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DE DANSKE EXPEDITIONER TIL ØSTGRØNLAND 1926–39
Under Ledelse af Lauge Koch

APPENDIX No. 2

ON THE HYDROGRAPHY OF THE GREENLAND SEA

BY

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WITH 22 FIGURES IN THE TEXT
AND 3 PLATES

KØBENHAVN
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BIANCO LUNOS BOGTRYKKERI A/S
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CONTENTS

DELIMITATION AND EXPLORATION OF THE GREENLAND SEA AND THE NORWEGIAN SEA

The sea between Norway and Greenland and north of Iceland and the Faroes has in the course of time been called by many different names, determined in part by its position and natural conditions, but also in part by our knowledge of these waters.

The early whalers, who commenced their whale-fishery in this area about the year 1600, as a rule called it the Greenland Sea, because the ice, which was closely associated with the name of Greenland, was of such great importance to them. ZORGDRAGER, too, mostly uses that name in his book (1723), though on his map he calls it the North Sea, while the Atlantic is termed the Great North Sea. Even SCORESBY (1820) uses the name Greenland Sea. Later on we find names such as the North Atlantic, the North Ocean, or, divided into two areas, the Greenland Sea for the western part and the North Ocean or Norwegian Sea for the eastern part; all these names were used e.g. by H. MOHN (1887). Finally, some authors regard it as part of the Arctic Sea.

However, a close investigation of the nature of the sea soon shows that it is neither a part of the Atlantic nor of the Arctic Sea, but a separate sea area, which, however, falls naturally into two parts: the Greenland Sea west of the line Iceland—Jan Mayen—Spitsbergen and the Norwegian Sea east of that line. These terms are, as a rule, used in the recent literature and will be employed here also. In the recent geological literature the name "The Scandic Sea" has been introduced for the whole waterway between Norway and Greenland, but it has not yet gained ground in geographical and hydrographical quarters, and it is perhaps doubtful whether it will ever do so, for geographers, in contrast to geologists, consider it convenient to distinguish between the Greenland Sea and the Norwegian Sea.

From the Atlantic Ocean, with depths of up to 5000—8000 m, it is sharply separated by the Wyville-Thomson Ridge, which occurs at depths of up to c. 500 m only and extends from the Shetland Islands over the Faroes and Iceland to Greenland. On the northeast it is bounded by the line Nordkap—Bear Island—Spitsbergen as far as the shallow-watered Barents Sea, while northwards the Nansen Ridge, extending between Spitsbergen and the northeasternmost point of Greenland, forms the boundary towards the Polar Sea. Since, however, this ridge occurs at a depth of several hundred metres (cf. p. 24), the Greenland Sea is much more closely associated with the Polar Sea in the north than with the Atlantic Ocean in the south. Thus the Norwegian Sea and the Greenland Sea together with the Polar Sea form a mediterranean sea[1]), which, issuing from the Atlantic, extends between the two continents of the northern hemisphere: Eurasia and North America. This mediterranean sea covers an area of c. 14 million sq. km or one-sixth of the Atlantic.

The southeastern part of the Norwegian Sea was no doubt well-known to the population of Europe as far back as Antiquity, and the seafarers were, no doubt, familiar with the chief currents there, though Martin Frobisher (1578) is recorded in the literature as the first to notice the entrance of the Gulf Stream into the Norwegian Sea (R. Collison 1867, p. 232).

The Greenland Sea, however, on account of its inaccessibility, long remained a closed sea, a corner of the globe dreaded by navigators. As early as Roman times the idea prevailed that somewhere in the far north there was a deep abyss by which the sea was swallowed up at ebb-tide to pour out again at flood-tide, and since several exploration expeditions to the northern tracts were actually caught in violent circular movements, they were believed to have reached the edge of this abyss; in this way the theory became more and more firmly established. Thus for instance an expedition from Germany bound for the North Pole in the year 1040 was caught in the vortex north of Iceland; and till late in the 15th century this vortex and the abyss in the sea were indicated in this place on the maps by curved lines and formidable colours (J. G. Kohl 1869). Of course maps are also available from these regions on which the abyss is not indicated, but they are extremely defective and distorted. It was not till the whale-fishery began about the year 1600 that the great discoveries of new land took place and our knowledge of the Greenland Sea was increased. The vikings, as is well known, were familiar with the ice and strong southward-moving current of the Denmark Strait, as mentioned in the Kongs-Skugg-Sio (Speculum regale) from 1220—30; but Jan Mayen was not discovered till 1611 (or perhaps a little later), and Spitsbergen and Bear Island not

[1]) By a mediterranean sea we will denote a sea which extends between large land masses and which exhibits its own hydrographical features determined by its connection with the ocean as well as by the physical conditions of the surrounding land-masses.

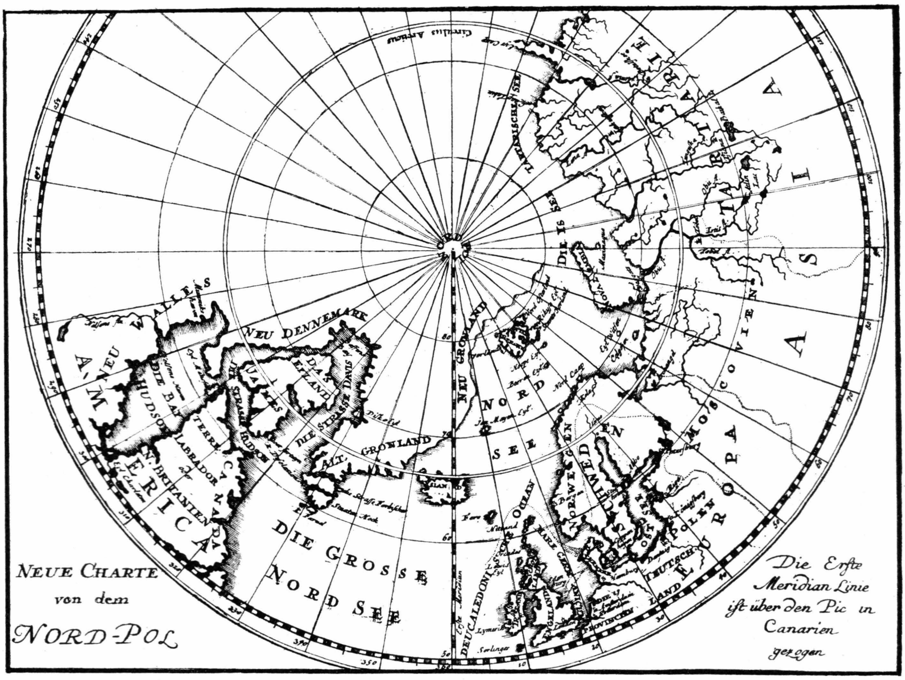

Fig. 1. Zorgdrager's map of the North Pole, 1723.

till 1596. The rocky shores of Greenland were sighted from a ship by Hudson in 1607 northward to 73° N. lat. and by Scoresby jun. in 1817 in 74—75° N. lat.

As appears from Zorgdrager's map from 1723 (Fig. 1), "Old Greenland" was assumed to continue northward and eastward, forming the northern limit of the Greenland Sea right across to Novaya Zemlya. This continuation, the so-called "New Greenland", was regarded as including all land areas in this part of the Arctic, originally also Spitsbergen, and it was unknown whether or not it was connected with Siberia.

The depths of the Greenland Sea were unknown by the whalers; but on observing the drift of the ice or wrecks or natural drift-wood, they could not avoid noticing the surface currents. Thus Zorgdrager describes not only the Atlantic current, which moves northeastward along the coasts of the British Isles and Norway into the White Sea, but also its continuation along Novaya Zemlya until it meets "Greenlandic America", when it swerves westward around Spitsbergen and onwards in a southwesterly direction to Kap Farvel and Davis Strait. As regards Spitsbergen, he further describes the southward movement of the current along the east side and its northward movement along the west side, after which it turns westward. It is doubtful, however, whether any importance should be attached to Zorndrager's assumption that at his time the currents moved twice as rapidly in nearly all navigable seas around Europe as fifty years previously (Zorgdrager p. 227).

Scoresby's map from 1820 (Fig. 2)—i. e. 100 years later—shows no essential improvements except that some outlines of the east coast of Greenland as far as 74° N. lat. are inserted. However, he indicates no northern limits to the Greenland Sea, but says that it extends as far northward as it is possible to push by ship. In his text he describes at length the ice conditions and currents of the sea; and the temperature and salinity, also, are discussed on the basis of his own as well as other observations. As regards the main currents, he adds nothing new to the picture given by Zorgdrager; but he has collected a fairly large material from the drift of various whalers, from which he finds that the current increases strongly in velocity on approaching the coast of Greenland (8—13 miles in twenty-four hours).

Of course he takes a great interest in the course of the ice edge and mentions at length "The Whale-fisher's Bight", through which the whalers even in the early summer months may push northward west of Spitsbergen. In this area he even made good hydrographical observations by means of his isolating water samplers of wood and brass and Six's thermometers, and found, quite correctly, that the temperature at a depth of 100—200 fathoms was 6°—7° F. (3°—4° C.) above the surface temperature. From this he draws the natural conclusion, in full agreement with the modern picture of the currents, that "it seems not improbable that the water below is a still farther extension of the Gulf Stream, which, on meeting with water near the ice lighter than itself, sinks below the surface, and becomes a counter under-current". But in addition he points out that this warm water also appears near the surface west of Spitsbergen, showing temperatures of 2°—3° C. even when the temperature of the air is several degrees below zero.

Thus Scoresby is the first to treat the hydrography of the Greenland Sea in a great work; but as early as 1773 Dr. Irving had made temperature observations near Spitsbergen down to considerable depths by means of the thermometer constructed in 1757 by Charles Cavendish, and thus ascertained that the temperature of the arctic seas does not decrease with the depth as in other seas (Joseph Prestwich 1876).

The first temperature registrations in deep water layers were made as early as 1749 by Captain Ellis northwest of Africa with an instrument devised by Dr. Hales.

W. A. Graah, in whose books of 1825 and 1832 the currents around southern Greenland are treated in great detail, draws entirely on the whalers as regards the Greenland Sea.

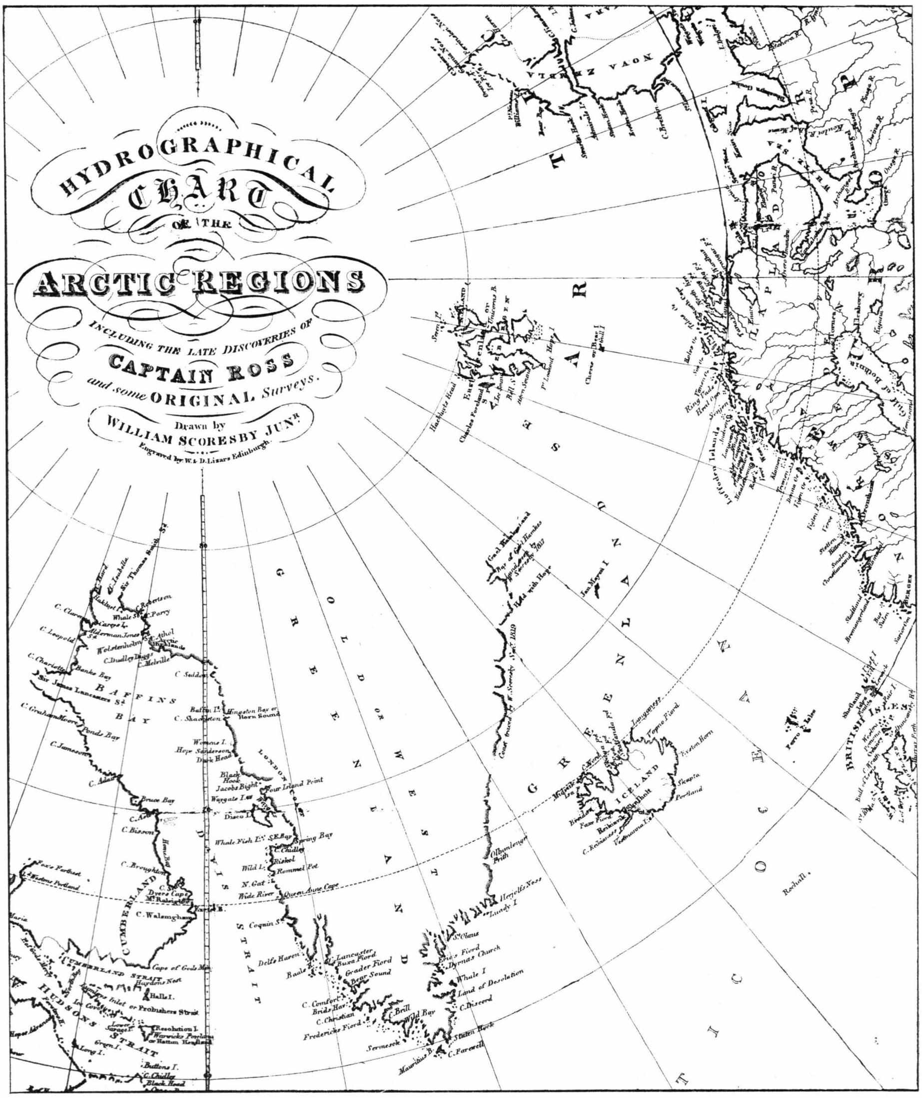

Fig. 2. W. Scoresby's map of the Arctic, 1820.

About the middle of the 19th century a great interest in the currents of the sea was displayed. A copious literature on this subject appeared, but as regards the Greenland seas C. Irminger deserves special mention. He described the warm current named after himself, which from Iceland bends westward and southwestward along the coast of southern Greenland; but he suggests, also, that part of it probably bends northward, passing through the Denmark Strait into the Greenland Sea (C. Irminger 1853); apart from this, however, he does not contribute to the hydrography of the Greenland Sea.

The papers by A. Petermann and A. Mühry (Pet. Mitt. 1865, 1867, 1870, A. Mühry 1869) date back to about the same period. Petermann's map of 1865 (Fig. 3) is based on a large and comprehensive material of observations, and it is the best chart from that period and better than many subsequent ones. He not only indicates the branches of the Gulf Stream along the west coast of Iceland and Spitsbergen, but he traces it even past the New Siberian Islands, where it had been observed as early as the beginning of the century. In this way he also shows that the East Greenland Polar Current forms the outlet of a large Polar sea and is not a local current associated with the whalers' delimited "Greenland Sea". The East Iceland Polar Current is indicated here for the first time. That he indicates Greenland as continuing across the North Pole almost as far as the Bering Strait, is due to the fact that large masses of drift-wood occur in the East Greenland current while nothing is found in Smith Sund.

Mühry received great credit for his theoretical studies; but since he did not utilise direct observations to the same extent as Petermann, his presentation of the currents is a step backward, though as to the Greenland Sea he follows Petermann in all essentials.

While all the descriptions of the Greenland Sea and the Norwegian Sea mentioned here are based on scattered and more or less casual observations, Mohn's great work on "The Norwegian North-Atlantic Expedition 1876—78" is a thorough and comprehensive treatment of all earlier results and of the large observation material collected on his expedition (H. Mohn 1887, Vol. 2). Thus the work gives the first physical treatment of the hydrography of this area of the sea and at the same time initiates the scientific and systematic exploration of the arctic seas.

Already at that time the east coast of Greenland was known in its main features except its northernmost part, where the sea is unnavigable, so Mohn supplies nothing new as to the delimitation of the Greenland Sea; but on the basis of the large number of measurements of depths made on his own expedition and a few of earlier date he prepared the first bathymetrical chart of the whole sea, a chart which is still unchallengable in its broad features.

Considering the not very perfect thermometers at his disposal, his temperature chart for different depths and the vertical temperature sections for the whole sea right down to the bottom are excellent; notably his temperature chart for depths of 100 fathoms provides an excellent picture of the currents in the upper water layers, and his vertical sections from the Shetland Islands northward to 78° N. lat. agree entirely with Nansen's sections from 1920 and Wüst's from 1942, drawn to prove that a formation of bottom water takes place between Jan Mayen and Spitsbergen.

Unfortunately MOHN did not consider the distribution of the temperature in his discussion of the course of the Atlantic and Polar currents; but in full agreement with the modern methods he computed dynamically the direction and velocity of the currents; however, here the data did not suffice. His chart of current surfaces (Fig. 4), similarly to recent

Fig. 3. Section of A. PETERMANN's map of the northern tracts. Pet. Mitt. 1865.

dynamic charts, shows the topography of the surface of the sea and the corresponding currents; but in contrast to the aforementioned temperature chart, this chart shows only the course of the main currents in broad features, while all details have disappeared, so it hardly means any progress from PETERMANN's or MÜHRY's charts. Finally, his methods of calculation probably result in too high current velocities.

In the accompanying text, however, MOHN mentions various facts which were not sufficiently well known previously. He mentions, for instance, that while the western part of the East Greenland Polar Current takes its rise in the interior of the Arctic Sea, its southeastern part in the farthest north is formed by water derived from the Atlantic branch that moves along the west side of Spitsbergen. He found the velocity of the Polar Current to be greatest near the ice edge—32 cm/sec. east of Jan Mayen—but only 4 cm/sec. close to the shores of Greenland. He further states that while the greater part of the current follows the coast of Greenland, moving southwestward through Denmark Strait, part of it continues directly southward to Iceland, where it moves along the north coast of the country towards the east and south, though with Atlantic water from the Irminger Current on its right side. This Iceland Polar Current does not pass across the ridge and into the Atlantic to any noteworthy extent, but bends eastward and northeastward again into the Norwegian Sea, where it makes itself felt as far as the Norwegian banks. Apart from the circumstance that Mohn shows the East Greenland Current to be so wide that it passes far beyond Jan Mayen, the picture outlined here agrees well with more recent investigations; and in his description of the currents that pass along Norway and around Bear Island and Spitsbergen he is in full agreement with the most recent maps. At one more point we must recognise Mohn's clear and correct conception of the hydrography of the Norwegian Sea, namely when he says (p. 189) that the bottom water is replaced by the surface water between Spitsbergen and Jan Mayen being cooled in the winter and sinking into the depths of the Norwegian Sea.

Thus Mohn's paper (1887) gives in the main a good and correct picture of the hydrography of the Norwegian Sea and the Greenland Sea. Only one important feature was not ascertained by him, viz. the Atlantic undercurrent below the East Greenland Polar Current demonstrated by C. Ryder in 1891, that is to say, the continuation of the current which, in the north, Mohn himself indicated as forming the southeastern part of the Greenland Current. Apart from this, the later investigations and treatments have merely resulted in corrections of details or supplementation, notably in the ice-filled areas.

A careful chronological review of the literature will not be continued here, for owing to the many details this would take us too far beyond the plan of the present work; only some of the most important facts relative to the later exploration of this area will be pointed out.

In 1891, as stated above, C. Ryder ascertained the presence of Atlantic water below the East Greenland Polar Current, and at once formed a correct idea of it, namely that it was a continuation of the warm current moving along the west coast of Spitsbergen. Since, however, in his northern section in c. 74° N. lat. he found the coldest water quite close to the shore, while farther southward he failed to find it in the corresponding place, he concluded that the main part of the East Greenland Current had bent southeastward through the Jan Mayen deep, while only a narrow and not very thick surface current continued southward through the Denmark Strait (C. Ryder 1895).

The large material of observations made by the "Ingolf" Expedition in the Icelandic waters in 1895 and 1896 was worked up by M. Knudsen in 1898; in this paper the correct relation between the two branches of the Irminger Current is also ascertained.

In the summer of 1900 G. Amdrup's (G. Amdrup 1902) and G. Kolthoff's (O. Pettersson and Hj. Östergren 1901) expeditions took

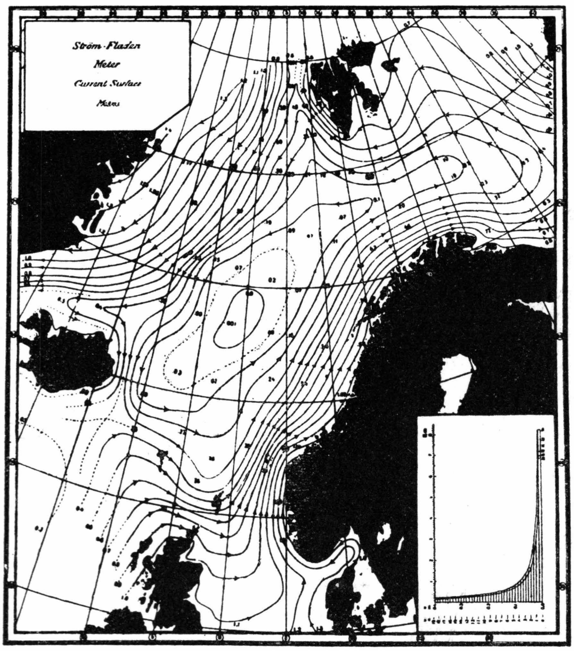

Fig. 4. The circulation of the Norwegian Sea as represented by Mohn (1887, Pl. XLIII).

some few stations off the east coast of Greenland; in both cases Ryder's observations as to the warm undercurrent are supported.

Ryder's idea as to the warm undercurrent was unfortunately opposed by Otto Pettersson, who at about the change of the century wrote a number of papers in which he especially propounds the theory of the importance of the melting ice for the currents and in this way to a fairly great extent goes into the question of the currents of the Greenland Sea[1]). As he worked very theoretically, and especially on the idea that the melting of the ice, as it were, sucked up the warm water, he arrived at his current map, which is reproduced here in Fig. 5. As usual, the East Greenland Current issues from the Polar Sea, moving

[1]) O. Petterson und G. Ekman 1898; O. Pettersson, Pet. Mitt. 1900; O. Pettersson, Ymer 1900; O. Pettersson 1908.

closely along the coast of Greenland; but in his text he expresses the opinion that by far the greater part of its water bends eastward, where its different ramifications make themselves felt far and wide. In the Norwegian Sea the Gulf Stream sends off no less than two branches westward towards the coast of Greenland below the Polar Current, for he could not imagine that the warm undercurrent could here have

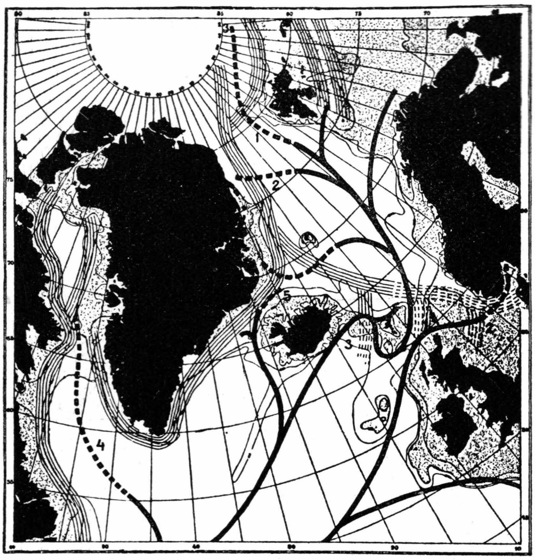

Fig. 5. The currents in the North Atlantic areas, after O. Pettersson 1900.

retained such a high temperature if it had first been so far northward as Spitsbergen.

In spite of Pettersson's clear map, which for some time was highly appreciated, Ryder's idea of a warm undercurrent was not shaken, and when Helland-Hansen and Nansen soon after issued their great works on the Norwegian Sea, Pettersson's map at once became obsolete.

About the year 1900 several important technical advances were made both in regard to the registration of the temperature and the determination of the salinity, for instance by the use of normal water, and these were immediately employed on the large-scale Norwegian expeditions in the following years. In this way hydrographers were enabled to work with greater accuracy and accordingly to place the main stress on the application of the physical laws.

In "Northern Waters" (1906) Nansen treats Amundsen's material from the "Gjøa" 1901 in connection with earlier observations. On the basis of determinations of the salinity he draws a more correct picture than had hitherto been given of the course of the main currents, especially between Jan Mayen and Spitsbergen. But his principal object was to prove the correctness of MOHN's assumption that the bottom water is formed by cooling of the surface water in the northern part of the area.

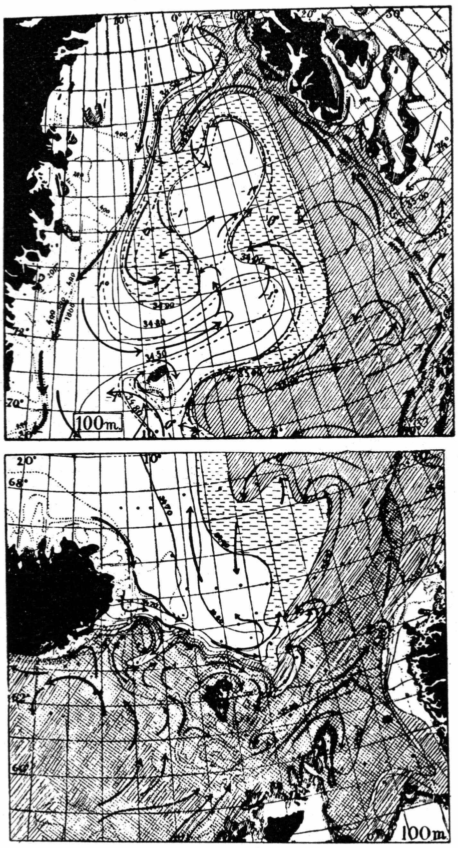

Fig. 6. The currents at a depth of 100 m in the Norwegian Sea and the Greenland Sea. After HELLAND-HANSEN and NANSEN, 1909.

And, indeed, in 73°—76° N. lat. the "Gjøa" found uniformly cold water from the uppermost layers to the bottom, or precisely such conditions as are required for the formation of bottom water. NANSEN goes very strongly against PETTERSSON. Whether this bottom water spreads from the Norwegian Sea to the Polar Sea, he does not venture to say positively, but he thinks the idea is tempting.

In their great work "The Norwegian Sea" (1909) HELLAND-HANSEN and NANSEN supply a very full and exhaustive treatment of the sea, and even at the present day it is the chief work dealing with the hydrography of the Norwegian Sea. Using all the available observations, and bringing together earlier theories as well as the results of new dynamic computations, the authors arrive at the picture of the currents which is reproduced here in the map in Fig. 6.

The authors deal especially with the cyclonic circulation in the middle of the sea. Southwest of Spitsbergen there is a distinct cyclonic vortex, where the warm water from Spitsbergen issues a branch towards the north and west around the colder water, viz. the area for the formation of bottom water, where the sea freezes up every winter, but the ice melts again in the summer. South of this point there is an approach to the formation of a minor whirl where the warm branch in c. 74° N. lat. is supposed to unite with the whalers' "Ice Bight", while the cold branch north of Jan Mayen is supposed to correspond to the "Isodden". The cyclonic circulation in the southern part of the sea is very irregular and is traceable far southward and eastward. Furthermore, the East Greenland Polar Current is seen, which in a place so far unexplored enters the Greenland Sea from the north, moving closely along the margin of the shelf, while smaller currents constantly branch off towards the east, the last one being the East Iceland Polar Current. In the text not only the character and mixture of the water masses are discussed, but also the velocity and water transport of the currents computed dynamically. Thus the work is fully up-to-date, and since it is largely based on observational data supplied by the "Michael Sars" and the "Belgica" after the year 1900, the results must be regarded as good, and the map is probably still the best available as regards the broad features of the paths of the currents.

Later expeditions have all been at work within fairly limited areas, and even though their observations have been of great value for the exploration of the Greenland Sea, they have been unable to alter the main features as represented by Helland-Hansen and Nansen in 1909.

Of questions which still await a solution mention must especially be made of the bathymetrical conditions and the course of the Polar Current in the extreme northern part of the Greenland Sea. The presence of the Nansen Ridge was ascertained indirectly by Nansen by his drifting across the Polar Sea and received support from some of Mohn's soundings as far as 100 miles northwest of Spitsbergen. Nansen estimated the greatest depth over the ridge to be 700—800 m; however, as will be mentioned below, recent observations and computations have rendered it probable that the greatest depth ranges between 1750 and 2000 m, and the whole ridge is situated a fairly great distance farther southward than originally assumed.

Furthermore, the position and extent of the Belgica Bank is still almost unknown, and on this account it is impossible to form even a fairly accurate picture of the course of the Polar Current north of 76—

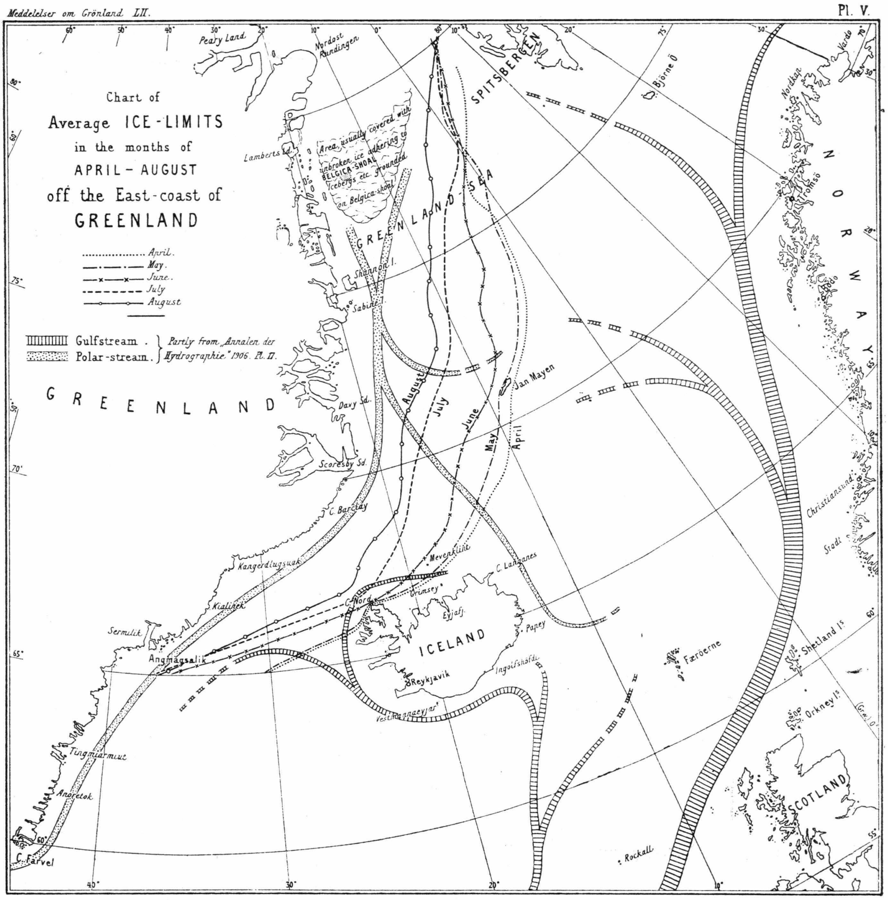

Fig. 7. Ejnar Mikkelsen's map of the currents in the Greenland Sea. Medd. om Grønl. 1922.

77° N. lat. On their map of 1909 Helland-Hansen and Nansen were so cautious as to draw only the main current above the margin of the shelf, that is to say, as far as 150 miles from the shore, and made no attempt at all to mark the weaker currents nearer the coast. Trolle (1913), also, indicates the main part of the current as following the margin of the shelf, but at the same time as spreading across the banks to their inner edge along an "imaginary line" extending from Nordost-rundingen to Shannon; inside this line comes the coast water with irregular, but weak currents.

Trolle's conception of the currents inside the shelf is strongly opposed by Ejnar Mikkelsen (1922), who on his current map, reproduced here in Fig. 7, indicates a branch of the Polar Current as coming from the north, moving along the inner side of the banks precisely where Trolle indicates calm land water; but if it were calm, Ejnar

MIKKELSEN says, the shore ice would spread over it, but this is not the case. MIKKELSEN assumes, however, that the Belgica Bank to the north extends much farther eastward than indicated by TROLLE, viz. as far as 2°—3° E. long.

On MIKKELSEN's map the ramifications of the Polar Current towards Jan Mayen and Iceland are indicated in accordance with the general conception, while those of the Gulf Stream terminate earlier than they should do.

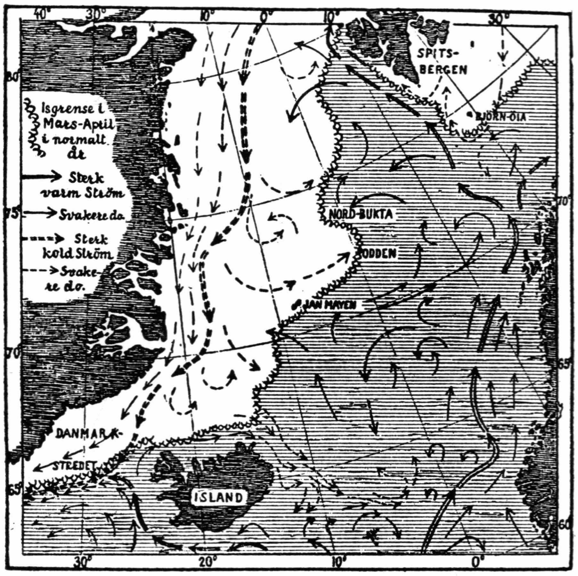

Fig. 8. NANSEN's map of the currents in the Norwegian Sea and the Greenland Sea and of the extension of the ice in March—April. (1924).

Of more recent descriptions of the currents in the Greenland Sea and the Norwegian Sea mention should be made of that by NANSEN of 1924 accompanied by the current map reproduced in Fig. 8. It is very similar to his and HELLAND-HANSEN's map of 1909, but here the weaker currents, also, above the Greenland shelf are suggested. He entirely ignores EJNAR MIKKELSEN's division of the Polar Current around the Belgica Bank, but on the whole does not discuss details regarding the current along the coast. The map has been prepared in order to show the agreement that exists between the currents and the distribution of the ice, especially the "Nord-bukta" and the "Odden".

In the twenties and thirties of the present century various expeditions collected minor series of observations from the coast regions and the fjords ("Godthaab" 1924, 1930, 1932, and 1933, "Veslekari" 1930, "Polarbjørn" 1931 and 1932); but they have secured no fresh results of importance[1]). Still RIIS-CARSTENSEN has made a dynamic investigation of the sea off the coast between 74° and 78° N. lat. on the basis of the most reliable of the available material. During this detailed investigation he found that the main current, in agreement with the earlier presentations, follows the margin of the shelf; but above the banks and in the shore water there are great irregularities owing to the configuration of the sea bottom. Notably it may be pointed out that he ascertained a northward-moving current in the shore water off Koldewey Ø, precisely as might be assumed from the ice drift, according to many observations.

JAKHELLN subjects the Norwegian stations from the Franz Josephs Fjord area to a careful dynamic investigation; but he also deals with the Greenland current as a whole, computing especially the total water transport in the different years.

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[1]) E. RIIS-CARSTENSEN 1938. G. THORSON 1934. R. SPÄRCK 1933. A. JAKHELLN 1936.

THE HYDROGRAPHY OF THE GREENLAND SEA

Since the Norwegian Sea and the Greenland Sea form the natural communication between the Atlantic in the south and the Polar Sea in the north, their hydrographic conditions must especially be determined by the currents through which the exchange of water takes place between these two seas. As regards the Greenland Sea, the Polar Current is by far the most important and will therefore in a special degree be made the subject of investigation; but the Atlantic water outside and below the Polar water will also be dealt with as well as the cold, rather calm water of the deep eastern areas. Finally we are to trace the drainage of the Greenland Sea north and east of Iceland as well as southwestward through the Denmark Strait.

As an introduction to the treatment of the Polar Current we must, however, briefly consider the hydrography of the Polar Sea.

The Polar Sea.

With its c. 12.5 million square kilometres the Polar Sea covers an area slightly larger than Europe. It has a marked oblong shape with its longitudinal direction from Spitsbergen via the North Pole to Alaska, and this is especially reflected in the shape of the deep part of the Polar Basin. The shallowness of the Banks Sea continues along the whole north coast of Asia in a width of several hundred miles seaward; thus minor sea areas with their own physical conditions are separated from the actual Polar Sea, e. g., the West Siberian Sea, the Laptev Sea, and the East Siberian Sea. On the Canadian-Greenland side the continental shelf is much smaller.

Even though the whole Polar Basin has not yet been investigated, it may be established with a fair amount of certainty that a nearly continuous deep, with more than 3000 m of water, extends from just north of the Nansen Ridge to near the coast of Alaska; north of Bering Strait the depths exceed 5000 m, and near the North Pole proper the Russian Drifting Polar Station in 1937 ascertained depths of more than 4000 m.

Even far north of Greenland the Russian expedition found two submarine ridges, which interrupt the Polar Basin to some extent, viz. one in 86° N. lat. with 3677 m of water and ond in 84° N. lat. with 2380 m of water; but south of this, c. 80 miles northeast of Nordostrundingen, the depth was again more than 4000 m; previously shallow water was indicated here, even on the most recent maps.

The opening between Spitsbergen and Greenland is c. 250 miles wide, and is the only one through which large water masses may be exchanged between the Polar Sea and the oceans, and precisely on this account the Polar Sea is of such decisive importance for the hydrography of the Norwegian Sea—especially the Greenland Sea. Small quantities of Atlantic water reach the Asiatic marginal area of the Polar Sea by way of the deepest channels in the shallow Barents Sea; but no water of any importance flows in the opposite direction. Some influx of Polar water to the Atlantic takes place through the Canadian straits, notably Lancaster Sound; and through the very shallow-watered Bering Strait (46 m) there is an inconsiderable afflux of surface water from the Bering Sea.

The main features of the hydrography of the Polar Sea were elucidated by NANSEN's drift in the "Fram" in 1893—96. Although his measurements were not sufficiently accurate, he was at once aware of the main currents. Of later expeditions the Russian expeditions should especially be mentioned, the most recent being the Drifting Polar Station 1937—38; but others also, e. g. H. U. SVERDRUP's expedition in the submarine "Nautilus", have brought home valuable observational results. These recent expeditions have supplied more accurate observations than those made by NANSEN, but only as regards the deeper water layers have they resulted in material alterations of NANSEN's theories.

The whole Polar Sea is covered by a layer of Polar water 100—250 m thick and with a low temperature and salinity. This surface water is sea water with an admixture of fresh water which must be chiefly derived from the Asiatic and Canadian rivers; for the melting of the ice cannot supply new water to the Polar Sea, and since the stability of the upper layers of the sea is great, the salter water formed by freezing cannot sink down to the bottom and thus deprive the surface water of salt. According to NANSEN's observations, the precipitation plays no important part in this respect. At the surface the temperature varies considerably with the seasons, though it very often ranges about the freezing point of the water (0°— —1.8° C.); in summer the salinity may decrease to nil in the cracks between the ice-floes; but 1—2 m beneath the ice it does not fall below 29 $^0/_{00}$, and at the end of the summer it here increases immediately to 31.00—31.60 $^0/_{00}$. The cooling in the winter is traceable to a depth of 50—75 m, so there a temperature minimum of —1.70°— —1.90° C. is found everywhere. The lower limit (0° isotherm) of this cold upper layer was found by Nansen to lie deepest, at a depth of 240 m, east of Severnaja Zemlya but only at c. 200 m towards the end of the drift. However, the expeditions of the last two decades have ascertained that this water layer has been reduced to a thickness of 100—150 m owing to an increase of the Atlantic afflux.

The cold water moves steadily but slowly out of the Polar Sea towards the Greenland Sea, and it is precisely the direct continuation of this current which constitutes the East Greenland Polar Current. Accordingly the current is no cyclonic movement within the Polar Basin, but should rather be compared to a current moving out of a fjord. It is due, in part, to the prevalent winds, but is also the natural, dynamically conditioned run-off from the less salty surface layer of the Polar Sea. From the drifting of the "Fram", the "Sedov", and the Drifting Polar Station we can compute that it will take several years for the surface water to be replaced; but at the same time it is seen from these and other expeditions that in recent years the velocity has increased to twice (c. 2 miles in 24 hours) the velocity during the drifting of the "Fram" in the nineties.

The Atlantic water, which represents the last offshoot of the Gulf Stream, enters the Polar Sea at intermediate depths, partly around the west of Spitsbergen, partly by way of the Barents Sea. In a cyclonic movement it closely follows the continental shelf and, as appears from Fig. 9, north of Asia it extends from a depth of c. 100 m down to 900 m, while at the Pole a positive temperature is only found from 250 m to 650 m. It is natural, also, that the maximum temperature (2°—3° C.) and the maximum salinity (34.99—35.08 ‰) are found nearest the shelf.

At the entrance to the Polar Sea the Atlantic water exhibits great fluctuations in its characters; mention may, for instance, be made of the strong increase in temperature and salinity during the present century; but on reaching the area of the Drifting Polar Station such fluctuations seem to have been levelled out (P. Shirshov 1938, p. 573). It is true that Breitfuss (1939) indicates an Atlantic undercurrent from the Nansen Ridge directly towards the Pole and onwards to the East Siberian Sea; but if this were correct, the same fluctuations in the character of the water as near Spitsbergen might be expected near the Pole. More probably, I should think, Sverdrup's picture is the correct one (1933, p. 39), when he says that the greater part of the Atlantic water follows the Asiatic shelf northeastward, but on its way the water gradually spreads farther northward.

Probably no water of an Atlantic character leaves the Polar Sea, not even across the deep-lying Nansen Ridge; it is first mixed with the upper cold water layer.

Beneath the Atlantic water the temperature decreases to —0.83°——0.87° C. at a depth of 2500—3000 m; but in the actual bottom water it increases again to —0.63°——0.69° C. at the bottom. This rise in

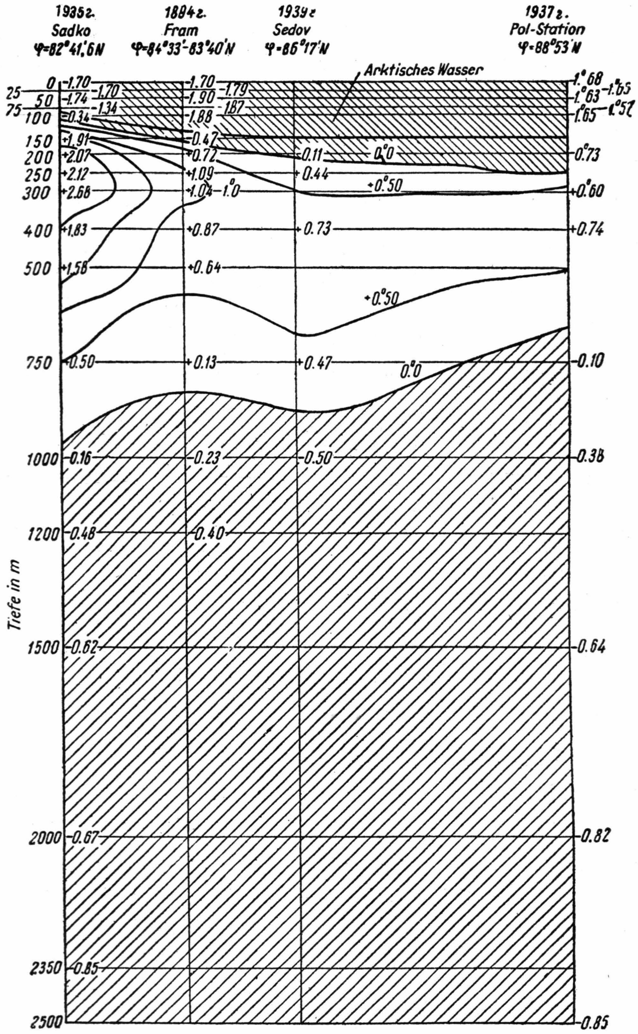

Fig. 9. Vertical temperature distribution along c. 80° E. long. between Nordland and the Pole (G. Wüst 1942).

temperature may be due to a small extent to the heat of the earth, possibly also to the decomposition processes of organic substances; but since all scientists agree in assuming that the bottom water has sunk down from higher water layers, the adiabatic heating, also, must be considered to be of essential importance; and precisely from this point of view Wüst (1942) computes the potential temperature (the temperature of the water at a pressure of one atmosphere) for the stations of the "Fram" and of later Russian stations. He found that the bottom water of the Polar Sea has a potential temperature of —0.93°— —0.95° C. or the same potential temperature as is found in the northern part of the Greenland Sea at a depth of 1200—1400 m, and since, moreover, the salinity is the same in these two places, he concludes that the deep water layers of the Norwegian Sea and the Greenland Sea, formed by cooling and sinking in the winter above the so-called Greenland Deep, drain across the Nansen Ridge into the Polar Sea, where they form the bottom water of this sea. In his figure, reproduced here in Fig. 10, Wüst has drawn contours for the same potential temperatures and indicated by arrows how he supposes that the cold water from the Greenland Sea passes across the Nansen Ridge, the depth of which he estimates at 1750—2000 m on this basis.

It will be evident from this brief treatment of the hydrography of the Polar Sea that an exchange of considerable water masses of different character takes place between this sea on the one hand and the Norwegian Sea and the Greenland Sea on the other.

The Depths of the Greenland Sea.

The bathymetrical map (Pl. 1) has been prepared on the basis of the most recent sources and will thus give a more correct picture of the bathymetric conditions of the Greenland Sea than the earlier maps representing the whole area. The basis of the map is, as a whole, the U. S. A. Hydrographic Office Chart of the Arctic Ocean, 4th edition 1933; but for smaller areas the following sources have been drawn upon: farthest northward, soundings made by the Russian Drifting Polar Station 1937—38 and Wüst's paper of 1942, and for the more southern areas along the Greenland coast the maps published by Riis-Carstensen 1938, Jakhelln 1936, and Helge Thomsen 1934. The series of deep-lying banks west of Jan Mayen were drawn after A. Trolle 1935, and finally, the depth contours around Spitsbergen have in all essentials been indicated after Sverdrup 1933, Wüst 1942, and the map of Greenland published by The Danish Geodetic Institute in 1938.

It will at once be evident from the map that the Greenland Sea is not separated bathymetrically from the Norwegian Sea. On the contrary the sea-bottom descends by steps towards the great depths (3000—4000 m) of the Norwegian Sea; but, as mentioned above, it is the distribution of the ice and the character of the upper water layers which warrant a distinction between the two seas.

The Nansen Ridge forms a sharp boundary between the Polar Sea and the Greenland Sea. According to the most recent investigations it

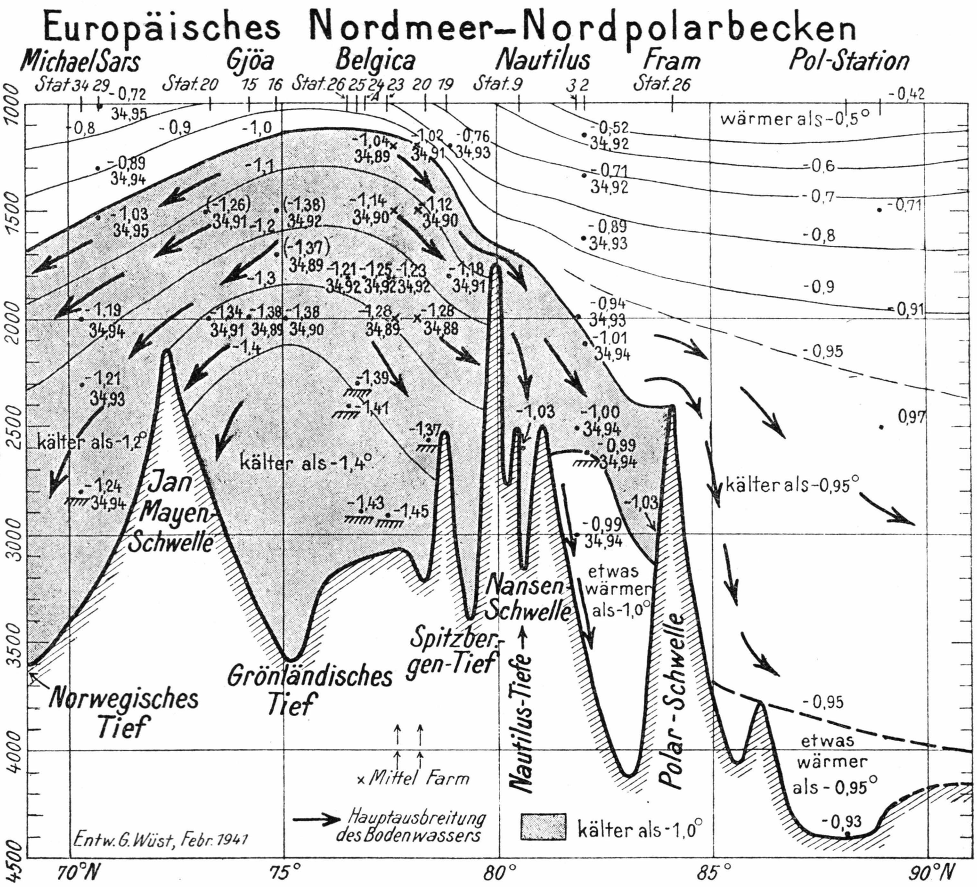

Fig. 10. The potential temperature along the 0° meridian at a depth of from 1000 to 4500 m (Wüst 1942).

seems to be situated just south of 80° N. lat. (Wüst 1942) and thus it does not, as first assumed, form a natural connection between Nordostrundingen on Greenland and the northwestern corner of Spitsbergen. Immediately outside Nordostrundingen the sea bottom descends steeply to a depth of several thousand metres, and midway between Greenland and Spitsbergen occurs the Nautilus Deep, more than 3000 m deep, as the southernmost offshoot of the Polar Sea. It is true that H. U. Sverdrup assumed that the Nautilus Deep belonged to the Greenland Sea; but Wüst points out that the bottom water in this deep is closely associated with that of the Polar Sea. The deepest-lying portion of the ridge seems to lie very near the 0° meridian, or a little nearer to Spitsbergen than to Greenland, and the depth is here estimated at 1750—2000 m.

Immediately west of the deepest part of the ridge we meet, in 2—4° W. long. the Greenland shelf, which is here 140—160 miles broad. On the innermost part of the shelf lies the Belgica Bank with depths as low as 60 m; but only its southernmost point is fairly well-known. Inside the bank, north of Île de France, depths of 400—500 m have been measured, but whether they continue northward as a channel along the coast of Greenland, is not known.

South of c. 77° N. lat. the shelf grows gradually narrower until off Liverpool Land it is only 30—40 miles broad. Along the whole stretch it is intersected by deep submarine fjords, the largest of which pass north of Île de France, south of Koldewey Ø, and towards Kong Oscars Fjord. Between these fjords the surface of the shelf is very rough.

South of Scoresby Sund the shelf is fairly narrow, but its limits are as a whole poorly known. It is broader off Kangerdlugssuak, but here lies the Øst Bank, southwest of which the shelf is cut through by the Kangerdlugssuak deep.

The greatest depths of the Greenland Sea, more than 3000 m, are found in its northern part, even quite close to the Nansen Ridge. South and southwest of Jan Mayen the sea bottom usually occurs at a depth of 1000—2000 m, whence a narrow deep with 1000 m of water extends southwestward into Denmark Strait. A series of deep-lying banks, possibly narrow and elongated, extends north-northeastward from North Iceland west of Jan Mayen to the northern part of the sea. Their distribution is very slightly known; but in spite of their depth they must be assumed to be of some importance to the sea currents.

From Jan Mayen the sea bottom slopes steeply northward down to great depths, while a minor plateau with inconsiderable depths extends southward.

The East Greenland Polar Current.

As already mentioned, the cold upper water layers of the Polar Sea probably move from all parts of the Polar Sea towards the opening between Greenland and Spitsbergen. The velocity must, of course, vary according to time and place, but it will always be less within this area than off the east coast of Greenland.

The Drifting Polar Station 1937—38 drifted roughly due southward from the Pole to a little outside Nordostrundingen, but while near the Pole the velocity was only c. 1 mile in twenty-four hours, it increased southward to 4—5 miles in twenty-four hours between 85° and 80° N. lat. The "Fram" and the "Sedov", drifting from the east, likewise showed an increasing velocity on approaching the entrance to the Greenland Sea. Whether north of Greenland, also, a current moves towards the Greenland Sea, is not definitely known, but it must be regarded as probable.

According to observations made on the Drifting Polar Station the current is due to the ice-drift, which, again, is under the influence of the prevalent winds; W. W. SHOULEJKIN (1938) even goes so far as to say that during the whole drift of the Polar station no trace of current of "non-drift origin" was observed, and he goes on to say: "In particular the origin of the so-called East Greenland current is cleared up: it is also a purely drift origin, caused by the movement of ice. The considerable constancy of this current is accounted for by a similar constancy of winds working off the Greenland coast." It is probably doubtful, however, whether it is justifiable thus to disregard entirely the dynamic forces in the sea. W. J. WIESE (1938) is, in fact, of opinion that the velocity of the drift at any time depends half on the wind at the moment and half on a constant current.

That part of the Polar current which comes from the north and northwest probably flows closely past Nordostrundingen, where depths of more than 3000 m are found close to the shore. It must be assumed that the velocity of the current may here be fairly considerable, perhaps to some extent with the formation of eddies; but since currents from the different parts of the Polar Sea cannot be so compact at the margin of the shelf in this place as farther southward, the velocity should not perhaps be estimated at more than 10—20 cm per sec. (5—9 miles in twenty-four hours). No hydrographic observations are available from this area, so we have to draw chiefly on the observations on the ice-drift. The various drifting expeditions all show an increasing velocity towards this area, and precisely in these latitudes the Russian Polar Station drifted at a rate of c. 10 cm per sec. (4.5 miles in twenty-four hours).

Almost following the meridian, the Russian station drifted obliquely across the shelf in c. 81° N. lat.; but since so far we know only very little of the observation material of the expedition, we do not know whether the current actually moved in that direction or whether the wind was of essential importance for the direction of the ice drift. Since the currents in the uppermost water layers, also, depend largely on the configuration of the sea bottom, it must be assumed that this drainage of surface water from the Polar Sea will mainly follow the isobaths of the bottom and accordingly bend southeastward towards the deepest part of the Nansen Ridge almost in the longitude of Greenwich.

Unfortunately no observations on the western half of the ridge are available so far, so here, too, the current map must be rather hypothetical. The nearest hydrographical stations are derived from the "Belgica" 1905 and are situated above the eastern half of the ridge or to the south

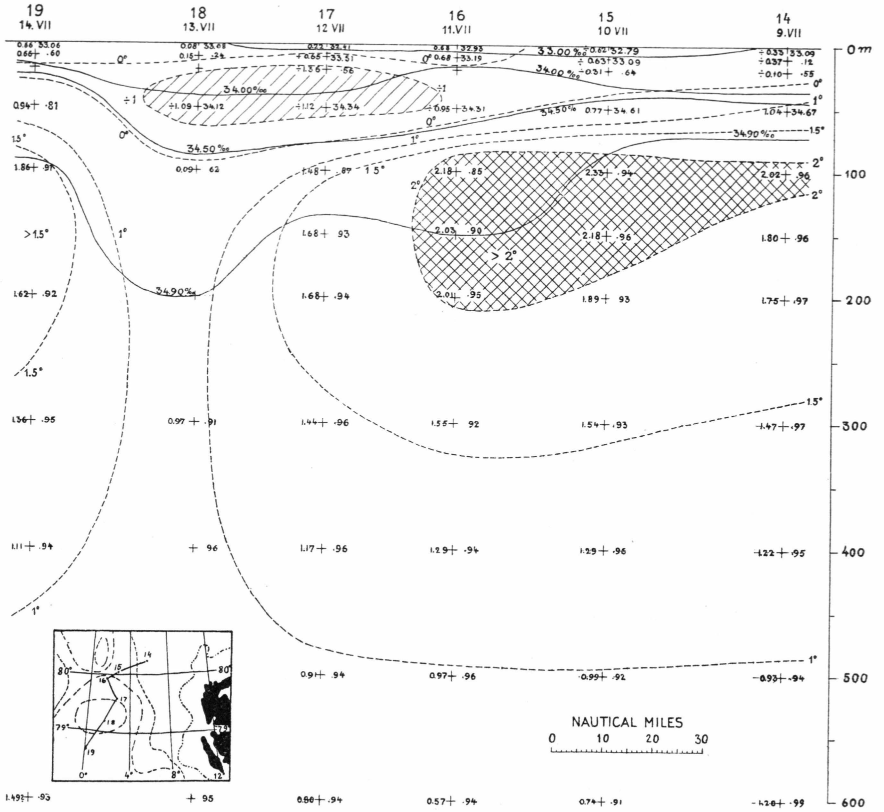

Fig. 11. Hydrographic section through the stations of the "Belgica" along the eastern part of and south of the Nansen Ridge. July 1905.

if it in deep water (Sts. 14—19). These stations, gathered in the section on Fig. 11, show, however, that at a depth of 20—50 m the Polar Current gives off an extreme outer branch right across the deep water at Sts. 17—18; but it appears from the TS-diagram in Fig. 12 that the Polar water at these stations is highly mixed with Atlantic water, and the Polar Current is, indeed, not traceable farther eastward.

In Fig. 12, PW, in agreement with Jakhelln (1936), represents the original character of the Polar water at the time it was formed beneath the ice of the Polar Sea (—1.85° C.; 34.00 ‰), and AW represents the character of the Atlantic undercurrent (2.10° C.; 34.97 ‰), which from Spitsbergen bends towards Greenland and moreover is distinctly seen in the section at Sts. 14—16. The points for 20 and 50 m depths lie, as a rule, closely around the connecting line between the pure Polar water and the Atlantic water, though nearest the PW. The water at these depths must accordingly be the result of a mixture of the two types of water, but contain most Polar water.

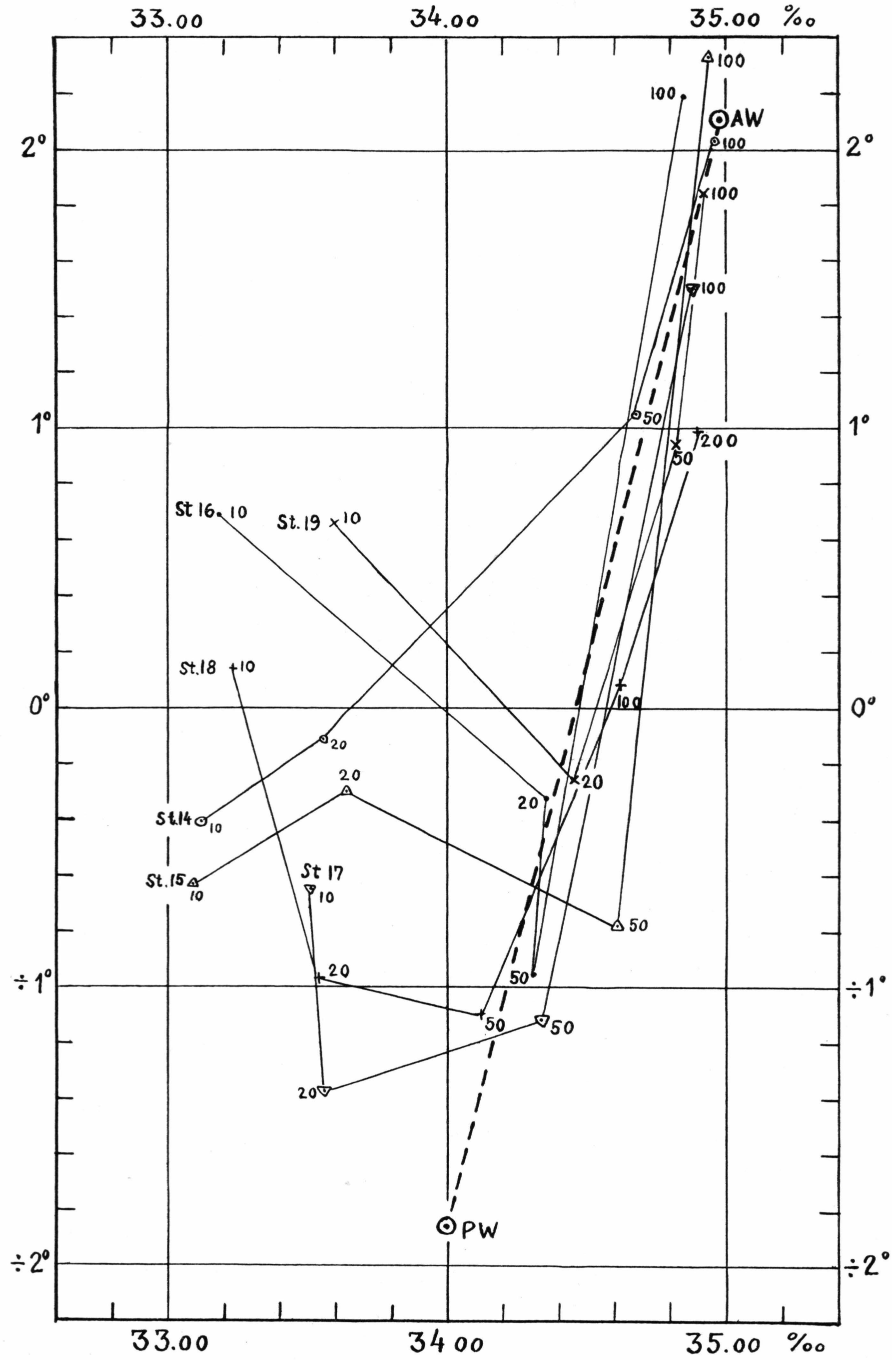

Fig. 12. TS-diagram for Sts. 16—19 of the "Belgica", showing a mixture of Polar water and Atlantic water.

This furnishes a proof that the Polar Current follows the continental slope southeastward, but that in the main it turns southward with this before reaching the middle of the ridge, and is only faintly traceable as far eastward as 2°—3° E. long.

A dynamic treatment of the stations of the "Belgica" may to some extent lend support to and supplement the picture of the currents; but firstly the observation material cannot be expected to be on a level with the modern material as regards accuracy, and secondly the results depend greatly on the depth of the reference level chosen. In the deeper water layers the isobaric surfaces often exhibit a considerable slope; but it is doubtful whether this part of the solenoid field should be included in the computation of the surface currents; more probably the lowermost part of the field belongs to the undercurrents beneath a higher-lying reference level.

A. Defant (1941) recommends the placing of the reference level in the depth interval in which the difference in velocity is least. In this way he finds for the lower latitudes in the Atlantic that it should be placed at a depth of 400—500 m, but farther northward at 1500—2000 m.

According to this principle the reference level, on the basis of the observations of the "Belgica", should be placed at a depth of 400—500 m near the Nansen Ridge. This would also seem to provide the best agreement between the computed currents in the upper water layers and the distribution of the different water masses. Computed in this way, a weak south-flowing surface current with a velocity of c. 5 cm per second (c. 2 miles in twenty-four hours) will be found over the whole middle part of the ridge. As the water of the surface proper depends so much on the melting of the ice, the computations of the currents have only been carried out up to a depth of 10 m, and in all the dynamic computations in the present work this depth has been regarded as the level of the sea.

Taking into consideration the observations supplied by the "Nautilus" and the "Quest" 1931, the view has been maintained in the preparation of the current map that the cold water above the middle part of the ridge is essentially derived from the Northeast and accordingly does not actually belong to the East Greenland Polar Current. Unfortunately the section of the "Nautilus" and part of the section of the "Belgica" lie parallel to the direction of the current and in these places, therefore, the velocity cannot be computed.

The observations from 1931 have been treated apart and no attempt has been made to coordinate the isobaric surfaces from that year with the corresponding ones from 1905 and thus to draw a total map of the dynamic topography of the surface. This can only be done with great uncertainty and hence be of little value; but the direction of the currents can be inserted on the common map with fair accuracy.

Whether or not the cold water above the Nansen Ridge is a part of the East Greenland Polar Current, the main current bends so soon southward that as far as c. 76° N. lat. it remains above the continental slope or the outermost part of the shelf.

Also from the area between 80° and 76° N. lat. the Belgica Expedition is that which has supplied us with the best observation material; but since its route here also roughly follows the direction of the current, computations of the velocity of the current can only be made to a limited extent. As to the southern part of this area the observations of the "Belgica" are supplied by some series made on the Danmark Expedition; however, these are rather sporadic.

Stations 21 A—22 of the "Belgica" are situated on the continental slope proper, somewhat displaced in relation to the direction of the current. Here the upper water layers move southward at a velocity of c. 30 cm per second (14 miles in twenty-four hours); but while the innermost station (22) with a depth of 1425 m exhibits marked Polar water at a depth of c. 100 m, station 21 A, situated only a few miles farther eastward at a depth of 2100 m, is dominated by water of Atlantic origin right up to above a depth of 20 m. In this place the edge of the Polar water or a branch of it accordingly extends right out above depths of 1500—2000 m; but the greater part of the Polar water must flow over the banks with depths probably of 200—400 m.

Owing to the sparcity of the observational data the current map for this whole area, as well as farther northward, must be regarded as hypothetical. However, we may draw support from the fact that the currents depend on the topography of the sea bottom, so if the bathymetric map is correct, the representation of the currents, also, must be roughly correct. Still it is far from certain that this vast area of banks north of c. 77° N. lat. is continuous without submarine fjords. The trend of the currents around stations 21 A and 22 as drawn on our map might indicate an indentation in c. 79° N. lat., and if such an indentation actually exists, it is justifiable to assume the presence of an eddy somewhat similar to that suggested on the map in 79°—80° N. lat. Such an eddy is in good accord with the observation that there is nearly always open water off Mallemukfjæld and at times in other places in the neighbourhood. The many finds of drift-wood on Holms Land and Amdrups Land may likewise be accounted for by the existence of such an eddy. They need not mean, as assumed by Ejnar Mikkelsen (1922, p. 199), that a branch of the Polar Current moves southward along the shore.

On a level with Île de France a submarine fjord with depths of more than 400 m intersects the shelf from the southeast, apparently continuing some distance northward inside the southernmost point of the Belgica Bank.

It must be assumed that the fjord exerts a considerable influence on the direction of the currents, but no observations confirming this are at hand.

It is evident from the sections of the "Belgica" from Île de France to the southernmost point of the Belgica Bank that cold water of a negative temperature occupies the channel from the surface to a depth of 250 m. Within the uppermost 100 m, however, it is highly mixed with thaw-water, the salinity being here less than 33 $^0/_{00}$ while the typical Polar water with a salinity of c. 34 $^0/_{00}$ occurs at a depth of 200 m, or much deeper than in the outer part of the current. Because of the slope of the isobaric surfaces, there must be a slight northward movement in the upper water layers inside the bank, but a southward or southwestward movement over the southern point of the bank itself.

Thus it may be assumed on the basis of these few stations that the Polar Current extends in breadth from the continental slope near the isobaths of the sea bottom for 1000—2000 m to the Belgica Bank, where the depth is less than 100 m. An eddy will then arise around the southernmost point of the bank, which causes a branch of the current to push northward into the channel behind the bank. This eddy is probably a concurrent cause of the ice-free water observed so frequently near Île de France, and perhaps it has also carried with it the drift-wood which has stranded on the north coast of Germania Land.

Data as to the velocity of the current over the broad shelf have hitherto only been supplied by the drift of the Russian Polar Station in January 1938. It passed this area at an average rate of c. 25 cm per second (12 miles in twenty-four hours); but, as stated above, part of the velocity—perhaps half—must be ascribed to the wind and the resulting ice drift, not to the constant current.

The Russian Polar Station drifted across the submarine fjord apparently without deviations in the direction of the drift.

The first continuous sections across the Polar Current available are from c. 76° N. lat., namely those of the "Belgica" 1905 and the "Danmark" 1906—08 (Figs. 13—14), and it is, in fact, this material which has most frequently been treated in the literature (Helland-Hansen and Koefoed 1907, A. Trolle 1913, J. N. Nielsen 1928, E. Riis-Carstensen 1938). While the stations of the "Belgica" are situated fairly close to each other and were taken in the course of some few days, those of the "Danmark" were rather scattered and are derived from two years, which makes them much less convenient for our purpose.

In the summer of 1905 the Polar water was met with already at St. 27 of the "Belgica" above a projecting portion of the continental

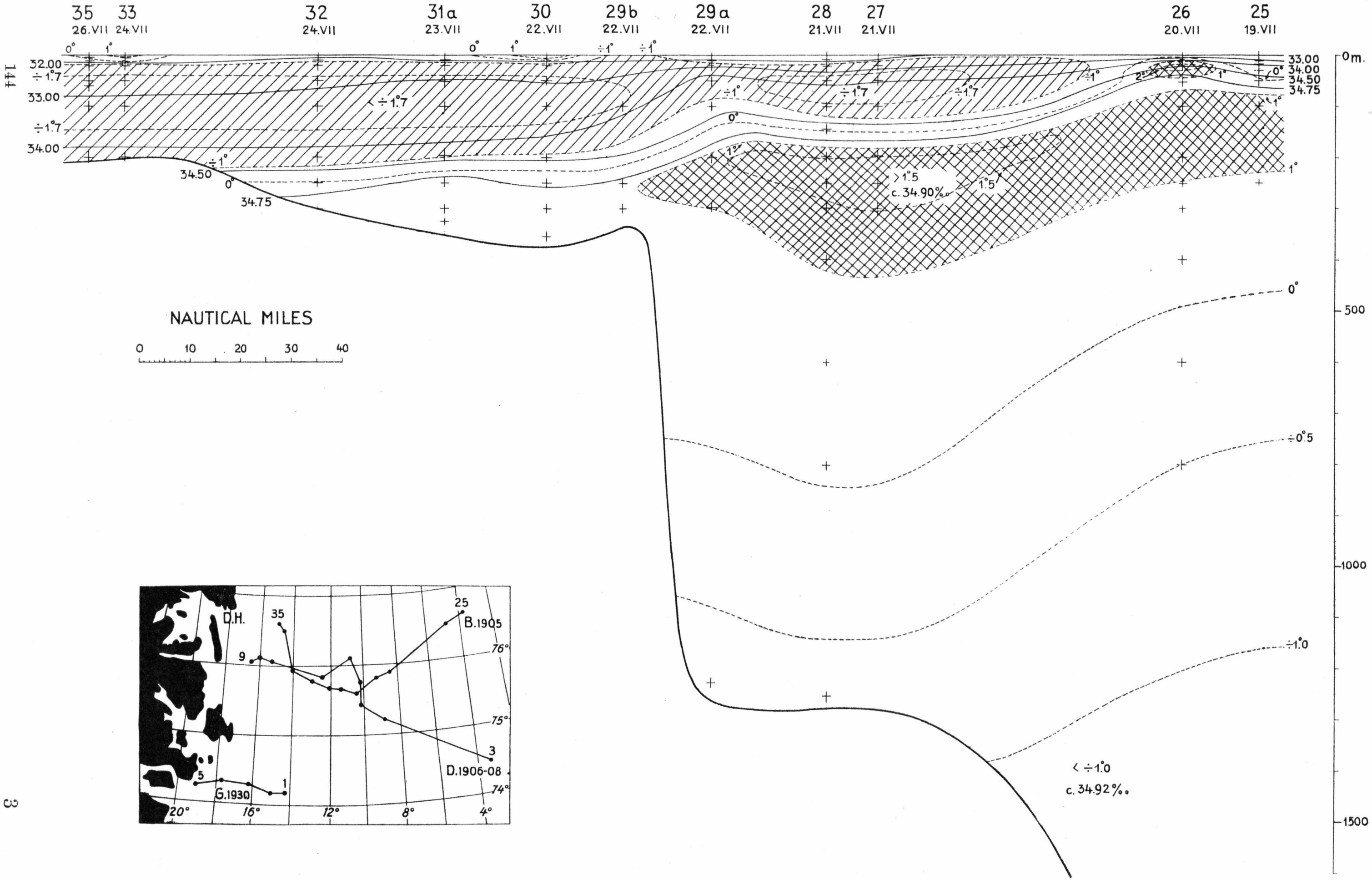

Fig. 13. Section eastward from Koldewey Ø. "Belgica" 1905.

slope with a depth of c. 1700 m. At a depth of 50 m, at this station and its neighbouring station just inside, St. 28, the most typical Polar water within the whole area was found (—1.74° C, 34.00 $^0/_{00}$), and since it even had a slightly lower temperature than the Polar water at St. 23 farther northward, it may be taken as evidence that this water had flowed southward across the outermost portion of the shelf inside St. 23, and that, in addition, it had passed across the outermost part of the submarine fjord without admixture of warmer water. Farther in over the bank, water of about the same temperature and salinity was found at the "Danmark"'s St. 78 in 1908.

Obviously it must be taken for granted that here in c. 76° N. lat. the core of the Polar Current with unmixed arctic water is found over the outermost part of the shelf and remains at a depth of c. 50 m. In the uppermost water layers the salinity decreases rapidly owing to the melting of the ice, and near the surface the external limit of the Polar Current may be drawn almost at the 32 $^0/_{00}$ isohaline, no matter whether the temperature is positive or negative. Beneath the core of the Polar Current the salinity increases rapidly even at a depth of 100 m and the temperature rises, so at a depth of 150 m the temperature is 0° C. (c. 34.70 $^0/_{00}$), at which isotherm the lower limit of the Polar Current may be drawn.

Farther in over the shelf, among the actual banks with water depths of less than 200 m, the lower limit of the Polar Current occurs at depths of 200—250 m, but as within the Belgica Bank, the upper layers are so strongly mixed with thaw water or coastal water that the temperature minimum probably still occurs near a depth of 50 m, but now coincides with the isohaline for 33 $^0/_{00}$ instead of that for 34 $^0/_{00}$. The most typical Polar water is accordingly to be found here, as in the channel inside the Belgica Bank, at a depth of c. 200 m.

In the TS-diagram in Fig. 15 the most typical Polar water within the areas dealt with here is indicated. At Sts. 27 and 28 it occurs at a depth of 50 m and is practically unmixed, while in all the stations situated nearer the shore it occurs at a depth of 200 m. The area above the bank (Sts. 32—35) shows a slight admixture of Atlantic water and, in addition, of the cold, but salter water from the deep part of the Greenland Sea. But a greater admixture of these kinds of water is found over the deeper channels inside the banks (Sts. 42—44 and 36a). This must be explained by assuming that the water over the banks only slowly receives an afflux of water from outside, while the renewal of the water is more effective over the submarine fjord. Sts. 43 and 44 are situated most directly within the fjord and have, indeed, the greatest admixture, while the water from outside only later reaches St. 36a outside Danmarks Havn, no matter whether it comes from the north or the south.

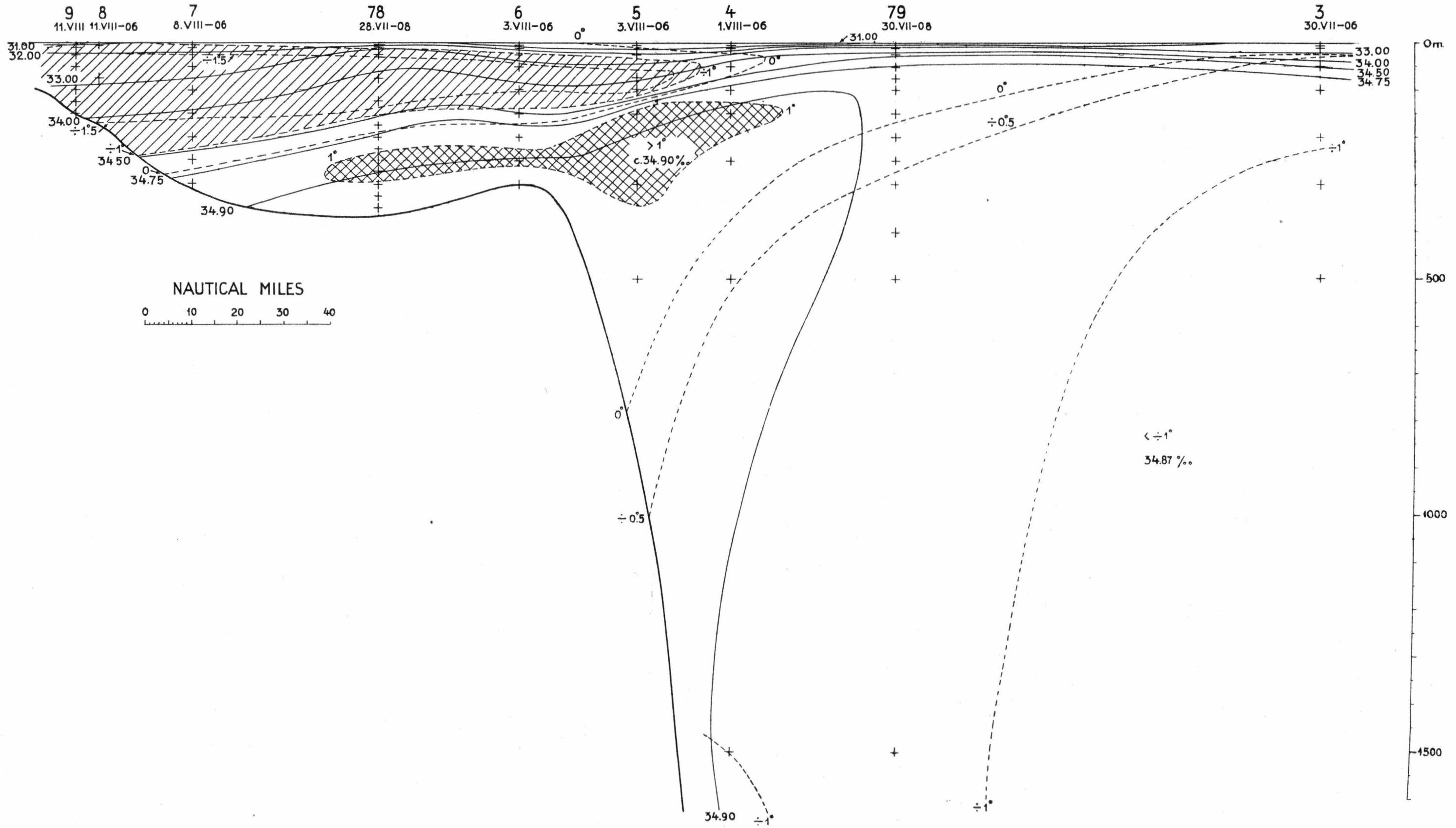

Fig. 14. Section eastward from Koldewey Ø. "Danmark" 1906—08.

The circulation of the upper water layers here in c. 75°—78° N. lat., as farther northward, has been computed with the 500 db-surface as the reference level, and the picture of the currents is roughly identical with that drawn by RIIS-CARSTENSEN in 1938. In computing the dynamic depths smaller intervals in the higher water layers (as a rule 20 db) have been used in the present work than in earlier treatments, in which way the sudden variations in the upper water layers can better be included in the computation. This, as a rule, results in a somewhat greater distance between the uppermost isobaric surfaces than is otherwise the case. In combining the deepest isobaric surfaces from station to station, the whole solenoid field has been inserted wherever possible, and the inclination of the deepest-lying surfaces has been computed by integration of the anomaly of the specific volume along the bottom and up along the deepest station to the same depth (see KIILERICH 1939, p. 19). In this way, also, a greater accuracy of the result is attained than by the method employed by J. P. JACOBSEN (1926) and RIIS-CARSTENSEN (1938). I have not found it advisable, however, to bring together the observations of different years or seasons in one continuous dynamic map, not even where the connection could be established by way of two stations from different years but situated in the same place. In this way RIIS CARSTENSEN established a connection between the stations of the "Belgica" from 1905 and those of the "Danmark" from 1906—08 by means of stations situated near the northernmost point of Koldewey Ø. However, the character of the water within the same area may vary so considerably from one year to the other or from season to season that it is a very questionable proceeding to put together such observations into one map.

On the basis of the observations of the "Belgica" alone one gains a fairly good idea of the currents in the upper water layers in these latitudes, always letting the isobaths of the surface of the sea follow the contours of the sea bottom as far as possible. The observation material of the "Danmark" computed for each of the two years apart would support the result in every way.

Along the continental slope the current moves southward with about the same velocity as farther northward. In c. 76° N. lat., where the slope is broad, the current is somewhat diffused and the velocity decreases, but south of this place, off the southeastern point of the bank, the current narrows again, and the velocity, according to the computations, increases to 25 cm per second (12 miles in twenty-four hours). But immediately after, a large branch of the current turns westward to flow at a fairly rapid rate along the southern margin of the banks in towards the deep between Koldewey Ø and Shannon.

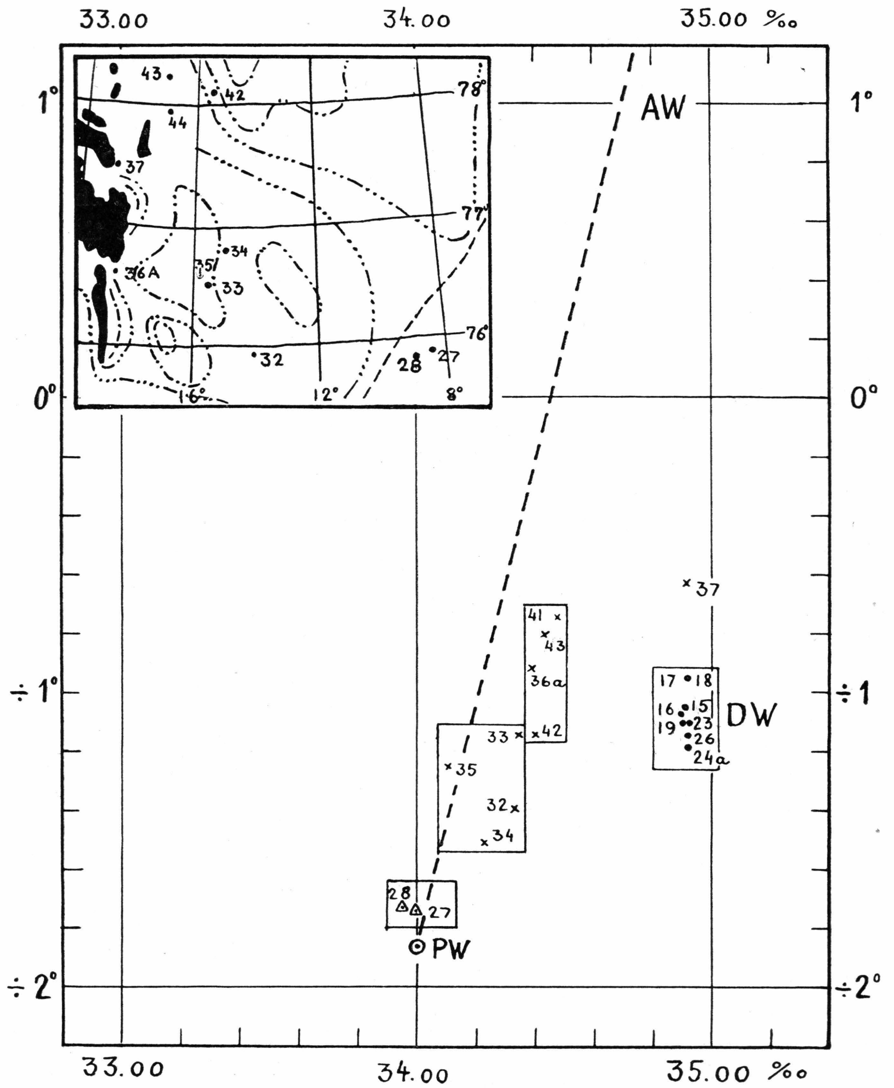

Fig. 15. TS-diagram showing the mixture of the Polar water (PW) in 76—78° N. lat. with Atlantic water (AW) and cold water from the deep of the Greenland Sea (DW).

The same picture is represented on Riis-Carstensen's map, and it likewise agrees with numerous observations of the ice drift. Similarly, the different investigations lead to results which agree in regard to the surface currents around Koldewey Ø. A current moves northward between this island and the bank outside. It may be ascertained by the drift of the icebergs; but it is also dynamically conditioned; and besides affluxes from the current from the east it receives water flowing out from Dove

Bugt around the south of Koldewey Ø. This current, flowing around the south point of the island and up along its east coast, is probably the cause of the ice-free water which is nearly always found outside the island. How far northward the current extends, we are unable to ascertain. RIIS-CARSTENSEN indicates a current through Store Bælt into Dove Bugt; but there can be no material afflux of water to the Bay by this route. For as to the deeper water layers it is evident that the afflux takes place from the south, and the higher water layers in the bay exhibit a strong admixture of thaw water. Possibly this thaw water is of essential importance for the outflowing current around the south of Koldewey Ø.

The main volume of that branch of the Polar Current which flows towards the shore along the south slope of the banks bends southward near Shannon. No hydrographical observations are available from this area, so in indicating the surface currents we have to draw support from direct observations, thus, for instance, of the accumulation of ice northeast of the island, the southward drift of the icebergs inside the island, drift-wood along the shores of the strait, ice-free water off the southeastern corner of the island, etc.

Our surface current map of the area around Shannon has been drawn in accordance with RIIS-CARSTENSEN's representation with a branch moving around the west of the island, while the main branch probably remains outside.

From the area between 75° and 74° N. lat. a fairly great observation material is available. It is derived from RYDER's expedition 1891 (C. RYDER 1895), NATHORST's expedition 1899 (F. ÅKERBLOM 1904), AMDRUP's expedition 1900 (G. AMDRUP 1902), the "Godthaab" 1924 (E. RIIS-CARSTENSEN 1938), the "Godthaab" 1930 (Bull. Hydr. 1930), and the "Polarbjørn" 1931 (A. JAKHELLN 1936).

These data include material for some good sections across the current; but even though the sections show complete agreement as to the characteristic structure of the current, each expedition will be dealt with apart in the dynamic treatment. In these sections the reference level cannot be placed deeper than at 250—300 db.

RYDER's section, which points towards Scoresby Sund from the northeast, is the oldest and is fundamental for the studies of the East Greenland Current, though the stations are situated at great intervals and the observation technique at that time was still rather deficient. As an example of a section across the current in these latitudes, however, a section from the "Godthaab" 1930 will be reproduced (Fig. 16).

The shelf is here only half as broad as farther northward, so the cold current has been compressed to a width of c. 70 miles. In the outer part of the current the typical Polar water (—1.74° C.; 34.04 $^{0}/_{00}$ at

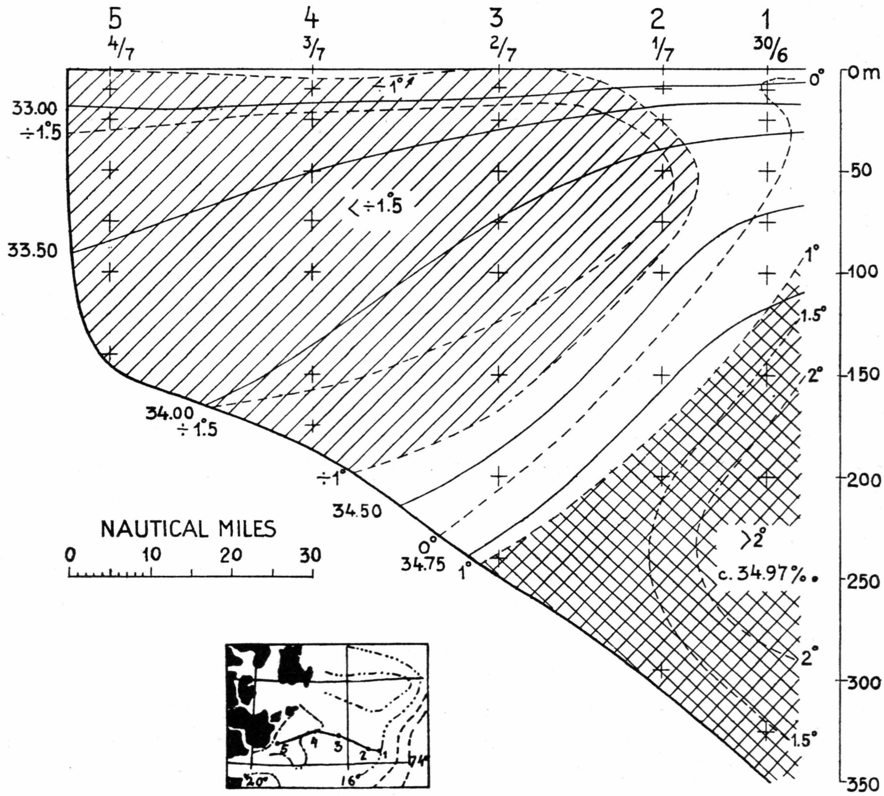

Fig. 16. Hydrographic section eastward from Sabine Ø. "Godthaab" 1930.

St. 2) still occurs at a depth of 50 m, while in the innermost part it sinks down to c. 150 m. The lower limit of the Polar water, which at St. 2 occurs at 125 m, descends shorewards to a depth of c. 225 m. The sections from the other years show precisely the same values at a corresponding distance from the shore.

On comparing these sections with those of the "Belgica" and the "Danmark" farther northward, one receives the impression of a more compressed Polar Current corresponding to the narrower shelf. The large volume of bank water with a strong admixture of thaw water in the innermost part of the current is not found here. The actual Polar water occupies the greater part of the area of the banks, and the replacement of the water takes place much more rapidly here than in the north. Thus for instance there is here only a water layer 20—30 m thick with a salinity of less than 33 ‰, while in the sections of the "Belgica" and the "Danmark" this isohaline descends towards the shore to a depth of 80—100 m.

Fig. 17 shows the inclination of the isobaric surfaces in relation to the 320 db-surface, and from this it appears, in fact, that the velocity of the current at right angles to the section is, indeed, greatest between Sts. 2 and 3 (at the surface up to 12.5 cm/sec.), but that a distinct south-flowing current (3 cm/sec.) is also found among the innermost stations.

However, the direction of the current intersects the section at a somewhat more acute angle, so the actual velocity of the current is somewhat greater than the computed one. In preparing this area of the map the same principles were followed as farther northward. The picture agrees closely with those given by Jakhelln and Riis-Carstensen.

Over the bank outside Shannon the current only moves slowly, but over the slope off the outermost point of the bank the velocity increases, as off the more northerly banks, to c. 15 cm/sec. (7 miles in twenty-four hours). Subsequently the current moves almost parallel to the shore in a southwesterly direction, passing Sabine Ø at a rate of c. 10 cm/sec. (4.5 miles in twenty-four hours).

However, the observation material of the "Godthaab" from 1924 shows such dynamic features that a southeastward-flowing branch must be assumed to be given off from the outermost part of the current almost on a level with Clavering Ø. It is true that these computations are based on a single station (VII) taken about two weeks after the adjacent stations; and the bathymetrical conditions of the sea bottom, in so far as they are known, show no irregularity that might give rise to such a deflection. But the difference in the dynamic height between this station and the others is so great that it can hardly be quite casual, nor can it be explained by the time interval alone. At station VII of the "Godthaab", in addition, the uppermost cold water layer, poor in salt, of the Polar Current is distinctly traceable down to a depth of 25—50 m. The position of this eddy in 73—74° N. lat. is in good accordance with the place of a similar one on Nansen's maps of 1909 and 1924; but this one station supplies too little information about the distribution and direction of the current to enable us to form an opinion as to whether it may be the same as that indicated by Nansen, which is supposed to be the cause of the "Isodden". The Drifting Polar Station 1938 showed a small southward deflection from its southwesterly course precisely in 74° N. lat.; but the drift took place over the banks at a greater distance from the margin, where such a deflection may perhaps be due to other causes.

Amdrup's St. III, July 20th, 1900, was situated 60 miles northeast of St. VII of the "Godthaab". This station, also, has the surface water, poor in salt, of the Polar Current; but neither this nor the other extremely scattered older stations can give any clue as to the fixing of the eddy dealt with here.

Only very few hydrographical observations of the Polar Current are available from the area south of 74° N. lat. In 1932 the "Polarbjørn" took a short section off Franz Josephs Fjord, and some few more southerly stations are recorded by RYDER 1891, NATHORST 1899, and the "Belgica" 1905. But apart from these, no observations are at hand except from much more southerly areas, thus from the Denmark

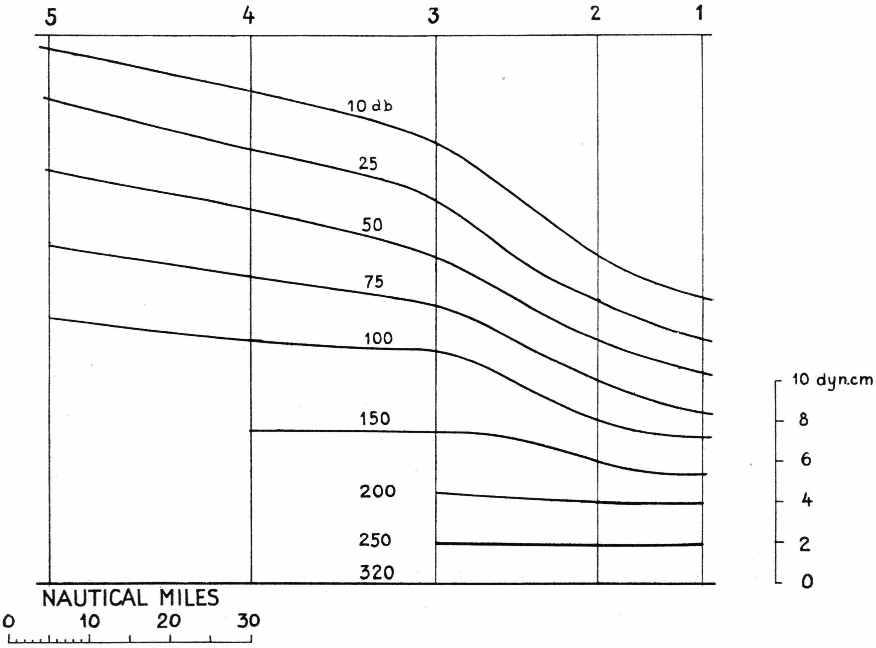

Fig. 17. The inclination of the isobaric surfaces in relation to the 320 db-surface. "Godthaab" 1930.

Strait or from the waters around Iceland and Jan Mayen. In 1933 the German expedition ship "Meteor" did indeed take a couple of well placed sections towards Scoresby Sund and thence northeastward in the direction of Spitsbergen, but this material is not accessible.

In recent years a number of investigations have likewise been made in some of the large fjords and just outside their mouths; they only show, however, that the various layers of the East Greenland Current extend into the fjords to the extent permitted by thresholds, if any such are present.

Our knowledge of this part of the Polar Current must accordingly be very deficient, and nothing new can be added to the earlier descriptions.

It appears from the observations of the "Polarbjørn" that the current is much disturbed during its passage across the submarine fjord and the succeeding banks off Franz Josephs Fjord; but the structure of the current is the same as farther northward, and no essential mixture of the typical Polar water with other water masses has taken place. In 1891 Ryder took two stations in the same place and found the same values for temperature and salinity in the core of the Polar water, but apparently a somewhat greater thickness of the current.

Off Liverpool Land the shelf grows very narrow, decreasing even to 40—50 miles. It might be expected, therefore, that the Polar Current would be correspondingly compressed in width, and that its velocity would be greatly increased. However, while Nathorst's two stations close to the shore show a distribution of temperature and salinity normal to the Polar Current, with the isostheral lines sloping down towards the shore corresponding to a good velocity southward, the three "Belgica" stations, the outermost of which is situated far outside the shelf, likewise exhibit typical Polar water, but no southward movement. The stations were taken in the ice, and in agreement with this both temperature and salinity at the surface were low; however, true Polar water (—c. 1.60°C.; c. 34.20 $^0/_{00}$) was met with at all three stations at a depth of 50 m, precisely as in the outer part of the current throughout its more northerly route.

In the northern regions the Polar Current nowhere spreads out as far over the deep water; but here it extends at any rate 90 miles outside the shelf or half the distance to Jan Mayen.

There is no doubt that this is due to the current moving offshore in great width from Kong Oscars Fjord towards Jan Mayen. A dynamic investigation of the current between Sts. 48 and 49 shows even a slight northward movement of the water no matter at what depth the reference level is placed; possibly, however, this is no constant and typical phenomenon. This is the first large branch of Polar water that is given off from the main current, and from our knowledge of the topography of the sea bottom we must assume that this branch begins as far north as Franz Josephs Fjord.

The eastward continuation of this branch is only traceable the in early observation material (e. g. Mohn, "Ingolf", "Michael Sars", Ryder), the more recent expeditions having chiefly been at work in the neighbourhood of Iceland without reaching the central part of the cold stream.

The Ingolf Expedition is, indeed, that which has collected the most copious observation material, but, as Nansen says (1906, p. 59), the determinations of the salinity are very doubtful and, on account of the methods of computation, at any rate too high. Hence the sections derived from this expedition, though favourably placed, cannot be used as a basis for a detailed investigation of the currents; but for the current picture in its broad features they are of great value. On the basis of various observations from the years 1899—1905 Helland-Hansen and

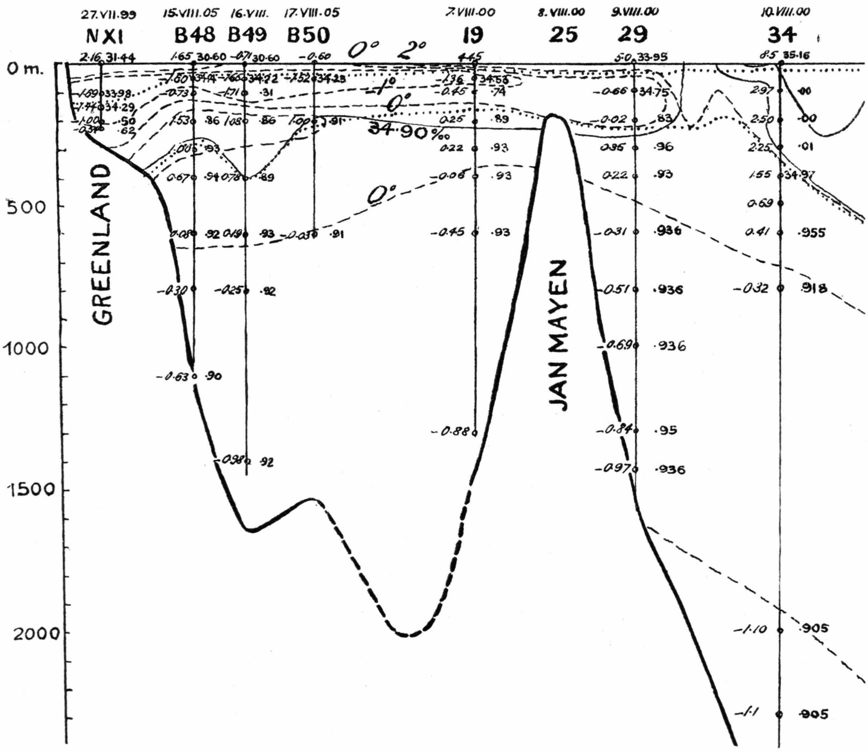

Fig. 18. Hydrographic section from Greenland to Jan Mayen (HELLAND-HANSEN and NANSEN 1909).

NANSEN (1909) drew a section from Greenland to Jan Mayen and another from Iceland to Jan Mayen (Figs. 18 and 19); but apart from these sections and the "Ingolf" sections, the stations are few and scattered (apart from the observations of the "Meteor", 1933).

If we compare the different observations, we obtain a rough picture of the eastward distribution of the Polar Current. It is distinctly traceable, still with negative temperatures, to a little east of Jan Mayen, south of this island to 6°—8° W. long., and southward to just northeast of Iceland; but as a constituent of cold mixed water it may, as mentioned above, be traced right across to the Norwegian coastal banks. The depth of the most characteristic water masses of the current is 50—100 m, or a little more than over the Greenland continental slope; but near Iceland the water layer with negative temperatures sinks to lower levels, getting into communication with the cold bottom water of the Norwegian Sea.

In the northern half of the opening between Iceland and Jan Mayen the water has preserved most of its polar character. The temperature

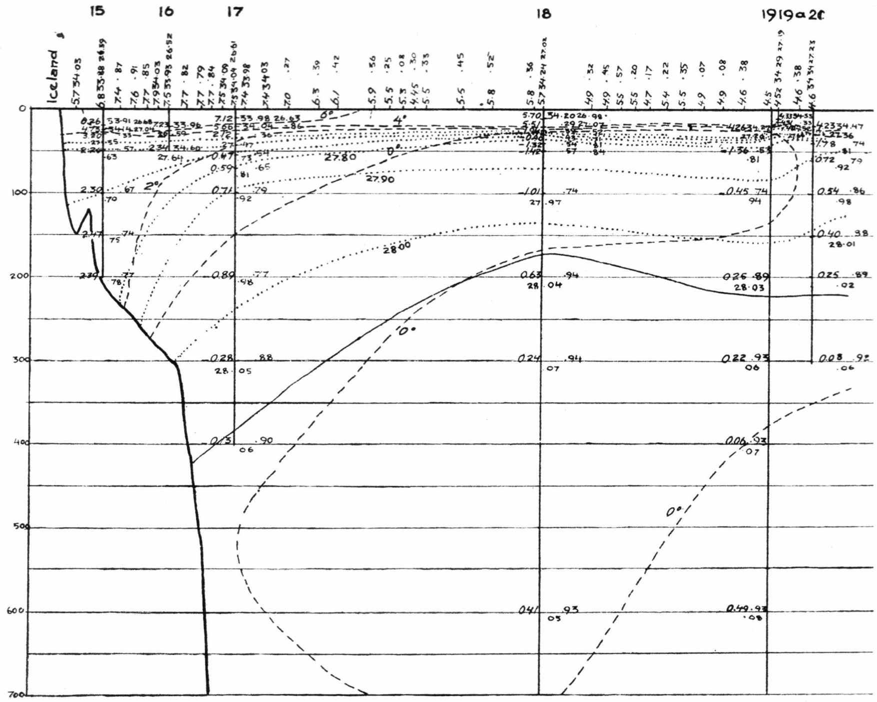

Fig. 19. Hydrographic section from Iceland to Jan Mayen, August 1900. (Helland-Hansen and Nansen 1909).

is still —1.3° C., but the salinity is as a rule more than 34.50 $^0/_{00}$, which shows that the mixture with the subjacent salter water layers (0—0.5° C.; 34.90 $^0/_{00}$) is making itself strongly felt. Actually the Polar water is here so greatly mixed with other water masses that the designation Polar Current should be applied no more. Helland-Hansen and Nansen call it "Arctic water", and they also speak of the "East Iceland arctic current" with a salinity of 34.60—34.90 $^0/_{00}$. Nor does the East Greenland ice follow it eastward in a noticeable degree, but drifts southwestward through the Denmark Strait. The temperature of the surface water in summer rises to 4°—6° C., and the high salinity shows that no material melting of the ice takes place.

The velocity of the current in these upper water layers must be inconsiderable between Iceland and Jan Mayen; however, the observations at hand do not permit any theoretical computation of it. One does not receive the impression that the current is continuous, as it is farther northward, but rather that cold water from the outer parts of the Polar Current spreads slowly eastward and southeastward because the southwestward run-off of the current is impeded. Around Jan Mayen Helland-Hansen and Nansen indicated a current moving in an anticyclonic direction, but the section in Fig. 19 shows that at that time the

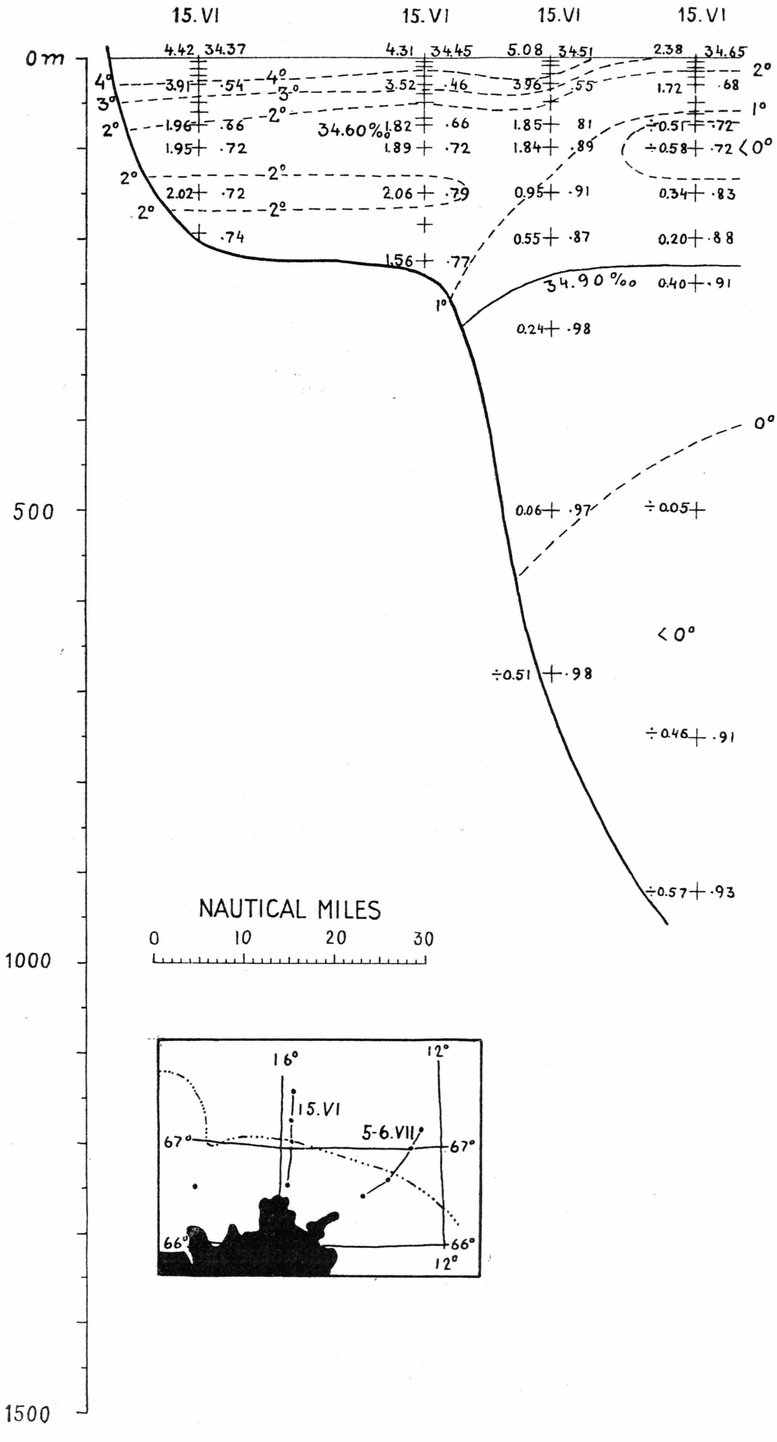

Fig. 20. Hydrographic section northwestward from Rifstangi. ("Rosemary" 1930).

current moved in the opposite direction. It must no doubt be taken for granted that within this mixing area the currents vary considerably from time to time.

Off the northernmost point of Iceland (Rifstangi) the cold arctic mixed water is encountered at a distance of 50—70 miles from the shore, here bordering on the warm coastal current from the west. This current, also, is the result of a mixture of water of different origin, notably the Atlantic water of the Irminger Current, coastal water poor in salt, and cold water from the north, both Polar Current water and water from the Atlantic undercurrent.

Around the northwestern corner of Iceland—on either side of Horn—the Atlantic water still predominates with a salinity of more than 35.00 ‰ and a temperature which in the course of the summer rises to 8°—10° C. Along the north coast of Iceland the Atlantic current receives the different admixtures, so in the region around Rifstangi the Iceland shelf is found to be covered with water with temperatures of c. 2° C. and a salinity of 34.60—34.80 ‰, while the uppermost 50 m are heatened and freshened to some extent during the summer. Figs. 20 and 21 show sections drawn on the basis of data collected by the British ship "Rosemary" in July 1930; here it is more readily seen than in the "Michael Sars" sections that the cold arctic water is forced to remain over the great depths, while the warm mixed water flows over the shelf and in the upper layers a little outside.

Figs. 20 and 21 further show that west of Rifstangi the arctic water still rests on a fairly thick layer of water with a positive temperature, while this layer is only faintly traceable east of Rifstangi, where the arctic water is accordingly in direct communication with the cold bottom water of the Norwegian Sea. The observations of the "Ingolf" also show that the warm intermediate layer decreases in volume and temperature eastward.

The observations repeated from Danish and Icelandic research ships northeast of Iceland show great variations in the hydrographic conditions from year to year and from season to season; it is, however, beyond our task to deal more fully with this question.

The terms "East Iceland Polar Current" or "East Iceland Arctic Current" are usually taken to mean the current that flows along North and East Iceland as a whole. Its polar character mostly consists in that it sometimes carries drift ice down from the Greenland Sea; but the water masses it carries with it are of such diverse nature that it should not be treated as a single current, but might at most be designated by the collective name: the East Iceland Current.

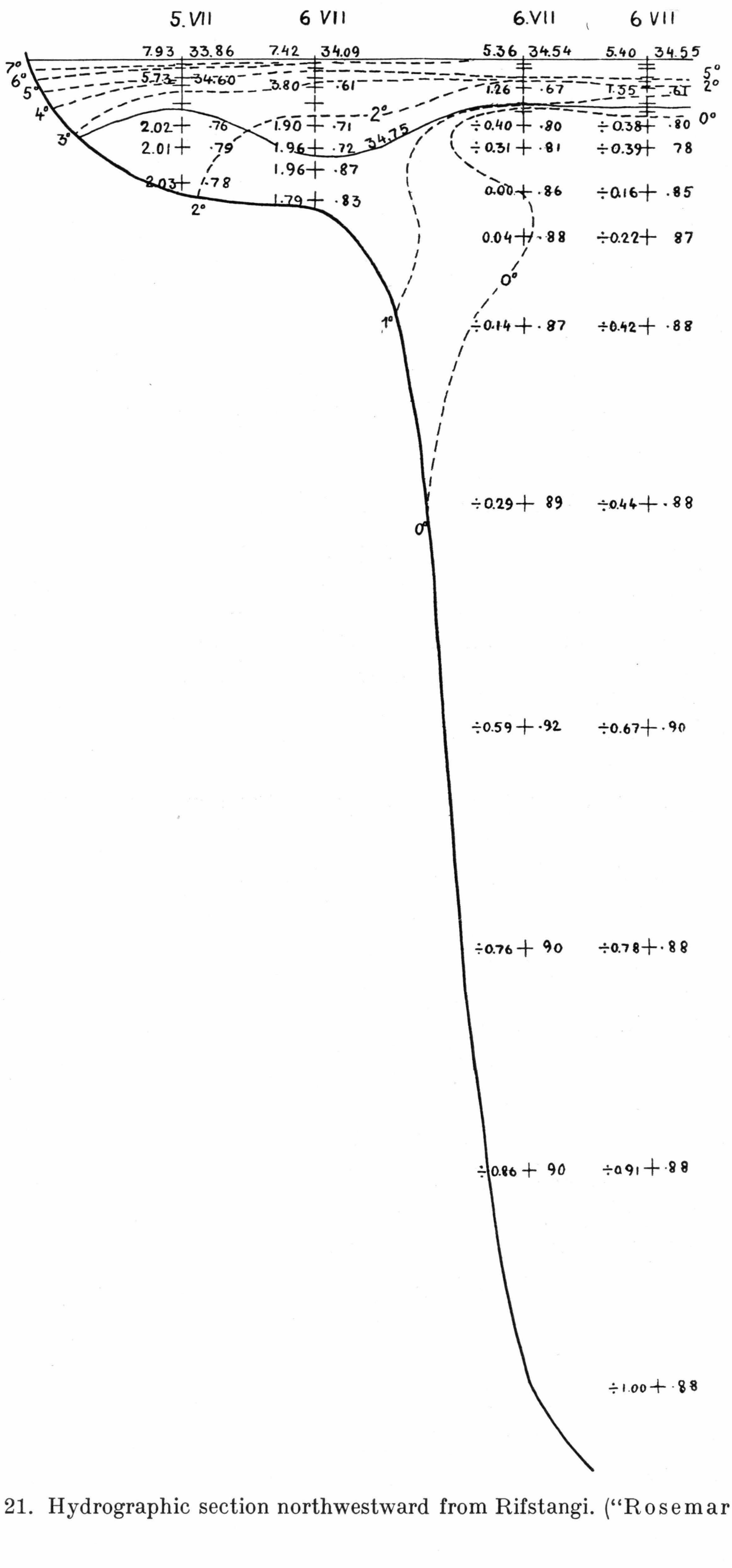

Fig. 21. Hydrographic section northwestward from Rifstangi. ("Rosemary" 1930).

The Atlantic Undercurrent in the Greenland Sea.

The afflux of Atlantic water to the Norwegian Sea and the Greenland Sea takes place almost exclusively between the Shetland Islands and the Faroes at a depth of up to 350—550 m. J. P. JACOBSEN found that in this place the Atlantic water averages 10.2° C. and 35.45 ‰; but even on the ridge it receives an admixture of cold water from the East Iceland Current, which shows on an average 2.5° C. and 34.90 ‰. The total northward transport of this mixed water is computed by JACOBSEN to be 12—15 km^3 per hour, which agrees well with HELLAND-HANSEN's and NANSEN's results.

The main current flows northeastward along the Norwegian continental slope, but it still gives off branches towards the west, so that off Lofoten there is only half as much water of more than 35.00 ‰ as near the Faroe-Shetland channel or, as computed by JACOBSEN, the core of the current here consists only by half of Atlantic water.

North of Norway the main quantity of the Atlantic water bends eastward into the Barents Sea, while the last branch, highly mixed with colder water, continues northward along the west coast of Spitsbergen, where the whalers, as is well known, have from early times benefited by it. HELLAND-HANSEN and NANSEN were of opinion that the characters of this current were very constant from year to year; but H. U. SVERDRUP (1933) shows that this is not the case. North of the northwestern corner of Spitsbergen MOSBY in the "Quest" in August 1931 found 3,18° C. and 35.10 ‰ at a depth of 200—400 m, while in August 1922 DEVIK found 3.70° C. and 35.05 ‰ in the same place at the same depth, and in August 1912 NANSEN found 1.70° C. and 34.90 ‰. Thus in 1922 and 1931 the current must have carried water of a much more Atlantic character than in 1912.

SVERDRUP gives the characters of the Atlantic water off Spitsbergen as 2°—3° C. and 34.99—35.08 ‰ and its depth as 100—500 m. The greater part of the warm water follows the Spitsbergen shelf northeastward, while a weak branch bends westward along the Nansen Ridge to follow the Polar Current southward along East Greenland outside and below this current.

JAKHELLN assumes that this Atlantic water has at first 2.10° C. and 34.97 ‰, these values occurring precisely at the northernmost stations (12—16) of the "Belgica" over the eastern part of the Nansen Ridge and again at some of the stations off Northeast Greenland. As soon as we go westward from Spitsbergen, however, we meet with the warm current at a somewhat higher level than indicated by SVERDRUP, since there it flows over the central cold water masses. At stations 15 and 16 the core lies at a depth of 100—200 m.

The current probably follows the southern slope of the ridge and subsequently the Greenland continental slope; but a considerable branch of warm water seems to flow across the deep sea 1—2 parallels of latitude south of the ridge and in part at a somewhat greater depth.

The core of the Atlantic current is not encountered at the "Belgica" stations near the continental slope in c. 78° N. lat., whereas its influence is strongly felt in both the "Belgica" section and the "Danmark" section towards Danmarks Havn (Figs. 13 and 14). Just outside the continental slope and partly some distance inward over the shelf occurs the warm salt current as a substratum to the Polar water. In 1906 and 1908 the temperature at a depth of 150—250 m rose to well over 1° C. with a salinity of 34.90—34.97 ‰, and in 1905 the temperature at 200—300 m depth was c. 1.5° and the salinity 34.84—34.92 ‰. The observation material does not permit a calculation of the rate of flow in this warm water; there is no doubt, however, that the velocity and accordingly the water transport are much less in the warm undercurrent than in the Polar Current (cf. p. 52).

Through the submarine fjords in the shelf the Atlantic water flows along the bottom right in to the Greenland coast, where positive temperatures will be met with at depths of more than 250—300 m. Thus for instance inside the Belgica Bank in 78°13′ N. lat. 0.61° C. and 34.92 ‰ were observed at the bottom at 490 m on August 1, 1905, that is to say, water which had preserved the salinity of the undercurrent but had been cooled almost by 1°. In July 1908, at a depth of 420 m in about the same place, the "Danmark" found very nearly the same values, and the same was the case with the bottom water in the channel outside Danmarks Havn, though here there was a slight admixture of Polar water. Even the deep water layer of Dove Bugt is of Atlantic origin (0.58° C., 34.87 ‰ at a depth of 350 m).

Ryder, who was the first to ascertain the warm undercurrent and at the same time to give the correct explanation of it, found it in July 1891 off Sabine Ø at two stations at the very edge of the shelf. Outside the shelf it occurred at a depth of 140—170 m, while over the shelf it lay quite close to the bottom at 140 m. The temperature was only 0.4° C. and the salinity 34.79—34.94 ‰. Outside Scoresby Sund Ryder found the undercurrent again with a temperature of 0.5—0.6° C. at a depth of 235—315 m, and the same was the case in the deeper parts of Scoresby Sund.

While, thus, the undercurrent seems to have been somewhat colder in 1891 than in 1905, 1906, and 1908, water of a more unmixed Atlantic character has later been met with, c. 2.15° C. and c. 35.00 ‰ having been found at a depth of 200 m by the "Godthaab" and the "Polarbjørn" in 1930 and 1932. This shows that just as the current west of Spitsbergen exhibits fluctuations in temperature and salinity, considerable fluctuations can also be noticed in the undercurrent off East Greenland. Whether these fluctuations are of a casual, possibly a local character, cannot be determined by means of the existing observation material; but the higher temperature and salinity in recent years are in good agreement with the wider distribution of Atlantic water which has been observed in many parts of the Polar regions during the last few decades.

Along the stretch from Franz Josephs Fjord to Scoresby Sund the warm undercurrent, like the Polar Current, is forced offshore, and there is good reason to assume that by far the greater part of its water continues southeastward either to take part in the mixture of the East Iceland Current or at a greater distance north of Iceland to form the warmer substratum of the cold water of the Polar Current, as is precisely the case west of Rifstangi. In the Denmark Strait the undercurrent is necessarily in the main stopped by the ridge, so only very small quantities of water with the characters peculiar to it leave the Greenland Sea by this route. The East Iceland Current, however, near the margin of the shelf—that is to say, in the same place as the warm undercurrent in the East Greenland Current—contains a fairly large mixed area with temperatures of 0—2° C. and a salinity of 34.75—34.90 ‰ (Figs. 20—21). In this area we must look for the last remnant of the branch of the Gulf Stream which along Spitsbergen and East Greenland now completes its circulation in the Norwegian Sea and the Greenland Sea.

The volume of this Atlantic water in the East Iceland Current must be small as compared with the other water masses which take part in the formation of the current. It has already been mentioned that the water transport in the undercurrent off Greenland is inconsiderable, and only a small part of this reaches Northeast Iceland. On the other hand, practically all water from the northward-flowing branch of the Irminger Current continues in this current, together with surface water poorer in salt.

The Water Transport of the Currents.

It would be of great interest and very helpful in the study of the course of the currents within the area of the Norwegian Sea and the Greenland Sea if we were able to compute the size of the transport of the different water masses. However, such calculations require not only a fairly copious and accurate material of observations, but at the same time the possibility of exactly fixing in each individual place the depth of the reference level; and finally, precisely in these boundary areas there are so many eddies that a theoretical computation of the volume of the currents for this reason, also, will be very uncertain. The hydrographers who have studied these seas, have, indeed, made great reservations on this point, so only some of the most important results will be recorded here.

Through the Faroe-Shetland channel the current transports 4—4.5 million m³ of water per second towards the northeast, but according to JACOBSEN's calculations only 50 per cent of this is pure Atlantic water, the remainder being cold mixed water that has come from the northwest. Off Cape Stad the transport, according to HELLAND-HANSEN and NANSEN, has decreased to 3.8 million m³ per second and off Lofoten to 2.3 million m³ per second. After giving off water to the Barents Sea, the current off the southernmost point of Spitsbergen still carries northward c. 1.5 million m³ of water per second, computed according to ISACHSEN's observations 1910 and with the reference level at a depth of 500 m. Off the west coast of Spitsbergen several branches are given off westward, so SVERDRUP's statement, that the greater part of the water reaching the northern end of the west coast of Spitsbergen bends northeastward, agrees well with MOSBY's calculations, viz. that 0.87 million m³ per second flows eastward along the north coast, all with a temperature of at least 1.5° C.

Thus according to these calculations c. 0.6 million m³ of water, which in these latitudes can be said to be of Atlantic origin, are transported westward from Spitsbergen every second. This is accordingly the beginning of the Atlantic undercurrent along the east coast of Greenland; but part of it is entangled in the circulation over the central parts of the Greenland Sea, and the remainder is constantly somewhat cooled during its passage between the colder water masses.

Through the "Belgica" section in c. 76° N. lat. of 1905 the total East Greenland Current transports c. 1.87 million m³ per second southward (reference level 500 m), and of these c. 0.4 million m³, or only a little over 20 per cent, have a positive temperature. The last-mentioned volume is accordingly the greatest water transport that can be ascribed to the warm undercurrent.

Farther southward, in 74° and 73° N. lat., JAKHELLN found somewhat lower values for the total current in 1931 and 1932, viz. 1.32 million m³ per second with 300 m as the reference depth. However, owing to lack of observations outside the current, he uses the "Belgica" station 23 from 1905 in 77° N. lat. for these calculations also, assuming that the character of the water out here is almost the same at the same season every year though in somewhat differing latitudes. Whether this assumption holds good, we are unable to decide, since no other stations have been taken at the same distance from the current as the "Belgica" stations. The station which lies nearest is the "Godthaab" St. I of 1930 in c. 74° N. lat., but it is situated in the middle of the Atlantic undercurrent, and despite a higher temperature it shows a lower salinity.

Since only part of the Atlantic current is included in the section of the "Godthaab", the computations must, of course arrive at a smaller water transport through this, and with the reference level at a depth of 300 m we arrive at 0.9 million m^3 per second for the whole section. Of this quantity the warm current with positive temperatures transports only the 0.18 million m^3, so the 0.72 million m^3 are derived from the Polar Current proper. The last-mentioned value is much lower than the corresponding one in the "Belgica" section farther northward; but it is difficult to decide whether the difference is due to casual fluctuations from year to year, or whether it is due to the sections having been taken in different places off the coast. We can hardly imagine, however, that such large quantities of Atlantic water should flow outside the "Godthaab" section that the total water transport would increase to the 1.3—1.8 million m^3 per second shown by the sections from the other years. Thus the probability is that the Polar Current exhibits considerable fluctuations in transport from year to year.

In spite of the great uncertainty in these determinations, it is evident that the quantity of water of the Polar Current far exceeds that of the Atlantic undercurrent; however, this was indeed to be expected, the Polar Current being the main outflow of the Polar Sea compensating the influx of Atlantic water, cold bottom water, river water, and possibly a minor inflow through the Bering Strait, and, finally, the precipitation. The Atlantic influx through the Barents Sea and west of Spitsbergen may, according to the values mentioned above, be roughly estimated at c. 2 million m^3 per second; the precipitation throughout the whole drainage area can hardly amount to more than 0.1—0.3 million m^3 per second; but the afflux of bottom water across the Nansen Ridge and the current through the Bering Strait are unknown, though probably of secondary importance compared with the Atlantic Current. The total afflux to the Polar Sea is perhaps nearly 3 million m^3 of water per second.

In my paper of 1939 I estimated the surplus of the southward water transport through the Davis Strait at somewhat more than 1 million m^3 per second, and this agrees fairly well with the values estimated here. The East Greenland Current transports 1.5—2 million m^3 of water per second southward across the Nansen Ridge, the current through the Davis Strait somewhat less.

Cold Deep Water in the Greenland Sea and the Norwegian Sea.

While the aforementioned currents in the Greenland Sea and the Norwegian Sea in the main occur near the shelf, large stagnant cold water masses, which are only slowly replaced, are found in the central parts of the seas. According to HELLAND-HANSEN and NANSEN these water masses occupy two-thirds of the whole basin of the Greenland and Norwegian Seas, the water spreading from the centre to all sides, moving down below the currents. Below the Atlantic Current off Norway the boundary to the south occurs at a depth of 600—650 m, but to the north at 900—1000 m, off Spitsbergen at 800—900 m, and below the East Greenland Current at 600—900 m. North and northeast of Jan Mayen, however, it almost reaches the surface, especially in the winter.

This cold water arises by the mixed water of the upper layers with a salinity of c. 34.90 $^0/_{00}$ in the area between Jan Mayen and Spitsbergen being cooled in the winter to —1.3°— —1.4° C. or an even lower temperature and thus acquiring sufficient density to sink to lower levels. During the sinking the water cannot be further cooled, but will be slightly heated owing to the compression. The lowest bottom temperature, c. —1.4° C., is found below the sinking area proper in 73°—76° N. lat. From this area the temperature of the bottom water rises slightly on all sides in accordance with the fact that the water flows slowly from this area to the other deep parts of the sea (see Fig. 10 and the text p. 24). Even over the Nansen Ridge the cold water of the Greenland Sea slides from depths of 1200—1400 m to sink down in the Polar Sea forming the bottom water of this sea. Hardly any of this cold water flows southward into the Atlantic.

The Denmark Strait.

A submarine ridge, which sharply separates the water masses of the Greenland Sea and the Denmark Strait, extends from Iceland in a west-northwesterly direction to Greenland a little north of Angmagssalik. It is, as a rule, difficult to work in the area owing to ice and rough weather; in recent years, however, it has been rather thoroughly sounded and a good deal of hydrographic material has been collected from it. The most detailed bathymetrical chart was published by H. THOMSEN 1934, and it is on this that our map in Pl. 1 has in the main been based.

Along the greater part of this stretch the depth of the water is less than 300—400 m, but some distance east of the middle a narrow channel with a depth of c. 550 m intersects the ridge. It has long been known and is, for instance, indicated almost alike by NANSEN 1924 and THOMSEN 1934; according to observations made from the "Heimland I" in 1933, however, the deepest area near the northern end of the channel seems to lie somewhat farther eastward, so the distance from this point to Iceland will be less than one-third of the width of the whole strait. On the northwestern end of the ridge, c. 30—80 miles from the Greenland coast, lies the Øst Bank with depths of c. 150 m, while a channel with water 500—600 m deep extends close to the shore. In addition a deep with more than 400 m of water extends from the south into the western part of the ridge in the direction of Kangerdlugssuak, possibly right in to the channel along the shore. South of the ridge the sea bottom descends steeply to more than 2000 m, and along the Greenland coast farther southward the shelf is generally less than 60—80 miles broad.

The East Greenland Polar Current flows in great width southward towards the northern entrance of the Denmark Strait, covering not only the Greenland shelf, but also the whole channel as far as the edge of the Icelandic shelf. On account of the configuration of the sea bottom, a very complicated current picture, varying from time to time, arises at the meeting of the cold current from the north and the Irminger Current from the south.

The section in Fig. 22 has been drawn on the basis of observations made from the "Heimland I" in July—August 1933, and shows a typical example of the distribution of the water masses at the northern entrance to the strait. Close to the coast of Greenland the current probably always moves southward with Polar water somewhat mixed with thaw water. The temperature minimum of c. —1.4° C. occurs at a depth of 50—100 m and coincides with a salinity of 33.00—33.50 ‰. As the Øst Bank forces the Polar Current out to the sides, a branch of the Irminger Current is able to push northward through the Kangerdlugssuak deep so that the bank is even at times flooded by Atlantic water; but at other times—as for instance in August 1933—the warm current only flows partially around the bank, while cold water remains over its top.

The remaining part of the Polar Current flows east of the bank, and gathered or split into branches it dominates in the uppermost 200—300 m above the deep channel. As in the western part, the temperature minimum is c. —1.4° C., but the salinity is in part, though very irregularly, somewhat higher, 33.00—34.00 ‰.

The main branch of the Irminger Current with pure Atlantic water of a temperature of more than 7° C. and a salinity of c. 35.20 ‰ is seen in the eastern side of the section. It flows northward at a rapid rate, following the Icelandic shelf.

Below the Polar Current, at a depth of 300—400 m, we refind the Atlantic undercurrent of the East Greenland Current. It has preserved its characters fairly unaltered along the whole Greenland coast, still presenting temperatures of 1.25°—1.60° C. and a salinity of 34.93—34.97 ‰. South of this section the Atlantic water is traceable as far as the deep channel cuts its way into the ridge, but immediately south of the highest crest of the ridge it is replaced by warm Atlantic water of the Irminger Current. That small quantities of the water of the under-

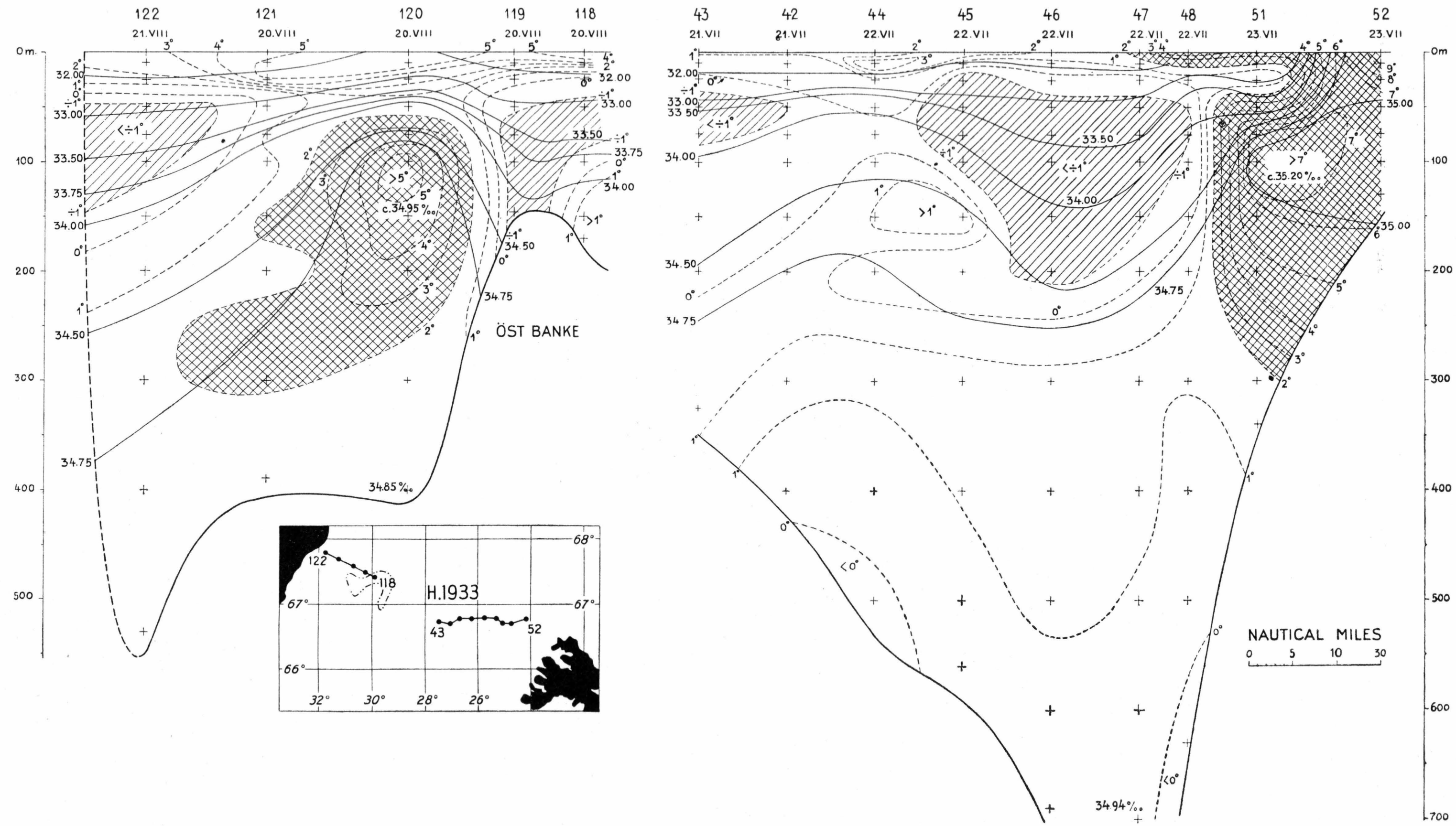

Fig. 22. Hydrographic section across the northern part of the Denmark Strait. "Heimland I" 1933.

current may from time to time flow southward across the ridge, is quite natural. In different observation material, e. g. in that of the "Dana" 1932, it is found along the bottom at great depths, to which it sinks on account of its great density as compared with the Atlantic water; but in higher layers also, in which the water of the Polar Current is mixed with that of the Irminger Current, its presence can be ascertained by means of TS-diagrams. Nansen (1912—13) was of opinion that it crossed the ridge in such great quantities that it was of essential importance for the formation of bottom water in the Atlantic; recent observations, however, do not seem to suggest this.

While Polar water predominates on the north side of the ridge, the south side is dominated by the Irminger Current, which in the Atlantic is split off from the Gulf Stream towards the Northwest, to flow in the direction of the southwestern corner of Iceland. It is stopped throughout the greater part of its width by the Reykjanæs Ridge, though this ridge occurs at a depth of 1500 m; but close to the Icelandic coast it continues across the ridge until, on approaching the Iceland-Greenland Ridge, it is deflected westward and southwestward. In contrast to the warm undercurrent, which bends westward from Spitsbergen to join the East Greenland Polar Current, the Irminger Current is a very warm and huge current. As regards its origin it is rather to be regarded as a surface current; still it extends down to considerable depths, and after it has met the East Greenland Current, it is in its somewhat deeper parts that the original characters are best preserved.

The boundary line between the cold water poor in salt of the East Greenland Current and the warm and salt water of the Irminger Current runs in the middle of the Strait almost along the 66th parallel, that is to say, a little south of the highest part of the ridge. Slightly west of the middle, however, the Atlantic water sends off the aforementioned tongue into the Kangerdlugssuak deep, and since this current depends on the topography of the sea bottom, it may be found every year.

Farther south along the coast of Greenland the boundary between the warm and the cold water runs near the edge of the shelf, but with an extensive formation of eddies. A number of the eddies are probably conditioned by the configuration of the sea bottom and are accordingly constant; but others move like the eddies along the Polar front in the atmosphere.

In the cyclonic eddies along the boundary line the water is sucked up from greater depths. This water contains less oxygen than the surrounding water, but at the same time it contains an abundance of inorganic nutritive salts, of which only inconsiderable quantities are found in the pure Polar water or in the surface water of the Irminger Current.

By this mixture the Irminger Current gradually loses part of its Atlantic character in the upper layers; but since it commands much larger water masses than the Polar Current, this reduction of temperature and salinity takes place very slowly. At mid-summer 6°—9° C. and more than 35.00 ‰ are found at the surface in several cases not only during the westerly flow of the current, but also far southward along the coast of Greenland.

Along the whole course mentioned here the Irminger Current is very broad and it is difficult to fix its external boundary. Only at a few hydrographic stations far out in the Irminger Sea does the salinity at the surface decrease to less than 35.00 ‰.

Off the southernmost part of the east coast of Greenland a branch is probably given off towards the southeast to take part in a cyclonic movement in the Irminger Sea; but a very vigorous branch moves around Kap Farvel, and in this place it still exhibits values of temperature and salinity which are not very much lower than those met with farther up the east coast.

In the early summer the uppermost 100—200 m of the warm current, where the admixture of Polar water is greatest, off Kap Farvel exhibit a temperature of 3°—5° C. and a salinity of 34.00—34.75 ‰; but the core of the current lies at some depth—in warm years at 200—400 m, in cold years somewhat deeper—and here the temperature is, as a rule, 4°—5° C. and the salinity 34.75—35.00 ‰. In the course of the summer the temperature of the upper water layers increases, as a rule to 6°—8°, at greater depths to 5°—6° C.; the salinity, however, will often show somewhat lower values.

Between this warm current and the southeast coast of Greenland flows the Polar Current. Just at the southern slope of the ridge, as stated above, it is forced entirely towards the Greenland coast. The boundary between the cold and the warm current is very irregular; but here in the northern part of the strait it almost coincides with the ice edge or the isohaline for 34.00 ‰, while the surface temperature may vary rather considerably from year to year independently of the extension of the ice. As in the Greenland Sea, we may use the 0° isotherm as the lower limit; this isotherm here lies between the 34.00 and 34.50 ‰ isohalines. Subsequently the thickness of the Polar Current near the ridge and the first distance along the south coast of Greenland will generally be 100—200 m.

The Polar Current decreases so much in width southward along the coast that it does not always reach as far as the edge of the shelf. Several times it shows a tendency to splitting into two parts with warmer water between, probably owing to inequalities of the sea bottom; Tåning (1934), however, is of opinion that near the edge of the shelf a ridge or a series of banks runs parallel to the coast, by which the area of the two currents is fixed in all essentials. During its southward course the depth of the current, according to the observations of the "Dana" 1933, decreases from c. 200 m to c. 100 m near the southernmost point of Greenland, and at the same time the temperature minimum decreases from — 1.33° (100 m) to — 0.64° C. (50 m), all owing to an admixture of Atlantic water. If we used the 0° isotherm as the outer limit of the Polar Current at the surface also, we should find that in all the "Dana" sections it would have a width of 15—18 miles; but along the stretches where the width of the shelf exceeds this figure, there occurs outside the cold water a mixing zone in which the upper water layers have a salinity so low that it may justifiably be regarded as belonging to the Polar Current. In the northern part of the area the 34 ‰ isohaline at the surface in August 1933 occurred twice as far from the shore as the 0° isotherm in the core of the current. And if we visit these places in the autumn, we may possibly find that the area of the negatively temperate water has been much reduced or has perhaps disappeared entirely and yet we must still speak of the East Greenland Polar Current on account of the origin, flow, and ice transport of the water.

Unfortunately not very many observations are available from the Polar Current off Kap Farvel, but the water masses that pass around this cape to move northward along the west coast may be roughly characterised as follows: In the upper layers the temperature is negative in early summer nearly throughout the whole width of the current, but towards the end of the summer the water has been heated so much that negative temperatures are only found within a very small area close to the shore or they even disappear entirely. In some years the temperature may rise to 2°—3° or even to 4° C. in water which on account of its flow and salinity should still be referred to the Polar Current. The salinity is as a rule 32.00—34.00 ‰, and if the limit of the Polar Current off Kap Farvel is fixed at the 34.00 ‰ isohaline, it will have a width of 30—50 miles in the upper water layers, that is to say, perhaps a little more than off the southern part of the east coast. At greater depths it does not extend so far out from the shore, though nearly always so far that it touches the coastal banks.

A theoretical computation of the velocity of the currents in the Denmark Strait cannot be made on account of the many eddies, owing to which the course of the reference level, also, will be irregular. The south-flowing current along Greenland and the north-flowing current along Iceland are plainly visible in the solenoid fields, but a computation of velocity and water transport will be too uncertain.

By direct observations, however, for instance of the drift of ships that have been beset by the ice or of the ice drift itself, we may gain some information about the currents.

In 1777 the shipwrecked whalers drifted through the Greenland Sea at an average rate of 12 miles a day, but in the Denmark Strait the rate increased to 18 miles. In July 1888 NANSEN drifted in the "Viking" along the southeast coast of Greenland close to the shore at an average rate of 24 miles a day, but on most days the rate was 26—27 miles. In the winter of 1869—70, however, the "Hansa" people drifted along the whole east coast at a rate of only 4—5 miles a day. These and other observations show that the rate of the drift is greater in the summer than in the winter; but at the same time the distance of the drift from the shore is of great importance, as in the Greenland Sea.

On the basis of the ice drift EJNAR MIKKELSEN (1922) computed the velocity of the current between Angmagssalik and Kap Farvel and found that it averaged 5.6 miles a day, though varying between 4 and 16 miles; and J. N. NIELSEN (1928), computing the rate of the Irminger Current, found its average rate along the stretch between the northern part of the Denmark Strait and Fiskernæsset to be c. 8 miles a day.

By far the greater part of the ice which is carried southward by the current through the Greenland Sea, drifts with it towards the Denmark Strait, while only a small quantity drifts towards Iceland. Off the south coast of Greenland the strong current usually makes the ice belt more open; but in addition the melting is now so far advanced that most of the ice originating from the Greenland Sea has disappeared. Nearly all the ice that passes round Kap Farvel originates from the Polar Sea.

At the end of the summer the afflux of ice from the north ceases, and for some months (August—October) the sea off Angmagssalik may be ice-free to a greater or smaller extent. In the autumn (November) the ice appears again and is then periodically continuous with the coast ice of the winter. Generally the ice reaches Kap Farvel after the middle of January; it must accordingly be ice which has left the Polar Sea or the Greenland Sea some time during the past summer; this icy period lasts till the end of next summer.

We have now followed the East Greenland Current from its origin near the northern boundary of the Greenland Sea to its disappearance from the East Greenlandic waters round Kap Farvel.

Along the whole distance it consists of two typical water masses: Polar water and Atlantic water. North of the Iceland-Greenland Ridge the Polar water predominates, while south of the ridge the Atlantic water is dominant. The Polar water flows as a broad current from the Polar Sea in the north and between 80° and 78° N. lat. receives several larger or smaller branches of Atlantic water from the east from the Spitsbergen Current. This warmer water will settle below and outside the Polar water, and without mixing in any noteworthy degree, the two currents flow southward side by side through the Greenland Sea.

In the present paper all the cold Polar water has, as is usual, without further discussion been considered as coming from the Polar Sea; possibly, however, a more detailed investigation will show that the core of the current is to a certain extent constantly renewed by the sinking of cold water from the surface during the formation of ice in the winter within the northern part of the Greenland Sea. For it is a striking feature that the same low temperature, c. —1.7° C., can be preserved, at any rate as far as Scoresby Sund, in a so comparatively thin water layer between the surface layers, heated in the summer, and the underlying warmer water. The velocity of the current ascertained at the surface might, in fact, justify us to assume a complete renewal of the cold water from the Polar Sea every year; but the velocity of the current decreases very rapidly with the depth, and, as a matter of fact, it is only a small quantity of the water which constantly has the same rate as the main current. During the passage through the southernmost part of the Greenland Sea the temperature of the Polar Current rises by some tenths of degrees.

The warm undercurrent has no possibility of supplementing its water masses in the Greenland Sea; but since there is evidently only a sparse development of eddies along its boundaries, it loses only little of its heat during its passage from northern Greenland to the Denmark Strait or northern Iceland. Since, moreover, its water transport is only a fragment of that of the Polar Current, its heating influence on the surrounding water masses is negligible.

South of the ridge it is the warm current that dominates, partly because of its considerable water transport owing to its great thickness and partly because of its high degrees of heat. The Polar Current is squeezed in between this current and the shore, and on account of mixing along the boundary surface and conduction of heat from above it is constantly losing a great deal of its original polar properties, so on passing round Kap Farvel it is a small seasonally varying remnant of the huge outflow from the Polar Sea.

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Færdig fra Trykkeriet den 23. Maj 1945.

PLATES

Plate 1.

Bathymetrical map of the Greenland Sea.

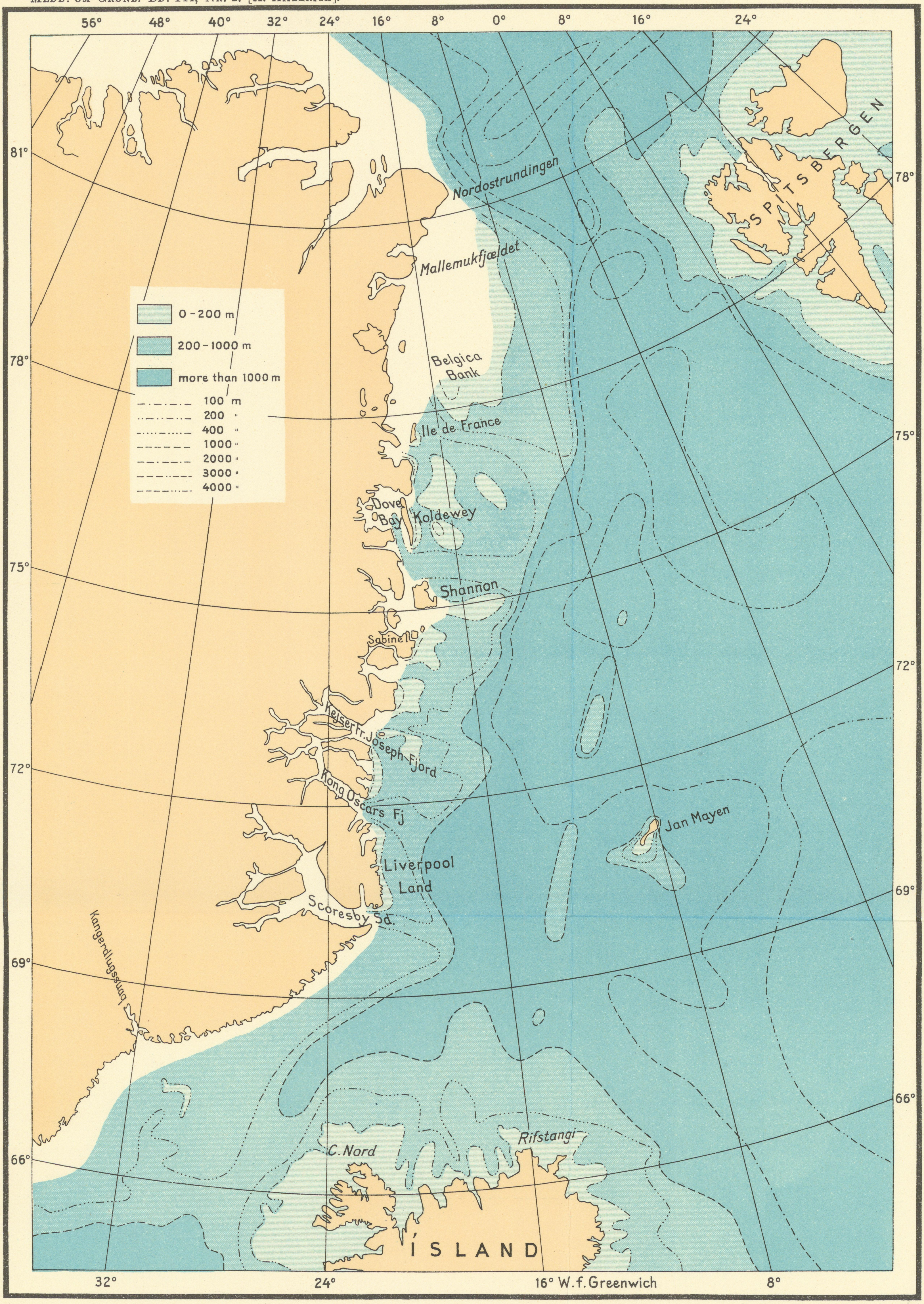

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Plate 2.

The most important hydrographical stations and sections used in the present work:

R 8—27	Ryder 1891.
I 110—129	"Ingolf" 1896.
N 6—12	Nathorst 1899.
A III	Amdrup 1900.
MS 15—29	"Michael Sars" 1900.
A 16—23	Amundsen 1901.
B 11a—50	"Belgica" 1905.
D 3—9	"Danmark" 1906.
D 73—79	"Danmark" 1908.
Is 4—29	Isachsen 1910.
G I—VII	"Godthaab" 1924.
G 1—5	"Godthaab" 1930.
R 15 VI and 6 VII	"Rosemary" 1930.
Na 1—9	"Nautilus" 1931.
P 1—5	"Polarbjørn" 1931.
P 14—28	"Polarbjørn" 1932.
H 30—136	"Heimland I" 1933.

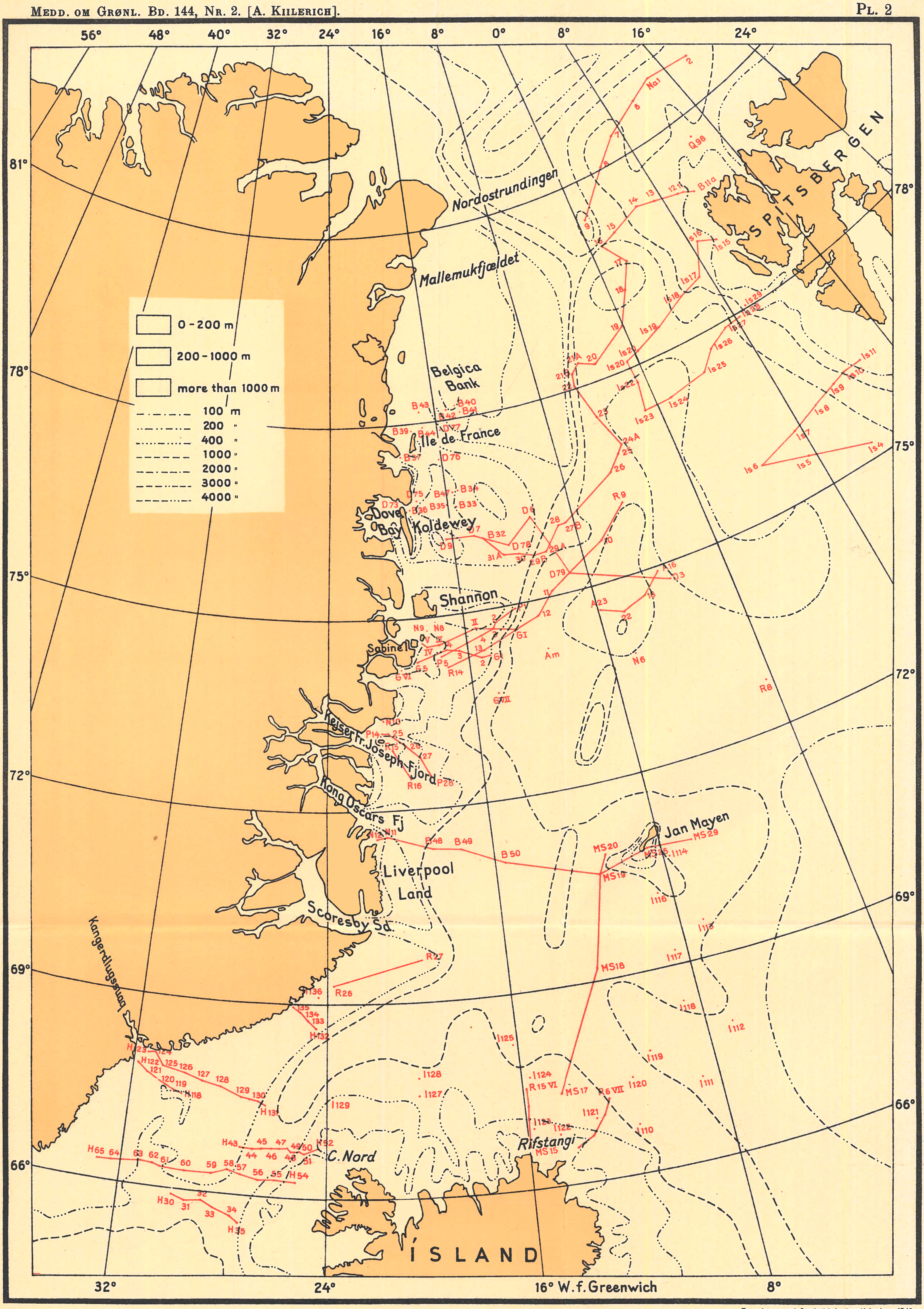

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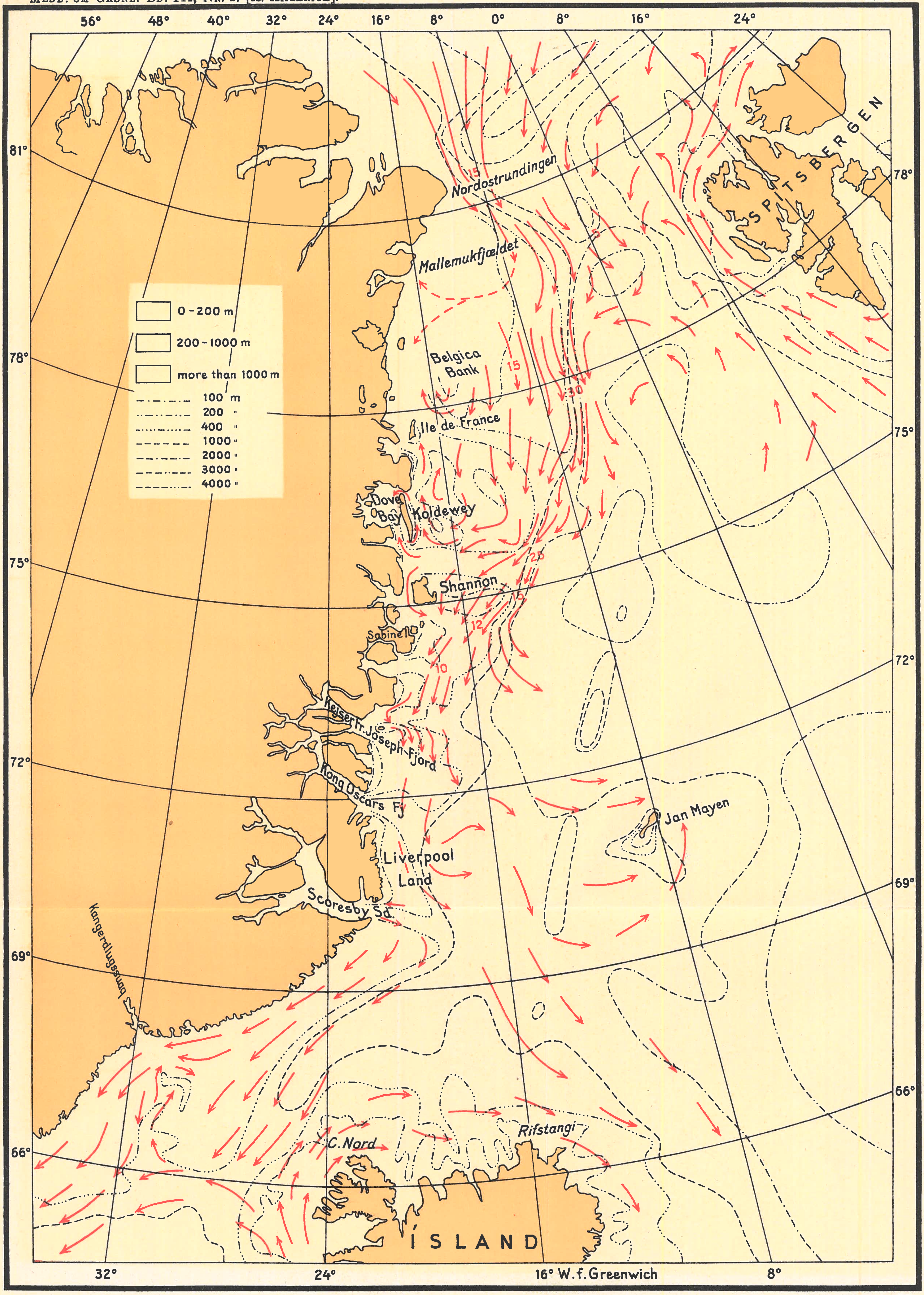
Plate 3.

The currents in the upper water layers. Where dynamical computations could be made, the chart applies to dephts of 10 m. The remaining parts of the chart have been drawn on the basis of ordinary hydrographic sections or the drifts of ice or ships. The velocity of the currents is indicated in cm/sec.



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