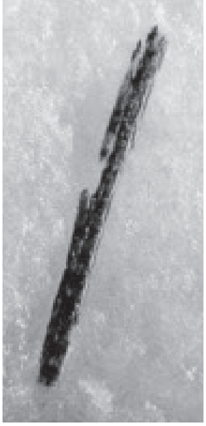

Fig. 14.10. *Here is the 1 cm long splinter of wood from a forrest that grew in North Greenland in a distant past. When analysed for DNA etc. the splinter ought to end up in the gallery.*

Frozen Annals

It was disappointing that the NGRIP core did not reach throughout the Eem. But it is an ill wind that blows nobody any good. The astonishing isotope correlation with the Portuguese ocean sediment core, the recovery of bottom water, and the slow thinning of the annual layers downward imply new information from glaciological, climatological and oceanographical points of view, and exciting perspectives for geological and biological research emerge from the recovery of the bottom water.

For example, transfer of the radiometrically derived ocean time scale to the NGRIP δ record shows that the mean annual ice layer thickness in the core is fairly constant of the order of 11 mm in the deepest 500 m! A modest improvement of the measuring resolution would therefore open the possibility of identifying the annual layers and thereby establishing an absolute time scale by counting the last perhaps 120,000 annual layers from surface. This implies, however, that the effective diffusion length (including the consequence of migrating water along crystal boundaries) of some seasonally varying parameter, e.g. the dust concentration, in the warm ice is less than 1 cm. If so, the transition from late Eem to the first cold glacial period (corresponding to Marine Isotope Stage 5d) may be precisely dated and studied in detail.

A 5-year grant from the Carlsberg Foundation has enabled a team of young and talented scientists, Katrine Krogh Andersen, Sune Rasmussen, Jørgen Peder Steffensen, and Anders Svensson, to look into such possibilities by studying the enormous stack of – frozen annals.

An encore

In the summer of 2004, the NGRIP drill hit bottom close to the "touch-down" point in 2003. No bottom water came up, but sensationally, a splinter of wood (Fig. 14.10) was found in the bottom water recovered in 2003 (Fig. 14.6).

How old is the splinter? 1 mio. years? 2 mio. years? Maybe we shall never know, but at least it is older than the Greenland Ice Sheet. And, in any case, it is a tidbit for the palaeo-botanists.

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Looking back to find the future

With a twinkle in his eye the author tells about miracles, cooking icebergs, and about drilling and analysing ice cores through the Polar ice sheets. The aim is to record the climate of the past thereby amplifying the climate scenarios of the future.