Further Investigations of the Greenland Ice Cap

By Børge Fristrup

In a paper by *B. Fristrup* (1959) the results of recent investigations of the Greenland ice cap were given, since then a number of expeditions have been working on the ice sheet, and important results regarding the geography and glaciology have been obtained. The present paper summarizes some of the latest achievements of the glaciological research concerning the Greenland ice cap.

Several expeditions have worked in Greenland. Among the most important are the expeditions organized by SIPRE (*U.S. Army Snow, Ice and Permafrost Research Establishment, Corps of Engineers*) from February 1961 CRREL *(U.S. Army Cold Regions Research and Engineering Laboratory)*, the work carried out by *Expedition Glaciologique Internationale au Groenland* (B. Fristrup (1961), *M. R. de Quervain* (1961)), and by *Arctic Institute of North America Greenland Expedition* 1958 *(D. C. Nutt* and *P. F. Scholander* (1961), *W. Dansgaard* (1961)). Papers summarizing the geographic information have been published by *Henri Bader* (1961), *Carl S. Benson* (1961, 1962), *M. Diamond* (1960), *B. Fristrup* (1963) and *R. W. Gerdel* (1961).

Accumulation and ablation studies

Snow investigations and pit studies have been carried out by U.S. military expeditions, and stratigraphic studies by *Carl S. Benson* (1962) have shown that the ice sheet can be treated as "a monomineralic rock formation, primarily metamorphic, but with sedimentary veneer of snow and firn". Based upon these studies four genetic facies are recognized: 1) the ablation facies, 2) the soaked facies, 3) the percolation facies, and 4) the dry snow facies. Analyses of density and permeability in connection with stratigraphic studies by *Carl S. Benson* (1962) and *R. W. Waterhouse* (1962) have made it possible to determine the annual accumulation. Such measurements were carried out by *Carl S. Benson* (1961, 1962) along a profile from Thule Air Base to Station Centrale and from here to the coast of Disko Bugt. Similar studies in North Greenland were made by *Chester C. Langway* (1961) and from southern and eastern parts of the ice cap by *R. H. Ragle* and *T. C. Davis* (1962). Based upon the new information the contour map of accumulation fig. 1 has been drawn.

Radiation measurements were made by *Walter Ambach* (1963) in connection with the *International Glaciological Expedition*. The radiation budget was determined, and radiation extinction measurements were made in ice and snow by means of a new technique. The heat balance of all energy contributions was determined. In case of an ice surface the energy excess was caused to 85 % by radiation exchange and was consumed to 92 % for melting the ice and 8 % for heating the ice. In case of snow-covered surface the energy excess was exclusively caused by radiation exchange where for heating and melting the ice 29 % and 71 % respectively of the excess energy are consumed.

Mass balance studies

Estimations of the mass budget for the whole ice sheet have been published during recent years. The first estimation by *F. Loewe* (1936) gave a budget essentially in equilibrium, while *A. Bauer* (1955) found a strongly negative budget. By recalculation and applying two corrections: the average annual accumulation value of 34 cm. water instead of 31 cm. water and a better determination of the relative areas of ablation and accumulation zone, *Carl S. Benson* (1961, 1962) confirmed the Loewe calculation as an equilibrium budget. According to *Henri Bader* (1961) the mean annual snow accumulation should be so high as 36.7 cm. water, and he found that "there were no doubt that the northern half of the ice sheet is gaining mass, while the southern half may be gaining or losing". For the whole ice cap Bader found an annual gain in mass of 120—270 km^3 water, but he admits, however, that the errors in estimating the mass budget parameters can be large, and in reality, according

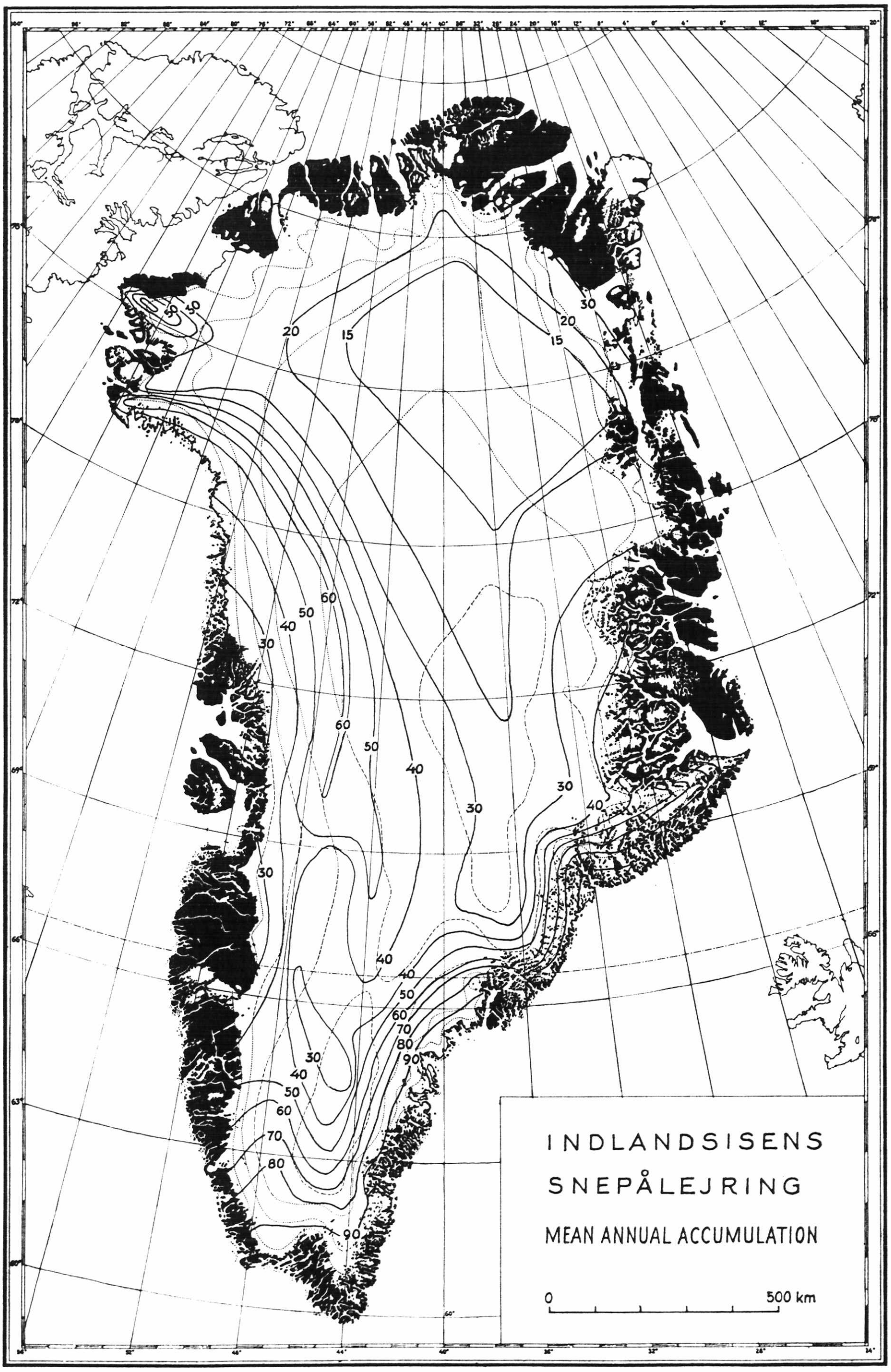

Fig. 1. Mean annual accumulation of snow in cm. of water equivalent. Based upon investigations and papers by *Carl S. Benson, R. W. Gerdel, H. Bader* and *C. Langway.*

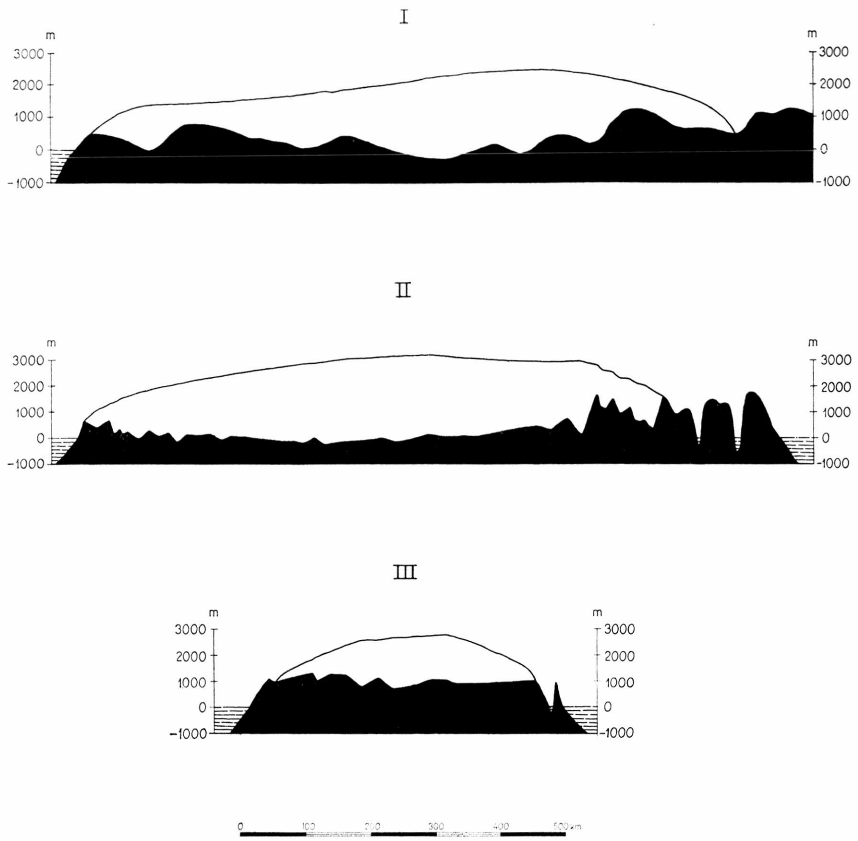

Fig. 2. 3 diagrams of the thickness of the ice cap. I. along a line from the Thule Air Base to Kap Georg Cohen. II. along the line from Disko Bugt over Station Centrale to Cecilia Nunatak. III. from I. A. D. Jensen Nunatakker to Skjoldungen. After *Jean-Jacques Holtzscherer*.

to *B. Fristrup* (1963), the errors in determining the ablation and the loss by iceberg calvings are so big that it is impossible to establish a balance calculation based upon the present information.

For solving this very important problem it is necessary to establish some profiles across the ice cap and measure accumulation and ablation for several years. The first profile was established 1959 by the *International Glaciological Expedition* with one line of markers across the ice cap from Disko Bugt to Cecilia Nunatak and another line north-south parallel with the coast from Umanak Bugt to Disko Bugt. The position of the markers was determined by trilateration with tellurometer by *W. Hofmann* (1961). Extension of the 7 metres high markers will take place in 1964 and resurveying is planned for 1965 or 1966.

Ice thickness

Diagrams of the ice thickness have been published by *Jean-Jacque Holtzscherer* (1954) based upon seismic soundings. Investigations have been carried out by the French Polar Expeditions south of 75° N and by British and American Expeditions in North Greenland between 78° and 80° N, but there is still a seismic unexplored region in the northern central part of the ice sheet. The results of Holtzscherer are given in diagram fig. 2. Seismic soundings and gravimetric measurements were made during the *International Glaciological Expedition* and gave a confirmation of the earlier French results. The profiles in central Greenland will only be insignificantly changed by incorporation of the recent thickness data, especially the difference in bedrock topography under the ice in East and West Greenland was confirmed (EGIG internal reports).

Age of the ice

Studies of the age of the ice from glacier fronts and recently discharged ice-bergs in West Greenland were made by *D. C. Nutt* and *P. F. Scholander* (1961), who found that of $Carbon^{14}$ datings of ice from 11 glaciers and among them some of the most productive glaciers in West Greenland, only two datings gave greater ages than 1000 years, and 3 samples were 100 years or less. These results were confirmed by 0^{18} studies by *W. Dansgaard* (1961, 1962). By measuring the 0^{18} content and relating it to the mean annual temperature on the ice cap, Dansgaard was able to demonstrate that all 11 samples were formed "at distances between 60 and 460 km. from the outlet glacier. Two of them came from more than 200 km. inland" and the average mean velocities of the ice movement were of the order of 150 m. per year. Much of the discharged ice, therefore, must have been moving in ice streams leaving the rest of the ice sheet and the deeper strata more or less stationary.

From a deep core drilling at Site 2 ice cores to a depth of 411 m. have been obtained. The age of the ice from these depths is about 1000 years as determined by *Chester C. Langway* (1962).

Formation and growth of the Greenland ice cap

During the pleistocene period the Greenland ice cap had a larger extent than at present. According to *David Ingle Smith* (1961) the ice tongue from Greenland never overforced the Ellesmere Island, and this island was glaciated by a local ice cap. The same has been the case in Peary Land as demonstrated by *William Davies* (1963). Con-

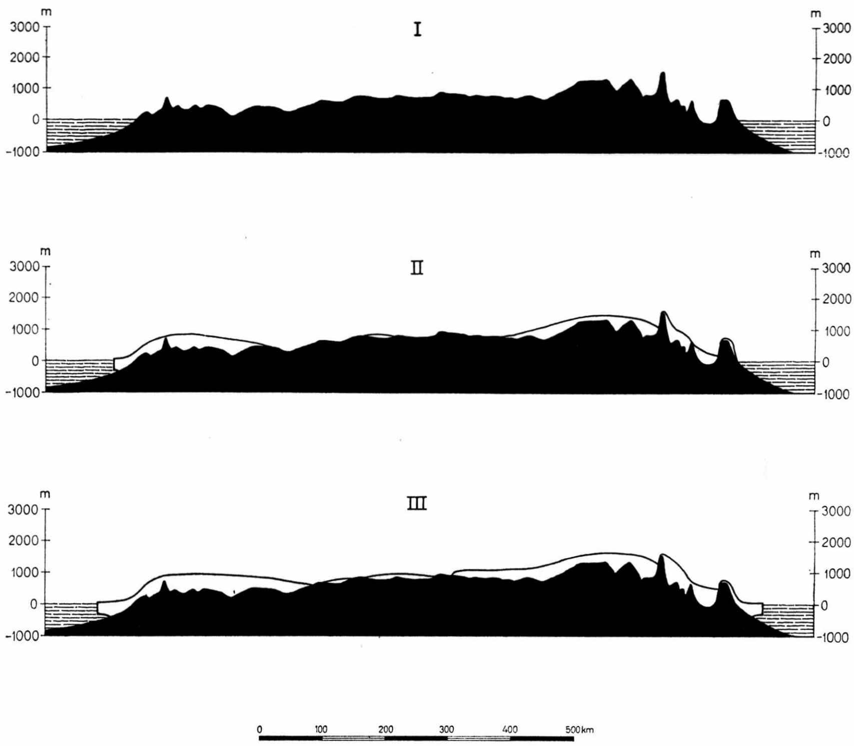

Fig. 3. Diagrams of the formation of the ice cap according to *B. Fristrup*, 1963. For details see the text p. 64—65.

trary to older conceptions it must now be considered confirmed that the Greenland ice cap has developed by increased growth of névés and glaciers on the mountains near the coast, and from here it has gradually extended down to the lowland for finally growing together and forming a single continued ice field above which only some nunatacs project. A diagram of the formations was given by *B. Fristrup* (1963) and here given as fig. 3 and 4.

During Tertiary none or very few glaciers existed in Greenland. A reconstruction of the preglacial topography is given in fig. 3 I after *C. B. Bull* (1958). When the climatic deterioration began, small glaciers and snow fields started to form on the higher mountains near the coast. The interior part of Greenland has been in precipitation lee of the mountains and most probably very arid. The growth of the glaciers has been fastest on the sea side and only slow on the land side, but at last small highland glaciers and glacier caps were formed in the inland of central Greenland. Because of the growth of the coastal glaciers the drainage of the central Greenland

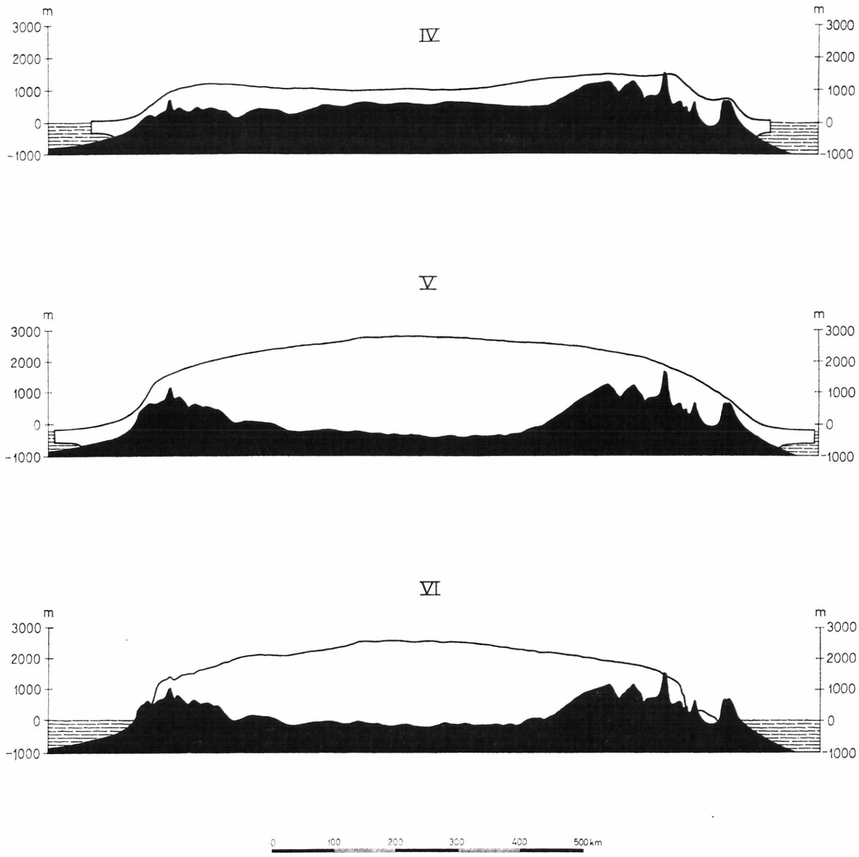

Fig. 4. Diagrams of the formation of the ice cap according to *B. Fristrup,* 1963. For details see text p. 64—65.

was hindered and a deterioration took place. Experience from Peary Land, *B. Fristrup* (1953), shows that even under extreme arid conditions surface icing of the ground and ice mounds can be formed during winter to big dimensions. Therefore, snow and ice fields started to grow in inner Greenland and finally merged together with the local glaciers in the marginal zone forming one single rather thin ice cap. With the increasing influence of the ice sheet upon the climate of Greenland the ice cap was being built up rather fast by some sort of autocatalyse. The southern part of the ice cap resting upon a highland must originally have been formed as a highland glaciation growing until it reached the rest of the ice cap. The load of the ice resulted in isostatic movements forcing the central part of Greenland down until the base of the ice sheet was below sea level, as fig. 4 V. With the amelioration of the climate again the ice cap started thinning out especially in the marginal zone, and also an isostatic rise has taken place up to the present stage in fig. 4 VI. In fig. 3 and 4 the eustatic changes of the sea level have been considered for the maximum extent of the glaciation only (fig. 4 V).

During the maximum glaciation the thickness of the ice has been different from the present extent, but how thick the ice has been at that time has been much discussed both among glaciologists and from a biological point of view of the interest of nunataks as refuges for plants and animals. *J. F. Nye* (1960) discussed the reactions of glaciers and ice sheets to climatic changes and especially the conditions for approaching a stable steady-state profile of the glacier. *J. Weertman* (1961) has studied the stability of ice-age ice caps and came to the conclusion that "a small arctic ice cap can become unstable and expand into a large ice-age sheet as a result of moderate changes in the regime of the ice cap. A large continental ice cap can also become unstable and shrink to nothing if the snow accumulation is reduced or the ablation rate increased". *R. Haefeli* (1961) had on the basis of Glen's flow law presented a theory for the stationary state motion of ice sheets, and for the Greenland ice cap he found that the calculated profile differed 1 % only from the actual measured profile, and he concludes on the basis of his theory that the height of the ice sheet is very insensitive to changes in accumulation. This is in good accordance with investigations of the ice margin features in the Julianehåb district made by *Anker Weidick* (1963), he has demonstrated that "the superficial conditions of the ice covering above an altitude of ab. 1700 m. do not seem to have altered much since the Tunugdliarfik stage", which means that although there has been great fluctuations of the marginal position of glacier fronts, there is only a very slight or no variations above the glaciation limit.

LITERATURE

Ambach, Walter (1963): Untersuchungen zum Energieumsatz in der Ablationszone des Grönländischen Inlandeises. Medd. om Grønland 174, No. 4.

Bader, Henri (1961): The Greenland Ice Sheet. Cold Regions Science and Engineering I, Vol. 2.

Bauer, A. (1955): The Balance of the Greenland Ice Sheet. Journ. of Glaciology 2, No. 17.

Benson, Carl S. (1961): Stratigraphic Studies in the Snow and Firn of the Greenland Ice Sheet. Folia Geogr. Danica IX.
– (1962): Stratigraphic Studies in the Snow and Firn of the Greenland Ice Sheet. SIPRE Research Report 70.
Bull, C. B. B. (1958): Discussion of the Geophysical Results. In R. A. Hamilton: Venture to the Arctic.
Dansgaard, W. (1961): The isotopic composition of natural waters with special reference to the Greenland ice cap. Medd. om Grønland 165, No. 2.
Davies, William E. (1963): Glacial Geology of Northern Greenland. Polarforschung Band V, Jahrg. 31 1/2.
Diamond, M. (1960): Air temperature and precipitation on the Greenland ice sheet. Journ. of Glaciology 3, No. 27.
Fristrup, Børge (1953): Winderosion within the Arctic Deserts. Geogr. Tidsskr. 52.
– (1961): The International Glaciological Expedition. Folia Geogr. Danica IX.
– (1963): Indlandsisen.
Gerdel, R. W. (1961): A Climatological Study of the Greenland Ice Sheet. Folia Geogr. Danica IX.
Haefeli, R. (1961): Contribution to the movement and the form of ice sheets in the Arctic and Antarctic. Journ. of Glaciology 3, No. 30.
Hofmann, Walther (1961): Tellurometer Measurements on the Greenland Ice Cap during the International Greenland Expedition (EGIG), Summer 1959. Folia Geogr. Danica IX.
Langway, Chester C. (1961): Accumulation and temperature on the inland ice of North Greenland, 1959. Journ. of Glaciology 3, No. 30.
– (1962): Some physical and chemical investigations of a 411 metres deep Greenland ice core and their relationship to accumulation. I. A. S. H. publication No. 58.
Loewe, F. (1936): Höhenverhältnisse und Massenhaushalt des Grönländischen Inlandeises. Gerlands Beiträge zur Geophysik 46, Hft. 3.
Nutt, D. C. and *Scholander, P. F.* (1961): Gases in Greenland Icebergs. Folia Geogr. Danica IX.
Nye, J. F. (1960): The response of glaciers and ice sheets to seasonal and climatic changes. Proceed. Royal Society Series A, Vol. 256.
de Quervain, M. R. (1961): On the Work carried out by the Group "Glaciology Indlandsis" of the International Glaciological Greenland Expedition 1959–60 (EGIG). Folia Geogr. Danica IX.
Ragle, R. H. and *Davis, T. C.* (1962): South Greenland traverses. Journ. of Glaciology 4, No. 31.
Smith, David Ingle (1961): The Glaciation of Northern Ellesmere Island. Folia Geogr. Danica IX.
Waterhouse, R. W. (1962): An analysis of density and permeability data from a snow profile. CRREL Research Report 90.
Weertman, J. (1961): Equilibrium profile of ice caps. Journ. of Glaciology 3, No. 30.
Weidick, Anker (1963): Ice margin features in the Julianehåb district, South Greenland. Medd. om Grønland 165, No. 3.