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THE ICELAND-FAROE RIDGE INTERNATIONAL (ICES) "OVERFLOW" EXPEDITION, MAY-JUNE, 1960.

AN INVESTIGATION OF COLD, DEEP WATER OVERSPILL INTO THE NORTH-EASTERN ATLANTIC OCEAN

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En Commission chez
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COPENHAGUE

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Assembly of research ships at Vestmanhavn, Faroes, 29 May, 1960.

Table of Contents

CHART PLAN OF THE EXPEDITION

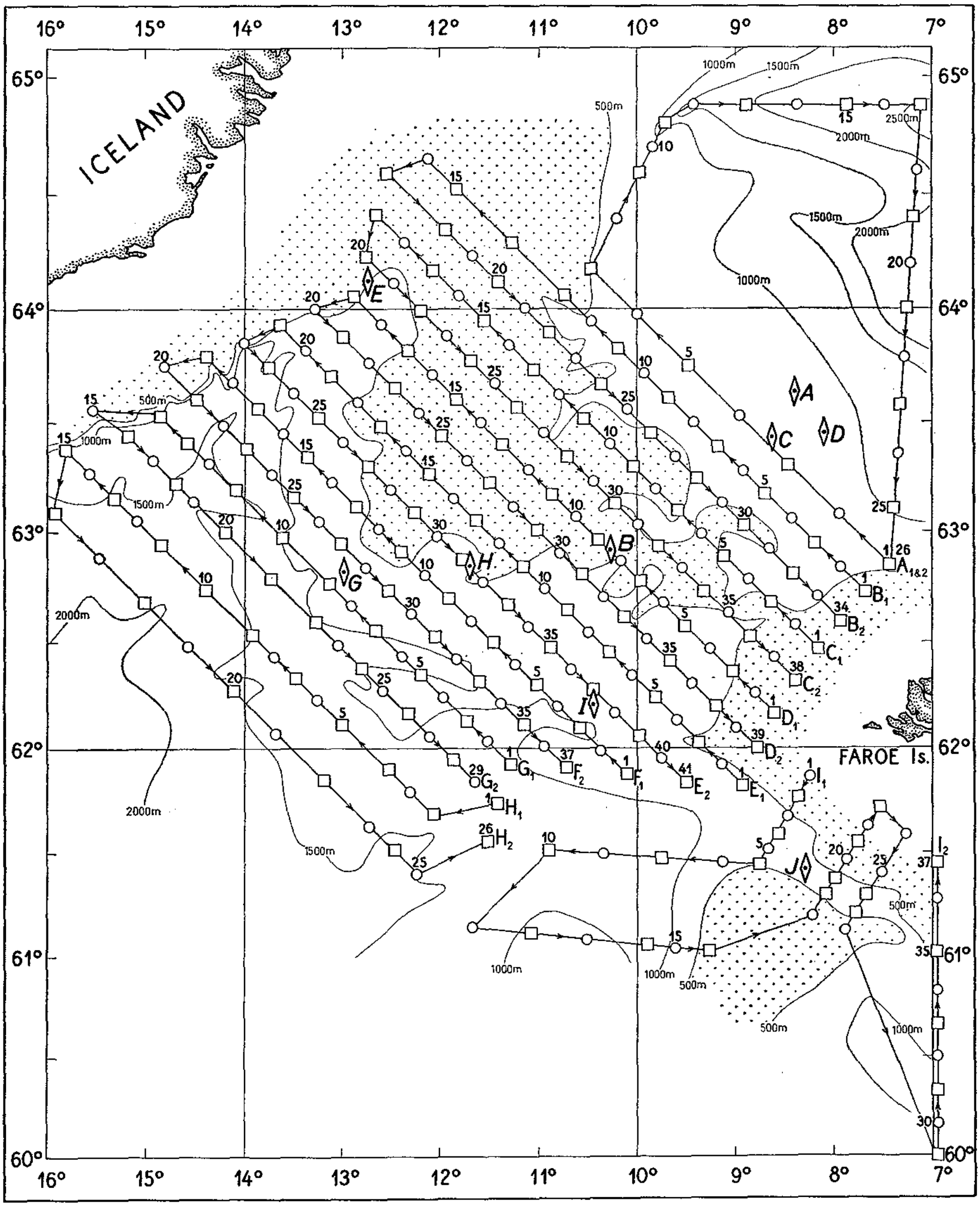

Figure 0:1. Chart plan of the Iceland-Faroe Ridge International (ICES) "Overflow" Expedition, May-June, 1960, showing the course followed by each participating research ship on each survey, and the approximate observation-stations on each course, also stations (diamond stations) for special observations. The Ridge is shaded between 500m bathymetric contours.

INTRODUCTION

PREVIOUS INVESTIGATIONS

From observations of the Danish "Ingolf" Expedition, 1895–1896, KNUDSEN (1899)[1] deduced the phenomenon of deep, cold-water overflow from the Norwegian Sea into the North Atlantic Ocean across the Greenland-Iceland and Iceland-Faroe submarine ridges. His deduction relative to the Iceland-Faroe Ridge stemmed from bottom hydrographic observations at two stations in particular, Nos. 42 and 43, situated approximately on latitude 61°40′N and about 5 to 8 miles west of longitude 10°W, that is, in the light of subsequent investigations, rather more in the path of cold bottom water effluent from the Faroe Bank Channel than in the region of influence of overspill from the Iceland-Faroe Ridge.

HELLAND-HANSEN and NANSEN (1909), from Danish observations in August 1903, demonstrated the existence at that time on top of the widest part of the Ridge from north to south, of a bottom layer, almost 100 metres thick, of cold Arctic-type water. NANSEN (1912) also illustrated, thermally, the actual overflow phenomenon from observations collected by "Frithjof" in July 1910, combined with those of "Thor" station D 16 of August 1903 and of "Michael Sars" station 46 of 1. September 1903. The section through these stations traversed, longitudinally, the narrowest part of the Iceland-Faroe Ridge near its northwestern limit over against the steep slope of the Icelandic shelf. Also, in view of the report to follow, it is germane to note NANSEN's further statement that deep water of the North Atlantic Ocean is to some extent derived from outflow from the Norwegian Sea through the bottom of the Faroe-Shetland Channel.

Citing NANSEN's overflow illustration, COOPER (1952) links with it, by way of substantiation of NANSEN's result, observations at "Dana" stations 5954–5957 in July 1938. It is important to observe, however, as will be evident in the following, that these stations, practically on latitude 62°N and almost between longitudes 11°W and 13°W, were situated in a different region, geographically and topographically, from those of the Nansen section, and again, as in the case of the "Ingolf" stations above-mentioned, more likely to be influenced primarily by effluent from the Faroe Bank Channel than by overflow from the Iceland-Faroe Ridge.

In a further paper, COOPER (1955) refers, hypothetically, to the overflow phenomenon as a discontinuous, intermittent, process, yielding large but discrete "boluses" of cold, heavy water to the northeastern Atlantic Basin.

Followed, in 1955 and 1956, investigations by "Anton Dohrn", which, as reported by DIETRICH (1956 and 1957) not only illustrated the overflow process, as at 5.–6. July 1955, practically along the same section as the Nansen section of 1912, but also substantially corroborated COOPER's hypotheses, with the additional rider that, when it did take place, the deep water overspill was probably restricted to limited parts of the Ridge determined by variations in its summit level.

Also in 1955 and 1956, detailed investigation of the region was undertaken by "Sevastopol" and "Rossya", the results being reported by VINOGRADOVA, KISLYAKOV, LITVIN, and PONOMARENKO (1959).

Subsequent investigations have included one by "Explorer" early in August 1958 during which STEELE (1959) revealed substantial overflow on a different part of the Ridge from the Nansen and Dietrich demonstrations above-cited. "Explorer" further proved the complete absence of overflow in the same region seven weeks later.

ORIGIN AND PLAN OF THE ICES EXPEDITION

In April 1956, at the instance of the International Association of Physical Oceanography, Dr. G. BÖHNECKE submitted, as an oceanographical problem of general importance requiring international collaboration for its solution, the problem of "Variations in the Overflow of Submarine Ridges". As special areas of investigation he cited (i) the Iceland-Faroe Ridge and (ii) the Greenland-Iceland Ridge, recommending (i) for first attention.

Six months later, as its Chairman, BÖHNECKE raised the problem for discussion in the Hydrographical Committee of the International Council for the Exploration of the Sea. Because of its obvious relation to important European fisheries and their problems, as well as of course its scientific interest, the problem was readily accepted by the Council as one for which it should accept responsibility.

Under the charge of a sub-committee[2] of the Council's Hydrographical Committee, a plan of investigation was formulated on the basis of the number of ships available. These, with certain particulars referring to the narrative plan following, are listed in Table 0:1.

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[1] For References see page 100.

[2] Messrs DIETRICH, HERMANN, and TAIT in the first instance, later supplemented by the co-option of Messrs EGGVIN and PREOBRAGENSKY, and ultimately including also the scientific leaders, Messrs ADROV, JOSEPH, LEE, STEFÁNSSON, SÆLEN, and COX, of the several participating ships. The sub-committee could meet only at infrequent intervals, its business being conducted largely by correspondence. At the same time it is fitting that the invaluable help which was received by way of professional advice, materials, accommodation, etc., from interested individuals and bodies should here be recorded.

Table 0:1
Information about participating ships

Country	Name of ship	Correspondent	Radio callsign and wave length	Navigational aids	Cruising speed (knots)	No. of scientists	Expedition course	Diamond station: Designation	Diamond station: Operations	Salinities by	Si., O., P.	Bottom observations by	Meteorological observations	Biological observations	Other observations
U.K. (England)	"Ernest Holt"	A. J. Lee	GFXD 2431 K/s 123·4 m	Loran, Decca, D.F.	10	6	D	B	mid and bottom currents, Pisa and totalizing current indicator	Salinometer	Si. O.P.	Photography	All ships standard routine meteorological observations	–	Sedimentation t°/depth recorder to 500 m
–	"Discovery II"	F. Hermann	GWVM 2431 K/s	Loran Decca, D.F.	8	8	H	G	mid and bottom currents, Pisa	Salinometer	Si.	Corer, Photography		–	Wave recorder, Secchi disc
Federal Republic of Germany	"Anton Dohrn"	G. Dietrich	DBFO 1665 K/s	Loran Decca, D.F.	10	15	G	H	bottom current by electric recorder, Pisa	"Gauss"	Si. O. P.	Corer, Grab, Photography		Plankton and trawl (after expedition)	Secchi disc
–	"Gauss"	J. Joseph	DBFB	Loran Decca, D.F.	9	9	C	E	bottom current by Pisa, also electric recorder	Salinometer	Si. O. P.	Grab		Seston	Transparency temperature, Secchi disc
Iceland	"María Júlía"	U. Stefánsson	TFLB	Loran	10	–	E	C	internal waves	"Ernest Holt"	O.	–		Plankton	
Norway	"Helland-Hansen"	O. Sælen	3YAI	Loran, D.F.	10	6	F	I	mid and bottom currents, by Ekman and Pisa	"Johan Hjort"	Si. O.	Grab		–	Secchi disc
–	"Johan Hjort"	J. Eggvin	JWUW 3217 K/s	Loran, D.F.	11	6	B	D	internal waves, mid and bottom currents	Salinometer	Si. O. P.	–		–	Secchi disc
U.K. (Scotland)	"Explorer"	J. B. Tait	MLBG 2306, 2431, 2231, 2226 K/s	Loran, Decca D.F.	10	5	I	J	mid and bottom currents, Pisa	Salinometer	Si. O. P.	Corer		Plankton	Secchi disc, Bottom temp. recorder
U.S.S.R.	"Perseus II"	M. M. Adrov	UNZB	D.F.	10	12	A	A	internal waves	"Explorer"	Si. O. P. N.	Corer and Grab		Plankton	Acoustic location of fish shoals

PLAN FOR THE INVESTIGATION OF COLD, SUB-ARCTIC, DEEP WATER OVERSPILL INTO THE NORTH ATLANTIC OCEAN FROM THE ICELAND-FAROE RIDGE

1. The investigation is a corollary to the Polar Front Survey investigations of the International Geophysical Year.

2. The investigation will be carried out between 30. May and 18. June, 1960, inclusive.

3. The following research ships will participate in the investigation:–

Ship A. "Perseus II" (U.S.S.R.)
– B. "Johan Hjort" (Norway)
– C. "Gauss" (Federal Republic of Germany)
– D. "Ernest Holt" (England)
– E. "María Júlía" (Iceland)
– F. "Helland-Hansen" (Norway)
– G. "Anton Dohrn" (Federal Republic of Germany)
– H. "Discovery II" (England)
– I. "Explorer" (Scotland)

4. All ships will assemble at Vestmanhavn, Faroe, between 0000 hours and 1200 hours, GMT, on 29. May, 1960. A council of the leading scientists of each participating ship will be held on board "Explorer" at 1400 hours on 29. May, 1960. A meeting of the radio-operators of the participating ships will be held on board "Ernest Holt" at 1800 hours on the same day. Thereafter, the several ships will disperse to their respective starting-points to commence the first survey of the region on 30. May, 1960, ships A, B, C, D, E, and I, at 0600 hours, ship F at 0900 hours, and ships G and H at 1200 hours, all times GMT.

5. The accompanying chart, (Figure 0:1)[3] shows the positions of the 307 stations of the survey. Positions are arranged in close and approximately parallel sections, and are linked in nine courses corresponding to the number of ships participating. Starting-positions are denoted by A_1, B_1, C_1 ... etc. and finishing positions by A_2, B_2, C_2 ... etc. Table 0:2 gives the approximate distances, in nautical miles, of the starting and finishing positions from the rendezvous of Vestmanhavn, as well as the approximate lengths of the courses and the numbers of stations on each course, with a breakdown of these numbers within given depth-ranges:–

6. Station-positions, except on Course I, have been determined with respect to the brown lanes of the Loran navigation lattice, which is the best position-fixing navigational aid for the greater part of the region to be surveyed. Loran would appear in fact to be almost an essential requirement on each ship for this investigation, even if the equipment is only on loan for the period, unless those ships which are not so equipped can, by intercommunication with Loran-equipped ships, check their positions with the latter.

The major part of the investigation area falls within good Loran fixing coverage. The accuracy should be of the order of one mile, but falls off rapidly northward of latitude 64°N. Almost the entire area falls within the limits of British Admiralty Chart L. 5312 (Loran). This is on a scale of 1/1,000,000. The adjacent area to the north and east appears on British Admiralty Chart L. 5323 (Loran) which is on the scale of 1/2,500,000.

7. For purposes of accurate depth-chart construction, a continuous record of the depth of the sea floor will be taken on all courses, and preserved. These records should be annotated at quarter-hour intervals, also at maximum and minimum points, by specific entries of the actual depths registered. They should also bear annotations of station-positions and the times (GMT) spent at each station.

8. The essential observations to be taken at all stations, except certain "diamond" stations (see below), shall be those of *temperature and salinity*. At the stations denoted by an open square on Figure 0:1 and asterisked in the accompanying Lists of Station Positions, temperature and salinity observations will be taken at all standard depths,[4] except that a single observation at 25 metres will be substituted for observations at 10, 20, and 30 metres. At stations marked by an open circle on the chart, temperature and salinity observations will be taken at 0, 100, 300, 400, 500, and 600 metres, thereafter at 200-metre intervals to 1,200 metres inclusive, then at 1,500 metres and at 500-metre intervals thereafter. *At all stations*, observations will be taken as near to the bottom as is practicable,[5] *and* at 25-metre intervals in the last 100 metres to the bottom, also at 25-metre intervals through discontinuity-layers (Sprungschichten).

9. Additional observations to be made at certain stations, within the time occupied by the essential observations (Item No. 8 above), are those of oxygen, free phosphate, and silicate, *giving priority to silicate*

[3] This chart, (Figure 0:1), the original of which was supplied by Professor G. DIETRICH, annuls any previous chart of the expedition.

[4] The Standard Depths of oceanographic observations agreed upon by the International Association of Physical Oceanography are, in metres:– 0, 10, 20, 30, 50, 75, 100, 150, 200, (250), 300, 400, 500, 600, (700), 800, 1,000, 1,200, 1,500, 2,000, 2,500, 3,000, 4,000, etc., the bracketted numbers being optional depths.

[5] Bottom observations should be within 5 metres of the sea floor in depths up to 500 metres, and within 10 metres of bottom in depths greater than 500 metres.

observations. These will be taken at the stations F and S designated in the Lists of Station Positions. At F stations, silicate observations will be taken at all standard depths. At S stations the observations will be:–

at 300 metres and near bottom on Courses A to E inclusive, and Course I,

– 400	– – – – – –	F
– 500	– – – – – –	G
– 600	– – – – – –	H

The seawater samples for silicate determinations will be collected in special polythene bottles to be supplied by "Explorer" at Vestmanhavn, Faroe, on 29. May, 1960. At the same time, the necessary standard solutions for silicate determinations by the molybdenum blue method (MULLIN and RILEY, 1955) will be furnished by "Explorer" to those ships which are equipped to make their own determinations. Those ships which are *not* so equipped (indeed all ships on which storage of the seawater samples for more than two to three hours is anticipated) should store their silicate seawater samples in the dark and preferably in deep-freeze until, either the analyses can be carried out on board, or by arrangement at Vestmanhavn on 29. May, 1960, the samples can be transferred to "Explorer", or another ship.

Silicate observations, as above, are to be taken on all three surveys, except that if they have already been done in full at F stations on the first survey, these stations can be considered as S stations on the second and third surveys.

Free phosphate and oxygen observations are to be taken at F and S stations on the lines:–

Stations Nos.	1–7, 12–17,	on Course	A
– –	17–34,	– –	B
– –	20–38,	– –	C
– –	20–39,	– –	D
– –	22–41,	– –	E
– –	20–37,	– –	F
– –	15–29,	– –	G
– –	16–25,	– –	H
– –	1–10, 17–23, 29–37	– –	I

Phosphate and oxygen observations should be taken at 100, 300, 400, 500, 1,000, 1,500, 2,000, 2,500 metres, always providing that an observation is taken near bottom. The observations may be taken on only one, or on all three surveys.

10. The entire field of operations will be accomplished within the same period of three days, commencing 30. May, 1960.

11. It is anticipated that at least five of the operating ships will be equipped with an electrical conductivity salinometer, thus enabling the salinity observations on these ships to be worked up *as the cruise proceeds.*

12. Immediately after the first complete survey which should terminate on 2. June 1960, all ships will re-assemble in Vestmanhavn, Faroe. There, first, all salinity determinations from the first survey will be completed; those from ships which are not equipped with a conductivity salinometer will be done by ships which are so equipped. It is expected that ships which are *not* so equipped will agree to this arrangement which will so vitally contribute to the success of the expedition as a whole.

Secondly, observations will then be entered upon uniform-scale charts, to be furnished by "Explorer", for the surface, 100, 300, 400, 500, 1,000, and 1,500 metres levels, and bottom, and on vertical section diagrams, the latter to be constructed on square-millimetre paper on the horizontal scale of 1:1,000,000 (i.e. 1 mm = 1 km) and the vertical scale of 1:5,000 (i.e. 1 mm = 5 m.).

Thirdly, a council of scientists will be held on 4. June, 1960, on board "Anton Dohrn", at 1400 hours, to examine these diagrams and to judge from them the suitability of the plan on the first survey for second and third surveys as below, as well as for the other operations designated under Items 16 and 17 below.

13. All ships will disperse to commence the second field survey of the region on 6. June, 1960, at the same times at the various starting points as are cited in Item 4 above, except in so far as re-adjustment may be made at the council of scientists mentioned in Item 12 above.

14. The second survey shall be completed on 9. June, 1960. Ships will thereupon proceed, immediately and according to the following plan, to the positions indicated on the accompanying chart by a diamond-marking about a point, thus ⟨·⟩, to engage in the operations described under Items 16 and 17 below, *until and inclusive of 12. June, 1960:* –

Ship	A	to diamond-station	A
–	B	– –	D
–	C	– –	E
–	D	– –	B
–	E	– –	C
–	F	– –	I
–	G	– –	H
–	H	– –	G
–	I	– –	J

Re-dispersal to the starting points for the third survey of the expedition, to commence on 13. June, 1960, at the times already designated for the previous surveys, will then immediately be made.

15. On 16. June, 1960, on completion of the third survey, ships will again proceed to their respective

Table 0:2.

Ship	Vestmanhavn to starting position A_1, B_1, C_1, ... etc. Naut. miles	Finishing position A_2, B_2, C_2, ... etc. to Vestmanhavn Naut. miles	Length of course, A_1–A_2, B_1–B_2, C_1-C_2 ... etc. Naut. miles	Numbers of stations						
				< 500 metres depth	501–750 m	751–1000 m	1001–1500 m	1501–2000 m	> 2000 m	Totals
A	48	48	345	–	9	2	5	4	6	26
B	42	37	353	19	15	–	–	–	–	34
C	35	37	345	35	3	–	–	–	–	38
D	42	47	340	29	10	–	–	–	–	39
E	55	70	350	16	18	7	–	–	–	41
F	86	103	325	4	8	19	6	–	–	37
G	118	130	295	1	–	11	15	2	–	29
H	125	132	350	–	–	–	16	10	–	26
I	40	45	462	16	10	6	5	–	–	37

diamond-stations as above, to repeat operations at these stations until 2400 hours on 18. June, 1960, when the expedition will be terminated.

16. Priority operations *for not less than 48 hours at* the diamond-stations are as follows: –

(i) Current measurements[6], particularly bottom current measurements, but also mid-water current measurements where these can be performed *simultaneously* with bottom current measurements, at diamond-stations B, E, G, H, I, and J. Bottom current measurements should be made within 2 metres of the sea floor.

Provided this can be accomplished without disrupting the continuity of current measurements, skeleton temperature observations should also be taken through discontinuity layers at these diamond-stations.

(ii) The essential observations of temperature and salinity at standard depths, with additions through discontinuity-layers as specified in Item 8 above, repeated hourly, for the assessment of internal waves, at diamond-stations A, C and D. If any or all of the three ships A, B and E can *at the same time* carry out mid-water and/or bottom current measurements, these will be a valuable addition to the investigation.

17. In so far as they can be carried out simultaneously with and within the period occupied by the essential observations on the three-day field surveys, or, alternatively, in any residium there may be of the periods given over *in the first instance* to operations under item 16 above, the following operations or observations are desired, in the order of priority given, from as many ships as are equipped to accomplish them: –

(i) Meteorological observations, e.g. air temperature and humidity, wind direction and speed, barometric pressure, cloud amount and definition, sunshine records, and sea state with such measurements as may be possible, e.g. Secchi disc, wave height and direction, amount and direction of swell, colour of sea. As regards Secchi-disc measurements, while it would be advantageous to use discs with a diameter of 50 cm, it is not suggested that new discs of this diameter should be prepared if discs of 30 cm diameter are available.

(ii) Bottom sediment collection by grab, or core samples if possible. Photographs of the bottom by underwater camera are also desired where possible.

(iii) Plankton sampling at specific depths or within specified depth-ranges, the method of sampling to be at the discretion of each ship.

(iv) Trawling operations[7].

PROSECUTION OF THE EXPEDITION

Apart from small adjustments in station-positions in a few cases, some minor curtailments of courses in order as far as possible to maintain the pre-arranged timing of the entire programme, this, despite unfavourable weather on occasions, was carried out almost exactly as planned.

[6] Vessels which are not equipped with current meters, recorders, or other accurate current measuring devices, or which may wish *additionally* to employ the "Pisa" deep water current indicator invented by Dr. J. N. CARRUTHERS, are recommended at once to communicate with Dr. CARRUTHERS at the National Institute of Oceanography, Wormley, Godalming, Surrey, England.

[7] It is not anticipated that there will be much scope for trawling operations during the period of the expedition, except by ships which may be advantageously sited for "diamond"-station operations.

The Frontispiece to this report, from a photograph by Mr. J. H. A. Martin, B.Sc. of "Explorer", illustrates the assembly of the nine research ships in Vestmanhavn, Faroe, on 29. May, 1960. In the afternoon of that day a meeting of all participating scientists was held on "Explorer" to make final adjustments to the first survey programme and to ensure complete understanding of the several parts of the exercise among all participants. Later the same day, ships' radio officers met on "Ernest Holt" to exchange the necessary information for intercommunication among ships during the investigation. The plan was formulated for all ships to transmit their positions, twice daily, to "Explorer", at 0830 and 1830 hours, at the same times as sea surface temperatures were submitted for purposes of daily regional weather forecasts from the meteorological laboratory of "Anton Dohrn". This arrangement was extended to include bottom sea temperatures on the second and third surveys, thus enabling each ship to compile a bottom thermal chart as each survey proceeded and so to obtain almost at once an estimate of the "overflow" position.

Deteriorating weather conditions prompted postponement of the beginning of the first survey by twelve hours. The survey was completed on 3. June, and all ships re-assembled in Vestmanhavn to interchange samples and observations and to discuss the first survey results at a meeting of scientists on "Anton Dohrn" on 4. June. The only amendments to the overall plan of the investigation which were found to be desirable for the second and third surveys were (i) the northward displacement, by 8 to 12 miles, of "Explorer" stations Nos. 7 to 10 inclusive, in order to bring these within the region of the cold deep water effluent from the Faroe Bank Channel, and (ii) the transition of certain diamond stations to more advantageous positions from the standpoint of deep current measurements.

The second survey was completed on 9. June, and after 48 to 60 hours' work on diamond stations, ships re-assembled in Vestmanhavn on 12. June. The weather being propitious for such a unique outing, all ships' companies were, on 13. June, handsomely entertained by Sysselmand, Mr. Gunnar Dahl-Olsen, and the local council of Vestmanhavn to a short trip on the Faroe fishery protection ship "Ternan" and thereafter by motor boats to the renowned sea caves and wild bird cliffs on the west coast of the Island of Strømø.

Commencement of the third survey was delayed by adverse weather for 24 hours, but was overtaken by 17. June, the final measurements for internal waves and currents having perforce to be curtailed, as a result, to a period of twelve hours.

All ships finally dispersed from Vestmanhavn on 18. June.

RESULTS OF THE EXPEDITION

General accounts of the Expedition and of its more obvious and immediate results were given on 27. July 1960 at a 'Symposium on the Overflow of the North Atlantic submarine ridges by cold, deep, sub-Arctic waters', at the XIIth Triennial Assembly of the International Association of Physical Oceanography at Helsinki, Finland, and, in greater detail, at a special evening session on 21. September, 1960, during the Forty-Eighth Annual Meeting in Moscow of the International Council for the Exploration of the Sea.

The above-mentioned Symposium included the following titles: –

"The North Atlantic overflow problem in terms of solid geometry". L. H. N. Cooper.

"The dynamics of flow on a submarine ridge". K. F. Bowden.

"On the overflow of the Iceland-Faroe Ridge; a contribution to the international investigation in June 1960". G. Dietrich.

"Some observations of cold water overflow in the Faroe Bank Channel and over the Faroe-Iceland Ridge". F. Hermann.

"The origins of the deep water south of Iceland". J. Steele.

"Preliminary results of the ICES' Iceland-Faroe Ridge deep water overflow expedition". J. B. Tait.

The plan of the scientific report on the Expedition was laid at the ICES meeting in Moscow, to include the following chapters: –

1. The bottom topography of the Iceland-Faroe Ridge region.
2. Meteorology and weather conditions during the expedition.
3. Temperature and salinity distributions and water masses of the region.
4. Dynamics and water-movements on and near the Ridge.
5. Bottom currents.
6. Internal waves investigations.
7. Silicate, oxygen, and phosphate distributions.
8. Other physical or chemical observations.
9. Trawling operations.
10. Summary chapter.

The observations of temperature, salinity, oxygen and phosphate will be published in ICES Oceanographic Data Lists, 1960, Nos. 6 and 7.

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LIST OF STATION POSITIONS [8]

COURSE A. "Perseus II" (U.S.S.R.)

Station No.	Latitude	Longitude	Loran U.K.	Loran U.A.	Silicate Stations
1	*62°52′N	7°24′W	4600		
2	63°05′	7°55′	4400		S
3	63°19′	8°26′	4200	3394	S
4	63°32′	8°56′	4000	3378	S
5	*63°45′	9°26′	3800	3364	
6	63°59′	9°58′	3600	3350	
7	*64°10′	10°24′	3440	3339	S
8	64°23′	10°08′	3446	3359	
9	*64°36′	9°53′	3452	3373	
10	64°42′	9°45′	3456	3380	
11	*64°48′	9°38′	3458	3385	S
12	64°53′	9°21′	3500	3394	S
13	*64°53′	8°50′	3600		
14	64°53′	8°18′	3700		
15	*64°53′	7°44′	3800		
16	64°53′	7°23′	3860		
17	*64°53′	7°04′	3920		F
18	64°37′	7°07′	4000		
19	*64°25′	7°10′	4060		
20	64°12′	7°12′	4121		S
21	*64°00′	7°14′	4190		
22	63°47′	7°16′	4260		
23	*63°35′	7°18′	4330		
24	63°21′	7°20′	4400		S
25	*63°07′	7°22′	4500		
26	*62°52′	7°24′	4600		

Positions of Diamond-Stations A, C, and D:–

A.	63°37·8′N	8°22·2′W
C.	63°26′N	8°36′W
D.	63°27′N	8°03·3′W

COURSE B. "Johan Hjort" (Norway)

Station No.	Latitude	Longitude	Loran U.K.	Loran U.A.	Silicate Stations
1	*62°45′N	7°40′W	4600	3412	
2	62°51′	7°55′	4500	3404	
3	*62°57′	8°10′	4400	3396	
4	63°03′	8°24′	4300	3387	S
5	*63°10′	8°39′	4200	3379	
6	63°17′	8°54′	4100	3370	S
7	*63°23′	9°09′	4000	3363	
8	63°29′	9°24′	3900	3356	S
9	*63°35′	9°38′	3800	3348	
10	63°41′	9°54′	3700	3340	
11	*63°49′	10°09′	3600	3334	
12	63°55′	10°26′	3500	3327	
13	*64°03′	10°42′	3400	3320	
14	*64°17′	11°15′	3200	3308	
15	*64°31′	11°50′	3000	3297	F
16	64°39′	12°09′	2900	3292	
17	*64°36′	12°34′	2800	3272	F
18	*64°21′	11°58′	3000	3281	S
19	64°13′	11°40′	3100	3286	
20	*64°06′	11°23′	3200	3292	
21	63°59′	11°07′	3300	3297	
22	*63°53′	10°51′	3400	3303	
23	63°46′	10°35′	3500	3310	
24	*63°39′	10°20′	3600	3316	
25	63°33′	10°05′	3700	3322	S
26	*63°27′	9°50′	3800	3330	
27	63°21′	9°35′	3900	3337	
28	*63°14′	9°21′	4000	3345	S
29	63°08′	9°07′	4100	3353	S
30	*63°02′	8°52′	4200	3362	
31	62°55′	8°38′	4300	3370	
32	*62°49′	8°23′	4400	3379	
33	62°43′	8°10′	4500	3389	
34	*62°37′	7°56′	4600	3398	

Positions of Diamond-Stations A, C, and D:–

A.	63°37·8′N	8°22·2′W
C.	63°26′N	8°36′W
D.	63°27′N	8°03·3′W

COURSE C. "Gauss" (Federal Republic of Germany)

Station No.	Latitude	Longitude	Loran U.K.	Loran U.A.	Silicate Stations
1	*62°29′N	8°09′W	4600	3379	
2	62°35′	8°23′	4500	3369	
3	*62°41′	8°36′	4400	3360	
4	62°47′	8°50′	4300	3350	S
5	*62°53′	9°04′	4200	3341	
6	62°59′	9°18′	4100	3333	S
7	*63°05′	9°32′	4000	3325	
8	63°11′	9°46′	3900	3317	S
9	*63°18′	10°01′	3800	3310	
10	63°25′	10°15′	3700	3303	S
11	*63°31′	10°30′	3600	3297	
12	63°37′	10°45′	3500	3290	
13	*63°43′	11°01′	3400	3285	
14	63°50′	11°16′	3300	3280	
15	*63°57′	11°32′	3200	3274	
16	64°04′	11°48′	3100	3270	
17	*64°11′	12°04′	3000	3265	S
18	64°18′	12°22′	2900	3260	
19	*64°25′	12°40′	2800	3256	
20	*64°14′	12°47′	2800	3237	S
21	64°07′	12°30′	2900	3240	S
22	*64°00′	12°13′	3000	3244	S
23	63°53′	11°57′	3100	3249	
24	*63°46′	11°41′	3200	3253	
25	63°40′	11°26′	3300	3258	
26	*63°33′	11°11′	3400	3262	
27	63°27′	10°55′	3500	3268	
28	*63°21′	10°41′	3600	3273	S
29	63°15′	10°26′	3700	3279	
30	*63°08′	10°12′	3800	3285	S
31	63°02′	9°58′	3900	3292	S
32	*62°56′	9°44′	4000	3300	S
33	62°50′	9°30′	4100	3306	S
34	*62°44′	9°16′	4200	3314	S
35	62°38′	9°03′	4300	3322	
36	*62°32′	8°49′	4400	3332	
37	62°26′	8°35′	4500	3342	
38	*62°20′	8°22′	4600	3352	

Position of Diamond-Station E: 64°07′N 12°45′W

[8] An auxiliary numbering of stations was employed for the Expedition, pending final numbering for each ship. This auxiliary numbering is adhered to in the present volume. The stations on each course bear fixed numbers, mounting to a 2-digit figure. At the first survey these station numbers are used; at the second and third surveys 100 and 200, respectively, are added. Thus, for instance, a station indicated by 19 (or 019) in the first survey will in the second and third surveys be indicated by 119 and 219, respectively.

LIST OF STATION POSITIONS
(CONTINUED)

COURSE D. "Ernest Holt" (U.K.)

Station No.	Latitude	Longitude	Loran U.K.	Loran U.A.	Silicate Stations
1	*62°11′N	8°35′W	4600	3316	
2	62°17′	8°48′	4500	3306	
3	*62°23′	9°01′	4400	3298	
4	62°29′	9°15′	4300	3290	
5	*62°34′	9°27′	4200	3284	
6	62°40′	9°41′	4100	3277	S
7	*62°46′	9°55′	4000	3270	S
8	62°52′	10°09′	3900	3263	
9	*62°58′	10°22′	3800	3257	S
10	63°05′	10°36′	3700	3252	
11	*63°11′	10°50′	3600	3247	S
12	63°17′	11°04′	3500	3243	S
13	*63°23′	11°19′	3400	3238	
14	63°30′	11°34′	3300	3234	
15	*63°36′	11°49′	3200	3230	
16	63°43′	12°04′	3100	3227	
17	*63°49′	12°20′	3000	3223	
18	63°56′	12°36′	2900	3220	S
19	*64°03′	12°53′	2800	3216	
20	64°00′	13°16′	2700	3193	
21	*63°53′	12°59′	2800	3195	S
22	63°46′	12°44′	2900	3197	S
23	*63°39′	12°28′	3000	3200	
24	63°33′	12°13′	3100	3202	
25	*63°26′	11°57′	3200	3205	
26	63°19′	11°43′	3300	3208	
27	*63°13′	11°28′	3400	3210	
28	63°07′	11°14′	3500	3214	S
29	*63°01′	11°00′	3600	3218	
30	62°55′	10°46′	3700	3222	S
31	*62°48′	10°33′	3800	3226	
32	62°42′	10°19′	3900	3230	S
33	*62°36′	10°05′	4000	3236	
34	62°30′	9°52′	4100	3240	
35	*62°24′	9°38′	4200	3246	
36	62°18′	9°25′	4300	3252	
37	*62°13′	9°12′	4400	3258	
38	62°07′	8°59′	4500	3264	
39	*62°01′	8°45′	4600	3270	

Position of Diamond-Station B: 62°52·1′N 10°14·4′W

COURSE E. "María Júlía" (Iceland)

Station No.	Latitude	Longitude	Loran U.K.	Loran U.A.	Silicate Stations
1	*61°50′N	8°55′W	4600	3208	
2	61°56′	9°09′	4500	3207	S
3	*62°02′	9°22′	4400	3205	
4	62°08′	9°35′	4300	3204	S
5	*62°14′	9°48′	4200	3202	
6	62°20′	10°02′	4100	3200	S
7	*62°26′	10°15′	4000	3198	
8	62°32′	10°29′	3900	3195	
9	*62°38′	10°42′	3800	3192	S
10	62°44′	10°56′	3700	3190	
11	*62°51′	11°09′	3600	3187	S
12	62°57′	11°23′	3500	3184	S
13	*63°03′	11°37′	3400	3181	
14	63°09′	11°51′	3300	3180	
15	*63°16′	12°05′	3200	3180	
16	63°23′	12°20′	3100	3177	
17	*63°29′	12°35′	3000	3176	
18	63°35′	12°50′	2900	3174	
19	*63°42′	13°05′	2800	3173	
20	63°49′	13°22′	2700	3172	S
21	*63°56′	13°38′	2600	3170	
22	63°51′	13°58′	2510	3146	
23	*63°45′	13°44′	2600	3146	S
24	63°38′	13°29′	2700	3146	
25	*63°31′	13°13′	2800	3146	
26	63°25′	12°57′	2900	3146	
27	*63°18′	12°43′	3000	3146	
28	63°12′	12°29′	3100	3146	
29	*63°05′	12°14′	3200	3147	
30	62°59′	12°00′	3300	3148	S
31	*62°53′	11°46′	3400	3149	
32	62°46′	11°32′	3500	3150	S
33	*62°40′	11°18′	3600	3150	
34	62°34′	11°05′	3700	3150	S
35	*62°28′	10°51′	3800	3150	
36	62°22′	10°38′	3900	3152	
37	*62°16′	10°25′	4000	3152	
38	62°09′	10°11′	4100	3153	
39	*62°04′	9°58′	4200	3154	S
40	61°58′	9°44′	4300	3154	
41	*61°51′	9°31′	4400	3154	

Positions of Diamond-Stations A, C, and D:–

A.	63°37·8′N	8°22·2′W
C.	63°26′N	8°36′W
D.	63°27′N	8°03·3′W

COURSE F. "Helland-Hansen" (Norway)

Station No.	Latitude	Longitude	Loran U.K.	Loran U.A.	Silicate Stations
1	*61°54′N	10°06′W	4200	3100	
2	62°00′	10°20′	4100	3104	
3	*62°06′	10°33′	4000	3105	S
4	62°12′	10°46′	3900	3108	
5	*62°18′	11°00′	3800	3109	S
6	62°24′	11°14′	3700	3110	
7	*62°30′	11°27′	3600	3110	S
8	62°36′	11°41′	3500	3110	
9	*62°43′	11°55′	3400	3112	S
10	62°49′	12°08′	3300	3113	
11	*62°55′	12°22′	3200	3114	S
12	63°01′	12°36′	3100	3115	
13	*63°08′	12°50′	3000	3116	
14	63°14′	13°05′	2900	3117	
15	*63°21′	13°20′	2800	3118	
16	63°27′	13°35′	2700	3119	
17	*63°34′	13°50′	2600	3120	S
18	63°41′	14°06′	2500	3120	S
19	*63°48′	14°22′	2400	3120	
20	63°45′	14°49′	2265	3094	
21	*63°36′	14°27′	2400	3094	
22	63°30′	14°15′	2500	3090	S
23	*63°23′	13°57′	2600	3088	
24	63°16′	13°42′	2700	3086	
25	*63°09′	13°27′	2800	3084	
26	63°03′	13°13′	2900	3082	
27	*62°57′	12°58′	3000	3080	
28	62°50′	12°45′	3100	3078	S
29	*62°44′	12°31′	3200	3076	
30	62°38′	12°17′	3300	3072	S

LIST OF STATION POSITIONS (CONTINUED)

Station No.	Latitude	Longitude	Loran U.K.	Loran U.A.	Silicate Stations
31	*62°32′	12°03′	3400	3070	
32	62°25′	11°50′	3500	3068	S
33	*62°19′	11°35′	3600	3065	
34	62°13′	11°22′	3700	3062	
35	*62°07′	11°08′	3800	3060	S
36	62°01′	10°54′	3900	3058	
37	*61°55′	10°41′	4000	3055	S

Position of Diamond-Station I: 62°15′N 10°25·5′W

COURSE G. "Anton Dohrn" (Federal Republic of Germany)

Station No.	Latitude	Longitude	Loran U.K.	Loran U.A.	Silicate Stations
1	*61°55′N	11°17′W	3800	3000	
2	62°02′	11°31′	3700	3008	S
3	*62°08′	11°44′	3600	3014	
4	62°14′	11°58′	3500	3020	
5	*62°20′	12°12′	3400	3024	
6	62°26′	12°24′	3330	3029	S
7	*62°33′	12°39′	3200	3033	
8	62°39′	12°53′	3100	3040	S
9	*62°46′	13°07′	3000	3043	
10	*62°59′	13°35′	2800	3050	
11	*63°11′	14°04′	2600	3058	
12	63°19′	14°20′	2485	3060	S
13	*63°25′	14°33′	2400	3064	S
14	*63°33′	14°51′	2290	3067	
15	63°33′	15°22′	2120	3043	
16	*63°27′	15°10′	2200	3040	
17	63°20′	14°54′	2300	3037	S
18	*63°14′	14°40′	2400	3032	
19	63°09′	14°28′	2468	3030	F
20	*63°01′	14°11′	2600	3024	
21	*62°48′	13°53′	2800	3014	S
22	*62°35′	13°15′	3000	3003	
23	62°28′	13°01′	3100	2999	S
24	*62°22′	12°47′	3200	2991	S
25	62°16′	12°33′	3300	2984	
26	*62°09′	12°20′	3400	2978	
27	62°03′	12°06′	3500	2970	
28	*61°57′	11°52′	3600	2960	S
29	61°51′	11°40′	3700	2952	

Position of Diamond Station H: 62°51·2′N 11°46·2′W

COURSE H. "Discovery II" (U.K.)

Station No.	Latitude	Longitude	Loran U.K.	Loran U.A.	Silicate Stations
1	*61°45′N	11°24′W	3800	2940	
2	*61°43′	12°02′	3600	2884	
3	61°49′	12°17′	3500	2896	
4	*61°55′	12°30′	3400	2908	S
5	*62°07′	12°58′	3200	2926	
6	62°13′	13°12′	3100	2934	
7	*62°20′	13°26′	3000	2943	
8	62°26′	13°40′	2900	2950	
9	*62°32′	13°54′	2800	2957	S
10	*62°45′	14°22′	2600	2970	
11	*62°57′	14°50′	2400	2982	S
12	63°03′	15°04′	2300	2987	
13	*63°10′	15°19′	2200	2992	S
14	63°16′	15°34′	2100	2997	
15	*63°23′	15°49′	2000	3002	
16	*63°06′	15°58′	2000	2955	
17	62°53′	15°30′	2200	2942	S
18	*62°41′	15°02′	2400	2928	F
19	62°28′	14°34′	2600	2912	
20	*62°16′	14°06′	2800	2894	S
21	62°03′	13°38′	3000	2873	S
22	*61°51′	13°10′	3200	2850	
23	61°38′	12°42′	3400	2823	
24	*61°32′	12°27′	3500	2808	S
25	61°25′	12°13′	3600	2790	
26	*61°35′	11°30′	3800	2888	

Position of Diamond-Station G: 62°49·5′N 13°00′W

COURSE I. "Explorer" (U.K.)

Station No.	Latitude	Longitude	Silicate Stations
1	61°52′N	8°17′W	
2	*61°46′	8°23′	
3	61°41′	8°31′	
4	*61°37′	8°36′	S
5	61°32′	8°43′	S
6	*61°27′	8°48′	
7	61°28′	9°10′	S
8	*61°30′	9°45′	
9	61°31′	10°20′	S
10	*61°33′	10°55′	
11	61°11′	11°44′	S
12	*61°09′	11°08′	
13	61°08′	10°32′	
14	*61°04′	9°56′	
15	61°02′	9°36′	
16	*61°01′	9°16′	
17	61°11′	8°16′	
18	*61°18′	8°07′	S
19	*61°23′	8°00′	
20	61°28′	7°53′	
21	*61°33′	7°46′	
22	61°38′	7°40′	
23	*61°43′	7°33′	
24	61°34′	7°17′	
25	61°24′	7°31′	
26	*61°18′	7°40′	S
27	*61°13′	7°47′	S
28	61°07′	7°55′	
29	*60°00′	7°00′	
30	60°10′	7°00′	
31	*60°20′	7°00′	
32	60°30′	7°00′	S
33	*60°40′	7°00′	
34	60°50′	7°00′	S
35	*61°00′	7°00′	
36	61°15′	7°00′	
37	*61°27′	7°00′	

Position of Diamond-Station J: 61°24·9′N 8°19′W

CHAPTER 1
THE BOTTOM TOPOGRAPHY OF THE ICELAND-FAROE RIDGE REGION

By

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The comprehensive international investigation of the sea area between Iceland and Faroe from 30. May to 18. June, 1960, included the continuous recording of depth on at least one of the thrice repeated courses undertaken by each ship. Table 1:1 summarizes the nature and extent of the data each ship made available to the German Hydrographic Institute, Hamburg, for purposes of evaluation and the construction of a bathymetric chart.

The ships positions were determined by dead reckoning. Measured depths taken from evaluated echograms were corrected according to Matthews (1939) and the corrected values entered on a fair chart on a scale of 1:500,000.

On the basis of these entries depth contours were constructed as represented on Figure 1:1. Only the soundings taken during the Expedition have been used, the reliability of previous data which cannot now be checked with respect to depth or position being more or less open to question.

In its general pattern the chart agrees with those of the region which are already known. The continuous crest of the Ridge is in all parts less than 500 metres in depth. As might be expected, the depth contours deviate in places as compared with older representations (see, for example, G. Dietrich (1960)).

In the northwestern part of the area investigated, that is, on the shelf slope into the Atlantic basin to the southeast of Iceland, the bottom topography is so irregular that the courses of the depth contours remain uncertain in some instances. Here, the distance of 10 nautical miles between sounding profiles turns out to be too great. Uncertainties in the pattern of the contours exist also in other parts of the chart where, however, they are not of any great morphological importance. Depth contours at intervals of 100 metres were designed. Further sub-dividing the shallower part of the Ridge, the depth contours of 350 metres and 450 metres are represented by broken curves.

Table 1:1.
General view of the data used for the compilation of the bathymetric chart

Ship	Nationality	Charts of the profiles run	Echograms	Nautical data	Sounding profiles (already corrected)
"Perseus II"	U.S.S.R.	–	–	–	4
"Johan Hjort"	Norway	–	1	1	–
"Gauss"	Federal Republic of Germany	3	6	1	–
"Ernest Holt"	United Kingdom	1	1	–	–
"María Júlía"	Iceland	1	6	–	–
"Helland-Hansen"	Norway	1	2	–	–
"Anton Dohrn"	Federal Republic of Germany	2	6	1	–
"Discovery II"	United Kingdom	1	4 files	–	–
"Explorer"	United Kingdom	1	2	–	–

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Matthews, D. J., 1939. "Tables of Velocity of Sound in Pure Water and Sea Water". British Admiralty Publication H. D.

Dietrich, G., 1960. "Die Überströmung des Island-Faröer-Rückens, eine Voruntersuchung zum internationalen "Overflow-Programme" im Juni 1960". Kieler Meeresforsch., **16**(1).

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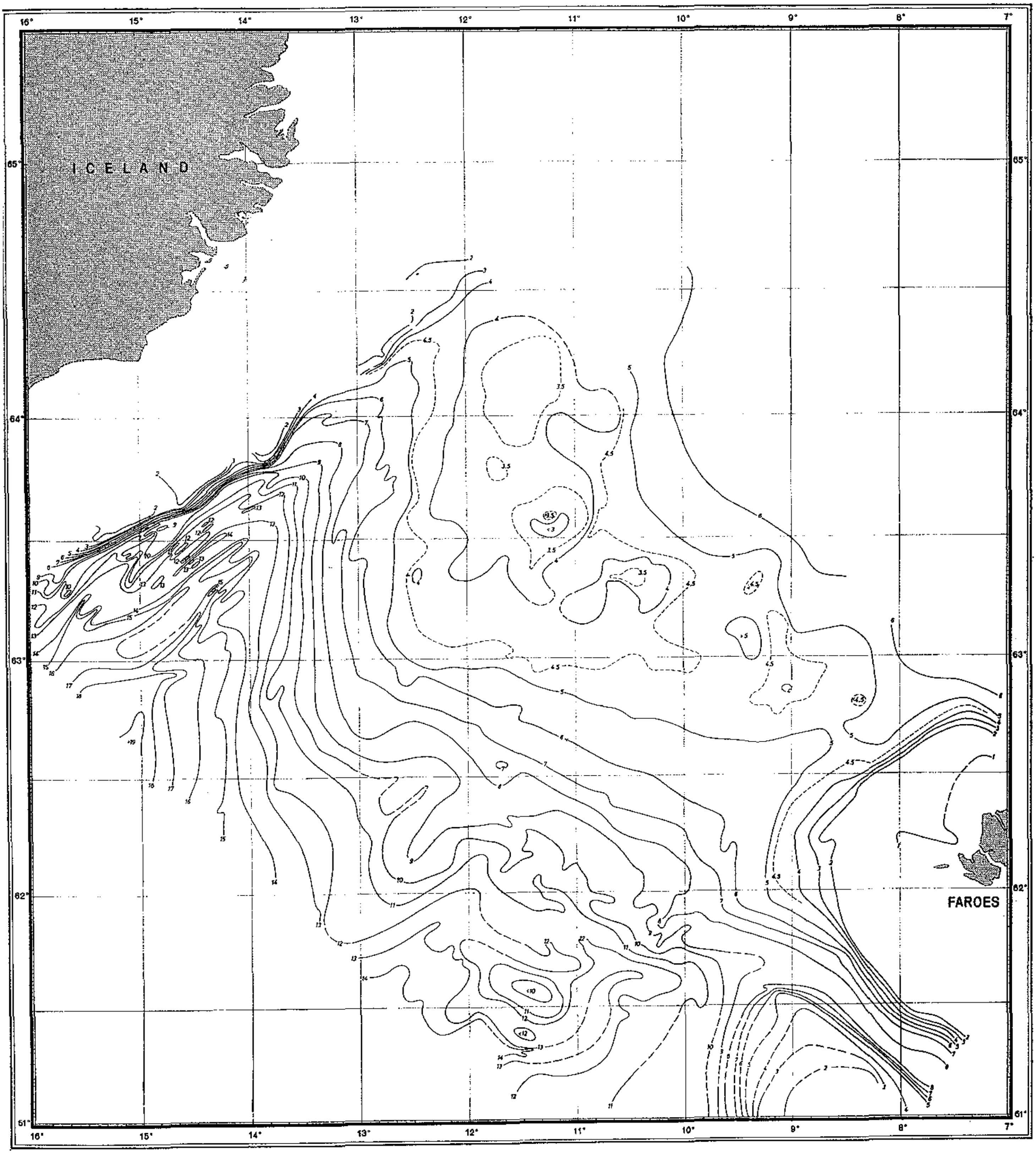

Figure 1:1. Depth-chart of the Iceland-Faroe Ridge region (Depth-figures: hectometres).

CHAPTER 2

METEOROLOGY AND WEATHER CONDITIONS PRECEDING AND DURING THE EXPEDITION

By

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The first part (by M. Rodewald) deals with the prevailing pattern of atmospheric circulation during the first six months of 1960. Charts of monthly (or bimonthly) mean pressure distributions and of respective pressure anomalies are presented, and the mean resultant winds for the "Overflow Area" are determined and discussed. Broadly speaking, the period had a lack of westerlies, and the mean resultant wind was from the southeast. This fact is reflected in the mean temperatures of the air and of the sea surface, and some tables show that the temperatures averaged well above normal in the months of May and June, 1960.

In the second part (by F. Krügler) – after notes on the forecasting work of the Meteorological Station of "Anton Dohrn", – mean pressure maps of the Northeast Atlantic for the various weather periods during the Expedition, as well as series of special synoptic weather maps of the Northeast Atlantic and the Iceland-Faroe Ridge areas are discussed, in order to enable oceanographers to study possible influences, for instance of pressure and of surface wind distribution, on the cold, deep water overflow.

THE NORTHEAST ATLANTIC PATTERN OF ATMOSPHERIC CIRCULATION DURING THE FIRST SIX MONTHS 1960

By

M. Rodewald

THE ATMOSPHERIC CIRCULATION DURING THE PERIOD JANUARY-APRIL, 1960

The maps, published in the "Grosswetterlagen Mitteleuropas", as well as the working charts for the monthly bulletin "Die Witterung in Übersee", which are available in the Seewetteramt, Deutscher Wetterdienst, served as a basis for this survey.

Since the type of circulation in February, 1960, was similar to that of January 1960, and the type of April 1960, similar to that of March 1960, these two pairs of months, which represent the background atmospheric conditions well in advance of the Expedition, were subsumed on the maps (Figures 2:1 and 2:3, Figures 2:2 and 2:4) respectively. Pressure deviations from the normal are given with reference to the period 1899–1939.

The mean pressure chart *January-February 1960*, (Figure 2:1) shows a rather increased Greenland High. The "Icelandic Low" has moved from its normal position approximately 1,000 nautical miles south to west into the sea area around the Ocean Wea Station (OWS) D, (44°N, 41°W). A trough runs f this depression via Faroe towards Northcape. It dicates the mean boundary between winds wit southerly and those with a northerly component; wind-shift line has been specially marked in all p sure charts.

Different from the normal conditions, the whole area between Iceland and Faroe is, on the ave January-February 1960, within an *air current j northeast to north-northeast.* The chart of the mean p sure deviations during this period (Figure 2:3) phasizes the wind anomaly. At the southeastern of the positive pressure anomaly over Greenl (+16 mb) there is a considerable "additional wi from NNE to NE.

On the mean pressure chart for *March-April 1.* (Figure 2:2) a thorough change of the circula pattern is noticeable, – at any rate, with respec the situation over the sea area Iceland-Faroe. "Icelandic Low", however, is still situated somewha the south of its normal position, but it now presen bulge which points via Northwest Iceland towa Bear Island. The Greenland High has retreated no ward, while on the other hand the developmen higher pressure in Scandinavia has increased.

Thus, in comparison with the situation du January-February 1960, the boundary between wi with southerly and northerly components respecti has been *displaced* in its total extent *to the Northwest* extends approximately from the OWS A (62 33°W) via Northwest Iceland towards the sea a northeastward of Jan Mayen. Consequently the area between Iceland and Faroe lies on the aver March-April 1960, within a *southerly air current.* chart of mean pressure deviation during this per (Figure 2:4) shows a positive anomaly (+8 mb) Scandinavia. A negative anomaly (–8 mb) at OWS C (53°N, 35°W), extends a tongue of relati low pressure to the sea area about Jan Mayen. "additional wind" within the region Iceland-Fa from SSW is nearly opposite in direction, although

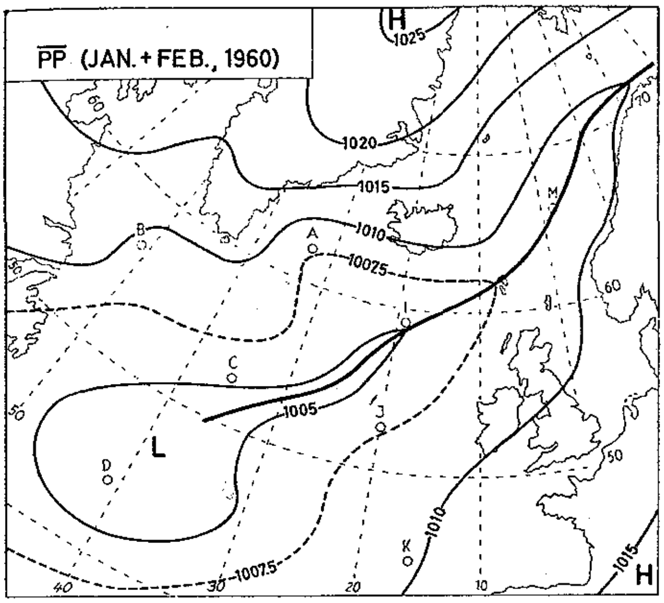

Figure 2:1

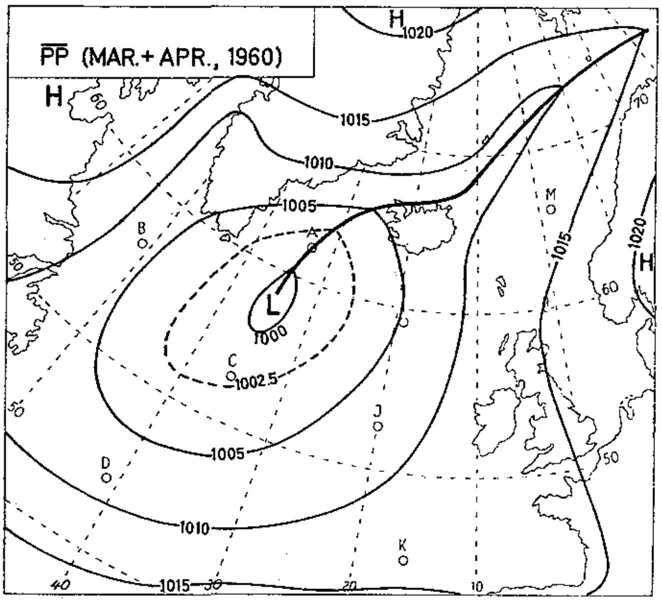

Figure 2:2

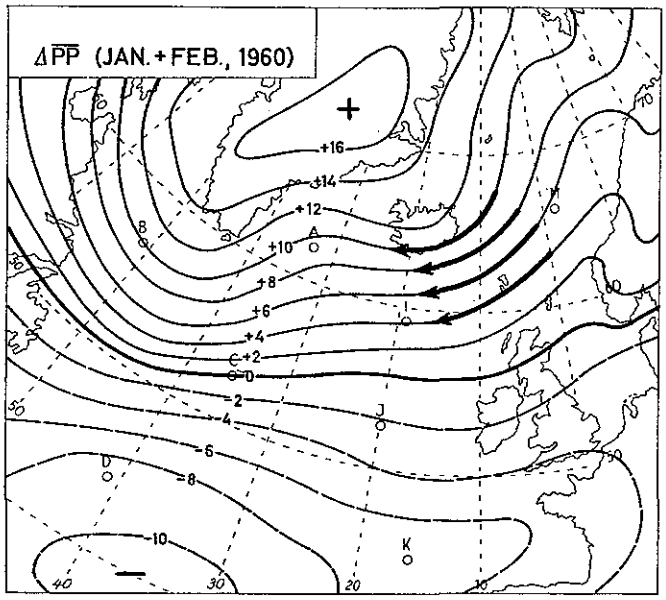

Figure 2:3

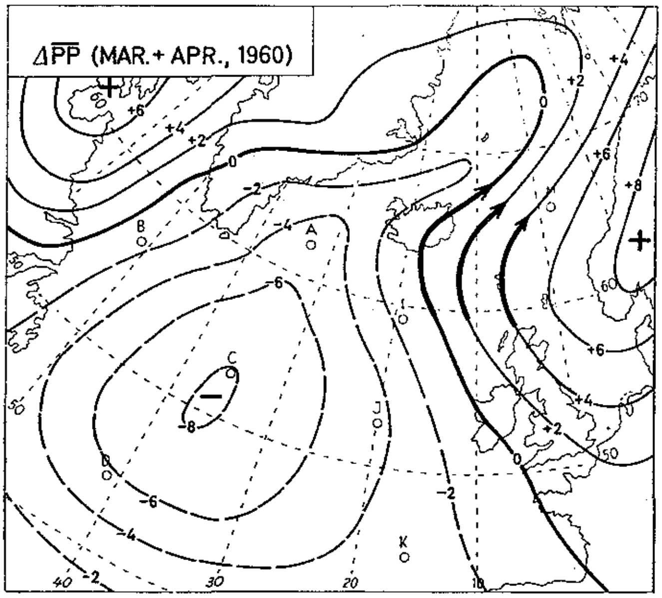

Figure 2:4

Figures 2:1–2:4. The atmospheric circulation during the period January-April 1960.

of equal force, compared with that of January-February 1960, (see special outline in Figures 2:3 and 2:4).

THE ATMOSPHERIC CIRCULATION IN MAY AND JUNE, 1960.

The circulation pattern in *May 1960*, (Figure 2:5), resembles that of March-April 1960. Adjacent to a southward displaced "Icelandic Low" which is lower than normal (see deviation chart Figure 2:7), there is a strong Scandinavian High in the east, which has increased towards the Norwegian Sea. Only a very weak trough runs from the North Atlantic depression towards Jan Mayen and Spitsbergen. The boundary between winds with a southerly and those with a northerly component stretches from the sea area off Northwest Iceland along Jan Mayen towards Spitsbergen. The region between Iceland and Faroe lies, on the monthly average, consistently within an *air*

Table 2:1.
Monthly mean wind vectors (in degrees and m/sec)

	Station I			Station M		
1960	Degrees	m/sec	N+	Degrees	m/sec	N*
Jan.	185	3·0	248	309	1·0	248
Feb.	28	4·7	232	20	2·2	230
March	137	5·6	247	200	4·0	245
April	222	6·6	234	227	5·2	232
May	168	4·6	247	179	0·8	247
June	220	3·1	240	333	1·5	239

N* = number of data used.

current from south to south-southeast. The chart of the mean pressure deviation, (Figure 2:7), illustrates the here existing southerly "additional wind".

In Figure 2:5 (and Figure 2:6) the mean monthly *wind vectors* at the OWS's, which have been evaluated from the daily radio weather reports, have been plotted according to direction (degrees) and velocity (m/sec). They correspond well to the specific run of the isobars. The OWS's I (59° N, 19° W) and M (66° N, 2° E) to the southwest and northeast respectively of the Iceland-Faroe Ridge show in the one case south to east and in the other south winds as the resultant winds for May 1960.

During *June 1960*, (Figure 2:6), the circulation of the air was, – contrary to the previous months, – without a distinct "type". As the chart of pressure deviations shows, (Figure 2:8), the pressure anomalies in the Northeast Atlantic Ocean and in the Norwegian Sea reach values only between 0 and ± 2 mb.

More in detail: Between the slightly increased "Icelandic Low" and the slightly deepened "Low" in North Sweden on the one hand, and between the Greenland High and the British ridge of the Azores High on the other, we have in the sea area north of Faroe a *saddle condition.* The neutral point lies at about 64° N, 4° W (x N. P. in Figure 2:6). The boundary between winds with southerly and those with northerly component now has a direction different from that in the previous months: it extended from North Iceland in an ESE direction approximately to this neutral point, N. P. Further eastward there was no longer any southerly component.

As to the sea area between Iceland and Faroe (south of the marked wind-shift line) there averaged a weak *air currrent from a southwest direction.* North of the line of demarcation, northerly to easterly winds blew on the average. The chart of pressure deviations, (Figure 2:8), shows only slight "additional wind" from the SE between Iceland and the Faroe. For the rest, it shows in the sea area south of Iceland a southwest current somewhat above normal, so that neverthe at the OWS I there results a vectorial wind of 3 m/ (from 220°).

THE MONTHLY MEAN WIND VECTORS AT THE OWS' AND M

The OWS's I and M flank the Iceland-Faroe Ri to the SW and NE respectively. Therefore the w vectors of these stations may be added here as s plementary data.

For the region *Iceland-Faroe Ridge* we may apply following vectorial wind averages:

January-February 1960	45°	3–4 m/sec
March-April –	180°	5 m/sec
May –	170°	3 m/sec
June –	210°	1–2 m/sec

Altogether a displacement of the air from *south north* was consequently dominating here during first six months 1960. A component from west to eas in the meaning of the "Westerlies" – was genera *not present* at all. The mean resultant wind during first six months of 1960 was approximately fr *southeast to south (153°) at* 1·7 m/sec.

This is in accordance with the resulting me distribution of atmospheric pressure for the first months 1960 for the area Iceland-Faroe (Figure 2: The respective pressure deviation from the norn pattern (Figure 2:10) shows that the normal circu tion was superimposed by an "additional wind" fr ESE. Thus the wind forces generally affected surface layers of the sea in such a way as to *retard cold East Iceland Current* and promote the extension the warmer water masses of the Northeast Atlan Drift.

SUPPLEMENTARY DATA FOR THE WIND CONDITION

The Tables 2:2 and 2:3 are based on the statist of the daily wireless reports of the North Atlan OWS's, made up by the Seewetteramt, Hambu Concised, they show the following: –

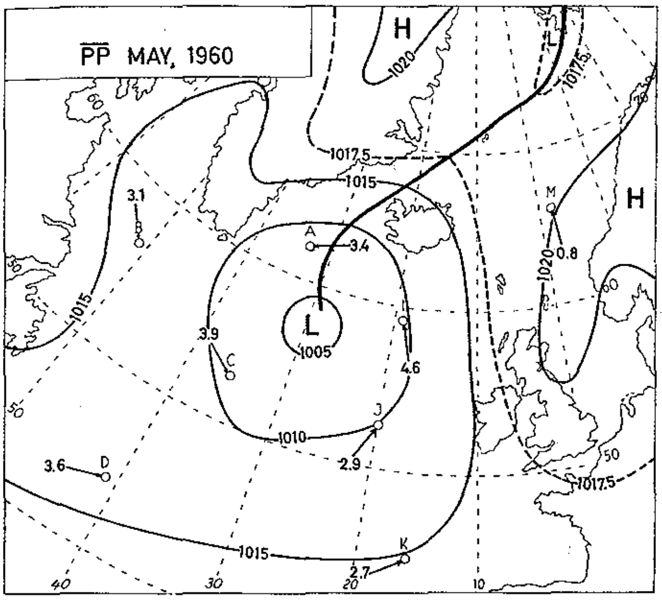

Figure 2:5

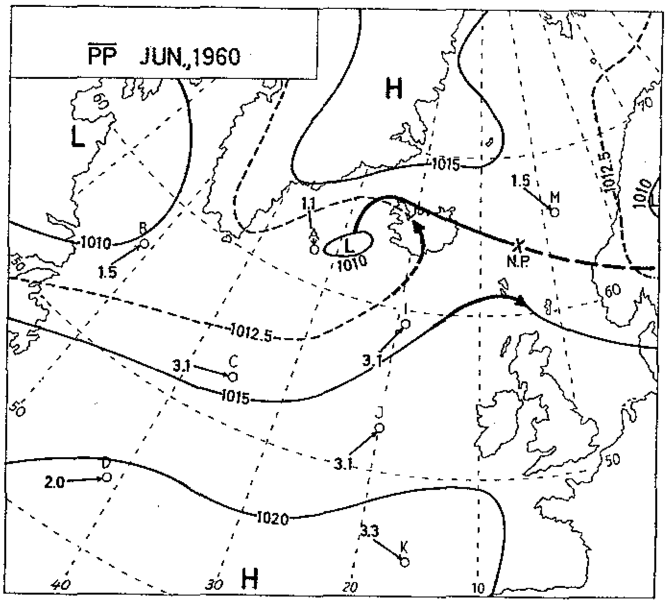

Figure 2:6

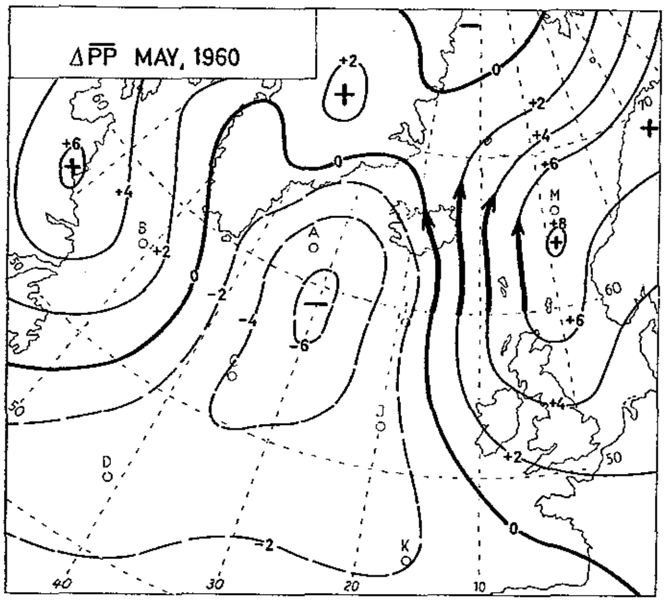

Figure 2:7

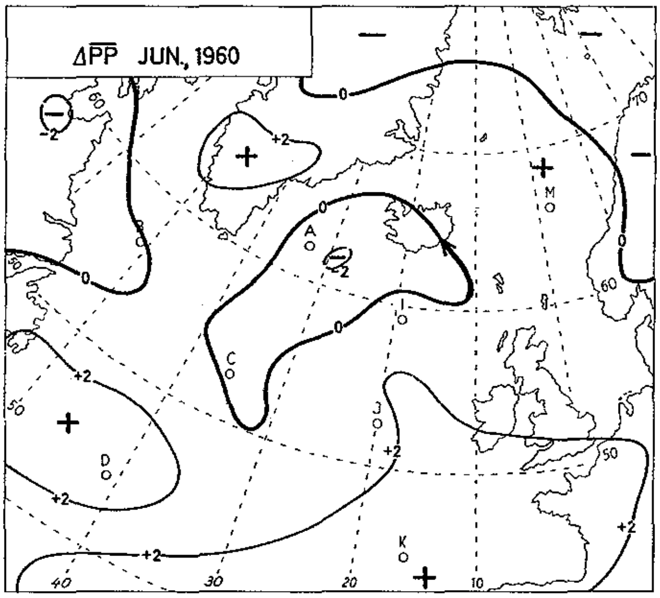

Figure 2:8

Figures 2:5–2:8. The atmospheric circulation in May and June 1960.

January 1960	.... relatively	less wind and storm
February –	.... relatively	*more wind and storm*
March –	.... relatively	less wind and storm
April –	.... relatively	*more wind and storm*
May –	.... relatively	less wind and storm
June –	.... at "I"	less wind and storm
	at "M"	near normal

On the whole, the first six months 1960 do not show any extreme deviations of wind velocities from the averages of the decade 1951–60. The seasonal decrease of strong wind and gale frequency in *May-June 1960* was, however, considerably greater than normal at the OWS I south of Iceland.

THE TEMPERATURE OF THE SURFACE WATER (AND OF THE AIR) AT THE OWS'S I AND M DURING THE FIRST SIX MONTHS 1960.

From the atmospheric conditions of circulation during the first six months of 1960, one could deduce

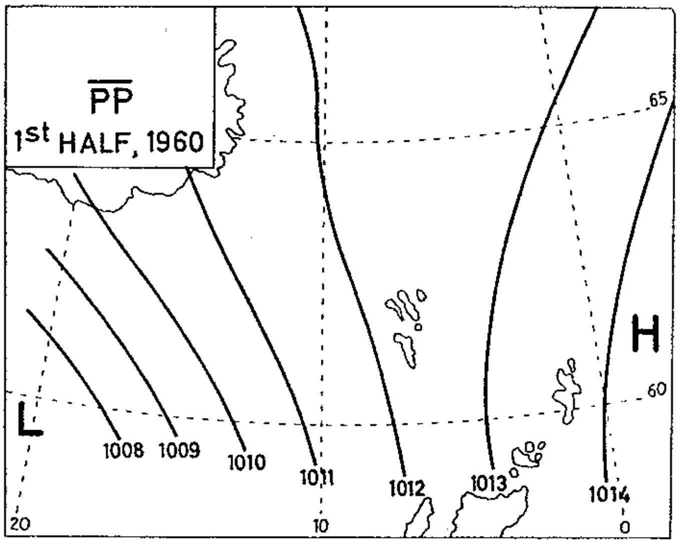

Figure 2:9

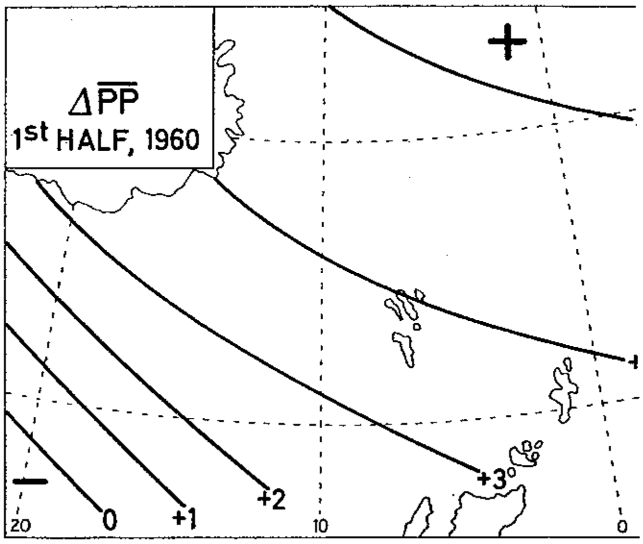

Figure 2:10

Figures 2:9–2:10. The mean atmospheric circulation during the first six months of 1960.

the existence of a period of above-normal warm surface waters in the sea area south and east of Iceland. Table 2:4 confirms the *warm period* for the OWS's I and M.

Again the data are based on the statistical evaluation of the daily radio weather reports of the OWS's. The values derived by the author (3) 1952, which approximately refer to the period 1900–1940, were used as *normal values*. We see:

(a) *During all the months*, January to June 1960, the mean water temperature at the stations I and M were *above* the averages of the decade 1951–60.

(b) Compared with the normal values, the magnitude of deviation was, at Station I, $+1{\cdot}0°\,C$, at Station M, $+1{\cdot}5°\,C$.

(c) Especially pronounced was the positive anom of the surface temperatures during the months *May* and *June 1960*.

That these conditions were unusual, is illustrated the fact that at Station M *each* of the six mon January till June 1960 showed the *maximum mont mean of water temperature of the decade 1951–60.* Station I the peculiarity was not so striking; nev theless, the months of *May* and *June 1960* were h the warmest of all the corresponding months of t decade 1951–60. (May 1959 was of the same temp ature as May 1960).

The temperatures of the air, given for comparis (in Table 2:5) show, – except for February 1960 - similar picture as the water temperatures. Posit anomalies (with reference to the decade 1951–60) a

Table 2:2.
Prevailing winds (degrees) and monthly mean wind velocities (knots) as well as their deviations from the decadal average 1951–1960

1960	Ocean Weather Station I: Prevailing wind (°)	Ocean Weather Station I: Mean wind velocity (kn)	Ocean Weather Station I: Deviation from 1951–1960 (kn)	Ocean Weather Station M: Prevailing wind (°)	Ocean Weather Station M: Mean wind velocity (kn)	Ocean Weather Station M: Deviation from 1951–1960 (kn)
Jan.	140	21·5	−3·1	50	17·1	−4·5
Feb.	40	25·3	+2·3	250	24·9	+3·4
March	140	21·5	−1·9	210	17·3	−2·2
April	250	24·6	+2·6	170	23·4	+4·7
May	190	16·7	−2·0	180	14·1	−0·9
June	230	13·7	−2·6	40	14·4	+0·6

Table 2:3.

Monthly frequencies of strong winds (22–33 kn) and gales (≥ 34 kn) and their deviations from the decadal averages 1951–60, given in per cent

1960	Station I Strong winds %	deviat. %	Gales %	deviat. %	Station M Strong winds %	deviat. %	Gales %	deviat. %
Jan.	40·0	− 2·2	7·7	− 12·0	22·6	− 15·2	8·1	− 5·3
Feb.	38·0	− 0·7	22·0	+ 8·2	38·2	+ 1·8	22·2	+ 9·6
March	36·8	− 2·3	12·1	− 4·9	22·4	− 12·4	3·3	− 3·2
April	34·6	− 2·3	21·4	+ 8·0	32·8	+ 1·1	19·0	+ 13·8
May	21·4	− 9·5	2·4	− 1·9	21·0	+ 0·3	0·4	− 1·5
June	11·2	−10·4	0·4	− 1·4	13·8	+ 0·4	–	− 0·4

Table 2:4.

Monthly mean surface temperatures of the sea (°C) at the stations I and M, as well as their deviations from the decadal averages 1951–60 and from the normal values

1960	Station I Water temp. °C	Deviation from the average 1951–60	Deviation from the normal value	Station M Water temp. °C	Deviation from the average 1951–60	Deviation from the normal value
Jan.	9·4	+0·2	+1·0	7·2	+0·6	+1·4
Feb.	9·2	+0·1	+1·0	6·8	+0·5	+1·3
March	9·2	+0·2	+1·0	7·1	+0·8	+1·7
April	9·3	+0·1	+0·7	6·9	+0.5	+0·9
May	10·6	+0·7	+1·2	8·5	+1·0	+1·6
June	12·0	+0·7	+1·4	9·9	+1·0	+1·5

Table 2:5.

Monthly means of the air temperature (°C) at the stations I and M and their deviations from the decadal average 1951–60

1960	Station I Air temperature	Deviation	Station M Air temperature	Deviation
Jan.	7·0	+1·1	3·7	+0·5
Feb.	6·0	−0·6	2·7	−0·4
March	8·0	+0·8	5·9	+2·1
April	8·4	+1·0	5·4	+1·1
May	10·3	+1·4	7·8	+1·8
June	11·2	+0·8	8·7	+1·0

mostly stronger than those of the surface water. At station M the months of March to May 1960 were the warmest in air of the spring months of the decade; June, 1960 was the second warmest of all June months after June 1953. At Station I, May and June 1960 had the highest mean air temperature of all months of May and June of the decade 1951–60.

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THE ACTUAL WEATHER SITUATION DURING THE EXPEDITION

By

F. Krügler

SOME REMARKS ON THE FORECASTING WORK OF THE METEOROLOGICAL STATION "ANTON DOHRN"

Before discussing the actual weather situations during the ICES Expedition, some notes may be given about organization and forecasting work of the meteorological station on board the German Fishery Research Ship "Anton Dohrn".

This meteorological station (as well as the corresponding stations on board the German fishery protection vessels "Meerkatze" and "Poseidon") belongs to "Deutscher Wetterdienst, Seewetteramt Hamburg". During the ICES Expedition the crew of the Meteorological Station "Anton Dohrn" consisted of one meteorologist[1] (forecaster) and one technical wireless assistant, as is usual during all normal research cruises of this ship.

The forecaster not only supplied the scientists and the ship's command of "Anton Dohrn" personally, but also provided by radio all the other research ships taking part in the Expedition with special weather forecasts for the region, in order to promote by this means as far as possible the expeditious prosecution of the investigations.

For this purpose, daily synoptic weather maps of the North Atlantic area were plotted and analysed, usually at 0600 and 1500 hours GMT, but if necessary also at 1200 and 1800 hours. Additional special weather maps of the Iceland-Faroe Ridge area were plotted at 0900 and 1800 hours GMT (if necessary also at 2100 hours). Upper air charts, tendency charts, forecast charts etc. were received daily by means of facsimile receivers (Hellfax) from the German Forecast Centre, Offenbach.

The forecasting work of the Meteorological Station "Anton Dohrn" during the Expedition was carried out nearly in the same routine manner as is usual during all research cruises of this ship. Twice daily, at 1000 and 2030 hours GMT, the forecaster issued weather reports, including a "general inference", a "forecast" for the next 12 hours, and an "outlook" for a further 12 hours for the Ridge area and its different parts. These were transmitted by radio in English to all research ships participating in the expedition.

In addition to the numerous observations of the International Weather Broadcast Programme, which were received daily, the regular weather observations, made by the expedition ships and transmitted to "Anton Dohrn" were an important basis, not only for this forecasting work during the expedition, but for preparing the special synoptic weather maps sented in the following paragraph.

[1] Forecaster during the ICES Expedition was the author of this report.

GENERAL REMARKS ON THE CHARTS PRESENTED

On the assumption that this may be the best to describe the weather situations during the pedition for the purposes of oceanographers, seri synoptic weather maps (Figures 2:12–2:19) of Northeast Atlantic area with pressure distribution fronts, as well as special synoptic maps (Figures 2 2:21) with pressure distribution, fronts and sur wind observations for the area itself and its envi ments, are presented below. These maps may en oceanographers to study the probable or possible fluence of the main meteorological factors on the n problem under investigation.

For plotting the following synoptic maps, weather maps prepared on "Anton Dohrn", as as the regular synoptic working maps of "Deuts Wetterdienst, Seewetteramt Hamburg" were u Other charts (Figure 2:11) are also presented, wl show the mean pressure field of some special wea periods during the expedition and some signifi mean surface wind vectors of and around the during these periods.

REMARKS ON THE MEAN CHARTS OF THE VAR WEATHER PERIODS

Figure 2:11A shows the mean pressure distribu for the period 21.–24. May, 1960, i.e. some days be the beginning of the expedition. A rather sha mean depression was then situated just east of Faroes and a corresponding north-northeastern m air current flowed through the Iceland-Faroe Ri area.

This period A was followed by a longer pe (25. May–3. June 1960) as shown in Figure 2: with a rather deep mean depression southwes Iceland and a south-southwest mean air current corresponding weather type in the Ridge area.

The succeeding period, 4.–7. June 1960 (Fig 2:11C) shows a shallow mean depression sout Iceland with a southeastern mean air current betw Iceland and Faroe. Then, with the transition into northeastern type, shown in Figure 2:11D (perio 8.–14. June 1960), a considerable change of general weather in the Ridge area took place wi rather deep mean depression southeastward an corresponding northeastern mean air current over area.

The last four days of the expedition, 15.–18. J 1960, can be subsumed as shown in Figure 2:

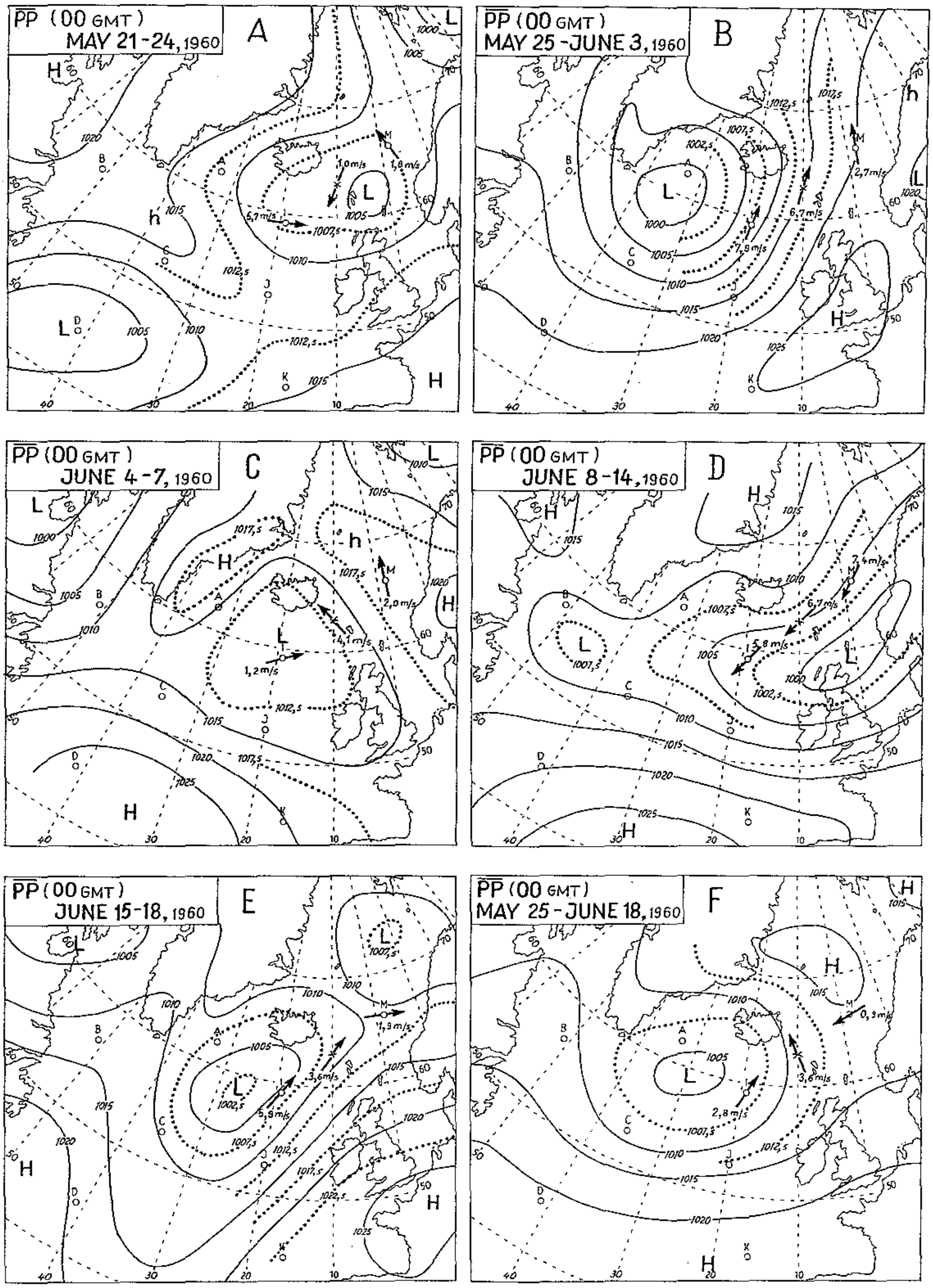

Figure 2:11 A–F. Mean pressure distribution over the Northeast Atlantic (00 GMT) and mean wind vectors at the Ocean Weather Stations I and M as well as at a fictitious centre of the overflow area for the periods

A: 21.–24. May, B: 25. May–3. June, C: 4.–7. June, D: 8.–14. June, E: 15.–18. June, F: 25. May–18. June 1960.

Table 2:6.
Mean wind vectors

Weather period	Ocean Weather Station "I"	Ocean Weather Station "M"	Fictitious centre of the Iceland-Faroe Ridge area (63°N, 10°W)
21.–24. May 1960	266° 5·7 m/sec	151° 1·8 m/sec	abt. 25° 1 m/sec
25. May–3. June 1960	202° 7·9 m/sec	183° 2·7 m/sec	abt. 195° 6·7 m/sec
4.–7. June 1960	245° 1·2 m/sec	178° 2·0 m/sec	abt. 140° 4·1 m/sec
8.–14. June 1960	35° 5·8 m/sec	34° 7·4 m/sec	abt. 50° 6·7 m/sec
15.–18. June 1960	213° 5·9 m/sec	272° 1·9 m/sec	abt. 215° 3·6 m/sec
25. May–18. June 1960	203° 2·8 m/sec	70° 0·9 m/sec	abt. 160° 3·6 m/sec

which presents a rather deep mean depression south-southwest of Iceland and a corresponding southwest to south-southwesterly mean air current and weather type between Iceland and Faroe.

When considering the four separate periods of Figure 2:11B, C, D, E, as on E_1 the mean circulation pattern shown in Figure 2:11F is derived, with a mean depression southwest of Iceland and a south-south-eastern mean air current over the Ridge area. This mean circulation pattern resembles the mean circulation charts of May and June 1960, shown in Figures 2:5 and 2:6 of this chapter.

Table 2:6 shows the mean surface wind vectors at the OWS's I and M as well as at a fictitious centre of the Iceland-Faroe Ridge area (namely, at 63°N, 10°W) during the different weather periods given in the charts 11A–F. The mean wind vectors at the OWS's were calculated by the Seewetteramt from statistics of the 3-hourly observations of these ships, whereas the mean wind vectors at the fictitious centre were obtained from the mean atmospheric pressure gradient at the position 63°N, 10°W, by means of the windnomograms by Rudloff (1960).

REMARKS ON THE SYNOPTIC WEATHER MAPS OF THE PERIOD OF THE EXPEDITION

Details of the general pressure distribution and surface wind situation over the Northeast Atlantic and their changes may be studied in the series of synoptic maps in Figures 2:12–2:19. Special details of the surface wind development in the region of the Iceland-Faroe Ridge can be read from the small special synoptic maps given in Figures 2:20–2:21. These maps include the surface wind observations of the research ships as well as of the OWS's I and M, and of German trawlers and other ships.

In order to get these maps as clear as possible, and assuming the atmospheric pressure and surface wind to be probably the most important meteorological factors for the "Overflow" problem, no other meteorological elements or symbols were plotted, but only isobars with the symbols for Highs and Lows, fronts and surface wind observations. The latter are from ships only and not from coastal stations which in most cases, due to orographic influences, are not sufficiently representative.

With regard to air temperature, it may be assumed that a northerly wind component normally brings cold air (relative to surface water temperature) and that a southerly wind component mostly brings relatively warm air into the Iceland-Faroe Ridge area.

Due to the comparatively short interval of only 6 hours between two maps of both overlapping types details about the beginning or the end of distinct surface wind system or about dates of pronounced changes in wind and pressure situations (front passages etc.) can probably be read from the maps with a sufficient degree of accuracy. The atmospheric pressure gradient may be taken from the distances between isobars (5 mb, occasionally also 2·5 mb).

REMARKS ON SOME PECULIARITIES OF THE SYNOPTIC WEATHER DEVELOPMENT DURING THE EXPEDITION

Wind speeds of more than 21 knots were observed in the area on several occasions with winds from the southeast and southwest quadrants (e.g. on 1., 2., 6. and 15. June 1960). In these cases the weather situations were of an unsettled type with comparatively quickly moving fronts, so that the strong winds generally did not last for more than 1/2 to 1 day without interruption.

The relatively most pronounced change in wind direction, with wind speeds of more than 21 knots throughout most of the area, occurred during 1. June 1960 when the wind veered from southeast to southwest. Less pronounced changes in wind direction with sporadic wind speeds of more than 21 knots from southeast, decreasing when veering, were observed on 2. June and 15.–16. June 1960.

(Continued on p. 37

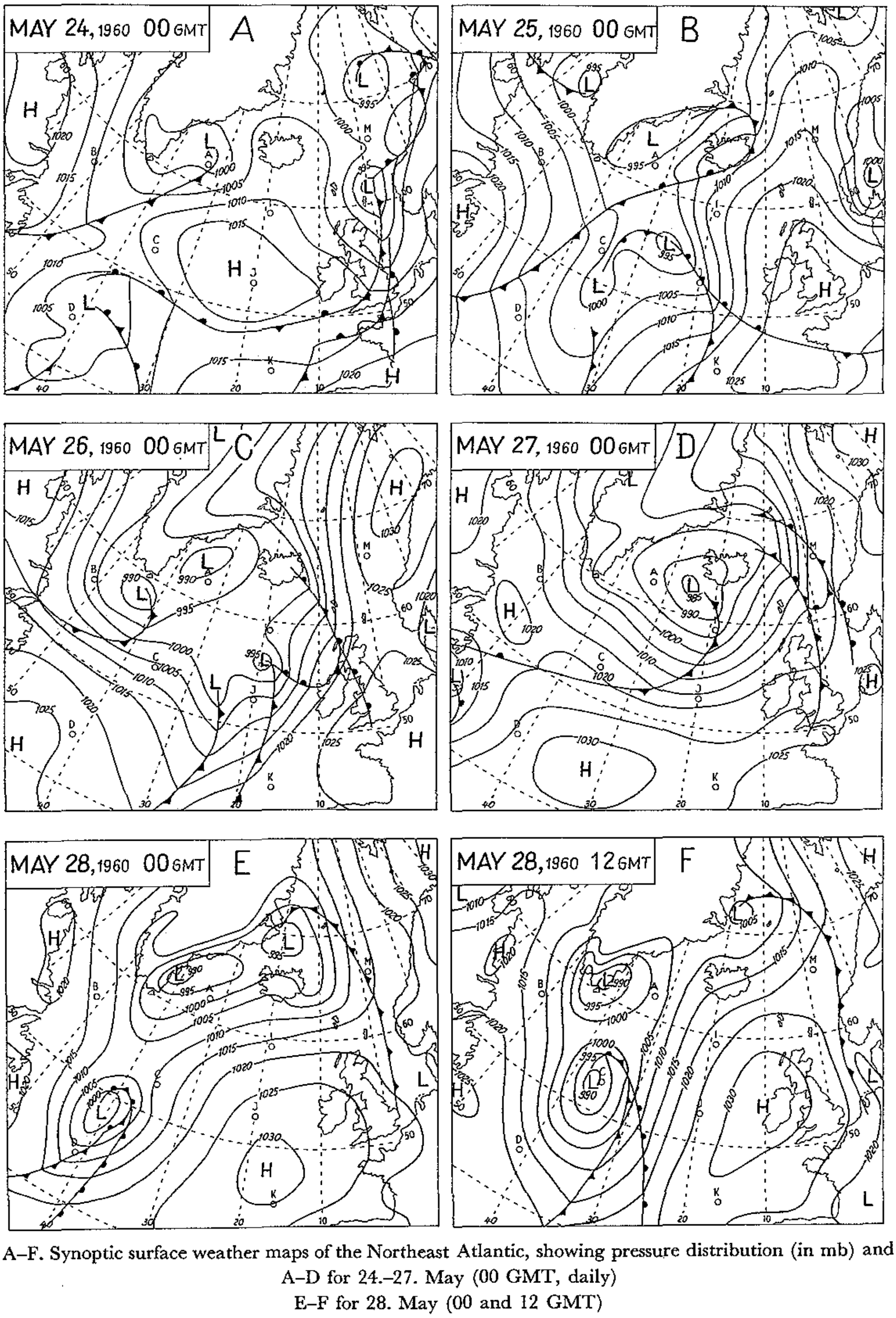

Figure 2:12 A–F. Synoptic surface weather maps of the Northeast Atlantic, showing pressure distribution (in mb) and fronts 1960.
A–D for 24.–27. May (00 GMT, daily)
E–F for 28. May (00 and 12 GMT)

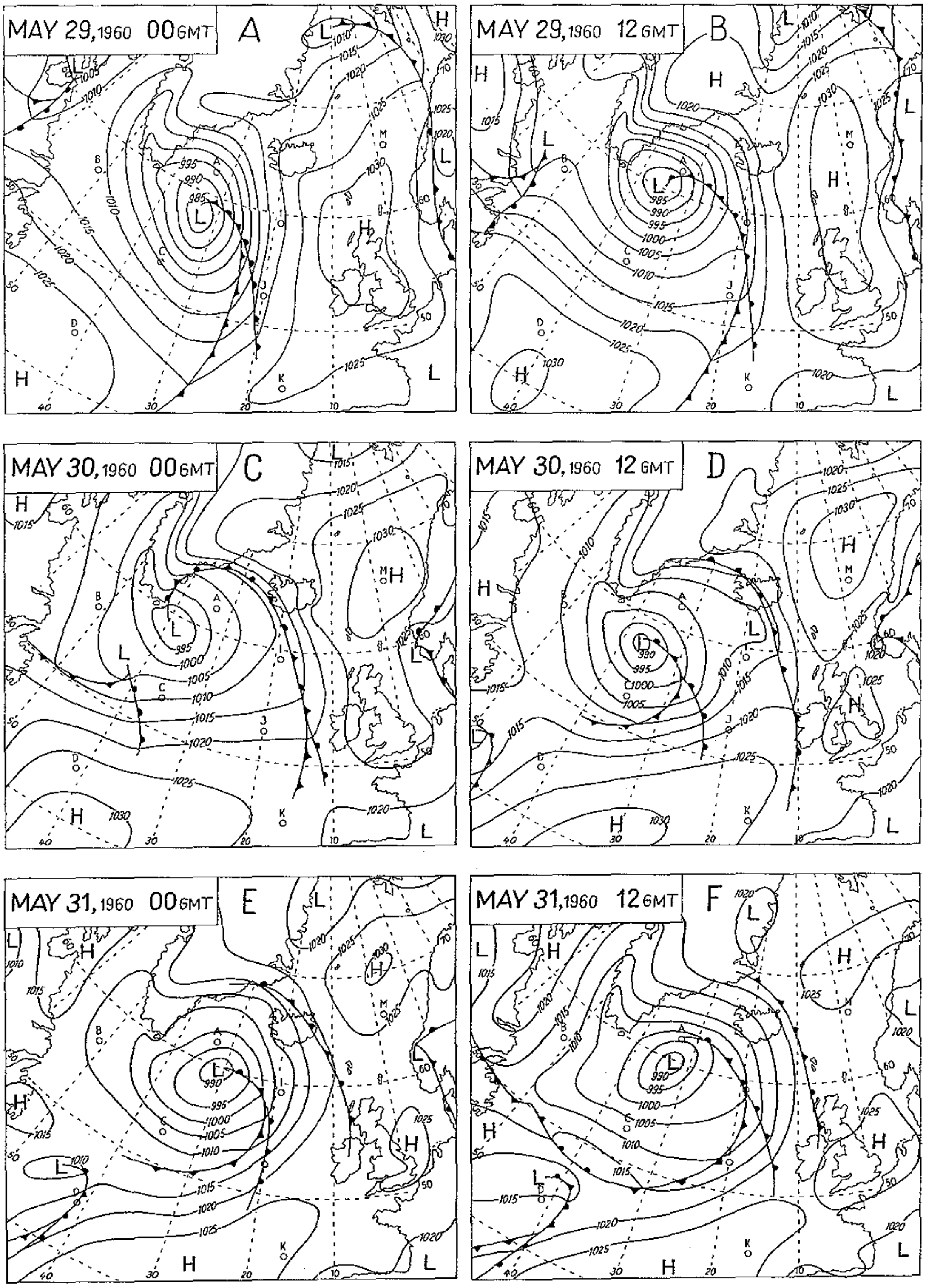

Figure 13 A–F. Synoptic surface weather maps of the Northeast Atlantic, showing pressure distribution (in mb) and fronts for 29.–31. May 1960 (00 and 12 GMT, daily).

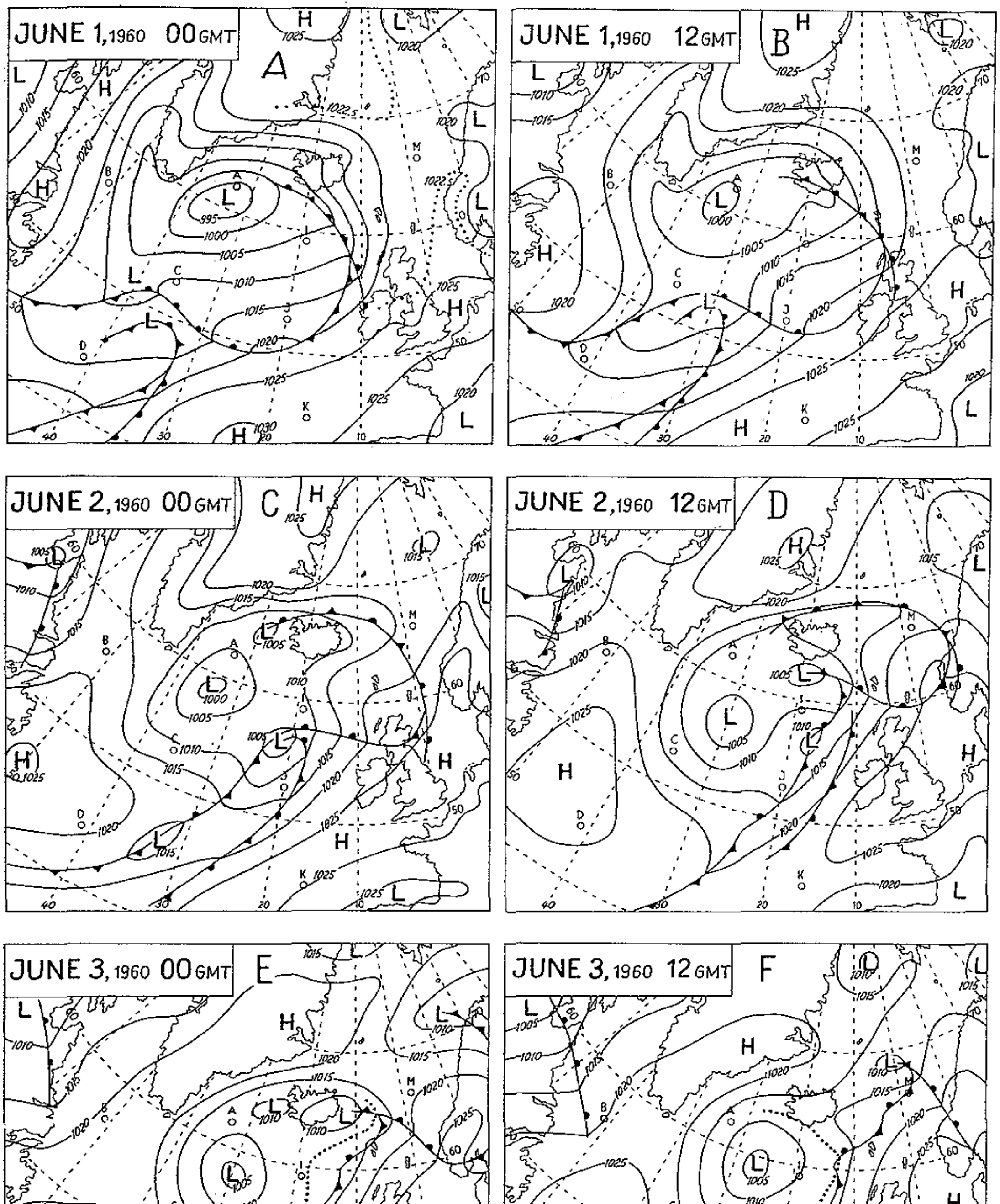

Figure 2:14 A–F. Synoptic surface weather maps of the Northeast Atlantic, showing pressure distribution (in mb) and fronts for 1.–3. June 1960 (00 and 12 GMT, daily).

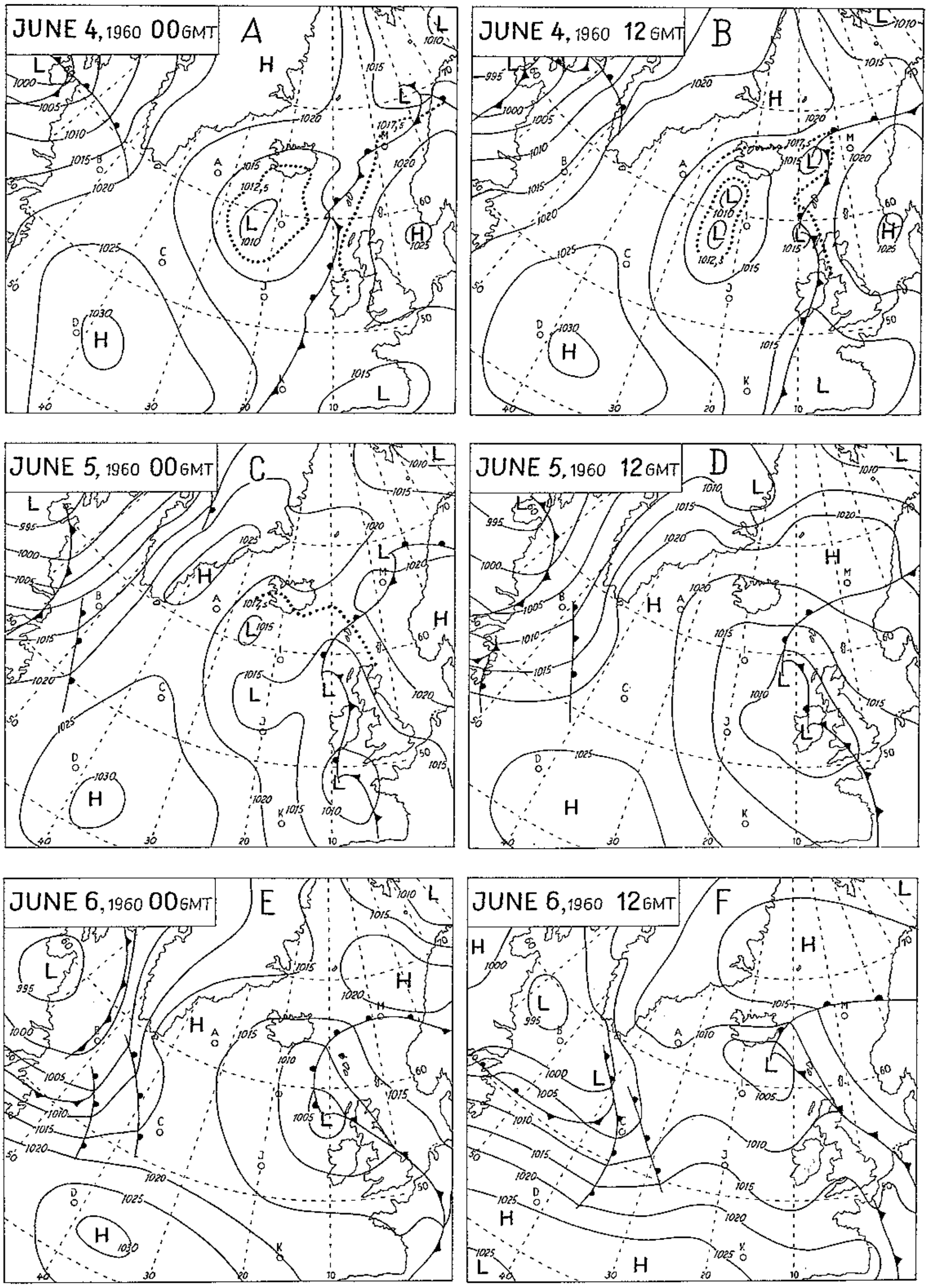

Figure 2:15 A–F. Synoptic surface weather maps of the Northeast Atlantic, showing pressure distribution (in mb) and fronts for 4.–6. June 1960 (00 and 12 GMT, daily).

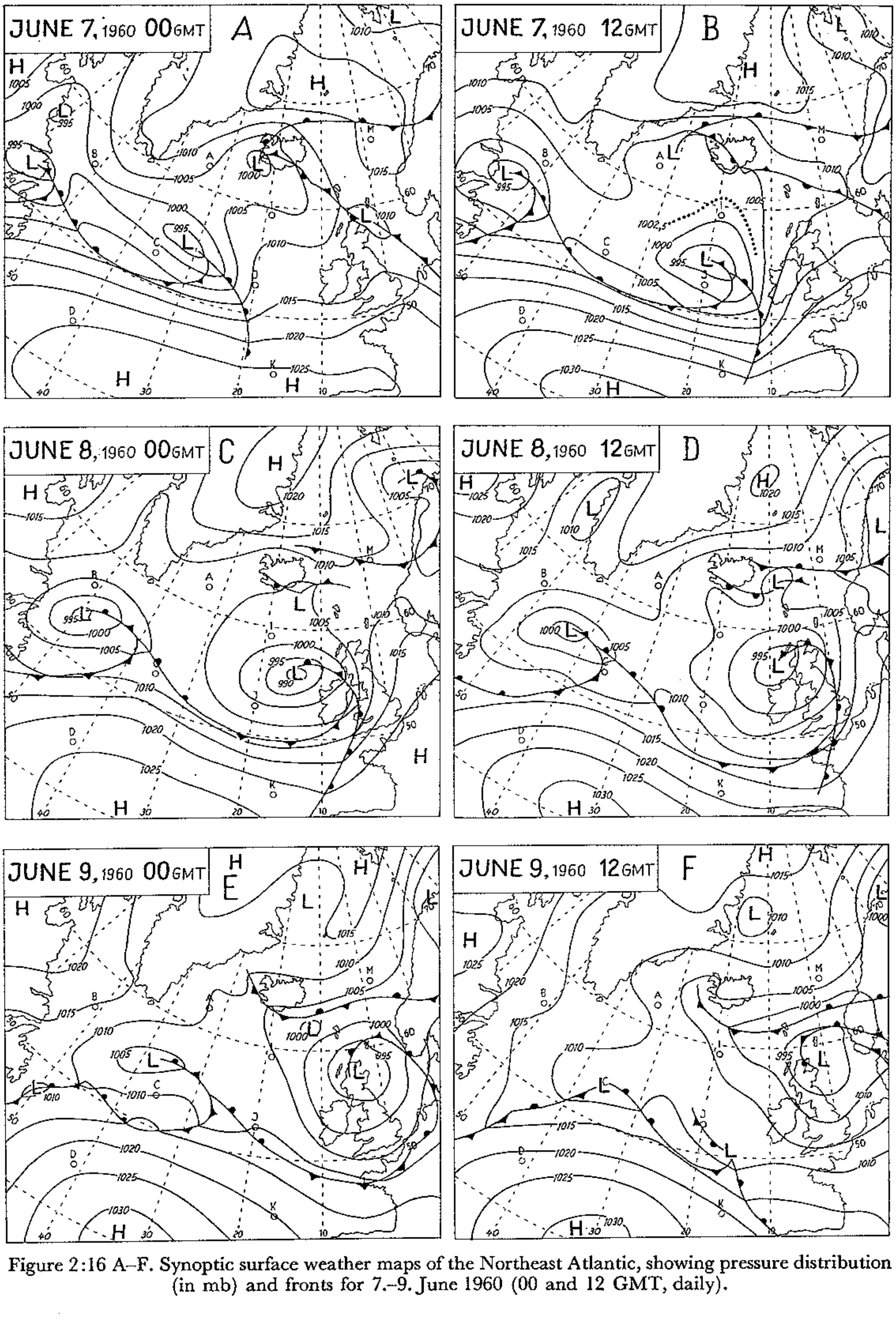

Figure 2:16 A–F. Synoptic surface weather maps of the Northeast Atlantic, showing pressure distribution (in mb) and fronts for 7.–9. June 1960 (00 and 12 GMT, daily).

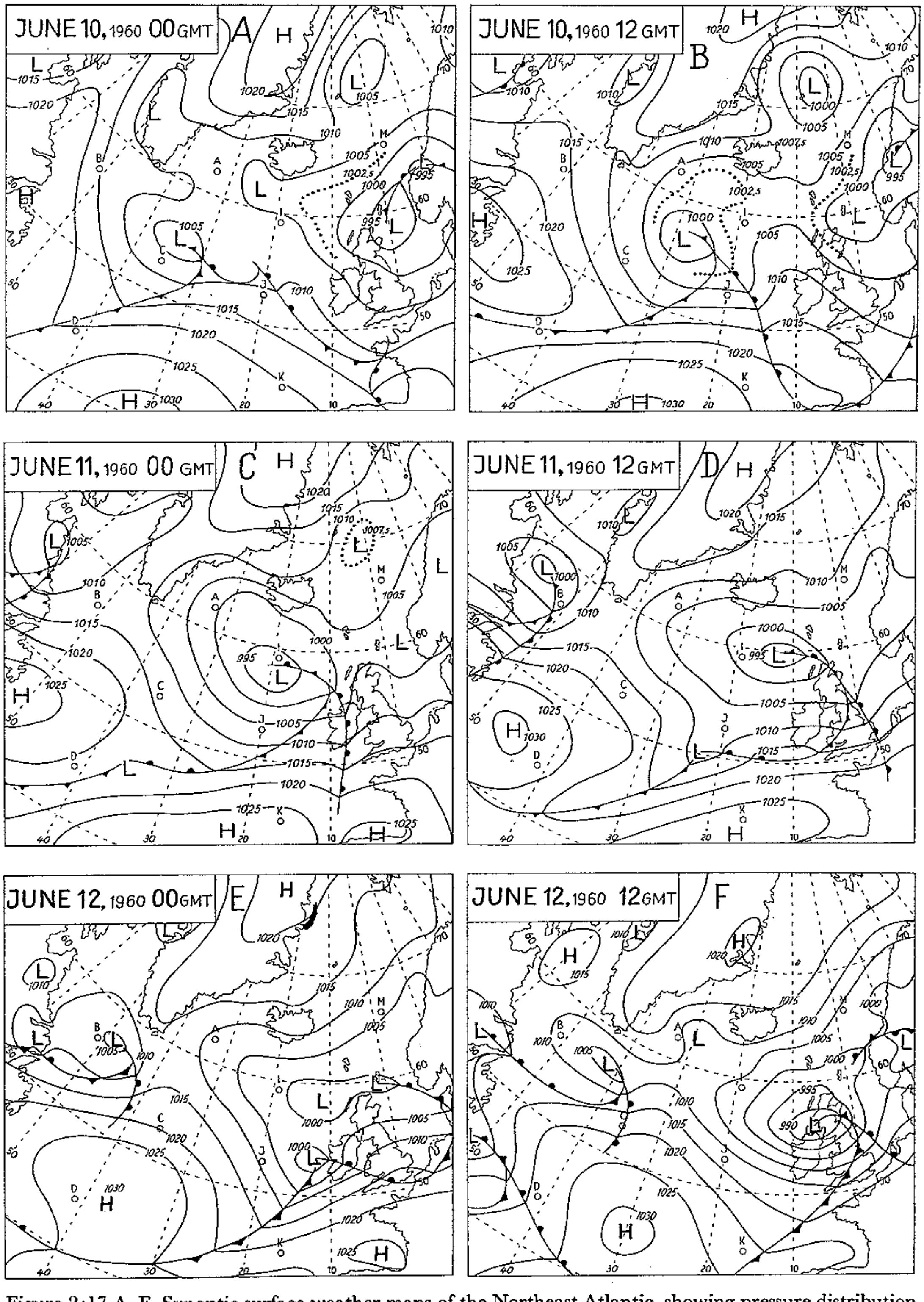

Figure 2:17 A–F. Synoptic surface weather maps of the Northeast Atlantic, showing pressure distribution (in mb) and fronts for 10.–12. June 1960 (00 and 12 GMT, daily).

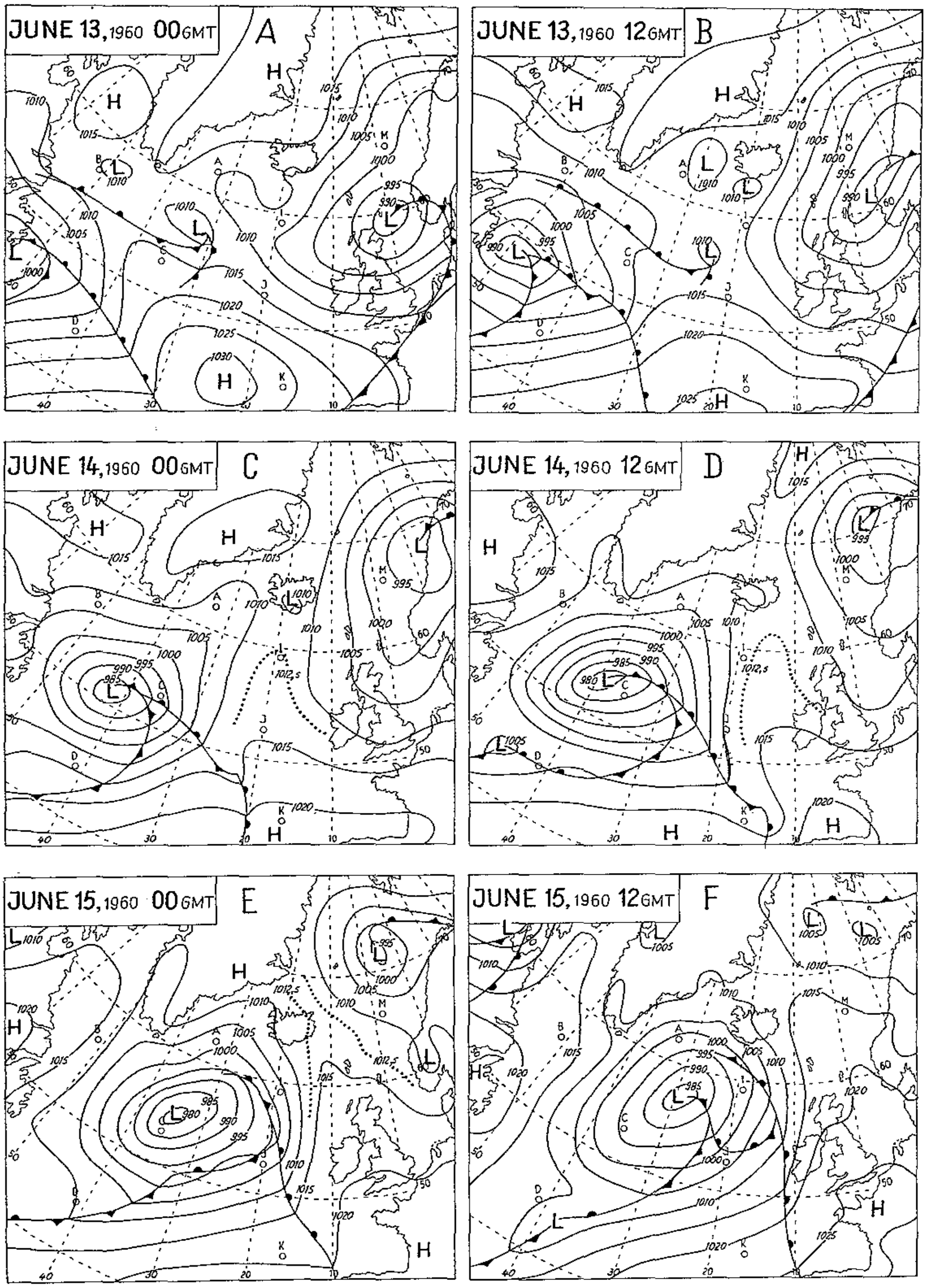

Figure 2:18 A–F. Synoptic surface weather maps of the Northeast Atlantic, showing pressure distribution (in mb) and fronts for 13.–15. June 1960 (00 and 12 GMT, daily).

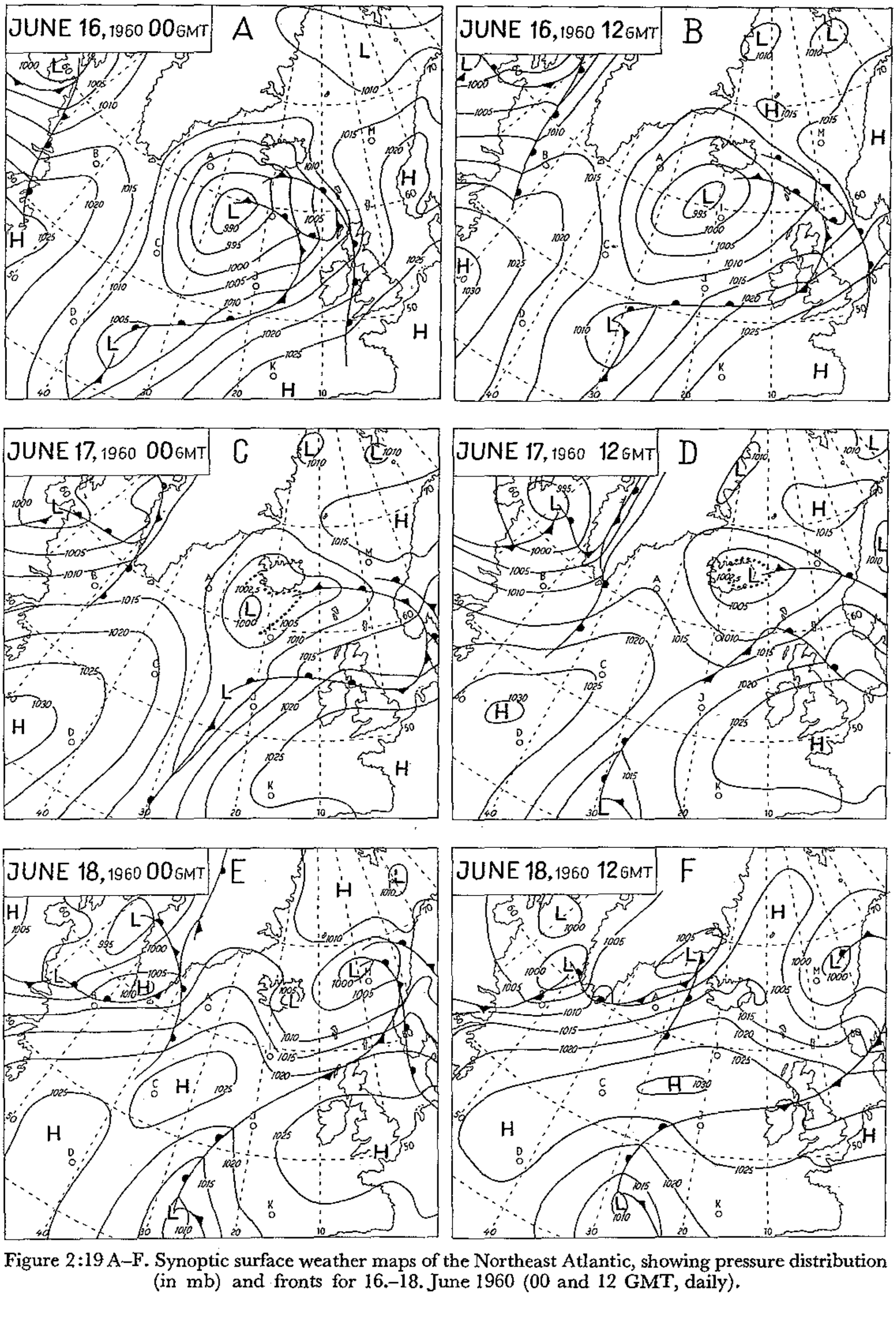

Figure 2:19 A–F. Synoptic surface weather maps of the Northeast Atlantic, showing pressure distribution (in mb) and fronts for 16.–18. June 1960 (00 and 12 GMT, daily).

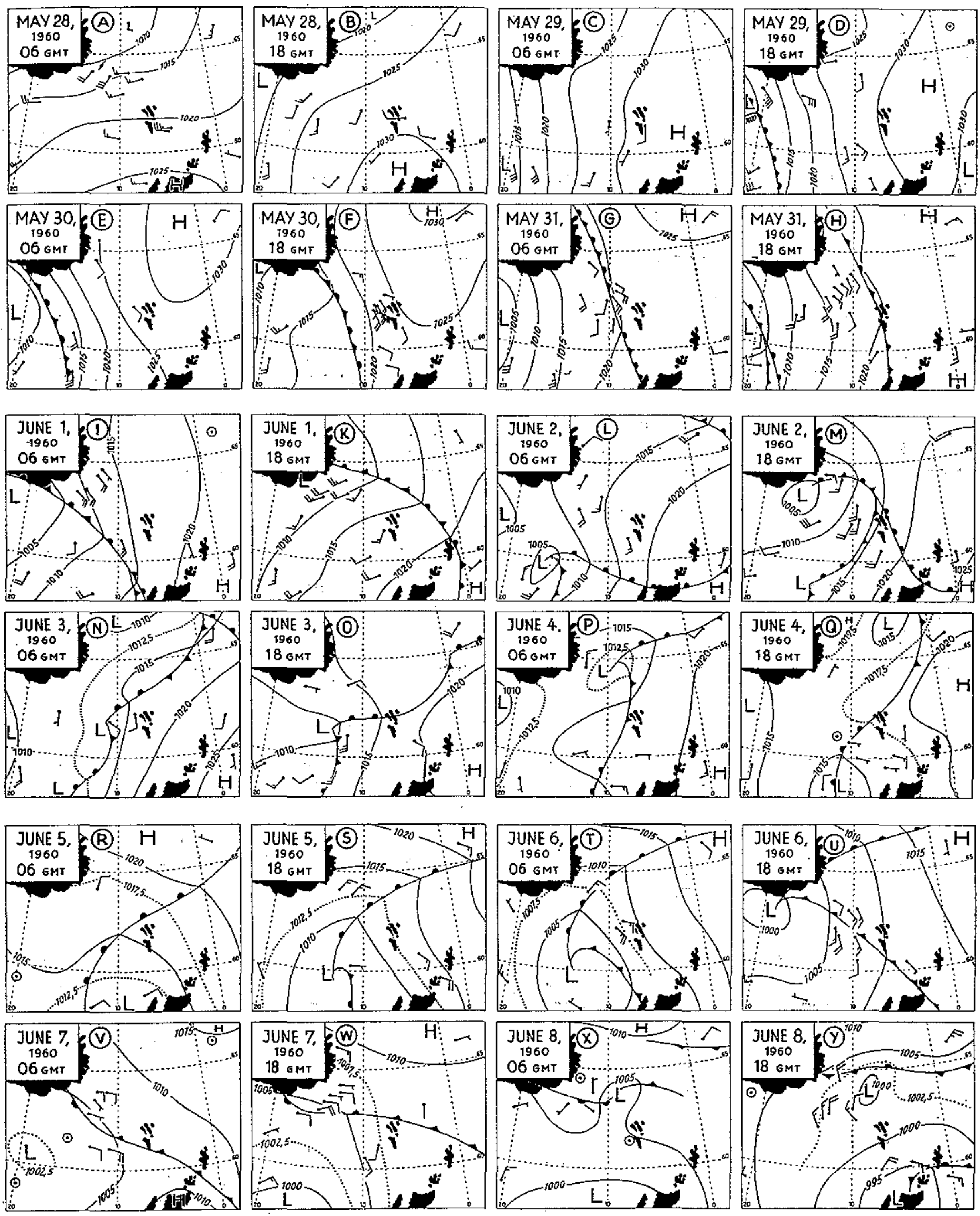

Figure 2:20 A–Y. Synoptic surface weather maps over the overflow area (Iceland-Faroes) and environments, showing pressure distribution (in mb), fronts and surface wind observations (in international symbols, windspeed in knots) for the period 28. May–8. June 1960 (0600 and 1800 GMT, daily).

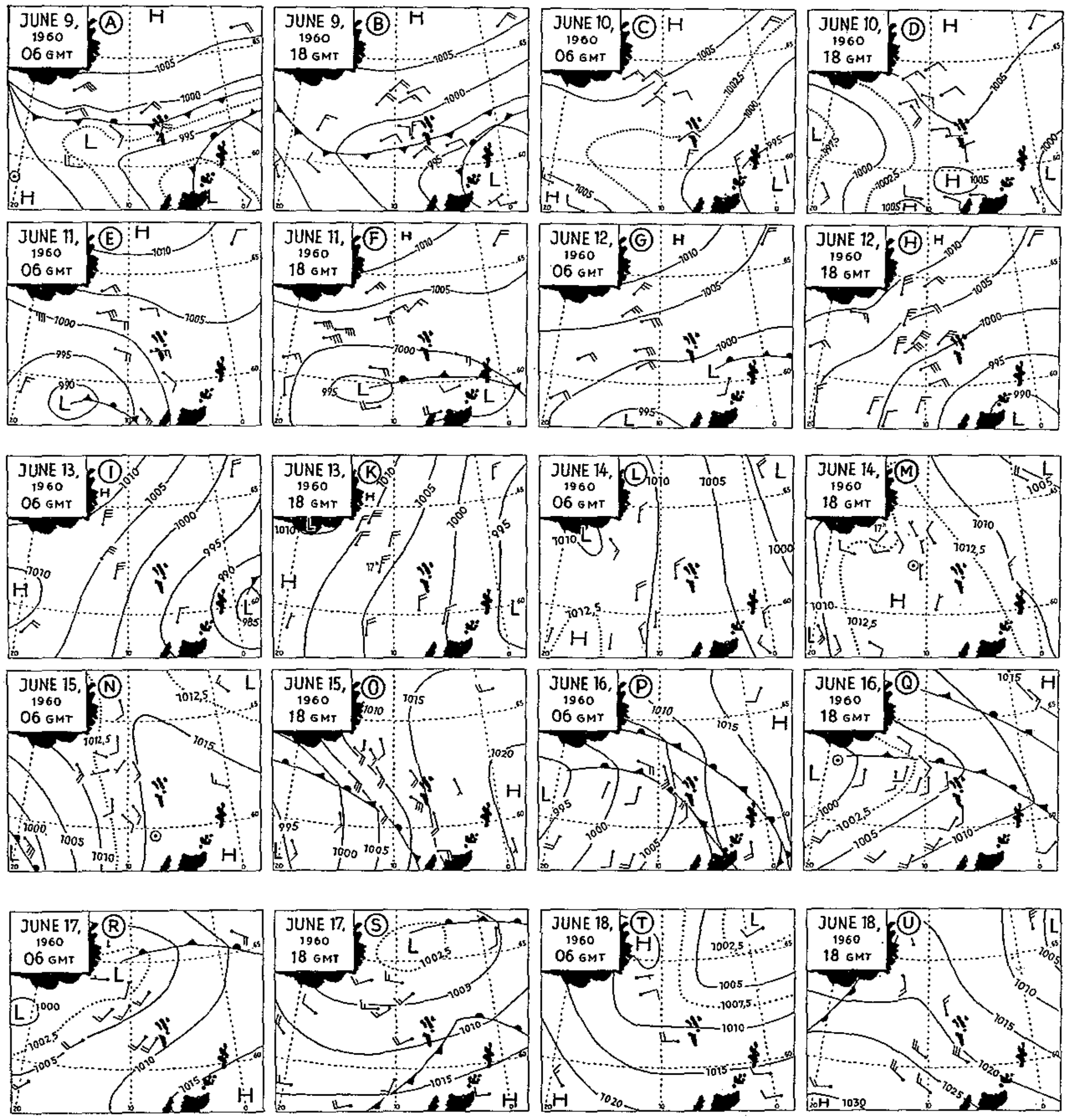

Figure 2:21 A–U. Synoptic surface weather maps over the overflow area (Iceland-Faroes) and environments, showing pressure distribution (in mb), fronts and surface wind observations (in international symbols, windspeed in knots) for the period 9.–18. June 1960 (0600 and 1800 GMT, daily).

The longest period with continuous strong winds or near gales occurred from early 11. June to late evening 13. June 1960 with winds from the northeast quadrant and speeds about 25–30 knots. This relatively settled weather situation with strong winds about northeast ended during the night from 13. to 14. June 1960 and was followed by light and variable winds during 14. June, with a change into an unsettled southwestern weather type afterwards.

On the whole, the weather during the period of the expedition may be described as unstable. Occasionally, considerable differences in wind and weather were observed between the different parts of the region as a whole. These local and temporal differences depended on the respective type of weather situation, e.g. on the direction of movements of Highs and Lows and fronts, and, at times, were so considerable that it seemed not to be advisable to try to characterize the weather development by general statements valid for all parts of the area. For this reason no table with uniform general wind and weather statements, valid for the whole region, has been given.

REFERENCE

Rudloff, W., 1960. "Windschätzung nach der Wetterkarte". Seewart, **21**(5): 192–97.

CHAPTER 3
TEMPERATURE AND SALINITY DISTRIBUTIONS AND WATER-MASSES OF THE REGION

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FOREWORD

While the main objective of the ICES international expedition of 1960 to the Iceland-Faroe Ridge region was the detection, delineation, and, as far as possible, the measurement, of cold, deep water overflow across the Ridge from the Norwegian Sea into the North Atlantic Ocean basin, the region has for so long been known as one of conjunction and conflict between relatively warm oceanic waters on the one hand, and cold, Arctic waters on the other, that the occasion of such a unique exercise in concentrated oceanographical observation should not be overlooked for the material it provides for a closer study of these conflicting phenomena than has previously been possible. An immediate reason, moreover, for such a study, from the ICES point of view, resides in the fact of the significance of the region from a fisheries standpoint. Here, as is well known, commercial fisheries are subject to wide and often apparently abrupt fluctuations from more or less ample abundance to complete absence, and the oceanographical nature of the region suggests that these fluctuations may be more or less closely associated with corresponding changes in the physico-chemical environmental milieu.

J. B. Tait

HORIZONTAL TEMPERATURE AND SALINITY DISTRIBUTIONS (J. B. Tait)

Taking, first, horizontal distributions and, in particular, those of temperature and salinity, Figures 3:1–3:21 give the dispositions of these parameters at the surface, 100, 300, 400, and 500 metres, and on the bottom, on each of the three surveys of the expedition. A general view of these diagrams reveals at once, on all three surveys, an increasing complexity of the pattern of temperature and salinity distributions from the surface downwards to at least 300 metres, where the complexity is greatest. It is only a little less so at 400 metres, but at 500 metres, the bathymetrics of this depth defining the northern and southern "shoulders" of the Ridge proper, the intervention of the Ridge physically separates the deep oceanic and cold northern water-masses, except for small overspills from one into the other. The temperature and salinity distribution patterns therefore at this level are comparatively straightforward and uncomplicated.

Figures 3:1, 3:8 and 3:15 represent surface temperature and salinity conditions on each of the three surveys. On all three occasions the Ridge area was completely overlaid, on the surface, by oceanic water which in fact extended northward far beyond the Ridge itself. Only in the northwest corner of the region investigated, as well as eastward beyond the Ridge, and farther north between about latitudes 64°30′N and 65°N, was there evidence of the near vicinity of Arctic type waters of low temperature ($<6°$C) and salinity of less than $34{\cdot}90\,^0/_{00}$. High salinity oceanic water, in excess of $35{\cdot}30\,^0/_{00}$, ocurred in patches over the Ridge and, on the first survey, beyond it. Highest salinity water, of over $35{\cdot}40\,^0/_{00}$ salinity, was found only over the southern end of the Faroe-Shetland Channel and, on the third survey only, some 30–40 miles northwest of the Faroe Bank and a similar distance northwest of the Faroe Islands respectively.

As between the first and second surveys, the relative

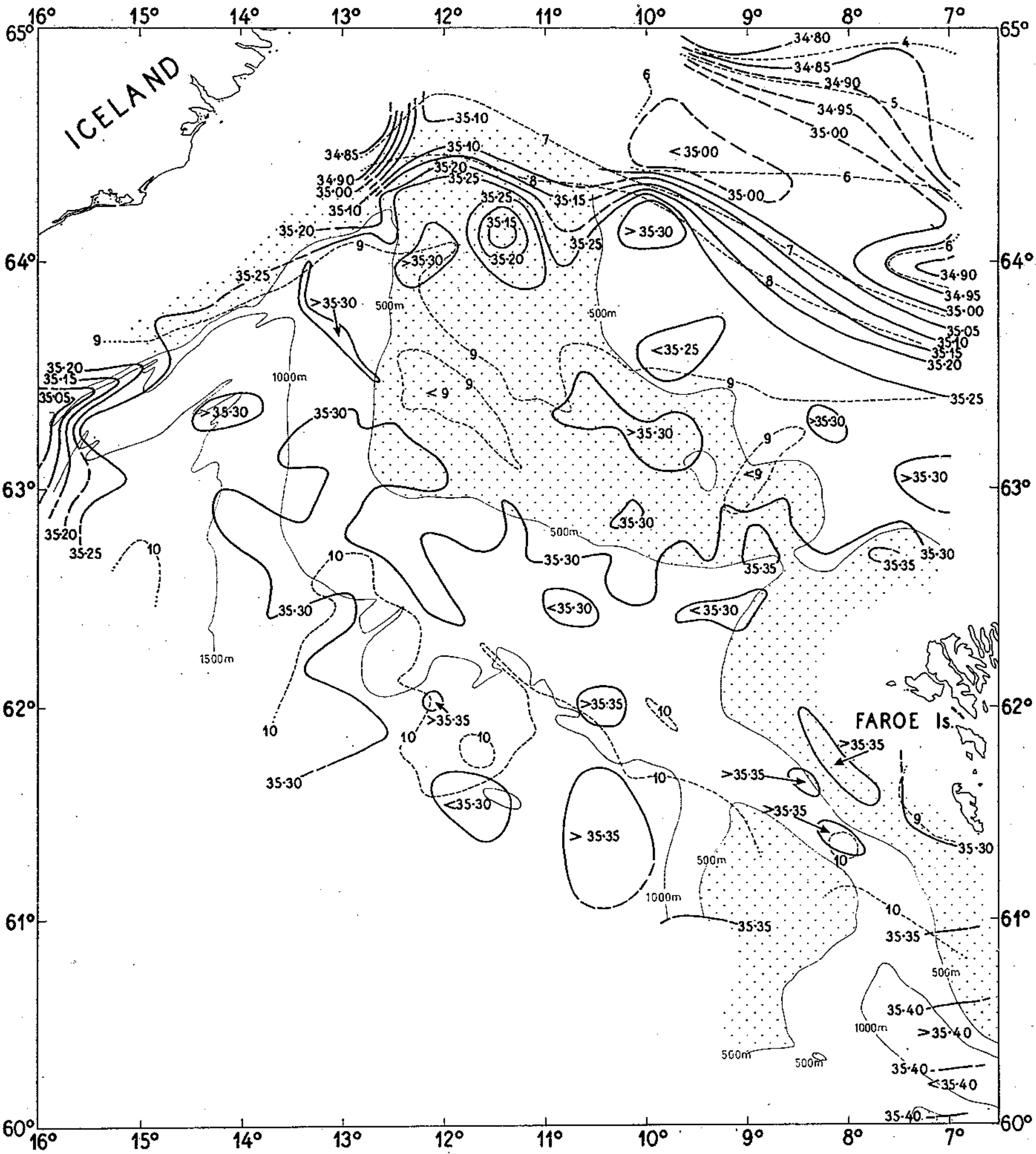

Figure 3:1. First Survey: surface temperature and salinity.

positions of the surface 9° C and 10° C isotherms, and the occurrence of the 11° C isotherm just within the region investigated on the second survey, argues an increasingly progressive surface oceanic influence northwards towards and over the Ridge, with, of course, a concomitant regression northwards of the Arctic influence tending to bear southwards towards the Ridge. On the whole, the salinity distributions of the first two surveys scarcely bear the same implication. Indeed, so far as salinity is an index, the difference between Figures 3:1 and 3:8 almost points in the reverse sense, namely, in favour of a slight impediment to the northern progress of oceanic influence over the Ridge by southerly directed Arctic influence. The difficulty in assessing the differential significance as between oceanic and Arctic influences of the surface salinity distributions of the first two surveys arises from the increased evidence of vorticity movement over the Ridge on the second survey. On the first survey there was apparently only one of those entities, but, as will appear later, probably a significant one, in the area over the Rose Garden (Rosengarten) fishing area. Here, on the first survey, the general salinity of the neighbourhood of over 35·25 ‰ was, presumably by influence from the north, reduced to below 35·15 ‰. On the second survey, in this same area and in a similar vortex, the surrounding salinity of about 35·25 ‰ was reduced in the centre of the vortex to a nuclear value of below 35·00 ‰, indicative it would appear of increasing influence, in this particular region at least, of colder fresher water from the north or northeast.

Farther south towards the narrowest part of the Ridge, but still on its northern boundary, a second, less intense vortex appeared on the surface on the second survey, reducing the salinity there from a general distribution of over 35·25 ‰ to below 35·20 ‰.

A third of these apparently diluting vortices appeared on the second survey on the southwestern shoulder of the Ridge, enclosing a minimum salinity of less than 35·15 ‰ in an area of 35·25 ‰ to 35·30 ‰ salinity water.

Despite these indications, however, by salinity, and while at the same time accepting the intrusive influence which they evidently signify, the total or aggregate interpretation of the surface temperature and salinity distributions from the first to the second survey points to the recession of the northern in favour of the southern, oceanic influence.

The difference between the surface distributions of the second and third surveys is on the whole less impressive. The 10° C, 9° C, and 8° C isotherms retained much the same positions geographically on the third survey, as on the second. The 11° C isotherm did not appear on the third survey, perhaps because the narrow region of its occurrence on the second survey was not included on the third occasion. Likewise, the main 35·30 ‰ isohalines of the two surveys were on the whole similarly disposed, although the third survey would appear to have witnessed a greater intrusion of higher salinity water, above 35·35 ‰, and indeed, in two places, corresponding very nearly to the two loci of maximum salinity surface waters on the first survey (> 35·35 ‰), above 35·40 ‰. These circumstances indicate still further progression of the oceanic influence northwards at the expense of the colder and fresher northern influence southward towards the Ridge.

On the other hand, the dilutive eddy or vortex over the Rose Garden area, which was noticed on both the previous surface charts, had evidently intensified in the third week of the exercise, reducing its nuclear surface salinity to below 34·95 ‰. Concomitantly, surface temperatures which had been between 8° C and 9° C on the first two surveys, were here reduced to below 7° C.

Passing to a consideration of conditions at 100 metres' depth (Figures 3:2, 3:9, and 3:12), it may be noticed at once that the vortex of the Rose Garden area, similarly increasing in intensity from the first, through the second, to the third survey, was again revealed at this level, with a marked change in position, however, as between the surface and 100 metres on the first survey, and as between the first and the second and the second and third surveys at the latter level. The curious feature is further noticeable at the 100 metres level (Figure 3:2) on the first survey that the thermal vortex was apparently entirely separate from the salinity entity. The 100 metres diagram of the first survey, however, as distinct from the others, contains, in the trends of isotherms and isohalines, a fairly clear indication of the direction from which dilution of the northward-tending oceanic water-mass proceeded. This was evidently more from the eastward than the northward, approximately along the latitude of 63°45′N.

On the broad general features of the three 100-metre charts, the relative positions of the main 35·30 ‰ isohalines undoubtedly denote at this level also a northwards progression of the oceanic water-mass, more marked between the first and second than between the second and third surveys. A similar inference attaches to the dispositions of the 35·35 ‰ and 35·40 ‰ isohalines over the region of the Faroe Bank Channel.

It seems rather odd, however, to find, on the third survey, (Figure 3:16) an indication of oceanic water so far north as almost on latitude 65° N, at longitude 7°30′W. Although in essence depending upon an

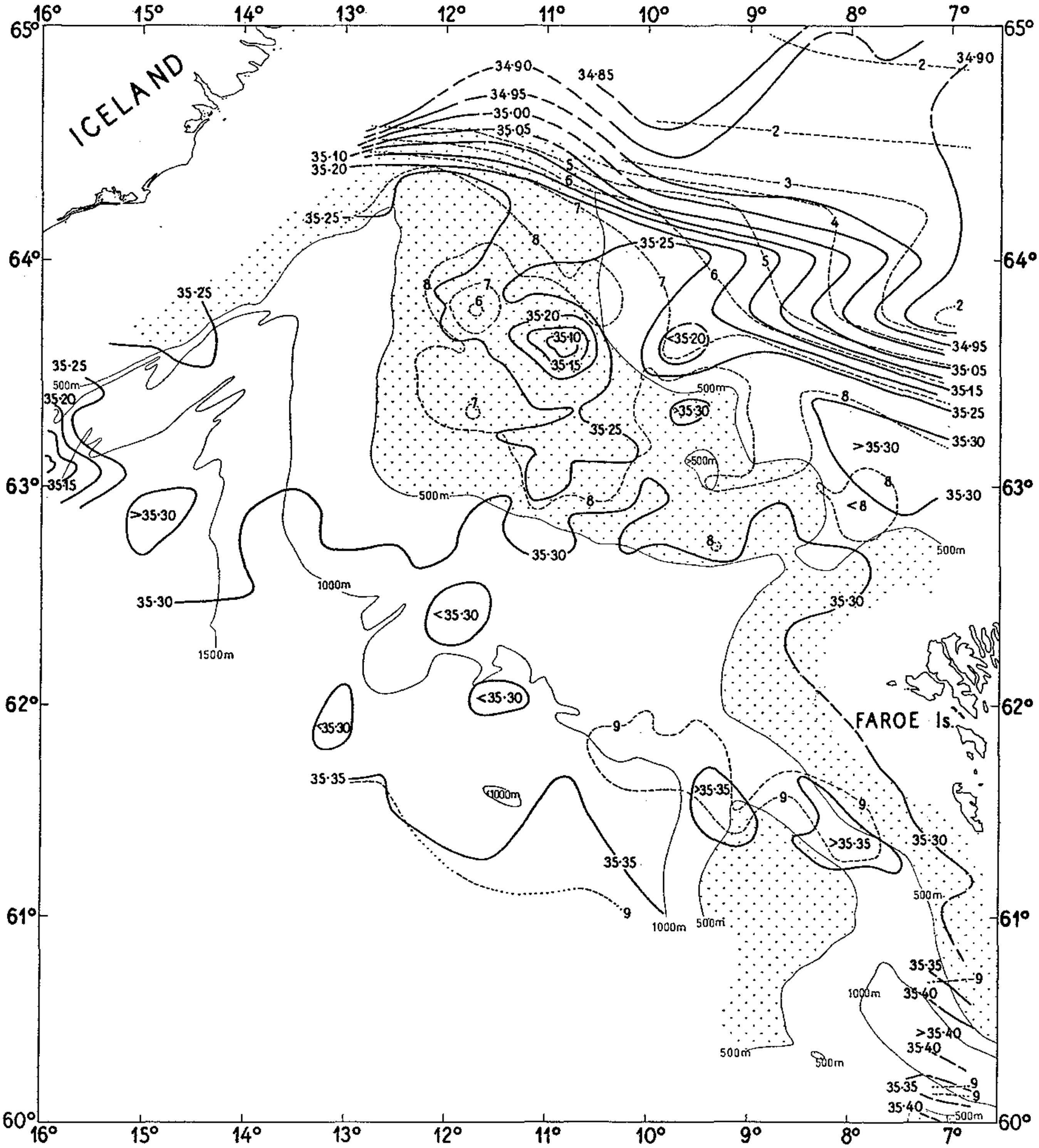

Figure 3:2. First Survey: temperature and salinity at 100 metres.

isolated observation, it must be conceded that the observation in question is to some extent supported by the next nearest observation southeastward on the third survey, as well as by the extreme northerly locations on the first and second surveys (Figures 3:2 and 3:9) of the 35·00 ‰ isohalines, as also by the particular trends in this region of the lesser surface isohalines of the first survey (Figure 3:1).

Isothermal dispositions at 100 metres present on the whole a less clear picture of a northward oceanic progression. This in itself is probably indicative of increasing impediment to this progression as the total three weeks' exercise proceeded. The difficulty in interpreting the main isothermal dispositions in this sense arises from the convolutions in water-movement which, throughout the period of the exercise and more clearly by the evidence of salinity than temperature distributions, were obviously taking place over the Ridge at the level of 100 metres.

These convolutions in water movement are obviously the most prominent feature of Figures 3:3, 3:10 and 3:17, representing conditions at 300 metres depth. It is obvious that, particularly on the first survey, but in only slightly lesser degree on the succeeding surveys, a turmoil of water movement was taking place on top of the Ridge. On the first survey two "pockets" of cold (<2°C) northern water (<34·95 ‰ salinity) were "caught" between the advancing oceanic water mass from the southwest over the Ridge and a closed circulation on the Rose Garden of oceanic water greater than 6°C in temperature and 35·15 ‰ in salinity. On either side of this circulation the cold northern waters penetrated more or less deeply into the oceanic water mass which nevertheless extended considerably northward beyond the Ridge proper along its southeastern part. At the same time, towards the narrowest part of the Ridge, two diluted oceanic incursions, one of which scarcely survived as such by the evidence of a nuclear salinity barely reaching 35·00 ‰, became isolated in swirl formations engendered no doubt by the conflict between southern and northern influences.

The closed oceanic water circulation of the first survey over the Rose Garden re-appeared in a more southerly position on the second survey, its place being taken by a colder, northern water swirl, probably that which had lain to the westward of it on the first survey. The second northern water circulation of the first survey, below the oceanic complex of the Rose Garden area was, on the second survey, displaced farther south and separated from its "fellow" by the displaced oceanic vortex. Then, moving southeastward towards the narrowest part of the Ridge, the two weak oceanic complexes of the first survey would appear to have moved northwestward in the next week and to have become further separated by intervention of a colder tongue of northern derivation, according to its salinity.

Although difficult to gauge, in the light of the above complications, the total impression of the result of the opposition between oceanic and northern influences at the 300 metres' level between the first and second weeks of the exercise, is one of perhaps small advantage in favour of the former, a deduction which would seem to derive some measure of support from the relative conditions at the same time in the southern Faroe-Shetland Channel region.

At the 300 metres' level, the argument for progression of the oceanic as opposed to the northerly-derived, southerly-directed water-masses, is on the whole clearer on the third survey as compared with the second. As denoted by salinity, with associated temperatures broadly corresponding, there is a distinct northwards advancement of the higher denominations from the second to the third survey, and a concomitant regression of the lower isotherms and isohalines, denoting retreat of the colder northern water-mass.

Probably the most interesting feature of the three charts of temperature and salinity distributions at the level of 400 metres (Figures 3:4, 3:11, 3:18), is their illustration of the extent to which cold northern waters had thus far overtopped (or more likely passed round the eastern boundaries of) the highest parts of the Faroe-Iceland Ridge on all three surveys, but decreasingly so from the first survey to the third. On Figure 3:4, appreciable areas of water of less than 2°C and 34·95 ‰ are delineated southwards below the 400 metres bathymetric. On Figure 3:11 these areas are somewhat less, while on Figure 3:18 of the third survey, they scarcely exist, the 34·95 ‰ isohaline having retreated considerably northwards on top of the Ridge.

Closed circulations of relatively high salinity (>35·15 ‰) and high temperature (>6°C) still appear at the 400 metres level on top of the Ridge towards its southeastern end, near the narrowest part of the Ridge; this on the first survey (Figure 3:4) when also two high salinity vortices appeared well northwards beyond the Ridge – >35·10 ‰ in one case and >35·25 ‰ in the other.

Some evidence of at least the latter remains on Figure 3:11, but the two smaller high salinity circulations of the first survey on top of the Ridge appear to have dissolved before the second survey whereon appeared, however, near the narrowest part of the Ridge, two new small circulations, one a cold low salinity (<34.95 ‰) complex and the other a higher temperature (>6°C) oceanic salinity (>35.25 ‰) vortex. On the third survey, these two entities would almost appear to have changed places and intensified

(Continued on p. 46)

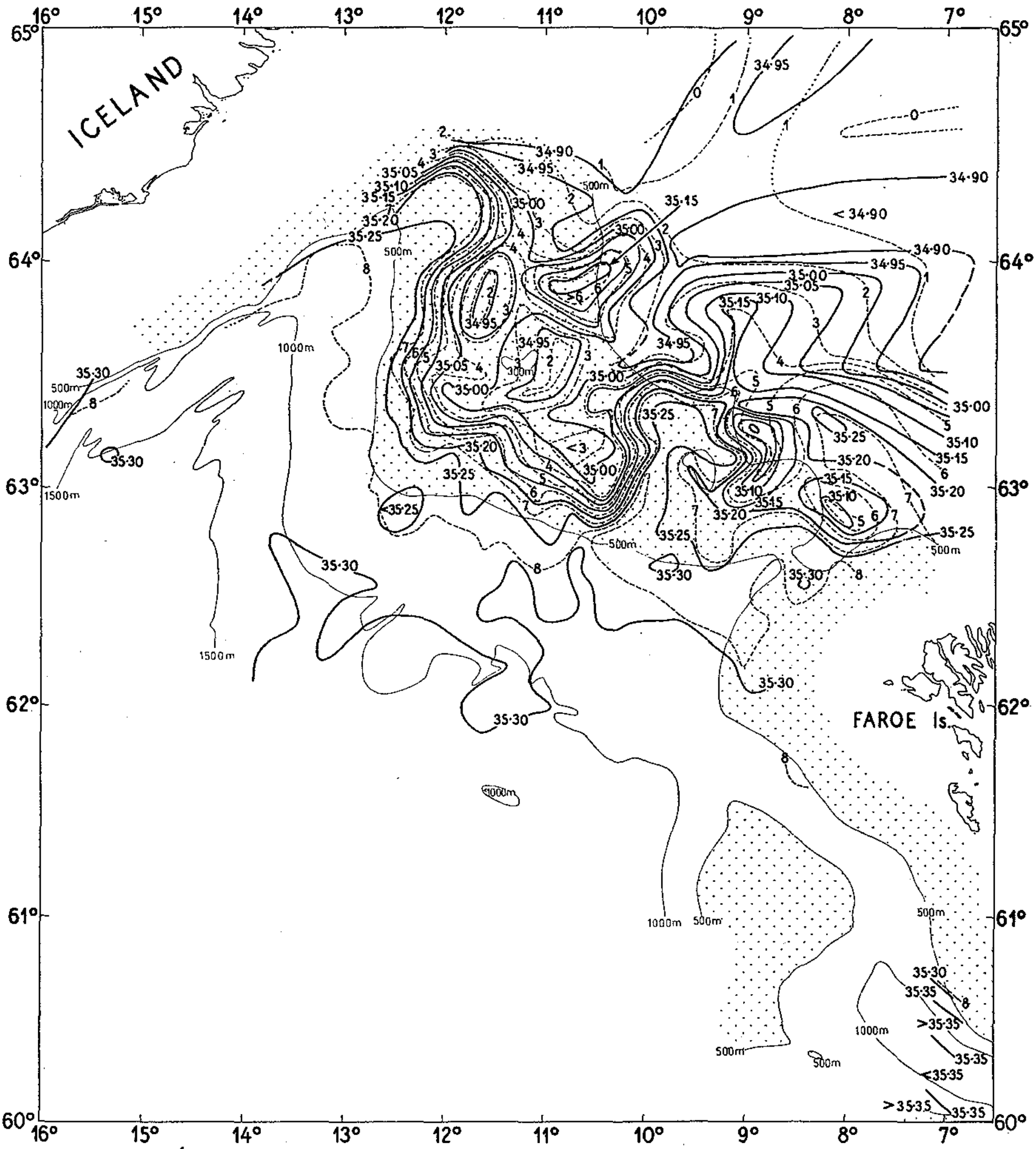

Figure 3:3. First Survey: temperature and salinity at 300 metres.

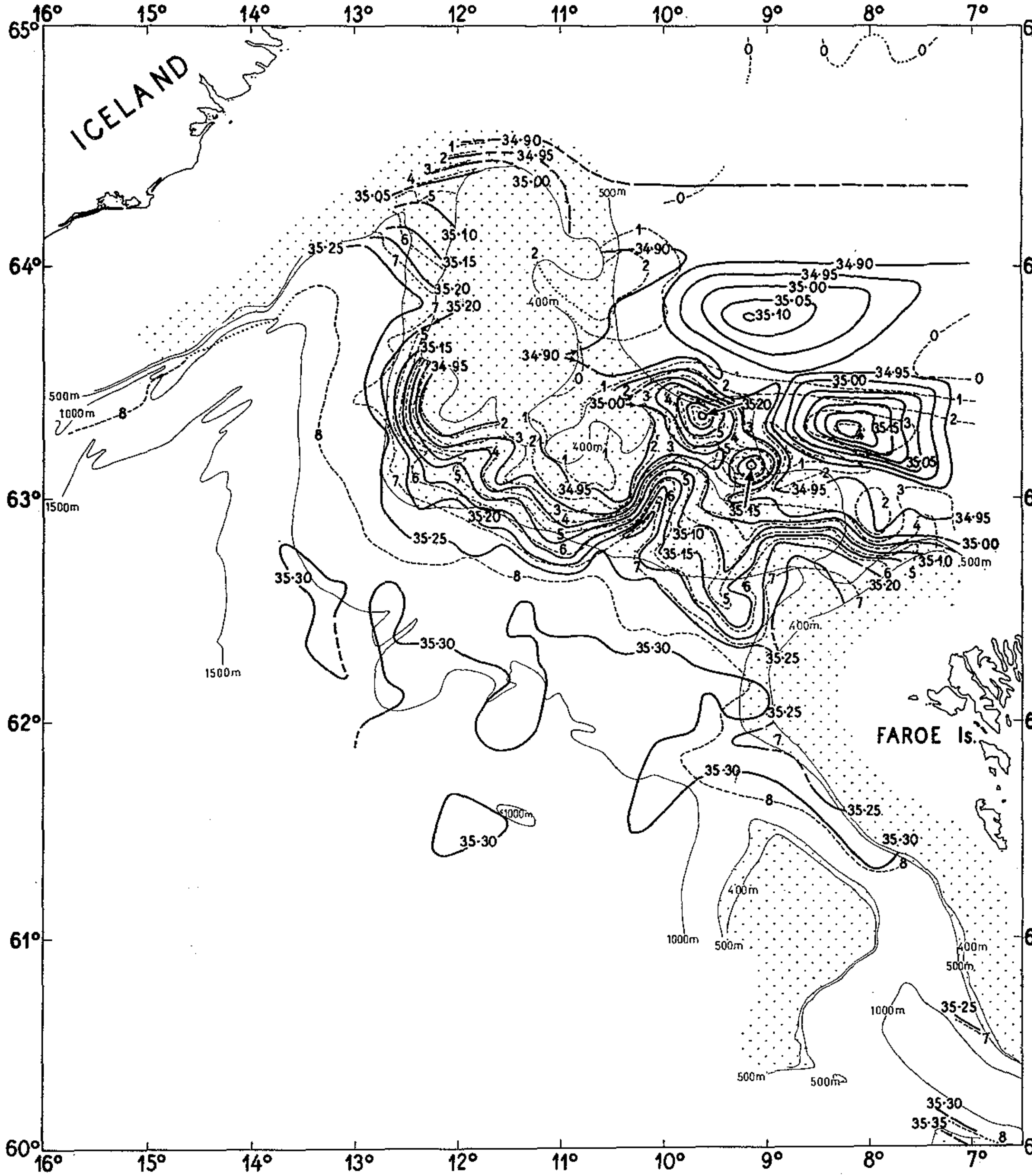

Figure 3:4. First Survey: temperature and salinity at 400 metres.

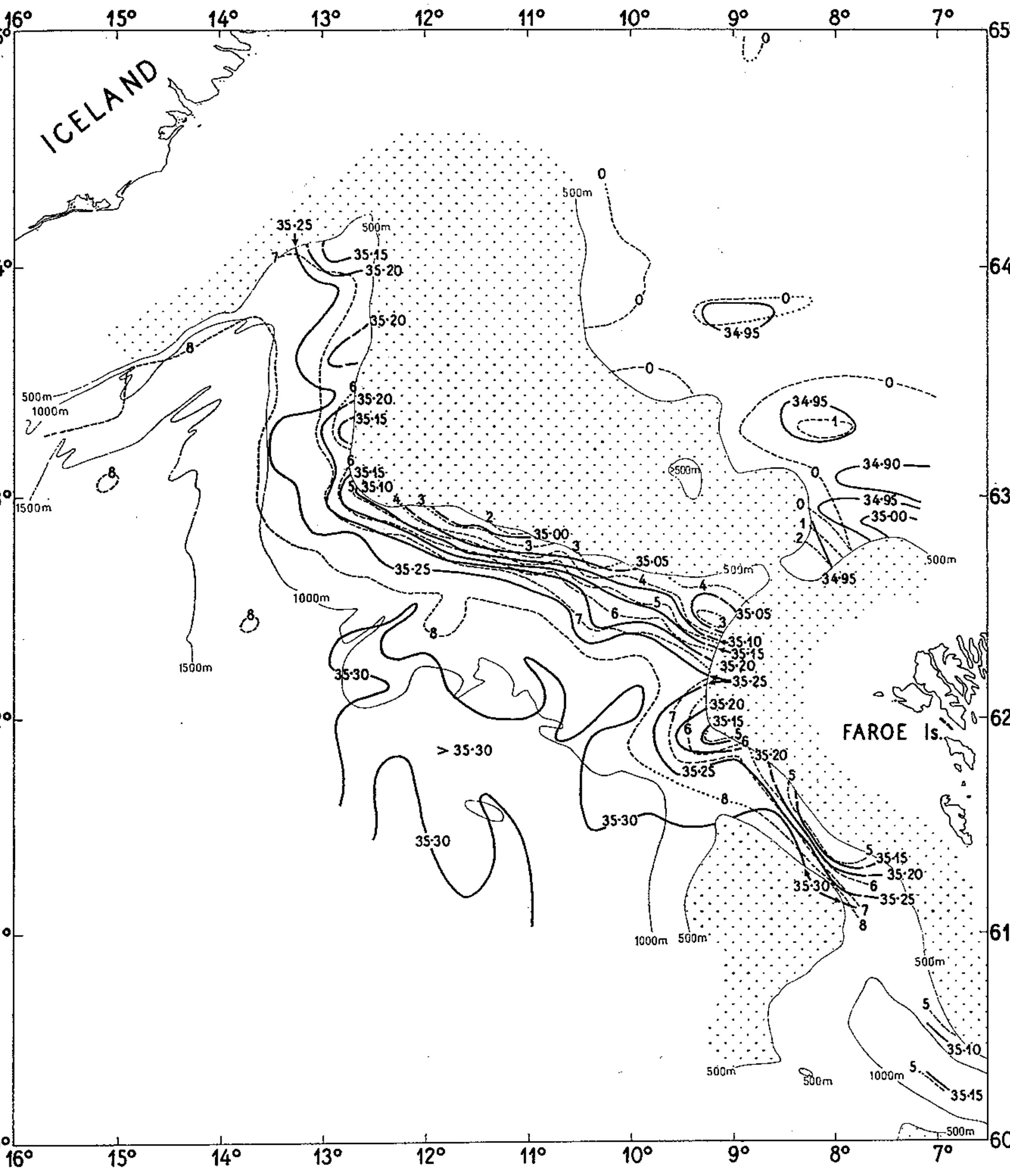

Figure 3:5. First Survey: temperature and salinity at 500 metres.

somewhat, although more probably these were new vortices which formed on the third survey on which a third made its appearance in approximately the same region near the Ridge's narrowest part.

Changes from one survey to the next in the Faroe Bank Channel would appear to reflect a slow gain in oceanic influence there, probably from the southeast.

Figures 3:5, 3:12 and 3:19, deal with the 500 metres level. Here the Ridge most decidedly intervenes to separate oceanic from northern waters. Only a small indication (by salinity) of oceanic water occurred north of the Ridge at its southeastern extremity on the first survey at 500 metres depth. At this level north of the Ridge practically all of the waters sampled registered less than 2° C in temperature, and from just under 34·90 $^0/_{00}$ salinity to over 34·95 $^0/_{00}$. On the south and west sides of the Ridge in Figure 3:5 are to be seen mainly oceanic characters of temperature and salinity except along its southern boundary where a narrow strip under 3° C to below 2° C, and less than 35·00 $^0/_{00}$ salinity, the only unmistakable evidence of cold deep water overflow, is to be found.

There is somewhat greater evidence, mainly by salinity, of oceanic water on the north side of the Ridge at 500 metres on the second survey, while, south of the Ridge, the cold water overflow would appear to have been less on the second than on the first survey. No temperatures of less than 2° C or salinities less than 35·00 $^0/_{00}$ were recorded at this level on the second survey.

On the third survey, the evidence for oceanic water north of the Ridge at the depth in question was slight, but on its south side in one small location cold northern overflow water was signalised by a temperature of under 1° C and salinity below 34·95 $^0/_{00}$.

Turning to the Faroe Bank Channel region at 500 metres, the evidence is all of oceanic water on all three surveys, with, however, on the second survey in particular, (Figure 3:12), an obvious tendency at the southern end of this Channel for cold, less saline waters from the Faroe-Shetland Channel to seek entry into the Faroe Bank Channel. On the third survey (Figure 3:19), what would appear to be a relic of this cold intrusion was isolated against the northern slope of the Faroe Bank Channel, an oceanic water surge behind it having separated it from its parent mass in the Faroe-Shetland Channel.

In view of the prime objective of the expedition, it is instructive to consider, irrespective of depth, the temperature and salinity conditions on the bottom of the region surveyed. For the greater clarity in delineating these conditions the bottom temperature and salinity distributions for each of the three surveys are illustrated on separate charts, (Figures 3:6 and 3:7 for the first survey, Figures 3:13 and 3:14 for the second, and Figures 3:20 and 3:21 for the third), and, in addition, graduated colour schemes, in red for temperature and blue for salinity, are introduced to aid visual appreciation of the interaction of the oceanic and northern water-masses.

Figure 3:6, illustrating bottom thermal conditions on the first survey, shows the zero isotherm only just encroaching on the Ridge proper over a small part of its northern, 500-metres' shoulder. The 2° C isotherm, which probably marks the southern boundary of relatively undiluted cold deep northern water, the Polar Front in other words, was not only far advanced over the top of the Ridge, but in two places completely crossed the Ridge into depths of 600 to 800 metres on its southwestern slope. The same isotherm also protruded far beyond the western end of the Faroe Bank Channel which indeed marked the limit approximately of sub-zero temperature water from the depths of the Faroe-Shetland Channel.

Despite the far advance of the "Polar Front" isotherm of 2° C over and across the Faroe-Iceland Ridge, high temperature (>6° C) oceanic water evidently secured a substantial circulatory base towards the northern end of the Ridge, and again, southwards towards the Ridge's narrowest part, the 2° C isotherm was pushed back halfway across the Ridge by a "pocket" of oceanic water in vorticial circulation. Conversely, as it were, a cold northern water circulation disputed the advance of the "oceanic front" over the bottom in the deep indentation of the 500-metres bathymetric contour on the south side of the Ridge. Similar, if less intense, cold water enclaves on the much deeper sea bed to the northwest of the Faroe Bank may be taken to have derived from the deep effluent from the Faroe Bank Channel rather than from Ridge overflow which in any case tends to move westward under geostrophic forces on overspill from the Ridge.

Turning to the haline character of the bottom water on and on either side the Ridge on the first survey, Figure 3:7 reveals, as might be expected from the bottom thermal distribution of Figure 3:6, the apparently tenuous hold on top of the Ridge, except in its northern part, of almost the weakest oceanic water of scarcely more than 35·00 $^0/_{00}$ salinity. The westward and southward boundary of the northern water, as indicated by the 34·95 $^0/_{00}$ isohaline, like the 2° C isotherm, lay for the most part far across the top of the Ridge. Perhaps less saline water than is depicted on Figure 3:7 on the southern slope of the Ridge might have been expected, but on the other hand there is an evident correspondence in the material parts between the 2° C isotherm of Figure 3:6 and the 35·00 $^0/_{00}$ isohaline of Figure 3:7 which points the reality of cold northern water overflow in these parts.

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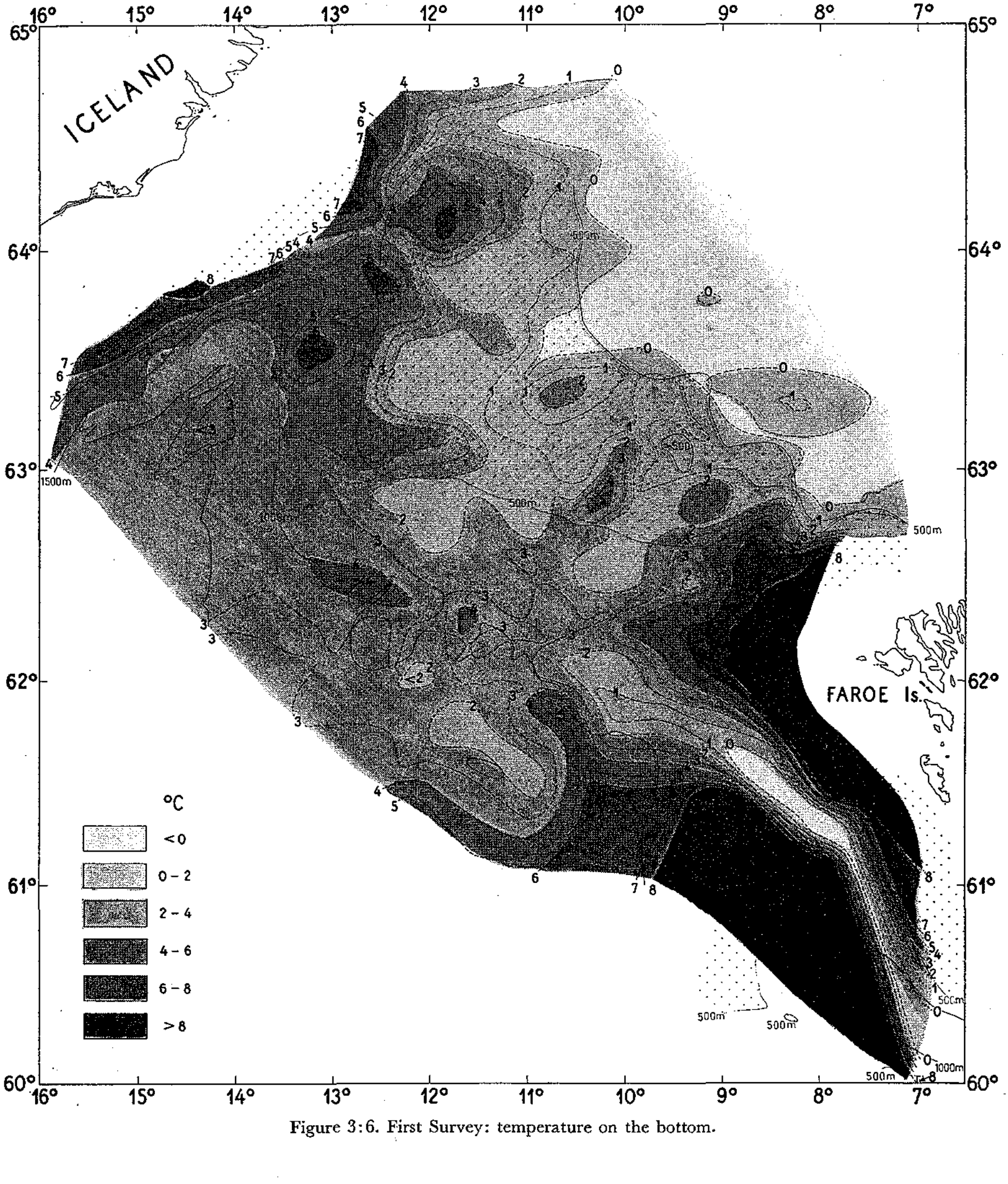


Figure 3:6. First Survey: temperature on the bottom.

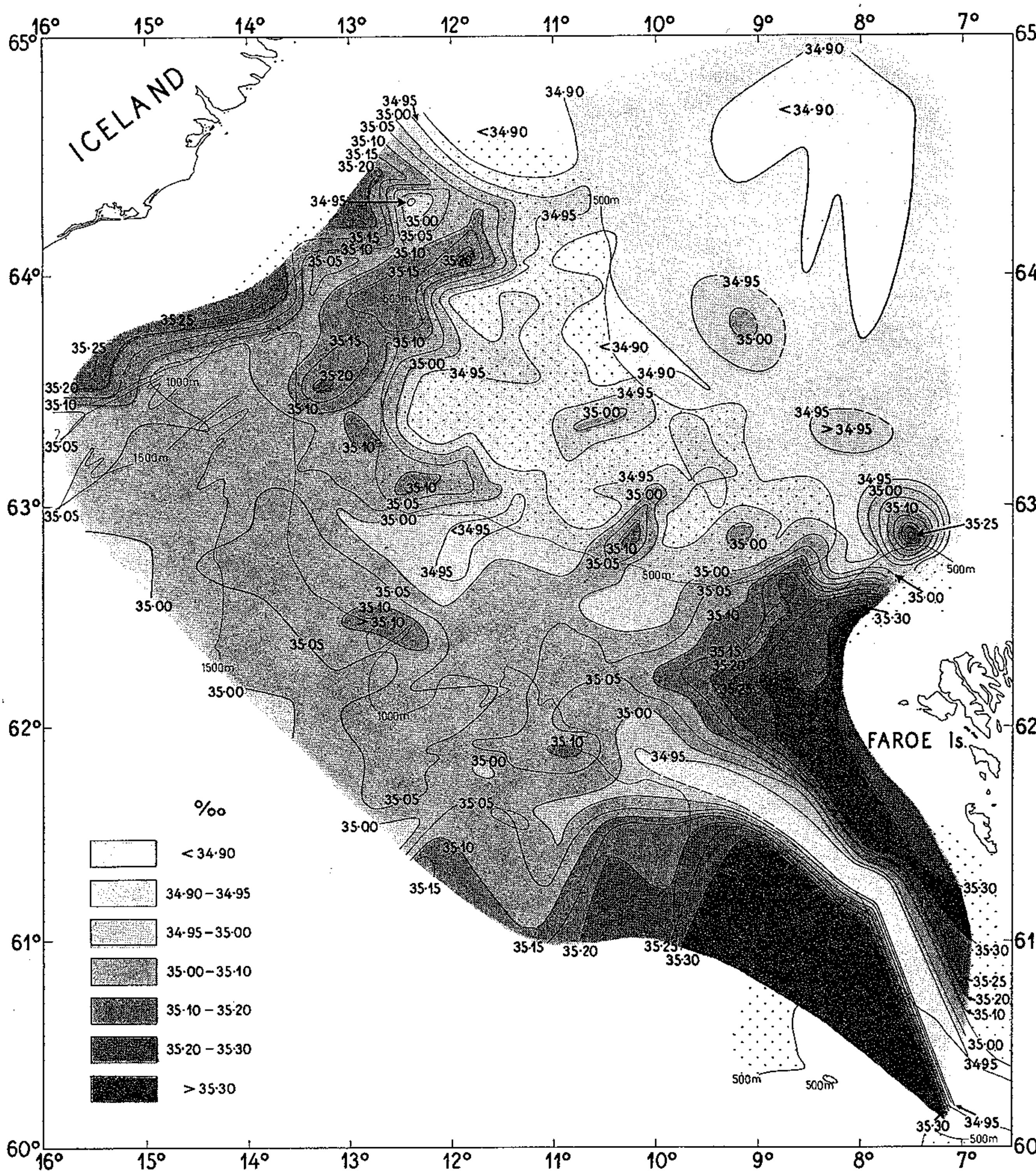


Figure 3:7. First Survey: salinity on the bottom.

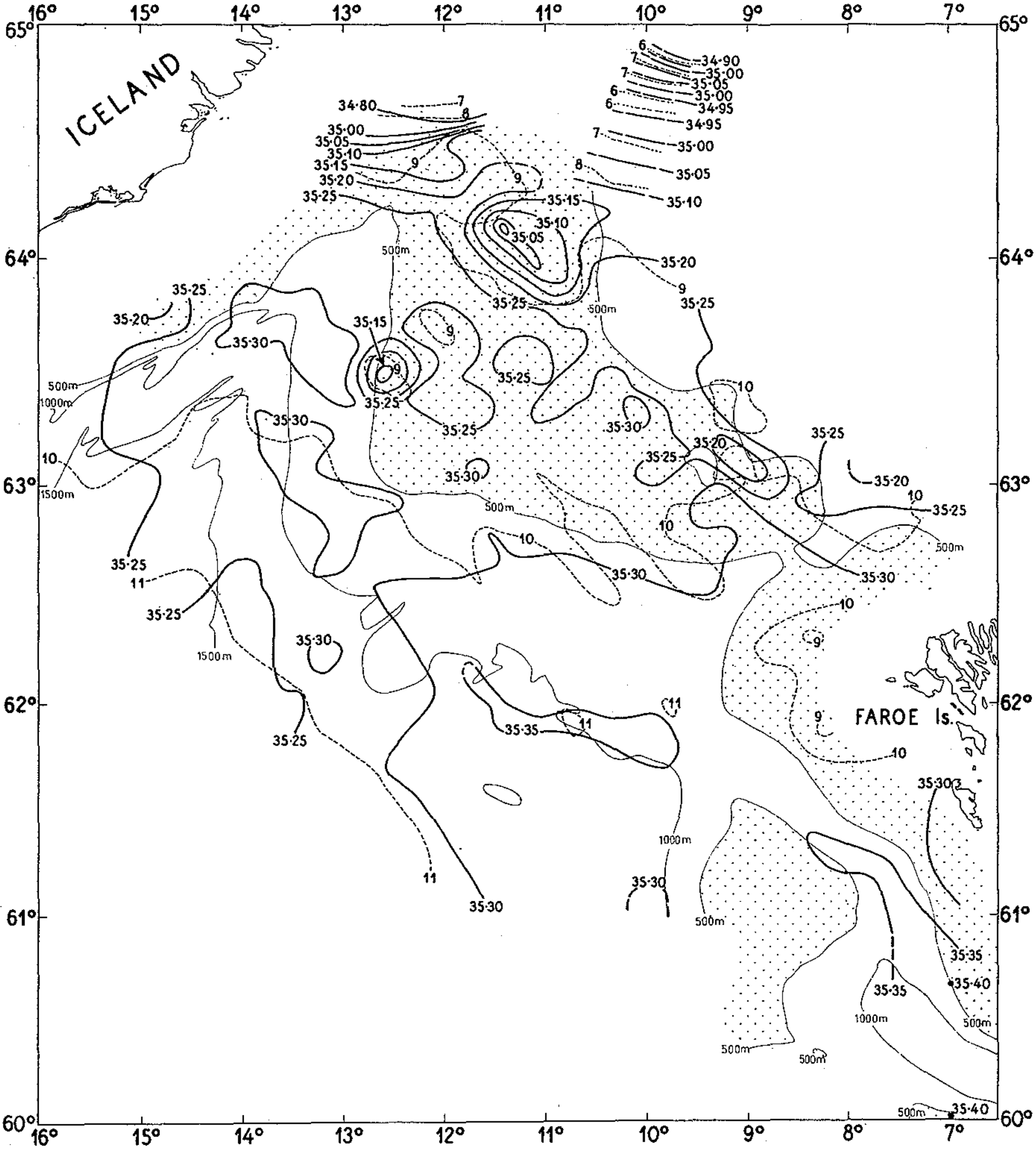


Figure 3:8. Second Survey: surface temperature and salinity.

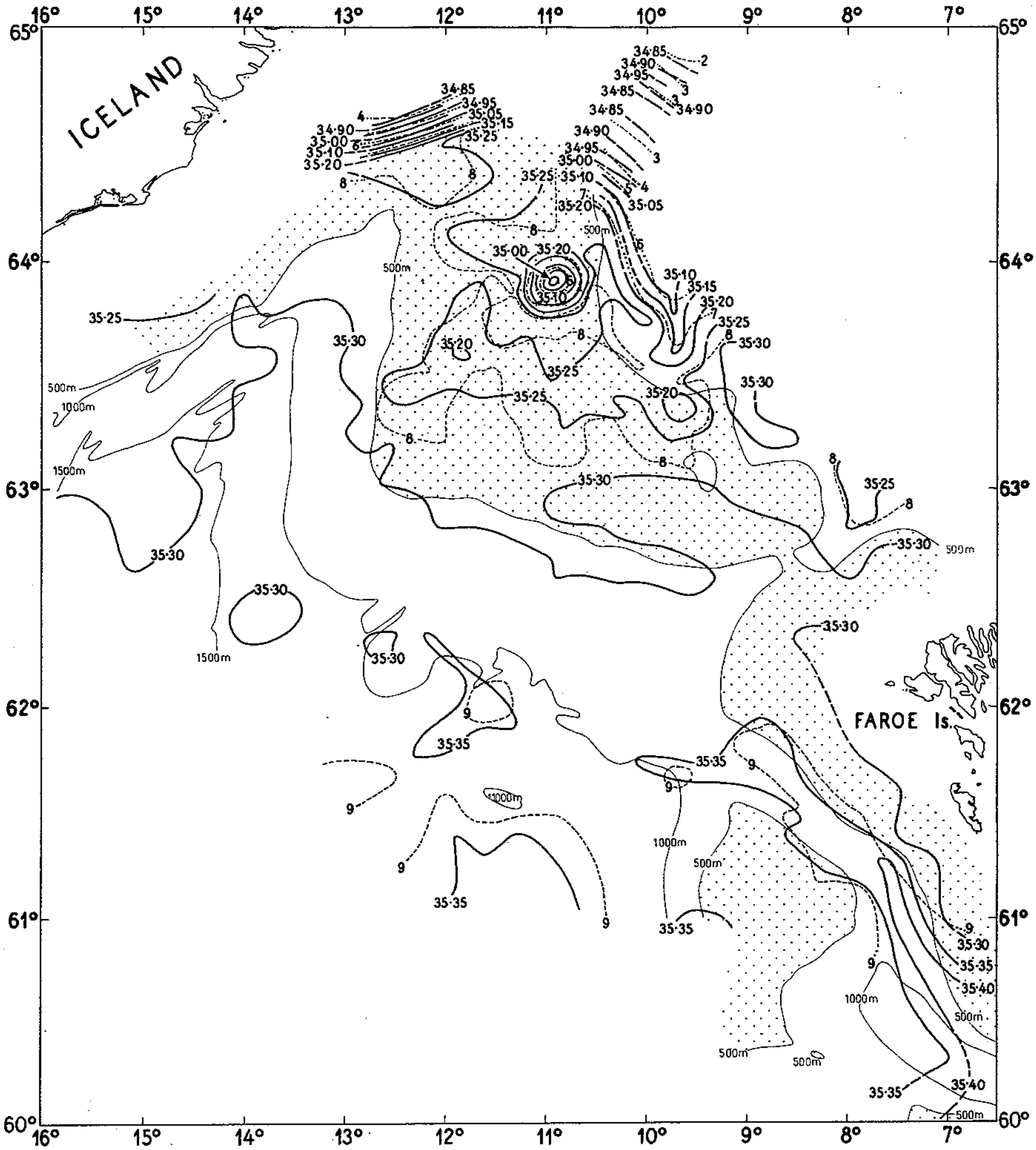


Figure 3:9. Second Survey: temperature and salinity at 100 metres.

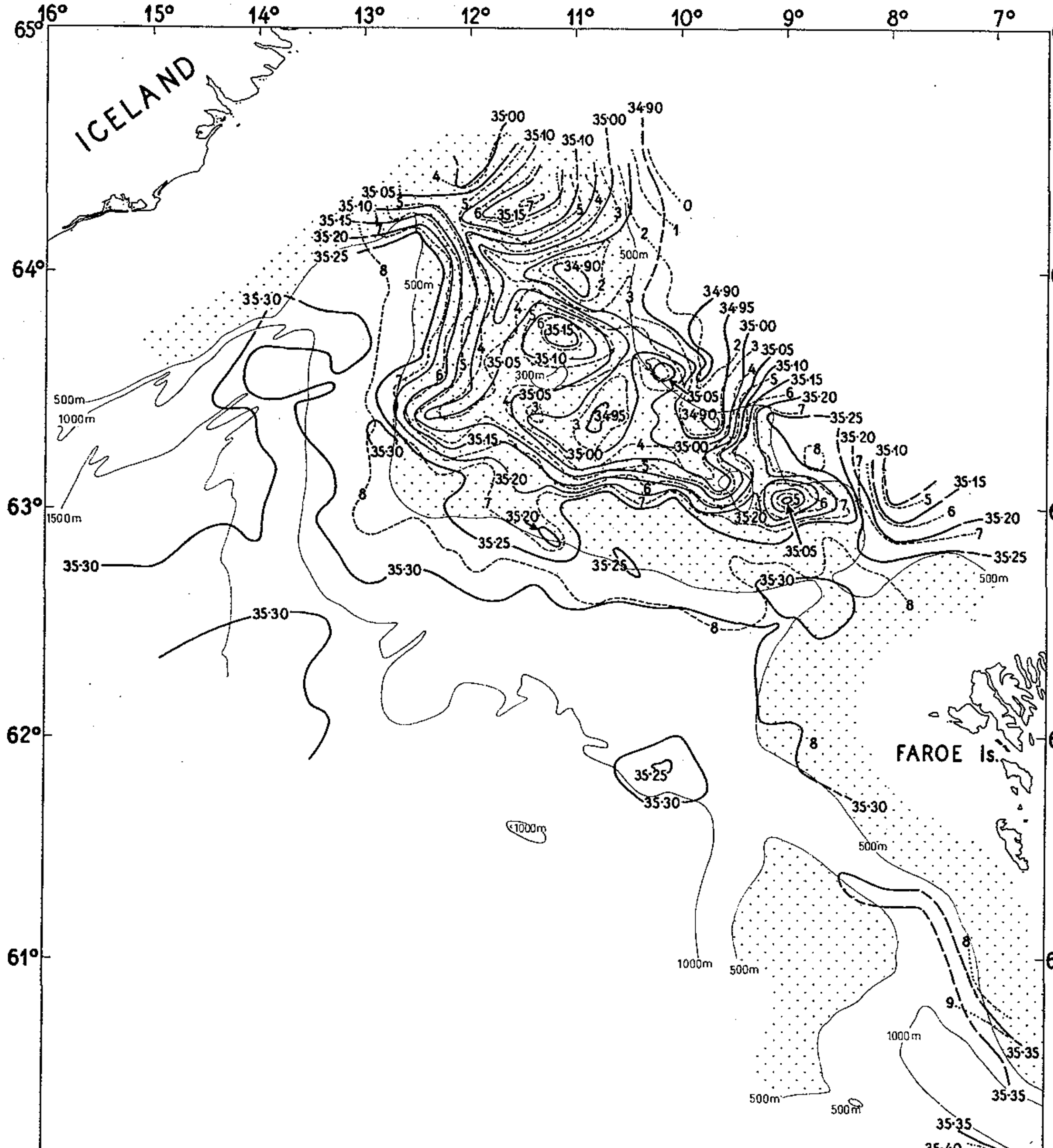


Figure 3:10. Second Survey: temperature and salinity at 300 metres.

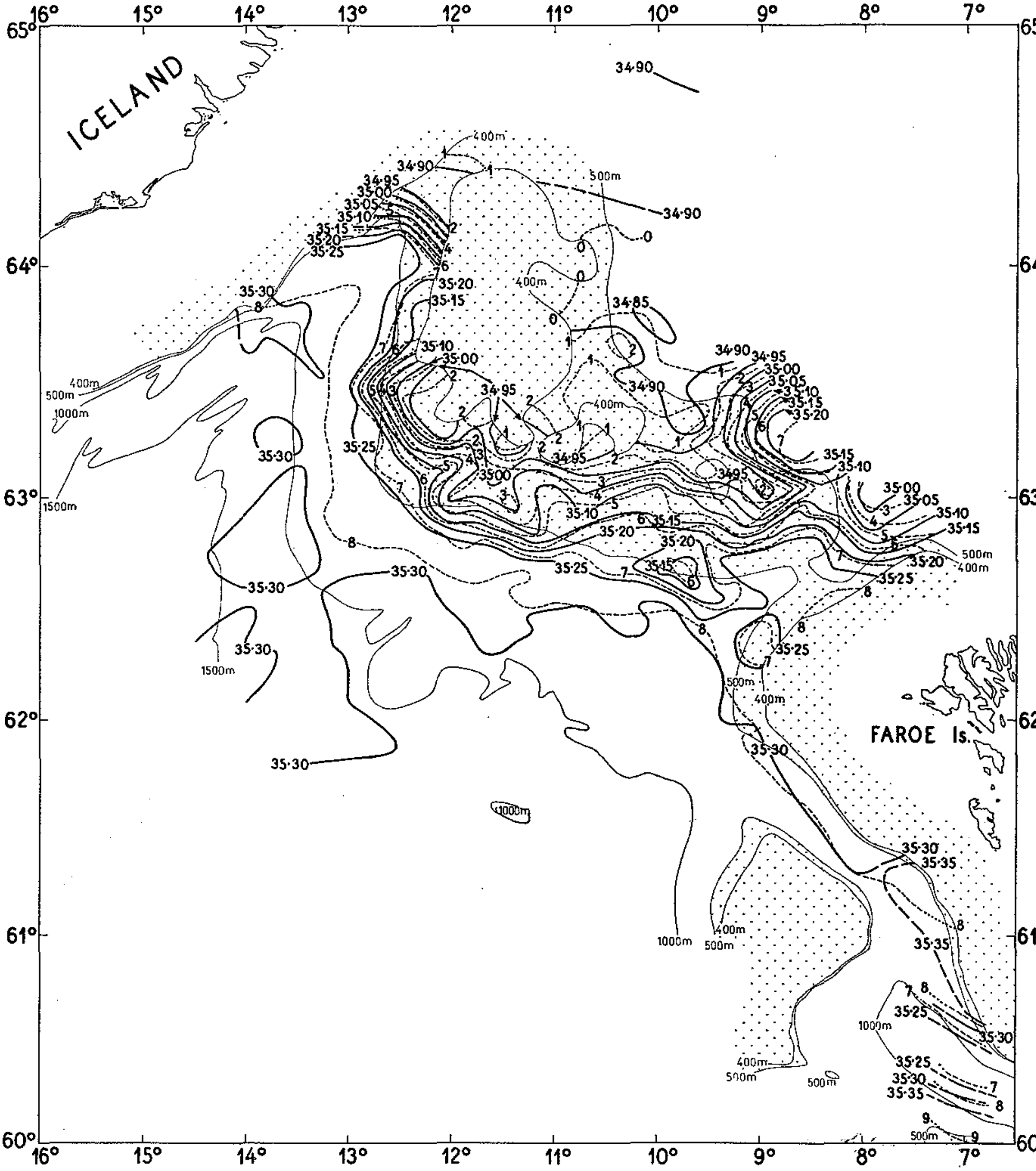


Figure 3:11. Second Survey: temperature and salinity at 400 metres.

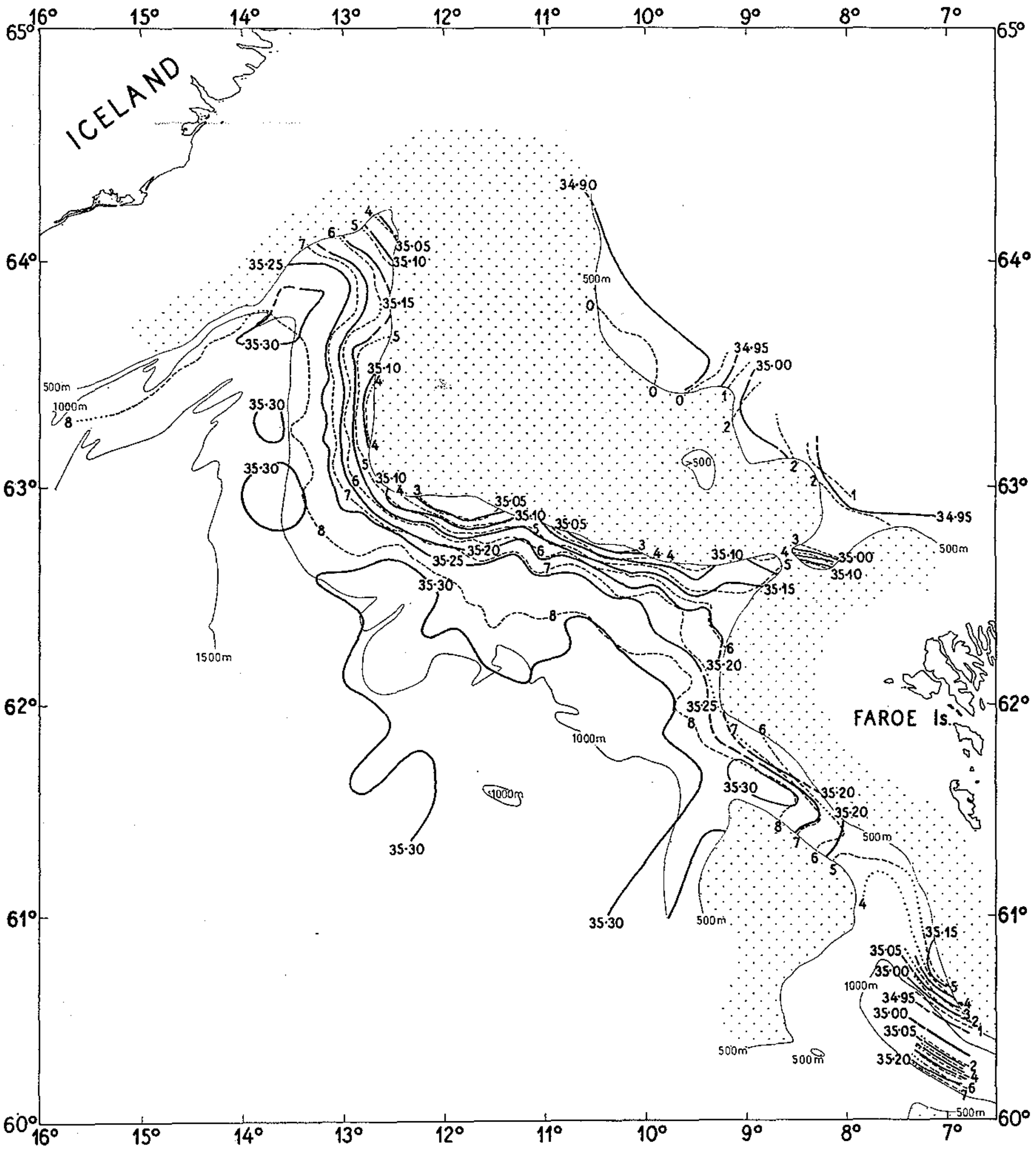


Figure 3:12. Second Survey: temperature and salinity at 500 metres.

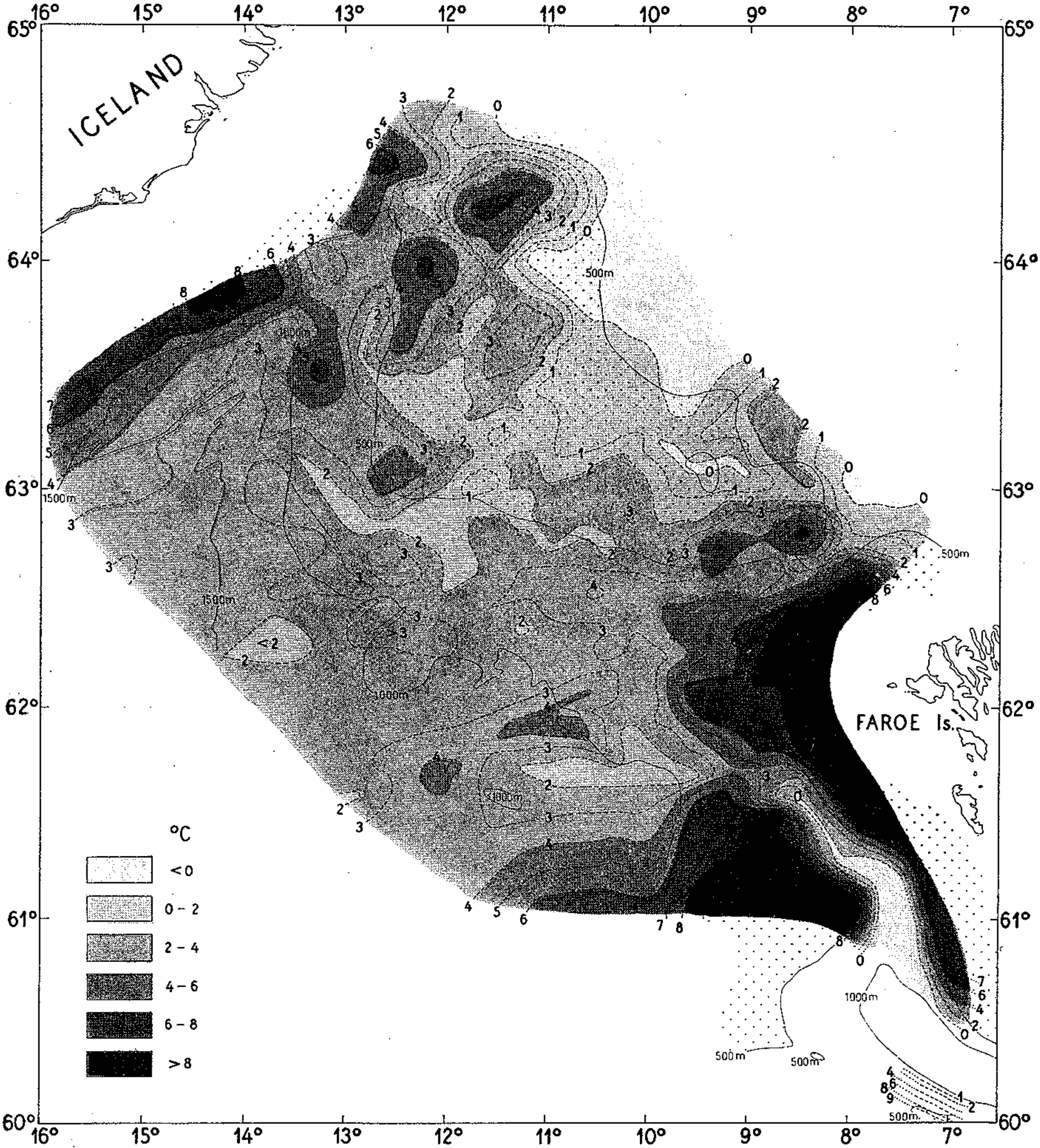


Figure 3:13. Second Survey: temperature on the bottom.

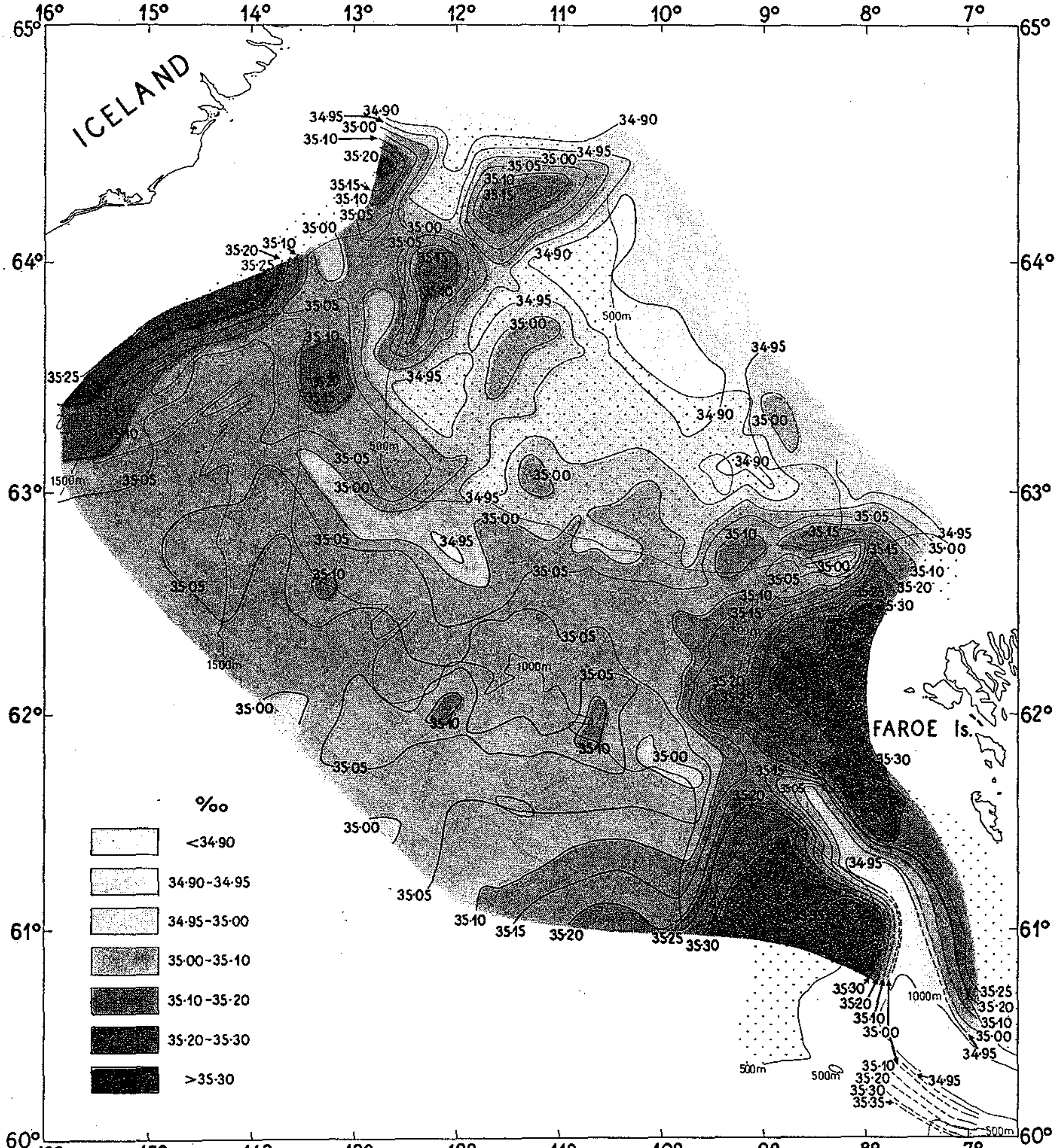


Figure 3:14. Second Survey: salinity on the bottom.

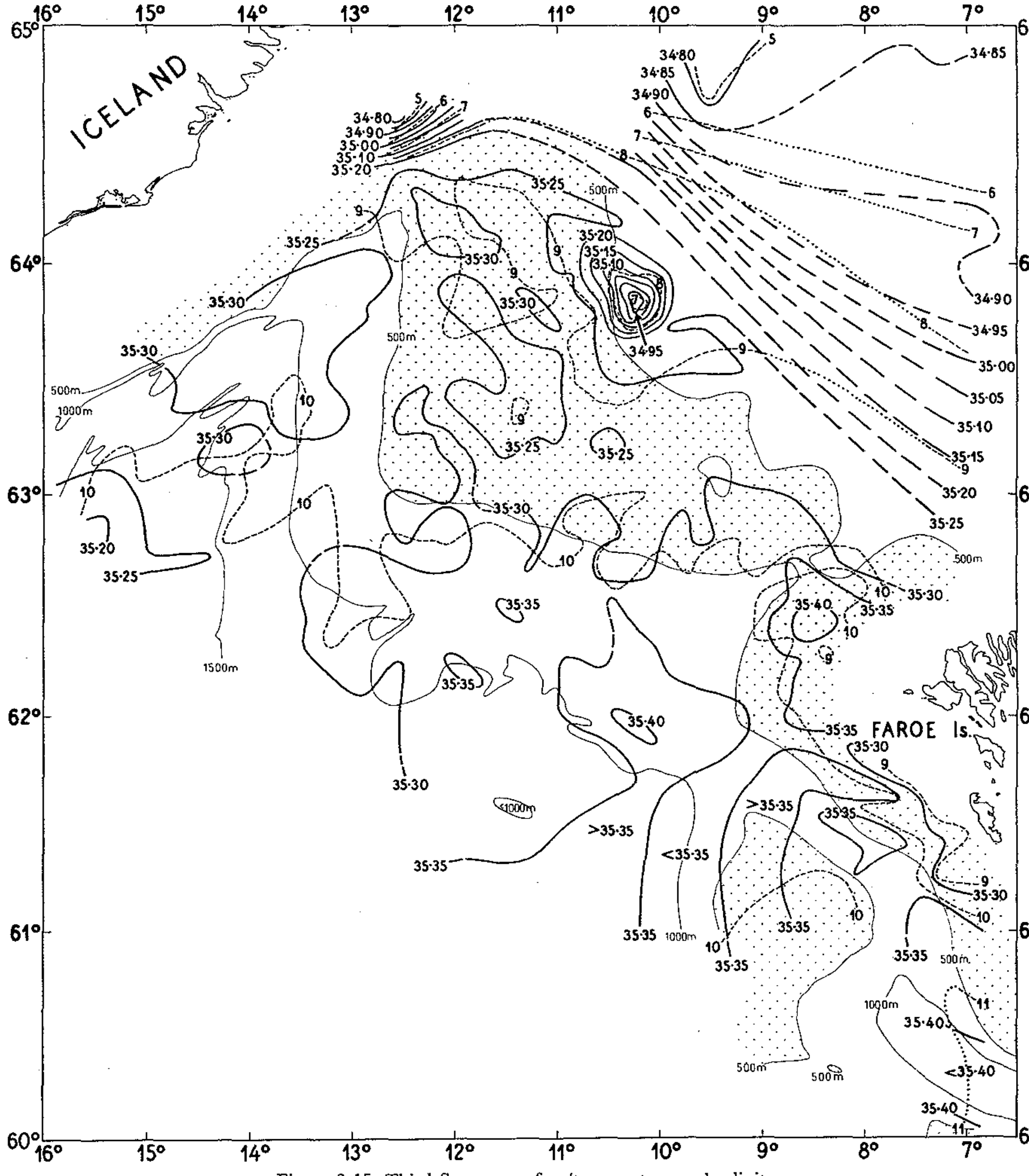


Figure 3:15. Third Survey: surface/temperature and salinity.

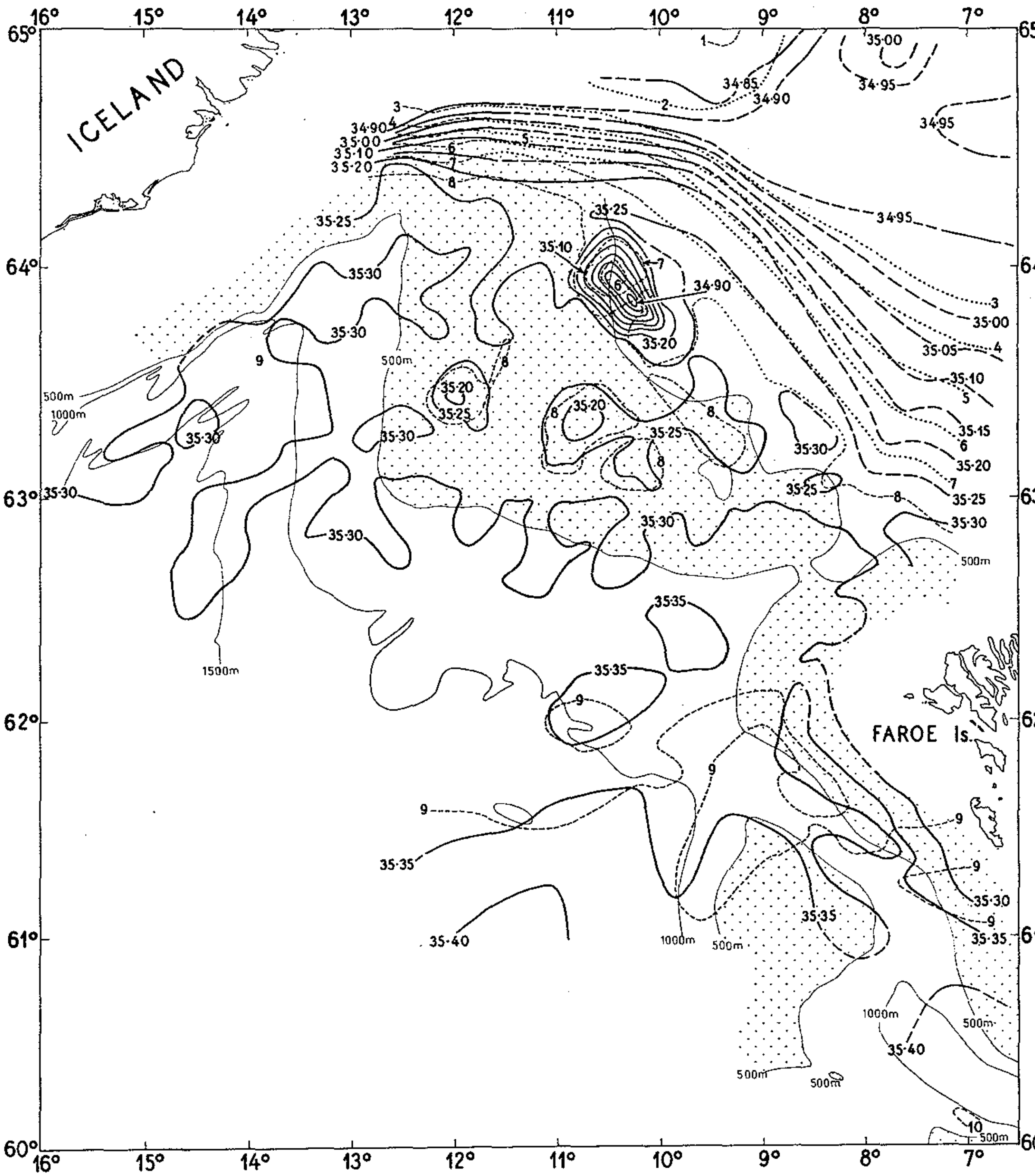


Figure 3:16. Third Survey: temperature and salinity at 100 metres.

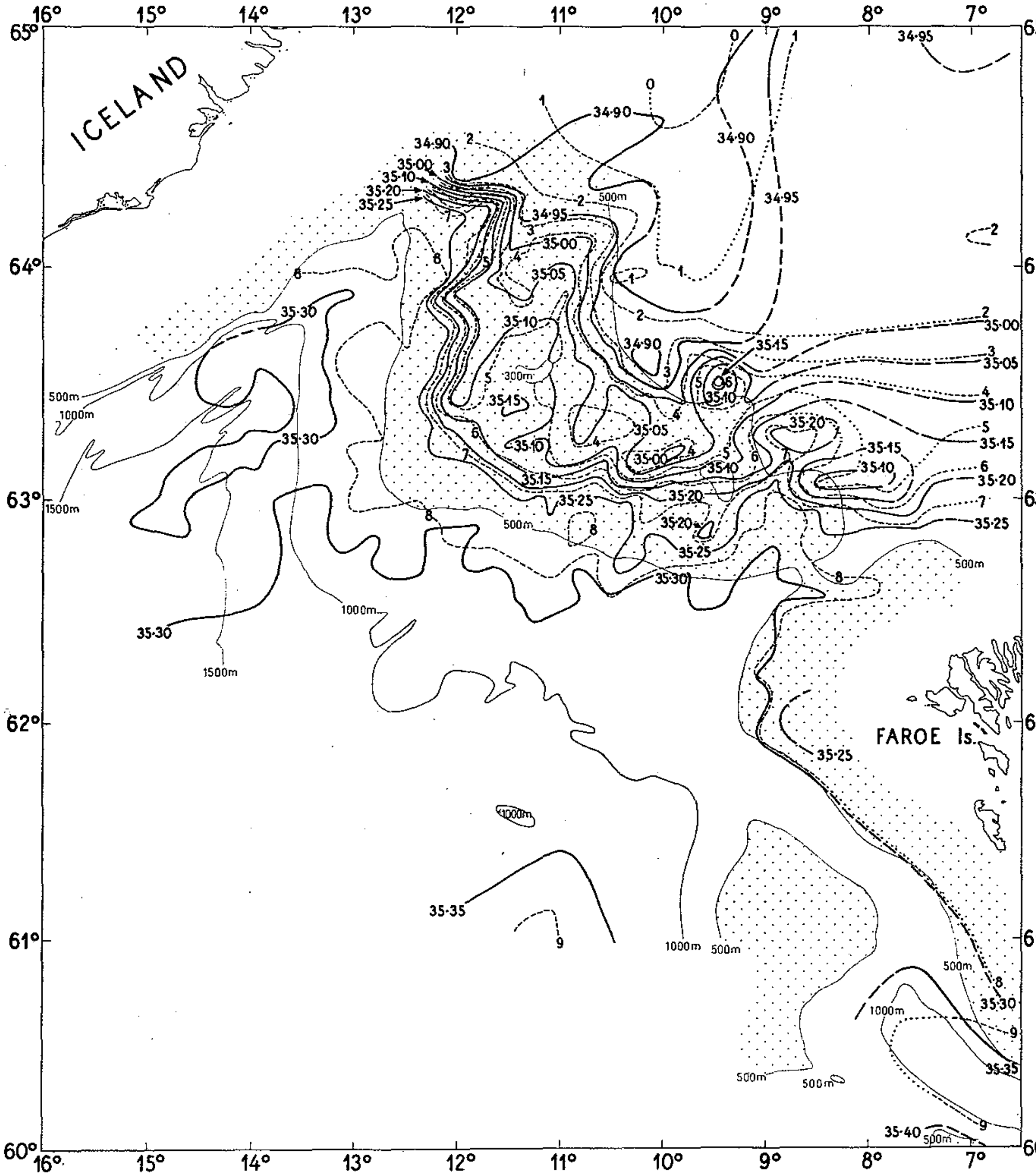


Figure 3:17. Third Survey: temperature and salinity at 300 metres.

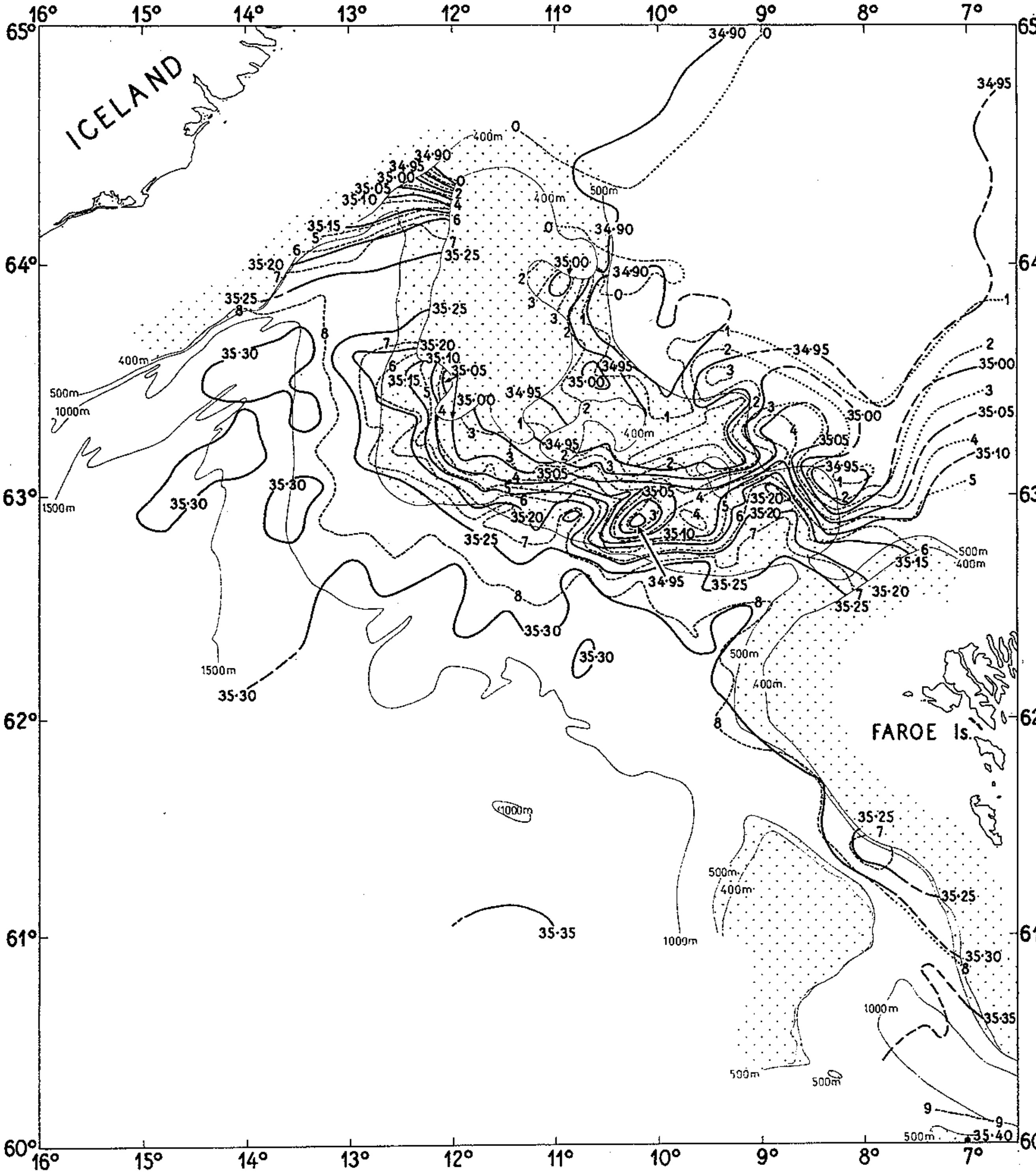


Figure 3:18. Third Survey: temperature and salinity at 400 metres.

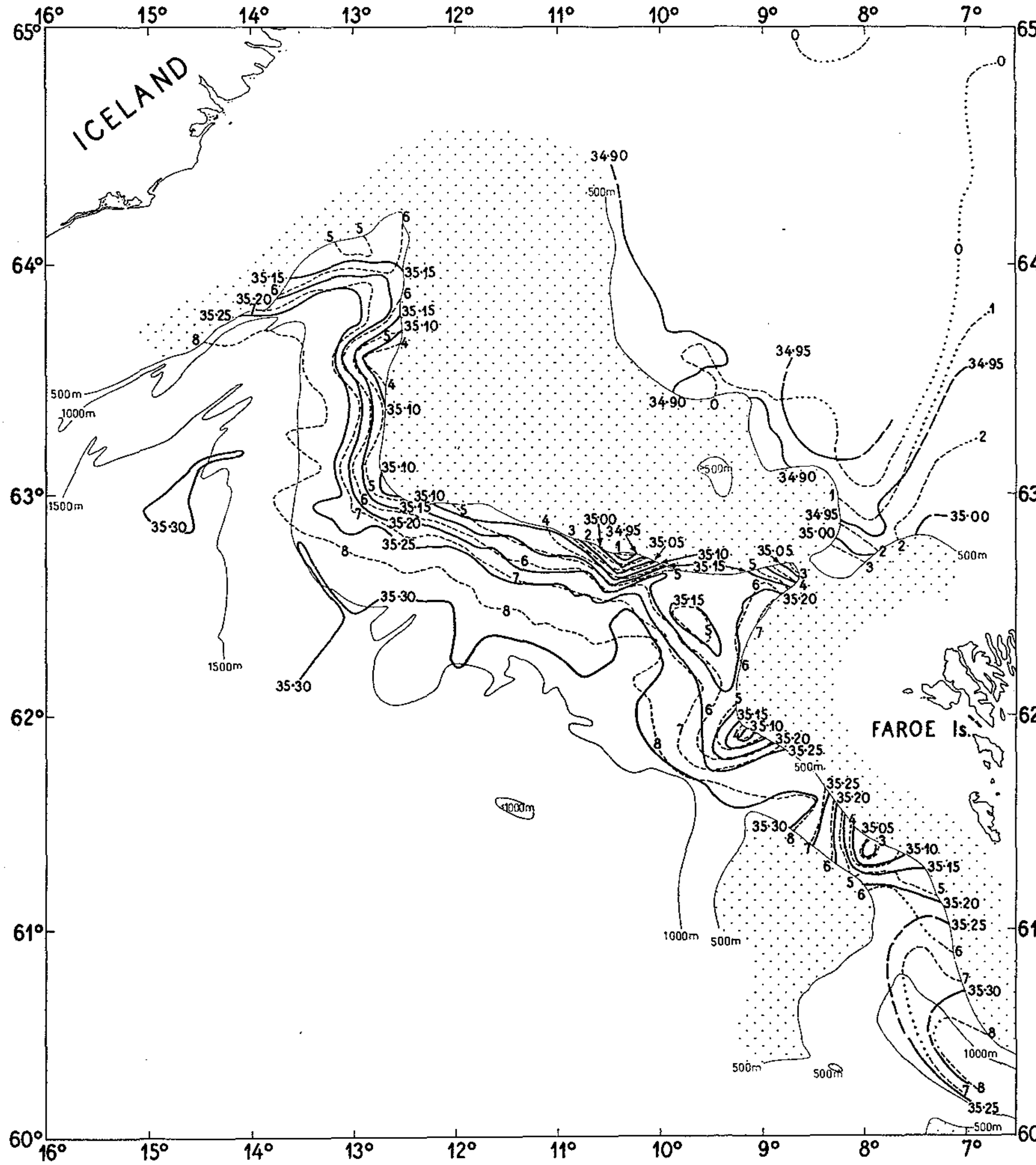


Figure 3:19. Third Survey: temperature and salinity at 500 metres.

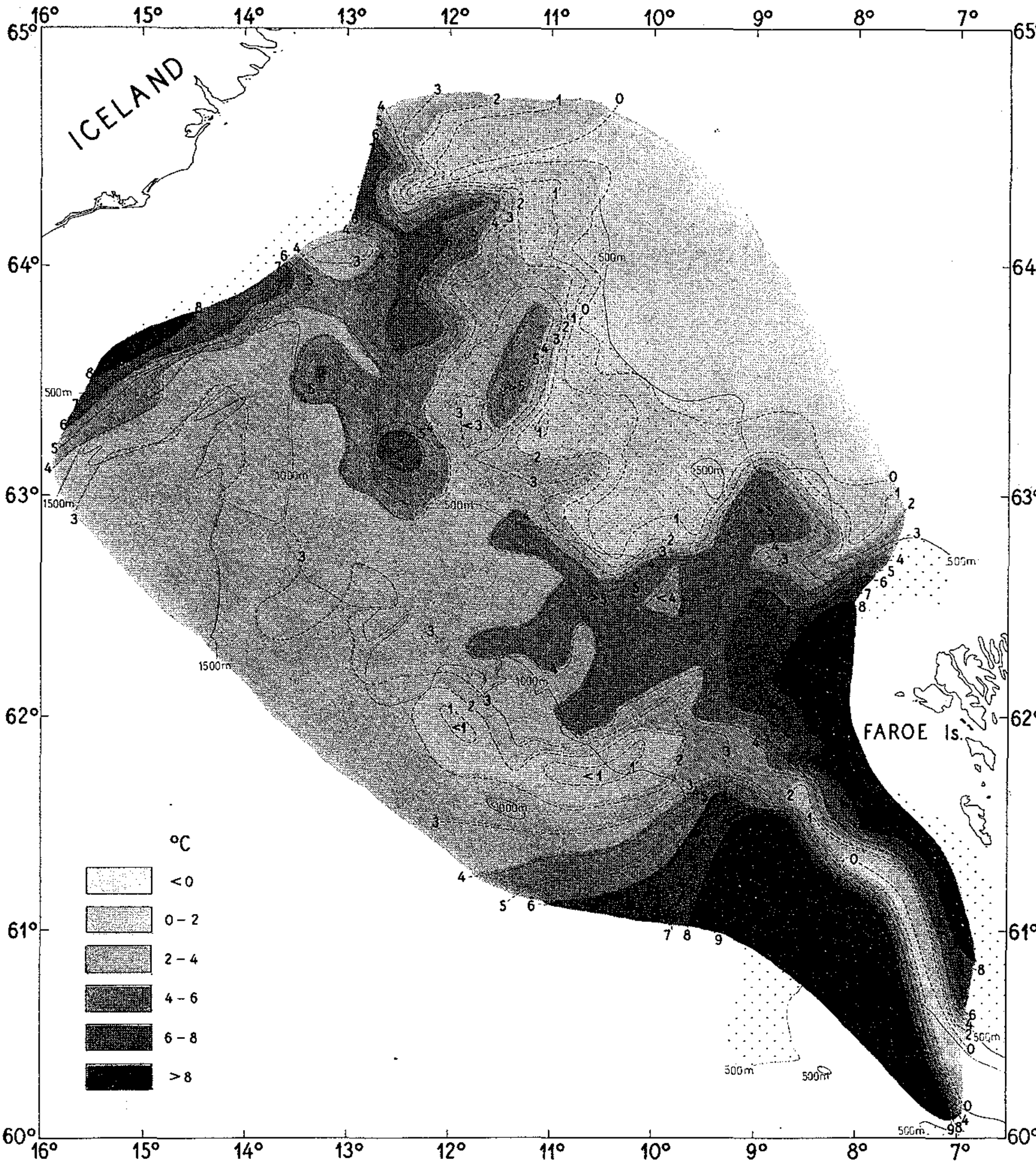


Figure 3:20. Third Survey: temperature on the bottom.

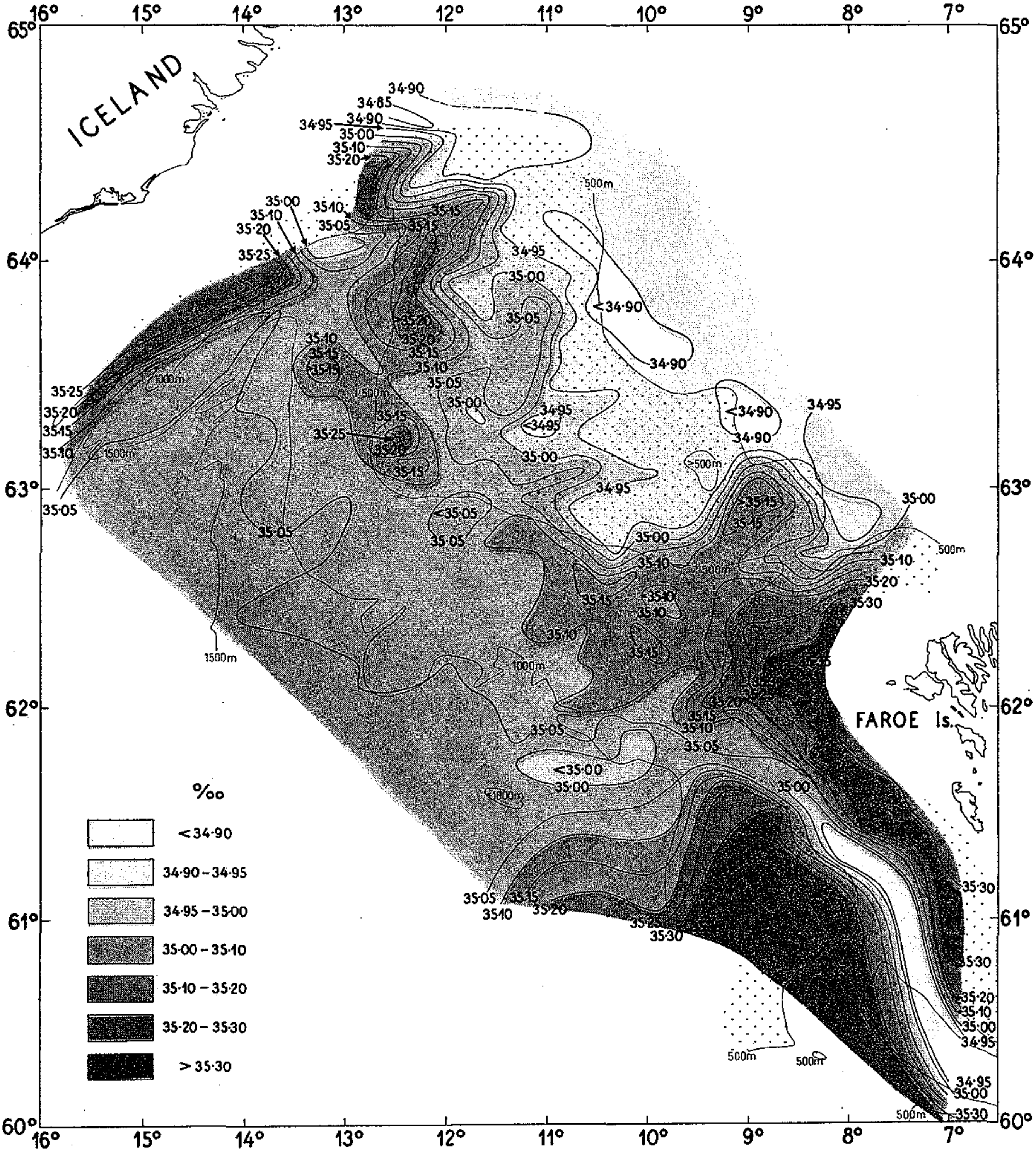


Figure 3:21. Third Survey: salinity on the bottom.

Similarly, in the Faroe Bank Channel region the 35·00 $^{0}/_{00}$ isohaline and, within it, that of 34·95 $^{0}/_{00}$, :orrespond remarkably closely to the 2° C and 1° C bottom isotherms, thus signifying the more undiluted bottom water cold effluent from this deep Channel.

There is on the whole remarkably little difference)etween the main features of the bottom thermal listribution of the second survey (Figure 3:13) and :hose of the first. Deep cold water of less than 2° C still completely overtopped the Ridge along a sub- ɪtantial part of its southern boundary during the second week of the exercise. The warm oceanic vortex at the ıorthern end of the Ridge persisted as well as two nore southwestward of it, one of them on the Ridge)roper and the other in deep water of from 600 to .,000 metres. A cold water complex on a narrower)art of the Ridge southward would appear to have ntensified, while the warm water circulation on the ame part of the Ridge during the first survey, besides)eing displaced eastward on the second exercise, was ılmost subdivided into two parts.

In the region of the Faroe Bank Channel the)ottom thermal situation was changed on the second urvey only to the extent of a small withdrawal into he Channel of the zero isotherm and, probably arising rom a similar tendency, the separation from the main ffluent of a part of the bottom water mass registering ɜss than 2° C, the main effluent receding somewhat ıto the narrow Channel.

Except that there does not appear on Figure 3:14 a ɜparation of correspondingly low saline water from he Faroe Bank Channel effluent, this, on the second ırvey is considerably less extensive than it was one reek previously. On the Ridge itself there is an ppreciable north to northeastward recession of the 4·95 $^{0}/_{00}$ isohaline between the first and second ırveys, with the remaining saline features of Figure 3:7 ıore or less repeated, with due regard for change of po- .tion, on Figure 3:14, these changes suggesting a small ɜcession of the cold northern influence before the ad- ance of oceanic waters over the summit of the Ridge.

On the whole, the zero isotherm would appear in ıe third week of the expedition to have made some dvance over the northern shoulder of the Ridge ?igure 3:20), particularly in the north where the ɜeanic circulation of the first two weeks is practically :ased. South of the Rose Garden area, however, the ɔld water bottom of the two previous weeks was ɜplaced by a distinctly warm water circulation, and ıother such circulation, even more distinctively ɜeanic, with a central temperature of over 7° C appeared in the third week on the southwestmost projection of the Ridge where waters of 2° to 4° C occurred before. Taking as a rough guide what may be looked upon as the "Polar Front" isotherm of 2° C, the general effect on the third survey as compared with the previous two weeks is of a further retraction north to northeastward of the cold bottom water overspill of the Ridge. Practically no water of under 2° C was found on the south or southwest slope of the Ridge during the third survey which distinguishes it more or less markedly from those of the previous two weeks.

The Faroe Bank Channel cold water effluent of the third survey shows a further recession southward along the Channel of the limit of the 0° C isotherm and a small recession of the 2° C isotherm, although the separated body of cold water from this effluent which was noted on the second survey as occupying the adjacent slopes in from 900 to 1,200 metres' depth approximately, registered on the third survey two cores of under 1° C temperature.

While bottom salinity on the third survey (Figure 3:21), depicts a southwards advance of the 34·95 $^{0}/_{00}$ isohaline on the southern part of the Ridge to the limit of its southern shoulder at 500-metres depth, this same isohaline on the northern broader part of the Ridge was obviously pushed back as it were during the third week of the survey by the advancing oceanic water-mass which achieved a closed circulation of greater than 35·20 $^{0}/_{00}$ central salinity within the western 500-metres bathymetric. Except for the above-mentioned southwards urge of the colder less saline northern water on the southern part of the Ridge the 35·00 $^{0}/_{00}$ isohaline had moved substantially farther northeastward across the Ridge summit by the time of the third survey. Likewise, although the relative position of the 34·95 $^{0}/_{00}$ and 35·00 $^{0}/_{00}$ isohalines as between the second and third surveys would appear from Figures 3:14 and 3:21 to have been very similar, the surrounding conditions, northward and southward of the Channel, suggest intensification of the oceanic influence in the last part of the exercise.

On the whole, therefore, these considerations of horizontal temperature and salinity distributions at the various levels from surface to bottom during the three weeks from the end of May until 18. June, 1960, bear the interpretation, despite obviously intensive mixing of the opposing water-masses in the levels immediately above the broad Ridge summit, of a receding cold deep-water overspill of the Iceland-Faroe Ridge during this period.

VERTICAL TEMPERATURE AND SALINITY DISTRIBUTIONS (J. B. Tait)

FIRST SURVEY

THE SECTIONS BY "PERSEUS II" (U.S.S.R.)

The hydrographic sections traversed by "Perseus II", together comprising course A of the survey plan as a whole and extending from the deeper slope waters on the north side of the Iceland-Faroe Ridge into the deep Norwegian Sea waters farther to the northeast, are illustrated in Figure 0:1 (page 6) of the introductory chapter to this report. Individual hydrographic stations are numbered 1 to 26 for the first survey, being designated A1, A2, ... etc. in narrative and 1, 2, 3, ... etc. on Figures 3:22–24. Station numbers on the second survey are 101–126 (Figures 3:22 and 3:24) with the designations A101, A102, ... etc. in the text; and, on the third survey, 201–226 (Figures 3:22–3:24), with textual reference, A201, A202, ... etc. Corresponding numbering and designations denote the hydrographic stations on courses B to I.[1]

The first section to be considered is that embracing stations A8 to A17, omitting station A10 because of its somewhat marked departure from the line of stations A8 to A11, and at the same time its relatively close proximity to A9 and A11. As will be observed from Figure 0:1, all nine stations of the section A_1I[2] (Figure 3:22 (a)) do not lie on one straight line. Nevertheless, it seems appropriate to treat the section, diagrammatically, as one, because of its disposition relative to the sea bottom configuration in this region, although, in this connection, notice should be taken of an appreciable difference in the region concerned between the chart upon which the survey plan was originally laid down and which was prepared by Professor G. Dietrich from cruise records of the West German research ship "Anton Dohrn" in 1955 and 1956, and the reproduction of an U.S.S.R. chart as Figure 2 in the paper by Vinogradova, Kislyakov, Litvin, and Ponomarenko (1959).

Temperature and salinity distributions on the first section A_1I are depicted on Figure 3:22 (a).

On the deepest part of the section, that is, from station A12 eastward, minimum surface water temperature of 3·32° C at station A12 lay within only a few miles of almost the maximum surface water temperature on the section, namely, 5·74° C at A11. Superficial temperatures on the eastern part of the section lay within the narrow range of only 4° C to 4·37° C.

From the southern part of the section where it ascended from 350 metres at A8 to 260 metres at A12, the zero isotherm dropped abruptly to over 500 metres at A13 and undulated between about 360 metres and 470 metres on the remainder of the eastern part of the section on latitude 64°53′N. It is noteworthy that on the southern part of the section, approaching towards the Iceland-Faroe Ridge, subzero temperature water occupied a 200-metres layer immediately above the mean summit level (ca. 500 metres) of the Ridge.

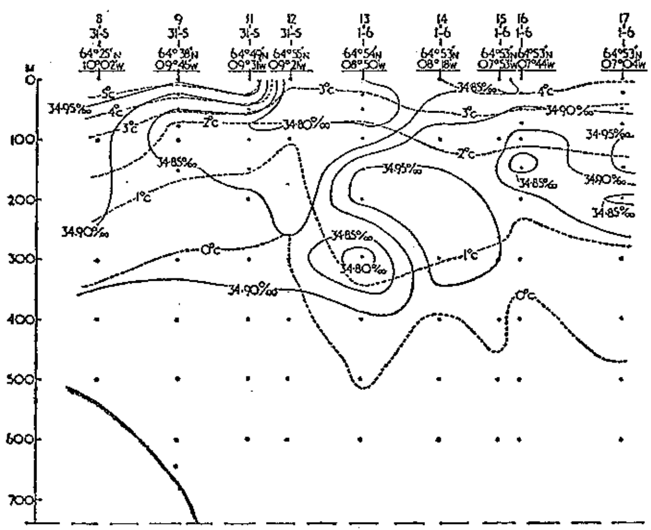
The configuration of the isohalines on Figure 3:22 (a) is more irregular than that of the isotherms, and presents some interesting features.

Except in the surface at A11 – and it tends to confirm the accuracy of the observations that almost exactly the same situation, in practically the same terms of temperature and salinity, was found at the nearby station A10 – no other such evidence of oceanic water occurred anywhere on the section under review. It would in fact appear that any tendency towards the easterly extension or an easterly progression of even very much diluted oceanic water on the latitude of approximately 64°45′N was effectively inhibited by the Polar type water-mass which is implicit in the salinity value of less than 34·80 $^0/_{00}$ recorded in the uppermost 75-metres layer at stations A12 and A13. Only slightly adulterated, as gauged by salinity observations up to 34·84 $^0/_{00}$, this same water-mass extended on the surface of the section from between stations A11 and A12 to between A16 and A15. It underlay, in from 50 to 150 metres, the sub-oceanic uppermost layer at stations A9 and A11, and registered a maximum thickness of no less than 250 metres at A12, besides occurring, in partial isolation – possibly as the result of turbulence or vorticity – between 250 and 350 metres depth around a nucleus of 34·77 $^0/_{00}$ salinity at 300 metres on A13, and also underneath and alongside what would appear from its salinity (> 34·95 $^0/_{00}$) to be an isolated portion of sub-oceanic water, cooled to between 1° and 2° C by contact with the colder and deeper northern waters and shut off between 150 and 350 metres between stations A13 and A16 inclusive. Further eastward on the section occurs another isolated portion of the sub-Arctic water-mass around two nuclear salinities of 34·84 $^0/_{00}$ one at 150 metres on A15 and the other at 200 metres on A17.

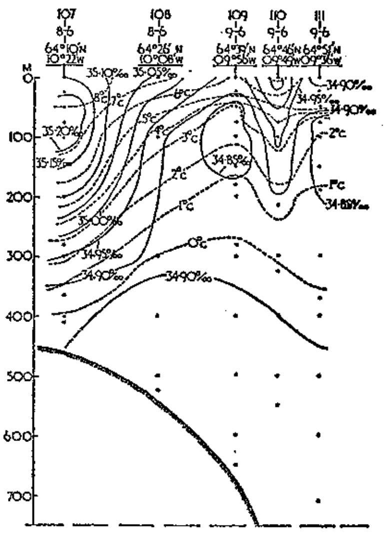
These complexities in the salinity distribution in the uppermost 350 metres of the section are in marked contrast to the almost unbroken uniformity in salinity at 34·92 $^0/_{00}$, in depths from 400 metres to over 2,000 metres over the entire section.

[1] In ICES Oceanographic Data Lists, 1960, Nos. 6 and 7, where the observations of temperature, salinity, oxygen and nutrients will be published, another numbering is used: the individual hydrographic station is there given the number to which it is due according to its place in the series of stations worked in 1960 by the ship in question.

[2] In sectional notation in this part of the Report the small index number attached to the capital, which specifies the course, denotes the survey concerned – first, second, or third, – while the capital Roman numeral signifies the section referred to.

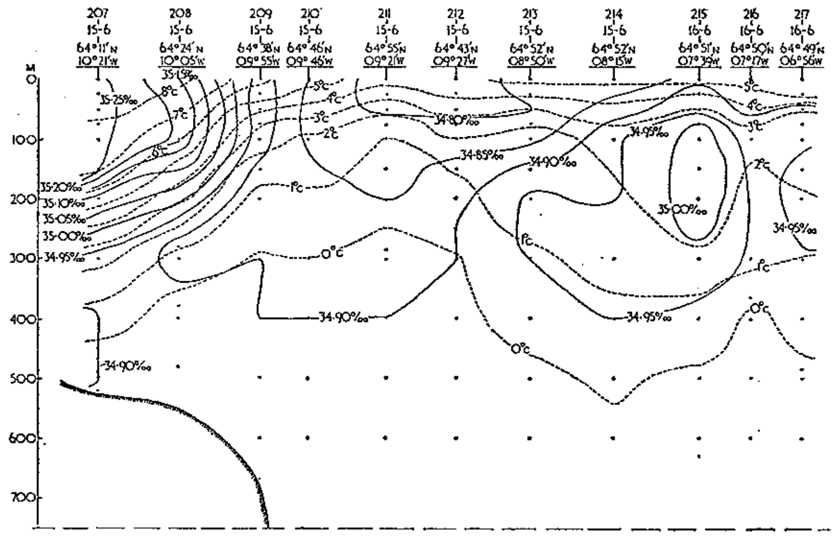


(a) Section A_1I



(b) Section A_2I

Figure 3:22.



(c) Section A_3I

Passing longitudinally southward from the deepest station, A17, of the "Perseus II" A_1I section, towards the Faroe Islands' submarine plateau into which the Iceland-Faroe Ridge merges at its southeastern end, Figure 3:23(a) (Section A_1II) depicts the temperature-salinity distributions on the hydrographic section which includes stations A17 to A26.

The uppermost waters of the southern half of this section were markedly oceanic, recording maximum salinities of over $35{\cdot}30\,^0/_{00}$ to a depth of 150 metres on station A25 and temperatures in this layer of 8° C to over 9·5° C on the surface. This oceanic water-mass which was no doubt a part of that normally to be found to the west and north of the Faroe Islands, was more than 400 metres thick against the northern slope of the Faroe submarine plateau, diminishing only gradually to 300 metres thickness over 30 nautical miles northward from A26, and thereafter to zero thickness in a further 25 miles.

The transition from oceanic to Norwegian Sea water of salinity $34{\cdot}92\,^0/_{00} \pm 0{\cdot}02\,^0/_{00}$ was relatively sharp, as can be seen from the dispositions of isotherms and isohalines on Figure 3:23(a). The uppermost 300–400 metres of the Norwegian Sea water-mass on the section enveloped some isolated portions of both sub-oceanic (salinity $34{\cdot}95\,^0/_{00}$–$34{\cdot}99\,^0/_{00}$) and Arctic (salinity $34{\cdot}79\,^0/_{00}$–$34{\cdot}89\,^0/_{00}$) water bodies. The former occurred superficially to about 50 metres on station A20, with temperatures of 5° C to nearly 7° C, and totally between 125 and 275 metres on A21, with a mean temperature around 2° C with small variation. There was also a hint of its intrusion, at the same

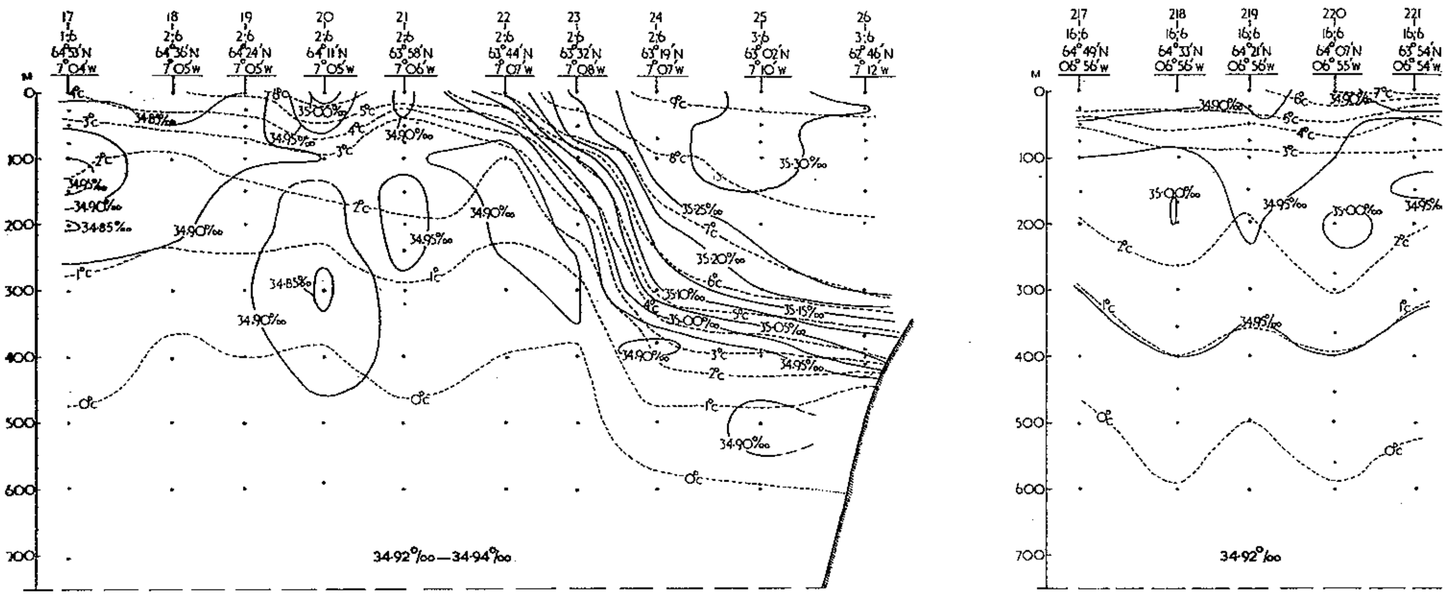


Figure 3:23. (a) Section A_1II (b) Section A_2II

mean temperature, between 100 and 150 metres on A17, into the Arctic water-mass which embraced A17 to A19 and sounded 250 metres on A17. The thermal condition of this water-mass was denoted by temperatures of about 1° C to just over 5° C.

The topmost water at A21, to 40 metres depth, was another isolated portion of the Arctic water-mass (salinity 34·87 ‰–34·88 ‰) in atmospheric contact. Totally enveloped Arctic water bodies on the section A_1II occurred between 130 and 460 metres on A20, between 75 and 350 metres on A22, at almost 400 metres on A24, and around 500 metres on A25. The mean temperature of these water bodies was approximately 1° C, varying from slightly below zero to just over 2° C.

Four hundred metres, that is, some 100 metres above the mean summit level of the Iceland-Faroe Ridge, was the mean level, with little variation, of the zero isotherm over the greater part of the section, only dipping some 200 metres to around 600 metres on the Faroe submarine slope.

Finally, and in a sense aggregating the water properties of the two sections above in the approach to the Iceland-Faroe Ridge, section A_1III (Figure 3:24(a)), lying approximately parallel to the northeastern slope of the Ridge, takes account of conditions between station A1 and A7 inclusive on the first survey.

On this section, sub-zero temperature water, with the salinity of Norwegian Sea water (about 34·92 ‰) was still in evidence, although in relatively small amount above the Ridge summit level of approximately 500 metres. The 2° C isotherm, however, which will subsequently be seen to denote the upper thermal limit of genuine cold deep overflow water across the Ridge, stood at more than 100 metres to over 200 metres above the Ridge summit level over the greater part of the section. At the station A3, however, on top of a marked rise in the sea bed to the equivalent depth of the Ridge summit, this isotherm dipped to within 50 metres of the bottom, rising again scarcely 50 metres at station A2. The situation of these two stations, in particular in relation to the narrowest part of the Iceland-Faroe Ridge over which apparently the greatest measure of overflow generally seems to occur, is therefore of some significance.

As might be expected from the evidence of section A_1II, marked oceanic water characteristics were observed on the southeastern end of the section under review, where temperatures over 9° C and salinities of 35·30 ‰ and over were recorded in the uppermost 150 metres at the first three stations of the section. It was perhaps less to be expected, however, that the uppermost waters of the entire section should be so markedly oceanic as denoted by temperatures greater than 8° C and salinities in excess of 35·25 ‰. Indeed the thickness of the oceanic water-mass as defined by the 35·00 ‰ isohaline on this section as a whole is remarkable, reaching to at least 475 metres at A5 from 150 metres at A7, and between 350 and 430 metres between A1 and A3, with a cold (0·05° C), high salinity (35·27 ‰) mass on the bottom between A1 and A2, probably denoting cascaded oceanic water from the Faroe submarine plateau. Moreover, and insofar as the record is a true one, a salinity of 35·02 ‰ observed at 570 metres on A5 in conjunction with a temperature of 0·06° C, is further suggestive of a cascaded body of water which formerly may have been associated with the deep-lying base of the oceanic water-mass above referred to at station A3 on top of the pronounced rise in the sea floor at this station as compared with the neighbouring stations A2, A4–A5.

This surprisingly extensive oceanic water-mass on the A_1III section of "Perseus II" overlay two apparently separated masses of Norwegian Sea water of 35·92 ‰ salinity, into the more westerly of which a small body of Arctic water of salinity 34·87 ‰–34·89 ‰ penetrated between 300 and 450 metres.

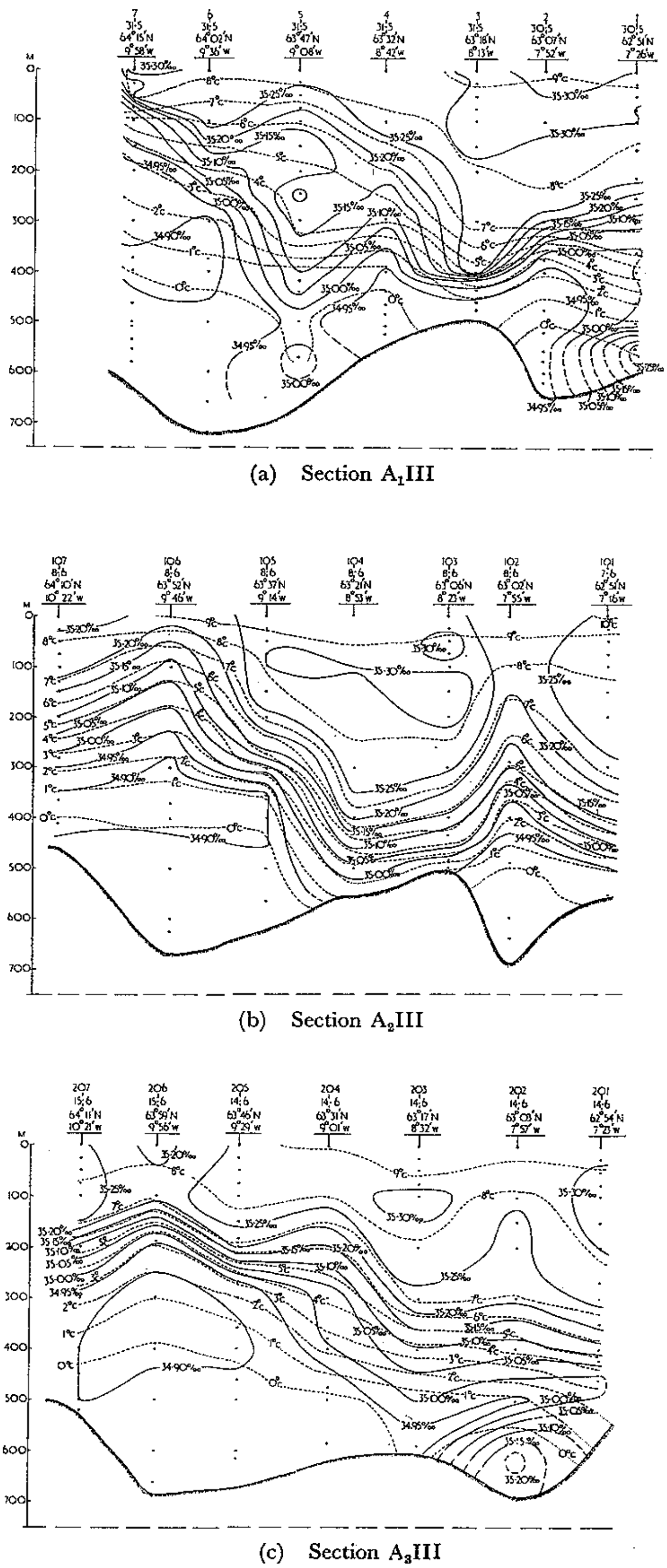
THE SECTIONS BY "JOHAN HJORT" (NORWAY)

Reference to Figure 0:1 shows that the two parallel sections of sixteen and eighteen hydrographic stations respectively, (course B) which were undertaken by "Johan Hjort" (Norway), lay for the most part on the northeastern slopes of the Iceland-Faroe Ridge. One or four to six stations at either end of each section were situated over the Ridge itself while several stations lay on or near the 500-metres bathymetric which marks the northeastern shoulder of the Ridge. These sections, therefore, designated B_1I and B_1II respectively may be expected to illustrate hydrographical transition from the more deeply situated "Perseus II" sections and those of the "Gauss" (West Germany) which were set almost entirely along the comparatively flat summit of the Ridge.

Compared with the immediately adjacent parallel and contemporary first survey sections of "Perseus II" (A_1III) to the northward (Figure 3:24(a)) and of "Gauss" (C_1I and C_1II) to the south (Figures 3:27(a) and 3:28(a)) those of "Johan Hjort" (B_1I and B_1II, Figure 3:25(a) and Figure 3:26(a) respectively), are remarkable for the relatively very small amounts of the highest salinity (> 35·30 ‰) water appearing in cross-section. The uppermost water-temperature areas, at above 9°C, correspond approximately on all five sections, but whereas the "Perseus II" and "Gauss" sections all show appreciable areas of > 35·30 ‰ salinity water, this is practically non-existent on "Johan Hjort" section B_1I and, except for the small area involving stations B33 and B34, is comparatively insignificant on Section B_1II. The cross-sectional areas of > 35·25 ‰ salinity water, however, correspond a little more nearly on all five sections.

The chief objective, however, of these surveys as a whole being the registration, so far as may be possible, of the amounts of cold deep water from the north which pass over the Iceland-Faroe Ridge, the assessment of this objective in the present part of the report were perhaps best achieved by recording the cross-

Figure 3:24.

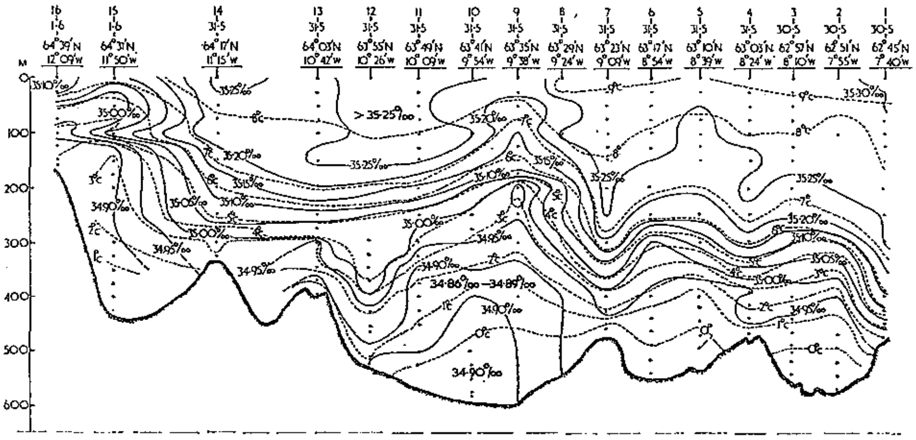


(a) Section A_1III

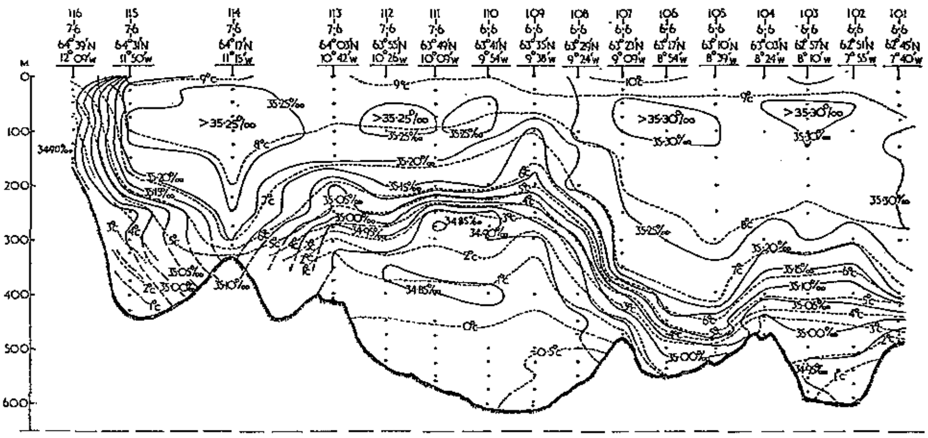
(b) Section A_2III

(c) Section A_3III

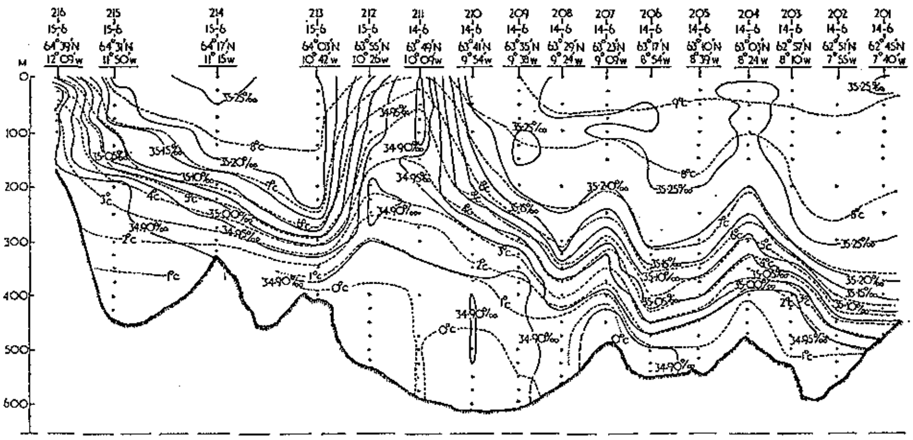
Figure 3:25.



(a) Section B_1I

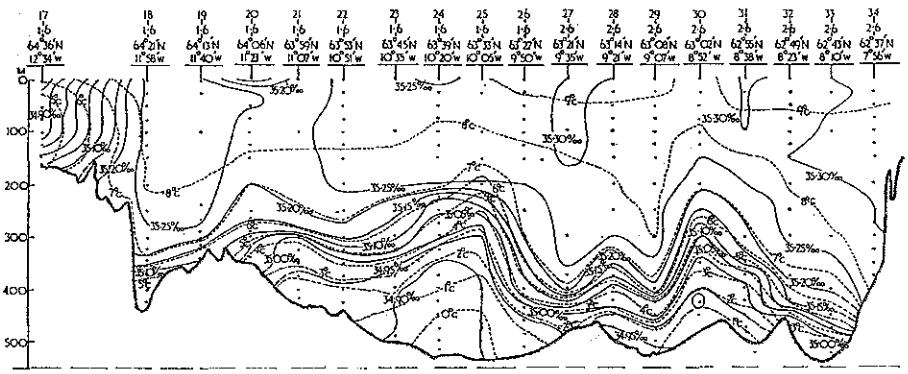


(b) Section B_2I

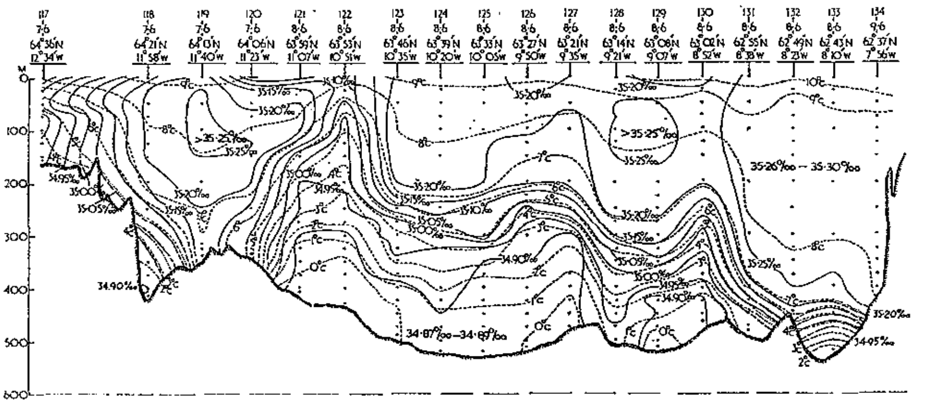


(c) Section B_3I

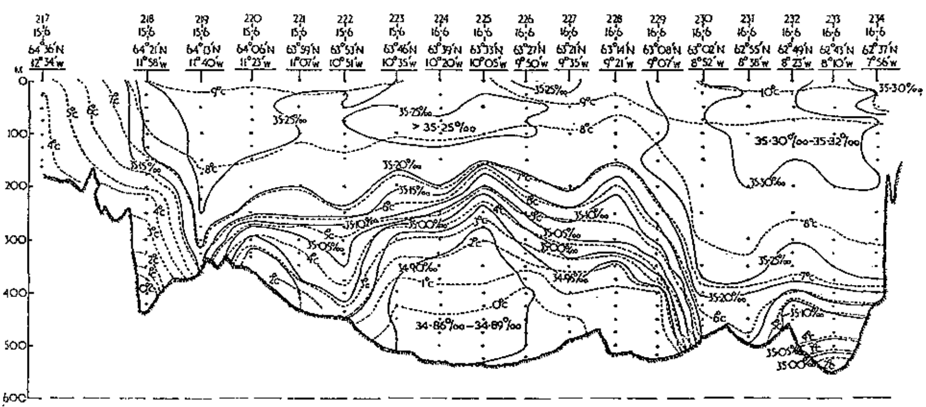
Figure 3:26.



(a) Section B_1II



(b) Section B_2II



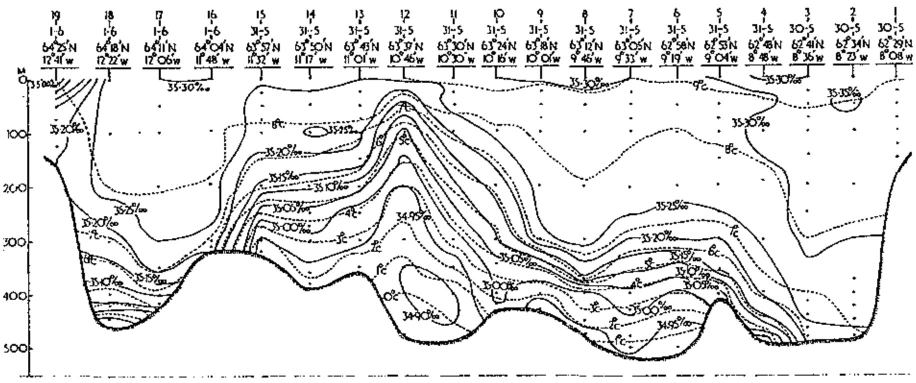
(c) Section B_3II

sectional areas of such water, according to the temperature observations, which appear on each hydrographic section above the summit level of the Ridge, namely 500 metres, assuming for the time being that all such water is moving southward towards and across the Ridge. For this assessment let the isotherms of 0° C and 2° C be the limiting data. Beginning with the A_1III section of "Perseus II", the following table then gives the approximate measures as read from the several sectional diagrams.

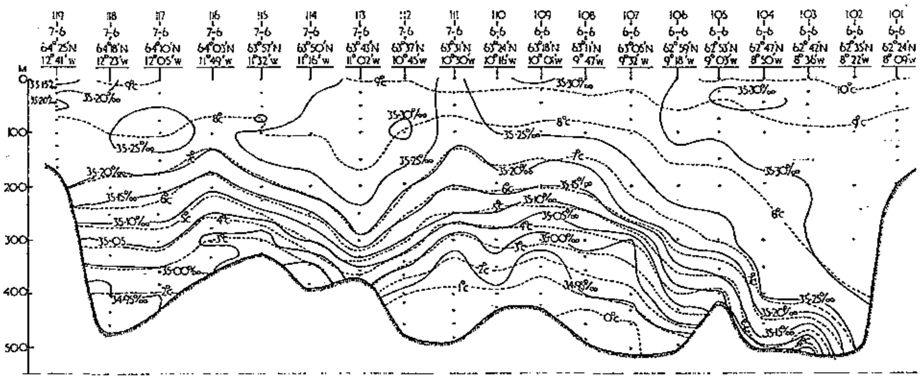
Section	Cross-sectional areas above 500 m level at < 0° C km²	at < 2° C km²
A_1III..........	4·96	23·56
B_1I	2·96	27·62
B_1II	1·32	12·62

Of necessity some of these measures can be only approximate because of the uncertainty, due to lack of observations in certain critical depths and places,

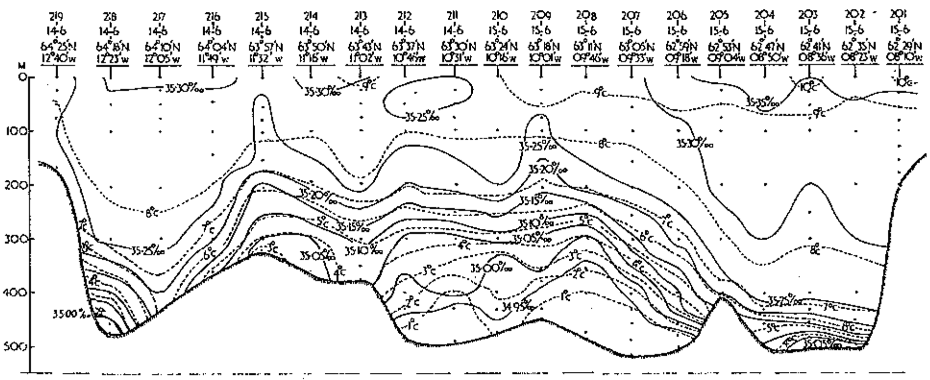
Figure 3:27.



(a) Section C_1I



(b) Section C_2I

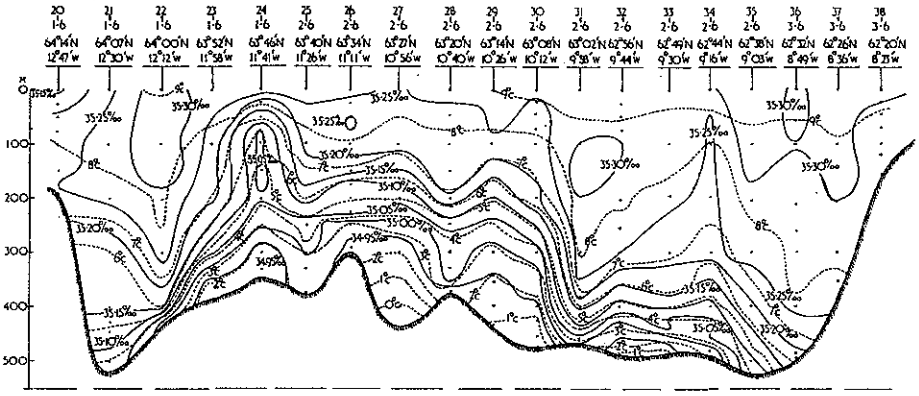


(c) Section C_3I

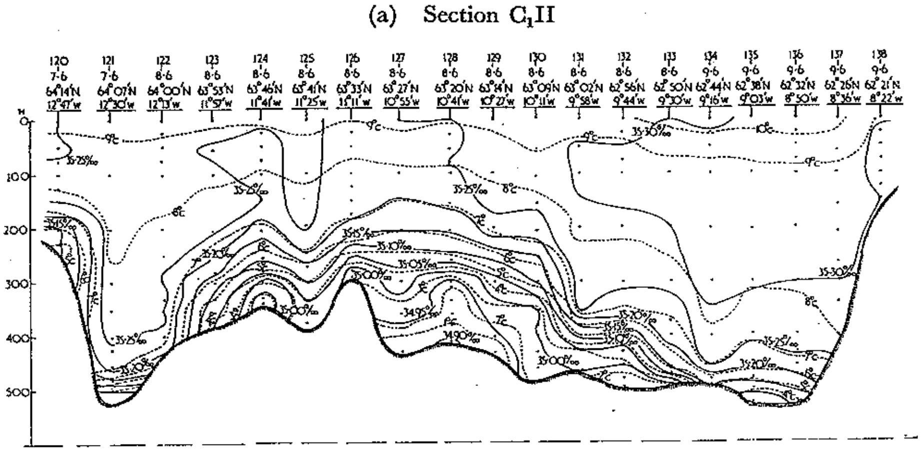
of terminal parts of the material isotherms, especially the 2° C isotherm, but, relatively, they afford a conception of the likelihood of cold-water overspill across the Iceland-Faroe Ridge in the approach thereto from the north. It is at once evident that the "promise", as it were, of the A_1III section as regards a very substantial overflow of cold, sub-zero temperature water across the Ridge, has become substantially reduced some 20 miles farther south on the B_1II section lying very nearly along the northern shoulder of the Ridge for the greater part, that is, in approximately 500 metres depth. The extent of the reduction is of the order of almost 75 per cent as regards sub-zero temperature water, and approximately 50 per cent of water which is under 2° C.

Except for two parts of the A_1III section, where it would appear that super-cooled bodies of oceanic water of salinity greater than $35{\cdot}00\,^0/_{00}$, had attained to bottom levels, practically all of the sub-zero temperature water on the three sections so far considered

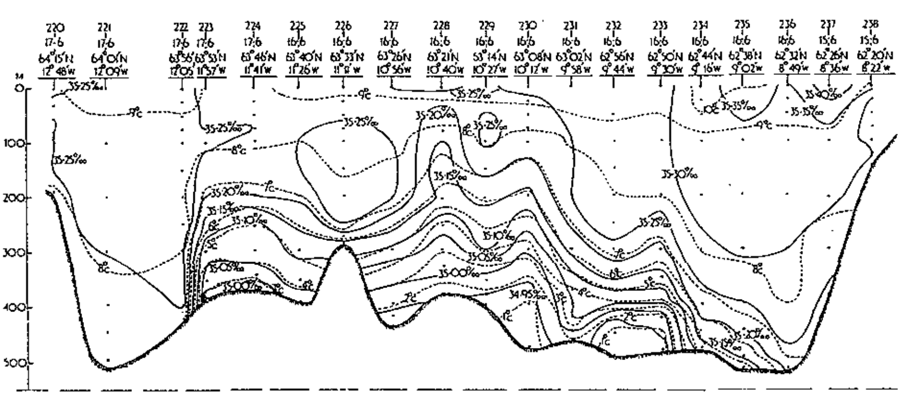
Figure 3:28.



(a) Section C_1II



(b) Section C_2II

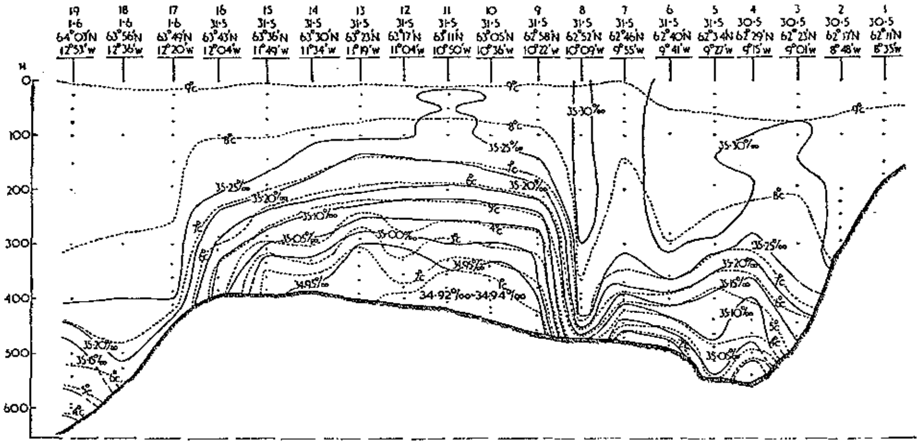


(c) Section C_3II

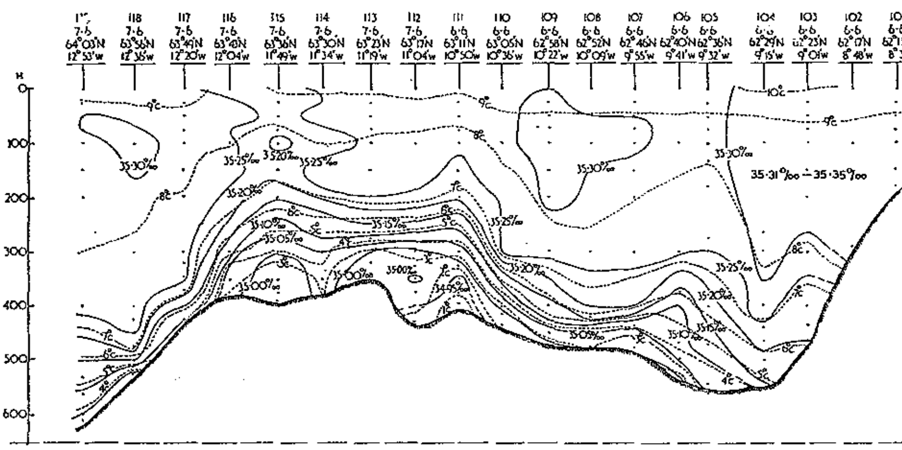
was of salinity 34·90 $^0/_{00}$ to 34·92 $^0/_{00}$, showing it to be of deep Norwegian Sea origin.

The cross-sectional areas between the 0° C and 2° C isotherms, however, include other water-types on all three sections. The A_1III section, for instance, between these two isotherms, contains only very little deep Norwegian Sea water, but embraces oceanic and sub-oceanic waters on the one hand, and waters of salinity below 34·90 $^0/_{00}$ to 34·87 $^0/_{00}$ on the other, indicative of the Intermediate Arctic water-mass. Predominantly Intermediate Arctic water occurs on the northwestern half of the B_1I section, while deep Norwegian Sea water is the main constituent water-mass on the southeastern half of the section between the 0° C and 2° C thermal boundaries. In the corresponding area of the B_1II section, except for the indication, by salinity, of the Intermediate Arctic water-mass at a single station (B26) towards the middle of the section, deep Norwegian Sea water is almost the sole representative water-mass.

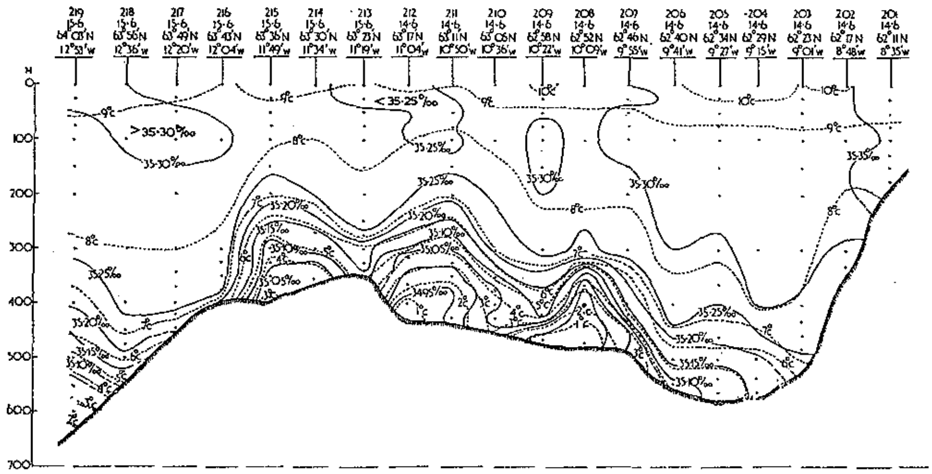
Figure 3:29.



(a) Section D_1I

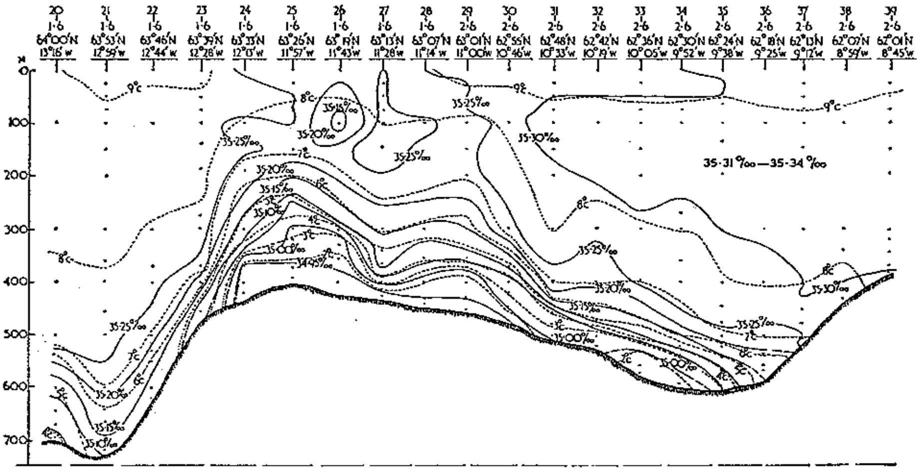


(b) Section D_2I

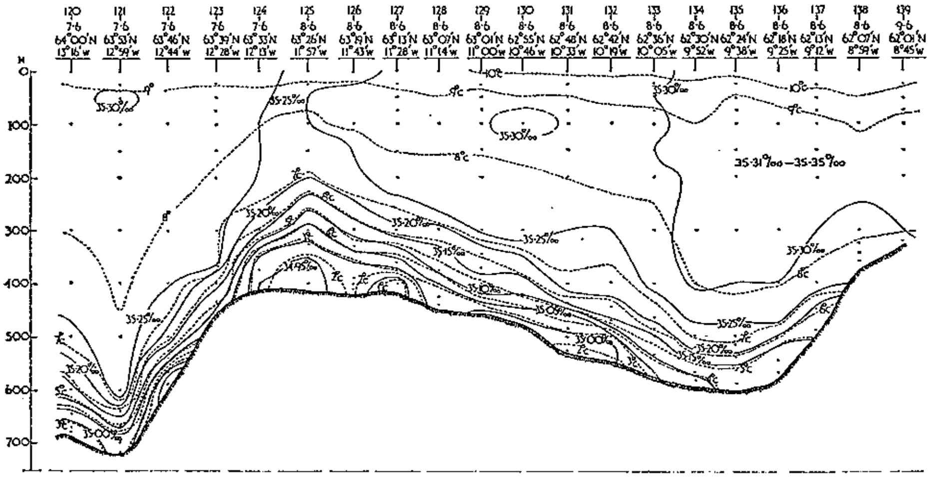


(c) Section D_3I

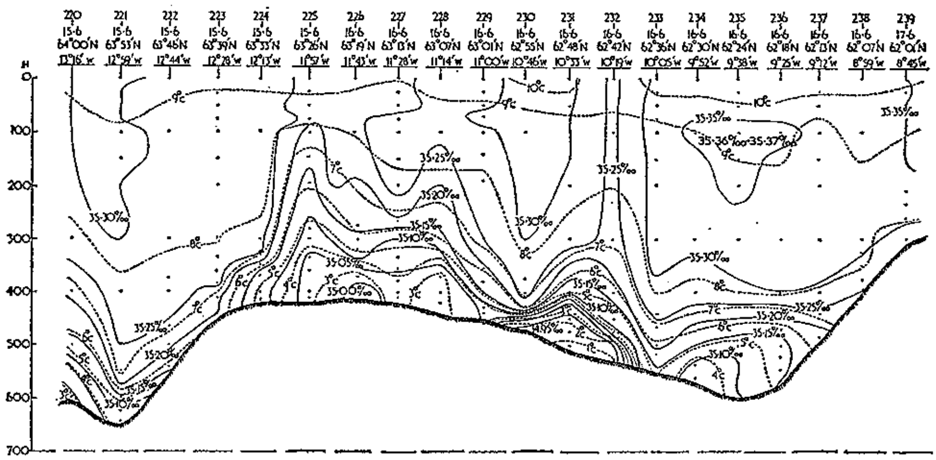
Figure 3:30.



(a) Section D_1II

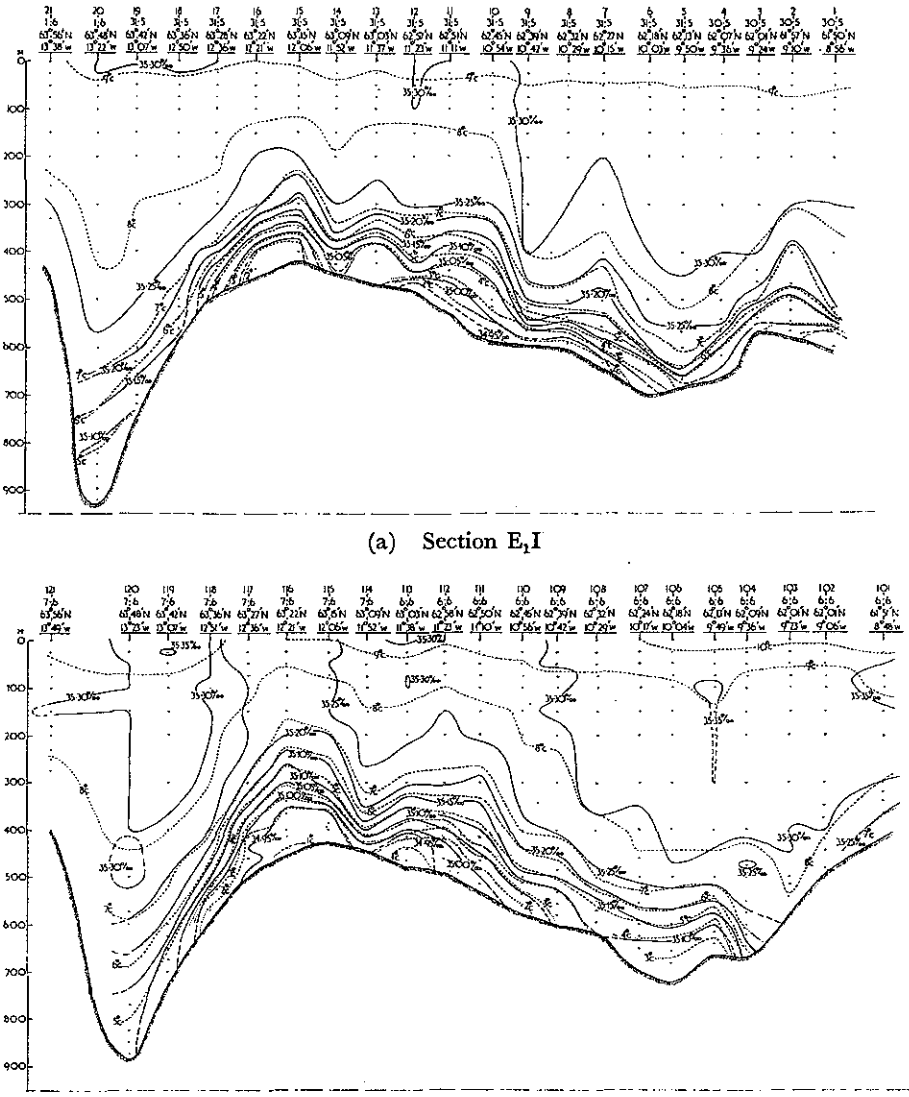


(b) Section D_2II



(c) Section D_3II

Figure 3:31.



(a) Section E_1I

(b) Section E_2I

THE SECTIONS BY "GAUSS" (FEDERAL REPUBLIC OF GERMANY)

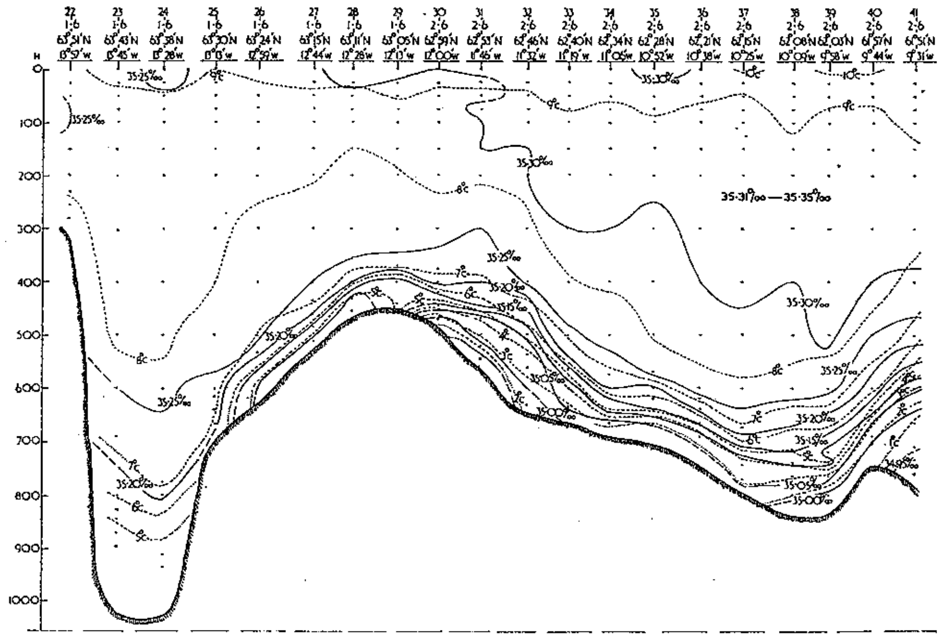
Next in order of progression from north to south – although it is to be remembered that the pairs of sections by each ship on each survey were carried out practically simultaneously – were the sections C_1I and C_1II, comprising hydrographic stations C1–19 and C20–38 respectively, undertaken by "Gauss" (see Figures 3:27(a) and 3:28(a)).

Except for only two stations on C_1I (C6 and C7) and three stations on C_1II (C21, C35 and C36) sounding more than 500 metres, both sections were situated entirely on the Ridge summit of less than 500 metres depth.

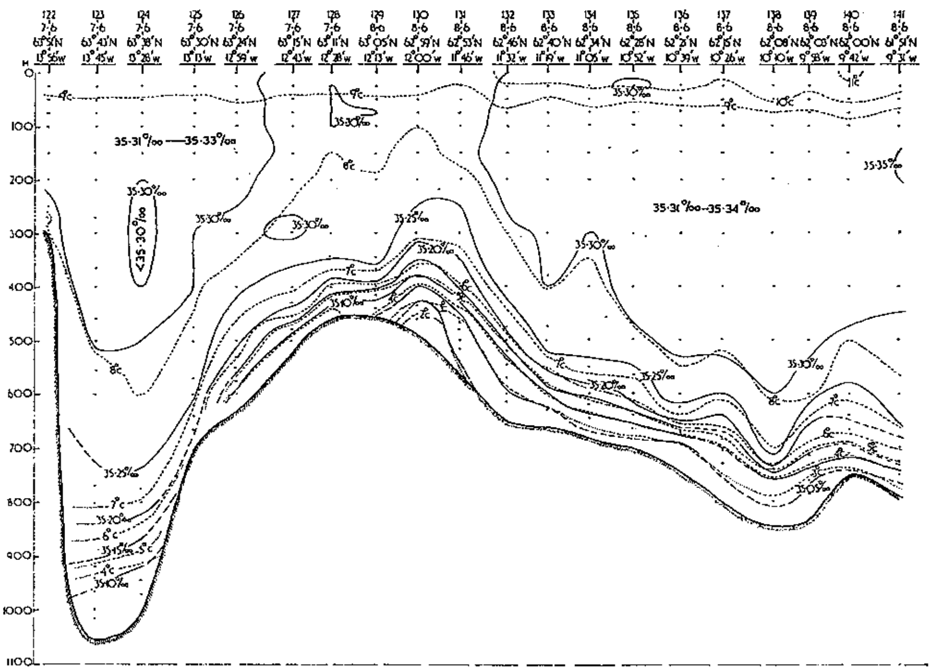
As on the three parallel sections already considered, the uppermost water temperatures on at least a part, or parts, of the C_1I and C_1II sections were in excess of 9° C.

A considerable cross-sectional bulk of oceanic water of greater salinity than $35{\cdot}30\,^0/_{00}$ occurred on the southeastern ends of both sections, which, it may be recalled, contrasts somewhat markedly with conditions on the "Johan Hjort" sections, B_1I and B_1II. On section C_1I, indeed, maximum salinity of $35{\cdot}36\,^0/_{00}$ was registered at the surface at station C4, and again at 50 metres on C2. Against the slope of the Faroe Islands' submarine plateau, this relatively high salinity oceanic water-mass plumbed depths of over 300 metres on the two "Gauss" sections, C_1I and C_1II. The total oceanic water-mass on each of the two sections as gauged by the limiting isohaline of $35{\cdot}00\,^0/_{00}$ was very considerable, as might of course

Figure 3:32.



(a) Section E_1II



(b) Section E_2II

be expected, reaching the bottom near to the Faroe Islands submarine slopes, and to depths of over 400 metres on other parts of section C_1I and more than 350–400 metres in open section on C_1II. On section C_1I, however, the effect of colder deeper waters pressing up the northern slope of the Ridge can be deduced from the contours of both isotherms and isohalines about station C12 on Figure 3:27(a). Figure 0:1 shows a deep indentation of the northern shoulder of the Ridge between stations C11 and C12, this indentation extending southward to section C_1II between stations C27 and C28. Isotherms and isohalines about the latter station on Figure 3:28(a) indicate, in lesser degree, a similar influence from below as around station C12 on section C_1I (Figure 3:27(a)).

Proceeding to the evaluation, so far as this can be done from these diagrams, of the encroachment of cold deep waters on top of the Iceland-Faroe Ridge, the figures for C_1I and C_1II are as follows: –

Section	Cross-sectional areas above 500 m level at < 0° C km²	at < 2° C km²
C_1I	1·72	10·38
C_1II..........	0·45	6·26

There is probably no significant difference between the relative quantities of sub-zero temperature waters on the adjacent sections B_1II and C_1I respectively. Within the parameter of the 2° C isotherm, however, the decline in the bulk quantities of this cold water-mass as represented by the cross-sectional measurements on these two sections, is as might be expected. Between the two "Gauss" sections on the other hand the mass diminutions represented within both the 0° C and 2° C parameters are substantial, indicating the effect of the Iceland-Faroe Ridge in delineating the quantities of cold deep water permitted to encroach on top of the Ridge from the north.

As in the case of the "Johan Hjort" sections, those of "Gauss" included only deep Norwegian Sea water below the 0° C isotherm, but in contrast to the former, and except for a slight indication of sub-oceanic water on the bottom at stations C7 and C8, the "Gauss" sections revealed no intermediate Arctic water within the 2° C isotherm, only deep Norwegian Sea water.

THE SECTIONS BY "ERNEST HOLT" (UNITED KINGDOM)

Reference to Figure 0:1 will show that these sections, D_1I and D_1II respectively, (Figures 3:29(a) and 3:30(a)), although substantially running along the top of the Ridge, also sampled, in two distinct regions, the waters on the southern shoulder and upper southern slope of the Ridge.

Substantial volumes of high salinity (>35·30 ‰) oceanic water are represented in cross-section on the southeastern ends of both sections. Surface temperature on the more northerly section everywhere exceeded 9° C to a maximum of 9·54° C at stations D1 and D6 respectively in the thickest part of the warm layer. This warm layer in excess of 9° C on the southern section, D_1II, was broken in an intermediate part of the section on top of the Ridge, between stations D24 and D28 inclusive, by somewhat cooler water, subdividing in this part the main body of the oceanic water-mass, as represented by the limiting 35·25 ‰ isohalines. The tendency towards a similar subdivision on the more northerly section was only just inhibited, as it were, in mid-section at station D11 where the 35·25 ‰ isohaline, continuous from one end of the section to the other, reaches to within 20 metres of the surface from depths of 400 metres and over on either side.

In contrast to previous sections now dealt with, it is noteworthy that no sub-zero temperature water occurred on either of the two first survey sections by "Ernest Holt". On the more northerly section, the minimum temperature on top of the Ridge itself was just above + 0·5° C, while on that small part of this section which sampled the deeper waters on the southeastern slope of the Ridge, the minimum temperature recorded was 1·53° C at a depth of 540 metres, in water which from its salinity of 34·97 ‰ would appear to represent a slight dilution by overspill water of the under side of the superincumbent oceanic water-mass. At the other, the northwestern end of this same northerly "Ernest Holt" section, where waters on the southern side of the Ridge were also sampled, the entire water body to the bottom in over 600 metres was oceanic in character as defined by salinities in excess of 35·05 ‰ and temperatures upwards of about 4° C.

On the southern section, towards its southeastern end, that is on the southern slope of the Ridge, the minimum temperature recorded was 1·44° C at 590 metres depth and again in water of 34·97 ‰ salinity; and in the deepest part of the northwestern end of this section, sounding more than 700 metres, temperature and salinity conditions were almost exactly the same as those above described for the corresponding part of section D_1I.

In areal cross-section, the measurements for the "Ernest Holt" sections, corresponding to those already made for "Perseus II", "Johan Hjort" and "Gauss" sections, are as follows, with this difference, that measures for the areas lying deeper than 500 metres, as probably representative in some degree of actual overspill from the north, are given additionally: –

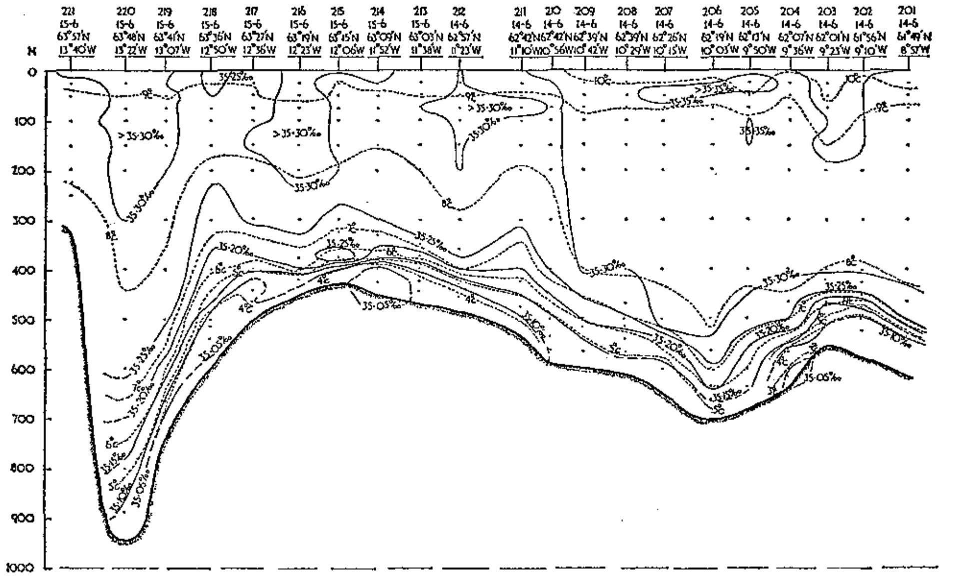
Section	Cross-sectional areas of water < 2° C above 500 m km²	below 500 m km²
D_1I	7·60	0·41
D_1II	5·42	0·88

The bottom water-mass on top of the Ridge on both sections which registered temperatures of less than 2° C was the only bottom Norwegian Sea water proper to appear on the "Ernest Holt" survey.

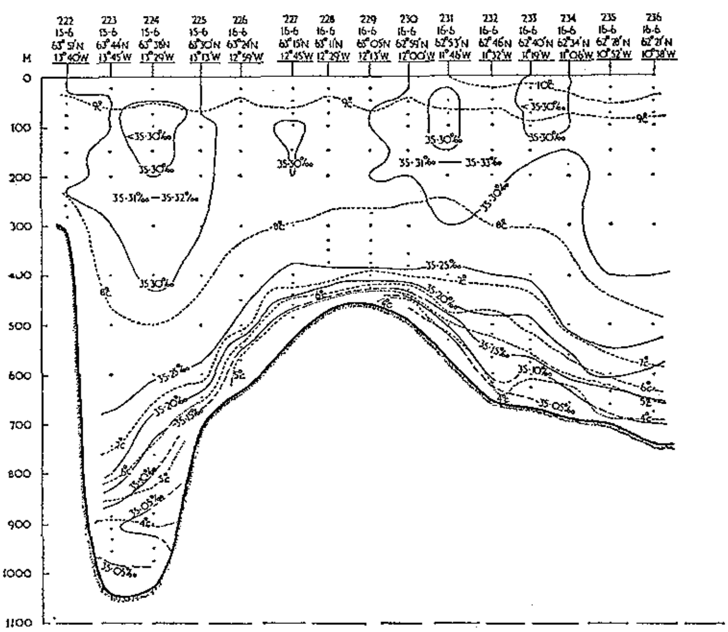
THE SECTIONS BY "MARÍA JÚLÍA" (ICELAND)

Comparatively, the lesser parts of the sections E_1I and E_1II (Figures 3:31(a) and 3:32(a)) embraced the summit of the Iceland-Faroe Ridge, the remainders being laid over the southwestern slopes of the Ridge

Figure 3:33.



(a) Section E_3I



(b) Section E_3II

(see Figure 0:1). The uppermost water temperatures were again in excess of 9° C on both sections except at the northwest terminal station on each, and 35·40 + $^0/_{00}$ salinity water bulked largely, especially on the southeastern halves of both, where depths of over 400 metres were sounded by this relatively unadulterated oceanic water-mass, at one station (E39) on the southern section, over 500 metres.

As might be expected after the "Ernest Holt" sections, no sub-zero temperature water occurred on the E sections, but as the following figures show, rather more < 2° C water below the 500 metres level in relation to those for sections D_1I and D_1II. On the sections E_1I and E_1II, however, this cold bottom water was in two distinct parts, one part between stations E6 and E11 on the northern section, and between stations E30 and E32 on the southern one, while the other distinct part involved only station E1 on the north section and stations E38–E41 inclusive, farther south. The former part, according to the accompanying salinities, evidently represents on the northern section, sub-oceanic water cooled by overspill water, and while on the southern section the same explanation may hold in actual fact, the sole salinity observation within the thermal parameter concerned is, at 34·93 $^0/_{00}$, suggestive of deep Norwegian Sea water. The second part of < 2° C bottom water, however, at the southeastern end of both sections embraces weak oceanic water (35·02 $^0/_{00}$ salinity) on the northern section and sub-oceanic (salinity 34·95 $^0/_{00}$ –34·99 $^0/_{00}$) on section E_1II, the cooling influence obviously deriving from the cold bottom water effluent from the Faroe-Shetland Channel through the Faroe Bank Channel. These differences are noted in the following table: –

Section	Cross-sectional areas of < 2° C water above 500 m	below 500 m	
		overspill	effluent
	km²	km²	km²
E_1I	1·66	1·71	0·02
E_1II...........	0·08	0·93	3·15

THE SECTIONS BY "HELLAND-HANSEN (NORWAY)

The sections F_1I and F_1II (Figure 3:34) lay almost entirely off and southward of the Iceland-Faroe Ridge. Only station F12 on the northern section seems to have been situated on its southern shoulder in approximately 500 metres.

The 10° C isotherm appears at the southeastern end of the southern section, involving only the surface waters of stations F37 and F38. Except for the northwestern terminal station on each section, the uppermost 50–75 metre layers in both cases registered temperatures greater than 9° C.

The oceanic water-mass, of course, of salinity greater than 35·00 $^0/_{00}$, bulked very largely on both sections, with the main core of the mass, in excess of 35·30 $^0/_{00}$ salinity, reaching substantially to depths of 500 metres and more on the southeastern parts of the sections. On both, the oceanic mass reached to the bottom in over 1,200 and 1,300 metres respectively between the southwesterly extension of the Ridge and the continental shelf of Iceland.

Less than 2° C bottom water is represented only on the northern "Helland-Hansen" section, in two separate parts, one between stations F8 and F11 in from 565 to 720 metres, and the other from 740 to 905 metres embraching stations F1 to F3. Both seem obviously to derive from the Faroe Bank Channel deep water effluent, their separation on section F_1I being doubtless due to the path of geostrophic flow in relation to the southern slope contour of the Ridge. The areal quantities of the two parts in cross-section are given here:

Section	Cross-sectional areas of < 2° C water 565–720 m	740–905 m
	km²	km²
F_1I	1·21	1·38

In terms of effluent these figures, in total, bear an understandable and reasonable relationship to the corresponding figure of 3·15 Km² in respect of the section E_1II.

Although section F_1II embraced no water of a temperature lower than 2·40° C, a subdivided cross-sectional area of 3·76 Km² of bottom water less than 3° C roughly corresponds with the somewhat colder bottom water of section F_1I. The former, however, by its salinity (> 34·99 $^0/_{00}$) was oceanic in character, while the latter, as indicated by salinities of 34·92 $^0/_{00}$ would appear to have included some deep Norwegian Sea water along with sub-oceanic water with a salinity of about 34·96 $^0/_{00}$.

THE SECTIONS BY "ANTON DOHRN"
(FEDERAL REPUBLIC OF GERMANY)

Further into the deeper waters off the southwestern slopes of the Iceland-Faroe Ridge lay the two parallel "Anton Dohrn" sections G_1I and G_1II, (Figure 3:37).

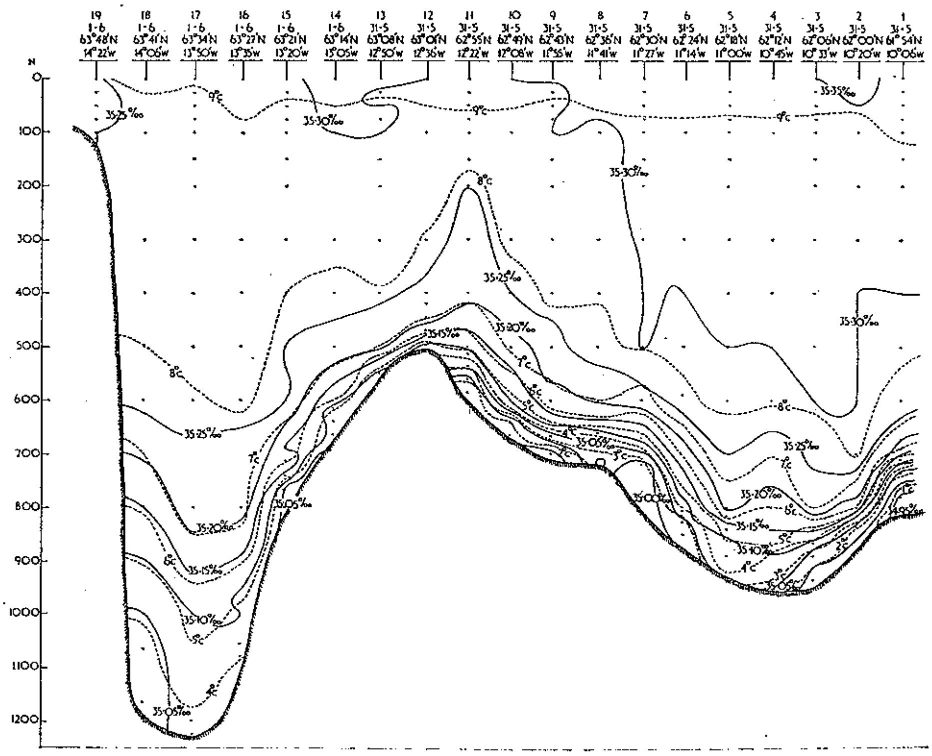
At station G1 and again at G4 can be seen on the bottom the coldest water, between 2° C and 3° C, on section G_1I. This obviously was an extension of the similar bottom water noted on section F_1II, with weak oceanic characteristics. A similar thin layer of cold dilute oceanic water, that is registering under 3° C but not so low as 2° C, which likewise probably had a counterpart on the extreme bottom below 1,300 metres at station F23, was recorded between 1,300 metres and probably about 1,500 metres at station G11.

On the G_1II section, to which for obvious reasons is added station H1 (see Figure 0:1), water of less than 2° C but with weak oceanic salinity appears within the bottom 100-metre layer about stations G27 and G29. Elsewhere on this section the lowest temperature is just under 3° C on the bottom, below 1,550 metres at station G19.

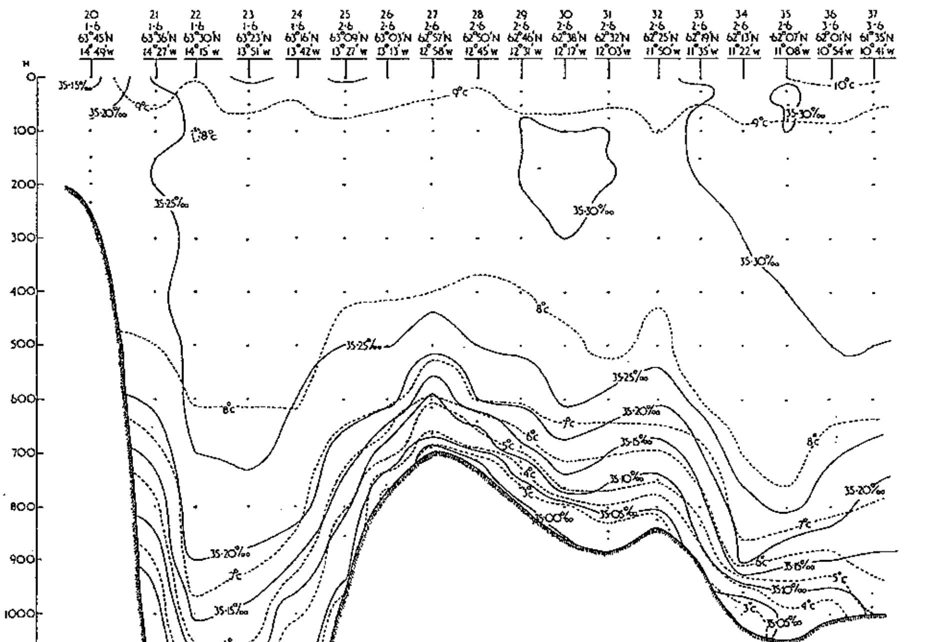
Uppermost water temperatures of just over 10° C occurred on small sections of the surface waters on both sections, the top 50–100 metres of which each register in excess of 9° C, mainly within the core of 35·30 + $^0/_{00}$ salinity water.

The isohaline configuration about station G2 on the G_1I section is strikingly indicative of what would appear to be a powerful upwelling movement, possibly engendered by the nature of the bottom configuration (see Figure 0:1) here.

Figure 3:34.

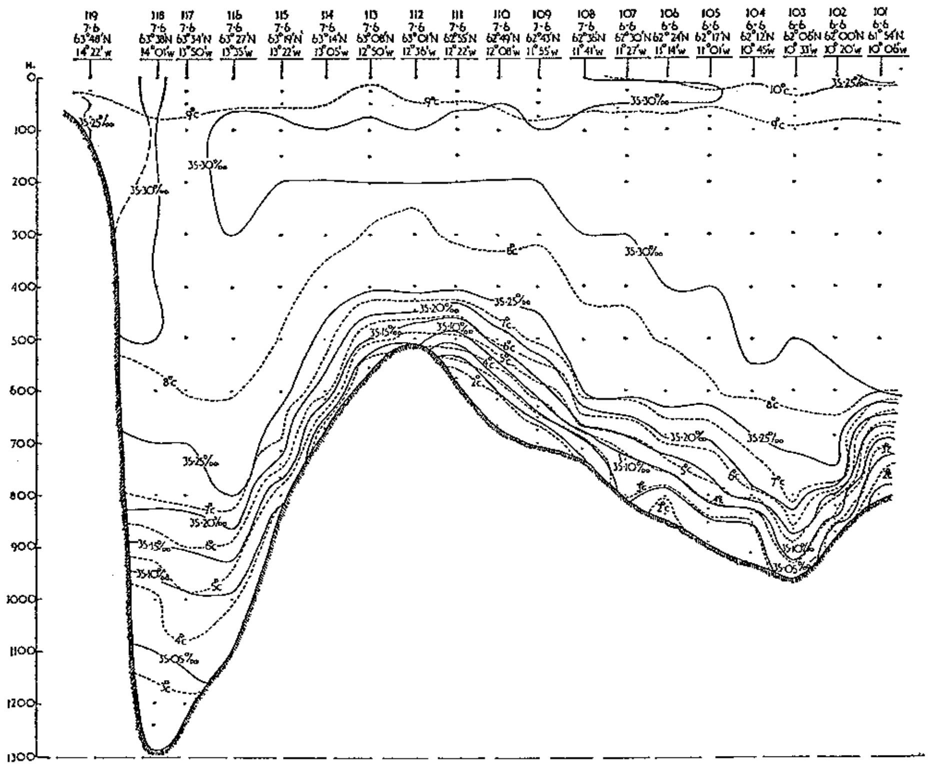


(a) Section F_1I

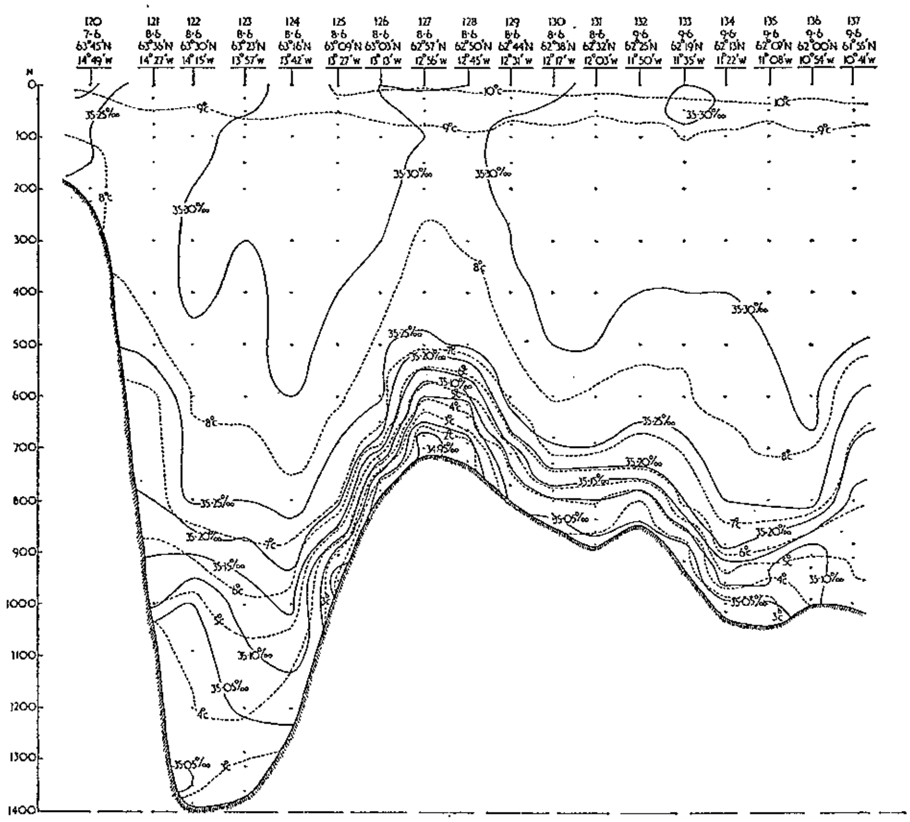


(b) Section F_1II

Figure 3:35.

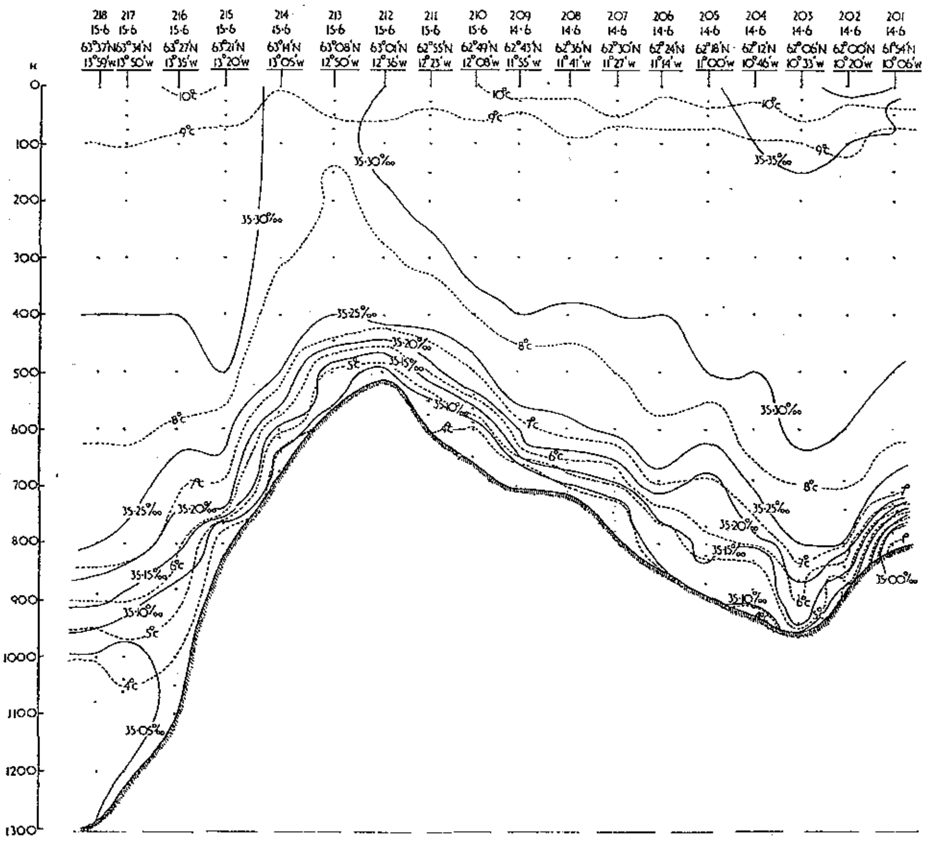


(a) Section F_2I

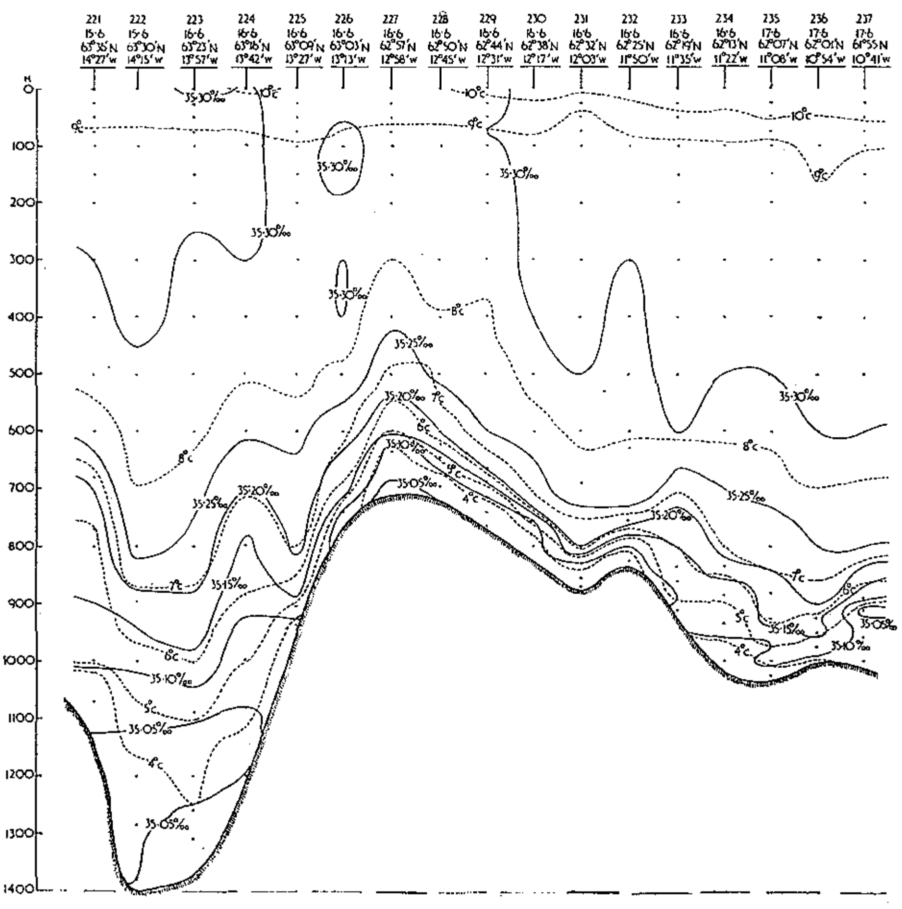


(b) Section F_2II

Figure 3:36.

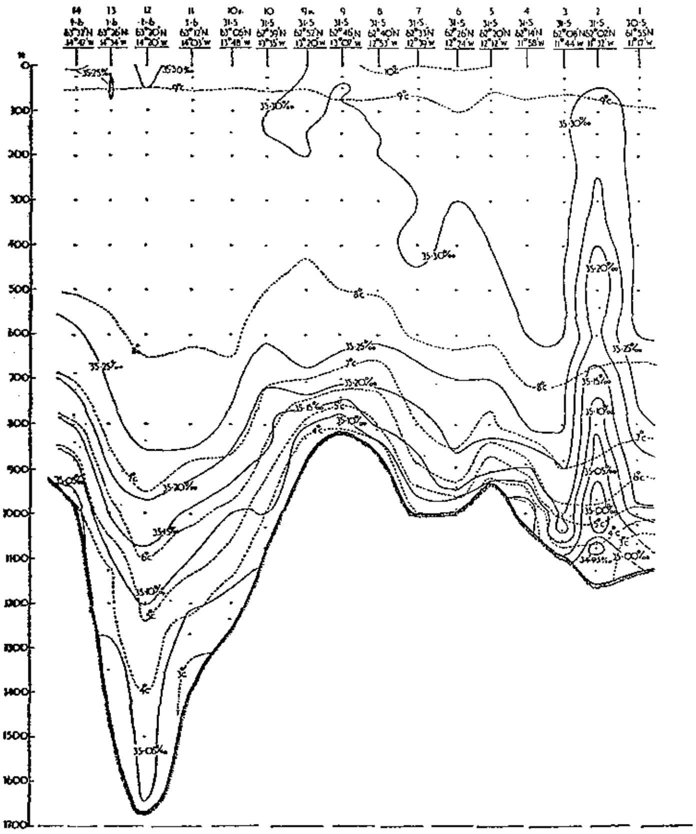


(a) Section F_3I

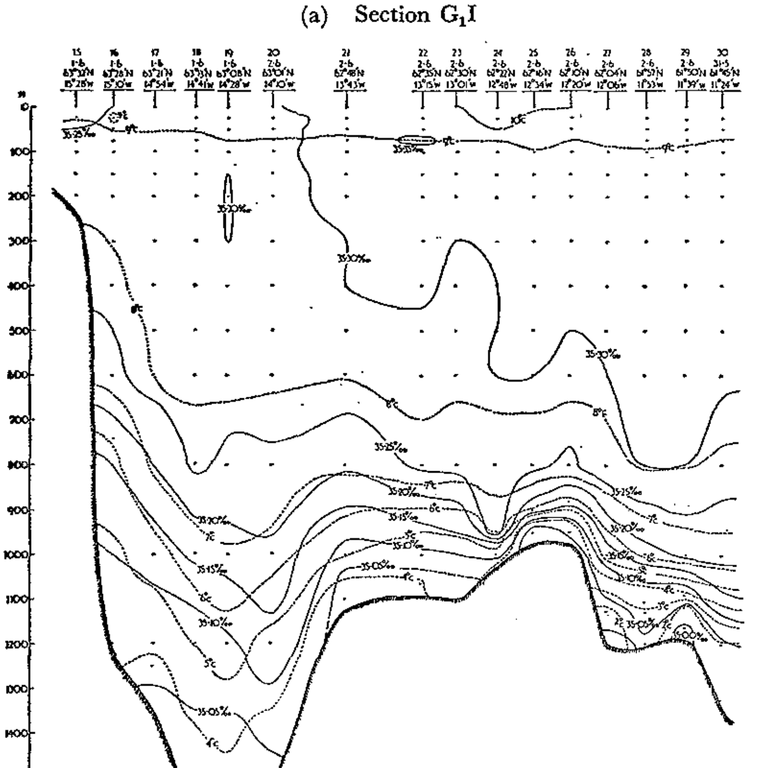


(b) Section F_3II

Figure 3:37.



(a) Section G_1I



(b) Section G_1II

THE SECTIONS BY "DISCOVERY II" (UNITED KINGDOM)

In depths ranging from about 1,000 metres to nearly 2,000 metres, the sections H_1I and H_1II, overtaken by "Discovery II", were planned to sample, from the viewpoint of the Iceland-Faroe Ridge, the least adulterated oceanic water masses approaching the "strategic" region. For reasons which will be obvious by inspecting Figure 0:1 the stations H26 and I11 have been included in the temperature-salinity sectional diagrams H_1I and H_1II, (Figure 3:40).

Almost none but oceanic water-masses pervaded these two sections. By the standards adopted, however, salinities of 34·98 ‰ at 1,500 and 1,650 metres on station H11 suggest the enclosure, probably by turbulence, of a small body of sub-oceanic water in this deepest part of the section H_1I. Its temperature was just under 4° C. A similar indication appears about the depth of 1,100 metres at station H22, the shallowest station on H_1II, but on this section, around a nucleus of minimum salinity 34·94 ‰ at 1,460 metres on H18 (only 15 miles distant from H11 on section H_1II) a much more extensive area of sub-oceanic water involved stations H17 to H21 inclusive between 1,250 and at least 1,900 metres, the water-mass so represented being, in all but a small part of the sea floor around H21, cushioned by oceanic water proper with a salinity in excess of 35·00 ‰, its temperature, like that of the sub-oceanic water immediately above, exceeding 3° C.

It would then appear from the "Discovery II" sections of the first survey that the isohaline of 35·30 ‰, bounding waters of salinity 35·30 ‰ to 35·34 ‰, represented undiluted oceanic water approaching the Iceland-Faroe Ridge from the south to southwest. Within this boundary on section H_1II two small areas occurred representative of water of greater salinity than 35·35 ‰, but these, as will be seen below, would seem to pertain rather to oceanic water-masses heading for the Faroe-Shetland Channel by way of the Faroe Bank Channel.

Apart from a small part of the surface of section H_1I, embracing stations H4 to H6 inclusive, where temperatures slightly in excess of 10° C were recorded the top 50- to 75-metre layer of H_1I, with a maximum thickness of about 140 metres at station H8, registered temperatures of between 9° C and 10° C. The corresponding layer on H_1II was somewhat thicker on the average, at 75 to 100 metres, and contained a 25- to 50-metre surface layer of 10° C to 10·5° C water on the southeastern end of the section from about station H21 through H25 to station I11.

THE SECTIONS BY "EXPLORER" (UNITED KINGDOM)

The special assignment to "Explorer" in the investigation of cold deep water overflow of the Iceland-

Faroe Ridge was the assessment of a similar deep cold water effluent which is believed to escape into the Northeast Atlantic Ocean from the Faroe-Shetland Channel through the Faroe Bank Channel. Hence (Figure 0:1) the disposition of four hydrographic sections along the length of the latter Channel and at right angles to its direction, with two further sections to the north and northwest of the Faroe Bank to discover any extension there might be towards this area of the cold, deep-water, Faroe-Shetland Channel effluent.

In what may, from this standpoint, be considered to be the more logical sequence, therefore, the hydrographic sections of "Explorer" are here dealt with more or less in the reverse order to that in which they were accomplished, except that the two westerly sections beyond the Faroe Bank are the last of the six to be considered.

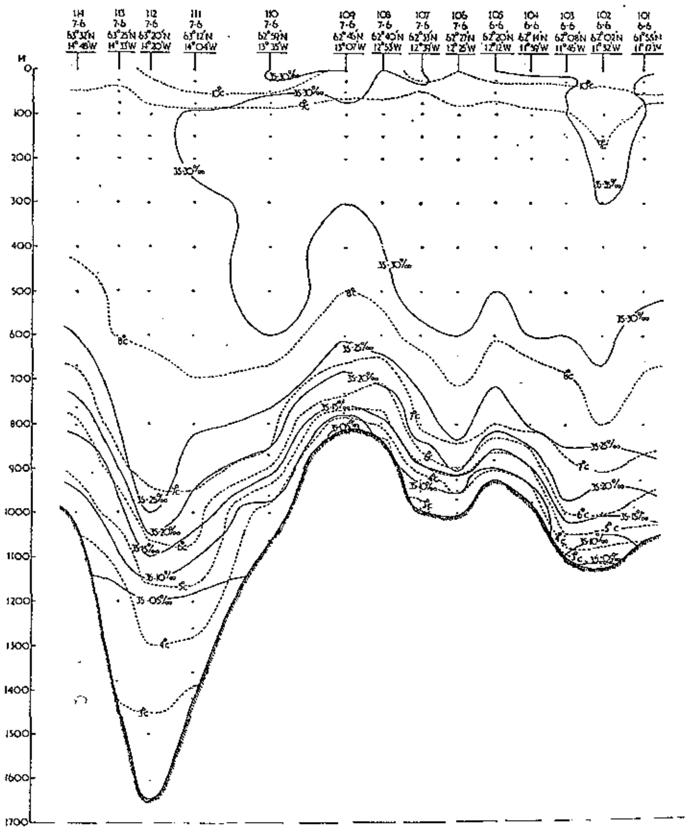
Section I_1I (Figure 3:43(a)), including stations I29 to I37, was laid along the meridian of 7°W between the latitudes of 60°N and 61°N, that is, from a point on the summit and towards the southeastern end of the Wyville Thomson Ridge, northward across the "instep" of the Faroe-Shetland Channel to a position on the Faroe Islands submarine shelf or platform. (See Figure 0:1). The geographical disposition of this section relative to the Faroe-Shetland and Faroe Bank Channels can be appreciated by reference to ROBINSON (1952), or TAIT (1957).

On this section the core of the Atlantic water-mass presumably passing eastward to northeastward through the section, registered a salinity of just over 35·40 ‰ and was a little more than 200 metres deep. Its maximum surface temperature was 10·52° C. The 9° C isotherm which on previous sections was largely confined to the uppermost 50-metres, on section I_1I ranged from about 50 to over 275 metres over almost the entire section, except for the northmost terminal station I37.

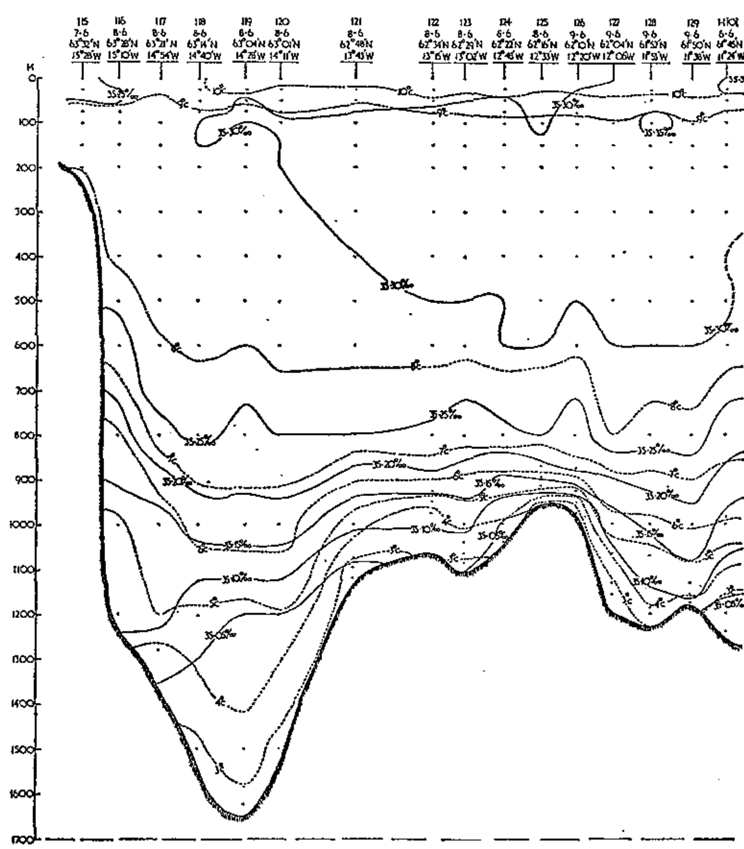
Below 600 metres to 775 metres in the deepest part of the section the entire water body was of deep Norwegian Sea water with salinity of 34·92 ‰–34·94 ‰ and temperature below 1° C to a minimum of −0·74° C. As will be seen from Figure 3:43(a) the 2° C isotherm on I_1I practically coincided with the 35·00 ‰ isohaline. The cross-sectional areas below the 2° C and 0° C isotherms were 25·5 Km^2 and 13·85 Km^2 respectively.

Section I_1II (stations I24–I28 inclusive, Figure 3:43(b)), spanned the narrow Faroe Bank Channel in the immediate approach to its narrowest part from the Faroe-Shetland Channel. The fact that the core of the oceanic water-mass was here completely sub-surface, bounded by the 35·38 ‰ salinity parameter around salinity observations not exceeding 35·38 ‰ suggests that this core, presumably flowing towards

Figure 3:38.

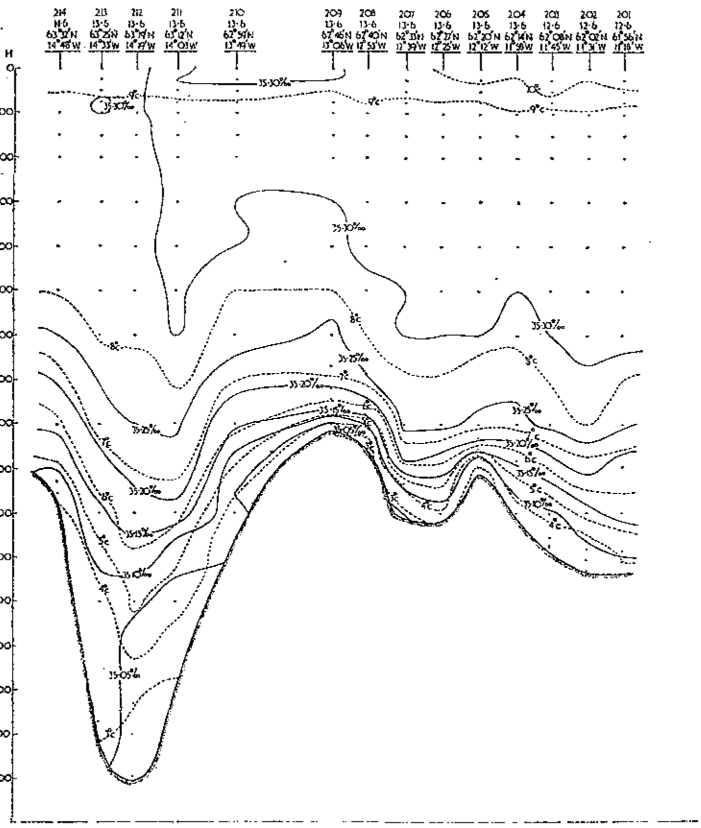


(a) Section G_2I

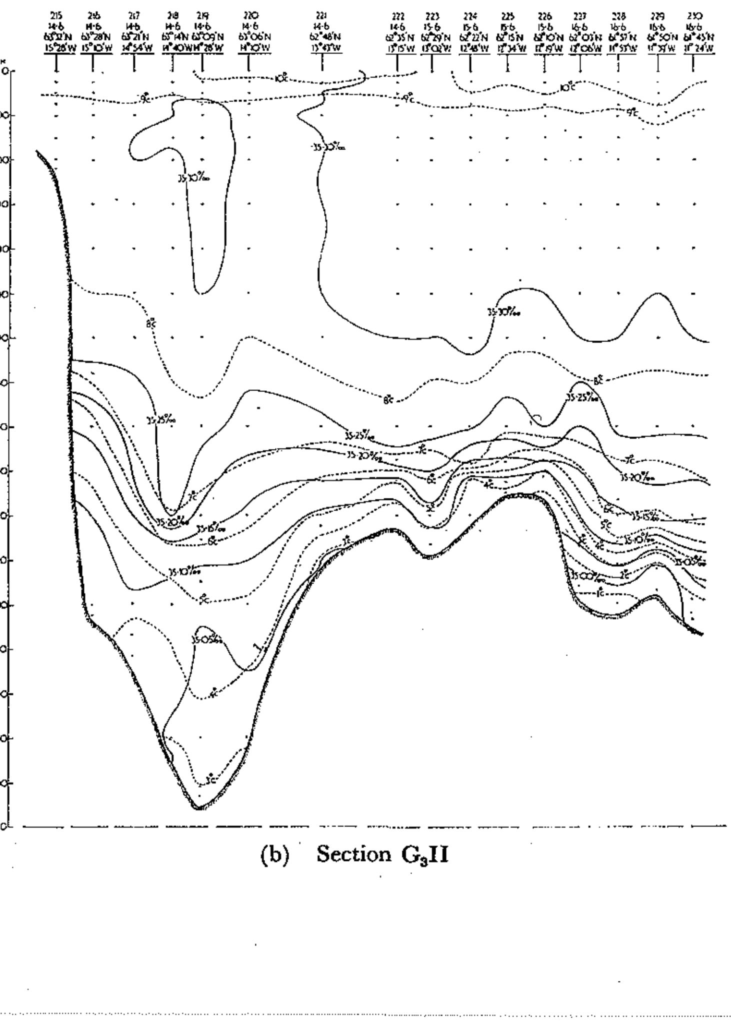


(b) Section G_2II

Figure 3:39.



(a) Section G_3I



(b) Section G_3II

the Faroe-Shetland Channel by way of the *north* of Faroe Bank, was not continuous with the higher salinity core of section I_1I which probably came by way of the *south* of Faroe Bank.

As was anticipated, the oceanic water-mass as defined at its lower limit by the 35·00 ‰ isohaline, superimposed, below about 600 metres, a layer of about 100 metres of sub-oceanic water with a salinity above 34·96 ‰ and temperature between about 0·5° C and 1° C, this layer in turn overlying cold deep Norwegian Sea water of 34·92 ‰–34·94 ‰ salinity and zero to sub-zero temperature to a minimum of −0·48° C.

The cross-sectional areas of the deep waters below 2° C and 0° C respectively on section I_1II (Figure 3:43(b)) were 5·25 Km² and 1·75 Km², approximately one-fifth and one-eighth respectively of the corresponding quantities relative to section I_1I which, however, sounded 1,140 metres at maximum depth as against I_1II's maximum depth of 895 metres. For more appropriate comparison, the areas on section I_1I above the 900 metres level were, at less than 2° C, 17·3 Km², and at less than 0° C, 5·65 Km². Both these measurements are just over three times the corresponding measurements on section I_1II.

Section I_1III (Figure 3:43(c)) again spanned the Faroe Bank Channel between Faroe Bank and the Faroe Islands submarine shelf, this time more nearly at its narrowest part. The same high salinity (> 35·35 ‰) core of the oceanic water-mass characterized I_1III, but in contrast to I_1II the core broke surface on I_1III around station I19 and showed a nucleus of 35·40 ‰ between 50 and 75 metres on this same station. The base of the oceanic water-mass on I_1III again averaged about 600 metres depth, but rose from 625 metres on the southern side of the Channel to 575 metres on its northern side. 5·16 Km² of deep Norwegian Sea water at less than 2° C were registered on the section, 1·84 Km² of this being at sub-zero temperature, quantities which bear very closely on those pertaining to section I_1II.

Farther to the northwestward and still transverse the Faroe Bank Channel almost at its debouchment into the Northeast Atlantic Ocean, section I_1IV, (Figure 3:43(d)) comprising stations I1 to I6 inclusive, yields a final measure of the cold deep water effluent from the Faroe-Shetland Channel region. On this section, as overtaken between 31. May and 1. June, 1960, the base of the oceanic water-mass as defined by the 35·00 ‰ isohaline was steeply inclined from approximately 725 metres on the south side of the Channel to 590 metres on the north side. The 2° C isotherm was similarly inclined between similar depths, while the 0° C parameter lay almost horizontally along the 735-metre level. The water body below 2° C to a maximum depth of 855 metres represented in cross-section an area of about 3·61 Km² of which 2·0 Km² represented water of less than 0° C temperature. Compared with the corresponding measurements in section I_1III, the former figure seems lower than might be expected, especially as the latter measures approximate fairly nearly to each other.

No significant high salinity core appears on section I_1IV, apart from a single 35·36 ‰ observation at 200 metres on station I4 and a small representation of 35·35 ‰ + salinity water between 20 and 50 metres on station I2 and involving I1 from the surface to 75 metres.

A similar sub-surface core of > 35·35 ‰ water appears between stations I7 and I8 on section I_1V (Figure 3:44(a)) running westward from the northwestern boundary of Faroe Bank. This was a deep water section the surface temperatures on which exceeded 10° C. Water of less than 2° C temperature occurred only on the westmost station I10 of the section in depths greater than 1,240 metres, although the salinity of this water scarcely fell below 35·00 ‰, indicating apparently only the utmost southwesterly influence of either cold water overspill of the Iceland-Faroe Ridge, or similar characteristic deep effluent from the Faroe Bank Channel. None of this influence was apparent on section I_1VI (Figure 3:44(b)) laid parallel to I_1V and some 15 nautical miles to the south of it. Even to the greatest depths of this section at over 1,200 metres only oceanic water of salinity about 35·10 ‰ and temperatures of between 5° C and 6° C penetrated. Surface temperatures along the whole of this section were in excess of 10° C, while the core of the oceanic water-mass was represented by a body of water slightly over 35·35 ‰ salinity and breaking surface at stations I13, I15 and I16.

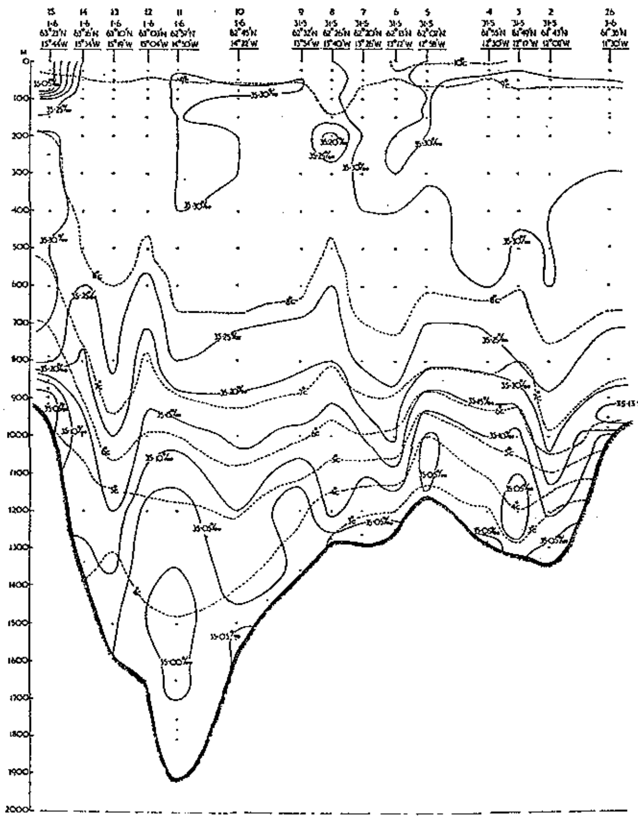
SECOND SURVEY

THE SECTIONS BY "PERSEUS II" (U.S.S.R.)

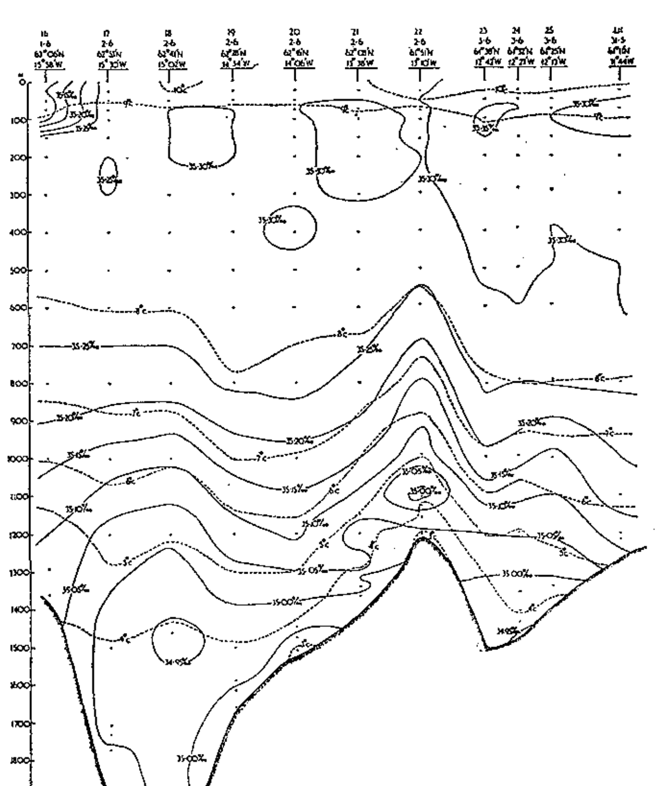
Circumstances allowed of only a part of the course A to be accomplished by "Perseus II" on the second survey, that part comprising stations A101–A111 inclusive. So that, for this survey, the deepest waters to the northeast of the Iceland-Faroe Ridge region were not observed.

Section A_2I (Figure 3:22(b)), including stations A107 to A111, embraces only that part of the corresponding section A_1I of the first survey which represents the departure from the northwestern shoulder of the Ridge northwards down the steeply sloping bottom into the fringe of the very deep area as demarcated by the 1,000 metres bathymetric contour. Never-

Figure 3:40.

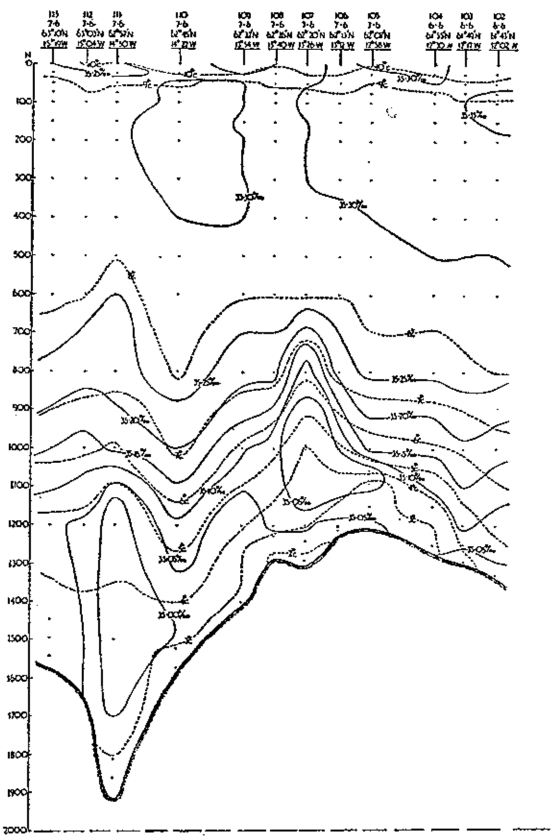


(a) Section H_1I

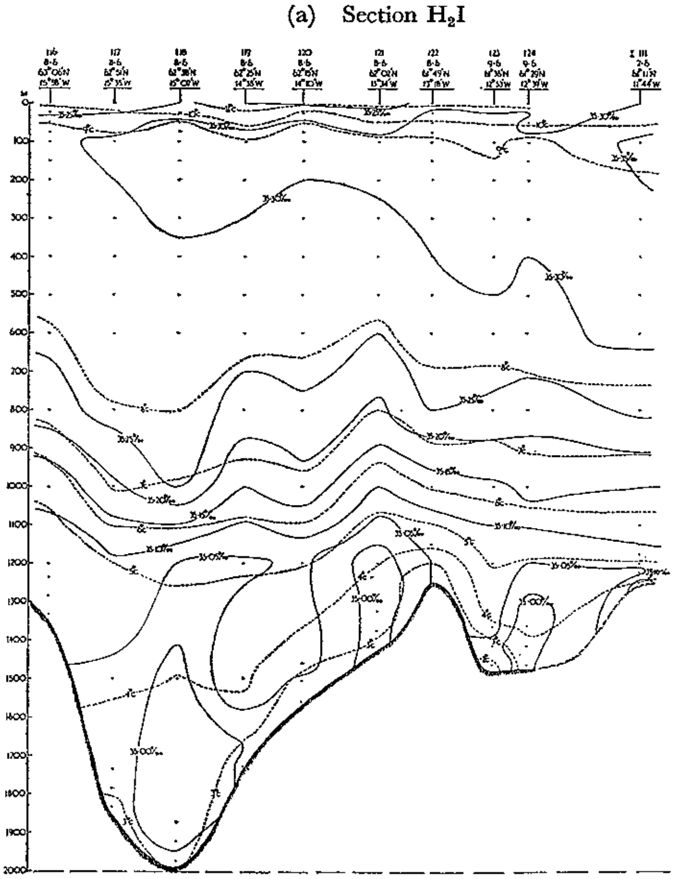


(b) Section H_1II

Figure 3:41.



(a) Section H_2I



(b) Section H_2II

theless, on this small section, sub-zero temperature waters of both Arctic and deep Norwegian Sea characteristics, were observed in depths greater than 270 to 400 metres, corresponding very nearly with conditions as they were on the first survey. And as also in that instance, Arctic type waters, although scarcely of such low salinity as one week earlier, and somewhat farther south than on that occasion, reached almost to the surface at station A109, around a low salinity (34·80 $^0/_{00}$) nucleus at 100 metres, subdividing at this position the uppermost oceanic waters of the section into two parts. Arctic water, however, again appeared on the surface and, from about 70 metres downwards to the deep Norwegian Sea bottom layer at 450 metres, at station A111.

Upper water temperatures were substantially higher on A_2I than was the case one week previously, ranging from considerably over 8° C to under 6° C at the surface. The 2° C isotherm, lying at 75 to about 150 metres on section A_1I, on A_2I was for the most part below 150 metres to over 300 metres, its minimum sounding being only 100 metres at station A111.

There being no section A_2II to correspond with A_1II, we pass directly to section A_2III (Figure 3:24(b)). On this section almost the entire top 50 metres layer registered temperatures in excess of 9° C, to nearly 10° C, that is, on the average about 1° C higher than in the previous week. The layer, however, was of slightly lesser salinity. The core of the oceanic water-mass at > 35·30 $^0/_{00}$ has become entirely a sub-surface phenomenon. The 35·00 $^0/_{00}$ isohaline on the other hand reaches a greater depth by 50 metres in mid-section than it did a week previously, and has had the effect apparently of subdividing the deep Norwegian Sea water mass formerly enveloping the rise in the sea-bed which appears between stations A5 and A2, also A105 and A102, into two distinct parts on either side of this rise, and in doing so the south-eastmost part of this cold bottom mass has displaced the somewhat anomalous cold oceanic bottom water-mass of the previous section between stations A1 and A2.

On the other end of the A_2III section, the same penetration of the deep Norwegian sea water by the intermediate Arctic water-mass as was revealed on section A_1III, reappears between the same depths, but extending farther to the southeast to embrace station A105.

The amounts of cold bottom water above the 500 metres level on section A_2III were represented cross-sectionally by 20·90 Km^2 under 2° C and 6·88 Km^2 under 0° C. It seems doubtful if these quantities differ at all significantly from the corresponding measures of 23·56 Km^2 and 4·96 Km^2 respectively pertaining to the section A_1III.

THE SECTIONS BY "JOHAN HJORT" (NORWAY)

In contrast to sections B_1I and B_1II of the first survey, whereon oceanic core salinities greater than $35{\cdot}30\,^0/_{00}$ were found on the latter, but practically not at all on the former, on the second survey it is the northern section B_2I (Figure 3:25(b)) which presents similar core salinities and B_2II (Figure 3:26(b)) from which they are almost absent. As on the Russian sections, uppermost water temperatures increased somewhat, to over 10° C in parts, in the week's interval between the first and second surveys.

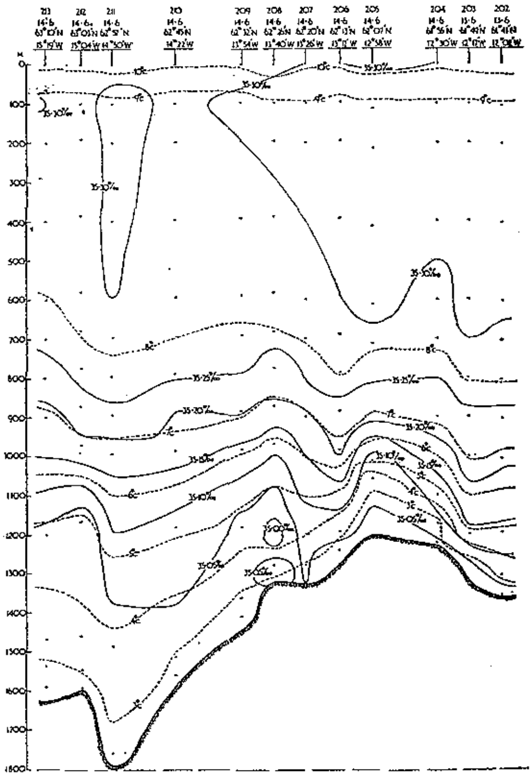
Cold bottom waters above the summit level of the Iceland-Faroe Ridge on section B_2I amounted in cross-section to 4·54 Km² at less than 0° C and 20·82 Km² below 2° C. While this representative quantity of sub-zero temperature water on section B_2I above Ridge level would appear to have been slightly greater than it was on B_1I (and the inference is supported by the occurrence on B_2I of a small body of water below −0·5° C), the bulk of <2° C water was evidently appreciably less on B_2I than it was a week previously. Very similar figures at 4·26 Km² for sub-zero temperature water and 19·69 Km² for <2° C water pertain to the section B_2II, both figures slightly less than the corresponding measurements on B_2I, but significantly greater, it would appear, than the corresponding values (1·32 and 12·6 respectively) for B_1II.

The cold bottom waters less than 2° C on both sections of the second survey comprised almost entirely intermediate Arctic water with salinity $34{\cdot}85\,^0/_{00}$ to $34{\cdot}89\,^0/_{00}$, with only a slight intrusion under the 2° C parameter of deep Norwegian Sea $34{\cdot}92\,^0/_{00}$ salinity water towards the southeastern ends of the sections. At the southeastern extremities, on the other hand, the water bodies registering less than 2° C in temperature occurred only below the 500-metre level and apparently comprised only deep Norwegian Sea water. These conditions then differ somewhat from those obtaining in the previous week when the 2° C and especially the 0° C parameter enclosed greater proportions of the deep Norwegian Sea water-mass as distinct from the Arctic type, although this was also present in appreciable quantity.

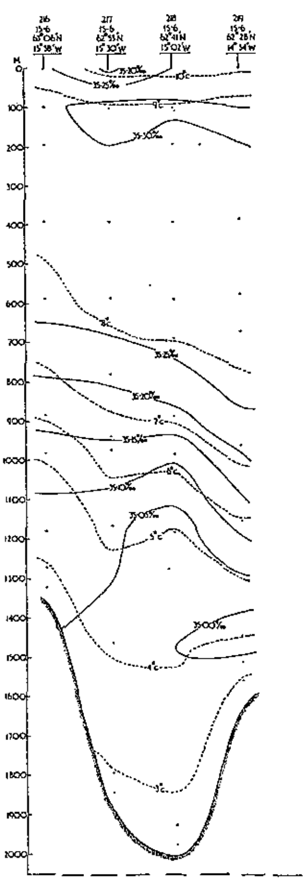
THE SECTIONS BY "GAUSS"
(FEDERAL REPUBLIC OF GERMANY)

The two "Gauss" sections, C_2I and C_2II of the second survey indicate, by their temperature and salinity distributions, less turbulence on the whole than in the previous week. Greater high salinity ($>35{\cdot}30\,^0/_{00}$) water-masses reaching to greater depths, are evident on Figures 3:27(b) and 3:28(b) as compared with 3:27(a) and 3:28(a), and maximum surface

Figure 3:42.

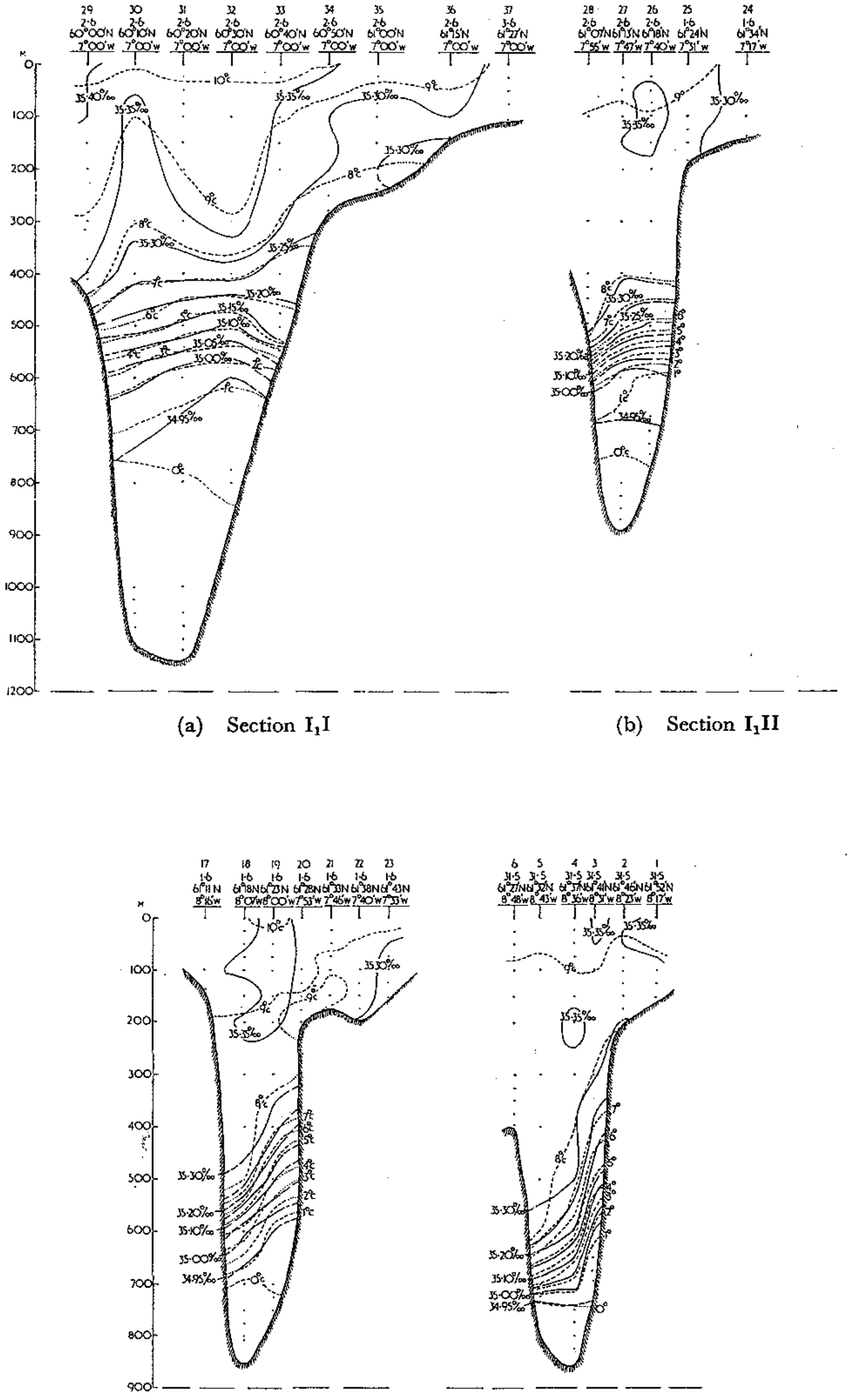


(a) Section H_3I



(b) Section H_3II

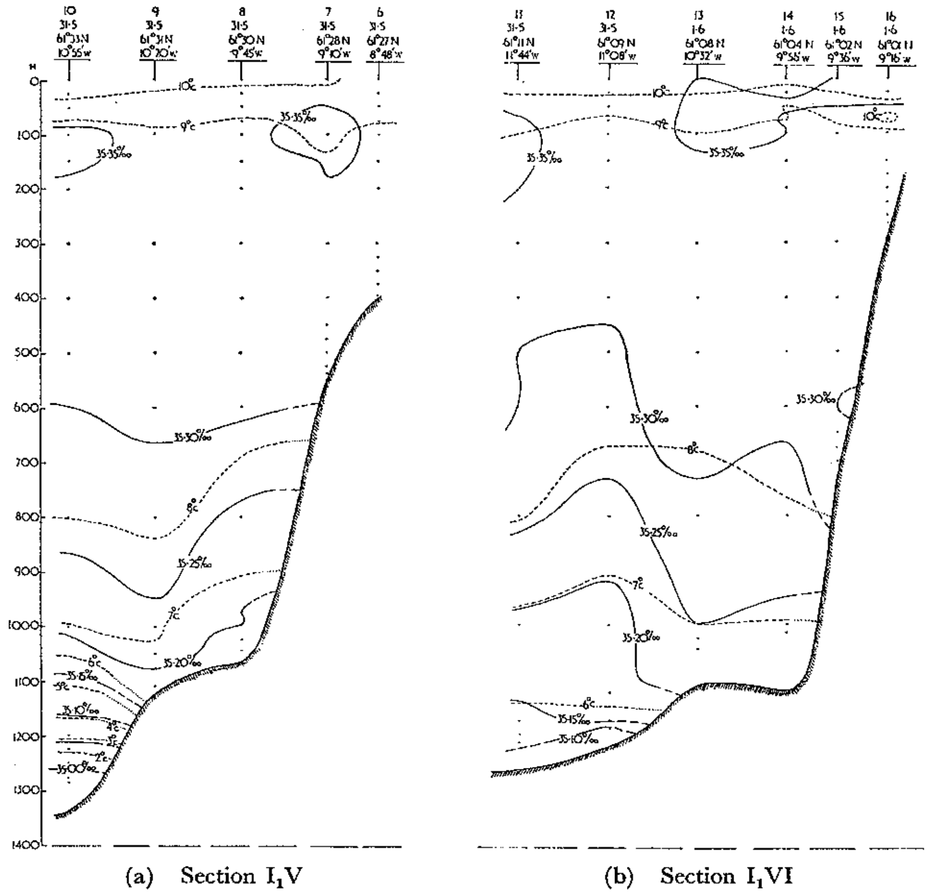
Figure 3:43.



(a) Section I_1I (b) Section I_1II

(c) Section I_1III (d) Section I_1IV

Figure 3:44.



(a) Section I_1V (b) Section I_1VI

temperatures to nearly 10·5° C were registered in the second week.

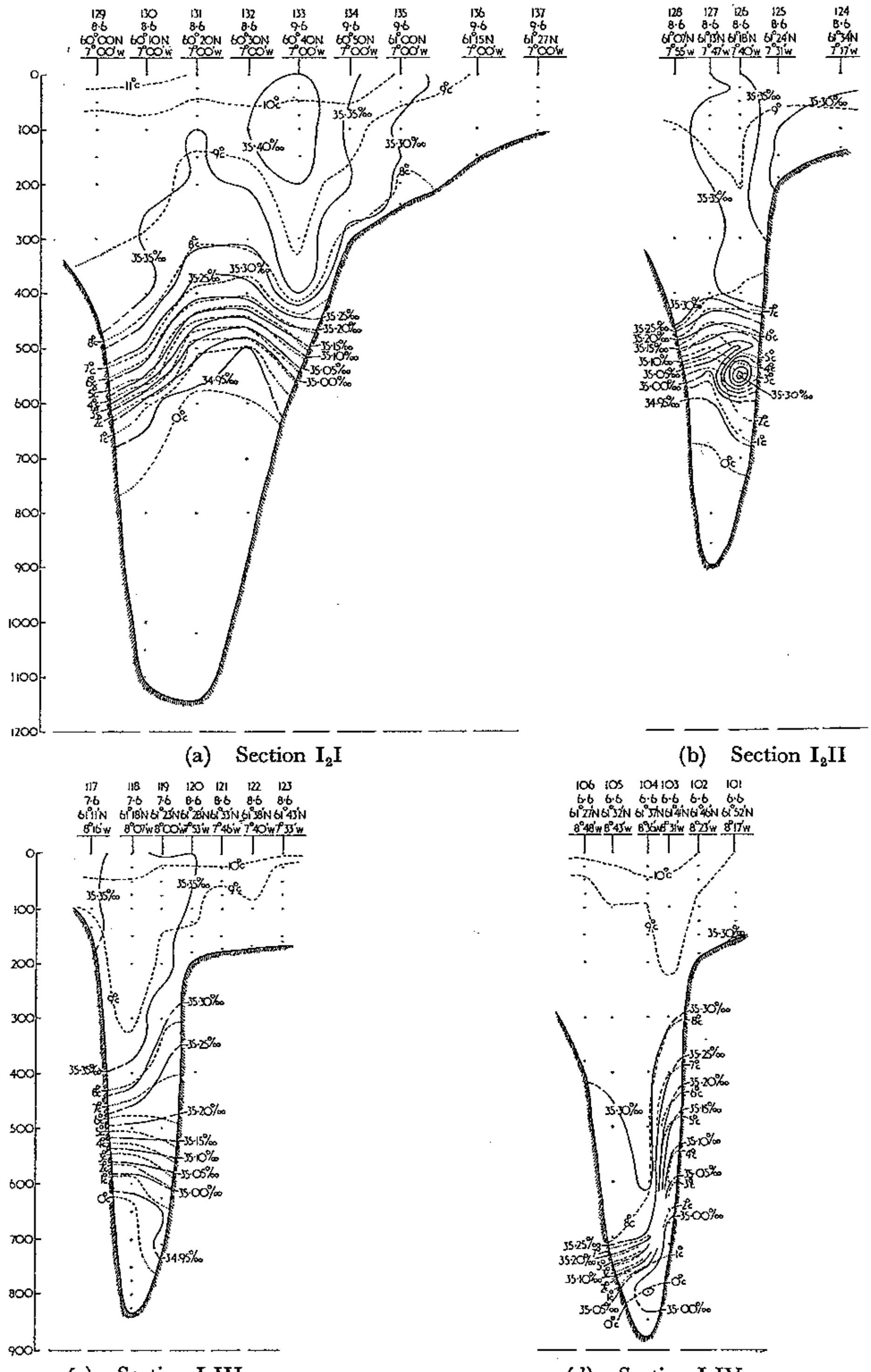
The areal measures of cold bottom water on the second survey sections show an understandable diminution in the representative amounts of sub-zero temperature waters as compared with the first survey. 1·45 Km² of this water is represented on section C_2I as compared with 1·73 Km² on section C_1I, while C_2II contains no such water-mass against the very low areal measure of 0·35 Km² on section C_1II. Within the 2° C isotherm, however, C_2I at 12·96 Km² shows an increase of nearly 3 Km² over the corresponding figure for C_1I. 3·58 Km² of less than 2° C bottom water on C_2II, however, is little more than half the quantity indicated on the same section one week before; so that, the interpretation of the three bottom temperature distribution figures 6, 13, and 20, to the effect that the cold deep water overflow was a receding phenomenon in course of the three weeks of the entire survey is so far borne out by these latter measures. Practically all of this cold bottom water on the second "Gauss" survey, as on the first, was of the deep Norwegian Sea type, except again at station C132, in the same position as station C32, where salinity characteristics of sub-oceanic water were recorded.

THE SECTIONS BY "ERNEST HOLT" (UNITED KINGDOM)

Maximum surface temperatures of over 10° C, as on the "Gauss" sections, differentiate the "Ernest Holt" sections D_2I (Figure 3:29(b)) and D_2II (Figure 3:30(b)) from D_1I (Figure 3:29(a)) and D_1II (Figure 3:30(a)). The 8° C isotherm on the other hand is in very similar positions on all four sections, with, on the whole, corresponding undulations between roughly the same depths. There would almost appear to be less of the high core salinity ($>35{\cdot}30\,^0/_{00}$) oceanic water-mass on the second survey sections than on the first, but in representative areal measures they probably work out very similarly. The same, however, cannot be said of the coldest bottom waters.

As in the previous week, no sub-zero temperature waters occurred on the D_2 sections, but the obvious areal contractions in waters of less than 2° C on the second survey are given point by the following measures. For comparison the corresponding quantities for the D_1 sections are cited: –

Figure 3:45.



(a) Section I_2I

(b) Section I_2II

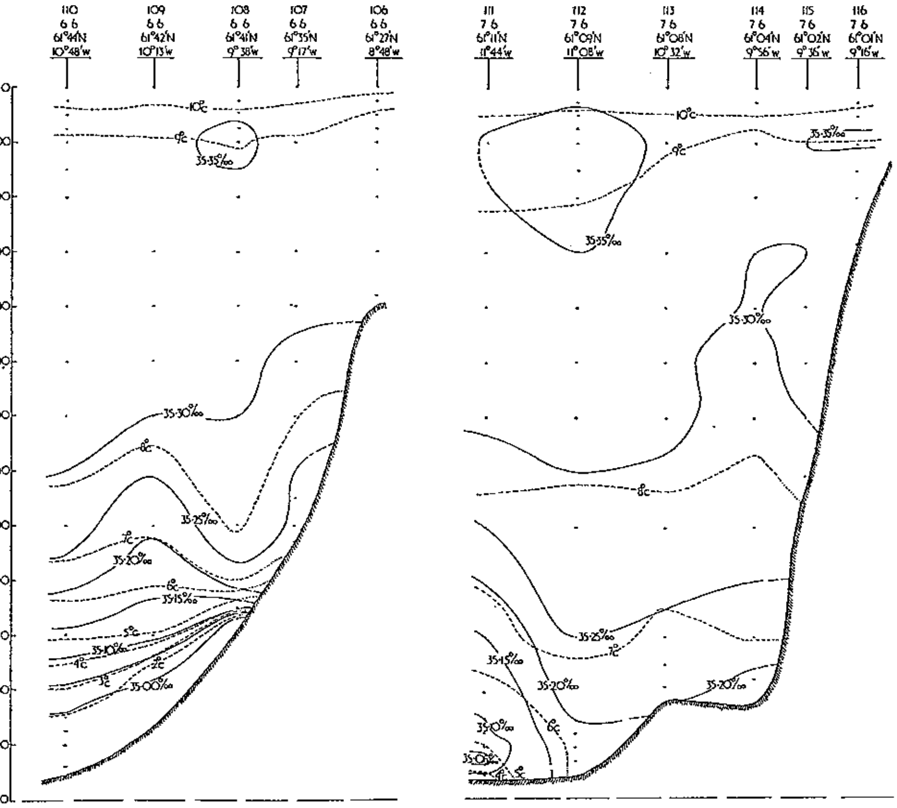
(c) Section I_2III

(d) Section I_2IV

Section	Cross-sectional areas of water < 2° C above 500 m Km²	below 500 m Km²
D_1I	7·60	0·41
D_1II	5·42	0·88
D_2I	1·57	0·06
D_2II	2·27	0·69

To begin with, let us compare the D_2 figures with the C_2 measurements. A total cold (<2° C) bottom water-mass cross-sectionally represented by 1·63 Km² on D_2I almost entirely on top of the Ridge compares with the similar indices of 3·58 Km² on C_2II almost wholly on the Ridge summit, and 10·96 Km² on C_2I

Figure 3:46.



(a) Section I_2V (b) Section I_2VI

which was more nearly associated with the Ridge's northeastern shoulder. The figures therefore are in understandable conformity; likewise, in fact, the figure of 2·96 Km^2 in respect of section D_2II in comparison with the C_2 sections. On the other hand, the greater figure for the D_2II section relative to that for the more northerly D_2I section seems anomalous at first sight until the composition of the figure is examined. That for section D_2II comprises four parts, as can be seen from Figure 3:30(b), two of which were below the 500 metres level. These, together, represent a cross-sectional area of 0·69 Km^2 approximately which reduces the representative quantity of this cold mass on top of the Ridge on section D_2II more nearly to that on D_2I, although still somewhat in excess of it which may to some extent be due to inaccuracies in the observations themselves or in the draughtmanship of the sections based on them.

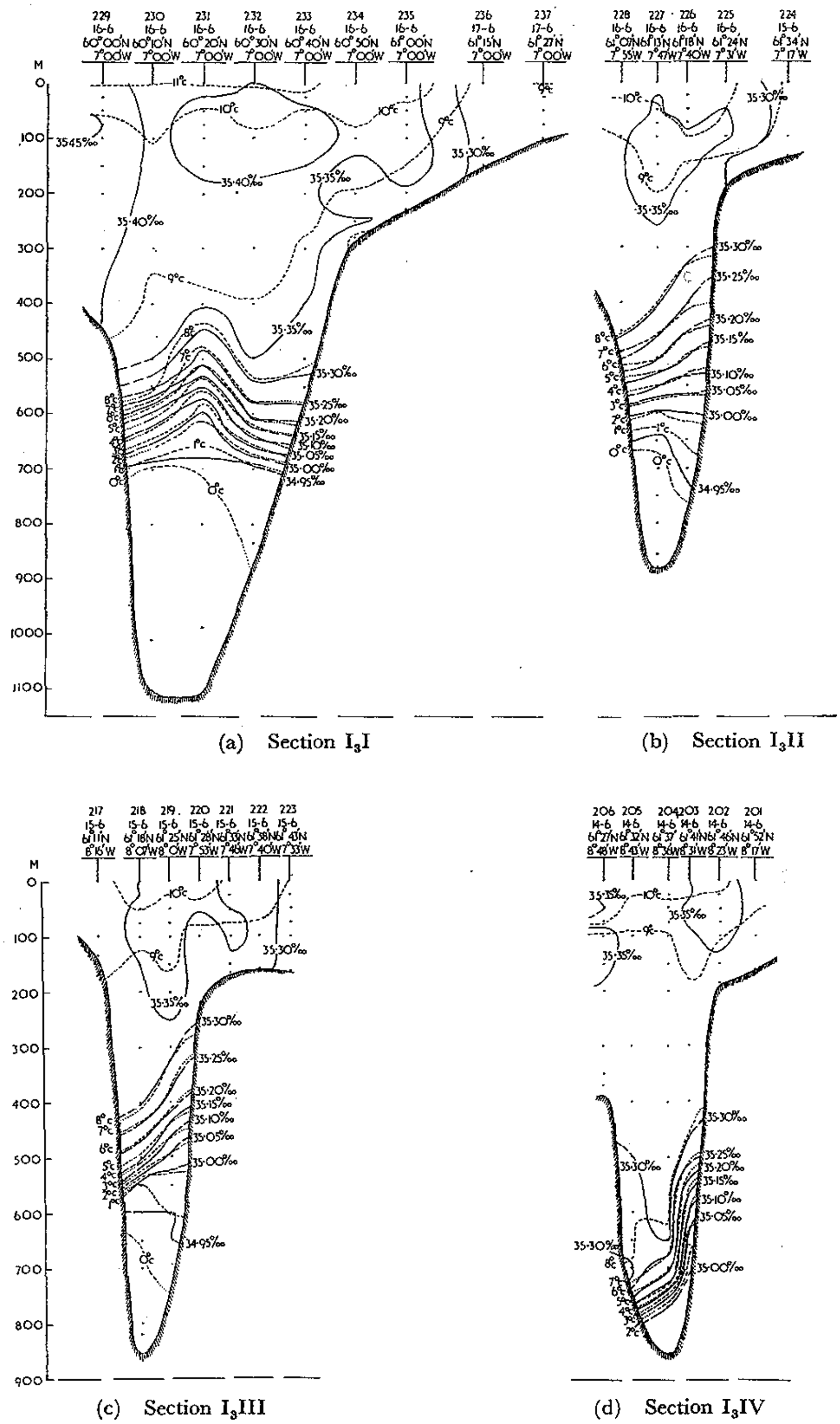
A further note about one of the two parts of the deepest cold water on the D_2II sections is that this occurred (station D122) towards the northwestern end of the section on the immediate slope of the Ridge adjacent, from which, by the evidence to follow from the more northerly of the two succeeding "María Júlía" sections, it seems to have overspilled, becoming detached from the similar water body on the Ridge summit. It is to be observed that this is the only evidence of overspill in this particular region that accrues from the survey as a whole.

THE SECTIONS BY "MARÍA JÚLÍA" (ICELAND)

As regards temperature and salinity distributions, the second survey sections by "María Júlía" (Figures 3:31(b) and 3:32(b)) are in their main features more or less closely similar to those of the first survey. There is, however, a slight indication, particularly on the more northerly of the two sections, of higher core nuclear salinity (35·36 $^0/_{00}$–35·38 $^0/_{00}$) in the oceanic water-mass on the second survey, suggestive perhaps of a stronger, oceanic influence than in the previous week, and as in the sections of the second survey already considered, maximum surface temperatures have also on the "María Júlía" sections risen to over 10° C, to over 11° C at one station (E140) on the southern section.

Considering the question of the cold deep bottom water, however, and its overflow of the Ridge, there are certain differences as between the corresponding sections of the two surveys which are worth noting. As to be expected after the "Ernest Holt" sections, of course, sub-zero temperature water did not appear on either of the "María Júlía" second survey sections.

Figure 3:47.



(a) Section I_3I (b) Section I_3II

(c) Section I_3III (d) Section I_3IV

Less than 2° C bottom water, however, apart from being, in the aggregate over the two sections as cross-sectionally represented, almost exactly the same on both surveys at 7·6 and 7·5 Km^2 respectively, was differently disposed in the second week. Roughly equally divided between the two sections of the first survey, practically 90 per cent of the total areal assessment of the second survey belonged to the more northerly section; and whereas, on the first survey, a substantial amount of this cold bottom water-mass, especially on the southern section, could reasonably be accredited to effluent from the Faroe-Shetland Channel through the Faroe Bank Channel, no direct evidence of this particular effluent, as a part of the deep northern water influence, was apparent on either of the second survey sections.

Again on the northern section, on the first survey, the bottom water of less than 2° C in temperature lay on the Ridge summit at stations E15 and E16, and also from between the summit stations E12 and E13 southeastward over the shoulder of the Ridge at station E11, down to over 650 metres between stations E6 and E7. On the same section of the second survey this <2° C bottom water-mass was found to have extended northwestwards beyond station E117 and indeed over the north*western* shoulder of the Ridge at station E118, to about 600 metres. The other part of the same cold water-mass seems also to have shifted northwestward in the second week to between stations E113 and E114, but at the other end faded out, as it were, just over the southeastern shoulder in just under 600 metres at station E110.

In the above circumstances it is perhaps curious that none of the < 2° C water was found off the shoulder of the Ridge at about stations E125, E126 or E127 on the second survey, but the small amount of this mass which was found on the southern section of the second survey was located on the bottom at stations E130 and E131 in a bay in the Ridge shoulder which was occupied by these two stations. Its salinity characteristic (34·96 ‰) was of sub-oceanic water, whereas on the northern section as also in the previous week, deep Norwegian Sea salinity characteristics were observed in addition to and alongside those of sub-oceanic water.

The relevant table for the "María Júlía" second survey sections to set alongside the corresponding table for the first survey is as follows: –

Section	Cross-sectional areas of < 2° C water above 500 m	below 500 m overspill	below 500 m effluent
	km^2	km^2	km^2
E_2I	5·56	1·18	0
E_2II	0·49	0·26	0

THE SECTIONS BY "HELLAND-HANSEN" (NORWAY)

According to Figure 0:1 and the pre-determined positions given for them, stations F11 and F12, likewise F111 and F112, were deemed to be situated on top of the Iceland-Faroe Ridge in less than 500 metres. In actual fact this did not turn out to be the case, although station F12 (also F112)) was probably on the Ridge shoulder. F11 however (and F111) was some 100 metres down the Ridge slope and, on both surveys, just sampled in the bottom 30–35 metres the northwestern limit of the coldest (<2° C) overspill water found on this section. On section F_2I (Figure 3:35(a)) the areal measure of this water, this time in three distinct parts, two of them very small, was 2·28 Km^2. It seems probable that the small measures of 0·24 Km^2 and 0·10 Km^2 registered around the bottom at stations F106 and F101 respectively, particularly the latter, represented bottom effluent water from the Faroe Bank Channel. This water, by its salinity was sub-oceanic rather than deep Norwegian Sea in origin.

Maximum surface temperatures on F_2I were again over 10° C on this second survey, within a top layer of over 9° C water, some 50 to 75 metres thick. The core of the oceanic water-mass (>35·30 ‰ salinity) was more extensive cross-sectionally over the section F_2I than on F_1I.

On F_2II (Figure 3:35(b)) there was a thin bottom layer, except at the shallowest stations F127 and F128 where it was approximately 50 metres thick, of cold bottom water of less than 2° C and this descended at station F125 to 950 metres on the western slope of the southerly projection, on about longitude 13°W, from the southern shoulder of the Ridge. The area of this cold thin bottom layer on the section was 1·56 Km^2. No correspondingly cold bottom water appeared at all, it may be recalled on section F_1II.

THE SECTIONS BY "ANTON DOHRN" (FEDERAL REPUBLIC OF GERMANY)

Maximum surface temperatures of over 10°C observed on the more northerly sections of the second survey, and registered also in small part on both first survey sections by "Anton Dohrn", were substantially reinforced and more widely extended over both the second survey sections (Figure 3:38) by this ship. The same applies to the greater extent, although not to greater depths reached, of the high core salinity of the oceanic water-mass on the second survey sections with the added feature, especially as regards G_2I, (Figure 3:38(a)) of an apparently substantial nucleus of >35·35 ‰ salinity water. Bottom water-masses on the second survey nowhere registered minimum temperatures of less than 2°C as on the first survey.

Moreover, in the second week the bottom waters showed rather more marked oceanic salinity ($>35{\cdot}00\,^0/_{00}$) as distinct from sub-oceanic characters.

Except by the occurrence of these bottom waters of less than 3° C, which, as before explained, may reflect the southwestmost extension of overspill or effluent influences, no other evidence of overspill waters was revealed by the second "Anton Dohrn" survey, and from the fact that minimum bottom temperatures were higher in the second week derives the inference of a lesser overspill as compared with the first week.

THE SECTIONS BY "DISCOVERY II" (UNITED KINGDOM)

Considerations of time made it necessary for "Discovery II", on the second survey, to curtail its course and, by agreement, stations H114 and H115 were omitted at the northwest end of the northern section H_2I (Figure 3:41(a)), and stations H125 and H126 from the southeastern end of H_2II, (Figure 3:41(b)).

The common feature on the second survey of higher surface water temperatures, to over 10° C, by all ships, and the extension of these along practically the entire lengths of the second survey sections, embraced also the sections H_2I and H_2II. Indeed, on the latter, more than half the length of the section was marked by surface temperatures in excess of 11° C.

Around nuclei of $>35{\cdot}35\,^0/_{00}$ salinity water between 75 and 175–200 metres on the southeastern ends of sections H_2I and H_2II, the parameter of $35{\cdot}30\,^0/_{00}$ defined the core waters of the oceanic mass. This parameter was in two substantial parts on H_2I, as on H_1II on which the same high salinity nucleus appeared in one of them in approximately the same position as on H_2II and H_2I.

On the bottom, in contradistinction to H_1I where the minimum temperatures registered were between 2° C and 3° C, the temperature observed at 1,290 metres depth at station H107 was 1·84° C, and similarly on H_2II where only minimum temperatures in excess of 2° C were observed, the bottom temperature in 1,465 metres on station H123 was 1·91° C. In both cases the salinity characteristic of the water concerned was oceanic, namely $35{\cdot}01\,^0/_{00}$. Again, as on the first survey, and probably related to the marked undulations in the sea floor over the region traversed, the dispositions of both isotherms and isohalines below about 600 metres on both sections, suggest a considerable degree of turbulence in these deep oceanic waters.

THE SECTIONS BY "EXPLORER" (UNITED KINGDOM)

With a small displacement northward along section I_2I as compared with section I_1I, the main oceanic core of this section remained as in the previous week, that is, defined by the $35{\cdot}40\,^0/_{00}$ parameter and extending to a depth of 200 metres, (see Figure 3:45(a)). There is also the same indication of its subdivision as between the main part and another, only just taking in the southmost station of the section. Maximum surface temperature, however, had increased to over 11° C along the southern half of the section.

The $35{\cdot}00\,^0/_{00}$ isohaline and the 2° C isotherm, roughly defining the base of the oceanic water-mass, stand higher on the section I_2I than a week before, namely between the depths of 480 and 620 metres as against 570 to 645 metres in the previous week. In conjunction with the fact of the 0° C isotherm also higher in the second week's section I_2I, a greater mass of deep Norwegian Sea water in the second week is the obvious inference, and perhaps the expectation therefore, of a greater effluent of this water through the Faroe Bank Channel.

Deep Norwegian Sea water in fact occupied the entire section below 500–715 metres on section I_2I which compares with the upper limiting depths of 600 to 775 metres on I_1I. The minimum temperature of this cold bottom water-mass in the second week was −0·76° C, and the cross-sectional areas below 2° C and 0° C respectively were 30·21 Km² and 22·57 Km². Of these areas the parts above the 900 metres level, for relation to the bottom water masses of section I_2II below, were 22·41 Km² and 14·77 Km² respectively.

The I_2II section (Figure 3:45(b)) presents the unusual but not altogether unknown feature (TAIT, 1957, Figure 10) of a high salinity ($35{\cdot}33\,^0/_{00}$) nucleus within 50 metres of the base of the oceanic water-mass, namely at 550 metres depth on station I126. The oceanic mass on this section presents another unusual feature in the elongated core of $35{\cdot}35\,^0/_{00}$ to $35{\cdot}40\,^0/_{00}$ salinity extending in mid-section from the surface to over 400 metres.

The head of cold bottom water of the Norwegian deep sea type on this section, proceeding towards the outlet of the Faroe Bank Channel into the Northeastern Atlantic Ocean, is signified by the cross-sectional measures of 4·81 Km² under 2° C of which 2·24 Km² is under 0° C, the minimum temperature of the section being −0·48° C as it was on section I_1II (Figure 3:43(b)). These areal measures compare with nearly five and over six times the respective measures above the 900 metres level on section I_2I, and relate inversely to the corresponding measures in section I_1II, in that the head of $<2°$ C water was smaller in the second week, the proportion of sub-zero temperature water however being greater.

Again with a minimum temperature of −0·46° C in 825 metres at station I 118, the respective heads of $<2°$ C and $<0°$ C deep water on section I_2III (Figure 3:45(c)) were 4·08 and 2·06 Km² respectively, slightly less than those on I_2II. The former was a little smaller than the corresponding measure on I_1III but the latter slightly higher.

The oceanic core was of similar characteristics on I_2III as on I_1III, i.e. over 35·35 ‰ to 35·40 ‰ but of greater cross-sectional area, and reaching to a much greater depth, thus directing presumably a greater mass transport of oceanic water through the Faroe Bank Channel in the opposite direction to the cold deep water effluent therefrom, and consequently probably restricting this effluent despite the very much larger head of the cold deep water in the southmost part of the Faroe-Shetland Channel in the second week of the survey.

Cold deep water effluent through section I_2IV (Figure 3:45(d)) showed a substantial curtailment from I_2III. As against 4·08 Km^2 of $< 2°C$ water on I_2III, section I_2IV carried only 2 Km^2 of which 0·9 Km^2 represented water of less than 0° C, less than half that on section I_2III. The corresponding figures on section I_1IV were 3·61 Km^2 at $< 2°C$ and 2 Km^2 at $< 0°C$, so that the effluent through this section was apparently considerably less in the second week than in the first. Associated with this apparently marked decline in the effluent of cold deep water through the Faroe Bank Channel in the second week of the survey, and perhaps to some extent indirectly in explanation of it, is the observation of sub-zero temperature oceanic water (salinity 35·02 ‰) at 850 metres depth, that is, within about 30 metres of the bottom, at station I 104, the deepest station of the section I_2IV. It may here be recalled that a not insignificant number of such apparently anomalous oceanic salinity observations occurred throughout the examination of trans-Faroe-Shetland Channel hydrographic sections between 1927 and 1952 (Tait, 1957, Figure 10). There is no apparent practical or experimental reason to doubt the salinity determination in the present instance and, moreover, a study of the pressure distribution as well as those of the temperature and salinity across this deep and narrow channel at the time in question suggests not merely the possibility but the likelihood of circumstances highly propitious towards the cascading down the steep slope of the Faroe Islands submarine shelf in this region, of a body of rapidly cooled (by conduction) oceanic water which has not had time to lose (by diffusion) very much, if any of its original salinity.

Turning to section I_2V (Figure 3:46(a)) it may be observed that the position of the stations on this section, stations I107 to I110 inclusive, differ considerably from those of the corresponding stations on I_1V. The whole section IV, after the results of the first survey, was moved some miles to the northward with the object of "trapping" more of the cold bottom water effluent from the Faroe Bank Channel than was found on section I_1V where it was all but missed altogether except for the deepest observations, from 1,250 metres downwards, at the terminal station I10 of the section. As will be seen from Figure 3:46(a), the second survey to the northwest of Faroe Bank sampled the cold (less than 2° C) bottom water from the Faroe Bank Channel from about 975 metres downwards to over 1,250 metres, at stations I108, I109 and I110, although it is to be noted that this cold water had the salinity characteristics of sub-oceanic water.

Except that, as in the previous week, a small core of the oceanic water-mass on this section was defined between approximately 50 and 150 metres depth by the 35·35 ‰ isohaline, and that the 35·30 ‰ isohaline lay somewhat deeper on the whole on I_2V than on I_1V, other features of the section seem less noteworthy and can readily be read from Figure I_2V.

The last section of "Explorer" survey, section I_2VI (Figure 3:46(b)) was over the same ground as section I_1VI and revealed on the whole similar characteristics of temperature and salinity distribution with corresponding equilines tending to lie deeper in the second week. The core of the oceanic water-mass for instance, as defined by the 35·35 ‰ parameter was entirely a subsurface phenomenon in the second survey, not breaking surface anywhere on the I_2VI section. At the same time the 10° C surface layer was approximately 25 metres thicker in the second week. As before, none of the deep cold effluent from Faroe Bank Channel reached this section although the bottom waters below 1,200 metres at station I 111 were probably at just under 4° C, a matter of 1° C or more cooler than a week before in the same place.

THIRD SURVEY

THE SECTIONS BY "PERSEUS II" (U.S.S.R.)

The only material change in the course A as overtaken by "Perseus II" on the third survey in mid-June, was that the five completed stations, A217 to A221, of the section A_3II (Figure 3:23(b)) were aligned some miles to the eastward of the course as laid down in Figure 0:1. The time-table for internal wave investigations at the diamond stations precluded the completion of this section in its entirety.

As before, the first section (A_3I) to be dealt with includes those stations, A207 to A217, running off from the northern shoulder of the Ridge into the deep waters of the Norwegian Sea and thence in from 1,000 to over 2,500 metres, eastward along latitude 64°50'N approximately (Figure 3:22(c)). Only the first part of this section was done in the second survey, to station A111, sufficient however to sample the fringe of the Arctic water-mass which is a feature of almost exactly the same part of the more extended section on both the first and the third surveys. The uppermost 60 metres between stations A211 to A213 was, except for a slight rise in surface temperature, occupied by almost exactly the same water body as was found two weeks before between stations A12 and A13 on section A_1I. Its salinity of 34·77 ‰ to 34·79 ‰ distinguishes this as the surface Arctic or Polar water-mass defined by HELLAND-HANSEN and NANSEN (1909) in their study of the Norwegian Sea.

The transition along the first part of section A_3I from marked oceanic characteristics of salinity (> 35·25 ‰) and temperature (> 8° C nearly to 9° C) to those of the intervening Arctic water-mass, for oceanic water was again encountered in from 75 to over 250 metres on station A215, was even sharper than in the previous week when similar characteristics were observed in similar distribution on this part of the section A_2I. No oceanic water-mass appeared on the section A_1I in the beginning of the investigation.

Between minimum and maximum depth registrations of 250 and 550 metres respectively, approximately as on the section A_1I, the zero isotherm on A_3I averaged approximately 400 metres. Beneath this depth, as on A_1I and A_2I, the waters, by their salinity (34·92 ‰), were entirely of deep Norwegian Sea origin, the minimum temperature recorded being −0·94° C (−1·02° C on A_1I) at 1,550 metres at station A214.

For the reason already given, only the northern half of section A_3II (Figure 3:23(b)) was completed. On this, the merest traces of oceanic water were observed in about 200 metres at stations A218 and A220. It may be recalled that the oceanic water-mass of section A_1II (there was no section A_2II), occurred entirely on the southern half of the section towards the Faroe Islands.

Again below 400 metres only deep Norwegian Sea water was found, the great bulk of it of sub-zero temperature to a minimum of −0·91° C in 1,480 metres on A217.

Section A_3III (Figure 3:24(c)) of the third survey shows similar thermal and haline stratification, with however somewhat less marked undulations, in the layers below about 100 metres to 500 metres, as on the two previous traverses of the same geographical section. The high salinity (> 35·30 ‰) oceanic core is again, as on A_2III, entirely sub-surface and again in two parts. But the re-emergence around the bottom of station A202 of the sub-zero temperature oceanic water body of salinity up to 35·20 ‰ which was a surprising feature of almost the same part of section A_1III, but was entirely unindicated on section A_2III, besides being equally surprising, affords a measure of confirmation in respect of both occurrences as apparent examples of cascading from the submarine shelf of the Faroe Islands plateau adjoining.

The intrusion, between the intermediate depths of 300 to 450 metres at the northwestern ends of the sections A_1III and A_2III, of the Intermediate Arctic water-mass denoted by salinity of 34·87 ‰ to 34·89 ‰ and which had encroached farther south-eastward into the section A_2III than it appeared on A_1III, had apparently become more or less a complete entity between about 250 and 500 metres on section A_3III.

The water-masses below 2° C and below 0° C respectively above the 500 metres level on the section A_3III are represented cross-sectionally by scale measures denoting 21·63 Km² and 6·5 Km² respectively. Putting these figures against the corresponding measures for A_1III and A_2III as in the following table, it is again doubtful if the respective measures for the three sections

Section	Cross-sectional areas represented above 500 m < 2° C km²	< 0° C km²
A_1III	23·56	4·96
A_2III	20·90	6·88
A_3III	21·63	6·5

differ at all significantly as regards at all events their meaning in terms of overspill of the Iceland-Faroe Ridge. In other words, from these sectional surveys of "Perseus II" it can only safely be deduced that the prospect of overspill was approximately the same at the end of the period of survey as at the beginning.

THE SECTIONS BY "JOHAN HJORT" (NORWAY)

It is curious that, while the third survey section A_3III of "Perseus II" showed a 35·30 ‰+ salinity oceanic core, this did not emerge on the more northerly of the "Johan Hjort" third survey sections, (Figures 3:25(c) and 3:26(c)) but re-appeared at the south-eastern end of the southern section, and to a depth of 150–200 metres on the four terminal stations thereof. Maximum surface temperatures of under 10° C on the northern section and a somewhat more restricted occurrence of these on the southern section also represent an apparent declination of the oceanic influence on the third traverse of the course B by "Johan Hjort" as compared with the second survey.

The intrusion in the uppermost 125 metres at station B211 of a small Arctic water-mass is a peculiar feature of the northern "Johan Hjort" section of the third survey which is not reflected in either the southern section or in the neighbouring A_3III section of "Perseus II".

Arctic water occupied the deepest parts practically all along the section B_3I, interspersed and finally replaced towards the southeastern end of the section by the deep Norwegian Sea water-mass.

Above the 500-metres level on section B_3I appears the extraordinary equivalent cross-sectional representation of 30·73 Km^2 of water below 2° C in temperature. The excess of this over the corresponding A_3III measurement of 21·63 Km^2 is probably accounted for by the extension of B_3I northwestward beyond the limit of A_3III and the same applies to the slight B_3I excess of sub-zero temperature bottom water (6·66 Km^2) over that (6·5 Km^2) of A_3III.

The corresponding quantities for section B_3II, a considerable part of which lay on top of the Iceland-Faroe Ridge, as compared with B_3I, were 5·28 Km^2 at less than 0° C and 18·69 Km^2 at less than 2° C.

THE SECTIONS BY "GAUSS" (FEDERAL REPUBLIC OF GERMANY)

As mentioned before, practically all of the two "Gauss" sections were situated along the summit of the Iceland-Faroe Ridge except for three considerable indentations of its northern shoulder as defined by the 500-metres bathymetric contour.

There was no sub-zero temperature water on either of the "Gauss" third survey sections (Figures 3:27(c) and 3:28(c)) and this circumstance at once indicates recession of the deep water overspill of the Ridge over the whole period of the three surveys, because such water appeared on both sections of the first survey, and on the northern section, but only the northern one, of the second.

10·02 Km^2 and 5·46 Km^2 of water of less than 2° C on C_3I and C_3II respectively compare with the corresponding measures of 12·96 Km^2 and 3·58 Km^2 on C_2I and C_2II.

Thus the second survey measures seem to be irregular, between those of the first and third surveys but if the mean of the pairs of measures for each survey are considered the results, 8·51, 8·27, and 7·74 for the first, second, and third surveys respectively again indicate a small recession at weekly intervals of the cold deep water overspill. On the third survey the overspill was again deep Norwegian Sea water, by its salinity, with no Arctic water influence indicated.

THE SECTIONS BY "ERNEST HOLT" (UNITED KINGDOM)

Because of their situation relative to the configuration of the Ridge, the "Ernest Holt" sections may be expected in certain restricted parts to register cold overspill water below the 500-metres level. In point of fact, on the third survey, only the southern section did so, between the stations D230 and D232, and that only in very small amount, cross-sectionally represented by 0·52 Km^2, the total cold water below 2° C on the southern section (D_3II, Figure 3:30(c)) being only 1·33 Km^2. On section D_3I (Figure 3:29(c)) there were two parts of this < 2° C water aggregating 3·21 Km^2 in cross-sectional scale.

As in the case of the "Gauss" sections, the second survey "Ernest Holt" section D_2I presents an apparent irregularity in the sequence of measures from D_1I to D_3I, nor in this case do the means of the paired values "correct" the anomaly significantly in the sense of suggesting a continuous regression of the overspill phenomenon during the three weeks of the survey.

The 35·30 ‰ salinity parameter continues to define, in more than one part on both the third survey "Ernest Holt" sections, the main core of the oceanic water mass, with however, the additional revelation of a stronger nucleus of salinity greater than 35·35 ‰ on both sections. Maximum surface temperatures were still in excess of 10° C on the southeastern ends of both sections.

THE SECTIONS BY "MARÍA JÚLÍA" (ICELAND)

Nuclear salinity in excees of 35·35 ‰ within the oceanic core was also a feature of the northern of the two "María Júlía" third survey sections (Figure 3:33). Two such nuclei appeared in the uppermost 200 metres of the northern section southeast of the longitude of 10°30′W. Unfortunately it was not possible to complete the corresponding part of the southern section which may explain why similar high salinity nuclei were not recorded on this section.

No bottom water of under 2° C temperature occurred on either section E_3I or E_3II. Indeed only a very small part of the northern section, again towards the southeastern end, showed a bottom temperature scarcely under 3° C and the entire section in both cases registered only oceanic water from the surface to the bottom. This circumstance distinguishes the "María Júlía" third survey sections from those of the previous two surveys all four of which exhibited more or less substantial bodies of cold bottom water of less than 2° C in temperature and representing both overspill water from the Iceland-Faroe Ridge and effluent water from the Faroe Bank Channel. Herein is further evidence for the recession of the overspill phenomenon as previously mentioned.

THE SECTIONS BY "HELLAND-HANSEN" (NORWAY)

Recession of the cold deep overspill phenomenon from the Ridge over the period of the entire survey is once again illustrated by the successive "Helland-Hansen" sections, situated, as shown in Figure 0:1, just beyond the Ridge's southern shoulder and at their southeastern ends, (that of the northern section in particular), within reach also of the similar deep cold water effluent from the Faroe Bank Channel. Although comprising for the most part sub-oceanic water, and only in minor degree in one part deep Norwegian Sea water, the northern section of the first survey revealed two areas of bottom bathed by waters of less than 2° C temperature – less than 1° C in fact on the bottom at station F1. The southern section of this survey was entirely oceanic in character with three bottom areas under 3° C, but none so low as 2° C.

Less than 2° C water occurred again on the second survey sections, both of them, but to a considerably less extent cross-sectionally on the northern section than on the first survey. All of it had sub-oceanic salinity characteristics. The small bottom area of this water on the southern section of the second survey probably represented, at stations F127 and F128 near the middle of the section and close to the southmost extension of the southern shoulder of the Ridge, the remains of geostrophic flow westwards of the cold water overspill from the previous survey.

Neither of the third survey sections (Figure 3:36) showed any bottom water even as cold as 3° C, save only in the bottom 50 metres layer at station F201 where the receding Faroe Bank Channel effluent appears just to have been sampled before withdrawing from the range of this section.

Beyond the foregoing factors are to be noted only the general rise in, and greater extension of, maximum surface temperatures to over 10° C which has been observed throughout the third survey sections to this stage, and the increase in areal representation of oceanic core water of greater than 35·30 ‰ salinity to nuclear maxima in fact of over 35·35 ‰ which is a new feature of the more southerly third survey sections.

THE SECTIONS BY "ANTON DOHRN" (FEDERAL REPUBLIC OF GERMANY)

Except for a small bottom cross-sectional area of sub-oceanic water lying deeper than 1,100 metres on stations G227, 228, and 229, in which the minimum recorded temperature was 0·70° C, the entire water mass on both the "Anton Dohrn" sections of the third survey (Figure 3:39) was oceanic, with temperatures in excess of 3° C, as in fact it was also on both sections of the second survey and over all but a small deep-lying patch on the northern section of the first survey. Bottom temperatures of under 2° C were recorded on only the southern section of the first and third surveys, to the areal extent of 2·70 Km² on the first survey and 4·36 Km² on the third. The difference would seem to be not altogether insignificant, but its explanation is elusive unless the re-appearance of the cold bottom mass on the third survey may represent a break-away from the receding effluent from the Faroe Bank Channel as is represented on Figure 3:20, illustrating the bottom water thermal situation over the whole area of the survey in the third week.

THE SECTIONS BY "DISCOVERY II" (UNITED KINGDOM)

Exigencies of time necessitated the curtailment of "Discovery II's" third survey of the investigation. The northern section, H_3I, (Figure 3:42(a)), however, was completed except for the two terminal stations H214 and H215 which the previous surveys had indicated as unlikely to be of major significance, but section H_3II (Figure 3:42(b)) had unfortunately to be terminated when only its deepest part had been hydrographically sounded.

Save for the disappearance of the very small quantity of bottom water of less than 2° C, the characters of section H_3I are broadly very similar to those of H_2I. The section was entirely pervaded by oceanic water with the characteristic core salinity of a little over 35·30 ‰ and maximum surface temperatures above 10° C. The deep-lying body of sub-oceanic water of section H_2I had also been "absorbed" as it were by the third week of the survey.

On the small part of H_3II which is available there is no feature of note to which particular attention need be directed.

THE SECTIONS BY "EXPLORER" (UNITED KINGDOM)

Maximum surface temperatures of somewhat higher order than those of other sections of the survey in the Iceland-Faroe Ridge region proper continued to be a feature of the "Explorer" sections of the third survey. More than half of the surface on section I_3I (Figure 3:47(a)) registered over 11° C. Two parameters of 35·40 ‰ salinity as on sections I_1I and I_2I again defined a bifurcated oceanic water-mass core on section I_3I.

The bottom water-mass, as to be expected, was again deep Norwegian Sea type, its minimum recorded temperature being −0·76° C. The zero isotherm at approximately 700 metres on the southern half of the section plunged to over 850 metres against the slope of the Faroe Islands shelf.

A total areal measure of 21·37 Km² of bottom water of less than 2° C of which 16·21 Km² represented sub-zero water, compared with over 25 Km² on section I_1I and over 30 Km² on I_2I, although the proportion of sub-zero temperature water was greater (76 %) on I_3I than on either of the other two – 54 % on I_1I and 75 % on I_2I. But in accordance with previous practice, the measures above the 900 metres level provide better gauges as to the amounts of the cold bottom mass which are available as it were for passage through the Faroe Bank Channel. These are, on I_3I, 13·7 Km² at less than 2° C, including 8·54 Km² at less than 0° C. Both numbers are considerably smaller than those for section I_2I. The former measure, namely that relating to < 2° C water is smaller also than the

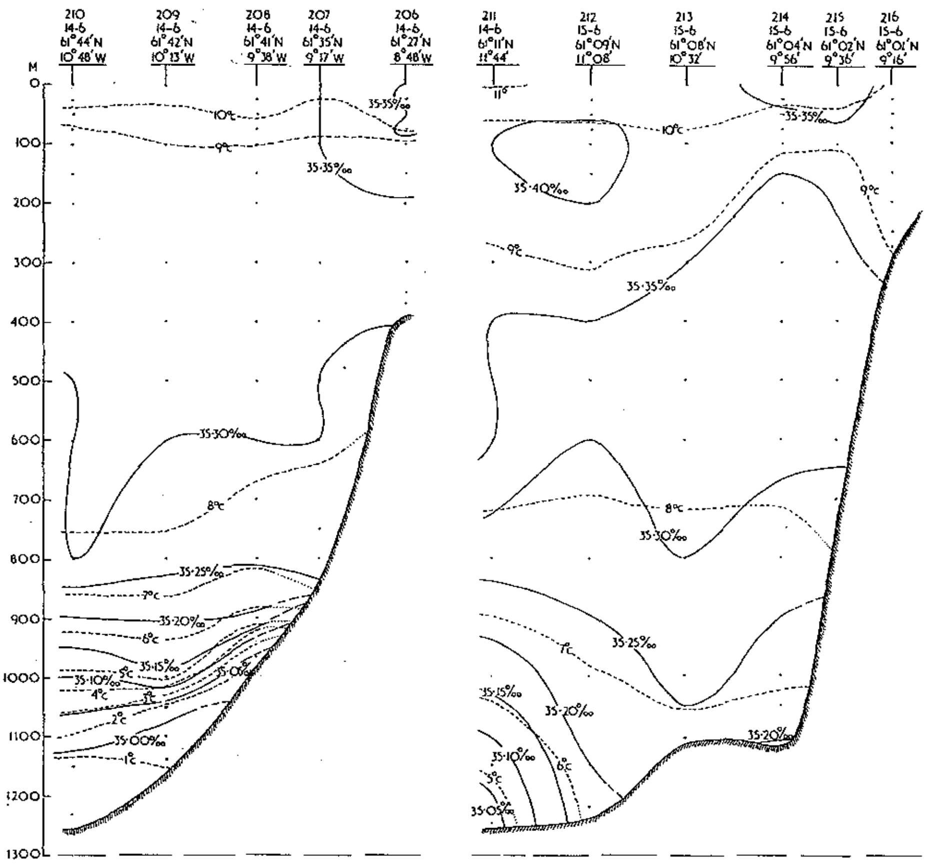


Figure 3:48. (a) Section I_3V (b) Section I_3VI

corresponding measure on I_1I but, as already pointed out, contains a higher ratio of $<0°$ C water.

Section I_3II (Figure 3:47(b)) presents the measures of 4·61 Km² bottom water below 2° C in temperature, including 2·45 Km² of sub-zero temperature water. The former measure represents a gradual decline in the head of cold bottom water of this category at the southeastern end of the Faroe Bank Channel, from the first survey section I_1II (5·25 Km²), through the second I_2II (4·81 Km²) to I_3II, but the latter measure on the other hand signifies a gradual increase from $33\,^1/_3\,\%$ to 58 % in the ratio of sub-zero water in the cold bottom mass as a whole.

I_3III (Figure 3:47(c)) yields a cross-section areal measure for bottom water under 2° C of 4·65 Km², practically identical with that for I_3II, but sub-zero temperature water included in this measure, at 1·51 Km², is just over half that on I_3II. As compared with measures on I_2III the above quantities represent an apparent slight increase in the quantity of $<2°$ C water – probably not significant although 0 °C water is distinctly less.

Finally, for the trans-Faroe Bank Channel sections, I_3IV (Figure 3:47(d)) which presents similar features in the temperature and salinity distributions as does I_2IV, 1·31 Km² of the deep waters of the section to the bottom were under 2° C. There was evidently no sub-zero temperature water on this section. Again the evidence of these areal measurements on the I IV sections from beginning to end of the survey reveal a distinct declination in the amounts of cold bottom water issuing from the Faroe Bank Channel into the NE Atlantic Ocean region as the following figures show: –

	$<0°$ C	$<2°$ C
I_1IV	2·0	3·61
I_2IV	0·9	2·0
I_3IV	–	1·31

In view of the above it may seem surprising that section I_3V (Figure 3:48(a)) should show more $<2°$ C bottom water than either sections I_1V or I_2V. I_3V in fact had bottom water of $<1°$ C which neither of its predecessors revealed, as shown in the following table.

	$<2°$ C	$<1°$ C
I_1V	0·72	–
I_2V	5·71	–
I_3V	5·93	2·47

The only significant difference between I_3VI (Figure 3:48(b)) and its predecessors is that it had a nuclear oceanic salinity in excess of 35·40 ‰.

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TEMPERATURE AND SALINITY DISTRIBUTIONS AS SHOWN BY SECTIONS NORMAL TO THE ICELAND-FAROE RIDGE

(A. J. Lee)

Five sections normal to the axis of the Ridge have been selected for investigation, and in addition a section along the axis of the channel between Faroe Islands and Faroe Bank, hereafter called the Faroe Bank Channel, and of the cold water debouching from that channel into the North Atlantic Ocean. The positions of these sections are shown in Figure 3:49. They were selected, following a consideration of the bottom temperature distributions for the three surveys, with the aim of showing conditions in typical areas where the overflow of cold bottom water was taking place and also in others where it was absent. The positions of the sections are virtually the same on all three surveys, but it was impossible to construct the additional section along the Faroe Bank Channel in the case of the first survey, since the station network in that area was different on that occasion.

The sections have been lettered α-ζ, as shown in Figure 3:49, and were constructed on the basis of rectilinear interpolation. The bottom topography for each of them is based on the soundings given for the various stations and not on that given in Figure 3:49. As a result some minor, but none the less important, features may have been omitted. In order to detect observational errors when drawing the temperature and salinity distributions along the sections, a T-S diagram was constructed for each section for each survey. These diagrams have also proved extremely useful in examining the water masses present in the survey area, and they are therefore included with the diagrams given here.

The main water masses to be considered in the investigation of the overflow of cold water are indicated in each of the T-S diagrams. North Atlantic (NA) water has been taken as having a temperature of 9° C and a salinity of 35·33 ‰: Dietrich (1957) puts the T-S relationship at 9·5° C, 35·35 ‰ and Steele, Barrett and Worthington (1962) put it at 9° C, 35·31 ‰. Norwegian Sea deep water (NS) has been taken as having a relationship of −0·4° C, 34·92 ‰. Mosby (1959) gives the mean vertical distribution of temperature and salinity in the Norwegian Sea, east of the Iceland-Jan Mayen Ridge, based on "Armauer Hansen" cruises in 1935 and 1936. The temperature and salinity at 800 m are −0·4° to −0·5° C and 34·92 ‰: 800 m is approximately the least depth in the Faroe Bank Channel along Section α, *i.e.* the depth at which overflow of this deep water is likely to occur. Helland-Hansen and Nansen (1909) noted an Arctic intermediate water mass on the northern slope of the Iceland-Faroe Ridge at 300–400 m depth with salinity between 34·86 ‰ and 34·90 ‰ and a low temperature: 450 m is approximately the greatest depth of the crest of the ridge. Tait (1955) provides further information about the characteristics of this water. Here we have characterized it by the relationship 0°, 34·86 ‰ and designated it EI, as it forms the lower levels of the East Icelandic Current and so that we may distinguish it from the Irminger Sea (AI) water, which occurs in the North Atlantic to the south of the ridge and which is defined by Steele, Barrett and Worthington (1962) as having a temperature of 3° C and a salinity of 34·89 ‰. The final water mass to be taken into consideration is North Icelandic Winter water (NI) as defined by Stefánsson (1962). This has been given the T-S relationship 2·5° C, 34·88 ‰, as Stefánsson considers its temperature to be between 2° and 3° C and its salinity between 34·85 and 34·90 ‰.

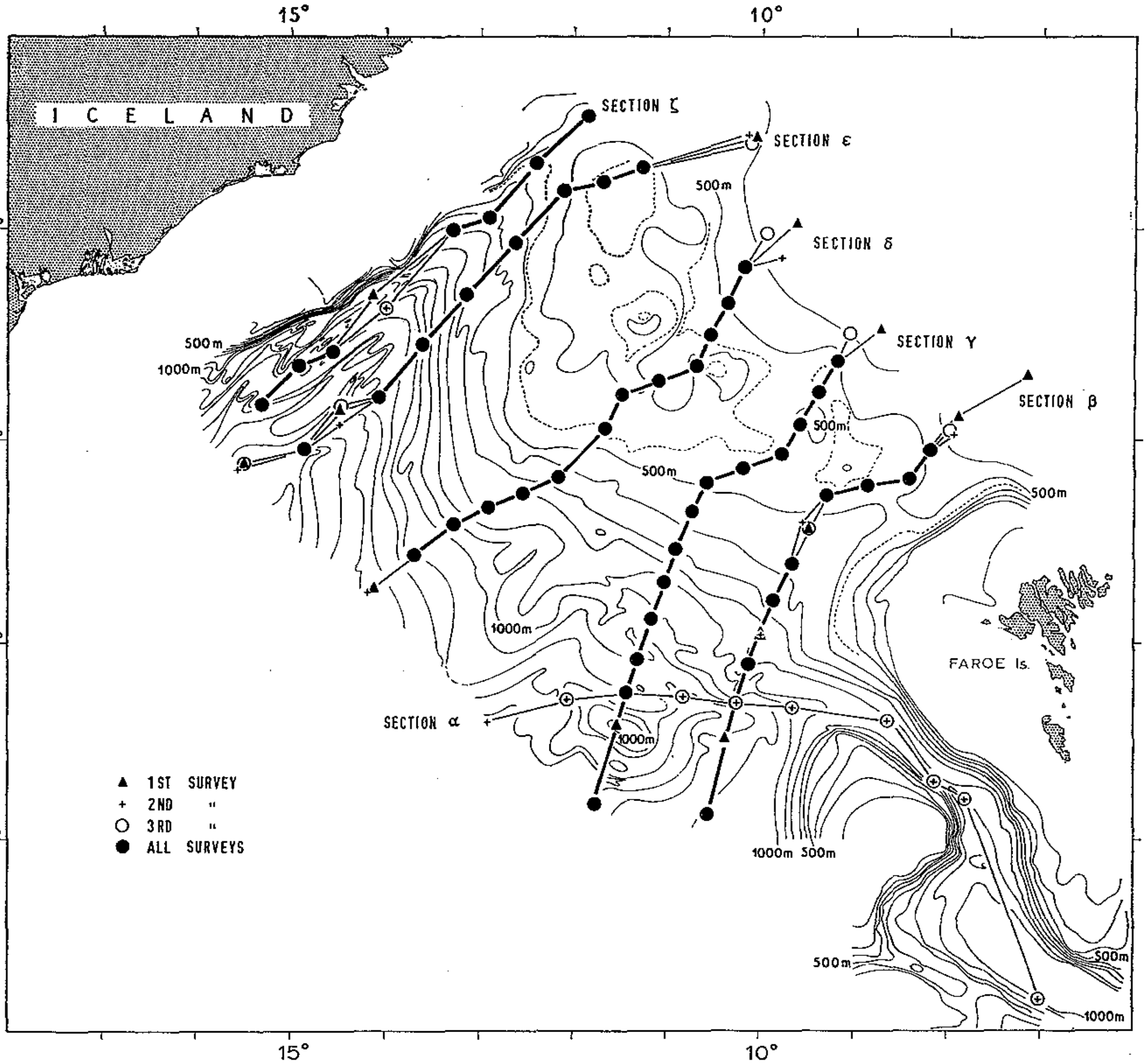

Figure 3:49. First to third Survey: sections α-ζ, position.

As the NA water mass mixes with the others to varying degrees, lines have been drawn on each T-S diagram to join the point defining the NA water to those defining the NS, EI, AI and NI water masses. Stefánsson (1962) has considered the contribution made by the NS and NI water masses to the overflow on these surveys and has taken into account only the NA–NI and NA–NS lines: he regards the EI water mass as making only a minor contribution. It is clear from what follows here, particularly from Diagram ζ, I, T-S, that the EI water mass is present in the survey area as it causes points which fall to the left of the NI–NS line. It cannot be ignored but the introduction of the NA–EI line complicates the T-S analysis as points with NA–EI characteristics can be brought about by mixing of the NA, NS and NI waters only and need not be due necessarily to any true EI influence. This possibility must be borne in mind when reading the sequel. Again, the AI water mass is not considered by Stefánsson (1962). The NA–AI line falls close to the NA–NI line and could confuse the analysis, but AI water originates to the south of the ridge whilst NI water from the north of it, and so a consideration of the geographical position of a station usually indicates which of these two water masses is involved.

It should be noted at this point that most of the T-S diagrams suggest that as far as the higher temperatures at least are concerned, the salinity observations made by "Discovery II" appear to be a little lower

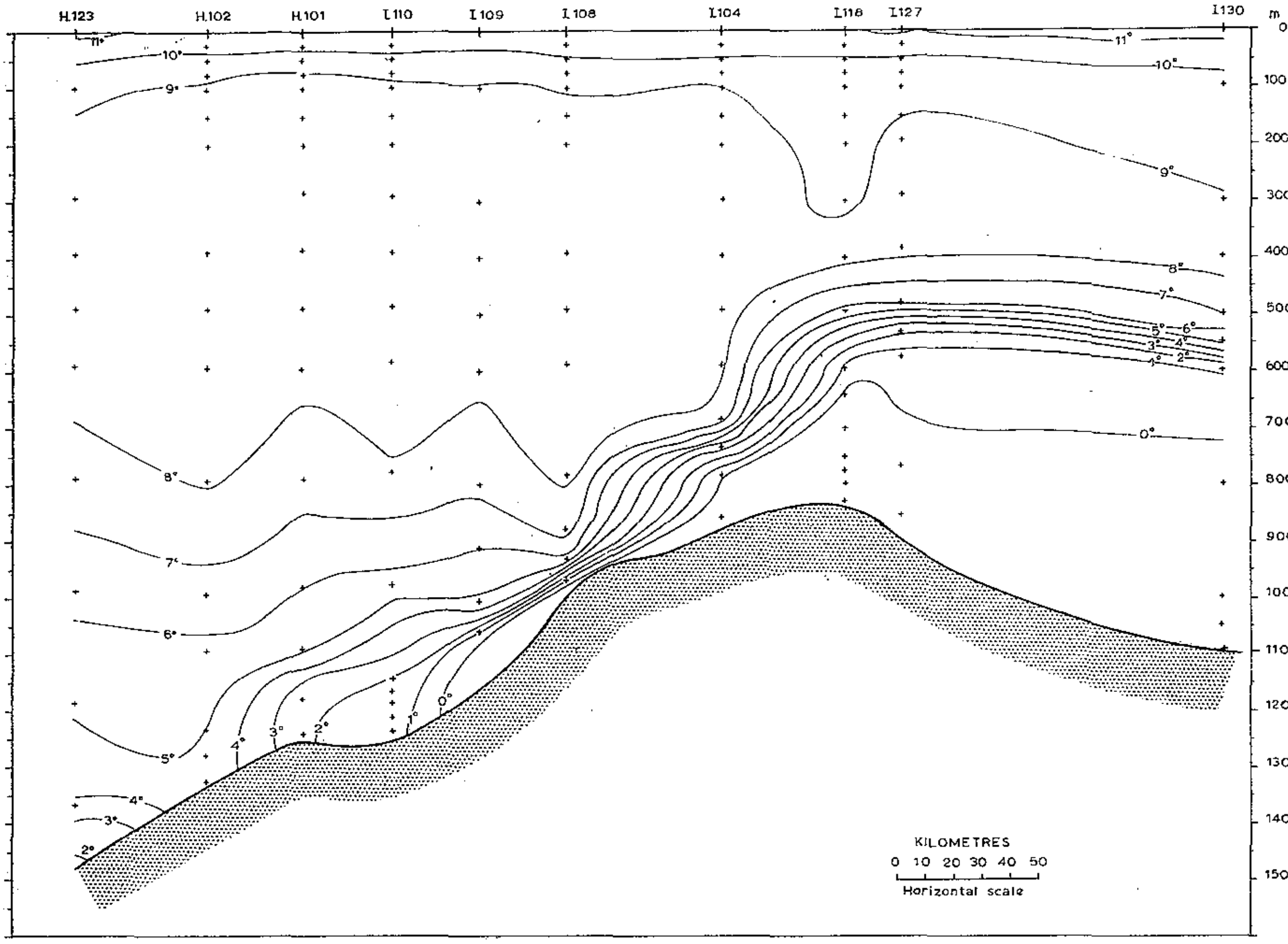

Figure 3:50. Section α, second Survey: temperature °C.

than those of the other vessels. In the case of most of the T-S diagrams for Sections β-ζ the salinity at each of the higher temperature levels increases on the whole from north to south along the section until the G stations occupied by the "Anton Dohrn" are reached. It then decreases at the H stations worked by "Discovery II" immediately to the south of the "Anton Dohrn" stations, and in the case of Section III it increases once again southward of the "Discovery" stations, namely at the "Explorer" or I stations. The effect of this is to put a trough in the isohalines of the salinity sections at the "Anton Dohrn" G stations where one does not necessarily occur in the isotherms of the temperature sections. The cause of this difference is not known, but experiments at the Fisheries Laboratory, Lowestoft, have shown that the rubber-washered, swing-stoppered sample bottles used by most of the ships tend to give higher salinity values than the new N.I.O. screw-stoppered sample bottles used by "Discovery II", and that the latter gives the more correct results.

SECTION α

Survey 2

Figures 3:50 and 3:51 show sub-zero temperature water with a salinity below 34·95 ‰ flowing along the bottom over the shallowest part of the Faroe Bank Channel and down into the Atlantic Ocean. At the westward end of the section, at station H102, the overflow appears to have been broken by a band of water warmer than 4° C, but this may be due to the section not following the axis of the overflow. At the eastern end of the section where the channel joins the Norwegian Sea the sub-zero water occupies the 400 m above the bottom and reaches to a depth of 650 m below the surface at station I 118 and of 800 m at station I 104. As the upper part of the water column at the Atlantic end of the section consists of water warmer than 8° C with a salinity above 35·25 ‰ reaching from the surface to 800 m depth to as far east as station I 108, steep temperature and salinity gradients occur at 800 m depth between that station

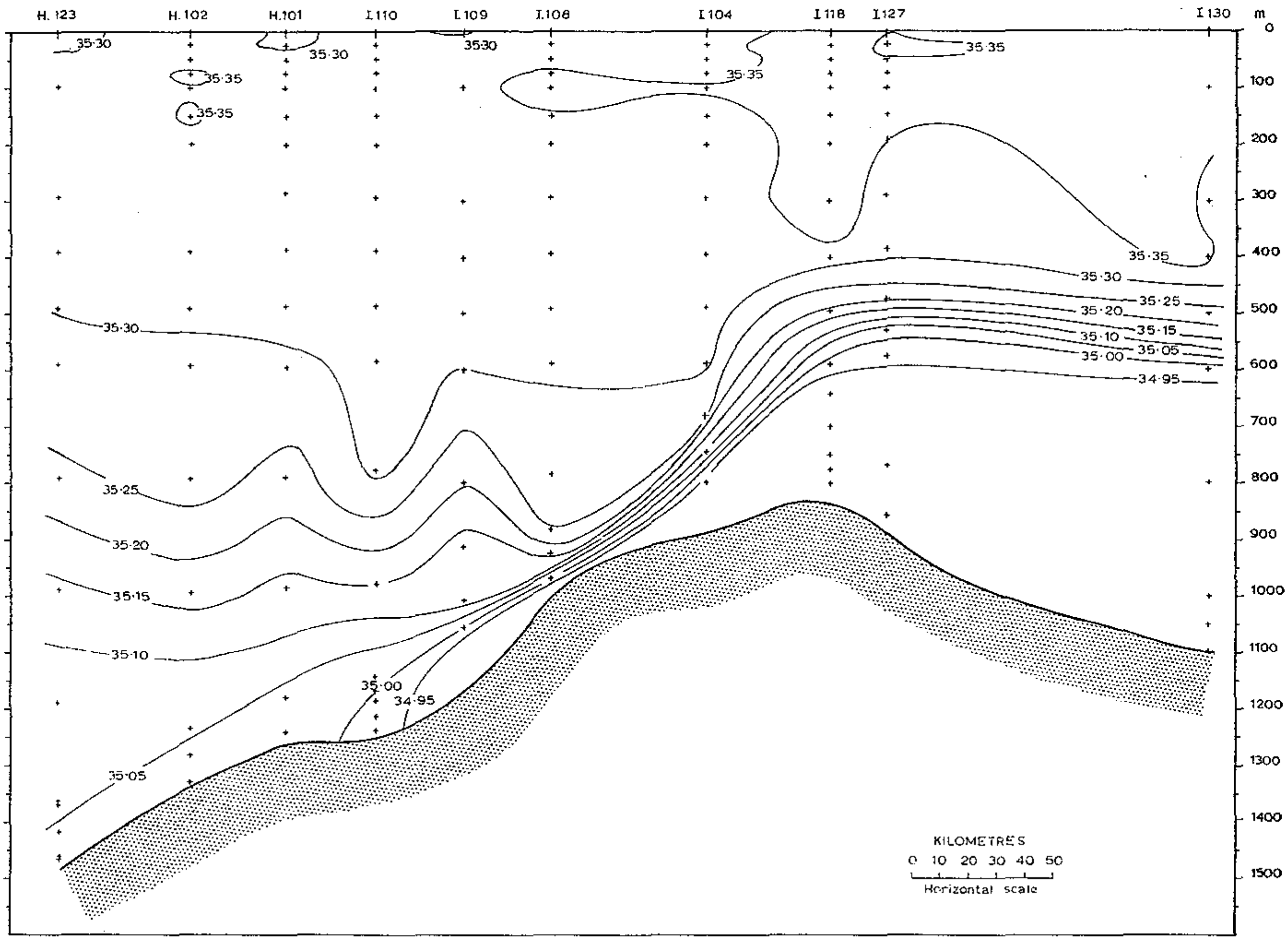

Figure 3:51. Section α, second Survey: salinity $^0/_{00}$.

and station I 104. The T-S diagram for the section (Figure 3:52) shows a straightforward mixing between the NA and NS water masses at the Norwegian Sea end of the section at stations I 130 to I 108. At station I 110 and those westward of it, however, there is mixing between NA and AI waters over that part of the water column with temperatures between 4·5° and 8° C, but near the bottom the T-S curves for these stations are influenced by NS water.

Survey 3

The diagrams for this survey (Figures 3:53 and 3:54) are essentially similar to those for Survey 2, except that the sub-zero temperature overflow does not reach far beyond station I 204 in this case, and that water above 1° C occurs on the bottom at stations I 208 and 209, but again the section may not be following the axis of the overflow. The T-S diagram (Figure 3:55) shows that mixing is taking place between the NA and NS water masses along the whole section, except at the two most westerly stations, H 201 and 202, between 800 and 1,100 m depth (6°–8° C) where the influence of AI water can be seen. This influence is thus less than on Survey 2.

SECTION β

Survey 1

Figures 3:56 and 3:57 show some overflow of water below 3° C but not of sub-zero temperature water across the crest of the ridge. Water with a temperature below 1° C and a salinity below 34·95 $^0/_{00}$ can be seen flowing along the southern slope of the Ridge at 800 m depth at station F1: this is water from the outflow through the Faroe Bank Channel and it occupies a nick in the southern slope of the Ridge. Elsewhere the slope is covered with water above 1° C, mainly above 2° C and above 35·0 $^0/_{00}$ salinity. In the Norwegian Sea the sub-zero temperature water has a salinity below 34·95 $^0/_{00}$ and is seen to fill the basin to 500 m, *i.e.* 50 m below the crest of the Ridge on this section. Small areas with salinity below 34·90 $^0/_{00}$ can be seen between 350 and 451 m depth at stations A2 and A24.

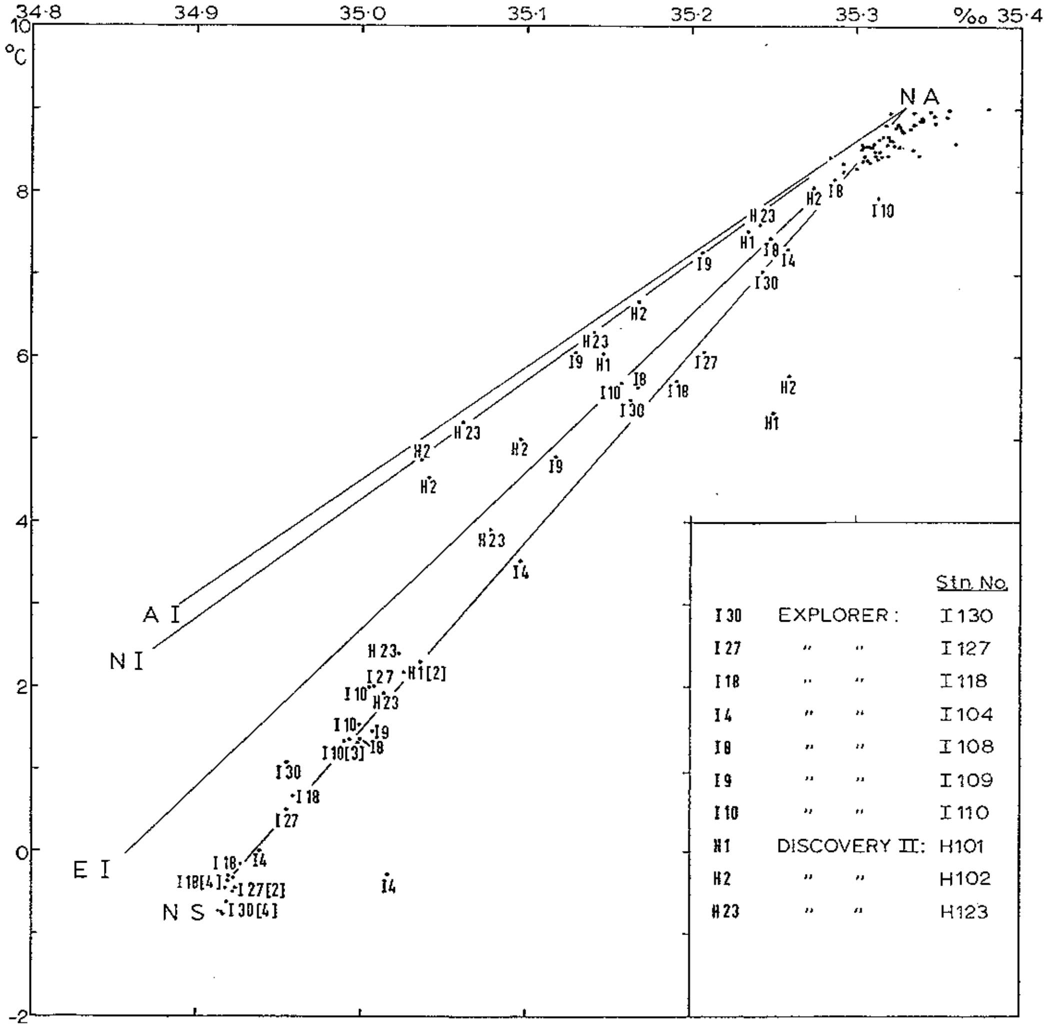

Figure 3:52. Section α, second Survey: temperature °C – salinity ‰.

The warmer waters of the upper layers on the southern side of the Ridge have a temperature above 8° C and a salinity above 35·25 ‰ down to 800 m depth. Steep salinity and temperature gradients occur in the 125 m above the bottom at all stations between and including B32 and F1.

The T-S diagram (Figure 3:58) suggests that at station A24, the northernmost of the three stations on the northern side of the Ridge, NI water is present at 350–400 m depth. It mixes with NA water at higher levels and with NS water below it. The T-S curves for the other two stations, A2 and B3, are similar but are closer to the NA–EI line, and at stations B32, C4 and C34, on the top of the Ridge, the T-S curves for the most part follow that line. The T-S curves for the five stations D5–F1 fall close to the line joining NA water to NS water and on that for station F1 NS water can be seen at the bottom marking the Faroe Bank Channel outflow.

Survey 2

The diagrams for this survey (Figures 3:59 and 3:60) are similar to those for Survey 1, except that sub-zero temperature water in the Norwegian Sea is now 150 m below the crest of the Ridge, that warmer water with temperatures up to 6° C occurs on the bottom between stations D135 and C104, and that any overflow which was occurring seems to have stopped. The temperature of the outflow found at station F101 is somewhat higher than that found at station F1. This outflow seems to cover a wider area than on Survey 1, but this may be due solely to a change in the station grid which brought station I 109 closer to F101 than was I9 to F1. The T-S diagram for this survey (Figure 3:61) shows hardly any NI influence on this occasion. At stations A102, B103 and B132 the influence of EI water can be seen down to 400–500 m when NS water begins to affect the curves, but at the remaining stations the T-S curves tend to fellow the NA–NS line,

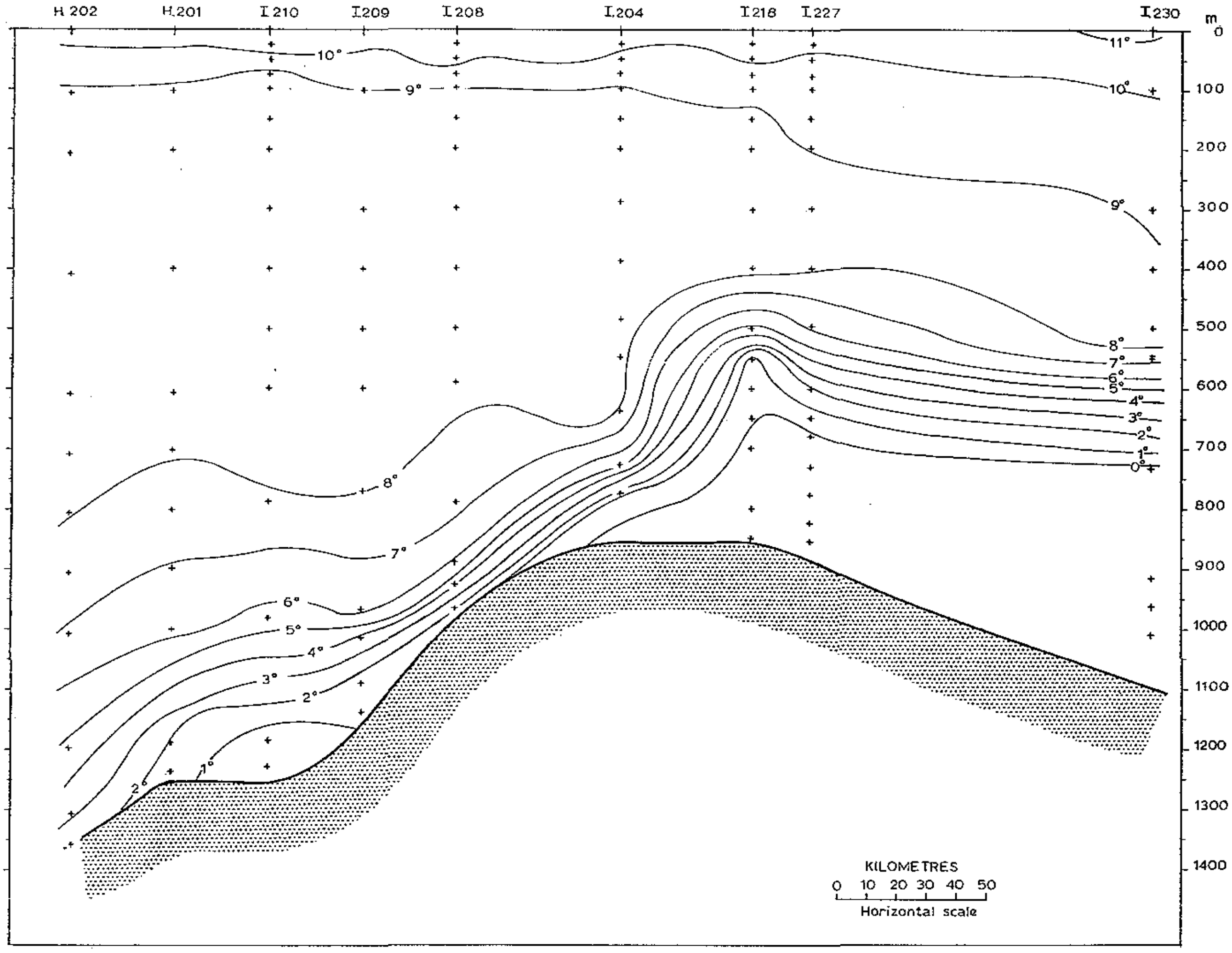

Figure 3:53. Section α, third Survey: temperature °C.

except at I 109 where the curve approaches the NA–AI line at 700–900 m depth (6–7·5° C).

Survey 3

The diagrams for this survey (Figures 3:62 and 3:63) are similar to those for Survey 2: they show the outflow from the Faroe Bank Channel flowing westward at the bottom at stations I 209 and F 201, but as on Survey 1 temperatures below 1° C are observed in it now. Further, overflow of the Ridge is yet again absent, and the bottom between stations E205 and B232 is this time covered with water between 4° and 6° C and a salinity above 35·1 ‰. Sub-zero temperature water in the Norwegian Sea is still 150 m below the crest of the Ridge. The T-S diagram (Figure 3:64) shows that the curves for the three stations on the northern side of the ridge follow the line joining the NA water mass to the EI water mass, and that at A202 NS water is present at the bottom. The remainder of the curves again fall between this line and the NA–NS line or about the latter.

SECTION γ

Survey 1

The diagrams for Section III on this survey (Figures 3:65 and 3:66) show no sub-zero temperature overflowing water and that the southern slope of the Ridge is covered with overflow water with a temperature below 3° C and a salinity above 35 ‰. The crest of the Ridge on this section is somewhat flattened and plateau-like. Temperatures and salinities at the seabed at the southern edge of the plateau are above 5° C and 35·1 ‰ and those at the northern edge below 1° C and 34·95 ‰. Sub-zero temperature water just reaches to the level of the top of the plateau on its northern side. As on Section β, water above 8° C and 35·25 ‰ is found from the surface down to 800 m on the southern side of the Ridge, and a sharp thermal

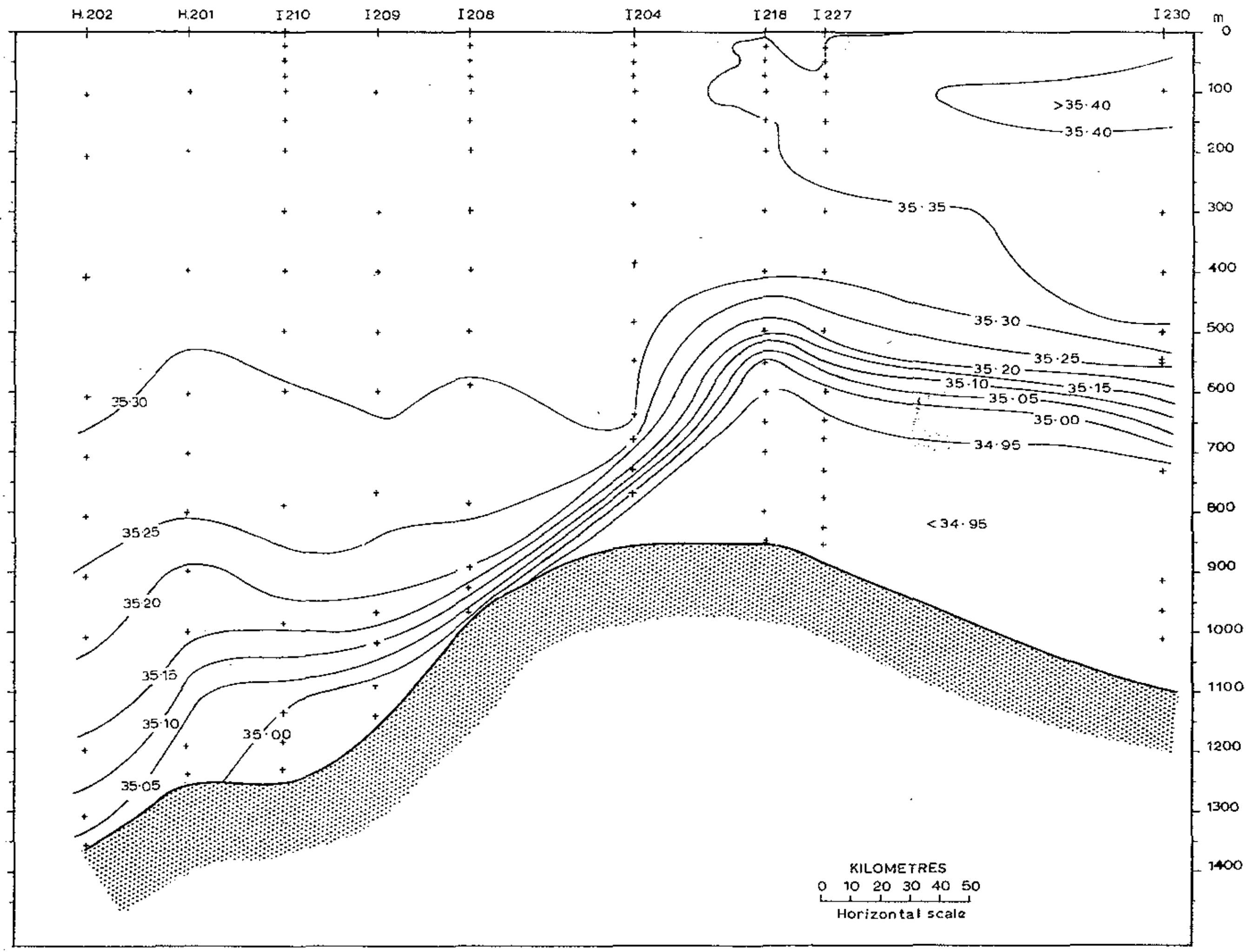

Figure 3:54. Section α, third Survey: salinity $^0/_{00}$.

gradient occurs in the 100 m above the bottom at most of the stations on the southern flank of the Ridge. At stations H26 and H1 the cold outflow from the Faroe Bank Channel is seen flowing westward as water with a minimal temperature below 2° C and a minimal salinity below 35 $^0/_{00}$. It is now at a depth greater than 1,200 m, compared with 750–1,150 m on Section β, and it again occupies a nick in the southern slope of the Ridge, this one being much more pronounced than that on Section β. A peculiar feature of Figure 3:66 is the waviness of the 35·3 $^0/_{00}$ isohaline. At the stations of each of the research vessels "Ernest Holt", "María Júlía" and "Helland-Hansen" (D, E and F stations respectively) this isohaline is shallower at the southern station than at the northern station which was worked first: this suggests some alteration in conditions during the survey.

The T-S diagram (Figure 3:67) shows the influence of NS water at the bottom at the five northernmost stations, A4–C32. Otherwise the T-S curves for these stations tend to fall between the NA–EI and NA–NI lines with C32 and B28 showing most NI influence at about 400 m depth. The T-S curves for the next four stations to the south, D8–E35, on the whole follow the NA–EI line although that for station E35 shows NS influence at the bottom as do the curves for stations F5 and 35: the latter also show AI influence. Stations G1 and H1 follow the NA–NS line and the NS outflow from the Faroe Bank Channel is clearly seen at the lower end of the curve for H1. At the two southernmost stations on the section H26 and I 11, the influence of AI water is seen below 800 m depth and NS influence is absent.

Survey 2

Figure 3:68 shows that, although the sea-bed on the southern flank of the Ridge is still largely covered with water above 2° C, a small part in the

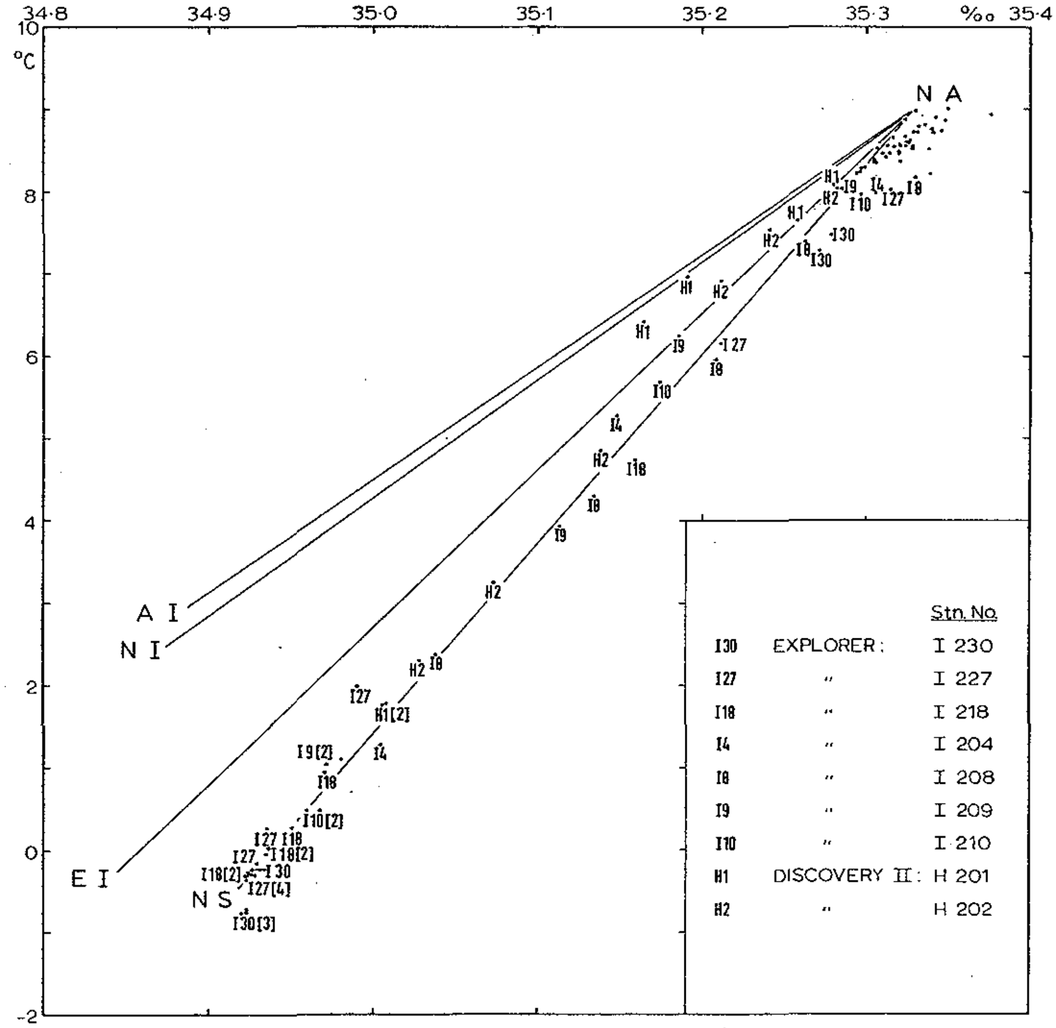

Figure 3:55. Section α, third Survey: temperature °C – salinity ‰.

vicinity of station D131 has a temperature below 2°C and the top of the plateau has a temperature below 0°C at station C107. Thus the development of the overflow is indicated on this survey. In the outflow from the Faroe Bank Channel, however, temperatures are higher than on Survey 1 and no temperatures below 2°C are observed.

The T-S diagram (Figure 3:70) shows that the northernmost station was subject to EI influence and its T-S curve closely follows the NA–EI line at all depths. At the next station southward, B128, however, there is considerable NI influence at 400 m depth, but as the bottom is approached EI influence is felt. Going further south again, the curves for stations C107–D131 follow the NA–EI line on the whole, but that for C107 approaches the point defining NS water at the bottom showing the presence there and at station B128 of overflowing NS water. At stations E109 and H101 the T-S curves approach the NA–NS line generally, but as one proceeds southwards the AI influence at about 1,000 m depth becomes more apparent, and at the southernmost station of the section the T-S curve follows the NA–AI line closely.

Survey 3

It can be seen from Figure 3:71 that the small overflow noted as developing on Survey 2 has extended farther by Survey 3 and that water with a temperature below 1°C covers the whole of the top of the plateau and part of its southern slope. Figure 3:72 shows this water to have a salinity below 34·95‰. Further south, however, water warmer than that observed on Survey 2 covers the slope, but in the nick holding the Faroe Bank Channel outflow a minimal temperature below 2°C occurs again as on Survey 1, thus indicating a strengthening of this flow.

The T-S diagram (Figure 3:73) shows that at the bottom at stations A204–D231 over the plateau NS water was present in the overflow, but the T-S curves for the shallower parts of the water column vary from

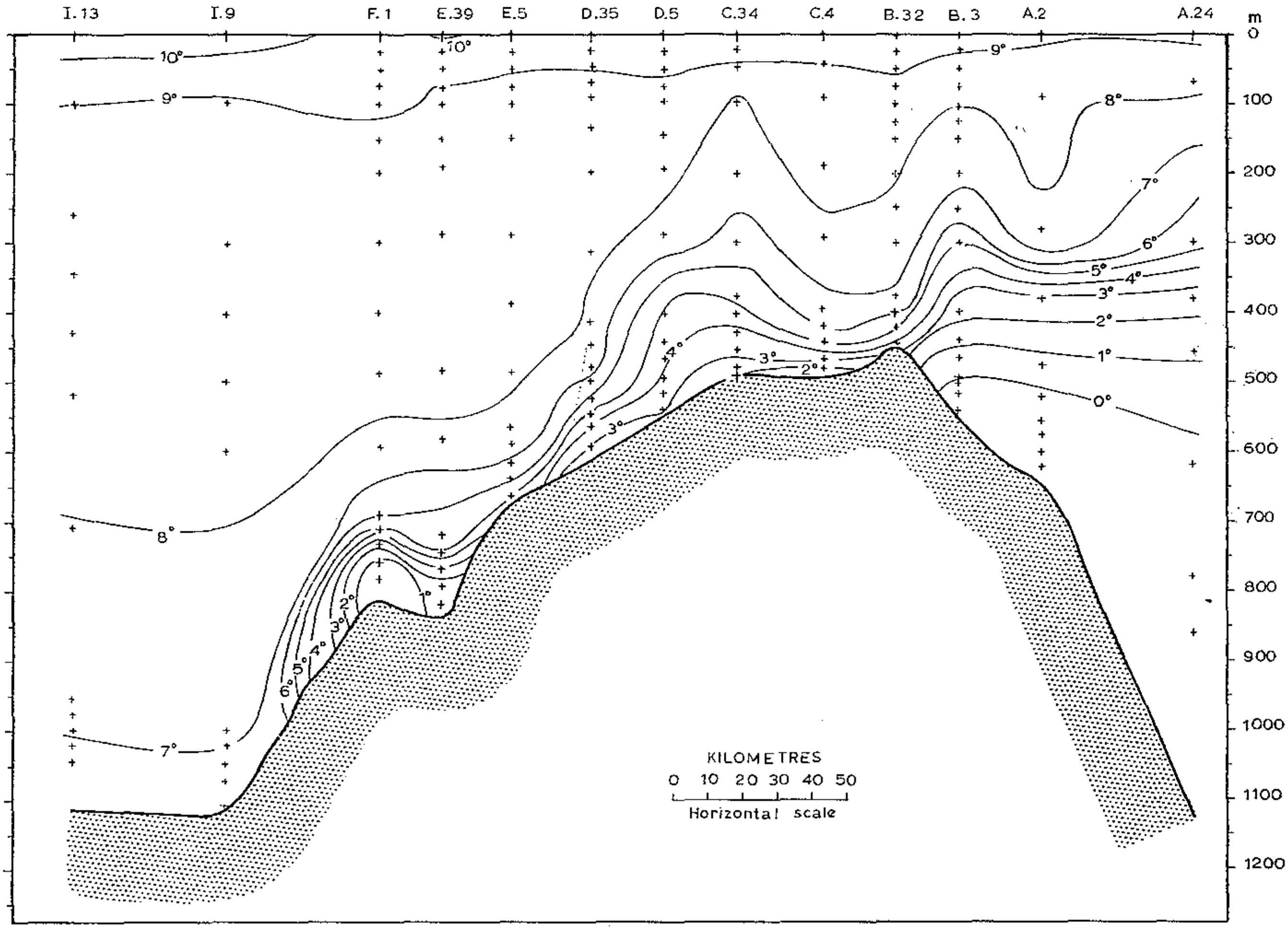

Figure 3:56. Section β, first Survey: temperature °C.

station to station. Stations A204, B207, B228, D208 and D231 tend on the whole towards the NA–NI line down to a depth of 300–400 m: stations C207 and C232, on the other hand, approach the NA–EI line. As on Survey 2, stations E209–H201 have curves which follow the NA–NS line generally and those for the more southerly stations show the influence of the NS water in the Faroe Bank Channel outflow, but AI influence is again seen at 1,000 m depth and the curve for the southernmost station on the section once more follows the NA–AI line closely.

SECTION δ

Survey 1

Figures 3:74 and 3:75 show a small amount of bottom water with a temperature below 1°C and salinity below 34·95 ‰ on the south side of the Ridge just below the crest at station D12, and temperatures at the sea-bed below 2°C with salinities less than 35·0 ‰ from the crest to a point a little south of station F10. Thus overflow of cold water is taking place on this section at this time. Sub-zero temperature water with a salinity below 34·9 ‰ in the Norwegian Sea reaches to within 70 m of the crest of the Ridge. At stations H8 and H20 water with a temperature below 2°C and a salinity below 35·05 ‰ occurs at the bottom, indicating the outflow from the Faroe Bank Channel as now being at depths below 1,250 m at this point in its westward progress. Over the remainder of the water column the sections resemble those for Sections β and γ.

The T-S curves (Figure 3:76) for this section show that those for stations B11 and B24 on the northern side of the Ridge follow the NA–NI line down to 300–350 m depth and that below this depth there is some EI influence and close to the bottom an approach to NS water. Such data as there are for station A6 suggest a similar curve for that station. On the other hand, station C11, also on the northern side of the Ridge, has a curve which tends more to the NA–EI line than to the NA–NI line but the effect of NS water at the bottom is still well marked. The curve for its southern

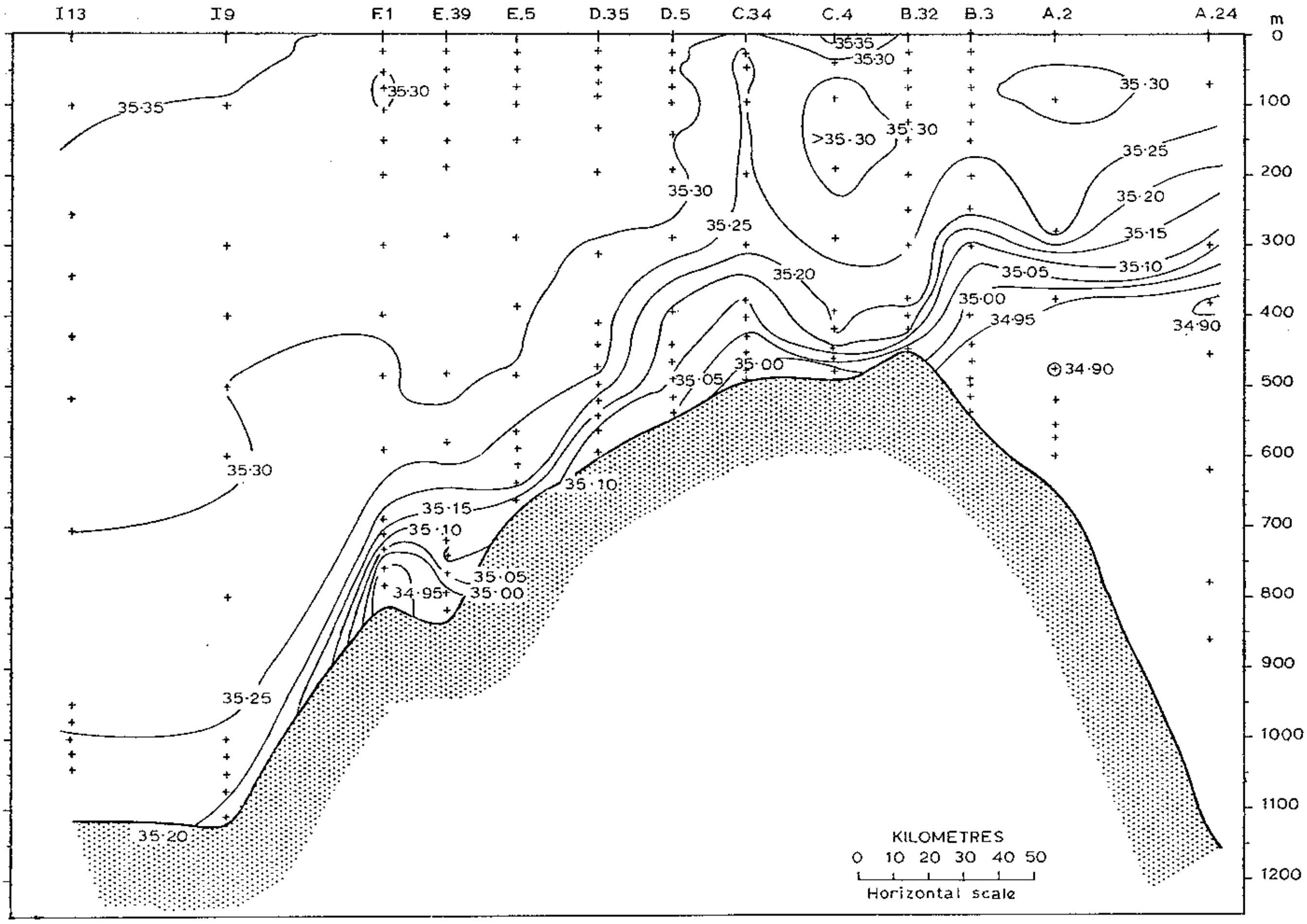

Figure 3:57. Section β, first Survey: salinity $^0/_{00}$.

neighbour, station C28, on the crest of the Ridge, also tends to the NA–EI line but there is no NS influence at the bottom here. On the southern side of the Ridge, the curve for station D12 follows the NA–NI line down to about 350 m depth and then shows first EI influence and then NS water in the overflow at the bottom. At the next six stations, D27–G22, the curves approach the NA–EI line and show no NS influence at the bottom. Some of these curves, such as those for stations G8 and 22, may be influenced by AI water, as at the two southernmost stations on the section, H8 and H20, the curves follow the NA–AI line to about 4°C, below 1,100 m, and then move towards the NA–NS line, due to the effect of the Faroe Bank Channel outflow.

Survey 2

The temperature and salinity sections for this survey (Figures 3:77 and 3:78) are similar to those for Survey 1, but the area of the sea-bed on the southern slope of the Ridge with a temperature below 1°C and a salinity below 34·95 $^0/_{00}$ has increased, suggesting that the overflow has developed much further, although on the northern side of the Ridge sub-zero temperature water does not reach to within 100 m of the crest of the Ridge. Moreover, the temperature at the sea-bed at stations H108 and H120 in the region of the Faroe Bank Channel outflow is now lower, below 2°C.

The T-S curves (Figure 3:79) for the three stations on the northern side of the Ridge as before follow the the NA–NI line down to 300–350 m depth and then show EI influence followed by NS influence at the bottom, but on this occasion NS water is not present at station B124. The curves for stations C111–F110, near the top of the Ridge, all fall between the NA–NI and NA–EI lines and all but D112 show NS influence at the bottom in the overflow. Stations F129–G122 further south, however, have curves which approach the NA–NS line, and the two southernmost stations on the section, H108 and 120, again follow the NA–AI line but have points near the bottom which on this survey actually fall on the NA–NS line, thus showing an increased effect of the Faroe Bank Channel outflow.

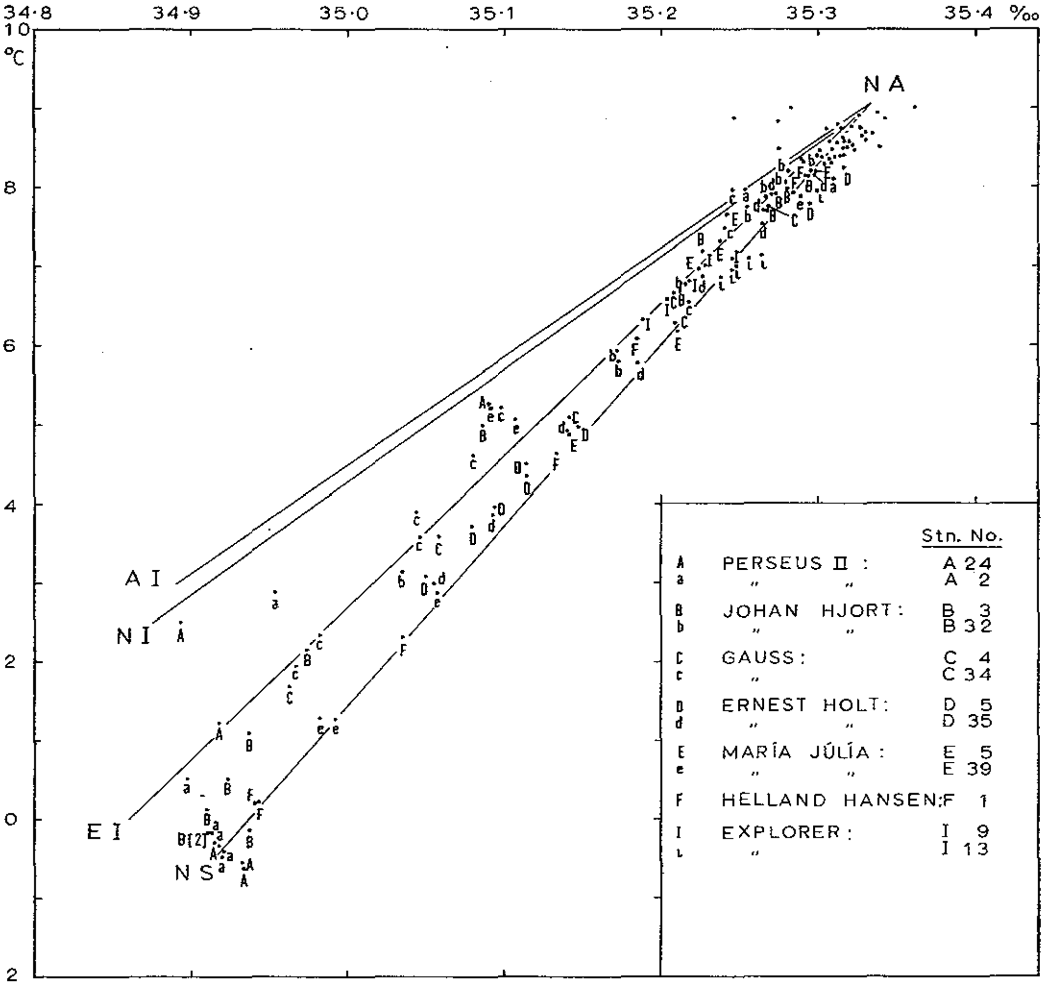

Figure 3:58.
Section β, first Survey: temperature °C – salinity ‰.

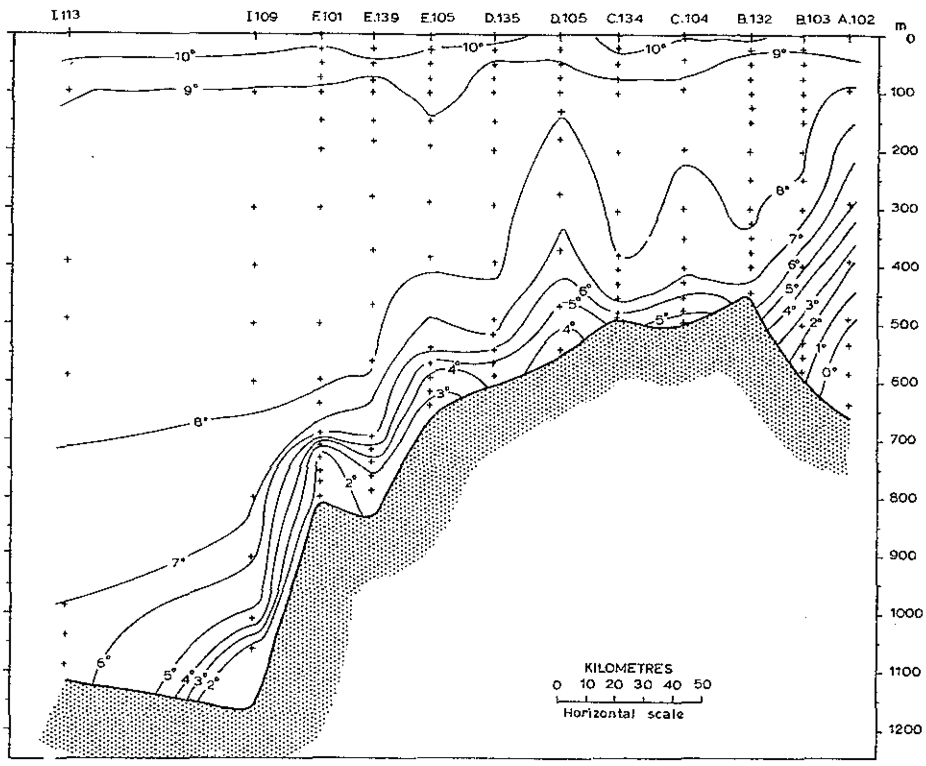

Figure 3:59
Section β, second Survey: temperature °C.

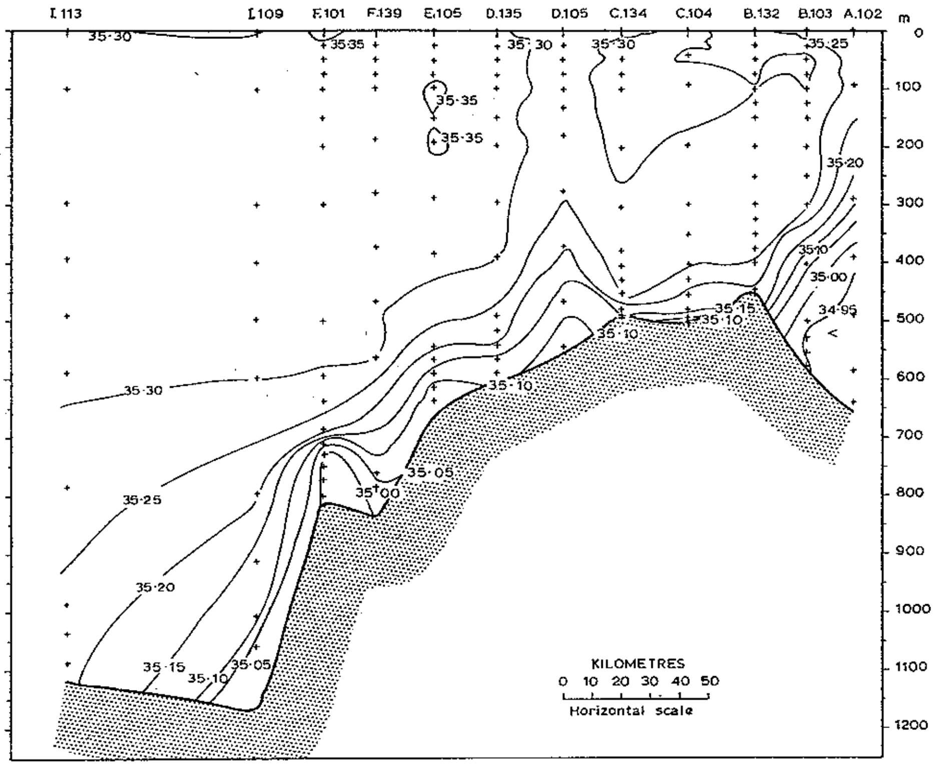

Figure 3:60.

Section β, second Survey: salinity $^0/_{00}$.

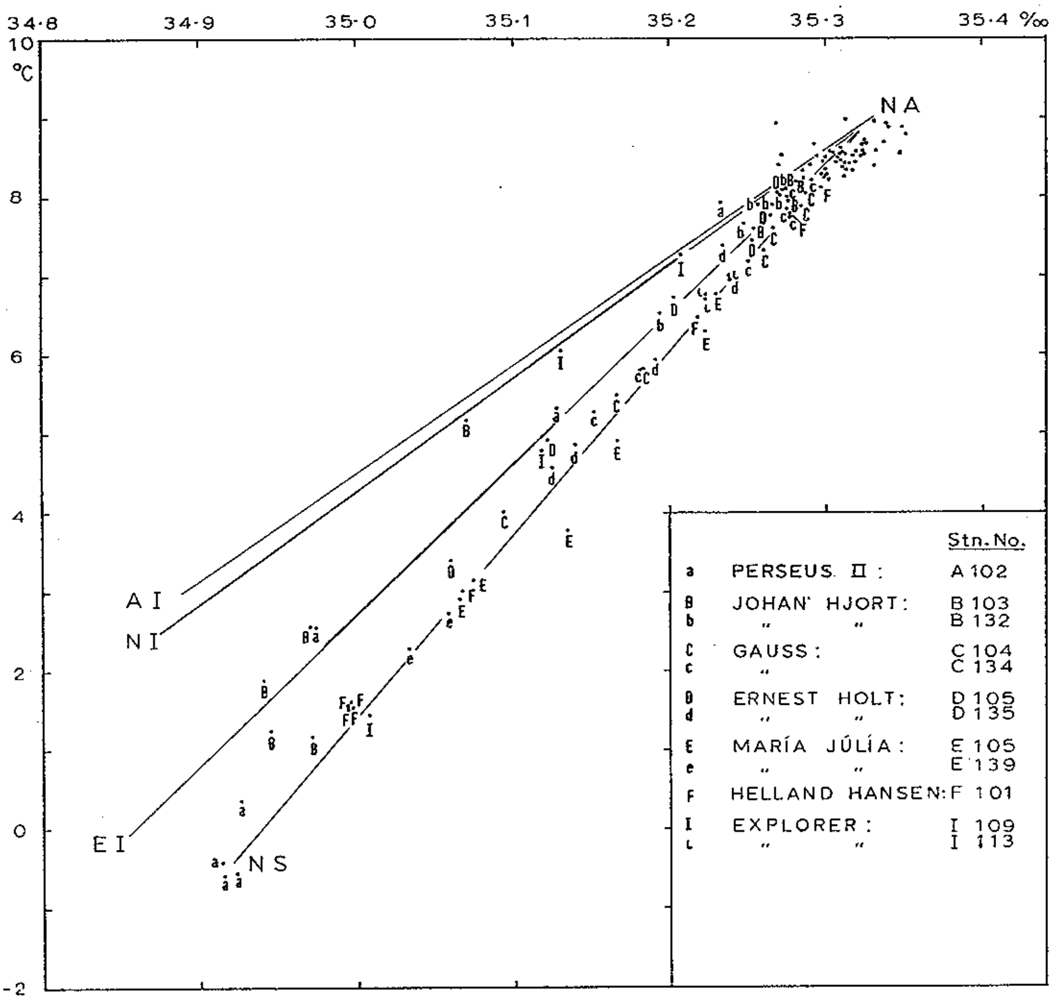

Figure 3:61.

Section β, second Survey: temperature °C – salinity $^0/_{00}$.

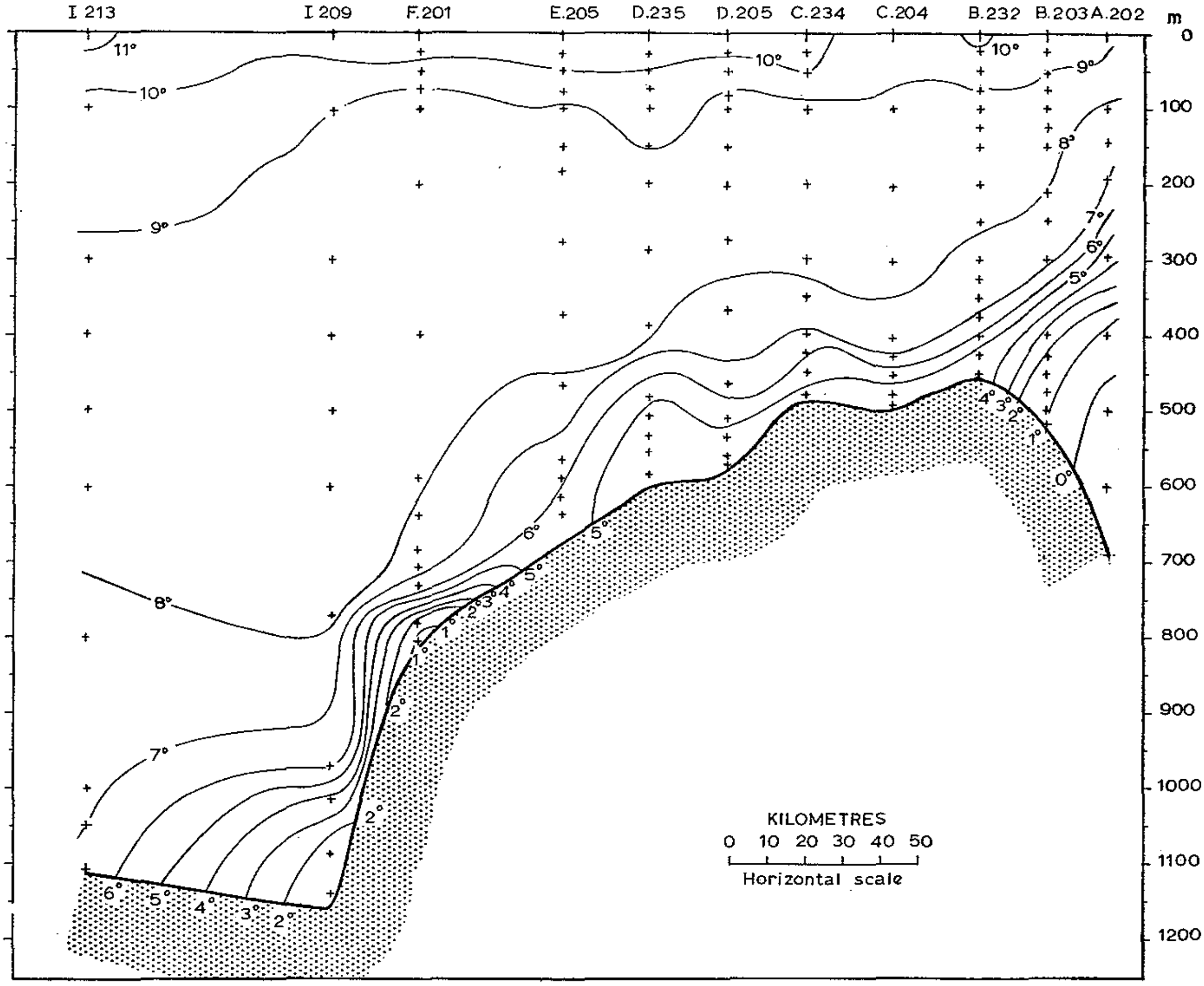

Figure 3:62. Section β, third Survey: temperature °C.

Survey 3

The sections for this survey (Figures 3:80 and 3:81) show a contraction of the overflow and no temperatures below 3° C on the southern flank of the Ridge, except near station D212, where the temperature at the sea-bed is below 1° C as on Survey 1, and near station G208. As on Survey 2 sub-zero temperature water is 100 m below the crest of the Ridge on its northern side. The effect of the Faroe Bank Channel outflow is not pronounced on this occasion, but the chart showing the bottom temperature distribution indicates that the water below 3° C at the bottom at station G208 is part of it. "Discovery II" did not work her station in about 1,500 m depth on this survey and so the overflow may not have been completely sampled.

Figure 3:82, T-S shows the T-S curves for the section and it can be seen that, as before, at the three northernmost stations the curves on the whole tend to the NA–NI line but that as the bottom is approached EI and then NS influence becomes apparent. The curves for the stations C211 to D227 near the top of the Ridge fall between the NA–NI and NA–EI lines and at C211 and D212 they show NS influence near the bottom. Proceeding south along the section, stations E213 and F210 this time have curves close to the NA–EI line, and those for stations F229 to G222 approach the NA–NS line and indicate that the water at the bottom at station G208 is Faroe Bank Channel outflow. At the southernmost station, H208 on this occasion, the curve again follows the NA–AI line between 700 and 1,150 m and moves to the NA–NS line near the bottom indicating some effect from the Faroe Bank Channel outflow but less than on Survey 2.

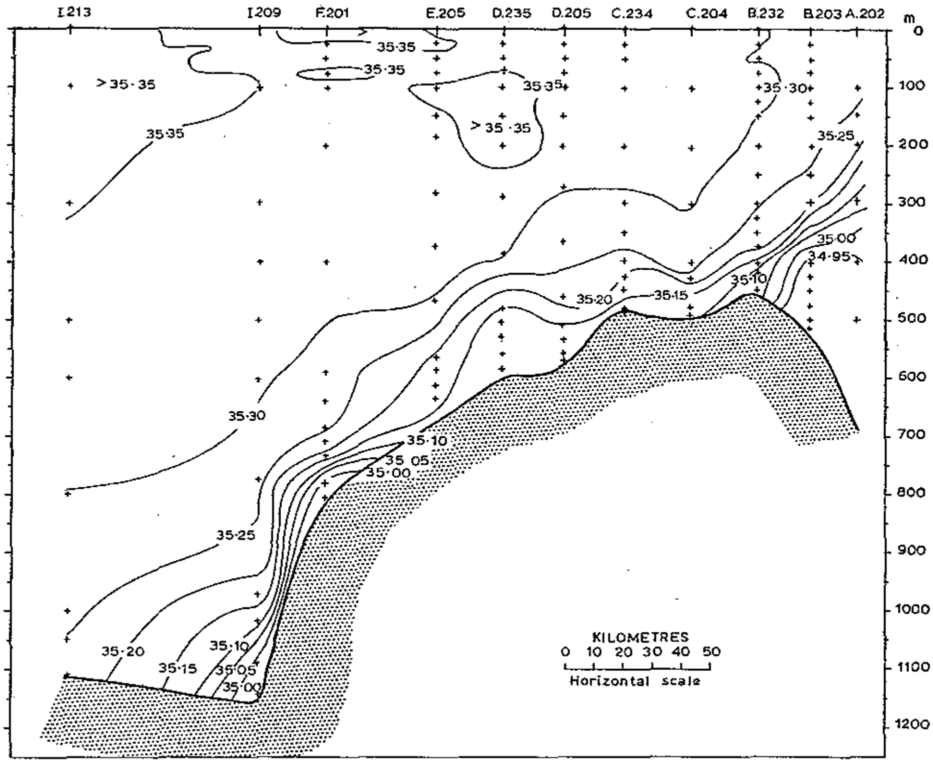

Figure 3:63.

Section β, third Survey: salinity ‰.

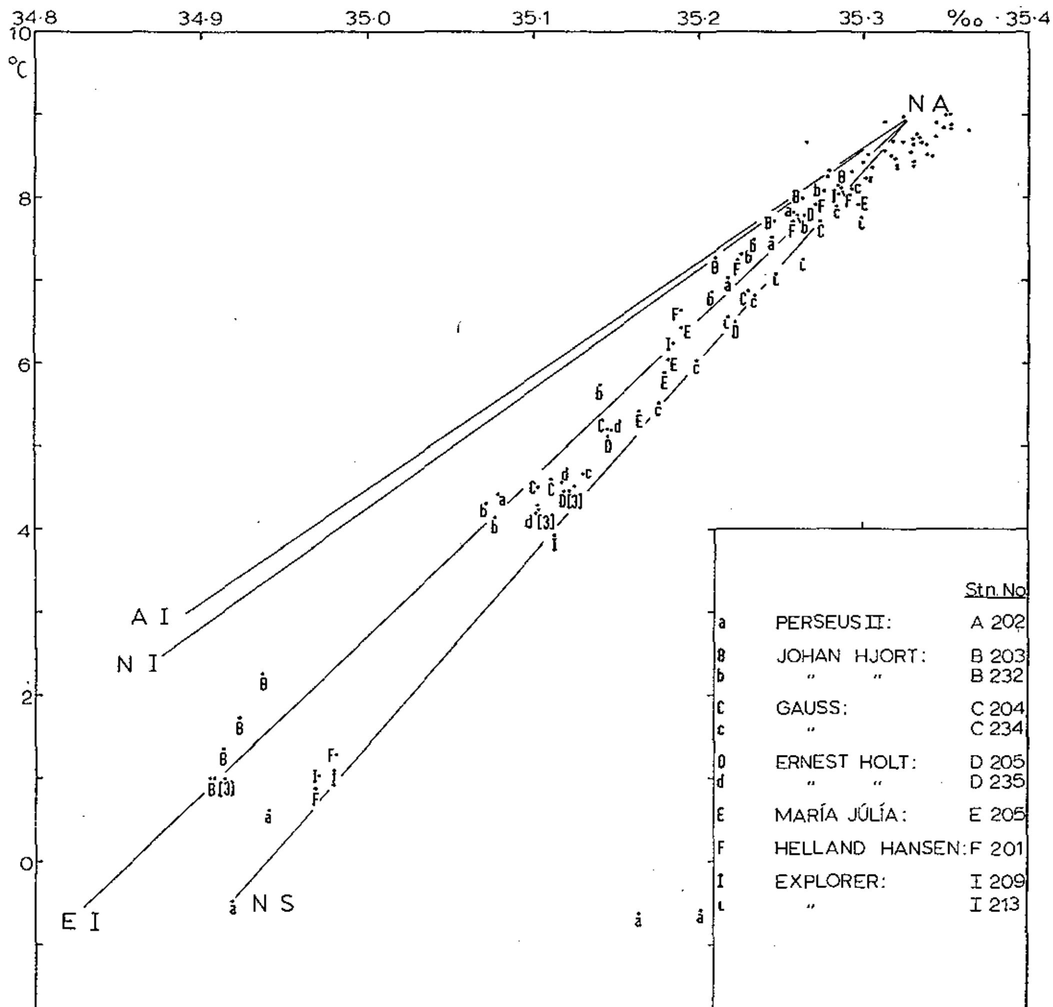

Figure 3:64.

Section β, third Survey: temperature °C – salinity ‰.

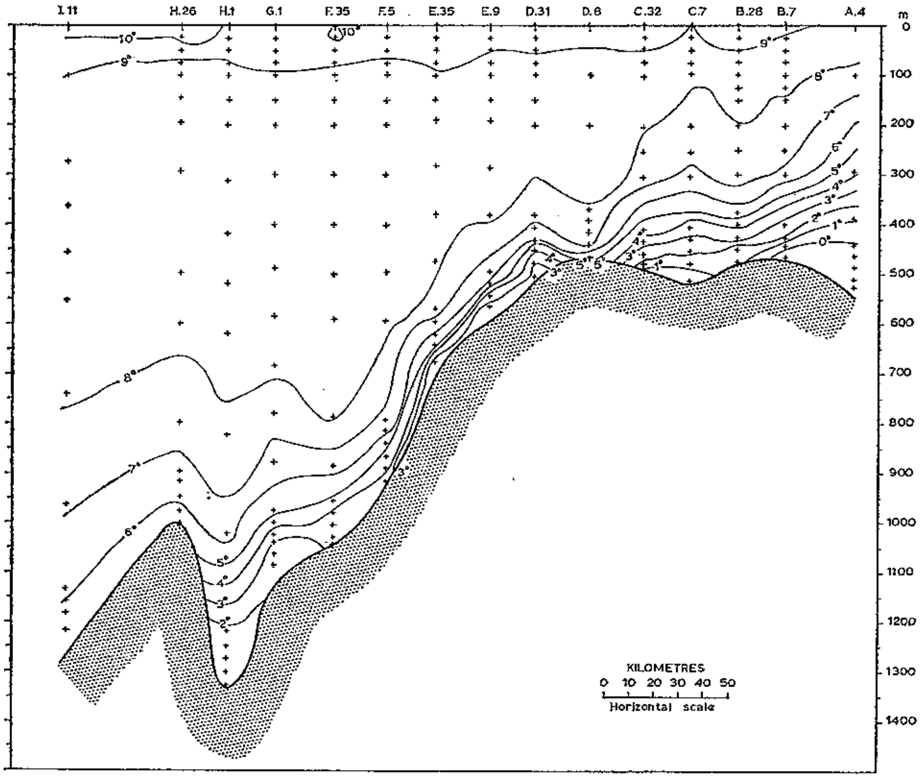

Figure 3:65. Section γ, first Survey: temperature °C.

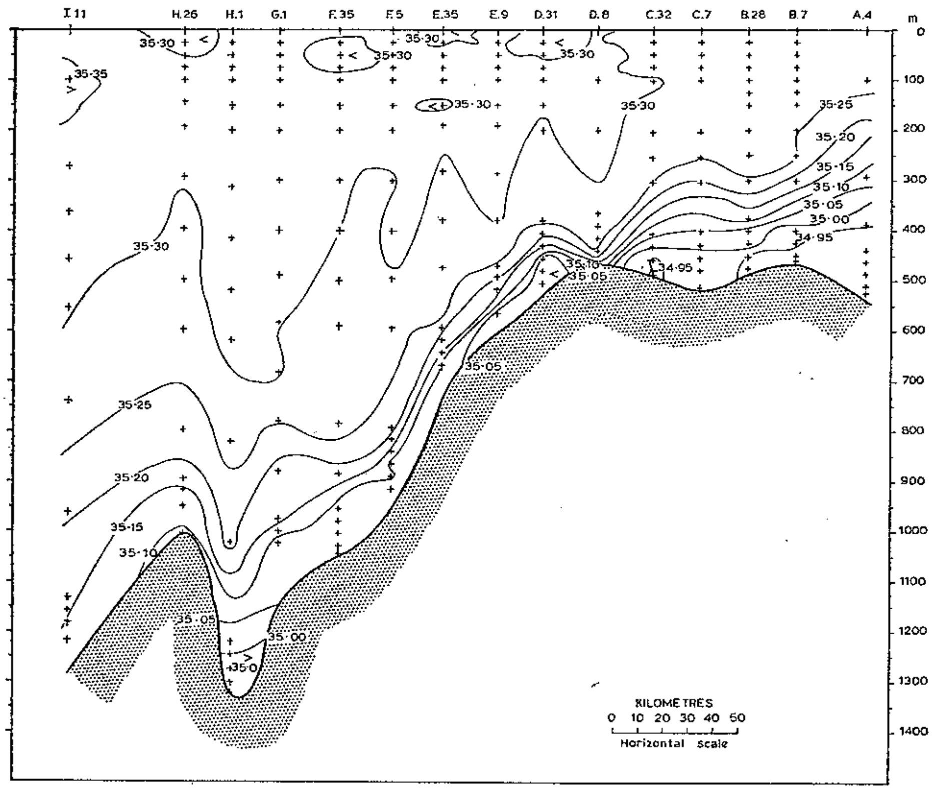

Figure 3:66. Section γ, first Survey: salinity $^0/_{00}$.

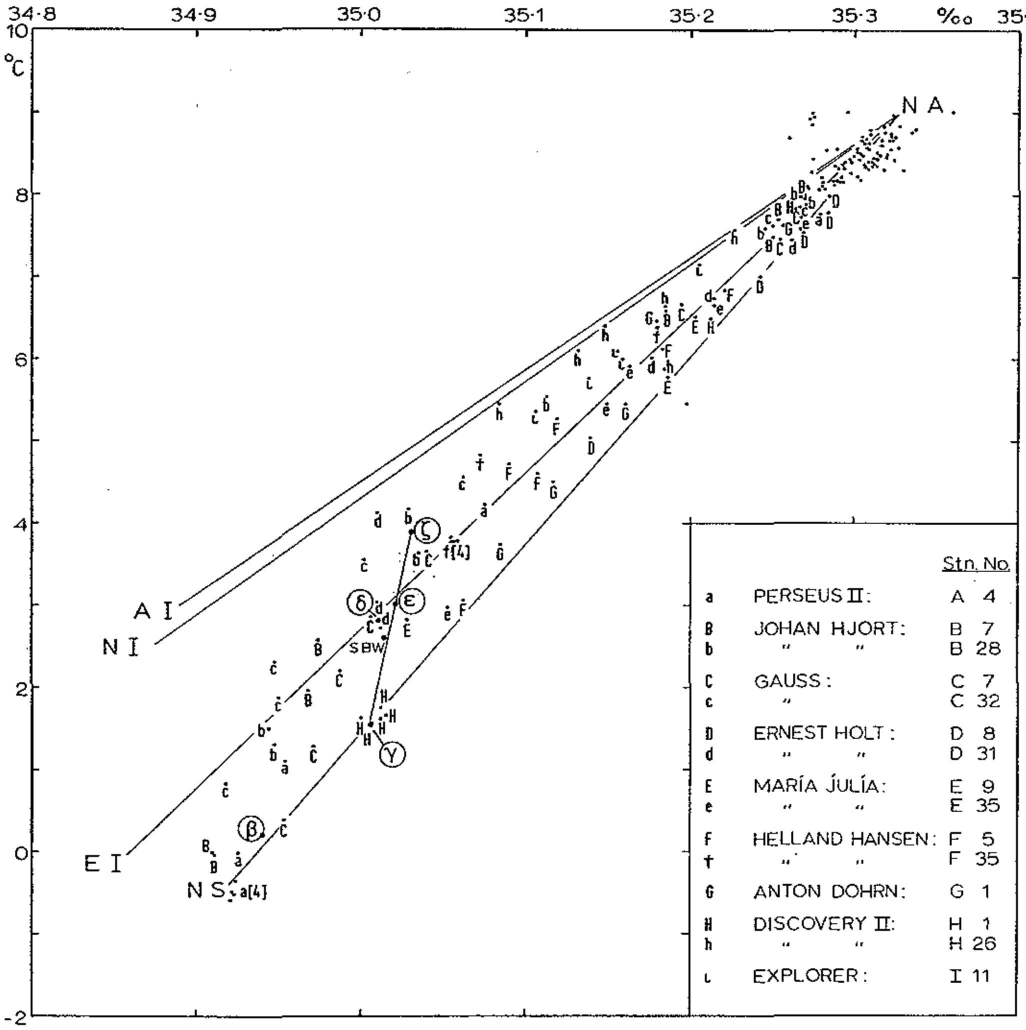

Figure 3:67. Section γ, first Survey: temperature °C – salinity ‰.

SECTION ε

Survey 1

The temperature and salinity sections (Figures 3:33 and 3:84) show the whole of the sea-bed on the southern slope of the Ridge to be covered with water warmer than 5°C having a salinity above 35·1 ‰ from the crest down to 800 m, below which depth the temperature falls to less than 3°C between 1,250 and 1,900 m. The salinity at these depths is below 35·05 ‰ and overflow water is present here, but it is not clear if it comes from the Faroe Channel outflow or as a result of further fall and deflection to the right of the overflow across the Ridge which was occurring down to 800 m on Section δ during this survey. At the northern end of the section sub-zero temperature water in the Norwegian Sea does not reach to within 150 m of the crest of the Ridge. Water with a salinity below 34·9 ‰ is present here at 300 m depth. As temperatures at the bottom are higher on this section the sharp thermal gradients above the bottom found on Sections β–δ tend to be absent.

The T-S curves (Figure 3:85) show the presence of EI water at about 300 m depth with NI water above and NS water below it at the northernmost station, A8. The curves for the stations on the top of the Ridge, B14 and B19, fall between the NA–NI and the NA–EI lines, but that for station C17 is close to the NA–NI line. On the southern side of the Ridge the curves for stations D18 and E19 fall between the NA–EI and NA–NS lines. Further south still the curves for stations F16 to H17 all approach the NA–AI line between 4–7°C, 800–1,500 m depth, and at greater depths move towards the NA–NS line indicating the presence of overflow water.

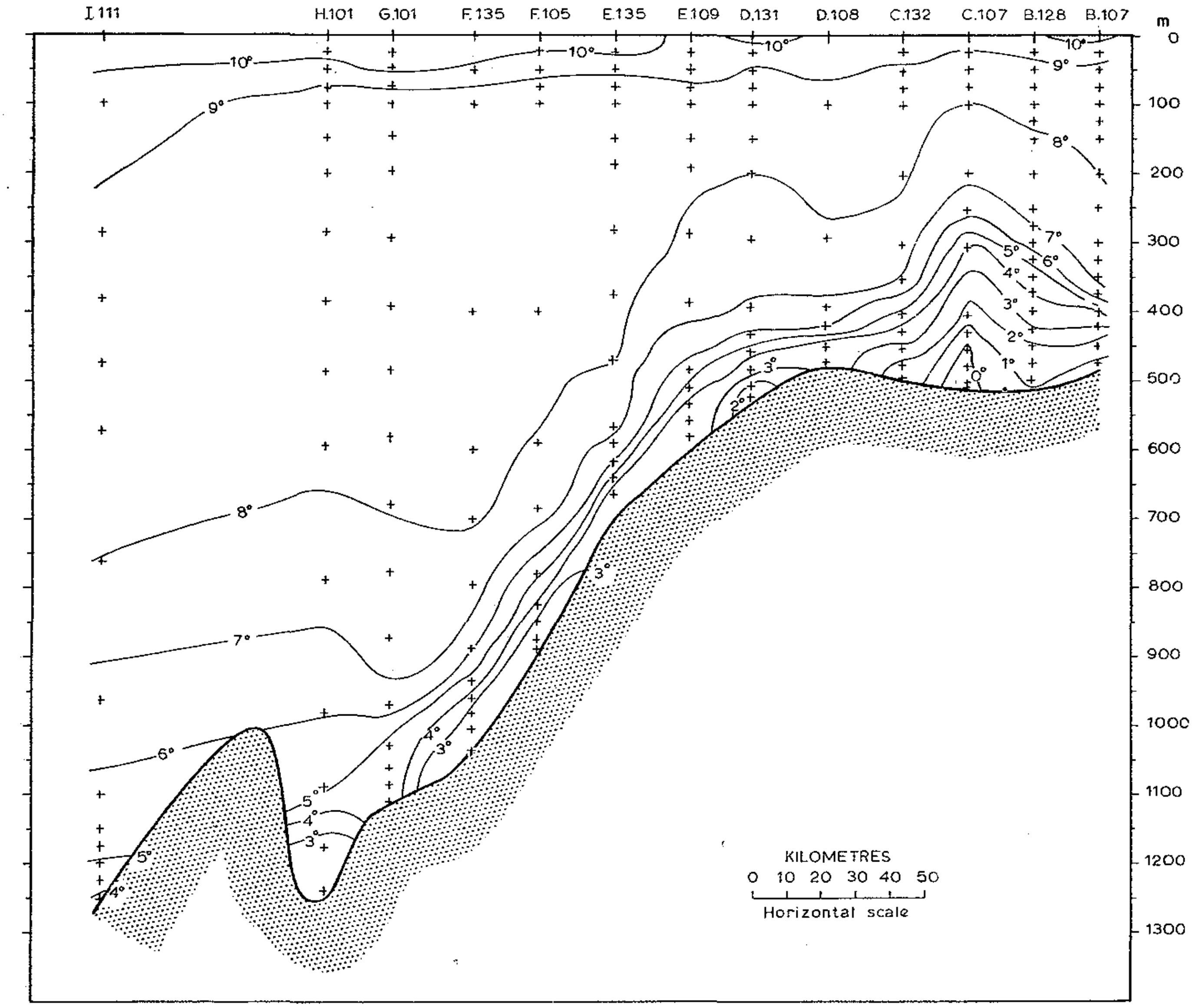

Figure 3:68. Section γ, second Survey: temperature °C.

Survey 2

Figure 3:86 shows cooler conditions on the bottom during this survey: on the southern slope at station C117 temperatures are below 2° C and at no point are temperatures above 4° C seen. At the southern end of the section water below 3° C is present on the bottom at depths below 1,150 m, and Figure 3:87, shows its salinity to be below 35·05 ‰, but as on the first survey this is higher than that of the water just off the slope at the same depth. This is again overflow water. In the Norwegian Sea water below 34·9 ‰ salinity is still present and the sub-zero temperature water is now within 125 m of the crest; but the crest itself is covered with water warmer than 7° C and the bottom temperature chart for the survey shows the cold water to the south of it at station C117 to be the product of one of the overflows taking place on either side of this section. It is not a discrete bolus of overflow water as might have been inferred if only a single section had been worked.

The T-S curves (Figure 3:88) again show the influence of EI water at 300 m depth at station A108 and of NI water at lesser and NS water at greater depths. The curves for stations B114 and B119 on the top of the Ridge once more fall between the NA–NI and NA–EI lines, but that for station C117 this time falls close to the NA–EI line even at the bottom. The curves for stations D118 and E119 also fall close to this line, but that for station F116 approaches the NA–NS line. The remaining stations on the section have curves which

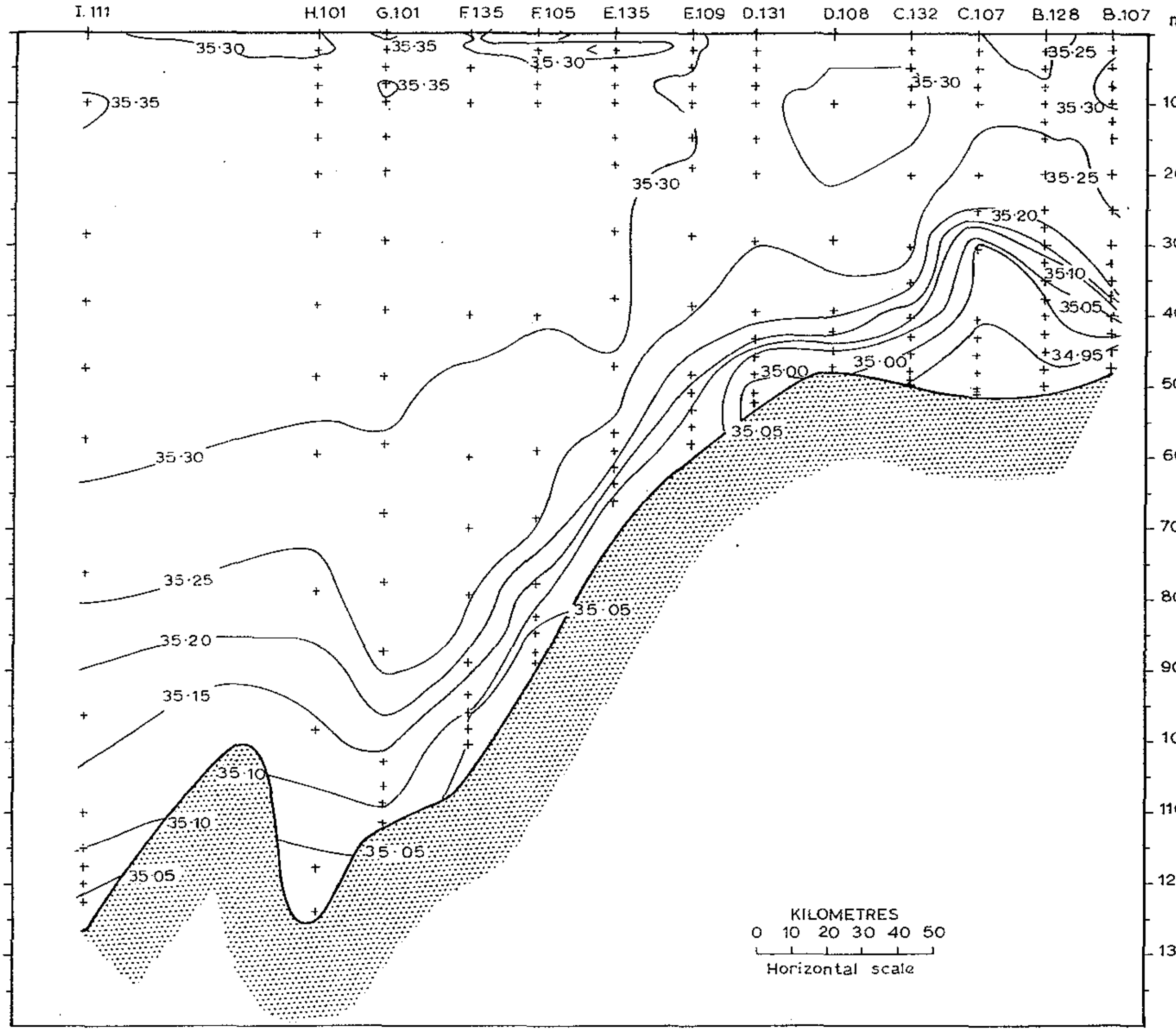

Figure 3:69. Section γ, second Survey: salinity $^0/_{00}$.

approach the NA–AI line between 4–7° C, below 800 m depth, and then near the bottom move towards the NA–NS line as overflow water is met. The chart of the bottom temperature distribution for the survey shows that the NS element in this overflow water at the southern end of the section has the two possible sources already discussed under Section ε, Survey 1, and that it might be augmented by an overflow of water which will be discussed under Section ζ: all these overflows converge on a deep trough which cuts back into the Ridge on this section.

Survey 3

Figure 3:89 shows a return to the warmer condition on the southern slope found on Survey 1. Bottom temperatures above 5° C are found from the crest down to 600 m and temperatures below 3° C are only found in the overflow water below 1,350 m depth. In the Norwegian Sea water with a salinity below 34·9 $^0/_{00}$ is again seen at 300 m depth and sub-zero temperature water now reaches to within 100 m of the crest of the Ridge.

The T-S curves (Figure 3:91) are similar to those for the corresponding stations on Surveys 1 and 2 as far as stations A208 and B219 are concerned, but that for station B214 now follows the NA–NI line and shows NS influence at the bottom. The curves for stations C217–E219 follow the NA–EI line as on Survey 2, and those for the five stations at the southern end of the section are also similar to those for the corresponding stations on Surveys 1 and 2.

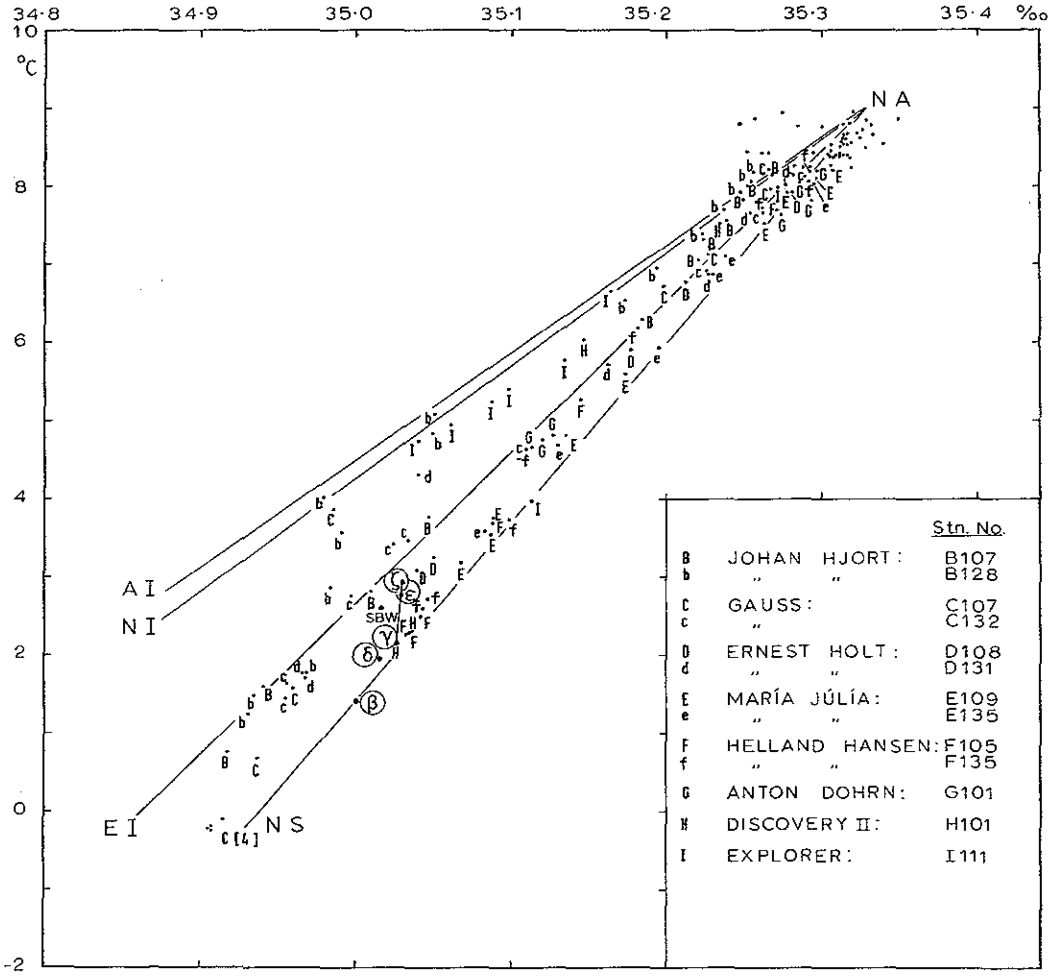

Figure 3:70.

Section γ, second Survey: temperature °C. – salinity ‰.

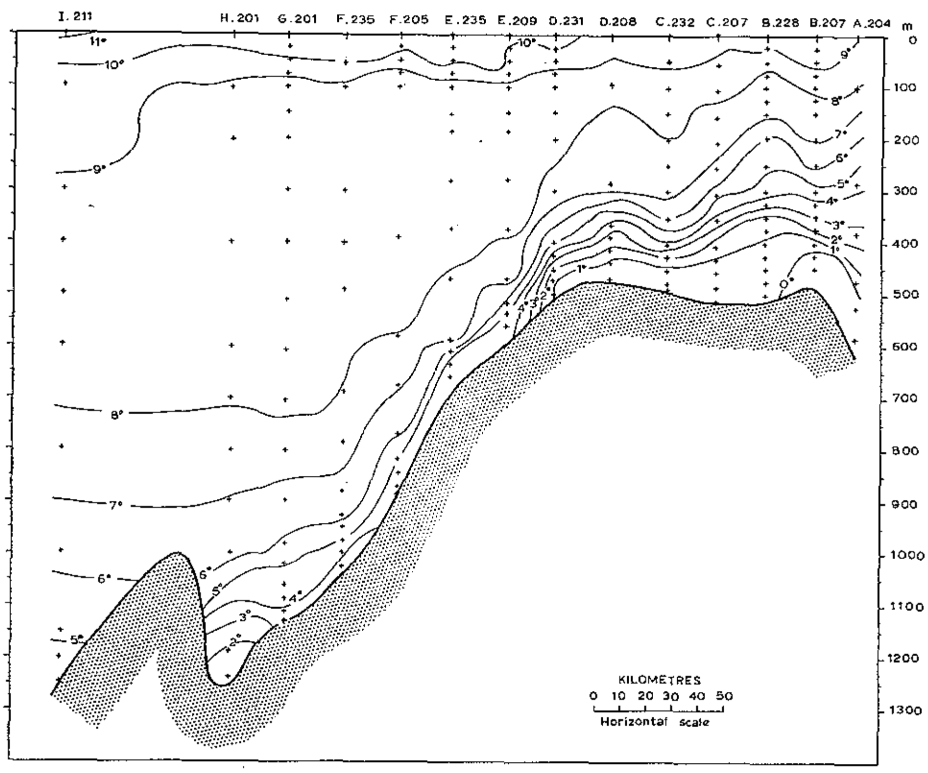

Figure 3:71.

Section γ, third Survey: temperature °C.

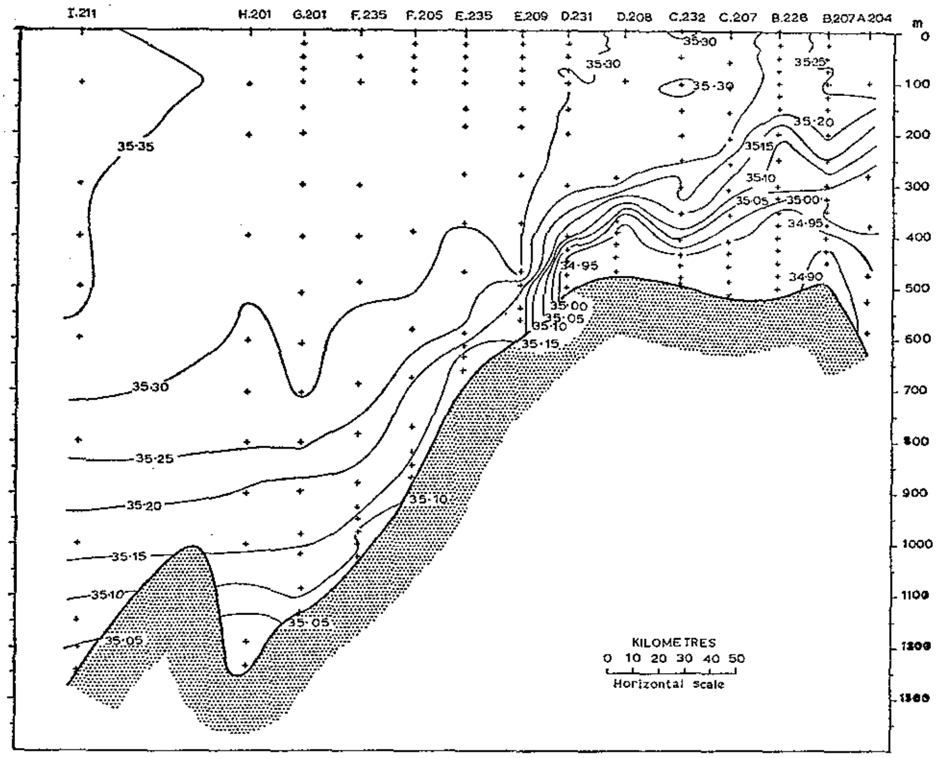

Figure 3:72.

Section γ, third Survey: salinity ‰.

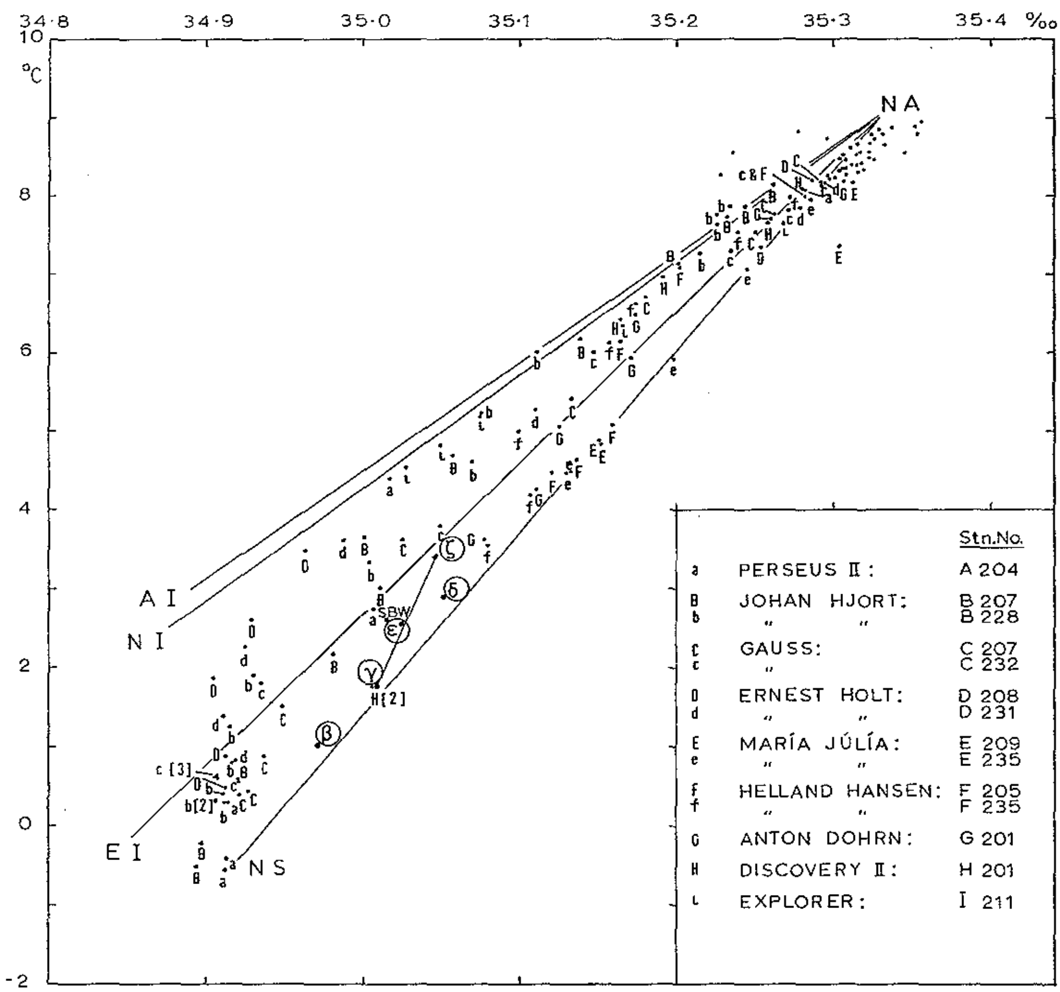

Figure 3:73.

Section γ, third Survey: temperature °C – salinity ‰.

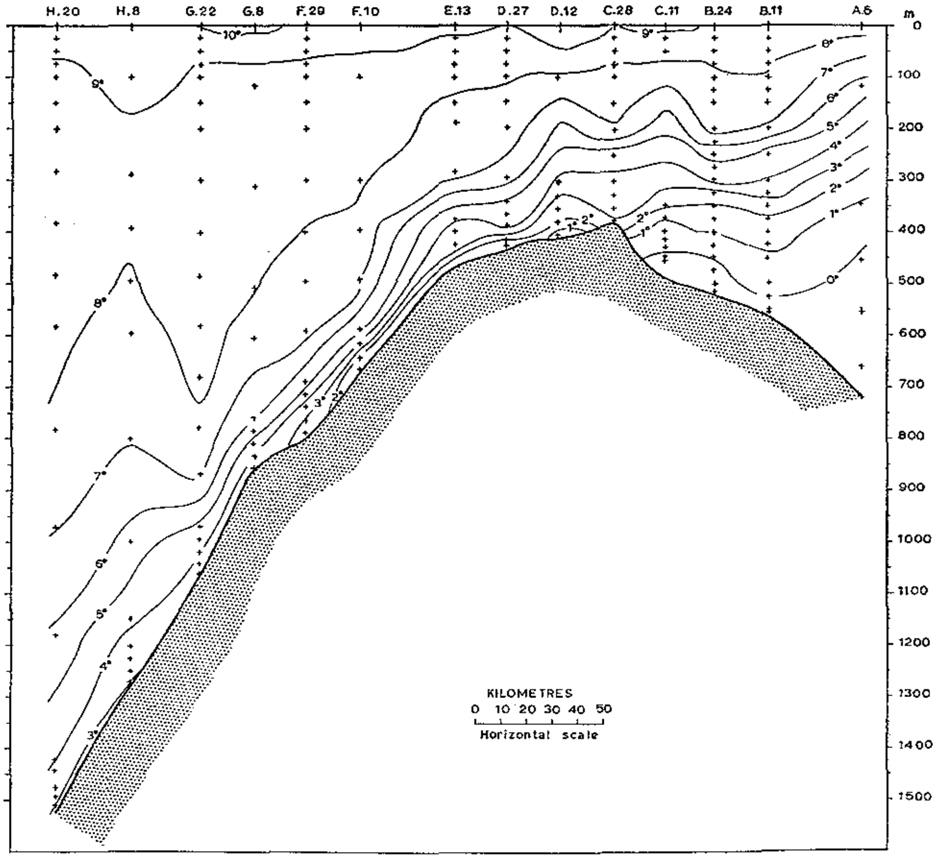

Figure 3:74.

Section δ, first Survey: temperature °C.

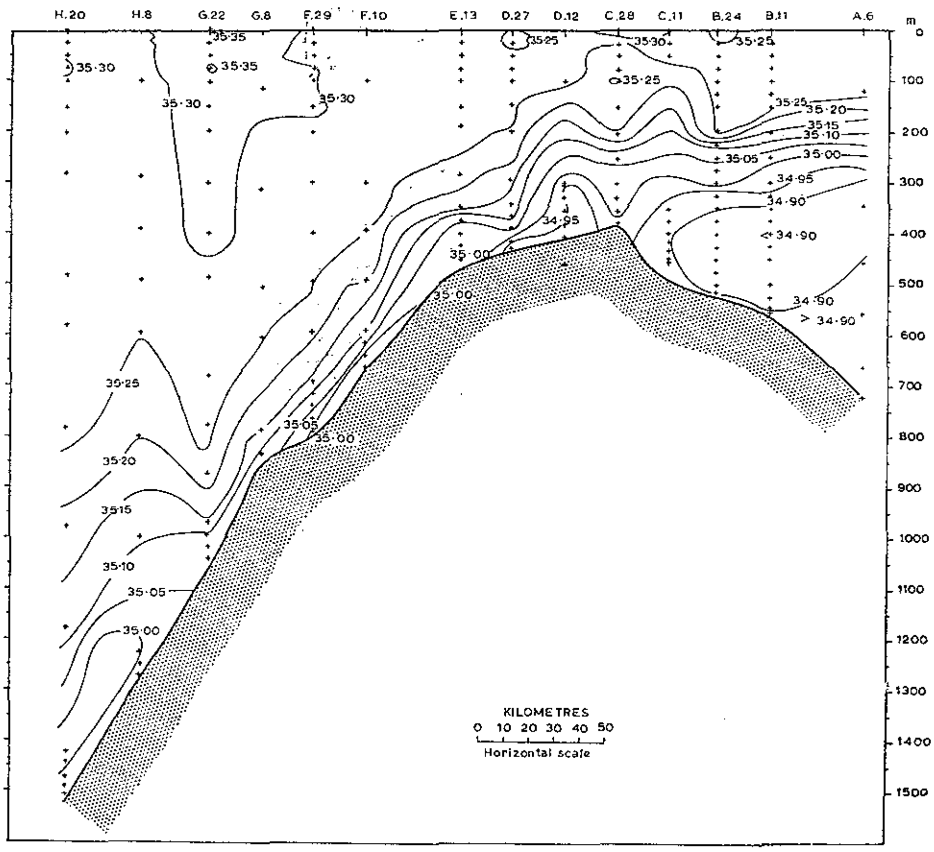

Figure 3:75.

Section δ, first Survey: salinity ‰.

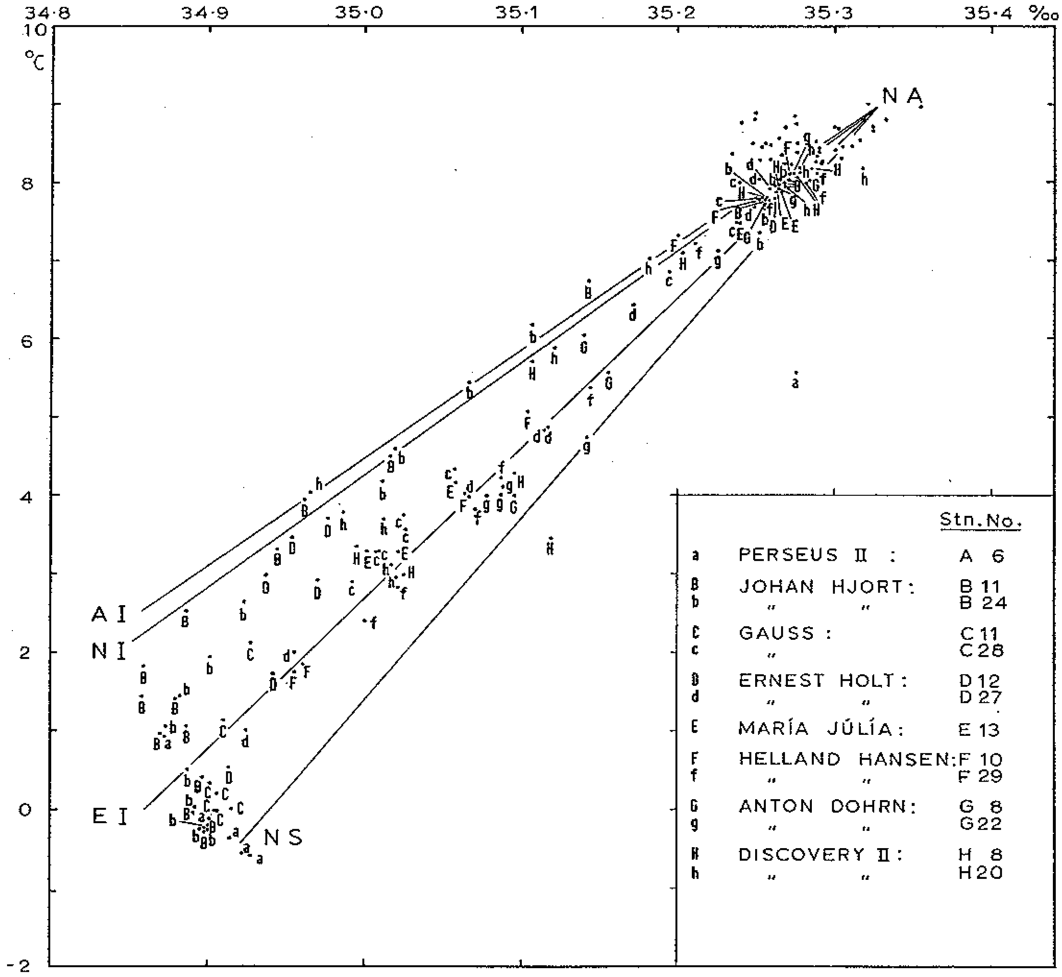

Figure 3:76. Section δ, first Survey, temperature °C – salinity ‰.

SECTION ζ

Survey 1

Figures 3:92 and 3:93 show that at the sea-bed the southern slope of the Ridge on this section during Survey 1 is covered with an overflow of water warmer than 3° C and on the whole more saline than 35·05 ‰, although water with a temperature below 1° C and a salinity below 34·9 ‰ is present on the crest of the Ridge. In the upper part of the water column on the south side of the Ridge water warmer than 8° C is only found down to 600 m depth compared with 700–800 m depth on most of the other sections. As on Section ε, the thermal gradient near the bottom here is not so steep as on the other sections.

The T-S diagram for the section (Figure 3:94) shows that at the most northerly station, B15, NI water is present at about 200 m depth with EI water below it at the bottom in 400 m depth. The two stations to the south of it, C18 and D19, have curves which approach the NA–NI line at 300 and 450 m respectively, but below these depths the curves move towards the NA–EI line as the bottom is approached. The curve for the next station south, D20, follows the NA–EI line fairly closely, but those for the remaining stations on the section show AI influence and lie between the NA–EI and the NA–AI lines between 8° and 4° C, 500–1,300 m depth. Near the bottom, however, they move towards the NA–EI line, but it is difficult to tell whether this is due to NS or EI influence. As far as station H13 is concerned the curve moves beyond the NA–EI line, and so at this station, at least, there would appear to be some NS influence at the bottom in 1,500 m depth: its possible sources are the same as those discussed under Section ε, Survey 1, when considering the NS influence at the bottom at the southern end of that section.

Survey 2

The temperature and salinity sections for this survey (Figures 3:95 and 3:96) are essentially similar to those for Survey 1, except that the overflow has, on the whole, a lower temperature, less than 3° C. The

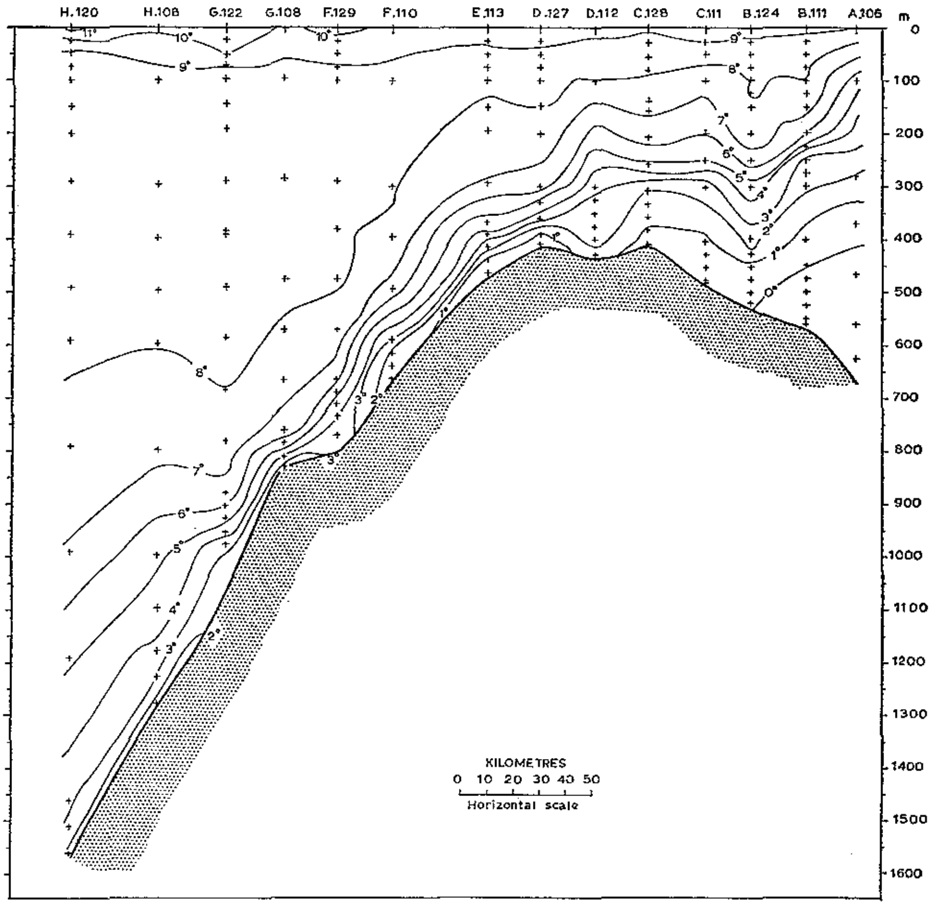

Figure 3:77.

Section δ, second Survey: temperature °C.

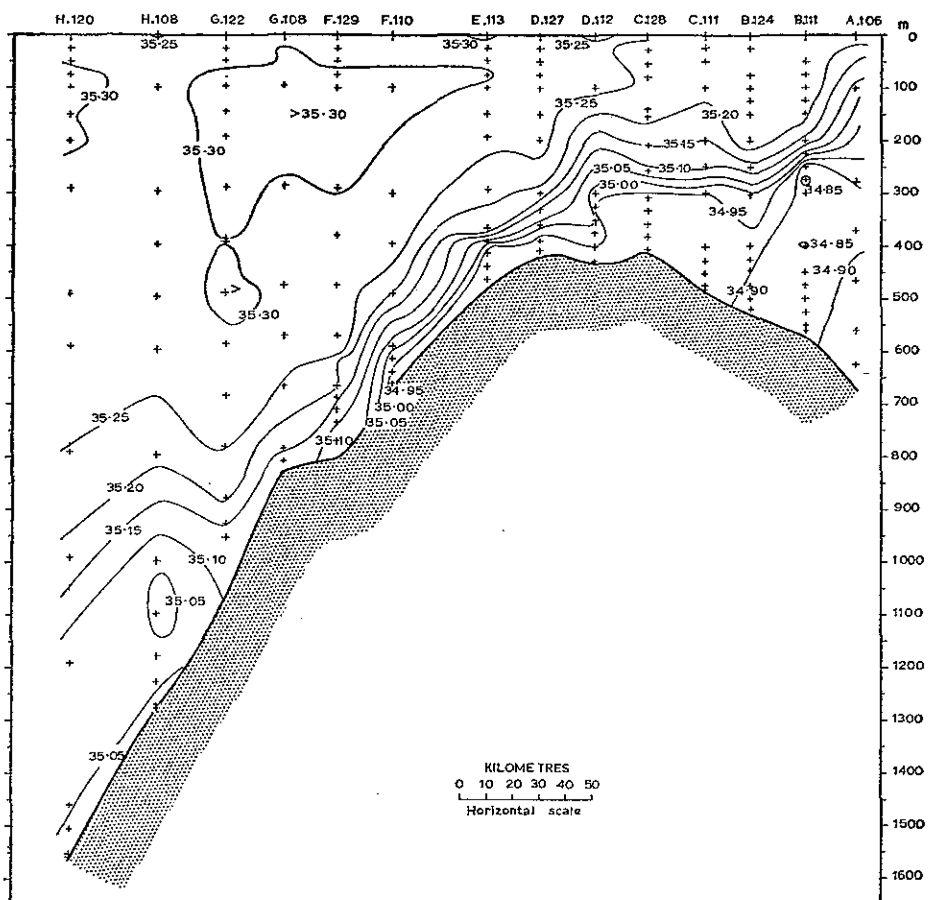

Figure 3:78.

Section δ, second Survey: salinity ‰.

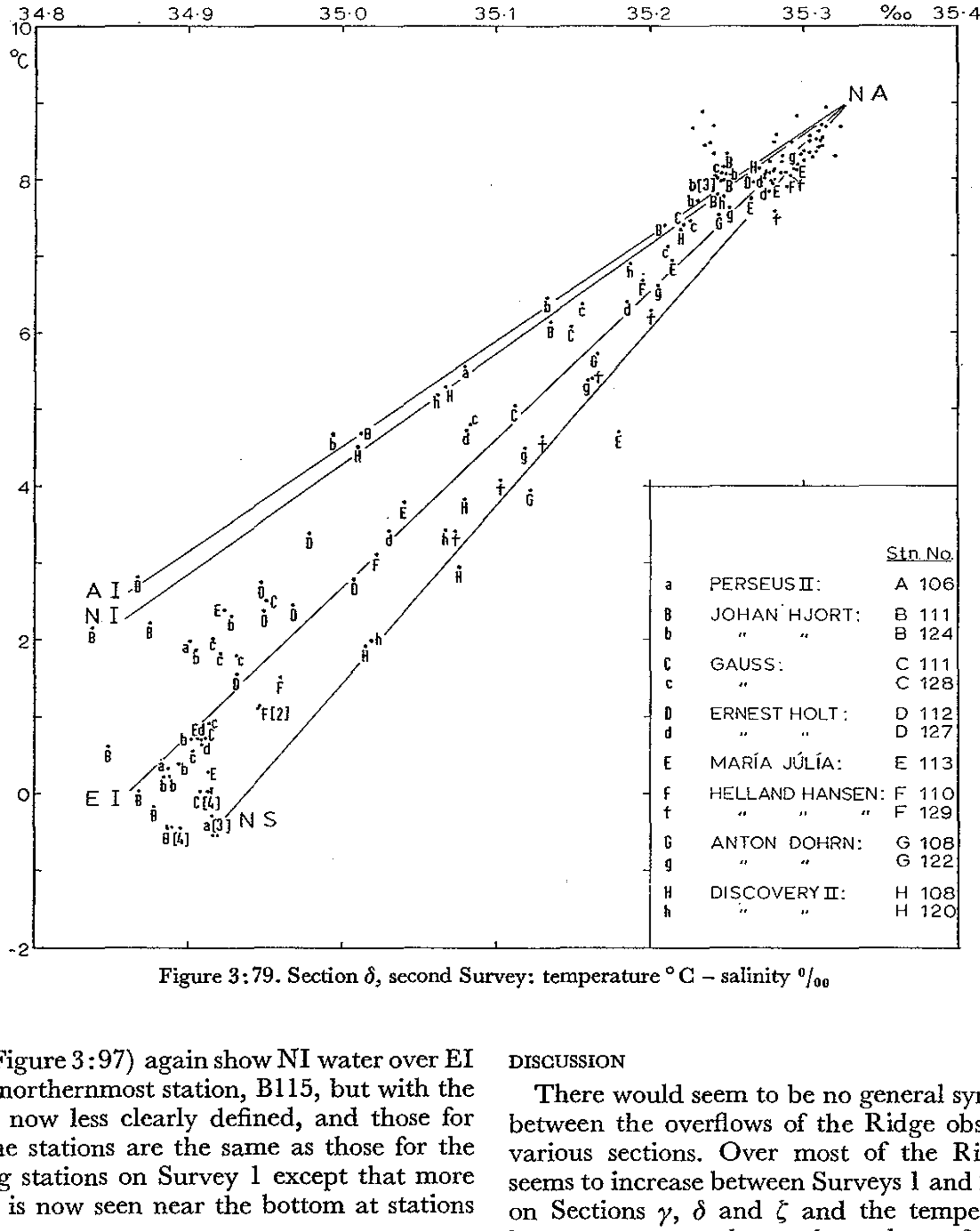

Figure 3:79. Section δ, second Survey: temperature °C – salinity ‰

T-S curves (Figure 3:97) again show NI water over EI water at the northernmost station, B115, but with the NI influence now less clearly defined, and those for the rest of the stations are the same as those for the corresponding stations on Survey 1 except that more NS influence is now seen near the bottom at stations F118–H113.

Survey 3

The diagrams for this survey (Figures 3:98 and 3:99) are again similar to those for Survey 1. Although the overflow is still colder than on Survey 1 and is below 3°C in its upper parts, it is warmer than on Survey 2. The T-S curves (Figure 3:100) are similar to those for the previous two surveys, except that no marked NI influence is present at station D219, both this station and D220 now following the NA–EI line closely, and that as on Survey 2 more NS influence is seen near the bottom at stations F218–H213 than on Survey 1.

DISCUSSION

There would seem to be no general synchronization between the overflows of the Ridge observed on the various sections. Over most of the Ridge overflow seems to increase between Surveys 1 and 2: it increases on Sections γ, δ and ζ and the temperature of the bottom water on the southern slope of the Ridge on Section ε decreases at the same time. But at the Faroe end of the Ridge such overflow as was present on Section β during Survey 1 disappears by Survey 2. Again, although at the northwestern end of the Ridge the overflow on Section δ decreases between Survey 2 and 3 and bottom temperatures on the southern slope increase on Sections ε and ζ, the overflow at the Faroe end of the Ridge increases as that on Section γ increases and the bottom temperatures on the southern slope on Section β decrease. As far as the Faroe Bank Channel outflow is concerned Section α was not examined during Survey 1, but conditions at the

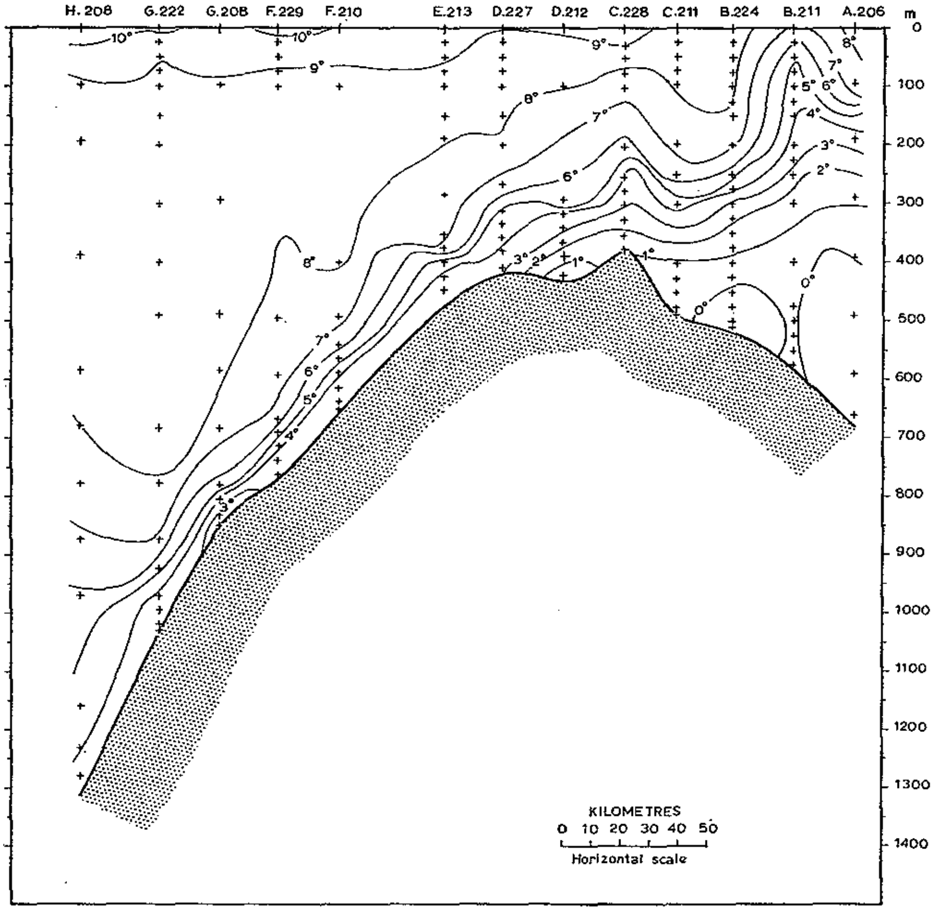

Figure 3:80.

Section δ, third Survey: temperature °C.

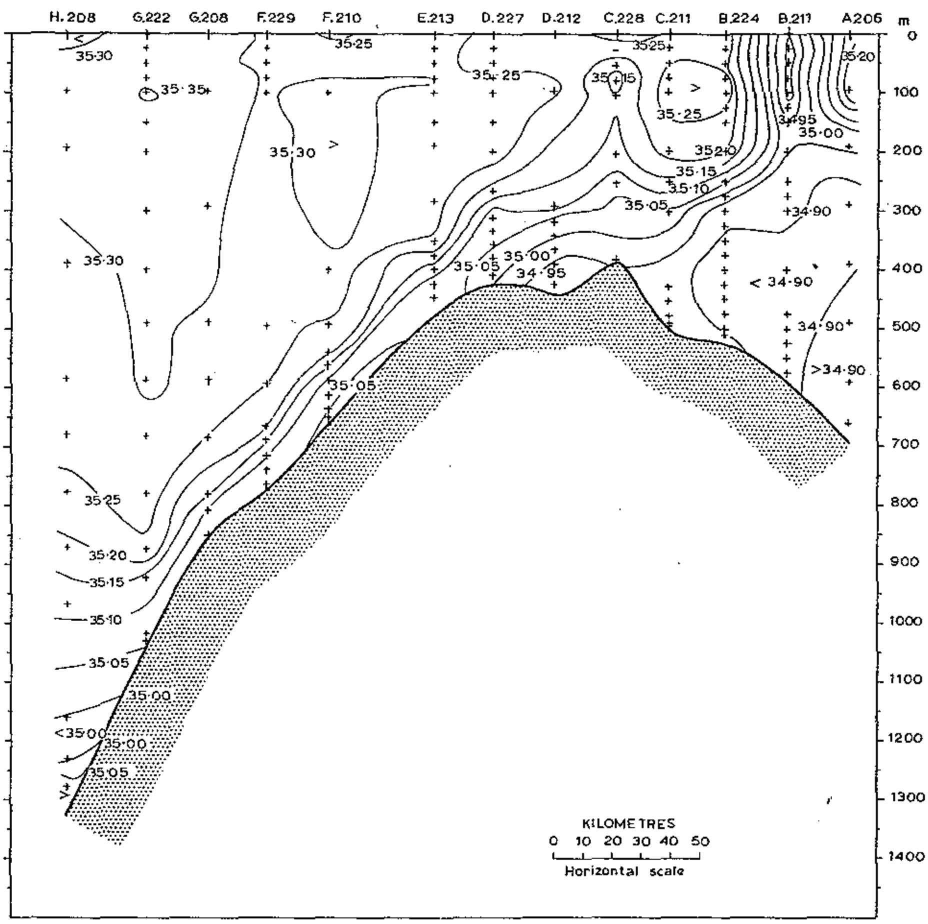

Figure 3:81.

Section δ, third Survey: salinity $^0/_{00}$.

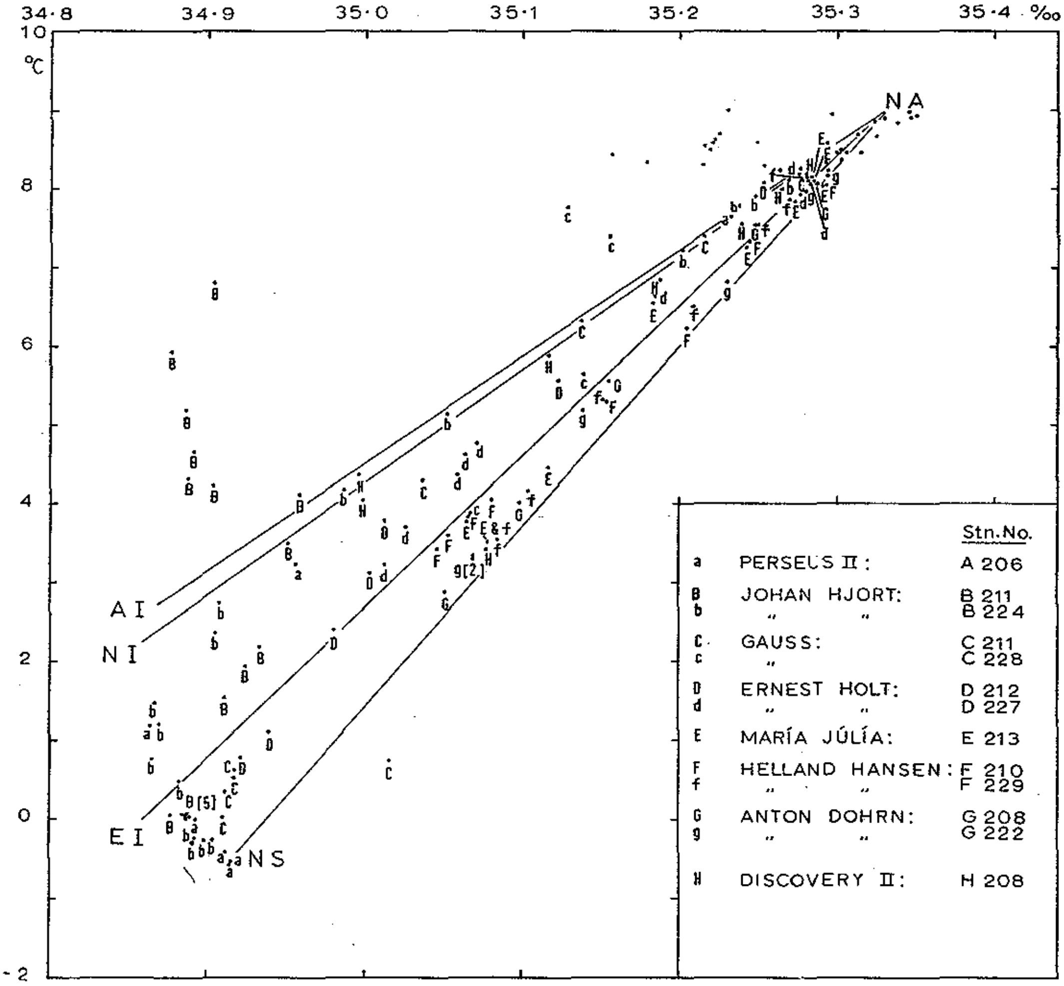

Figure 3:82.

Section δ, third Survey: temperature °C – salinity °/₀₀.

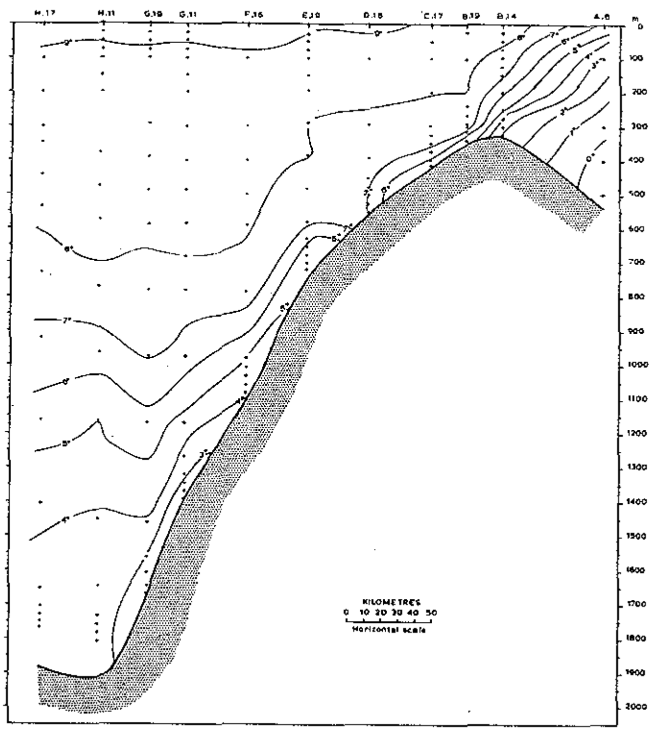

Figure 3:83.

Section ε, first Survey: temperature °C.

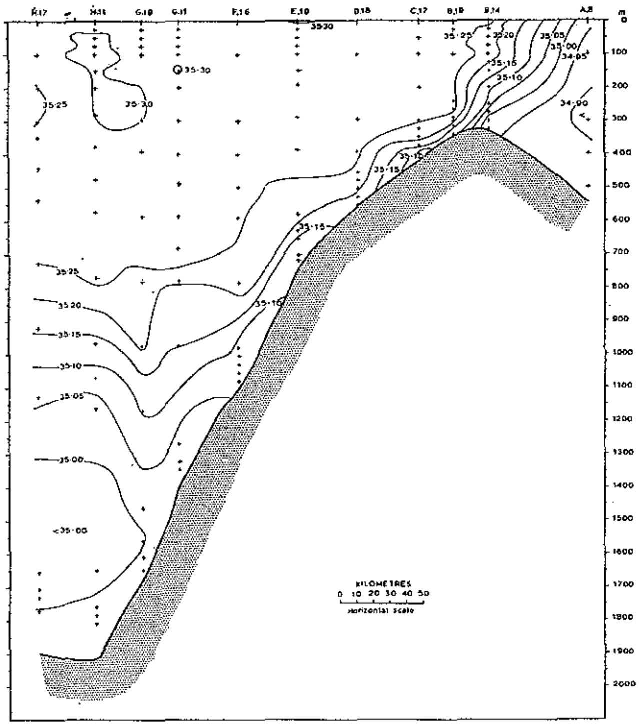

Figure 3:84.
Section ε, first Survey: salinity ‰.

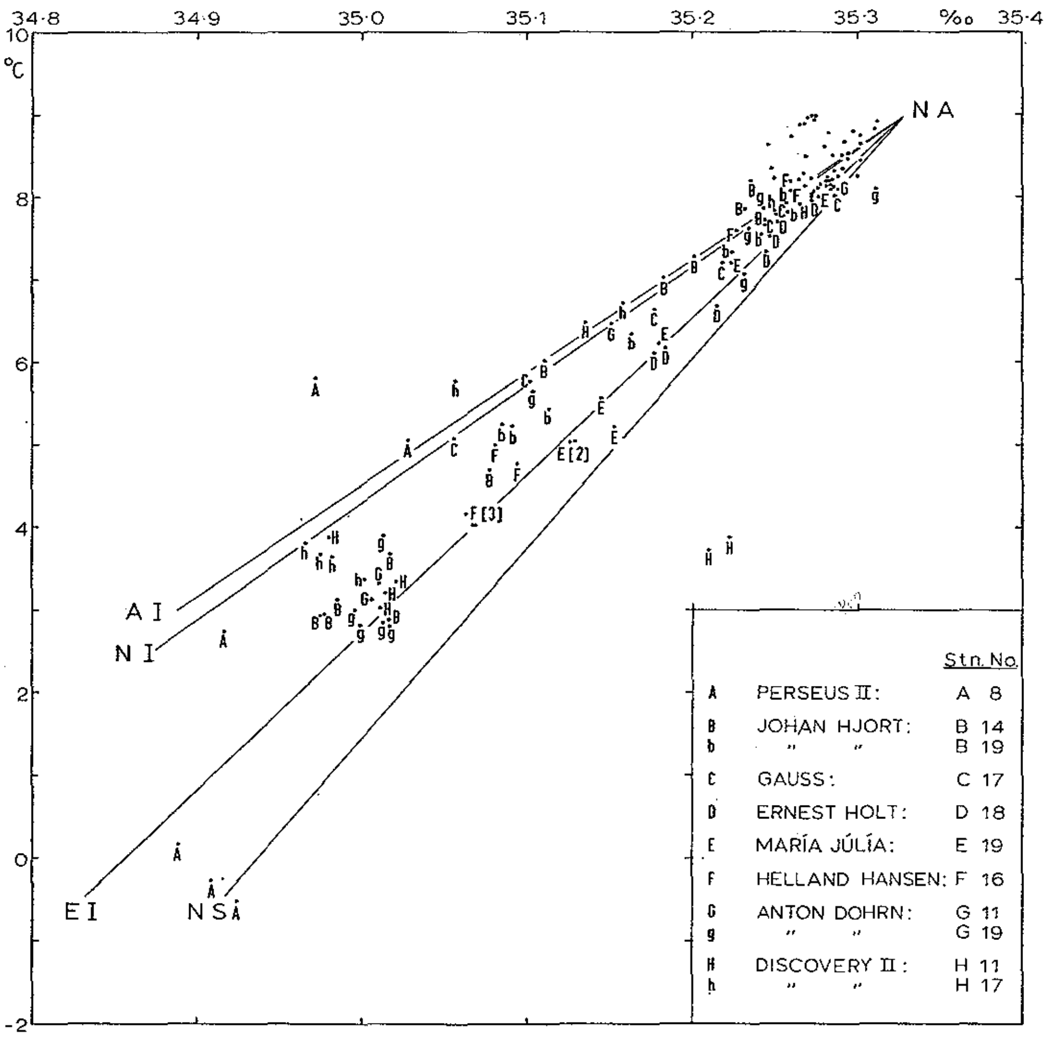

Figure 3:85.
Section ε, first Survey: temperature °C – salinity ‰.

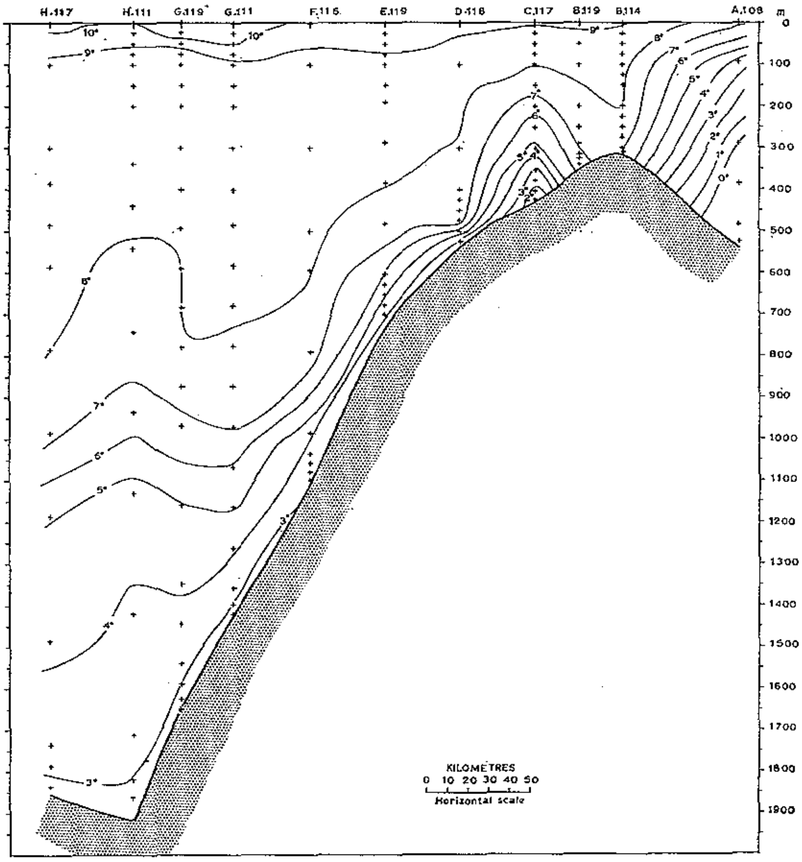

Figure 3:86.

Section ε, second Survey: temperature °C.

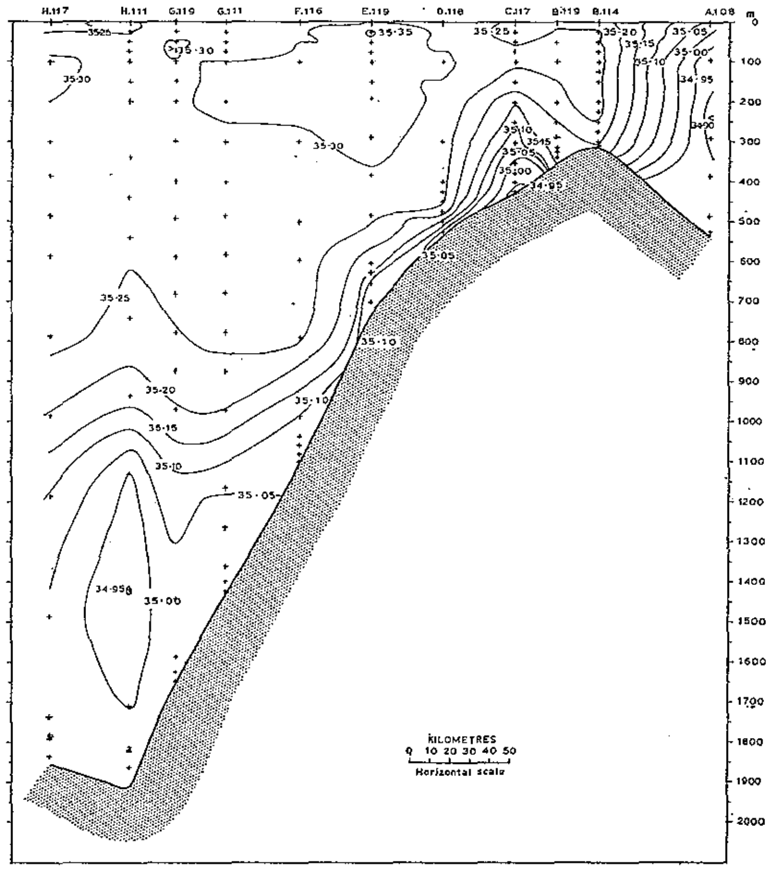

Figure 3:87.

Section ε, second Survey: salinity ‰.

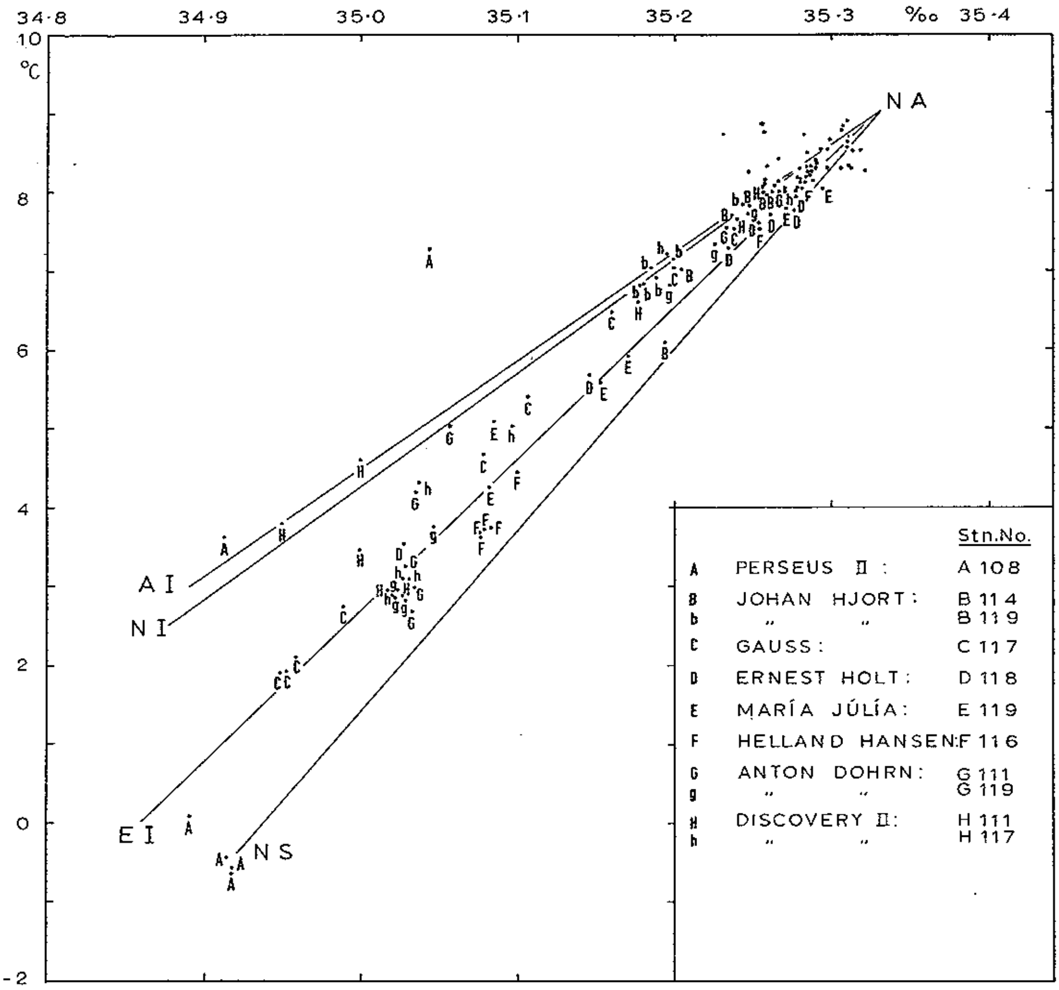

Figure 3:88.

Section ε, second Survey: temperature °C – salinity ‰.

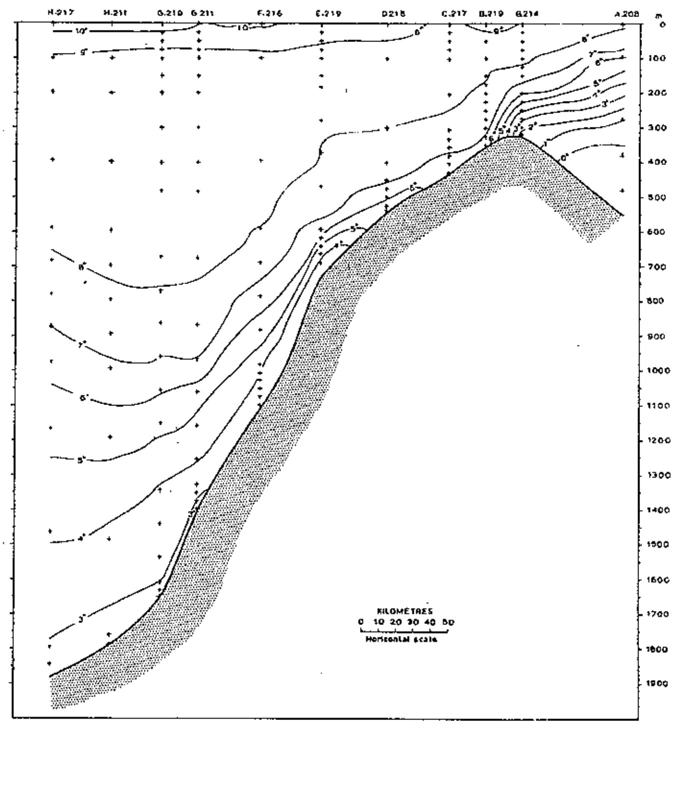

Figure 3:89.

Section ε, third Survey: temperature °C.

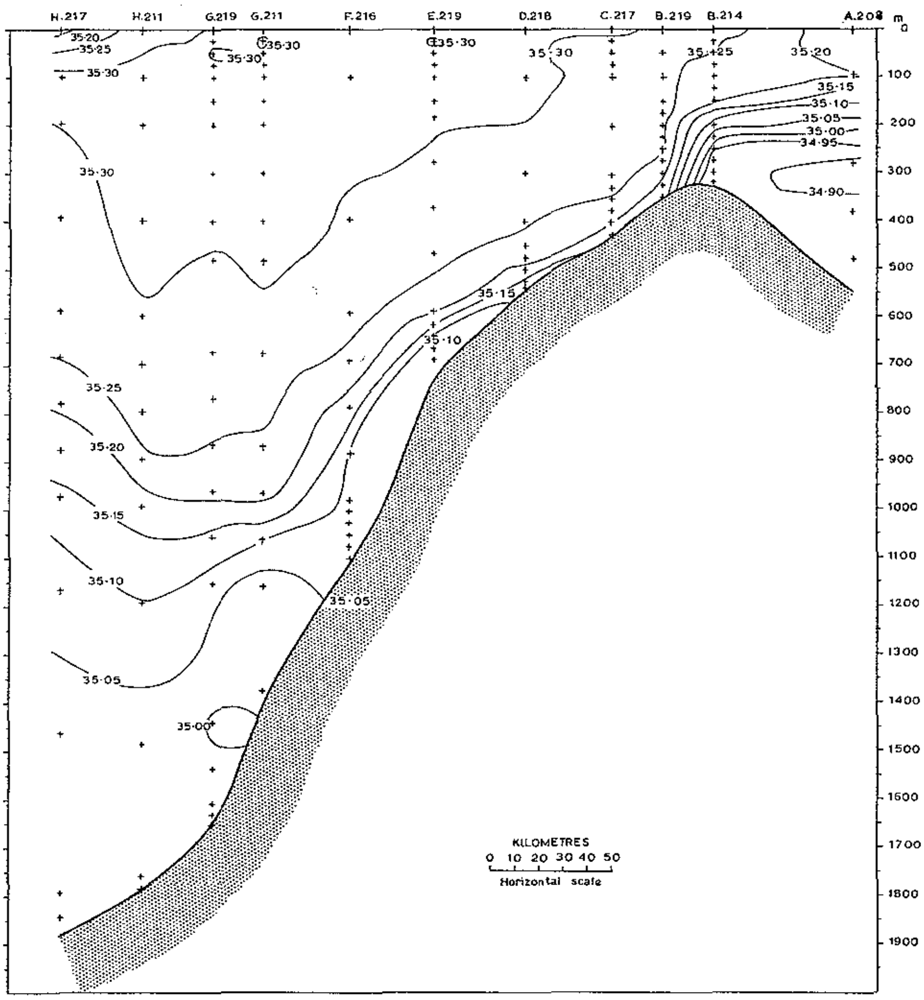

Figure 3:90. Section ε, third Survey: salinity $^0/_{00}$.

southern ends of Sections β and γ show a decrease in the outflow between Surveys 1 and 2 and an increase between Surveys 2 and 3. Conditions at the southern ends of Sections δ–ζ, however, show an increasing NS influence in the region of the outflow between Surveys 1 and 2 and no change between Surveys 2 and 3, but this increase by Survey 2 may have been due to a contribution from the strong overflow seen on Section δ at this time. Thus this outflow and the overflow at the Faroe end of the Ridge would seem to behave in the same way whilst the overflow at the Icelandic end of the Ridge is out of phase.

The level of the 0° C isotherm on the northern slope of the Ridge on a section does not necessarily bear any relation to the amount of overflow on that section. On Section β it falls between Surveys 1 and 2 as the overflow there decreases, and on Section γ it rises as the overflow increases. On Section δ, however, it falls between Surveys 1 and 2 as the overflow increases and then rises again between Surveys 2 and 3 as the overflow decreases. Again on Section ε, although the level rises as conditions on the southern slope get colder between Surveys 1 and 2, it continues to rise as they get warmer between Surveys 2 and 3.

As far as the contributions made by the various water masses are concerned, the outflow from the Faroe Bank Channel obviously contains a large NS element and the overflows of the Ridge seen on Sections α–δ also contain some of this water. Those on Sections γ and δ seem to contain a considerable proportion of EI and/or NI water. The overflow on Section ζ near Iceland consists also almost entirely of EI and/or NI water. STEFÁNSSON (1962) regards the NI water mass as making a bigger contribution than EI water to these overflows, but my analysis shows that over most of our area EI water lies below NI water on the northern side of the Ridge and therefore nearer to the crest of the Ridge, and it is my opinion that on the whole this water might possibly make the bigger contribution to the overflows on Sections γ, δ and ζ.

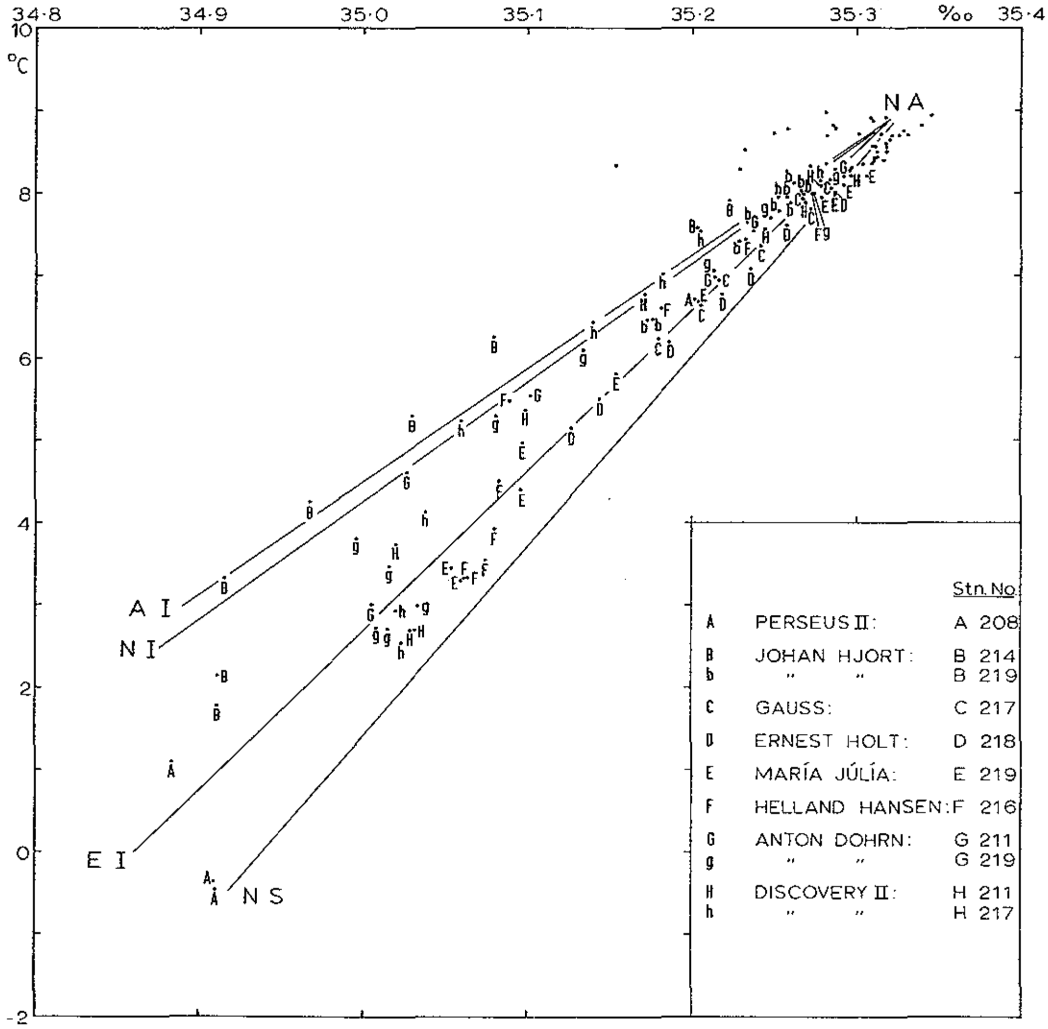

Figure 3:91. Section ε, third Survey: temperature °C – salinity ‰.

The Faroe Bank Channel outflow changes its T-S characteristics as it flows westwards. As far as Section γ they fall on the NA–NS line, but on Section ε, and sometimes on Section δ, they tend to the NA–EI line. This shift can be seen in Figures 3:67, 3:70 and 3:73 where the characteristics of the outflow as it crosses Sections β–ε on each survey have been plotted. Also plotted on these three diagrams are the characteristics of that part of the outflow containing most NS water on the "Chain" section examined in October 1960 by Steele, Barrett and Worthington (1962). This section lies about 25 n.mi. southwestwards of our southernmost G line of stations and it can be seen that the core of the overflow on it is similar to that on Section ε in its T-S relationship. Steele, Barrett and Worthington regard the overflow as containing much entrained NA–AI water on their section. The influence of AI water is certainly stronger on our most westerly sections and so indeed may account for the modification of the outflow beyond Section γ. However, also plotted in Figures 3:67, 3:70 and 3:73 are the characteristics of the overflow water on Section ζ as it passes stations F18, 118 and 218 respectively. It can be seen that the Faroe Bank Channel outflow on Section ε and on the "Chain" section always has characteristics which place it close to the line joining the point characterizing it on Section γ with that characterizing the overflow on Section ζ. On Survey 1 the point characterizing the outflow on Section δ also falls close to this line. Thus, it appears that the Faroe Bank Channel outflow may be modified to some extent in the neighbourhood of Sections δ and ε by the overflow of water with NA–EI characteristics on Section ζ and it is of interest to note that this outflow and particular overflow are the only two continuous flows from the Norwegian Sea into the North Atlantic found in the Iceland-Faroes area during this survey.

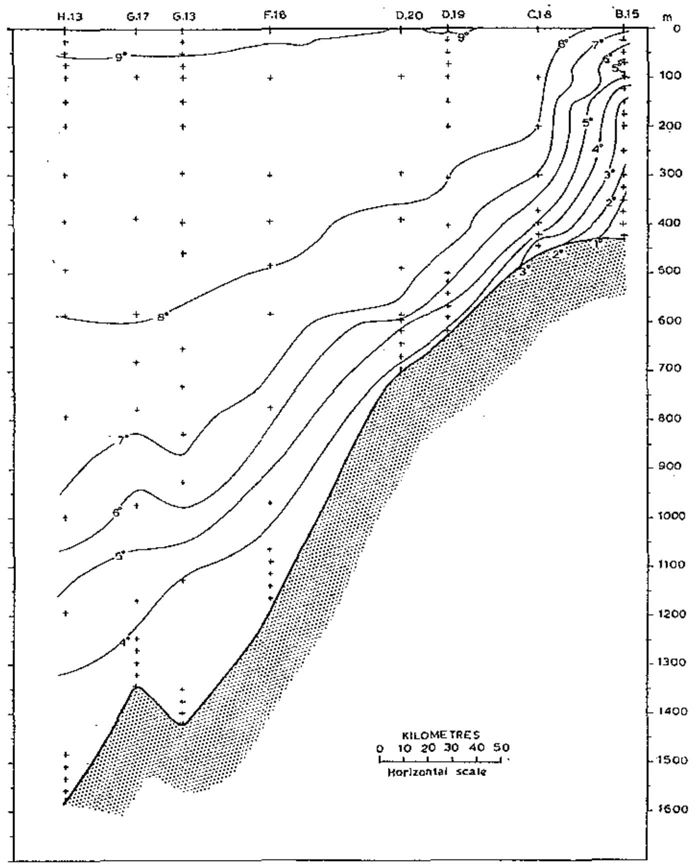

Figure 3:92.

Section ζ, first Survey: temperature °C.

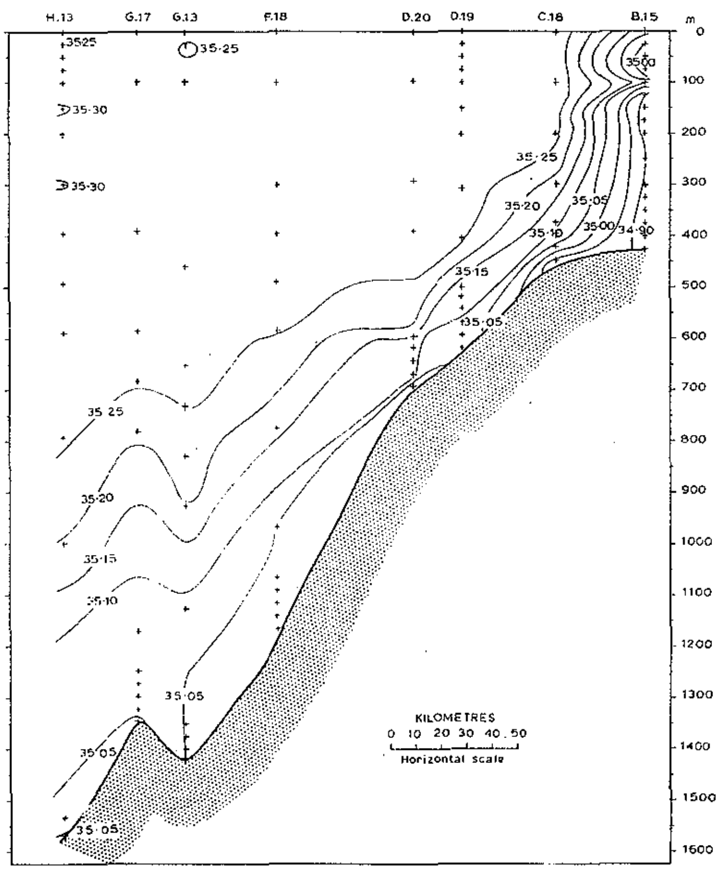

Figure 3:93.

Section ζ, first Survey: salinity $^0/_{00}$.

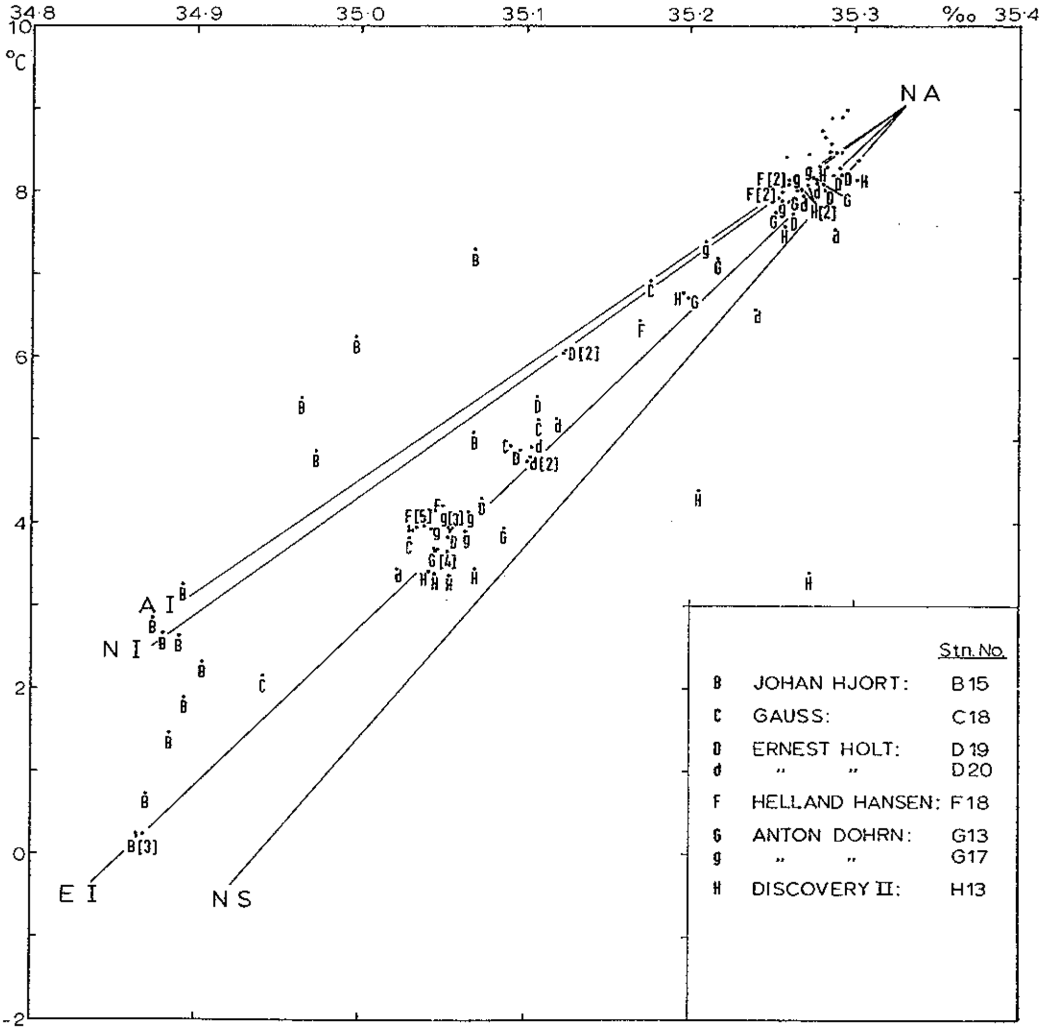

Figure 3:94.

Section ζ, first Survey: temperature °C – salinity ‰.

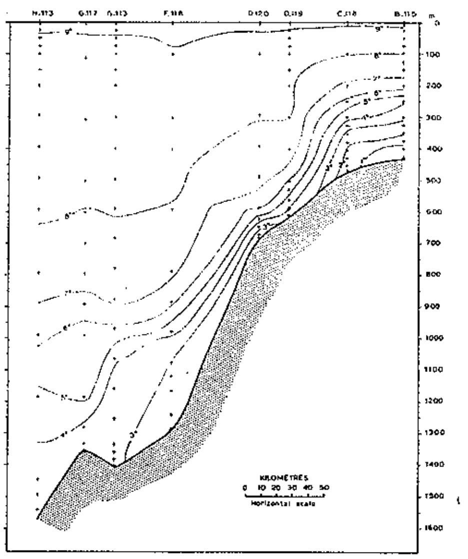

Figure 3:95.

Section ζ, second Survey: temperature °C.

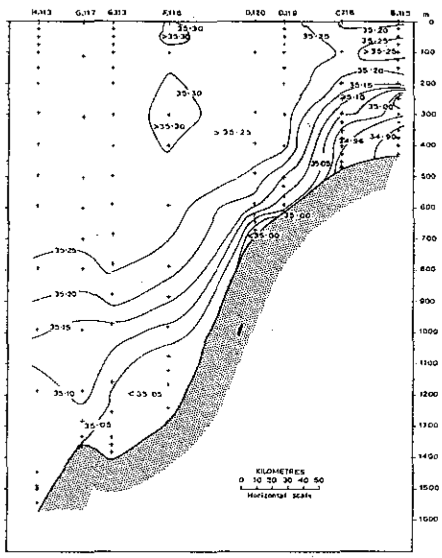

Figure 3:96.

Section ζ, second Survey: salinity ‰.

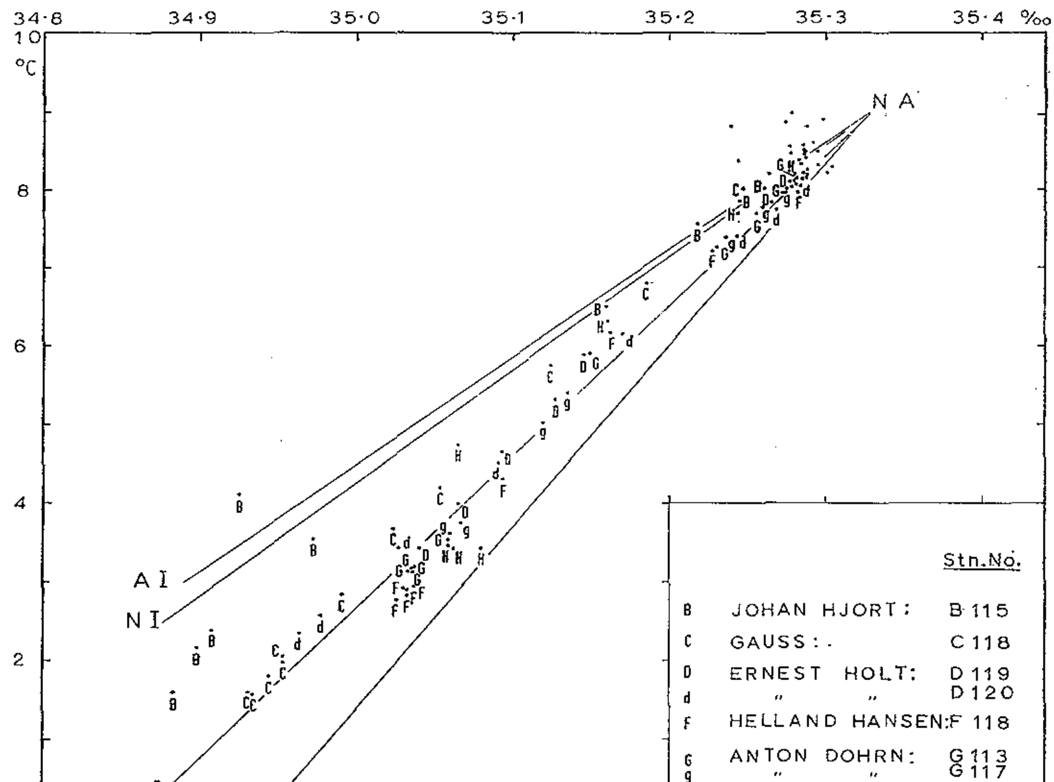

Figure 3:97.

Section ζ, second Survey: temperature °C – salinity ‰.

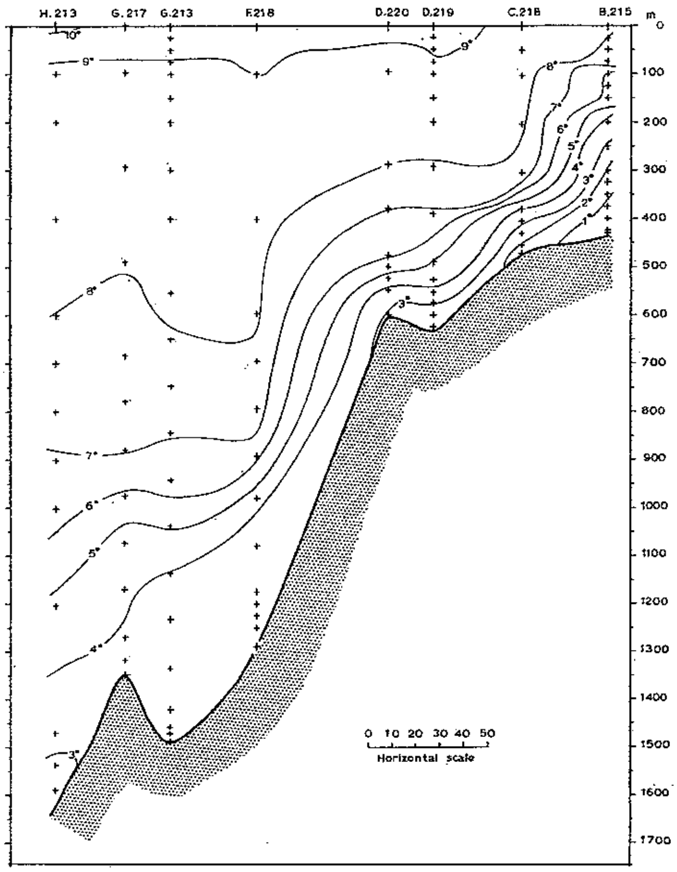

Figure 3:98.

Section ζ, third Survey: temperature °C.

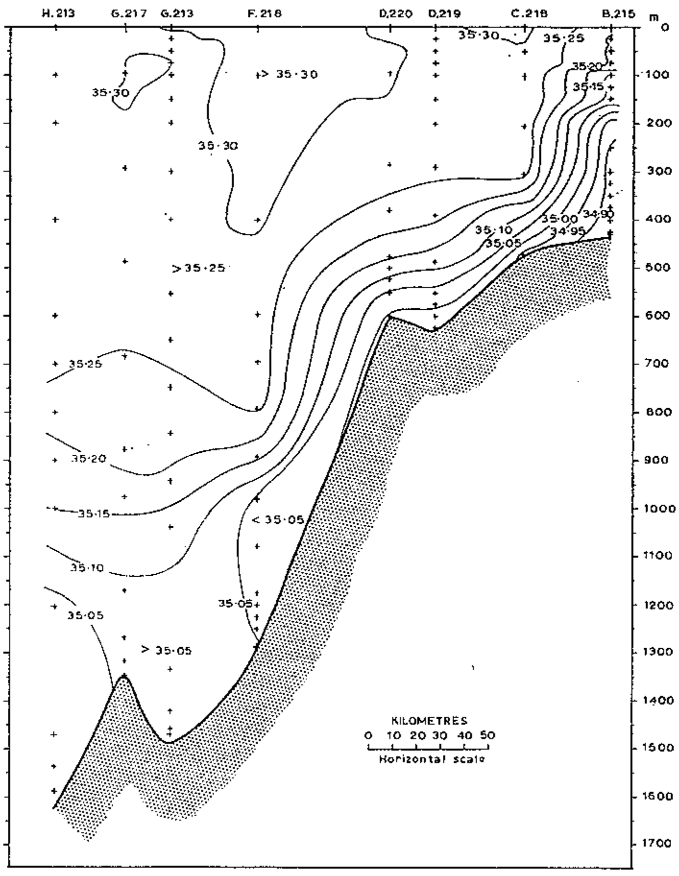

Figure 3:99.

Section ζ, third Survey: salinity ‰.

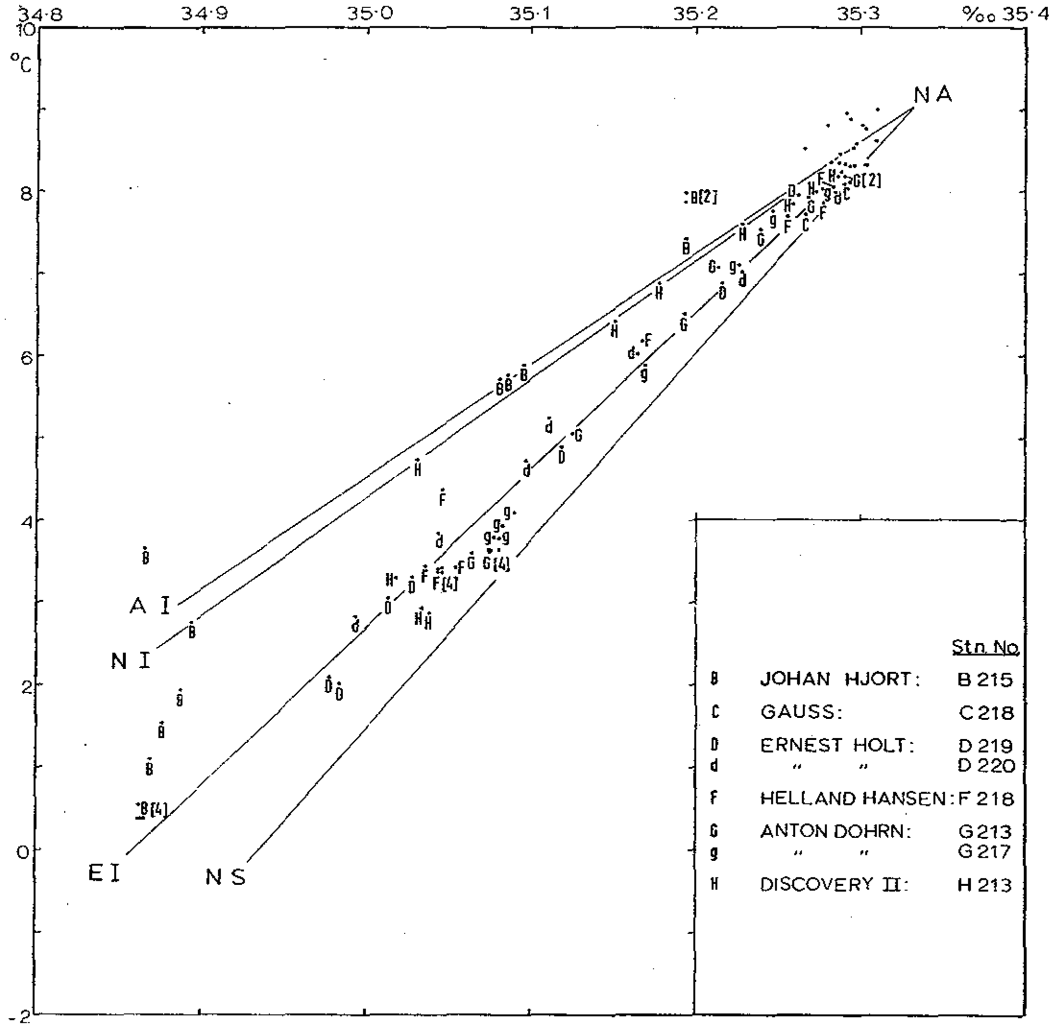

Figure 3:100. Section ζ, third Survey: temperature ° C – salinity ‰.

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THE OVERFLOW OF NORTH ICELANDIC WINTER WATER ACROSS THE ICELAND-FAROE RIDGE

(U. STEFÁNSSON)

North Icelandic winter water is formed in the shelf area north and northeast of Iceland in late winter by vertical mixing of Atlantic water and Arctic water (STEFÁNSSON, 1962), The resulting homogeneous water found in the uppermost 200–300 metres varies only slightly in composition from year to year, depending upon the degree of dilution of the Atlantic water and meteorological conditions. In the eastern part of the region the winter water has a temperature of about 2–3° and a salinity of 34·87–34·92 ‰.

This homogenization process is of great importance not only as regards the hydrography of North Icelandic waters, but also as regards the conditions in the southern Norwegian Sea and on the Iceland-Faroe Ridge. JACOBSEN (1943), in his studies of the hydrography of the Faroe-Shetland Channel, recognizes the North Icelandic winter water when he refers to "waters of 2·5° C temperature and 34·90 $^0/_{00}$ salinity found north and northeast of Iceland at depths of about 300–400 metres and also largely extended in the Norwegian Sea", (*loc. cit.* p. 8). This water, however, is not generally found at depths below 300 metres in the region north and northeast of Iceland.

Among the many problems to be studied in connection with the overflow of cold, deep waters across the Iceland-Faroe Ridge are the temperature salinity relations of the Arctic waters flowing down the western slope of the Ridge. The extensive data collected during the international investigations in June 1960 provide material for this study. The present note discusses briefly the part played by the North Icelandic winter water in the overflow.

As pointed out by STEELE (1962) there is probably a more or less continuous overflow of 2–4° C water which is formed by mixing on top of the Iceland-Faroe Ridge between "Atlantic" and "Arctic" type water masses. DIETRICH (1956, 1957) has considered Arctic bottom water (T = –0·6°, S = 34·90 $^0/_{00}$) as being the chief component of the cold overflow. DIETRICH's view is in agreement with observations made in certain areas of the Ridge. Thus the relatively high salinity of the cold bottom water found in the southeastern part of the Ridge (DIETRICH, 1956, 1959) indicates an overflow of a mixture of Arctic bottom water and Northeast Atlantic water. However, in the northwestern part of the Ridge, the influence of Arctic bottom water appears to be generally only slight. This is clear from Figure 3:101 which shows the T, S relation of the "Anton Dohrn" stations 253–260 DIETRICH (1957).

The T, S values shown in Figure 3:101 are from 200 to 400 metres for the stations on the east side of the Ridge, but from 200 metres down to the bottom for stations on the west side. The distribution of the points suggests that the bottom water in this region consists mostly of a mixture of North Icelandic winter water (T = 2·0°, S = 34·87 $^0/_{00}$) and Northeast Atlantic water (T = 9·0°, S = 35·34 $^0/_{00}$). The North Icelandic winter water is carried southwards by the East Icelandic Current along the insular shelf east of Iceland and probably forms the major part of the bottom water north of the "Rosengarten" area. Here the conditions are analogous to those found on the Iceland-Greenland Ridge where the Arctic intermediate water is the main component of the bottom current on the East Greenland continental slope, whereas the Arctic bottom water probably overflows only intermittently.

The "María Júlía" material from June 1960 afforded an opportunity to make a preliminary investigation of the changes in the T, S relations along the western slope of the Iceland-Faroe Ridge. The T, S values of observations made below 200 metres during the first Survey are shown in Fig. 3:102. It can be seen from Fig. 3:102 that in the southeastern part of the area (Stations E1–6 and E36–41, indicated by black dots on the T, S diagram) the bottom water is essentially a mixture of Atlantic water and "pure" Arctic bottom water, whereas in the northwestern part (stations E13–20 and E23–30, indicated by circles) the bottom water appears to be mostly a mixture of Atlantic water and North Icelandic winter water. In the middle part of the area (stations E7–12 and E31–35, indicated by the small triangles) the Arctic water intermixing with the Atlantic water seems to be a mixture of North Icelandic winter water and Arctic bottom water. Practically all the points are seen to fall inside the triangle formed by joining the extreme values for the three dominating water masses.

An attempt was made to determine the fraction of North Icelandic winter water in the Arctic waters mixing with the Atlantic water. This was done by means of the scaled three component diagram, shown in Fig. 3:103. Here the T, S curves of three typical stations have been entered. Since the T, S values for Station E41 practically coincide with one side of the triangle, the curve represents a mixture of two components only, viz. Atlantic water and Arctic bottom water. The water nearest to the bottom at E41 is seen to contain about 90 $^0/_0$ Arctic bottom water and 10 $^0/_0$ Atlantic water. At station E15 the upper intermediate layers seem to be a mixture of Atlantic water and practically "pure" North Icelandic winter water. At temperatures below 5·5° C the influence of a third water mass, *i.e.* Arctic bottom water is indicated, and this influence becomes progressively greater near the bottom. This is a general feature of most of the T, S curves and can be explained by the fact that the Arctic bottom water has a greater density than the North Icelandic winter water. At station E30 all the T, S values fall within the triangle. Here the deep layers appear to consist of Atlantic water and a mixture of almost equal volumes of Arctic bottom water and North Icelandic winter water.

From the T, S curves for the individual stations the salinity values corresponding to a given temperature can be read and from the scaled three-component diagram we can determine the fraction of North Icelandic winter water contained in the Arctic waters mixing with Atlantic water to give the temperature in question. The results for the temperatures 2° C and

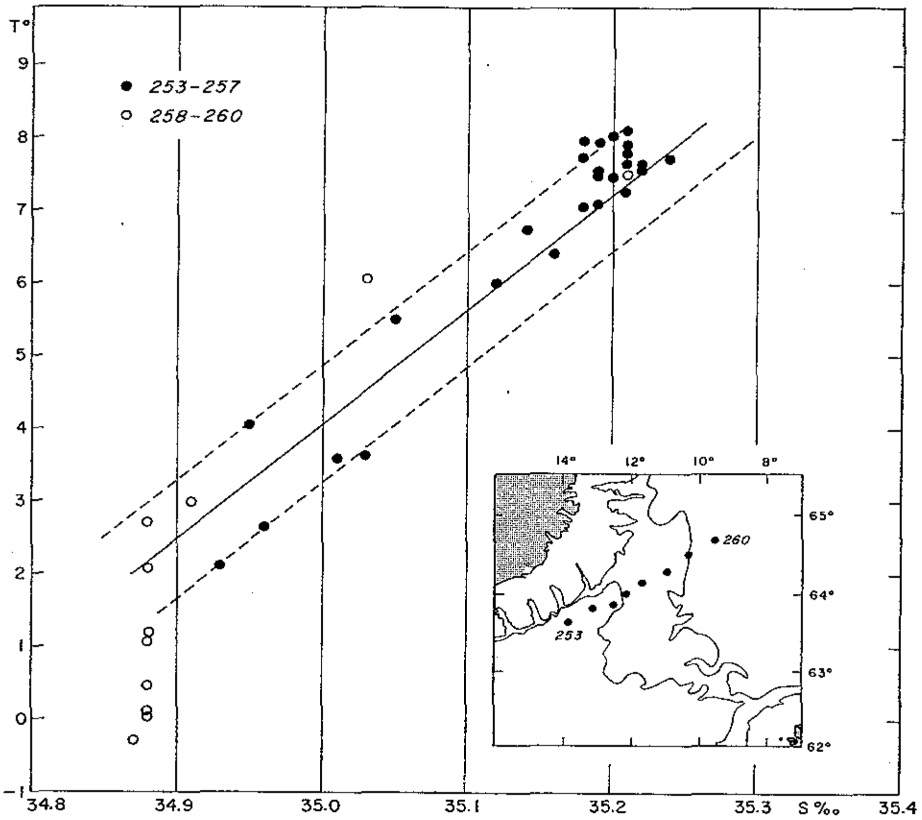

Figure 3:101. T – S relations of the "Anton Dohrn" stations 253–260, June 1955. The positions of the stations are also shown.

4° C respectively at stations E1–20 are shown in Fig. 3:104. The fraction of North Icelandic winter water is seen to be relatively smaller at 2° C than at 4° C. This is in agreement with the increased influence of Arctic bottom water in the deepest layers. Generally, the quantity of North Icelandic winter water on the western slope of the Ridge increases from southeast to northwest. Near station E16 which is located southwest of the "Rosengarten", the fraction of North Icelandic winter water reaches a maximum. A secondary maximum is found at stations E10–11 somewhat farther south. In the southernmost part of the section where the cold bottom water probably comes from the Faroe-Shetland Channel, the influence of North Icelandic winter water appears to be negligible. Similar results were found for the other section (stations E23–41) as well as the stations worked during the second Survey and the third Survey.

It seems possible that the method here outlined could be applied to follow the distribution of North Icelandic winter water in the bottom layers in the different parts of the Iceland-Faroe Ridge and in the slope region west of the Ridge.

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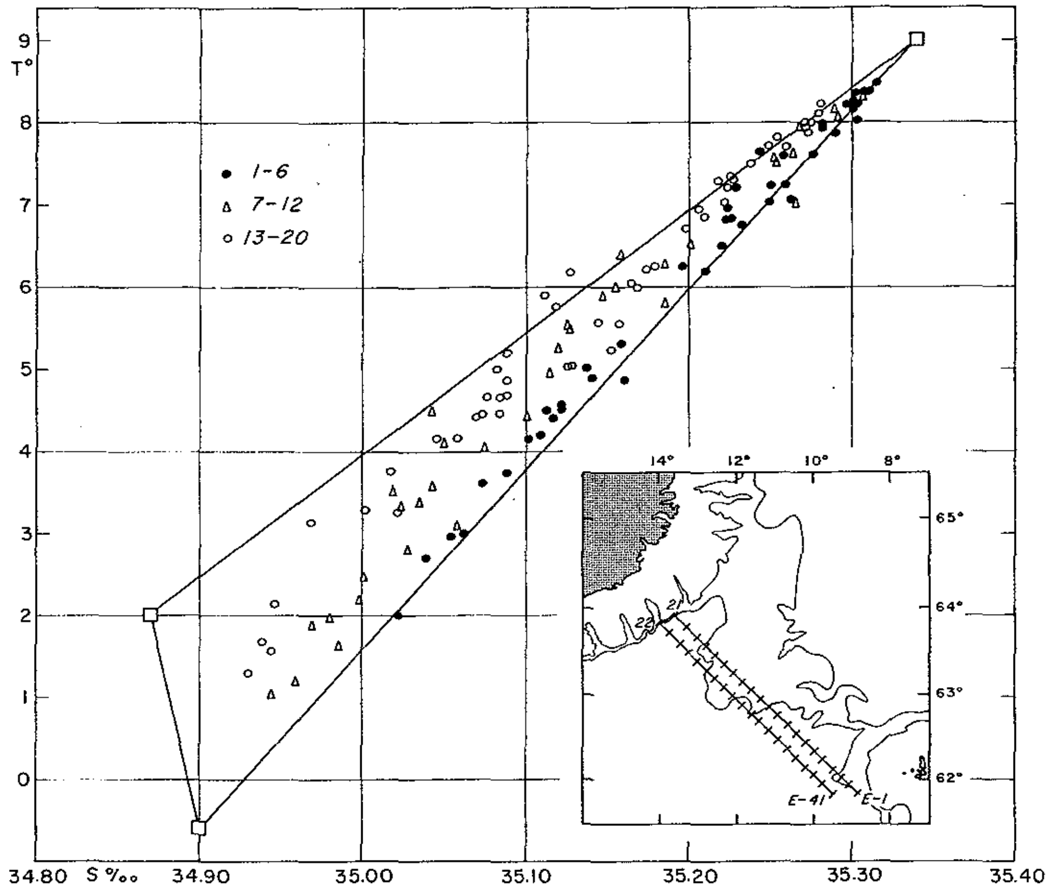

Figure 3:102 A.

T – S relations of the "María Júlía" stations E 1–20 (30. May-2. June, 1960). The positions of the stations are also shown.

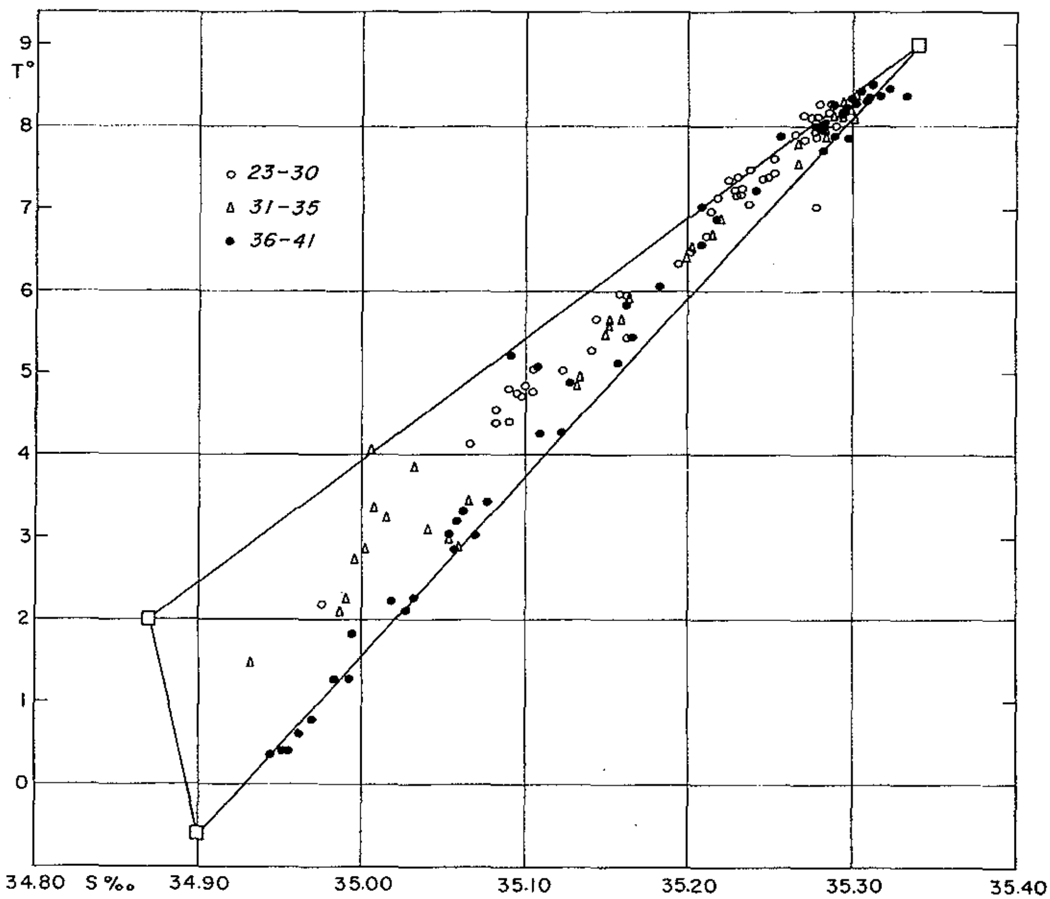

Figure 3:102 B.

T – S relations of the "María Júlía" stations E 23–41 (30. May-2. June, 1960). The positions of the stations are shown at Figure 3:102 A.

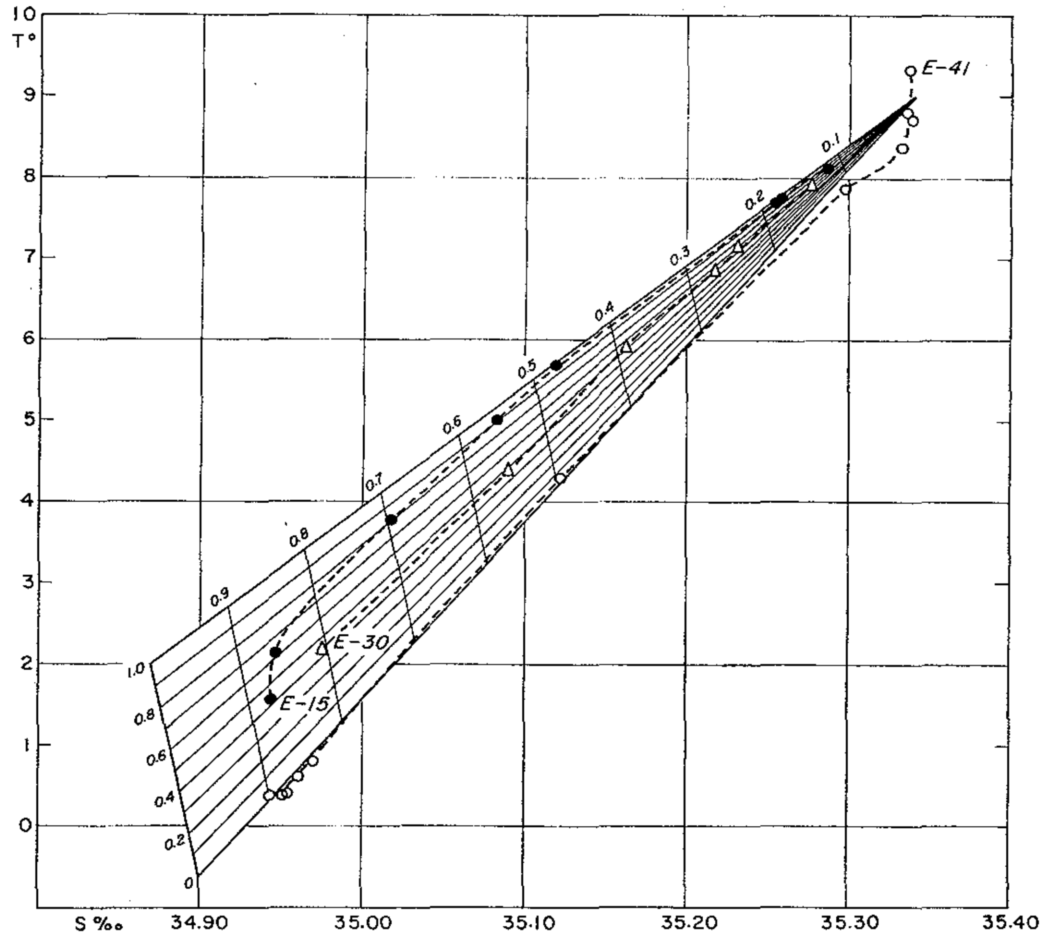

Figure 3:103. Three components mixing diagram between Atlantic water, North Icelandic winter water and Arctic bottom water. T – S curves for three typical stations are also shown.

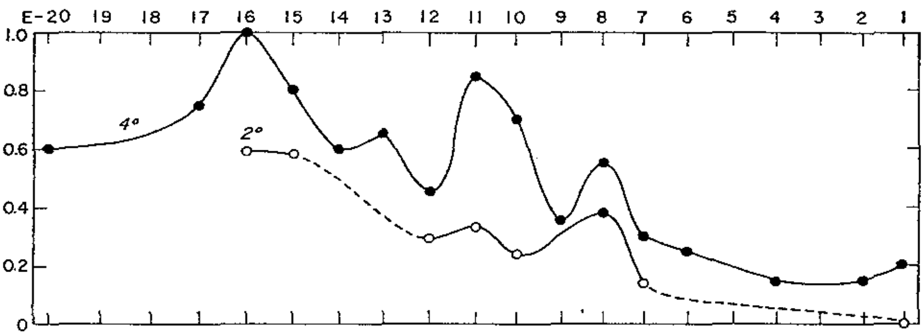

Figure 3:104. The fraction of North Icelandic winter water contained in the Arctic waters mixing with Atlantic water to give a temperature of 2° and 4° respectively, at stations E1–20, vertical scale (ordinate).

THE T-S DIAGRAM ANALYSIS OF THE WATER MASSES OVER THE ICELAND-FAROE RIDGE AND IN THE FAROE BANK CHANNEL (F. Hermann)

The aims of this section of Chapter 3 are as follows:

1. To identify the water masses which are mixing over the Iceland-Faroe Ridge.
2. To calculate the percentage of overflow water in different areas.
3. To calculate the total amount of overflow water given as equivalent thickness of overflow water.
4. To try to give an estimate of the volume transport of the overflow water.

5. To discuss the new water types which are formed by the mixing processes.

The water types found in the area have been discussed by LEE (this volume, pp. 100). In his T-S diagrams LEE uses the following water types:

		t°	S‰
North Atlantic water:	NA	9·0	35·33
Irminger Sea water:	AI	3·0	34·89
North Icelandic winter water..	NI	2·5	34·88
Arctic Intermediate water	EI	0·0	34·86
Norwegian Sea deep water: ...	NS	−0·4	34·92

After inspection of all the T-S diagrams from the stations in the three surveys of the expedition and also from a number of stations in the deep basin south of Iceland, the author has accepted the following water types as the most important for the area in question:

		t°	S‰
North Atlantic water:	NA	9·0	35·33
Irminger Sea water:	AI	3·5	34·93
North Icelandic winter water: .	NI	2·5	34·88
Norwegian Sea deep water: ...	NS	−0·5	34·92

It will be seen that these water types are nearly identical with those used by LEE.

Omission of the Arctic intermediate water type does not mean that the author denies its existence. As STEFÁNSSON (1962) mentions, however this water type seems only to penetrate over the summit of the Iceland-Faroe Ridge in small quantities. Furthermore, as this water type lies near the line connecting the points representing the NI and NS waters in the T-S diagram, overflow water will formally be regarded as a mixture of NI and NS waters in the following calculations.

The water masses from the Atlantic side of the Ridge consist of water types NA and AI. The T-S value of the AI water has been changed a little from the value used by LEE, but this will practically not change the position of NA–AI line, which also is in fairly good agreement with the corresponding line used by STEELE, BARRETT and WORTHINGTON (1962).

Inspection of the T-S values of the Atlantic water found in the upper layers southwest of the Ridge shows that water with such high temperature and salinity as 9·0° and 35·33‰ is found only in the Faroe Bank Channel area and in the southeastern part of the area investigated. Over the main part of the Ridge area and its southern slope the T-S values deviate considerably from those of the NA water type. Instead of using different T-S values in different areas for the Atlantic water it is more practical in the T-S diagram analysis of the amount of overflow water to use the values 9·0° and 35·33‰ on all stations and then apply a correction for the deviation from this adopted value. This will be discussed in detail later.

CALCULATION OF EQUIVALENT THICKNESS OF OVERFLOW WATER

When 1 g of a water mass (t, S) has been formed by mixing of three water masses (t_1, S_1), (t_2, S_2) and $t_3, S_3)$ in the proportion $m_1 : m_2 : m_3$, the mixing can be described by the following three equations: –

$$1 = m_1 + m_2 + m_3$$
$$t = m_1 \cdot t_1 + m_2 \cdot t_2 + m_3 \cdot t_3$$
$$S = m_1 \cdot S_1 + m_2 \cdot S_2 + m_3 \cdot S_3$$

These equations have the following solutions: –

$$(1)\ m_1 = \frac{1}{D}\left(t\,(S_2 - S_3) - S(t_2 - t_3) + t_2 \cdot S_3 - t_3 \cdot S_2\right)$$

$$(2)\ m_2 = \frac{1}{D}\left(t\,(S_3 - S_1) - S(t_3 - t_1) + t_3 \cdot S_1 - t_1 \cdot S_3\right)$$

$$(3)\ m_3 = \frac{1}{D}\left(t\,(S_1 - S_2) - S(t_1 - t_2) + t_1 \cdot S_2 - t_2 \cdot S_1\right)$$

where $D = t_1\,(S_2 - S_3) + t_2\,(S_3 - S_1) + t_3\,(S_1 - S_2)$.

When the points (t_1, S_1), (t_2, S_2) and (t_3, S_3) in the T-S diagram do not lie on a straight line $(D \neq 0)$ there will always be a solution, but only when the point (t, S) lies inside the triangle (t_1, S_1) (t_2, S_2), (t_3, S_3) will m_1, m_2 and m_3 be positive. It is thus possible to calculate the fractions m_1, m_2 and m_3 of each water type for a water mass (t, S) lying inside the above-mentioned triangle.

If four or more water types are involved in the mixing, it is generally not possible to calculate the fractions of each type occurring in the mixed water. In the case, however, where four water types mix and where the points representing three of the types lie on a straight line in the T-S diagram it is possible to calculate the fraction of the fourth water type as follows: –

Suppose four water types (t_1, S_1), (t_2, S_2), (t_3, S_3) and (t_4, S_4) mix with the mass fractions m_1, m_2, m_3 and m_4 to form water type (t, S). Suppose further that the points (t_1, S_1), (t_2, S_2) and (t_4, S_4) lie on a straight line. We then have the following equations: –

$$t_4 - t_1 = a(t_1 - t_2)$$
$$S_4 - S_1 = a(S_1 - S_2)$$
$$1 = m_1 + m_2 + m_3 + m_4$$
$$t = m_1 \cdot t_1 + m_2 \cdot t_2 + m_3 \cdot t_3 + m_4 \cdot t_4$$
$$S = m_1 \cdot S_1 + m_2 \cdot S_2 + m_3 \cdot S_3 + m_4 \cdot S_4$$

Elimination of t_4 and S_4 gives

$$1 = (m_1+m_4\ (1+a)) + (m_2-m_4\ .\ a) + m_3$$
$$t = (m_1+m_4\ (1+a))\ .\ t_1 + (m_2-m_4\ .\ a)\ .\ t_2 + m_3\ .\ t_3$$
$$S = (m_1+m_4\ (1+a))\ .\ S_1 + (m_2-m_4\ .\ a)\ .\ S_2 + m_3\ .\ S_3$$

from which we get:

$$(4)\ m_3 = \frac{1}{D}\ (t\ (S_1-S_2) - S\ (t_1-t_2) + t_1\ .\ S_2 - t_2\ .\ S_1)$$

where $D = t_1\ (S_2-S_3) + t_2\ (S_3-S_1) + t_3\ (S_1-S_2)$ which is identical with equation (3).

This case is of interest in the analysis of the water masses in the overflow area where the water types NA, AI and NI lie approximately on a straight line in the T-S diagram. It is thus possible to calculate the fraction of NS water in the mixture even if all four water components are present.

Over the great depth in the deep basin south of Iceland, T-S diagrams show negligible admixture of AI water in the upper 700 m. As it is water from this area which overflows the Iceland-Faroe Ridge in the upper layers, it is assumed that, northeast of the 700 metre bottom curve of the southern slope of the Ridge, the admixture of AI water can be neglected. For this part of the overflow area the fractions of the water types NA, NI and NS can be calculated by equations (1) to (3). This was done graphically. In a T-S diagram lines were constructed for $m_1 = 0{\cdot}1,\ 0{\cdot}2,\ 0{\cdot}3,\ 0{\cdot}4, \ldots, 1{\cdot}0$ and for $m_3 = 0{\cdot}2,\ 0{\cdot}4,\ 0{\cdot}6,\ 0{\cdot}8$ and $1{\cdot}0$ where m_1 is the fraction of NA water and m_3 the fraction of NS water. These lines form two systems of equidistant lines parallel to the NI–NS line and the NA–NI line respectively. Such a diagram is shown in Figure 3:105. The fraction m_2 of NI water can be calculated from $m_2 = 1 - m_1 + m_3$.

When the T-S values for a station are plotted in this diagram the fractions m_1 and m_2 can be read for each observation depth. Figure 3:106a shows the vertical distribution of m_1 (NA water). In these calculations it was assumed that the Atlantic water was of the type NA (9·0°, 35·33 ‰). As already mentioned the type of Atlantic water in most localities will deviate from that adopted for NA water. If the Atlantic water, as found in the upper homogeneous layer at a particular station, is found by applying the diagram Figure 3:105 to contain the fraction k of NA water, and if the fraction of NA water at some observation depth is found to be m_1, then $\frac{m_1}{k}$ will be the fraction of the Atlantic water present in the water at that depth.

At station F11 for which Figure 3:106 a was drawn, k was found to be 0·84. Figure 3:106 b shows the corrected curve $\frac{m_1}{k}$ for the vertical distribution of Atlantic water. The fraction of overflow water $1-\frac{m_1}{k}=\frac{1}{k}(k-m_1)$ can be read in the same figure using the lower scale.

If the fraction of NS water is read to m_3 on the diagram Figure 3:105, the corrected fraction of this water type can with sufficient approximation be calculated as $\frac{m_3}{1-m_1} \cdot \frac{1}{k}(k-m_1)$ and the corrected fraction of NI water will be $\frac{1}{k}(k-m_1) - \frac{m_3}{1-m_1} \cdot \frac{1}{k}(k-m_1)$. Figure 3:106c shows the vertical distribution of the fractions of NS water and NI water for station F11.

The vertical distribution of the fractions of water types shown in Figure 3:106 is in many respects typical for the Ridge area well south of its summit. Nearest the bottom we find a nearly homogeneous layer varying in thickness, but often about 50 metres thick. Above this layer, the fraction of overflow water increases with depth and in the upper layers we have the nearly homogeneous Atlantic water.

As Figure 3:106c shows, NS water constitutes a greater part of the overflow water in the near-bottom layer than at greater distance from the bottom. The thickness of the homogeneous near-bottom layer cannot be used as a full measure of the amount of overflow water as a considerable amount of overflow water occurs above this layer.

The following procedure was adopted in working up the observations from the overflow surveys: –

T-S diagrams were drawn for all stations for observations below 100 metres. A few salinities which were obviously wrong were discarded and where salinities were missing, these were derived from the temperature and the T-S relation. The fraction m_1 and m_3 of NA water and NS water respectively were determined from T-S diagrams using the diagram Figure 3:105.

Curves for the vertical distribution of m_1 were drawn for all stations of the first survey and the value of k determined as the value of m_1 in the upper homogeneous layer. k varied between 1·0 and 0·82.

The equivalent thickness of overflow water was calculated as $\int_{z_b}^{100} \frac{1}{k}(k-m_1)\,dz$, where z indicates depth in metres and z_b the depth to bottom.

This was done by planimetric integration for Survey 1 and by numerical integration for Surveys 2 and 3. For Survey 2 and 3 the value of k at the corresponding station in Survey 1 was used.

The mean value of the equivalent thickness of overflow water over the three surveys was calculated for each station as well as the anomaly for each survey from this mean value.

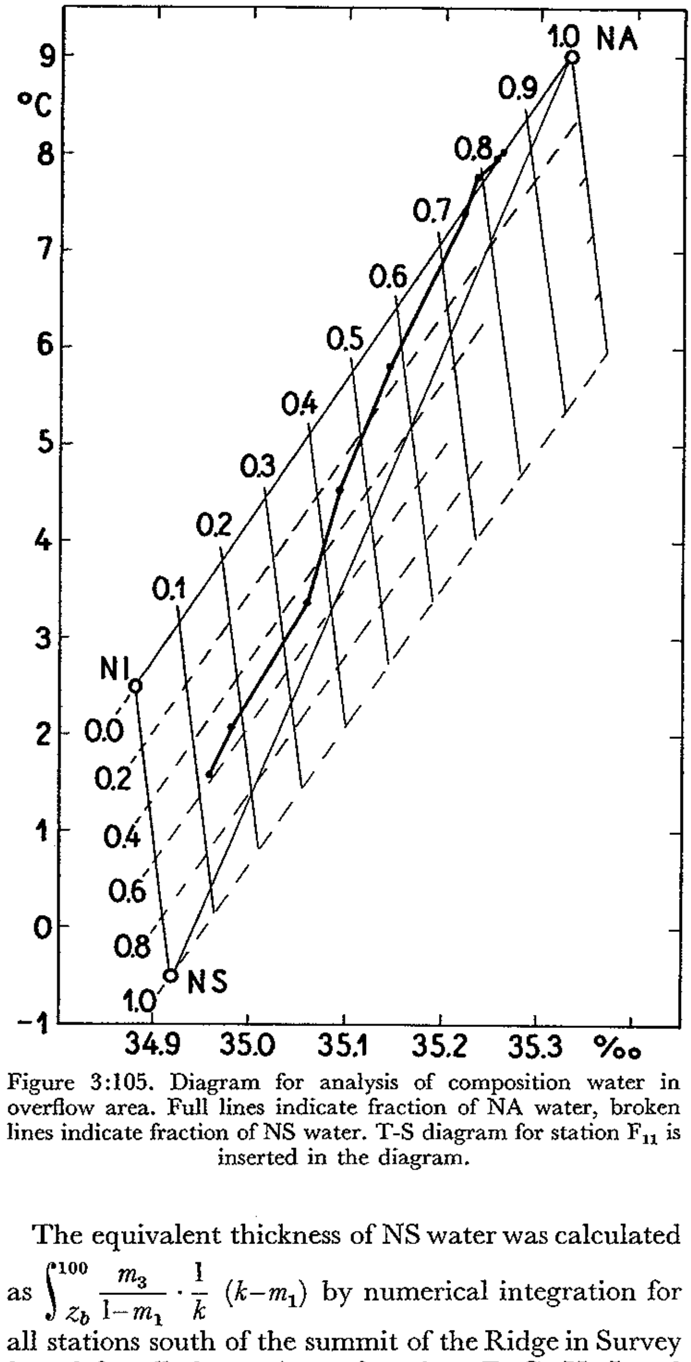

Figure 3:105. Diagram for analysis of composition water in overflow area. Full lines indicate fraction of NA water, broken lines indicate fraction of NS water. T-S diagram for station F_{11} is inserted in the diagram.

The equivalent thickness of NS water was calculated as $\int_{z_b}^{100} \frac{m_3}{1-m_1} \cdot \frac{1}{k}\,(k-m_1)$ by numerical integration for all stations south of the summit of the Ridge in Survey 1 and for all the stations of sections F, G, H, I and some of the deeper stations of section E. The mean value for the three surveys was calculated as well as the anomalies from the mean values for the single surveys.

As already mentioned the fraction of NS water is approximately correct even if AI water is present in the mixture.

HORIZONTAL DISTRIBUTION OF OVERFLOW WATER

Figure 3:107 shows the equivalent thickness of NS water as a percentage of the equivalent thickness of total overflow water for that part of the area which lies southwest of the Ridge and where it can be assumed that no AI water is present. The map shows that the composition of the overflow water varies with the locality. Near the Icelandic shelf the overflow water contains only about 30 % NS water and over the southeastern part of the Ridge it contains more than 60 % NS water. The highest percentage, 90 % NS water was found at the outlet of the Faroe Bank Channel.

In Figure 3:108 the mean value of the three surveys for the equivalent thickness of overflow water is given for that part of the Ridge which lies northeast of its southern 700 m depth curve.

The map shows that overflow water is found nearly everywhere over the Ridge where the depth exceeds 300 metres. It is, however, far from being evenly distributed, but is mainly concentrated in four branches, which appear in the map as tongues with maximum equivalent thickness of overflow water. The courses of these tongues which are indicated by hatched lines are supposed to indicate the mean direction of the overflow current during the period of the expedition. When the overflow current is well over the summit of the Ridge, it seems to be deflected to the right and to run nearly parallel to the depth curves. This could be expected from the calculations of Bowden (1960) and is in good agreement with the results of direct current measurements, made during the expedition. (Joseph, this volume, pp. 157–72).

Calculation of the equivalent thickness of overflow water in the southern part of the area investigated was complicated by the presence of AI water. It was based on the following considerations: As the overflow water penetrating over the Iceland-Faroe Ridge is deflected to the right it will not sink to depths below 1,000 metres before it is near the slope of the Icelandic shelf. The overflow water which is found west of the outlet through the Faroe Bank Channel must therefore

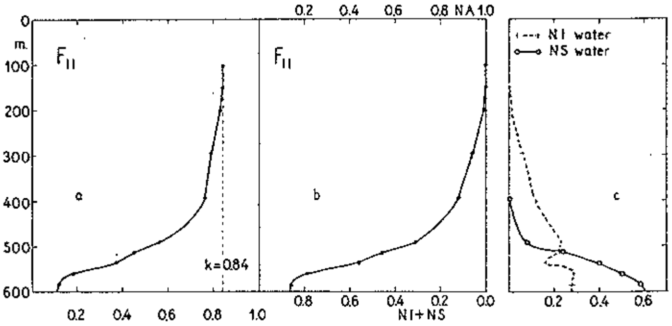

Figure 3:106. a) Uncorrected vertical distribution of NA water.
b) Corrected vertical distribution of Atlantic water (upper scale) and of overflow water (lower scale).
c) Vertical distribution of NS water and NI water.

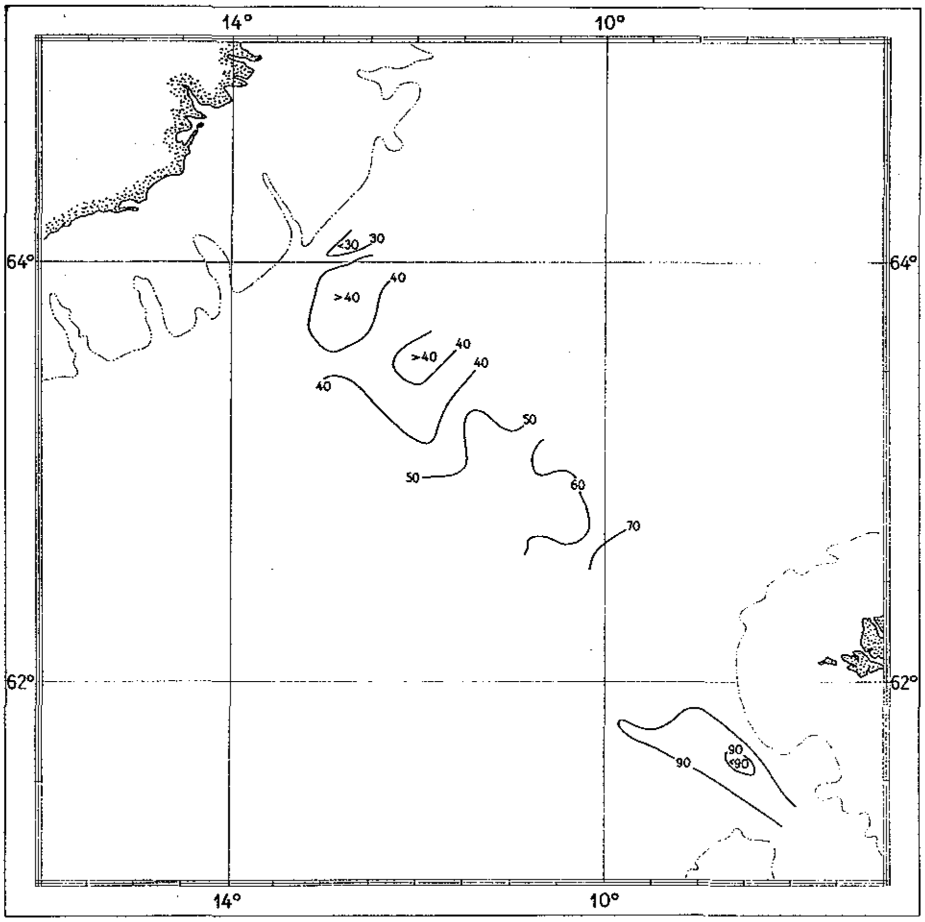

Figure 3:107. Percentage of NS water in the overflow water, Survey 1.

originate from this Channel. As the overflow water in the Faroe Bank Channel consists of 90 % NS water and 10 % NI water, the equivalent thickness of overflow water in the area west of the Faroe Bank Channel is found by adding 10 % to the equivalent thickness of NS water, which could be calculated even where NI water is present.

As seen in the map Figure 3:108 the overflow water from the Faroe Bank Channel subdivides into two branches which follow the Atlantic slope of the Iceland-Faroe Ridge, gradually sinking to greater depths. This course of the outflow is in good agreement with the ideas of Cooper (1955), who first pointed out the importance of this deep connection between the Atlantic and the Norwegian Sea.

In the northwestmost part of the area investigated it was found impossible to calculate the equivalent thickness of overflow water as all four water types were present.

The map Figure 3:109 shows the percentage of overflow water in the near-bottom layer drawn from mean values from the three surveys. The same branches of the overflow current as were found on Figure 3:108 appear as tongues with maximum values of overflow water.

ESTIMATION OF VELOCITIES IN THE OVERFLOW CURRENT

In the three surveys considerable deviations were found from the mean values of the equivalent thickness of overflow water given in Figure 3:108. Such anomalies will be used in the following to estimate the speed of the overflow current. If a typical anomaly in one of the overflow branches is found in one of the surveys, we could expect that it would travel downstream with the velocity of the current and that it could be found again in the next survey. From the distance travelled and the interval between the surveys it should then be possible to calculate the velocity.

For each of the overflow branches A, B, C, D, E and F, the anomaly of equivalent thickness for each survey was calculated for the points shown in Figure 3:110 as the average of the values from a number of adjacent stations (Table 3:1).

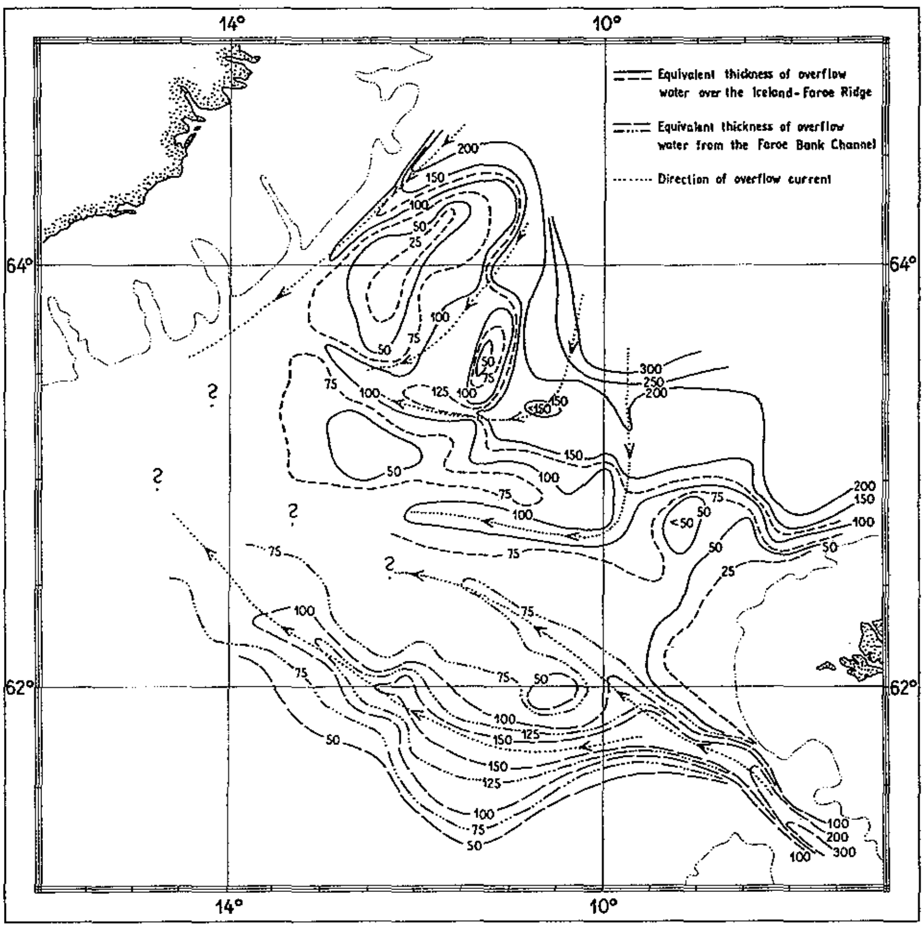

Figure 3:108. Mean value for the three surveys of equivalent thickness of overflow water. The direction of the overflow in the six main branches is indicated by hatched lines.

The anomalies along the overflow branches are plotted in Figure 3:111 a and b (A, B, C, D, E and F) for each survey. Anomalies which with some degree of certainty can be identified in two consecutive surveys are marked with the same letter with the survey number as index. Table 3:2 gives the distance travelled, the time which is taken as 7 days between two surveys and the calculated velocities.

The weakness of this method is that it is impossible to prove that the anomalies which are here identified in successive surveys really are of the same origin. In fact the method should not be used unless the results can be checked against direct current measurements.

Current measurement stations B_1 and B_2, situated in Branch A, give mean residual currents of 23 and 28 cm/sec. respectively, which is in good agreement with the value 25 cm/sec. found for Branch A. (Table 3:2).

Current measurement station D, in branch E gives a mean residual current of 18 cm/sec., which agrees fairly well with the value 21 cm/sec. in Table 3:2.

Current measurement stations E and F lie near branch D, but their results: 28 cm/sec. and 3 cm/sec. are so different that a comparison is impossible.

As the results for the branches A and E are in fairly good agreement with the measured currents, there is reason also to trust the results for the other branches.

ESTIMATE OF THE VOLUME TRANSPORT OF THE OVERFLOW CURRENT

A rough estimate of the volume transport of overflow water into the Atlantic Ocean can now be made. For the cross sections A, B, C, D, E and F Figure 3:110) over the branches A, B, C, D, E and F of the overflow current the mean equivalent thickness of overflow water was calculated using the value of the map, Figure 3:108. These cross sections are near the mean position of the distances over which the velocity is measured. At stations adjacent to the cross sections the percentage of the total amount of overflow water

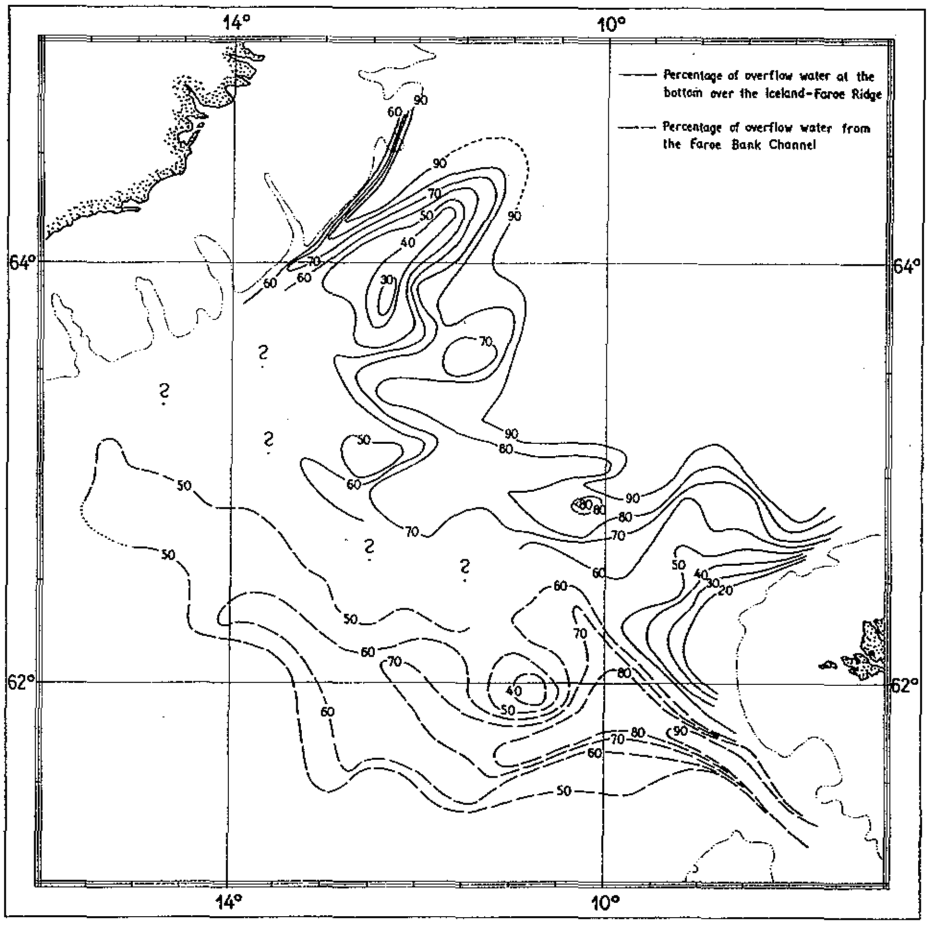

Figure 3:109. Percentage of overflow water in the near-bottom layer.

which was found in the homogeneous bottom layer was computed. By means of this percentage the mean equivalent thickness of the overflow water contained in the homogeneous layer was calculated.

If it is assumed that all the overflow water moves with the velocity given in Table 3:2 and the corresponding volume transport is calculated, we will certainly get an overestimate of the transport of overflow water, since the upper part of this water is strongly mixed with Atlantic water and must have a velocity considerably smaller than that given in Table 3:2.

Table 3:1.

Point Number	Branch A Stations used	Branch B Stations used	Branch C Stations used	Branch D Stations used	Branch E Stations used	Branch F Stations used
1	B_{15}	B_{13}, B_{14}	B_{10}, B_{11}, B_{12}	B_8, B_9, B_{10}	I_{18}, I_{19}, I_{26}, I_{27}	I_4, I_9, F_1
2	B_{18}	B_{20}, B_{21}, B_{22}	B_{23}, B_{24}, B_{25}	B_{26}, B_{27}, B_{28}	I_3, I_4, I_{18}, I_{19}	H_1, H_2, G_{29}, G_1
3	C_{18}	C_{13}, C_{14}, C_{15}	C_9, C_{10}, C_{11}, C_{12}	C_6, C_7, C_8	E_{41}, E_{39}, F_1	H_3, H_4, G_{27}, G_{28}
4	D_{19}	C_{23}, C_{24}, C_{25}	C_{27}, C_{28}, C_{29}	C_{31}, C_{32}, C_{33}	E_6,E_{38}, F_2, F_3	H_5, H_6
5	D_{20}	D_{14}, D_{15}, D_{16}	D_{11}, D_{12}, D_{13}	D_6, D_7, D_8	E_7, F_3, F_4	H_7, H_8
6	F_{18}	D_{23}, D_{24}, D_{25}	D_{25}, D_{26}, D_{27}	D_{31}, D_{32}, D_{33}	E_{36}, F_4, F_5	H_{19}, H_9, H_{10}, G_{31}
7	F_{21}	E_{17}, E_{18}, E_{19}	E_{15}, E_{16}, E_{17}	E_{10}, E_{11}, E_{12}	E_{34}, F_6, F_{33}	H_{10}, H_{11}, H_{18}, G_{20}
8	G_{14}			E_{30}, E_{31}, E_{32}	F_8, F_{32}	H_{12}, H_{13}, G_{17}, G_{18}
9				F_9, F_{10}, F_{11}	G_6, G_7, F_{30}, F_{31}	

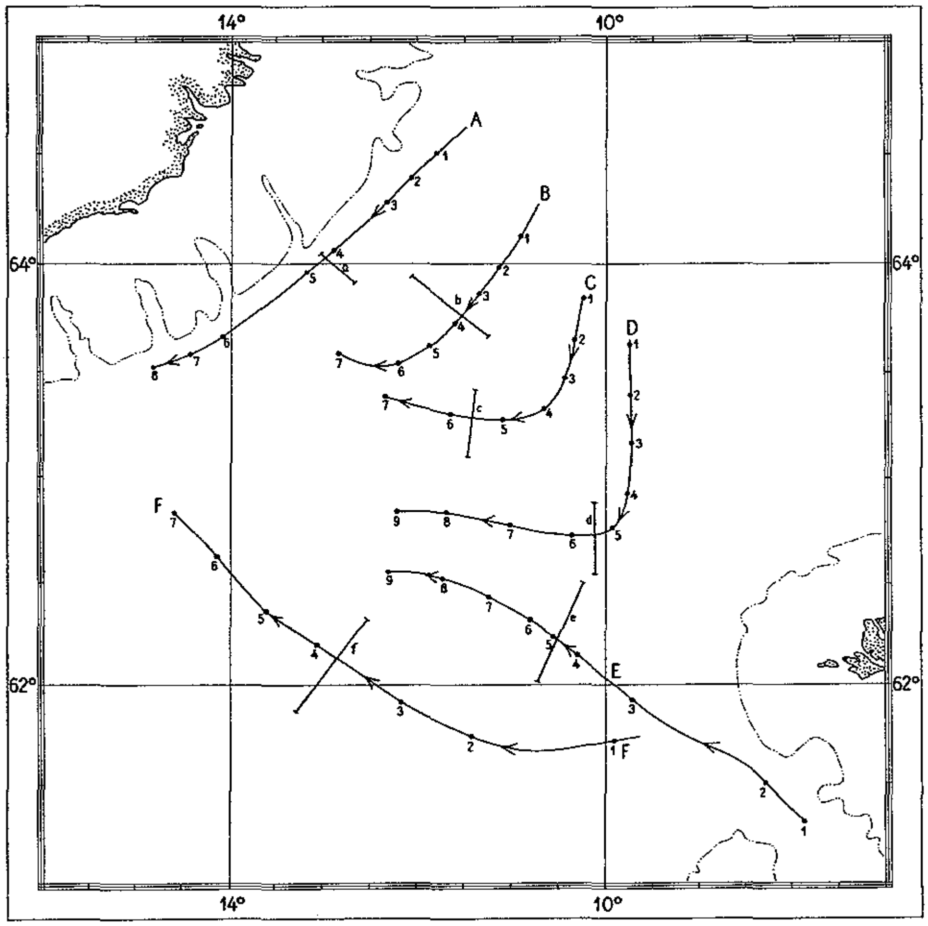

Figure 3:110. Cores of the main overflow branches with indication of the points, where anomaly of equivalent thickness has been calculated. The position of the cross-sections over the branches is indicated.

Table 3:2.

Overflow branch	Anomaly	Distance in miles	Time days	Velocity cm/sec.	Mean Velocity cm/sec.
A	a_1 to a_2	82	7	25·1	25·1
B	a_1 to a_2	19	7	5·8	5·4
	a_2 to a_3	16	7	4·9	
	b_1 to b_2	19	7	5·8	
	c_2 to c_3	17	7	5·2	
C	a_1 to a_2	44	7	13·5	11·8
	b_2 to b_3	33	7	10·1	
D	a_1 to a_2	34	7	10·4	10·8
	a_2 to a_3	41	7	12·6	
	b_2 to b_3	32	7	9·8	
E	a_1 to a_2	63	7	19·3	21·4
	b_1 to b_2	82	7	25·1	
	b_2 to b_3	65	7	19·9	
F	a_1 to a_2	73	7	22·3	22·6
	b_1 to b_2	78	7	23·9	
	c_2 to c_3	71	7	21·7	

Table 3:3.

Overflow branch	Velocity cm/sec.	Length of cross-sect. naut. miles	Equival. thickness of overflow water: total m	Equival. thickness of overflow water: hom. layer m	Over-estimate of volume transport m^3/sec.	Under-estimate of volume transport m^3/sec.
A	25·1	13	62	47	$0.38 \cdot 10^6$	$0.29 \cdot 10^6$
B	5·4	28	90	38	$0.25 \cdot 10^6$	$0.11 \cdot 10^6$
C	11·8	22·5	88	36	$0.43 \cdot 10^6$	$0.18 \cdot 10^6$
D	10·9	20	82	39	$0.33 \cdot 10^6$	$0.16 \cdot 10^6$
A + B + C + D		(Ridge overflow)			$1.39 \cdot 10^6$	$0.74 \cdot 10^6$
E	21·4	30	70	29	$0.83 \cdot 10^6$	$0.35 \cdot 10^6$
F	22·6	34	78	40	$1.11 \cdot 10^6$	$0.57 \cdot 10^6$
E + F	(Faroe Bank Channel outflow)				$1.94 \cdot 10^6$	$0.92 \cdot 10^6$
Total A + B + C + D + E + F					$3.3 \cdot 10^6$	$1.7 \cdot 10^6$
						m^3/sec.
Mean value of estimates A + B + C + D						$1.1 \cdot 10^6$
– – – – E + F						$1.4 \cdot 10^6$
Total overflow volume transport						$2.5 \cdot 10^6$

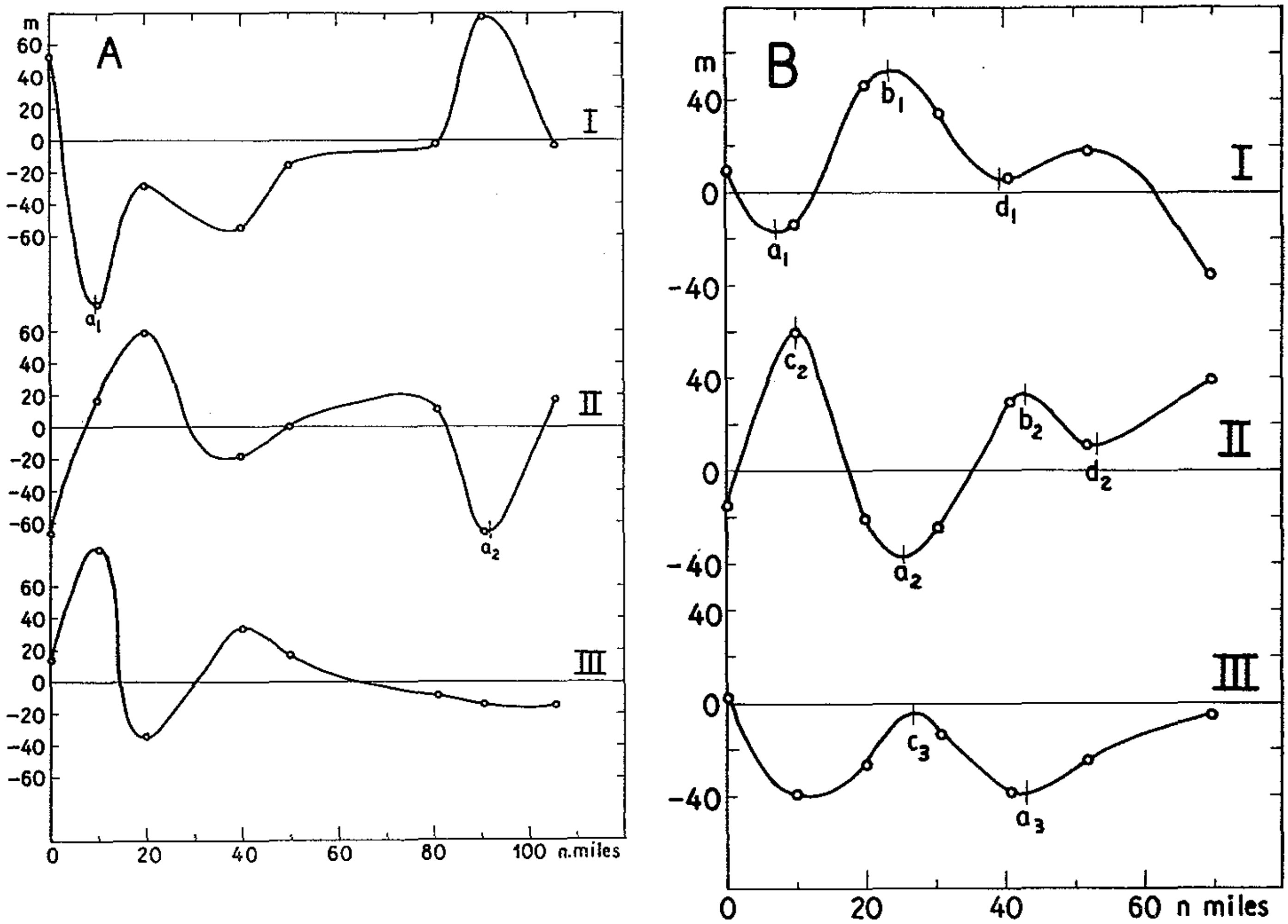

Figure 3:111 a. Anomalies of equivalent thickness of overflow water along the cores of the overflow branches A and B, for the Surveys I, II, III. The Atlantic part of the branches is found to the right.

On the other hand an underestimate of the volume transport will result if it is assumed that the transport takes place in the homogeneous near-bottom layer only. Both overestimate and underestimate are given in Table 3:3, as well as the mean value of the estimates.

As shown in the table the total volume transport of overflow water is likely to be between $1.7 \cdot 10^6$ m^3/sec. and $3.3 \cdot 10^6$ m^3/sec. The mean value of these two estimates, namely $2.5 \cdot 10^6$ m^3/sec., is probably the best estimate that can be made by this rough method. The outflow through the Faroe Bank Channel seems to be a little higher than the overflow over the Iceland-Faroe Ridge.

It is of interest to compare the above results with those obtained by Steele, Barrett and Worthington (1962). In their analysis they use the characters $0{\cdot}0^0$ and $34{\cdot}95\,^0/_{00}$ to designate overflow water. This is nearly identical with the water type called NS water here. Consequently their analysis of the proportion of overflow water will give very nearly correct values for the deeper water layers (below abt. 1,500 metres) where the overflow water can be assumed to originate from the Faroe Bank Channel, but at smaller depths their method will give a marked underestimate of the proportion of overflow water as this here must mainly originate from the Ridge area, where roughly $50\,^0/_0$ of the overflow water is of the NI water type. It is thus probable that the value $1.4 \cdot 10^6$ m^3/sec. given by the authors for the volume transport of overflow water is somewhat too low.

WATER TYPES FORMED BY THE MIXING PROCESSES

When overflow water mixes with Atlantic water all degrees of intermediate admixtures are formed. It is

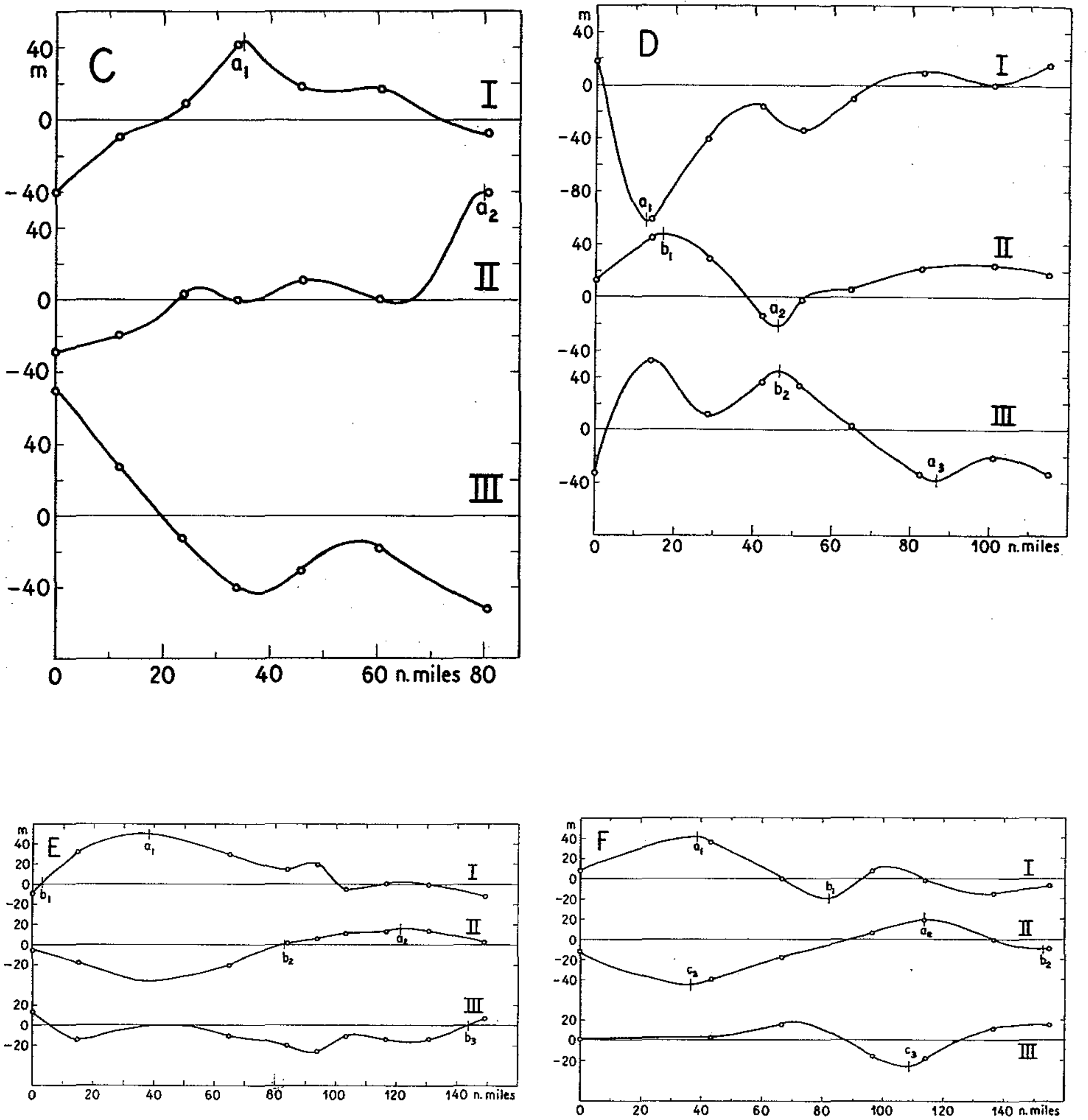

Figure 3:111 b. Anomalies of equivalent thickness of overflow water along the cores of the overflow branches C, D, E and F for the Surveys I, II, III.
The Atlantic part of the branches is found to the right.

of interest to note then that a great part of the mixed water will have densities lower than the density of AI water. This part of the mixed water will not be found in the near-bottom layer in the North Atlantic, but will be distributed above the sub-Arctic water.

The bottom water on the Atlantic side of the Ridge is not of a very homogeneous composition. In the core of the current from the Faroe Bank Channel the bottom water has, however, a T-S value of about. 2·8°, 35·03 ‰, where it is found at depths greater than 1,200 metres.

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CHAPTER 4

WATER MASS DYMAMICS IN THE ICELAND-FAROE RIDGE AREA

By

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In accordance with an earlier recommendation from the Hydrographical Committee of the International Council for the Exploration of the Sea (ICES), an international expedition of nine vessels from different countries carried out three hydrological surveys in the Faroe-Iceland area in the summer of 1960. The main aim of the investigations was to study the overflow of Norwegian Sea bottom water across the Iceland-Faroe Ridge into the North Atlantic Ocean.

All countries participating in the expedition were provided with data collected during the above surveys. In addition, the Hydrographical Committee put forward several main problems to be investigated on the basis of the data obtained and appropriate executors were appointed. Particularly, we, the authors of this paper, in collaboration with Dr. O. H. Sælen, Bergen, Norway, were responsible for the problem of the water mass dynamics in the Iceland-Faroe Ridge area.

During each of the three surveys all nine vessels took about 300 hydrographical stations, seven of the ships taking about 250 stations grouped in 14 parallel sections. These 14 sections evenly covered the aquatic area of the Ridge. The direction of the sections from southeast to northwest, i.e. along and parallel to the Ridge, was appropriate to the investigation of the overflow of the Norwegian Sea bottom waters across the Ridge (Figure 0:1 of the Introductory Chapter), and reflected also existing ideas on water mass movement in the area from the Norwegian Sea into the Atlantic Ocean and vice versa. These can be found particularly in the Soviet sources – for example, in the scheme of the Norwegian Sea currents worked out by A. Alekseev, and B. Istoshin (1956), scientific workers of the Polar Research Institute, Murmansk (Figure 4:1), and in the winter and summer schemes of the Atlantic Ocean currents as illustrated in "Sea Atlas", vol. II (1953). According to both these sources there are two oppositely directed flows in the Iceland-Faroe Ridge area: one in the eastern part of the area from the Atlantic into the Norwegian Sea, and the other in the opposite direction southwards along the coast of Iceland. In addition, one more detail should be explained in these schemes. The main direction of the Atlantic flow towards the Faroe-Iceland and the Faroe-Shetland areas from southwest is toward the Faroe Islands. This flow divides before reaching the Faroe Islands, the eastern part going through the Faroe-Shetland Channel into the Norwegian Sea. The western part goes partly eastward south of the Iceland-Faroe Ridge and partly to the northwest toward the southeast coast of Iceland. In view of such water mass dynamics in the Iceland-Faroe Ridge area, one might suppose that the overflow of bottom water from the Norwegian Sea into the Atlantic Ocean would occur all along the Iceland-Faroe Ridge and be directed towards the southwest.

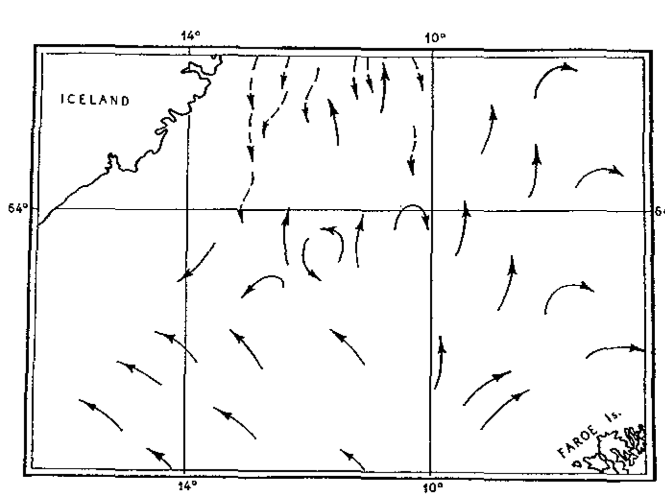

Figure 4: 1. Scheme of currents in the Iceland-Faroe Ridge area, by Alekseev and Istoshin.
⟶ warm current - - - → current of mixed water

In the beginning it was decided to process the

1st SURVEY

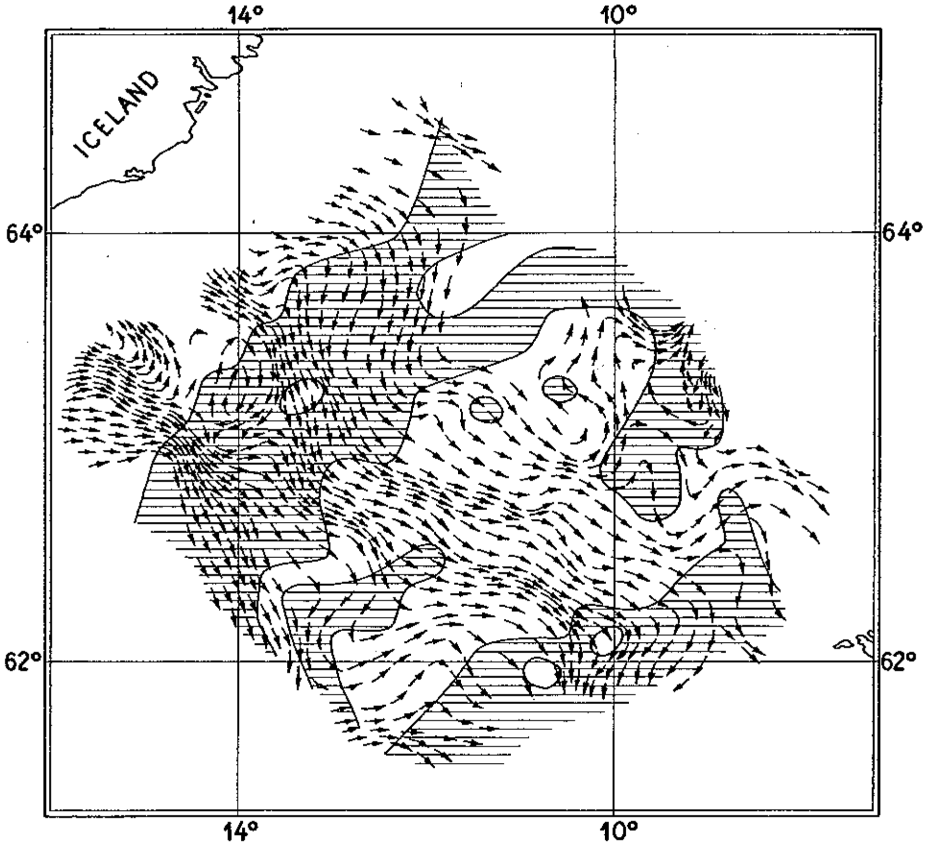

Figure 4:2. Chart of the actual sea topography in the Iceland-Faroe Ridge area according to data of the survey in the period 30. May–3. June, 1960.

available information by a common dynamic method. According to this method, the materials are arranged in sections approximately at right angles to the presumed direction of water movement. The direction of the hydrographic sections carried out during the expedition met this requirement, having in mind that the dynamics of water masses in the area of the Iceland-Faroe Ridge is a through movement from the northern part of the Atlantic Ocean into the Norwegian Sea, and vice versa.

The technical part of our work was greatly assisted by the kind co-operation of Dr. O. H. Sælen, who carried out all the preliminary computations in the University of Bergen, providing computed values of relative density (σ_t), anomalies of specific volume ($\triangle\alpha \times 10^5$) and anomalies of dynamic depths ($\triangle D \times 10^4$) for each section.

In order better to study the problem of the overflow of deep Norwegian Sea waters into the Atlantic Ocean, we aimed at a quantitative expression of the displacement of the water masses across the Iceland-Faroe Ridge in both directions. To get a detailed picture of the water exchange across the Ridge, it was decided to compute the transport in separate layers each 200 metres thick. Accordingly, a method of computation was chosen on the basis of the values of the anomalies of dynamic depths. The speeds of the currents between each pair of stations on the standard sections were worked out, currents from the Atlantic to the Norwegian Sea being taken as positive and those in the opposite direction as negative. A similar procedure was applied to layer transports of water computed on the basis of the calculated speeds. Layer transports between each pair of stations were reckoned as half the sum of the current speeds on the upper and lower boundaries of the layer, multiplied by the thickness of the layer and the distance between the stations. Calculation of the current speeds was carried out as follows: –

Anomalies of dynamic depths, calculated for each station were equated according to depth for each pair of adjacent stations with the help of a method proposed by Helland-Hansen (1934). For this purpose, half the sum of the bottom anomalies of specific volume ($\times 10^5$) at two adjacent stations was multiplied by the depth difference between the two stations, and the product added to the dynamic depth anomaly of a

2ND SURVEY

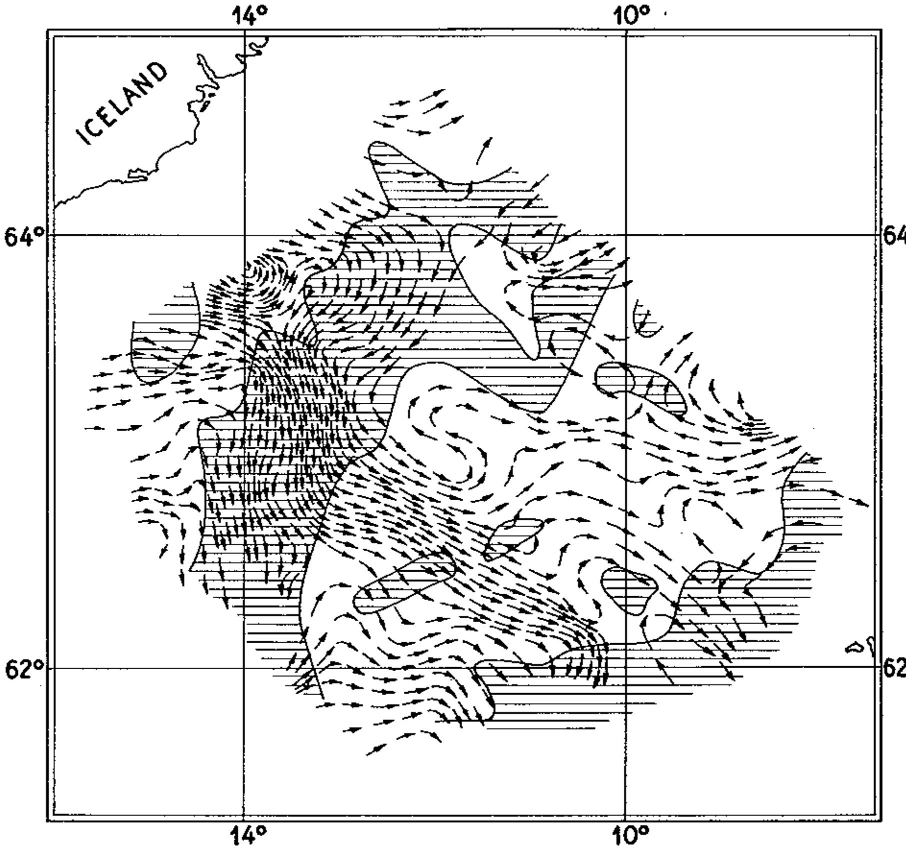

Figure 4:3. Chart of the actual sea topography in the Iceland-Faroe Ridge area according to data of the survey in the period 6.–9. June, 1960.

shallower station. Since in most cases the depths of adjacent stations do not differ much, it is permissible to apply this method. Dynamic depth anomalies were then converted into anomalies of dynamic heights and from their differences current speeds were computed for separate levels.

In the first assay the data for the 14 sections made during each of the three surveys on the Ridge itself and in the area of both its falls were used. The data of "Perseus II" and "Explorer" relating to sections situated off the Ridge were not used.

If in the period of the investigation water mass movements in the area of the Ridge had corresponded to the above picture of water masses moving from the Atlantic into the Norwegian Sea and vice versa, then the resultant water transports should have been almost the same for all sections. At least the order of these values had to be the same, if not in all 42 cases, then for each group of 14 sections of the same survey. This follows from the assumed nature of water movement and the direction of the sections traversed by the vessels. In fact, however, this did not turn out to be the case. At several occasions water transports differed from each other from one section to another. Minimum transports were noted in sections located near the summit of the Ridge, maximum transports in the sections on the slopes of the Ridge. The greatest transports were noted in the sections situated along the southern (Atlantic) slope of the Ridge. From north to south, the mean values of water transport for each ship's sections were: –

"Johan Hjort"	$3{,}086 \times 10^3$	m³/sec.	
"Gauss"	$1{,}886 \times 10^3$	–	
"Ernest Holt"	915×10^3	–	
"María Júlía"	246×10^3	–	
"Helland-Hansen"	469×10^3	–	
"Anton Dohrn"	$5{,}089 \times 10^3$	–	
"Discovery II"	$2{,}444 \times 10^3$	–	(incomplete sections)

To illustrate these differences the transports for each pair of stations were plotted on charts. Three such charts were made corresponding to the three surveys. This, however, did not yield the expected result. On each of the three charts only two zones with

3rd SURVEY

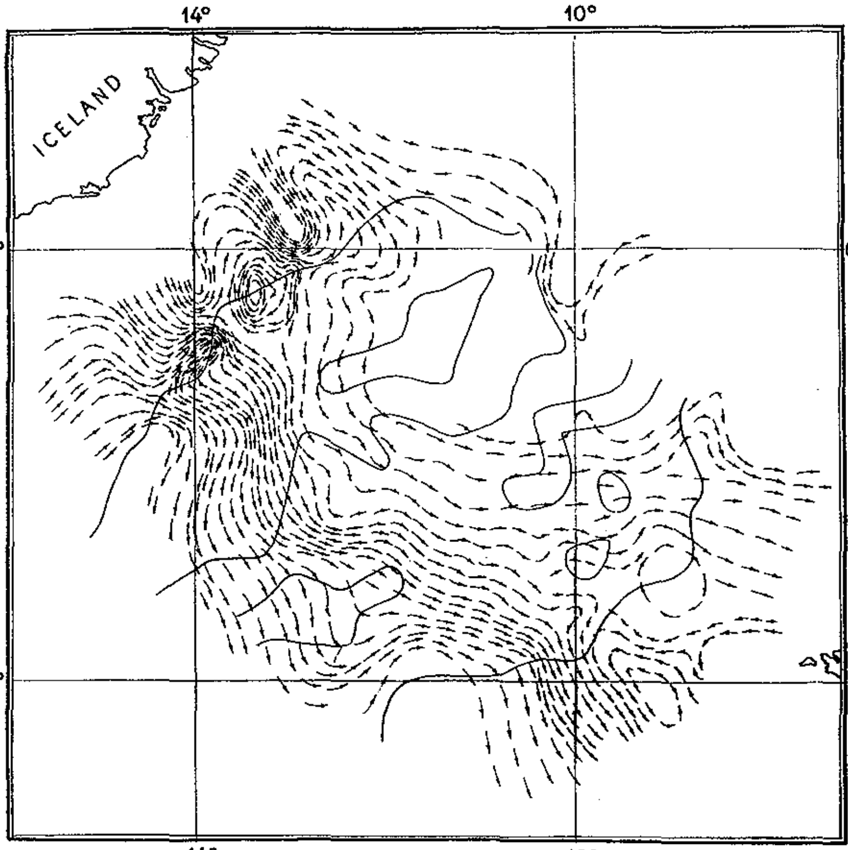

Figure 4:4. Chart of the actual sea topography in the Iceland-Faroe Ridge area according to data of the survey in the period 14.–18. June, 1960.

"negative" transports were found where flows were directed from the Norwegian Sea into the Atlantic. The location of the two zones on all three charts is generally the same.

The first zone is situated across the Ridge from northeast to southwest along the coastal slope of Iceland; the second zone (a smaller one) is in the same direction in the southeastern part of the region along the Faroe archipelago's coasts. In Figure 4:2–4:4 these zones are marked with a darker colour.

A similar chart was drawn up for the bottom 200-metre layer and again two similar zones with "negative" discharges were distinctly marked on it. The distribution of resultant water transports by sections shows a trend similar to that mentioned above, viz.: –

"Johan Hjort"	403×10^3	m³/sec.
"Gauss"	381×10^3	–
"Ernest Holt"	72×10^3	–
"María Júlía"	917×10^3	–
"Helland-Hansen"	$2{,}272 \times 10^3$	–
"Anton Dohrn"	$2{,}095 \times 10^3$	–
"Discovery II"	-960×10^3	–

Simultaneously with the above estimations the following work was done in collaboration with the section of oceanography of the Moscow State University.

Preliminary data of dynamic processing obtained early were used by V. A. Shulepov for drawing up dynamic charts for each survey and for various sections. For this the selection of a zero surface was found to be most difficult. Attempts to determine the zero surface with the help of the Defant method, *i.e.* by analysis of curves of vertical distribution of dynamic depth differences did not yield the result expected. The absence of these curves of vertical sections and uniformity of curves taken separately led to the conclusion that currents penetrated to the bottom in the area in question. Since the depths of the stations taken during the survey vary considerably it was impossible to take the bottom as the zero surface. For this reason, while drawing up dynamic charts it was decided to employ a method of coupling dynamic heights as the most suitable one in this case. Station No. 9 of 700-metres depth at which the vessel "Helland-Hansen" was

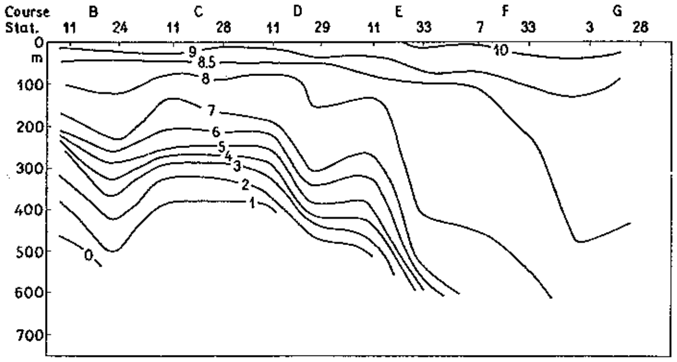

Figure 4:5. Distribution of temperatures on a section along the Iceland-Faroe Ridge according to data of the international survey 1960.

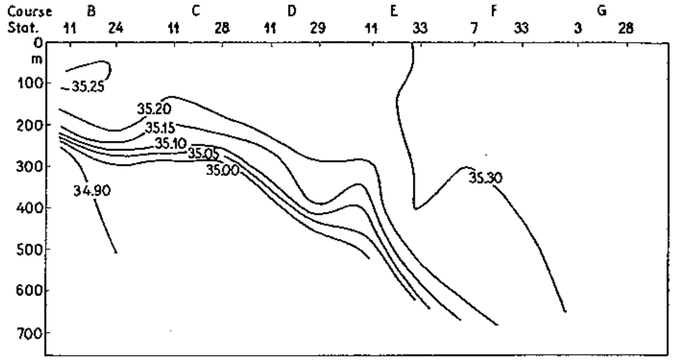

Figure 4:6. Distribution of salinity on a section along the Iceland-Faroe Ridge according to data of the international survey 1960.

working was taken as the main station. This station was selected because it lies beyond the boundaries of the shallowest part of the area investigated and near its centre. Dynamic heights of the stations located on the same section were calculated by means of coupling each station to a neighbour one. The same procedure was applied to calculation of actual differences of dynamic heights on standard horizons for the remaining sections. To switch over from a "main" section to a neighbouring one a method of oceanographic triangulation was used. Two stations of a triangle were taken on a worked-up section and a third station on a section being processed. With the help of such triangulation not only the linking of a new section but also the accuracy of dynamic heights' coupling were checked. Data of all three surveys were processed by this method. The further check-up showed that by this method discrepancies do not exceed the limits permitted in drawing up dynamic charts. As a result of this examination the 700-metre depth was taken as the zero surface.

Schemes of currents in the Iceland-Faroe Ridge area ultimately worked out proved to be very different from the assumed scheme mentioned above. These newly worked out schemes of currents are shown with arrows in Figures 4:2–4:4. It turned out, in particular, that in the period of the expedition (short term of observations does not allow for assumption of constancy of the scheme of current worked out) the movement of waters in the Faroe-Iceland area was mainly along the Ridge and not across it, the current directions corresponding with the bottom topography.

In particular, the Norwegian flow which according to former ideas ran through the western part of the area into the Atlantic, runs in the present case within the area from northwest to the southeast, moving along the northern slope of the Iceland-Faroe Ridge. A more striking picture appears in the southern part of the area. A great flow of Atlantic waters passes from the Icelandic coast along the southern slope of the Ridge toward the Faroe archipelago, filling all the bends of the southern slope's topography and reaching partly to the summit of the Ridge.

Over the Ridge two water masses moving into and from the Norwegian Sea interact, and the area of the Ridge is a zone of active intermingling of these water masses. The presence of two different water masses on either side of the Ridge is confirmed by the distribution of temperature, salinity, and specific volume. Figures 4:5–4:7 show the distribution of these elements on the section made along a median axis of the Faroe-Iceland region.

The direction of flow of the southwestern branch of the Atlantic water mass appeared from the scheme of currents to be most surprising. Contrary to previous ideas the direction of this flow turned out to be from the coast of Iceland to the southeast and not as formerly believed to the northwest towards the coast of Iceland. Such direction of this current can be partly explained by the fact that in 1960 there was observed an increase in the North Atlantic current in a branch disjoining from the Rockall Bank and running to the southeast coast of Iceland south of the region investigated. As a result a flow appears which runs from Iceland to the southeast along the southern slope of the Iceland-Faroe Ridge, i.e. in the direction opposite to the accepted scheme.

In the light of the above, puzzling questions which arose from the first assay become clear. Sections of some of the vessels which took part in the expedition did not cross the same flow, but operated in different parts of a complicated scheme of currents which was formed by two independent flows. Hence the great differences in the values of water transports in respect to some of the sections, depending on the average depth of one or other section and the angle between the direction of a section and that of the currents. Originally it was presupposed that the planned sec-

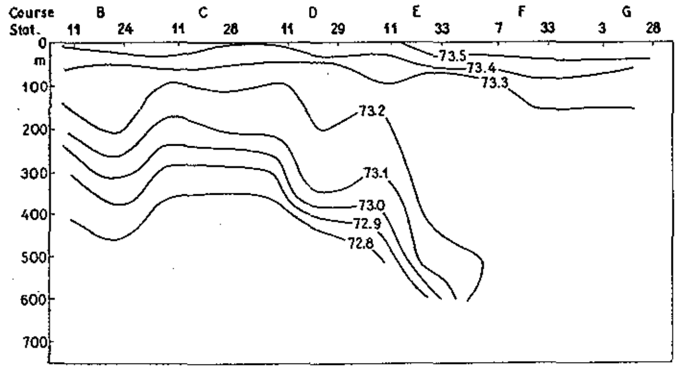

Figure 4:7. Distribution of relative specific volume on a section along the Iceland-Faroe Ridge according to data of the international survey 1960.

tions were more or less at right angles to the directions of the currents which is a prerequisite for the success of the dynamic method. In fact, however, it appears that the direction of the sections often approximated to that of the currents and when these directions coincide with each other the dynamic method cannot be employed. In these circumstances current speeds, and consequently transports, approach zero. In particular, minimum transports worked out from the data obtained by the vessels "María Júlía" and "Helland-Hansen" can probably be accounted for in this way.

The last question to be clarified is the existence of two zones of "negative" transport recorded during the first assay above. Joint consideration of the results worked out by both methods showed that there were local deviations from the general direction of both flows (Figures 4:2–4:4). In addition, in zones of "negative" transport, southern components predominate in the directions of flows and these create an illusion of outflow from the Norwegian Sea into the Atlantic. Here, one should take into account the difference in methods used in the two parts of the work. In the first, transports were worked out for each pair of stations, from the surface to the bottom, and in the second the depth of 700 m was provisionally taken as the zero horizon. This is why, while examining Figures 4:2–4:4, one cannot expect complete coincidence of the zones of "negative" transport with a southerly direction of flow.

Further in support of the conclusions arrived at, the following final verification was carried out. Following the scheme of currents worked out, two sections were selected which passed from NNE to SSW across the Ridge (Figure 0:1), i.e. which crossed approximately at right angles the flows of two water masses of different origin. The first of these sections included the stations B15 and B18 ("Johan Hjort"), C17 and C22 ("Gauss"), D17 and D23 ("Ernest Holt"), E17 and E27 ("María Júlía"), F13 og F27 ("Helland-Hansen"), G9 and G22 ("Anton Dohrn"), and H7 ("Discovery II"). Similarly, the second section accomodated the stations B11 and B24, C11 and C28, D11 and D29, E11 and E33, F7 and F33, G3 and G28.

Volume transports on these sections were calculated between each pair of the stations from the surface to the bottom, using the same methods as before. As a result of these calculations it appeared that the volume transport through the first section was $17{,}923 \times 10^3$ m^3/sec., and through the second, $19{,}537 \times 10^3$ m^3/sec. Using the scheme of currents worked out by us and also taking into consideration the relief of the bottom, the volume transports through these sections were divided into two groups, namely, Norwegian and Atlantic. "Norwegian" transport was $4{,}362 \times 10^3$ m^3/sec. on the first section and $5{,}267 \times 10^3$ m^3/sec. on the second. "Atlantic" transports were respectively $13{,}561 \times 10^3$ m^3/sec. and $14{,}270 \times 10^3$ m^3/sec. The small differences between figures characterizing both types of transport through the two sections, together with distribution of these transports among water flows of different origin, permit of confidence in them and warrants the conclusion that both sections cross the same flows designated "Norwegian" and "Atlantic" respectively.

It should also be noted that the above correlation between the volume transports is in conformity with their relative intensities in nature.

The following conclusions, therefore, can be drawn on the basis of the foregoing results: –

1) Intensive penetration of bottom waters from the Norwegian Sea into the Atlantic during the period of the expedition was not observed. It was not so insignificant, however, that it was unrecorded.

2) In the area of the Iceland-Faroe Ridge there is a zone of intensive intermingling of the two water masses of different origin which occur here and this favours water exchange between the Norwegian Sea and the Atlantic.

3) In certain years the current scheme in the area changes considerably, owing to changes in the intensity of the North Atlantic current and its branches. Thus, during the period of the expedition flows were found to be directed *along* the Iceland-Faroe Ridge rather than across it, and this applied not only to upper layers but to the deeper layers as well (Figure 4:8).

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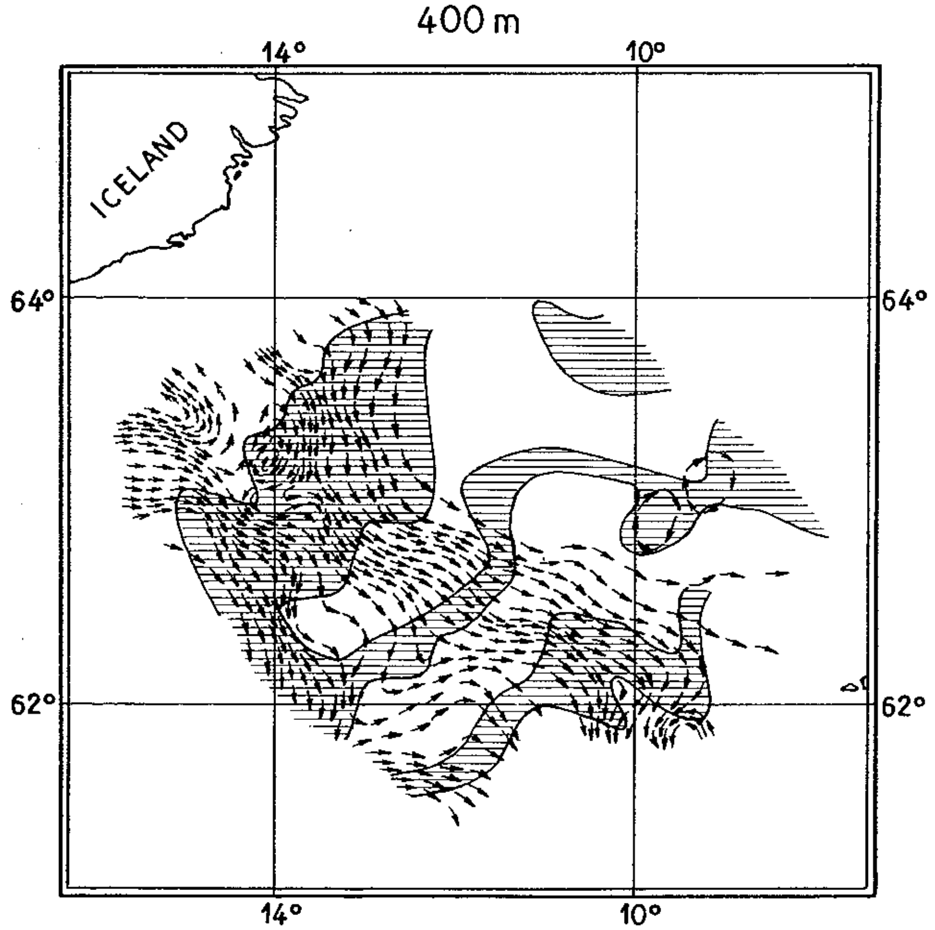

Figure 4:8. Chart of the actual topography of an isobaric 400 m surface.

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CHAPTER 5
CURRENT MEASUREMENTS DURING THE INTERNATIONAL ICELAND-FAROE RIDGE EXPEDITION, 30. MAY TO 18. JUNE, 1960

By

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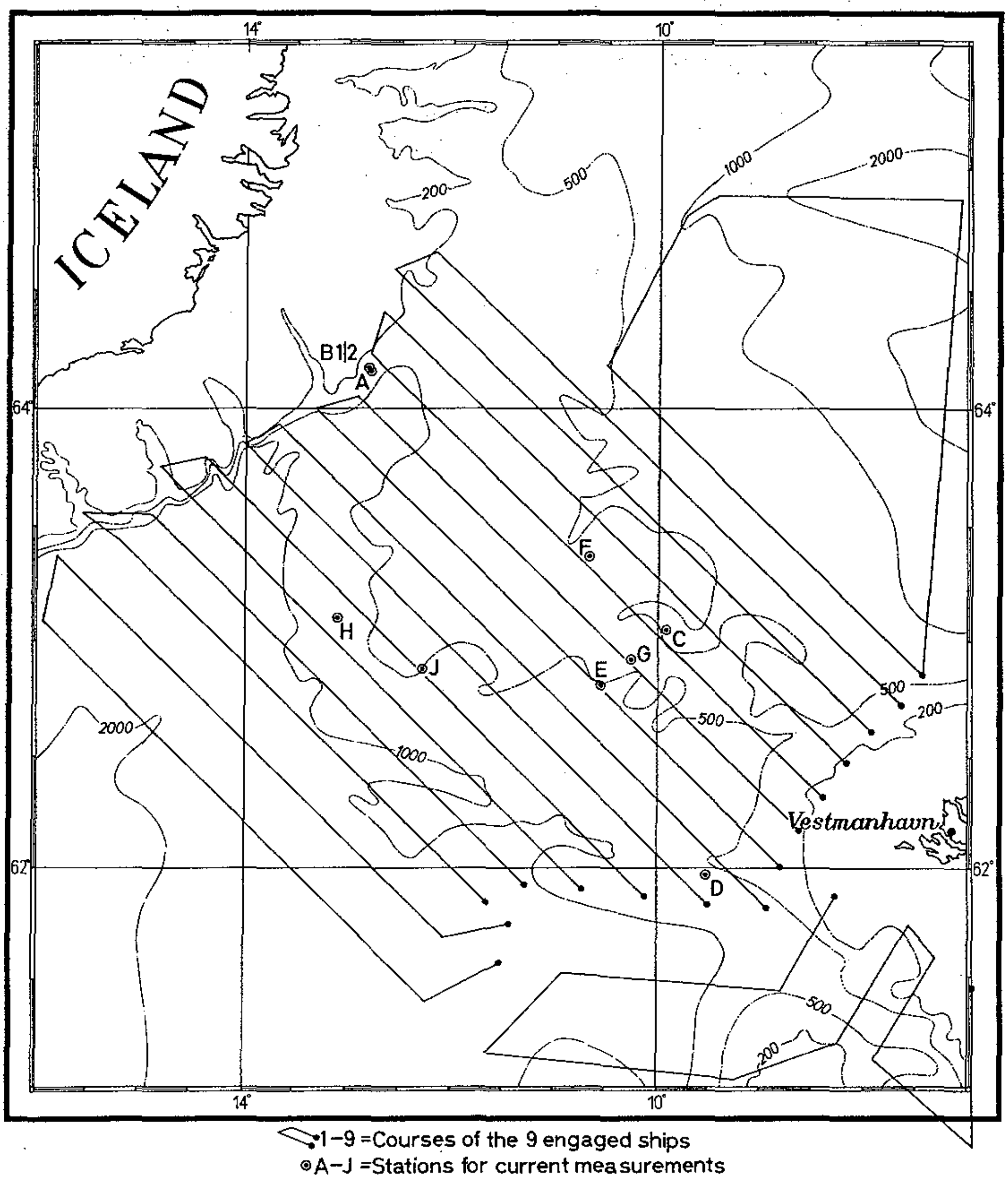


Figure 5:1. Map of the Overflow-Expedition with stations of current measurements.

[1] Present address: International Laboratory of Marine Radioactivity, Oceanographic Museum, Monaco. The observational material is available at the "Deutsches Hydrographisches Institut", Hamburg.

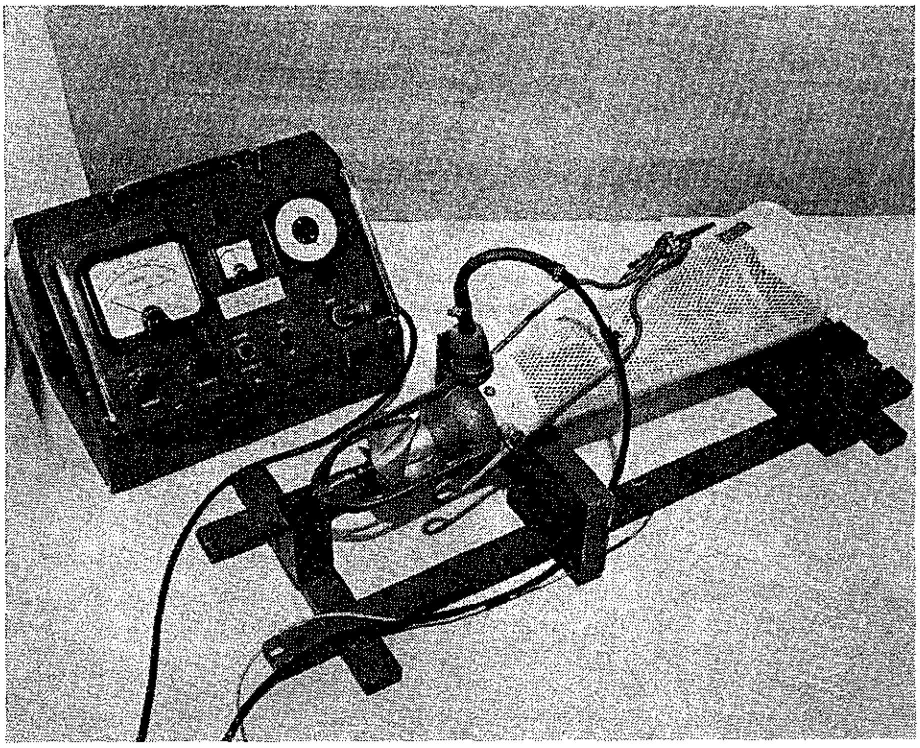


Figure 5:2a. Kelvin-Hughes Direct Reading Current Meter.

During the above expedition in May–June 1960 current measurements at the surface and near bottom were carried out in the area between Iceland and the Faroes from the vessels "Discovery II", "Ernest Holt", "Gauss" and "Helland-Hansen". The results after uniform processing are given in the present contribution.

Figure 5:1 shows the positions of the stations, indicated by A–J, at which measurements were carried out.

Table 5:1 summarizes the positions, the bottom depths, the levels of measurement, the type of current meters used, the duration of the records, and the technique used by the various vessels in carrying out the measurements.

THE CURRENT METERS

Automatically registering current meters were used at the positions B1, B2 and C only (see Figure 5:1). At all other stations the current meters were operated from moored or drifting ship. The following seven types of current meters were employed: –

(a) KELVIN-HUGHES DIRECT READING CURRENT METER

This instrument, shown in Figure 5:2a was used from "Ernest Holt". The underwater unit consists of a central fish-shaped body carrying a propeller which acts as speed sensor, and a conical tail made of perforated aluminum coated with plastic paint. This unit is mounted on trunnions in a brass hanger attached to the cord on which the unit is lowered from an anchored ship. Lead weights are secured below the hanger keeping the meter at the required depth. The body is oil-filled and carries the direction sensor, which is a Fluxgate mechanism, a sensitive magnetic detector element and the cam and contacts for the speed measuring circuit, the drive between the propeller and the inside of the body being through a magnetic coupling. A 6-core screened cable connects the underwater unit to the deck unit. This consists of a micro-ammeter with a dial graduated so as to allow the speed of the current to be read directly, and a direction of flow dial and a balancing knob, which has to be turned to give a zero position on a small meter before the current direction can be read directly from the main dial. The minimum speed of response of the meter is 7 cm/sec.

(b) MOSBY DEEP CURRENT METER

This instrument, which is shown in Figures 5:2b and 5:2c, was used from "Helland-Hansen". It was constructed by MOSBY and is essentially an Ekman current meter mounted on a vertical rod that is based on a large, heavy iron ring. It is lowered from the ship until the ring reaches the bottom. A releasing mechanism then sets the meter free to operate. When the apparatus is lifted from the bottom again, usually after five to ten minutes, the meter is automatically relocked. In this way current measurements are made

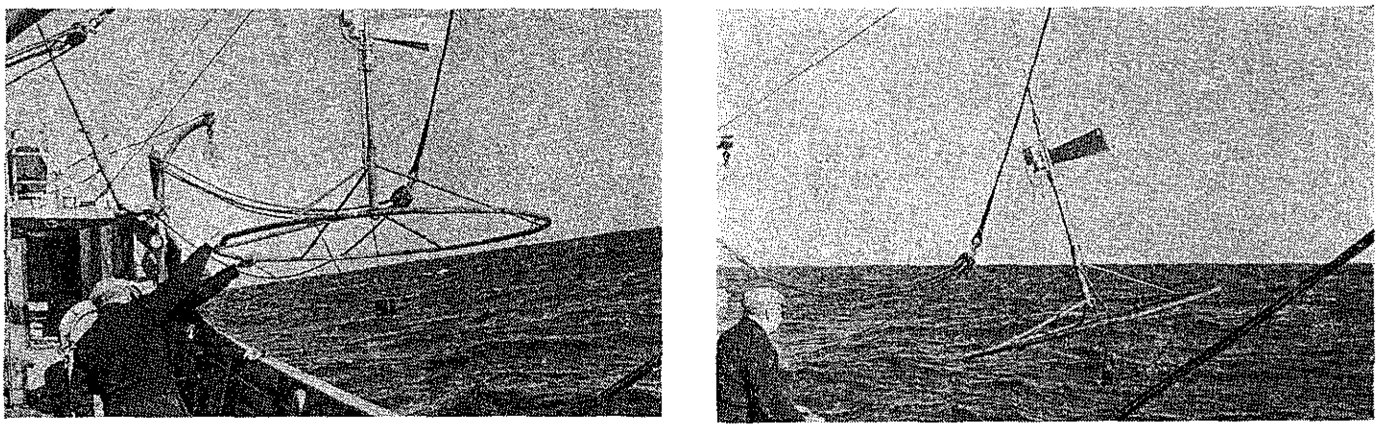


Figure 5:2b, c. Mosby Bottom Current Meter.

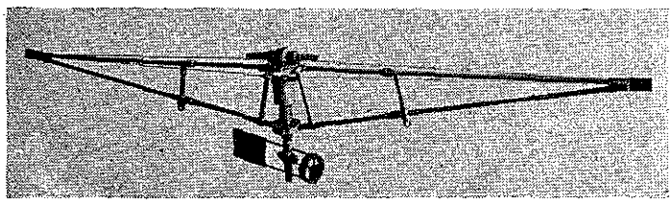


Figure 5:2d. Bifilar Current Meter.

very close to the bottom, about 130 cm above it, uninfluenced by the ship's movements because the suspending wire is given enough slack so that it does not drag the apparatus.

(c) BÖHNECKE CURRENT METER

This instrument was used from "Gauss". It is operated from the ship. The speed of the current is measured by means of a propeller, the direction by means of a magnetic compass. The observed values are recorded within the instrument by impress into a tin-foil at intervals of two, five or ten minutes. The instrument is pressure-adjusted and may be used in any depth desired.

(d) DHI BIFILAR CURRENT METER

Was used by "Gauss". The implements to be lowered from the ship are shown in Figure 5:2 d. The current meter is fastened to a frame which in two cables parallel to the longitudinal axis of the ship can be lowered to measuring depths of up to 50 m. The current speed is measured by a propeller with magnetic coupling, the revolutions being recorded or printed aboard. The direction of the current meter vane in relation to the frame is instantaneously transmitted aboard, here automatically added to the ship's course, and the current direction thus obtained is recorded or printed.

(e) EKMAN-MERZ CURRENT METER

This generally known instrument was used by "Helland-Hansen". For each lowering is obtained only average values of current direction and current speed over the period of measurement.

(f) PISA BOTTOM CURRENT INDICATOR

Was used by "Discovery II" and "Ernest Holt". The instrument is shown in Figures 5:2e and 5:2f. The pisa, constructed by CARRUTHERS, operates because of its buoyancy as an "uphanging" negative pendulum which is placed on the sea-bed in a way that, although leaving it linked to the observing ship, lets it remain undisturbed by the ship's movements for some minutes. The indicating unit is a half-pint pyrex bottle half filled with gelatine solution, and half with pigmented castor oil. Centrally within the bottle a powerfully magnetized compass disc hangs just within the jelly which is hot when filled in, and is kept hot by a special construction until the pisa is at the sea bed. When the bottom is reached the bottle quickly cools to produce a firm separation surface between

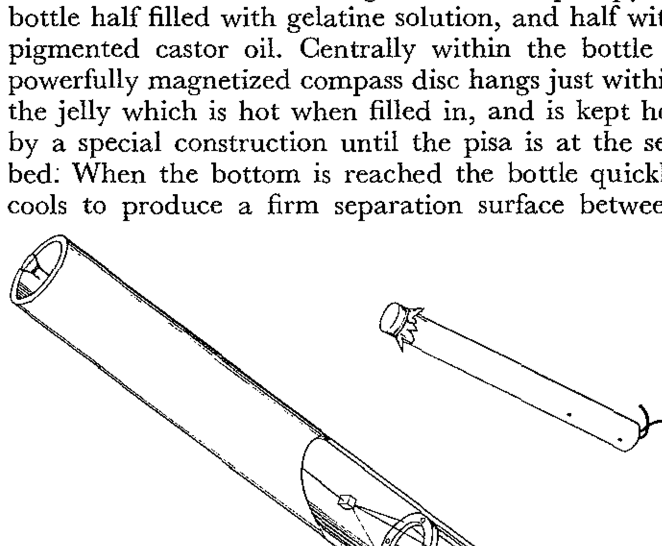


Figure 5:2e. Pisa Indicator. Showing (above) the external appearance of the Pisa when ready for use, and (below) how the bottle-holder is placed.

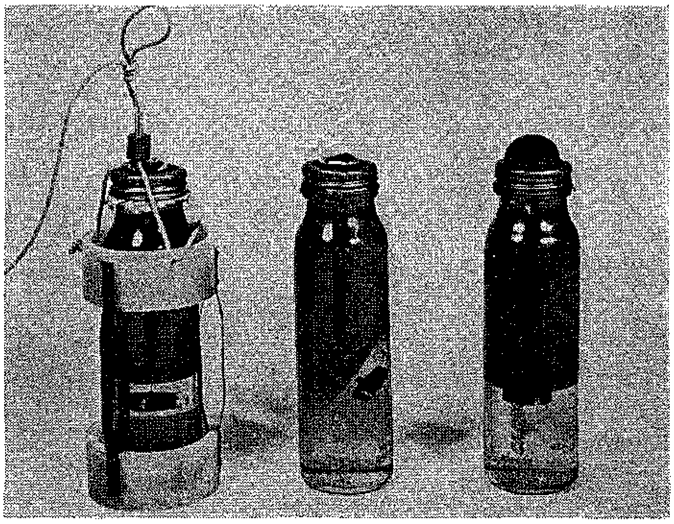


Figure 5:2f. The indicating bottle of the Pisa. Right: when hot and ready for use. Left: in holder. Middle: as recovered cold after use in a pronounced current.

the oil and the solidified jelly. The presence of a current results in this surface being sloped in a direction revealed by the "frozen-in" compass, and to a degree interpretable into speed from prior calibration.

(g) DHI-DEEP CURRENT METER

Was used by "Gauss". It is an automatically registering instrument that can be placed near the bottom. It represents a further development of the well-known paddle-wheel current meter. Instead of the paddle-wheel, however, it has a double-winged screw. Its starting-speed amounts to 2–3 cm/sec. The revolutions of the wing and the direction of the compass are photographed at five minute intervals. The duration of registration is four weeks. Figures 5:2g and 5:2h show respectively the principle of mooring and the instrument being put out. Buoyancy is obtained by means of ball floats enclosed in nylon-netting. During the ICES expedition the instrument was used to a depth of about 500 m; it may, however, be used down to 1,000 m.

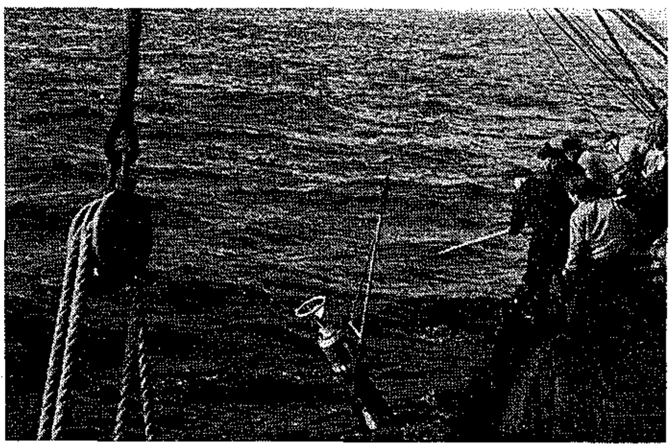


Figure 5:2h. DHI-Deep Current Meter.

THE OBSERVATION DATA

The periods during which current measurements were carried out at the various stations are indicated in Figure 5:3. The measurements were carried out mainly at anchor stations some of which unfortunately had to be interrupted prematurely because of bad weather, so that simultaneous records from different stations are available for very short periods only. In Figures 5:4a and 5:4b the current speeds are presented as functions of time for all measurements. Thereby the observations, or, for records of very short intervals of time, their mean values, were connected by straight lines. Figure 5:4a is a presentation of the records of Depth Current Meters laid out from "Gauss" totalling 8,242 observations during 687 hours of recording. From 7. to 9. June two instruments were working simultaneously, one on the slope of the Icelandic Shelf (Station B1), the other about midway between Iceland and the Faroe Islands (Station C). Preliminary investigations indicated that these two localities were likely to be within the path of any overflow. Subsequently the two instruments were re-

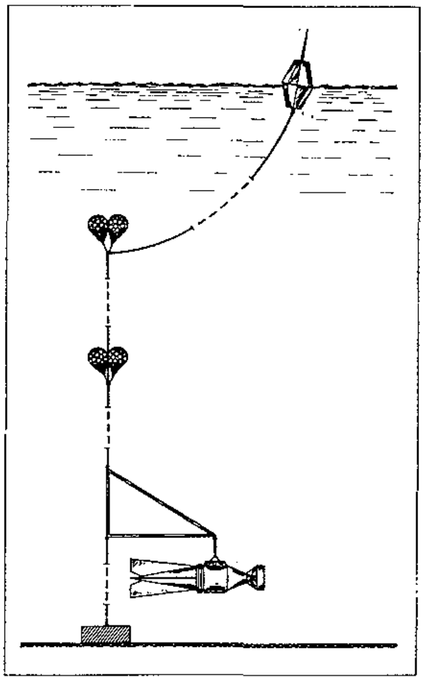


Figure 5:2g. DHI-Deep Current Meter. – Principle of mooring.

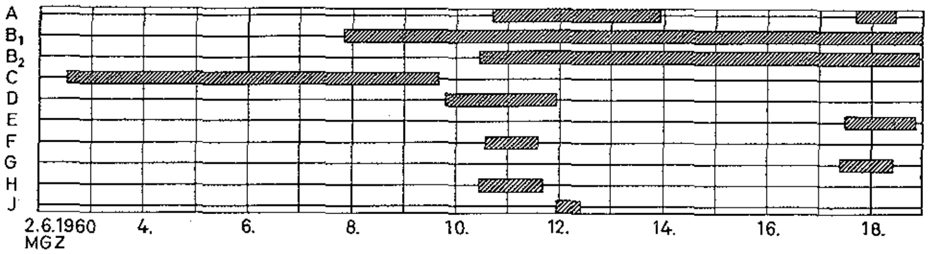


Figure 5:3. Periods of current measurements at the stations A–J.

moved to the neighbourhood of Station A, in order to measure the bottom current when the "Gauss" anchor station was worked (Stations B1 and B2). At the same time current observations at the surface and in medium depth were carried out from "Gauss"; these observations, together with those of the other vessels, are presented in Figure 5:4b. Thus Figure 5:4 a records the observations collected by laid-out instruments, Figure 5:4b those collected by instruments operated from the ships.

Already from these presentations it is to be recognized that the currents have a periodical component, caused by the tides, and a non-periodical component. The latter is designated residual current.

The maximum current speeds occurring at the surface and in small depths are of the magnitude of 1 m/sec. Such values were still observed at Stations A and F at depths of 10–20 m. At Station D a maximum speed of 80 cm/sec. occurred at a depth of 50 m.

A comparison of the measurements on 11.–12. June (Stations A, D, E) with those on 17.–18. June (Stations A, G) shows clearly, from the decline of the maximum speed to about half its value, the influence of spring tide and neap tide. However, the observations available did not suffice for calculating with sufficient accuracy the deceleration at spring tide.

According to whether the periodical or the non-periodical component of the currents predominates the direction of the current changes or remains steady with only slight fluctuations. The former happens mainly in the surface, the latter mainly at the bottom. For further understanding a separation of these two components is therefore necessary.

WORKING-UP OF THE DATA

(a) THE TIDAL CURRENT

For separation of the periodical and non-periodical components of the currents, amplitudes and phases of the M_2-tide, as well as the residual currents, were calculated from the observations by the method of

Table 5:1.
Current measurements during the Overflow-Expedition

Station	Position Lat. N	Position Long. W	Vessel	Depth to bottom	Depth of the recorder	Current meter	Duration of the record	Number of observations	Interval between two observations
A	64° 9·3′	12°47·0′	"Gauss"	500	20	Bifilar	10.–13. June	4,185	1 min.
A	64° 9·3′	12°47·0′	"Gauss"	500	250	Böhnecke	10.–11. –	186	2 –
A	64° 9·3′	12°47·0′	"Gauss"	500	20	Bifilar	17.–18. –	1,072	1 –
A	64° 9·3′	12°47·0′	"Gauss"	500	250	Böhnecke	18. –	203	2 –
B1	64°10·2′	12°47·7′	"Gauss"	476	476	Deep current meter DHI	7.–18. –	3,386	5 –
B2	64° 9·3′	12°47·0′	"Gauss"	504	504	,, ,,	10.–18. –	2,469	5 –
C	63° 2·8′	9°55·3′	"Gauss"	462	462	,, ,,	2.– 9. –	2,387	5 –
D	61°58′	9°31′	"Helland-Hansen"	770–820	50	Ekman-Merz	9.–10. –	60	about 15 min.
D	61°58′	9°31′	"Helland-Hansen"	770–820	770–820	Mosby Deep current meter	9.–11. –	34	1 to 2 hours
E	62°48′	10°33′	"Helland-Hansen"	510–520	510–520	,, ,,	17.–18. –	33	1 to 2 –
F	63°22′	10°41′	"Ernest Holt"	420	10	Kelv.-Hugh.	10.–11. –	41	30 min.
F	63°22′	10°41′	"Ernest Holt"	420	413	Pisa	10.–11. –	25	1 hour
G	62°55′	10°16′	"Ernest Holt"	480	25	Kelv.-Hugh.	17.–18. –	50	30 min.
G	62°55′	10°16′	"Ernest Holt"	480	473	Pisa	17.–18. –	23	1 hour
H	63° 6′	13° 5′	"Discovery II"	666	666	Pisa	10.–11. –	28	1 hour
J	62°52·5′	12°16·0′	"Discovery II"	507	507	Pisa	11.–12. –	12	1 hour

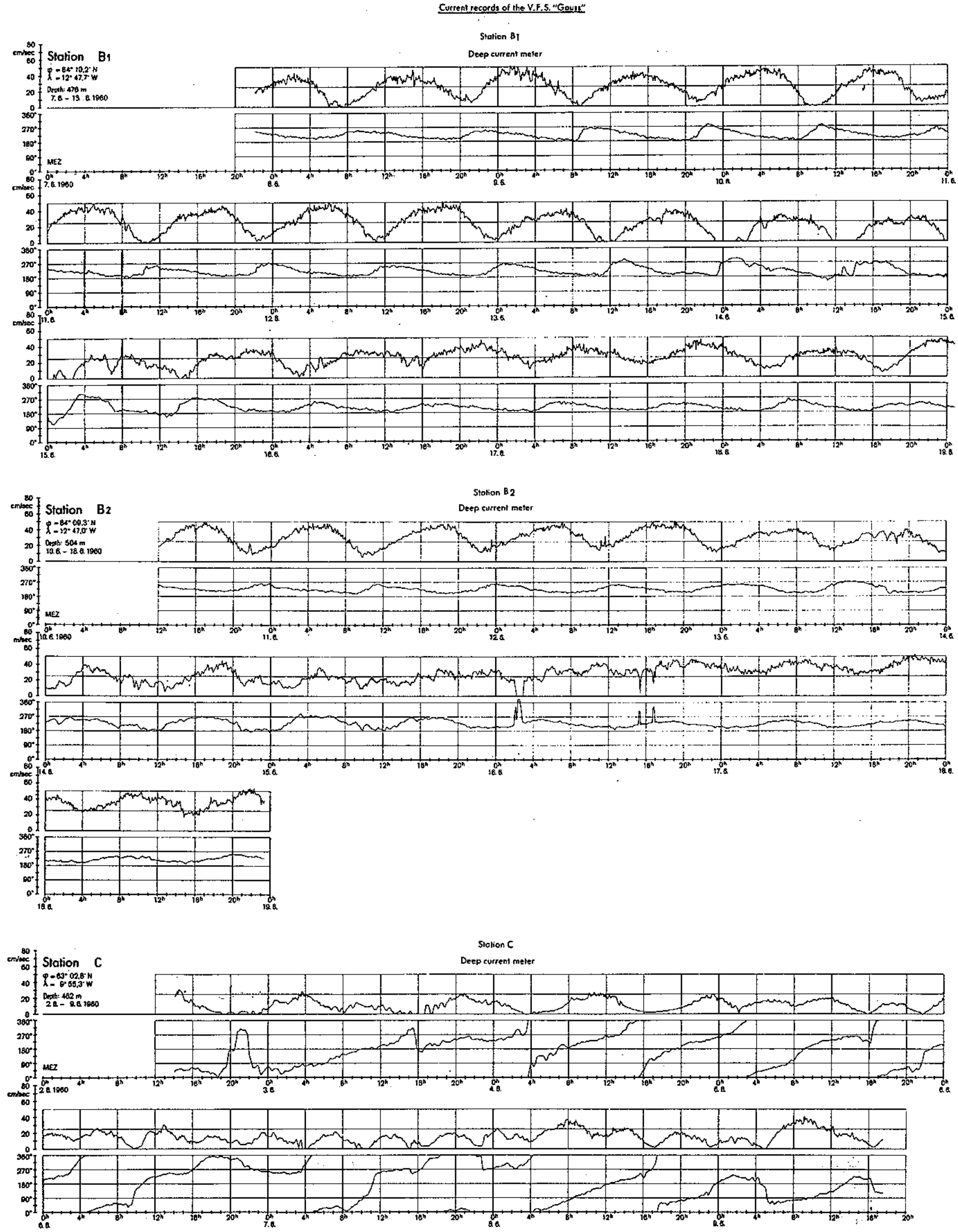


Figure 5:4a. Current Records of the DHI-Deep Current Meter at stations B1, B2 and C.

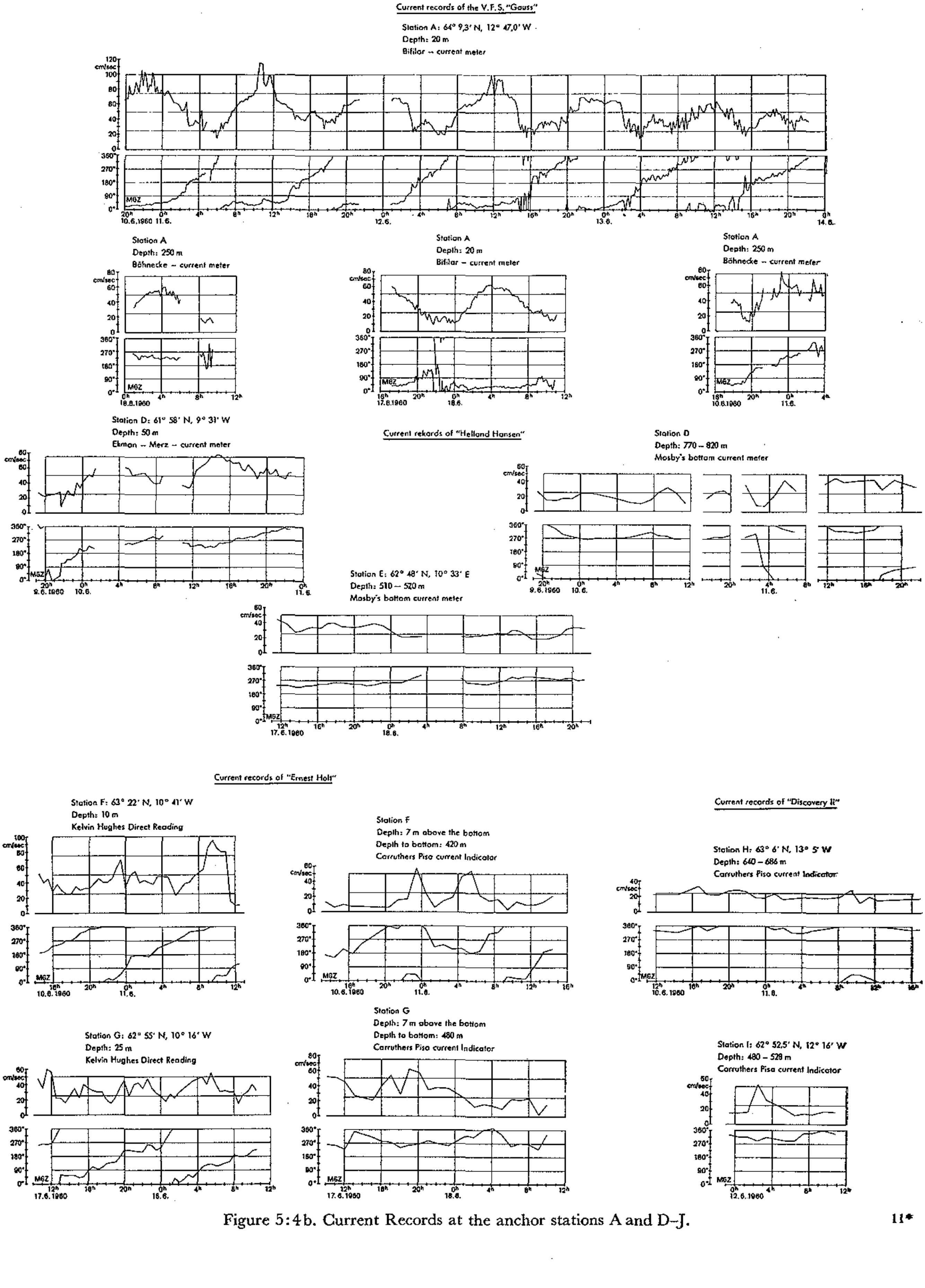


Figure 5:4b. Current Records at the anchor stations A and D–J.

Table 5:2.
Current ellipses and residual currents

Part I: Period of analysis: 13 hours.

Station	Depth of measure-ment	Period of analysis	Phase	Current ellipses: Main semi-axis Direc-tion°	Main semi-axis Velocity cm/sec.	Small semi-axis Velocity cm/sec.	Rotation -: cum sole	Ratio of the axes	See Fig.	Residual currents Direc-tion°	Residual currents Velocity cm/sec.
A	250	10. June 18^h–11. June 04^h	+3^{h}49^m	15	43·5	37·2	–	0·86	5:5a	243	14·4
	20	20^h – 08^h	+2 39	209	61·1	21·4	–	0·35		42	38·4
	20	12. June 07^h–12. June 19^h	+2 36	229	46·9	16·6	–	0·35		37	38·3
	20	20^h–13. June 08^h	+1 50	197	54·0	22·1	–	0·41	5:5a	19	21·6
	20	13. June 09^h– – 21^h	+1 49	211	49·5	24·6	–	0·50		338	7·0
	20	17. June 21^h–18. June 10^h	+3 03	204	27·9	4·4	–	0·16	5:9b	35	33·3
	250	18. June 01^h– – 10^h	+2 23	46	26·0	6·2	+	0·24	5:5b, 5:9b	234	29·9
B1	476	7. June 23^h– 8. June 11^h	+2 15	212	16·7	6·9	+	0·41		222	20·7
		8. June 12^h– 9. June 00^h	+1 36	234	13·8	10·9	+	0·79		220	25·3
		9. June 01^h– – 13^h	+2 09	216	19·2	11·7	+	0·61	5:9a	223	23·1
		14^h–10. June 02^h	+2 50	189	17·1	12·4	+	0·73		215	23·7
		10. June 03^h– – 15^h	+2 41	196	22·1	10·0	+	0·45	5:5a	209	23·9
		16^h–11. June 04^h	+1 51	205	19·4	6·7	+	0·35		216	26·2
		11. June 05^h– – 17^h	+2 20	200	18·9	9·3	+	0·49		211	24·3
		18^h–12. June 06^h	+2 15	191	21·9	8·6	+	0·39		214	25·7
		12. June 07^h– – 19^h	+2 08	191	20·2	12·2	+	0·60		214	26·6
		12. June 20^h–13. June 08^h	+2^{h}35^m	182°	16·8	9·8	+	0·58		215	22·1
		13. June 09^h– – 21^h	+1 55	189	18·7	7·3	+	0·39		214	19·4
		22^h–14. June 10^h	+1 20	214	15·0	9·0	+	0·60		218	15·7
		14. June 11^h– – 23^h	+3 10	161	13·2	10·7	+	0·81		220	13·3
		15. June 00^h–15. June 12^h	+4 12	146	16·1	9·1	+	0·57		221	12·2
		13^h–16. June 01^h	+3 54	160	18·6	8·8	+	0·47		219	19·5
		16. June 02^h– – 14^h	+3 38	170	12·3	4·6	+	0·37		209	23·2
		15^h–17. June 03^h	+1 04	243	10·9	8·3	+	0·76	5:5b	211	28·6
		17. June 04^h– – 16^h	+0 11	273	11·9	6·8	+	0·57		215	26·0
		17^h–18. June 05^h	+1 22	237	15·2	9·7	+	0·64		211	27·2
		17. June 21^h–18. June 09^h	+5 29	128	12·5	12·0	+	0·96	5:9b	212	22·9
		18. June 06^h– – 18^h	+5 27	128	12·7	11·0	+	0·87		215	22·7
B2	504	10. June 16^h–11. June 04^h	+2 23	204	17·8	4·4	+	0·25		225	29·0
		11. June 05^h– – 17^h	+2 22	200	18·0	7·9	+	0·44	5:5a	219	27·7
		18^h–12. June 06^h	+2 46	185	17·7	7·3	+	0·41		223	29·9
		12. June 07^h– – 19^h	+2 23	190	15·8	9·5	+	0·60		224	33·5
		12. June 20^h–13. June 08^h	+2 59	171	16·0	7·1	+	0·44		229	27·9
		13. June 09^h– – 21^h	+3 10	154	18·3	6·8	+	0·37		229	25·1
		22^h–14. June 10^h	+5 33	89	12·4	6·5	+	0·52		233	20·0
		14. June 11^h– – 23^h	+5 33	110	19·3	5·4	+	0·28		234	20·3
		15. June 00^h–15. June 12^h	+5 20	132	16·1	3·1	+	0·19		239	17·0
		13^h–16. June 01^h	+4 30	146	14·4	5·3	+	0·37		231	23·0
		16. June 02^h– – 14^h	+4 23	157	11·9	4·3	+	0·36		222	29·1
		15^h–17. June 03^h	+5 41	106	11·3	5·3	+	0·47	5:5b	220	35·3
		17. June 04^h–17. June 16^h	+5^{h}22^m	116°	13·5	5·3	+	0·39		224	35·0
		17^h–18. June 05^h	+0 14	281	14·5	7·5	+	0·52		223	35·2
		18. June 06^h– – 18^h	+0 12	274	13·4	5·4	+	0·40		225	34·2
C	462	2. June 14^h– 3. June 02^h	+1 35	234	10·9	0·1	+	0·01		52	7·7
		3. June 03^h– – 15^h	+3 45	231	10·0	3·8	–	0·38		137	5·1
		16^h– 4. June 04^h	+1 39	245	10·1	1·6	–	0·16		236	10·9
		4. June 05^h– – 17^h	+2 21	238	13·3	8·3	–	0·62		236	9·2
		18^h– 5. June 06^h	+2 04	234	18·7	6·9	–	0·37		265	2·4
		5. June 07^h– – 19^h	+2 40	226	14·8	5·2	–	0·35		226	3·9
		20^h– 6. June 08^h	+2 56	215	19·9	6·2	–	0·31		344	1·9
		6. June 09^h– – 21^h	+2 48	209	15·6	3·6	–	0·23		266	8·5
		22^h– 7. June 10^h	+2 21	226	14·7	0·6	–	0·04		325	3·7
		7. June 11^h– – 23^h	+2 12	221	13·2	1·6	+	0·12		314	7·5
		8. June 00^h– 8. June 12^h	+2 08	254	22·1	17·9	–	0·81		76	7·3
		13^h– 9. June 01^h	+1 58	235	17·1	2·3	–	0·13		146	4·3
		9. June 02^h– – 14^h	+1 56	247	23·0	10·8	–	0·47	5:5a, 5:9a	105	14·1

Table 5:2. (continued)

Station	Depth of measurement	Period of analysis	Phase	Current ellipses: Main semi-axis Direction°	Main semi-axis Velocity cm/sec.	Small semi-axis Velocity cm/sec.	Rotation -: cum sole	Ratio of the axes	See Fig.	Residual currents Direction°	Residual currents Velocity cm/sec.
D	50	9. June 19^h–10. June 08^h	+2 28	230	45·9	23·9	–	0·52	5:5a	235	30·9
	770–820	9. June 19^h–10. June 08^h	+1 48	234	15·0	2·0	+	0·13	5:5a	289	14·4
	50	10. June 08^h– – 21^h	+0 44	192	40·3	14·5	–	0·36		268	47·7
	770–820	10. June 09^h– – 20^h	+1 06	120	19·8	3·4	+	0·17		274	13·8
		11. June 01^h–11. June 14^h	+1 56	166	19·6	3·5	+	0·18		334	32·7
E	510–520	17. June 11^h–17. June 23^h	+0 01	317	5·8	2·0	+	0·35		241	35·3
		18. June 08^h–18. June 20^h	+2 26	195	7·7	0·0		0·00	5:5b	261	24·9
J	507	11. June 23^h–12. June 11^h	+0 38	256	15·0	2·0	+	0·13	5:5a	295	19·2
Part II: Period of analysis: the whole measurements.											
A	20	10. June 18^h–13. June 22^h	+2^{h}34^m	217°	54·2	22·7	–	0·42	5:5c	33	26·5
		17. June 17^h–18. June 11^h	+2 44	198	26·6	6·0	–	0·23	5:5b	38	32·0
B1	476	7. June 21^h–19. June 00^h	+1 51	206	16·5	10·6	+	0·64	5:5c	216	23·1
B2	504	10. June 11^h–18. June 22^h	+4 38	131	11·7	9·6	+	0·82	5:5c	226	28·5
C	462	2. June 13^h– 9. June 16^h	+2 18	231	14·2	4·1	–	0·29	5:5c	203	0·8
D	50	9. June 19^h–11. June 23^h	+1 59	224	39·5	29·7	–	0·75		260	36·0
	770–820	9. June 19^h–11. June 23^h	+1 29	207	3·1	2·1	+	0·68		304	18·3
E	510–520	17. June 12^h–18. June 21^h	+2 14	233	3·9	2·9	+	0·74		258	28·4
F	10	10. June 13^h–11. June 14^h	+1 36	191	55·0	29·8	–	0·54	5:5a	330	5·2
	413	10. June 13^h–11. June 14^h	+3 08	204	21·6	2·5	–	0·12	5:5a	219	3·4
G	25	17. June 10^h–18. June 11^h	+2 52	250	37·6	21·4	–	0·57	5:5b	165	8·1
	473	17. June 10^h–18. June 11^h	+1 40	235	13·2	0·5	+	0·04	5:5b	274	25·7
H	666	10. June 11^h–11. June 17^h	+1 55	235	8·8	2·2	–	0·25	5:5a	332	19·8

least squares. The period of analysis was 13 hours. In cases of longer series of observations, successive 13-hour periods were analysed. For equidistant observations hourly mean values (Depth Current Meter), half-hourly mean values (Bifilar Current Meter) or 10-minutes mean values (Böhnecke Current Meter) were used as basis for the analyses, for non-equidistant observations the individual data were used.

For observation series of more than 25 hours' duration, analyses were carried out for the whole period, in addition to the 13-hours analyses mentioned above.

The results of these analyses, in the form of the elements of the M_2 tidal current ellipse and of the residual current, have been listed in Table 5:2. For each station are indicated observation depths, periods of analysis (in chronological order), phase (referred to the culmination of the moon in Greenwich), direction and magnitude of the main and the small axis of the tidal ellipse, direction of rotation, and ratio of the axes, as well as direction and speed of the residual current. For direction of rotation a positive sign means that the current rotates anti-clockwise, a negative sign means clockwise rotation.

A collection of tidal current ellipses is presented in Figures 5:5a, 5:5b and 5:5c. The ellipses of Figures 5:5a and 5:5b arose from 13-hours analyses and represent observations for the periods 9.–12. June and 15.–18. June, *i.e.*, separated by about a week. Also in these representations a difference in conditions at spring tide and neap tide is to be seen. In order to elucidate within which limits tidal currents may change in this area the ellipses with the greatest values of the main axis were chosen for Figure 5:5a and those with the smallest value of this axis for Figure 5:5b.

The ellipses presented in Figure 5:5c are based on analyses of observation periods of greater length (Table 5:2,II).

An attempt was made to calculate the S_2 tide from the long series of observations of the bottom current at Stations B1 and C. For the main axes were found

at Station B1: M_2 15·6 cm/sec. S_2 3·2 cm/sec.
at Station C: M_2 14·2 cm/sec. S_2 4·5 cm/sec.

The corresponding ratios between axes (S_2:M_2) are 0·21 and 0·32, respectively. These values, however, are inaccurate and can be taken to give only the order of magnitude of the S_2 tide.

(b) THE RESIDUAL CURRENT

The establishment of the residual current, especially in so far as it is directed from the Norwegian Sea towards the Atlantic Ocean, was the main purpose of

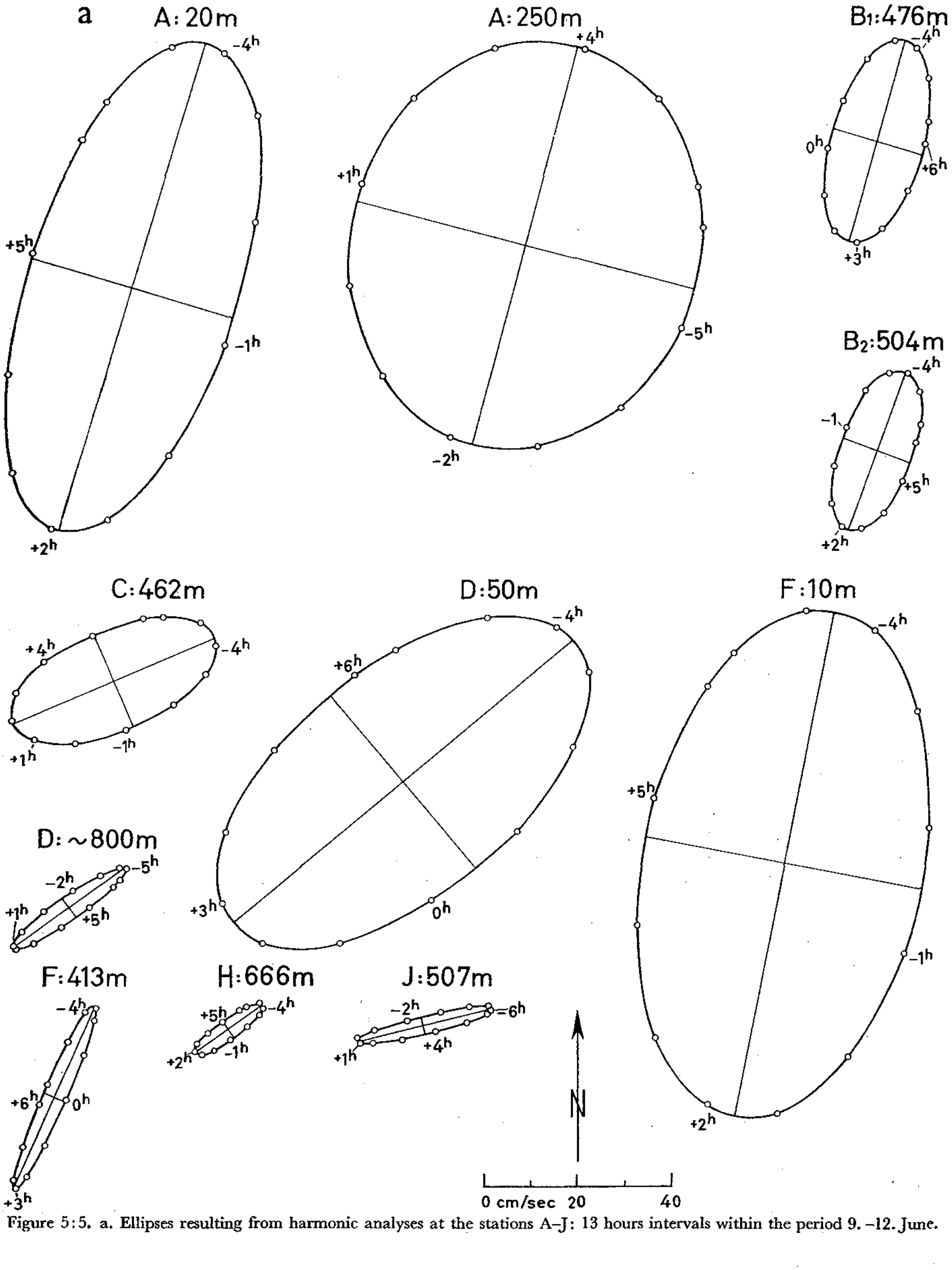


Figure 5:5. a. Ellipses resulting from harmonic analyses at the stations A–J: 13 hours intervals within the period 9.–12. June.

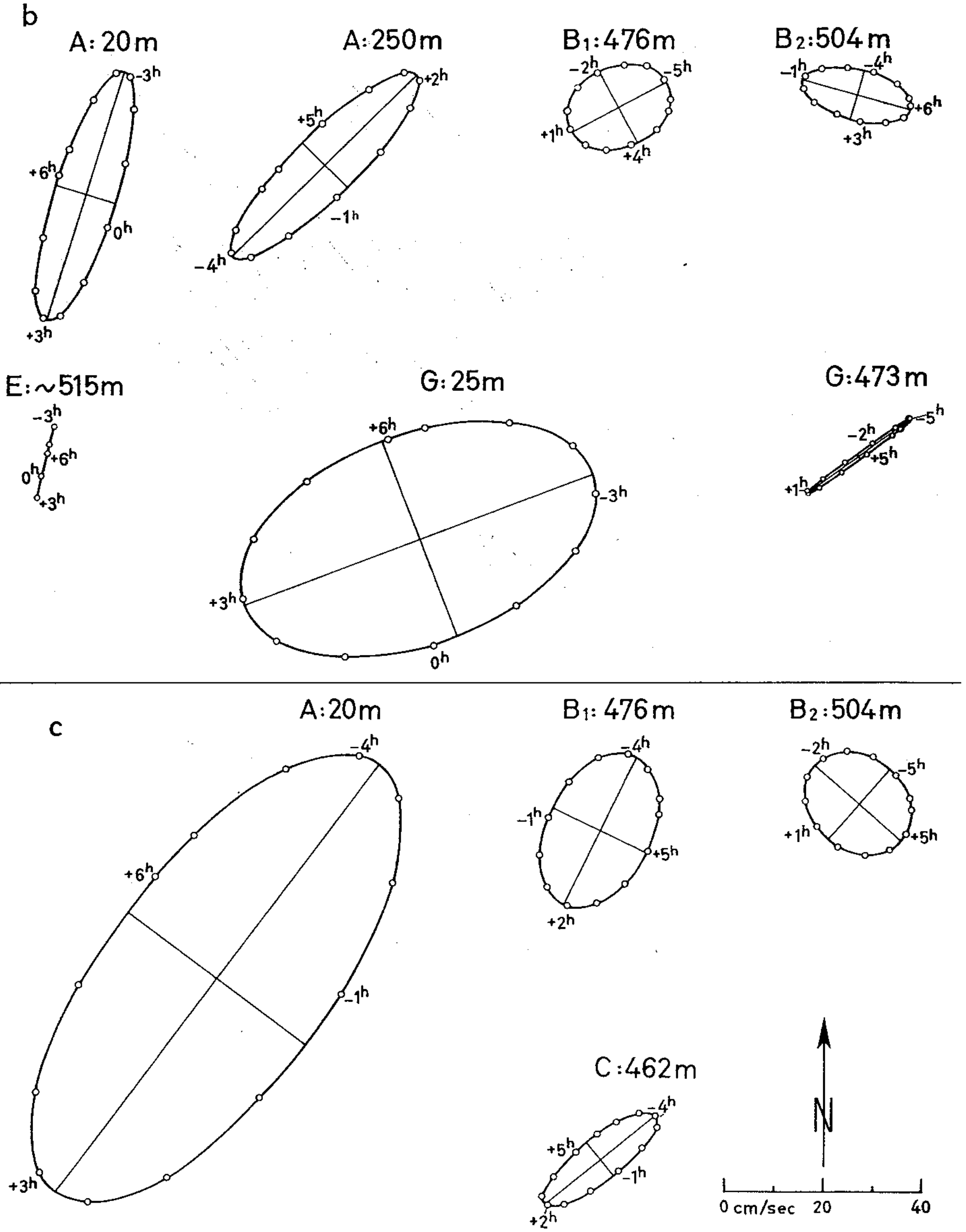


Figure 5:5 b, c. Ellipses resulting from harmonic analyses at the stations A–J:
b) 13 hours intervals within the period 15.–18. June.
c) Long range intervals.

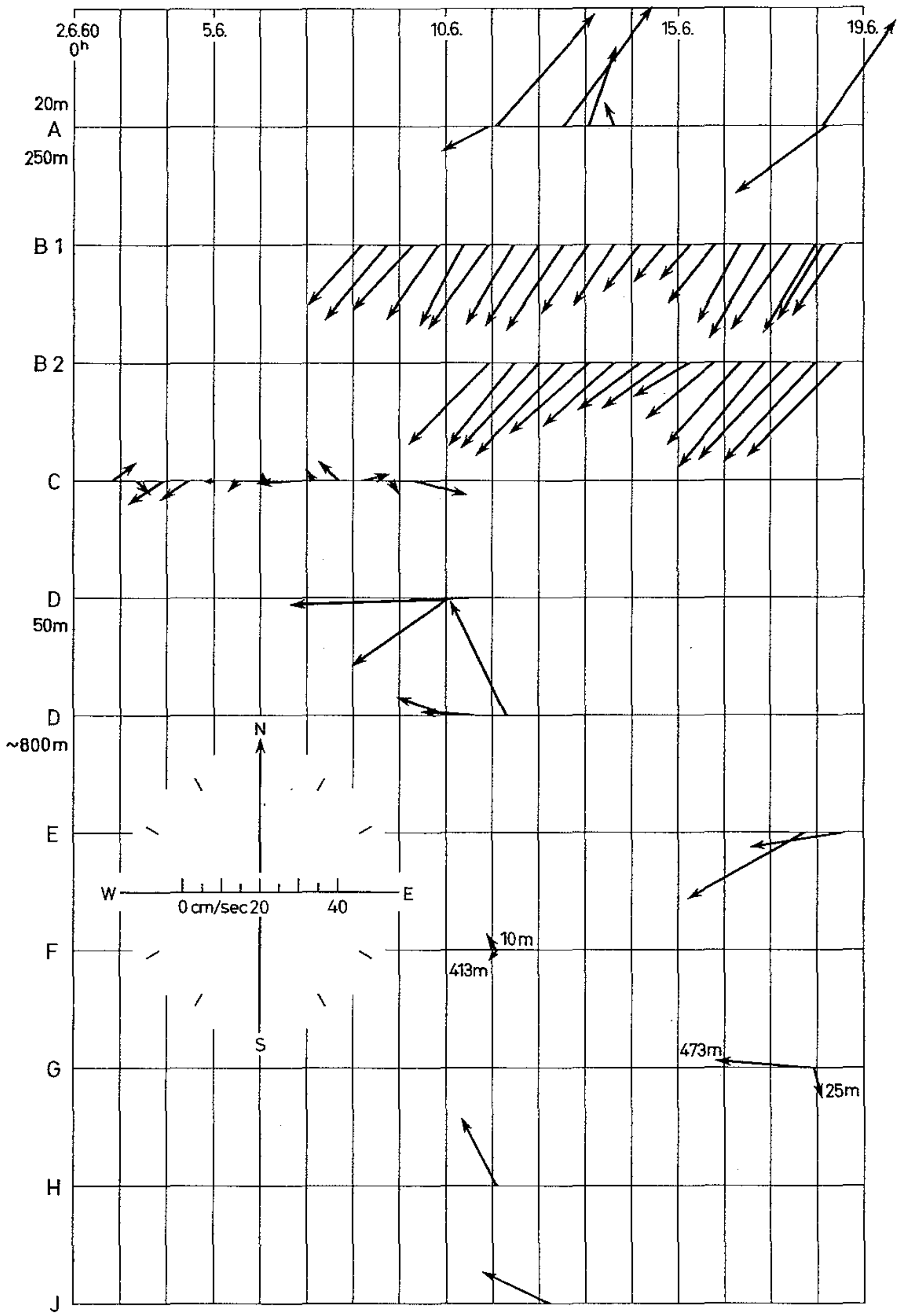


Figure 5:6. Residual currents at the stations A–J.

Residual currents

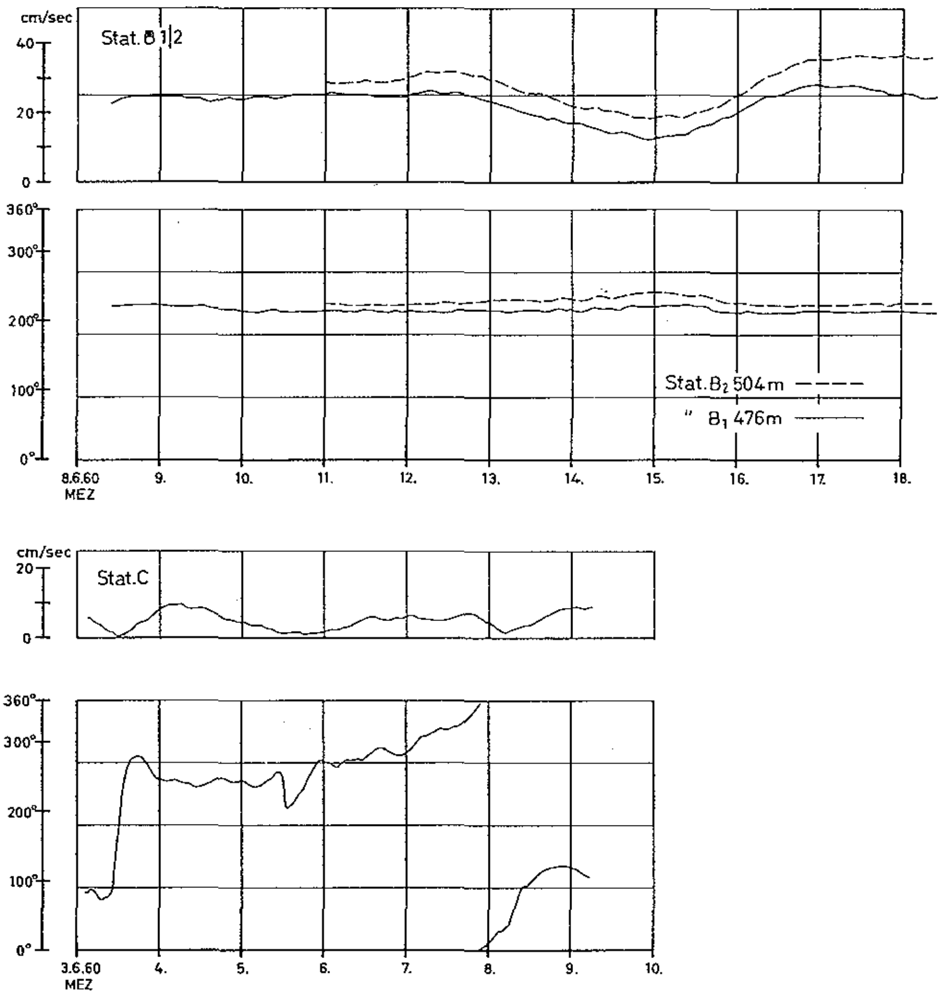


Figure 5:7. Residual currents computed from overlapping mean values of twenty-five hours.

the Expedition. The results of the analyses (Table 5:2) are presented in Figure 5:6. Near the Icelandic shelf (Station B1/2) the bottom current during the whole period of observation was directed towards SSW–SW, *i.e.* towards the Atlantic. In some cases its speed considerably exceeded that of the maximum tidal current (main semi-axis of the ellipse). The same was found, however, at a depth of 250 m at Station A in the immediate neighbourhood. This gives reason to suppose that near the shelf of Iceland this residual current was not limited to a layer near the bottom, but embraced at least half the depth of the water. At station C on the other hand, which, according to earlier investigations was the likeliest place for an overflow, no uniform residual current can be demonstrated. From the analysis covering the whole period of observations (Table 5:2, II) it must be concluded that at Station C the residual currents almost cancelled out. For stations D, E, G and H, on the contrary, the analysis gave strong residual currents. At E and G these were directed towards W to WSW, at D and H towards WNW to NW. The speed was of the same order of magnitude as for the tidal currents (Table 5:2).

Another procedure for the determination of the residual currents which, however, can be used for observation series of some length only, is the formation of overlapping means. By forming twenty-four-hour mean values at hourly intervals the tides may be eliminated to a considerable degree. This procedure was applied to the series of observations at Stations B1, B2 and C. The results are presented in Figure 5:7. This presentation, that supplements Figure 5:6, shows at Stations B1 and B2 a residual current very uniform as to direction and speed whereas at Station C the re-

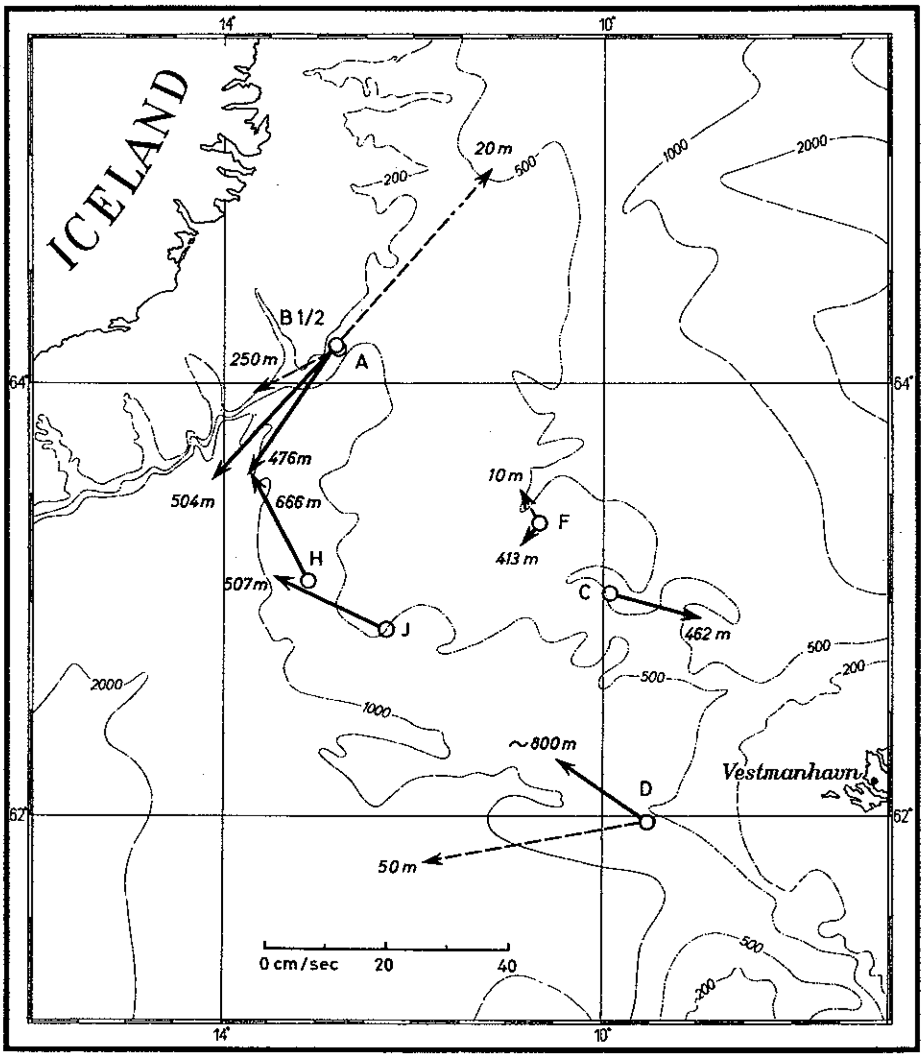


Figure 5:8a. Residual currents, 9.–12. June.

sidual current fluctuated widely in intensity and traversed all directions. There is indication of a long period.

SYNOPTIC CURRENT PICTURES

It was the purpose of the expedition to obtain a picture as synoptic as possible of the current conditions for the period when the anchor stations were worked. As Figure 5:3 shows this purpose could be accomplished in a very incomplete way only. Simultaneous observations at stations wide apart are available only for some hours. Figures 5:8a and 5:8b show the residual currents from the simultaneous periods of analysis of 9.–12. June and 17.–18. June, respectively. They give the impression that the residual current on the slope to the Atlantic Ocean has a course deflected to the right parallel to the depth lines. Again the bottom current at Station C constitutes an exception.

Two synoptic pictures of the horizontal and vertical distribution of the tidal currents conclude these presentations.

Figure 5:9a shows the ellipses of the bottom current at Stations B1 and C. The common period of analysis is the time 6. June from 02^h to 14^h GMT. The stations are situated on the Iceland-Faroe Ridge 104 nautical miles apart. The ellipses are of the same order of magnitude, but have opposite directions of rotation. No great importance should be attached to the residual currents which are also sketched in the figure, as the residual current at Station C is valid for this period of analysis only.

Figure 5:9b gives a synoptic picture of the vertical distribution of the current at the neighbouring stations A and B1, situated on the Icelandic shelf, for the period of analysis from 17.6. 21^h to 18.6. 09^h GMT.

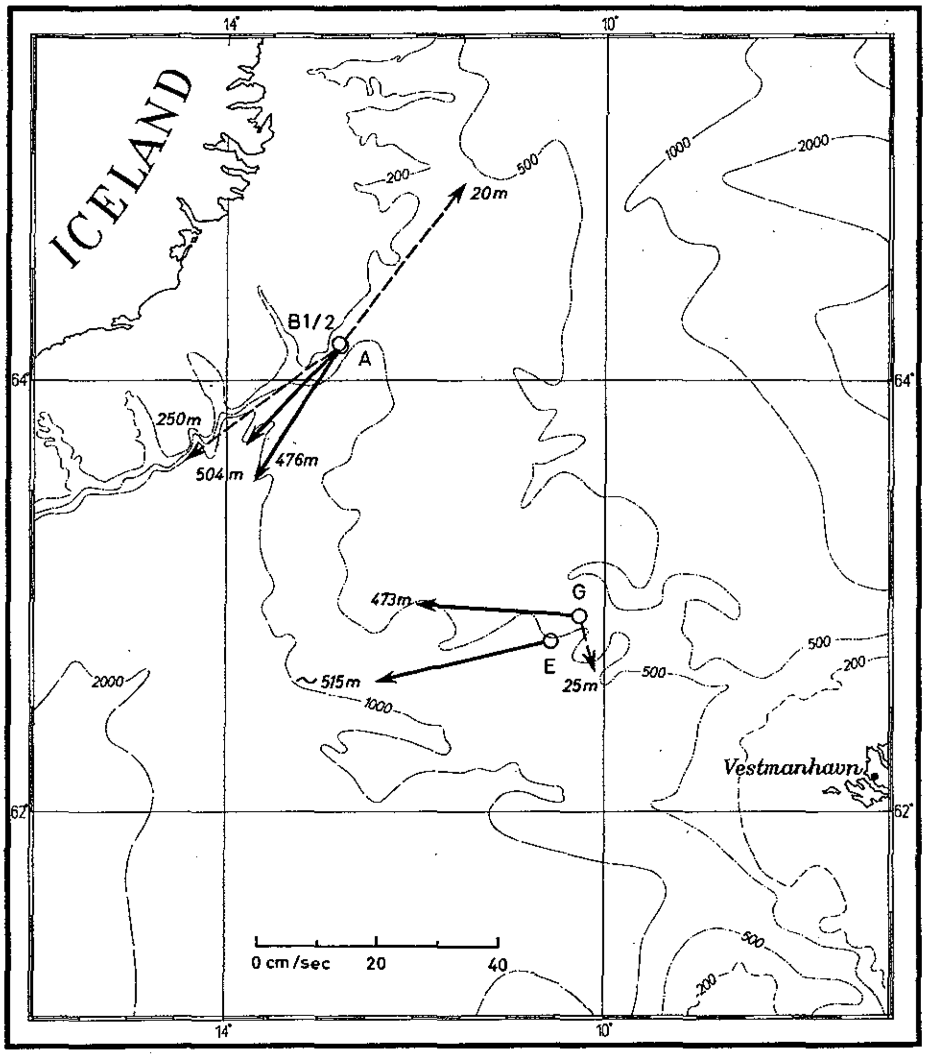


Figure 5:8b. Residual currents, 17.–18. June.

At the surface the tidal current in this period is nearly alternate, as appears from the value 0·16 for the ratio of the axes. In 250 m depth the direction of rotation has reversed and the ratio of the axes has increased to 0·24. At the bottom, in 476 m depth, the value of 0·96 for the ratio of the axes shows that the current is a nearly pure rotation-current; the direction of rotation is the same as for the intermediate depth.

The nearly equal residual currents at the bottom and in the intermediate depth are directed opposite to those at the surface (also Figures 5:6 and 5:7).

The residual current at the surface seems to be caused by an extensive stream. As appears from Table 5:1, only on 13. June, near the termination of the work of "Gauss" at the anchor station, this stream was influenced perceptibly by a gale, of force 7–8 Beaufort, from NE, *i.e.*, opposite to the current.

SUMMARY

It can be established that the currents measured during the Expedition consisted of a periodical component, caused by the tides, and a non-periodical component, the residual current. In the surface the tidal current dominated. At the bottom the residual current was often either stronger than the tidal current, or of the same order of magnitude. The observed residual currents were predominantly directed towards the Atlantic. However, they did not flow perpendicularly to the Ridge, but deflected to the right along the depth lines of the slope. A typical "overflow", the appearance of a thin, cold layer of bottom water crossing the ridge towards the Atlantic, could not be demonstrated by direct current measurements during the period of observation.

The superposition of periodical and non-periodical

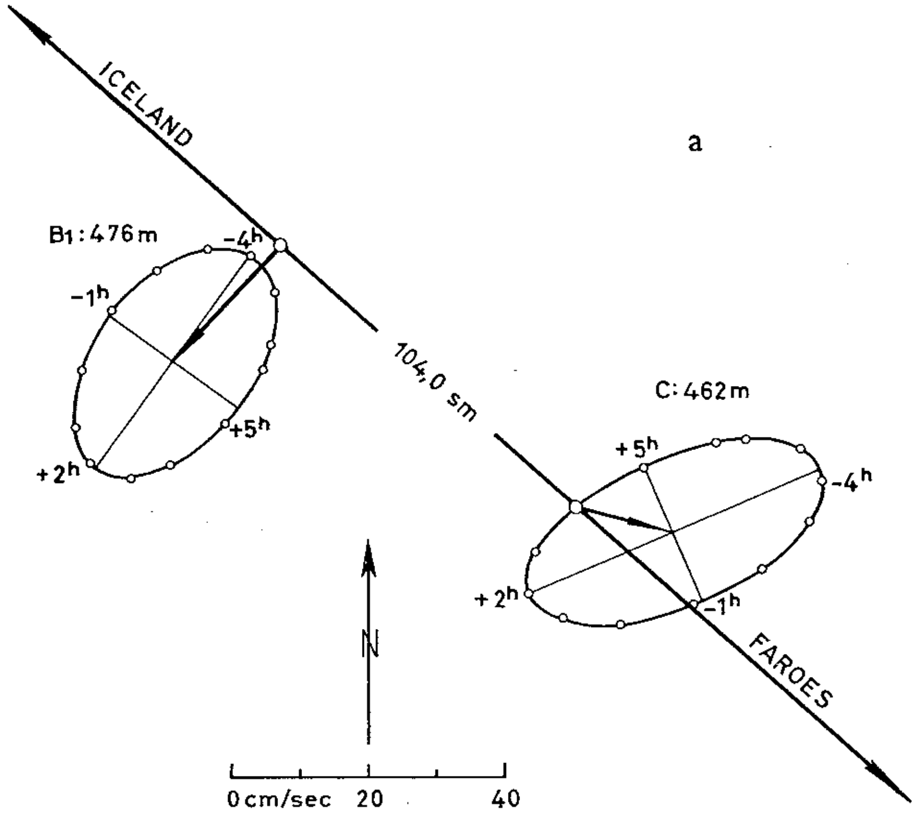
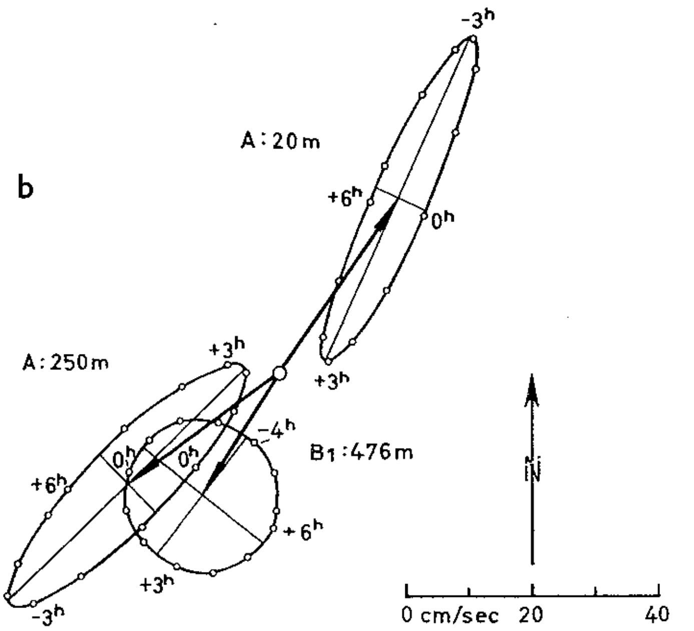


Figure 5:9. Results of harmonic analyses from simultaneous periods.
a) Bottom currents at the stations B1 and C, 9.6 02h – 14h GMT
b) Currents of different depths at the stations A and B1 (17.6 21h–18.6 09h GMT).

(arrows = residual currents; ellipses = tidal currents)



currents which in their turn are subject to fluctuations in space and time leads to a rather complicated current picture. For future investigations it appears therefore, to be little promising to undertake isolated current measurements in this area. A deeper insight into the dynamical processes in the area between Iceland and the Faroes can only be obtained from long series of observations at selected positions and in different depths. For this purpose moored or buoy-suspended self-recording current meters are best suited.

CHAPTER 6
INTERNAL WAVES AT DIAMOND STATIONS DURING THE INTERNATIONAL ICELAND–FAROE RIDGE EXPEDITION, MAY-JUNE, 1960

By

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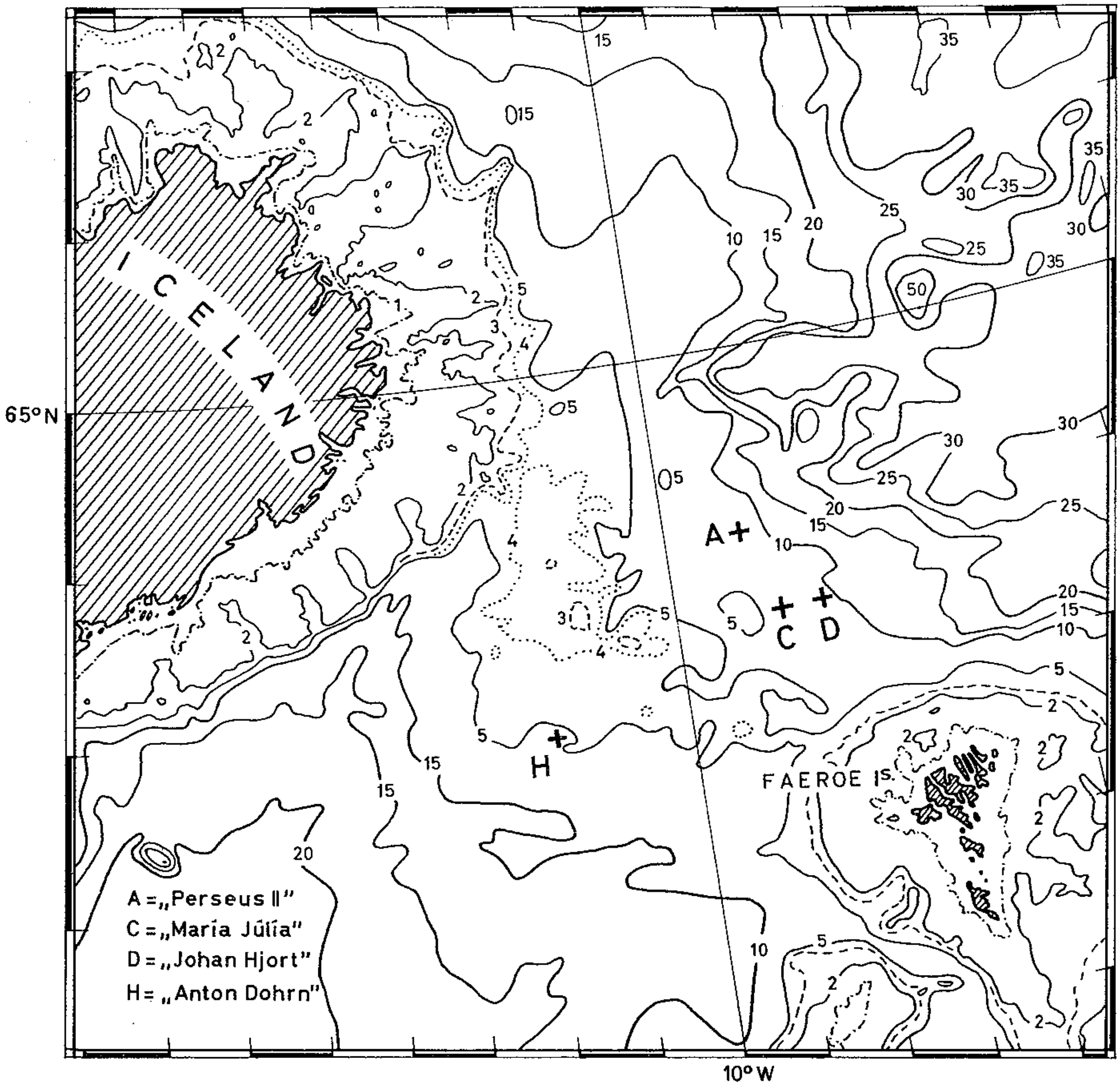

Figure 6:1. The positions of the Diamond stations on the Iceland-Faroe Ridge.

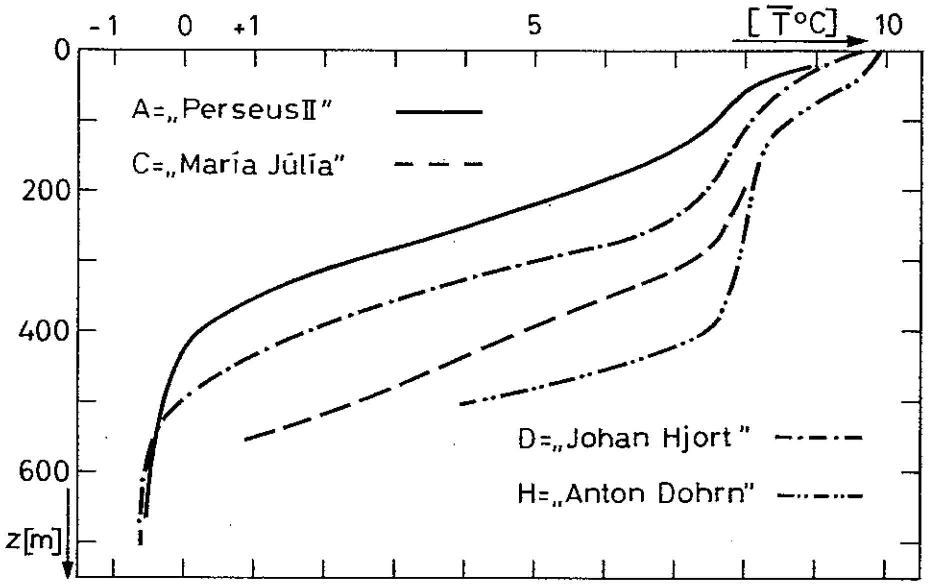

Figure 6:2. Mean temperature distribution.

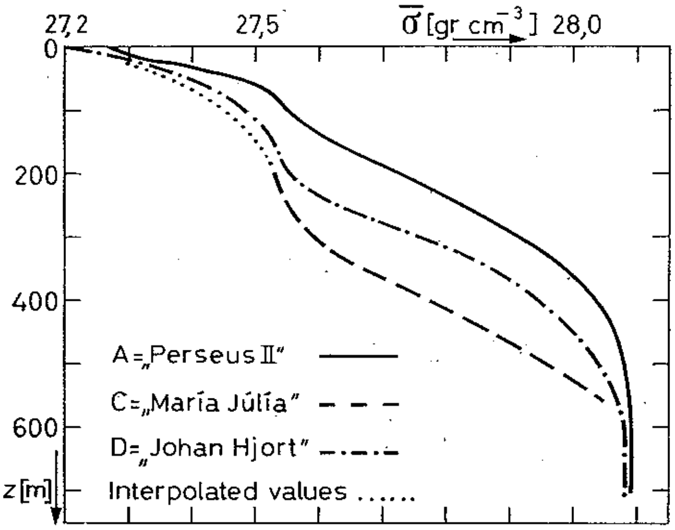

Figure 6:3. Mean density distribution.

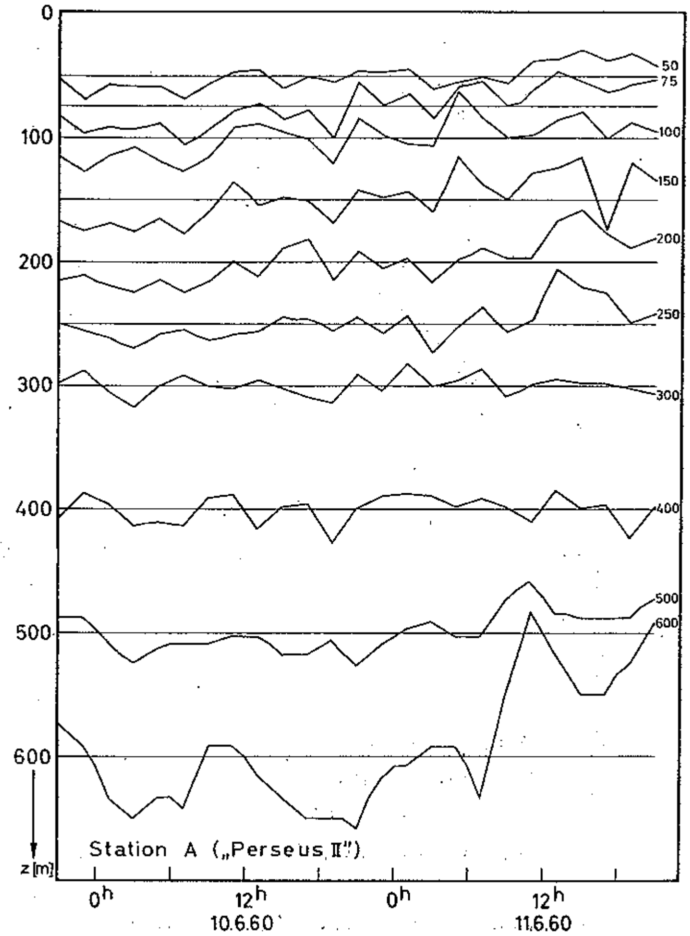

Figure 6:4. ζ-distribution at station A (first permanent station only).

The hydrographic data of the Diamond stations A, C, D, H have been analysed with regard to internal waves. It is shown that internal tides of high amplitude occur at stations C and D. Additional effects play a role at station H, which is situated in the overflow region on the southern slope of the Ridge.

THE DATA

During the Expedition, four research vessels twice made systematic measurements of temperature and salinity at different depths at pre-selected positions, called Diamond stations. The first measurements were

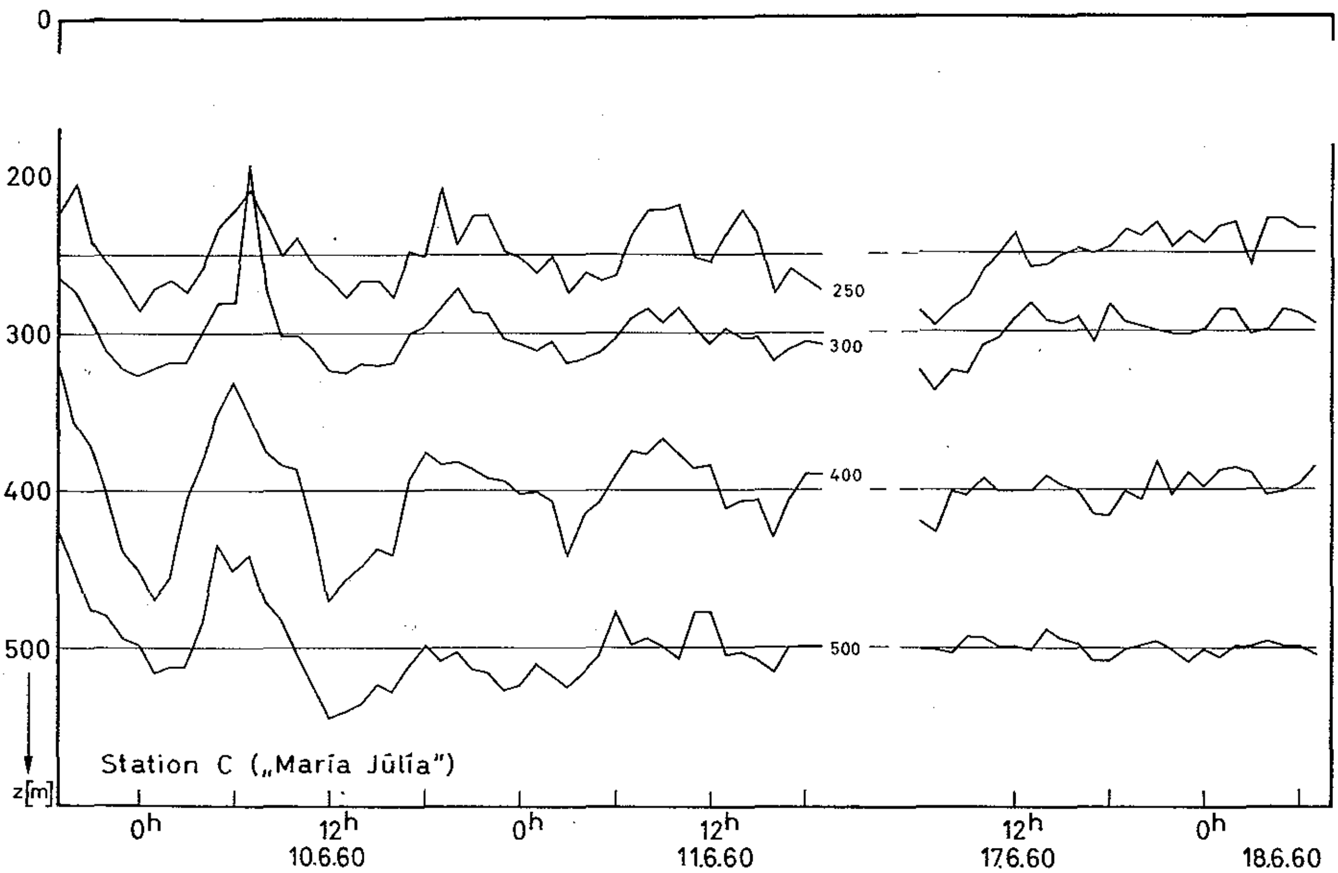

Figure 6:5. ζ-distribution at station C.

made from 9.–12. June, and the second from 17.–18. June. The positions of Diamond stations A ("Perseus II"), C ("María Júlía"), D ("Johan Hjort") and H ("Anton Dohrn") are shown in Figure (6:1). Stations A, C, D form a triangle at the northeastern slope of the Iceland-Faroe Ridge ($\overline{AC}$ = 57 km; $\overline{AD}$ = 70 km; $\overline{CD}$ = 27 km) while station H lies on the southern slope of the Ridge. Soundings were 795 m at station A, 615 m at C, 745 m at D, and 550 m at H. In most cases, the records taken by the vessels had a time interval Δ t = 1 h. Those with Δ t = 2 h were interpolated linearly with respect to time to get always Δ t = 1 h. At some stations the records had to be interpolated also with respect to depth to get data at the same depths at all times. These interpolations were made graphically.

THE VERTICAL MOVEMENTS OF THE WATER PARTICLES

Assuming the temperature T and the salinity S to be conservative quantities for the time in question we have

$$\frac{\partial\psi}{\partial t} + u\,\frac{\partial\psi}{\partial x} + w\,\frac{\partial\psi}{\partial z} = 0$$

(ψ standing for T or S, u and w horizontal and vertical component motion, z directed downwards).

We assume $\frac{\partial\psi}{\partial x}$ to be very small so that we are allowed to neglect the term $u\frac{\partial\psi}{\partial x}$ and get $w = -\frac{\partial\psi}{\partial t}\Big/\frac{\partial\psi}{\partial z}$. Now let $\overline{\psi}$ be the mean value of ψ with respect to time: $\psi = \overline{\psi} + \psi'$ where ψ' is the perturbation of ψ.

Hence to the first order we have

$$w = -\frac{\partial\psi'}{\partial t}\Big/\frac{\partial\overline{\psi}}{\partial z}.$$

The deviation ζ of a water particle out of its mean position satisfies $\frac{\partial\zeta}{\partial t} = -w$ ($\zeta > 0$ upwards). Integrating we get

$$\zeta = \left(\frac{\partial\overline{\psi}}{\partial z}\right)^{-1}(\psi - \overline{\psi}), \qquad \text{using } \overline{\zeta} = 0.$$

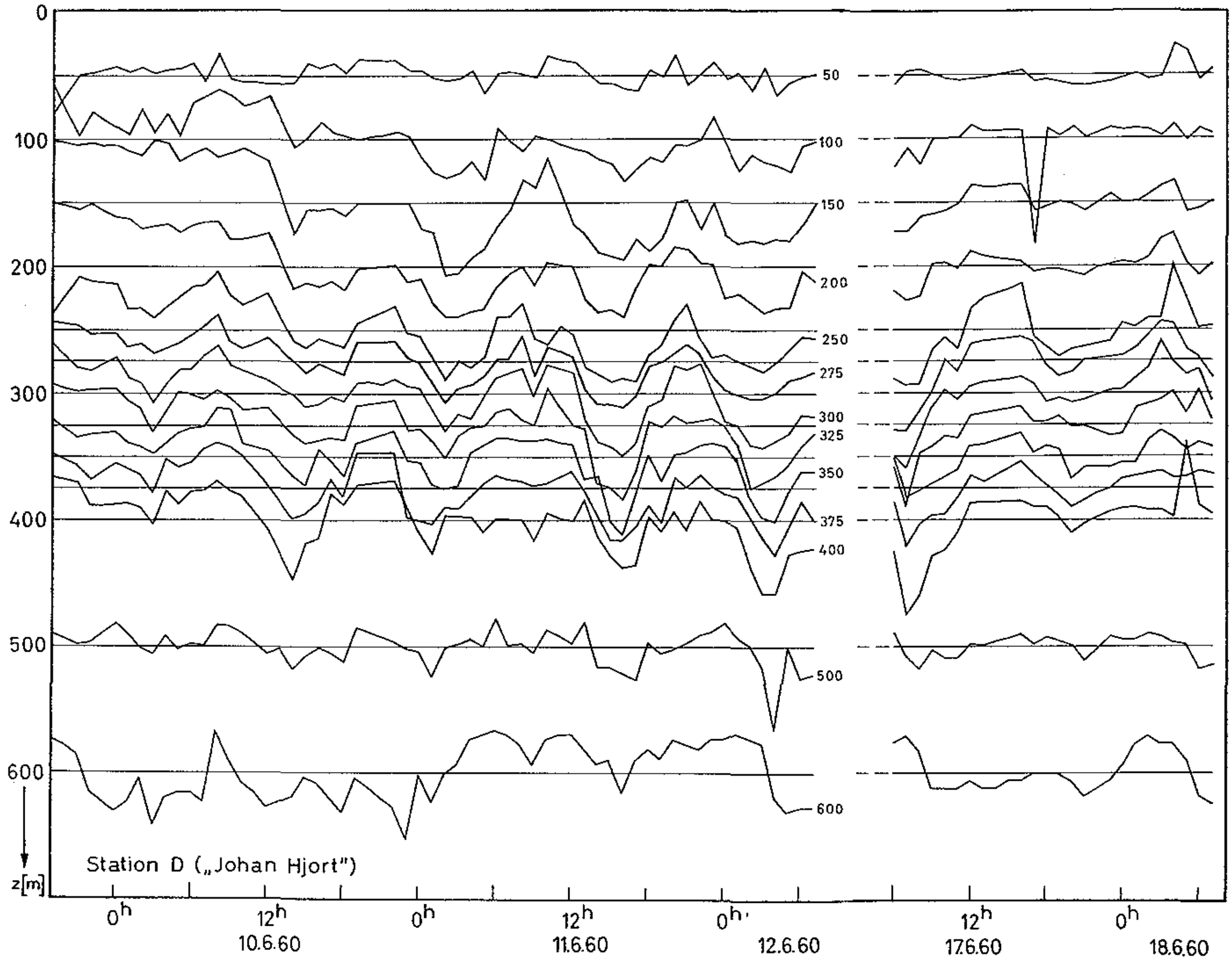

Figure 6:6. ζ-distribution at station D.

ζ can be computed by means of the temperature or the salinity. But using the temperature we get a much higher accuracy. The relative error of the salinity and the temperature values is of the same order of magnitude. But the ratio $\left(\frac{\partial \bar{S}}{\partial z}\right)^{-1} \Big/ \left(\frac{\partial \bar{T}}{\partial z}\right)^{-1}$ is of the order 10 or even more. So the relative error of ζ is ten times larger in computation by means of salinity than by temperature. Therefore we prefer the temperature records. The mean temperature distribution is shown in Figure 6:2. Because of the large values of $\frac{\partial \bar{T}}{\partial z}$ we shall get the most accurate values of ζ in medium layers. Figures 6:4–6:8 show the ζ-values computed by means of the temperature. In Figure 6:7 we compare ζ-values computed by means of the temperature with those computed by means of salinity. As expected the correspondence is rather good in medium layers because of the smallness of $\left(\frac{\partial \bar{T}}{\partial z}\right)^{-1}$ and $\left(\frac{\partial \bar{S}}{\partial z}\right)^{-1}$. In the upper and lower layers we have larger deviations.

We can already see from the figures without further analysis that there is a periodic component in the ζ-distribution with a period of about twelve hours. This period turns out to be persistent also from the first to the second part of the measurements at the Diamond stations.

SPECTRUM ANALYSIS

The shortness of the records leads to two disadvantages: –

(1) Filtering is impossible because it makes the records even shorter. Therefore long periodic components of the record may influence the spectral range under consideration.

(2) The resolution of the spectrum is small.

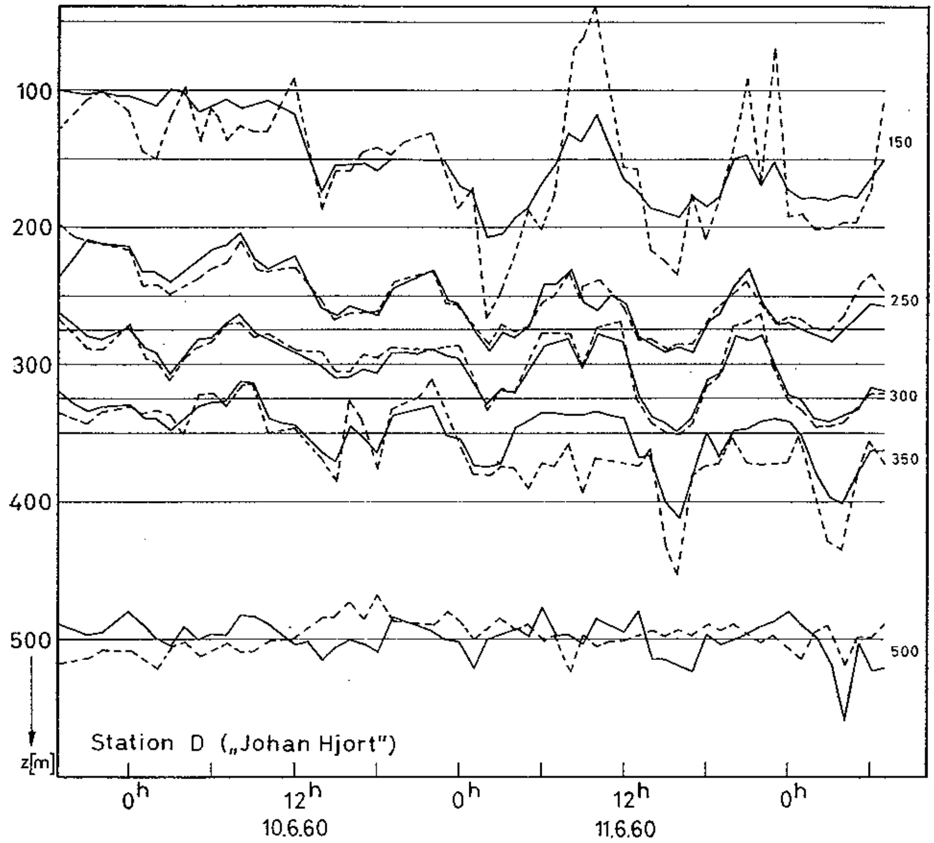

Figure 6:7.

Comparison between ζ-values computed by means of the temperature (full lines) and by means of the salinity (broken lines) at station D.

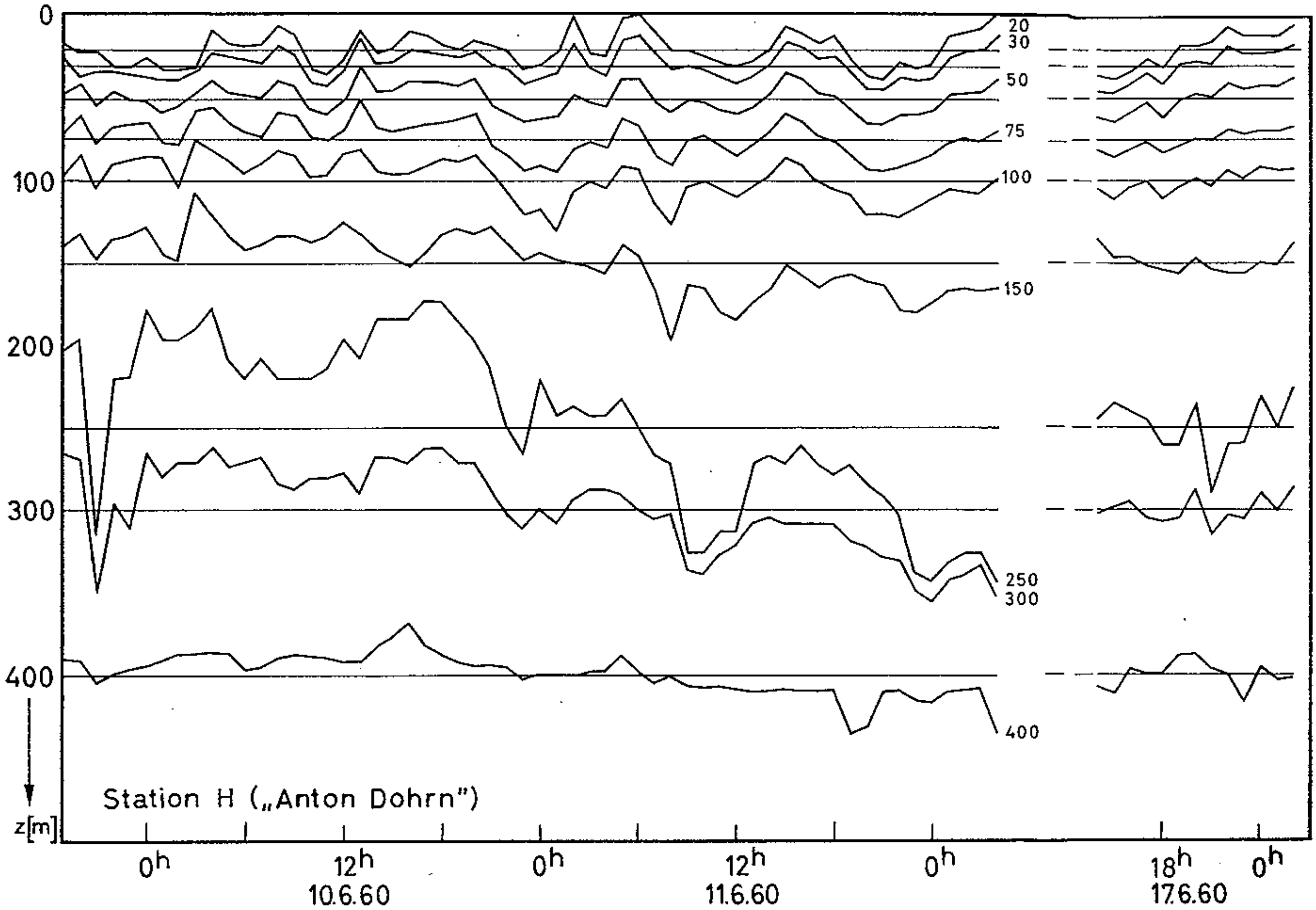

Figure 6:8. ζ-distribution at station H.

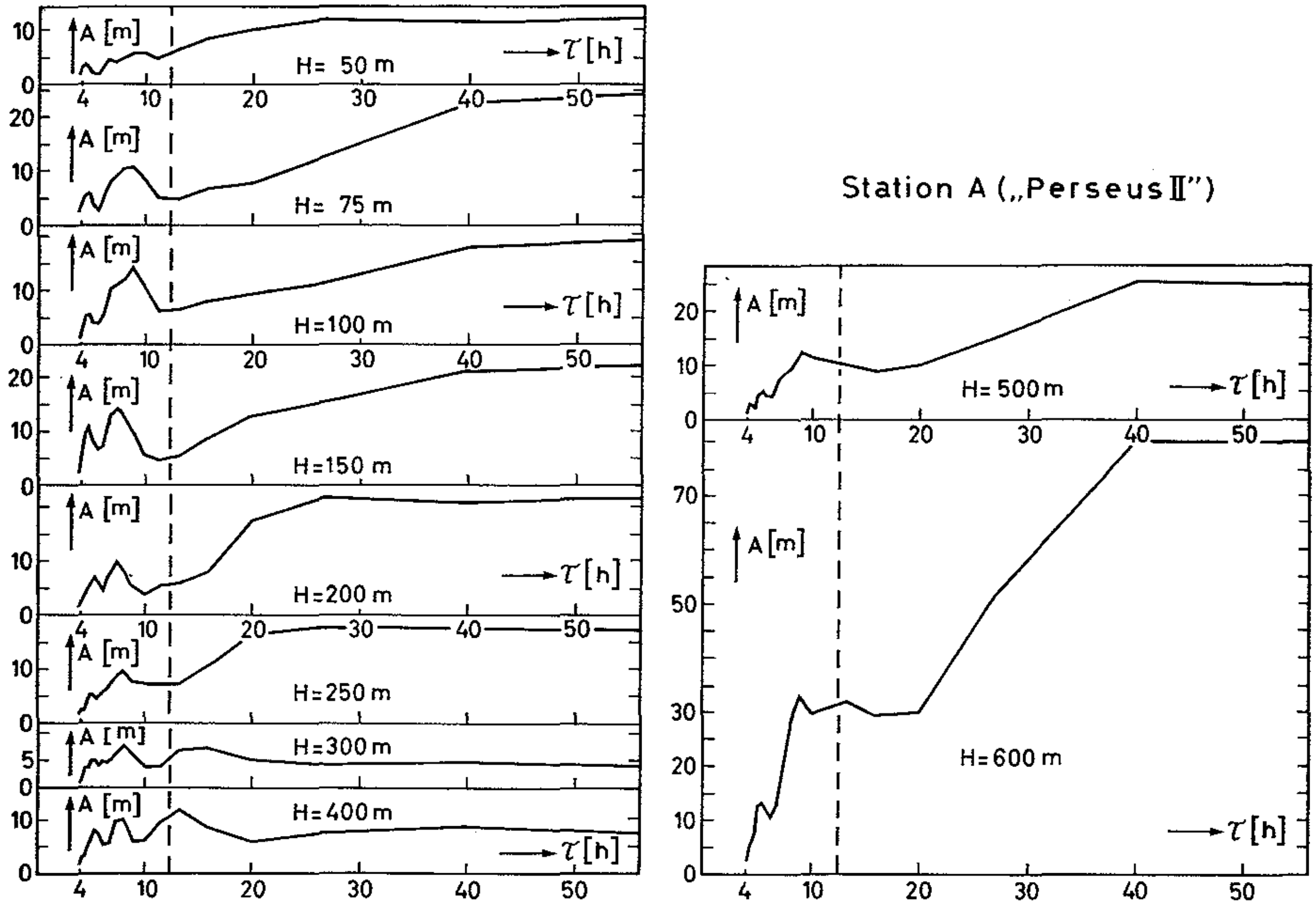

Figure 6:9. Amplitude spectrum of the ζ-distribution at station A (first permanent station only).

Table 6:1.

Comparison of observed and computed values (first five modes) for the vertical component of motion at station C ("María Júlía")

w_α [mm sec.$^{-1}$]

Depth [m]	w_α obs	w_α comp	$c_1^{(\alpha)} w_1$	$c_2^{(\alpha)} w_2$	$c_3^{(\alpha)} w_3$	$c_4^{(\alpha)} w_4$	$c_5^{(\alpha)} w_5$
250	1·41	1·42	– 1·84	– 9·93	3·47	4·96	4·76
300	1·47	1·47	– 2·06	– 6·36	7·66	3·75	– 1·52
400	2·33	2·34	– 2·09	4·00	3·54	– 3·71	0·60
500	0·92	0·91	– 1·38	8·61	– 8·51	2·13	0·06

w_β [mm sec.$^{-1}$]

Depth [m]	w_β obs	w_β comp	$c_1^{(\beta)} w_1$	$c_2^{(\beta)} w_2$	$c_3^{(\beta)} w_3$	$c_4^{(\beta)} w_4$	$c_5^{(\beta)} w_5$
250	4·42	4·42	10·23	11·90	– 4·66	–7·78	–5·27
300	4·61	4·63	11·50	7·62	–10·30	–5·88	1·69
400	7·28	7·29	11·67	– 4·79	– 4·76	5·83	–0·66
500	5·40	5·41	7·70	–10·32	11·44	–3·35	–0·06

The spectra of the first Diamond stations are shown in Figures 6:9–6:12. Obviously there is a predominance of a periodic component with the period of the M_2 – tide at the stations C, D and H whilst at station A this component completely vanishes. In the spectra at stations C, D, H there is a z-dependence of the amplitude a with a maximum in medium layers. We also find an x-dependence: The amplitude a varies from station to station and especially vanishes at station A. These features indicate an internal tide with a nodal line or an area of very small amplitudes at station A.

For the periodic component we get an approximate representation by

$$\zeta\ (z, t) = a\ (z)\ \cos\left(\frac{2\pi}{T}\ t - \varphi\ (z)\right)$$

where $T = 12{\cdot}4$ h.

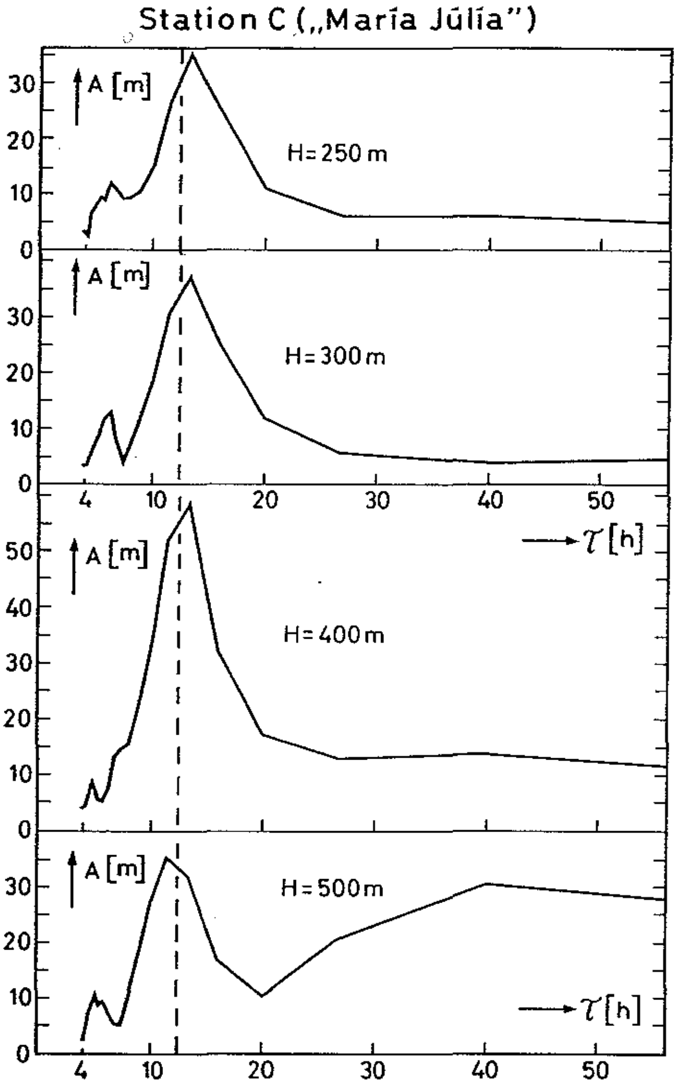

Figure 6:10. Amplitude spectrum of the ζ-distribution at station C (first permanent station only).

Table 6:2.

Comparison of observed and computed values (first five modes) for the vertical component of motion at station D ("Johan Hjort")

w_α [mm sec. $^{-1}$]

Depth [m]	w_α obs	w_α comp	$c_1^{(\alpha)}$ w$_1$	$c_2^{(\alpha)}$ w$_2$	$c_3^{(\alpha)}$ w$_3$	$c_4^{(\alpha)}$ w$_4$	$c_5^{(\alpha)}$ w$_5$
50	− 0·39	− 0·39	− 0·35	− 0·10	− 0·07	0·01	0·12
100	− 0·92	− 1·03	− 0·67	− 0·15	− 0·07	0·00	− 0·14
150	− 1·62	− 1·38	− 0·96	− 0·16	− 0·03	− 0·01	− 0·22
200	− 1·32	− 1·48	− 1·23	− 0·14	0·01	− 0·02	− 0·10
250	− 1·40	− 1·41	− 1·46	− 0·09	0·05	− 0·01	0·10
275	− 1·27	− 1·40	− 1·54	− 0·05	0·06	0·00	0·13
300	− 1·69	− 1·47	− 1·58	0·00	0·05	0·01	0·05
325	− 1·58	− 1·57	− 1·59	0·05	0·02	0·02	− 0·07
350	− 1·60	− 1·62	− 1·58	0·09	0·00	0·01	− 0·14
375	− 1·51	− 1·55	− 1·53	0·12	− 0·03	0·01	− 0·12
400	− 1·35	− 1·42	− 1·47	0·14	− 0·05	0·00	− 0·04
500	− 0·79	− 0·86	− 1·09	0·14	− 0·07	− 0·02	0·18
600	− 0·80	− 0·51	− 0·65	0·08	− 0·04	− 0·01	0·11

w_β [mm sec. $^{-1}$]

Depth [m]	w_β obs	w_β comp	$c_1^{(\beta)}$ w$_1$	$c_2^{(\beta)}$ w$_2$	$c_3^{(\beta)}$ w$_3$	$c_4^{(\beta)}$ w$_4$	$a_5^{(\beta)}$ w$_5$
50	0·98	1·00	0·88	0·26	0·17	− 0·02	− 0·29
100	2·32	2·61	1·69	0·38	0·18	0·00	0·36
150	4·08	3·47	2·42	0·39	0·09	0·03	0·54
200	3·34	3·72	3·11	0·35	− 0·03	0·04	0·25
250	3·53	3·54	3·68	0·22	− 0·13	0·02	− 0·25
275	3·20	3·54	3·88	0·12	− 0·14	0·00	− 0·32
300	4·28	3·71	3·99	0·00	− 0·12	− 0·03	− 0·13
325	4·00	3·98	4·03	− 0·12	− 0·06	− 0·04	0·17
350	4·03	4·09	3·98	− 0·22	0·01	− 0·03	0·35
375	3·81	3·95	3·87	− 0·30	0·08	− 0·01	0·31
400	3·42	3·61	3·71	− 0·35	0·13	0·01	0·11
500	1·99	2·19	2·76	− 0·35	0·18	0·05	− 0·45
600	2·02	1·29	1·63	− 0·21	0·11	0·03	− 0·27

The values for φ (z) were taken directly from the ζ-distribution. It turned out that there is no essential phase difference $\Delta\,\varphi$ between stations A, C, D, but between that triangle and station H we found $\Delta\,\varphi \approx 8$ h.

For the surface tide we have $\Delta\,\varphi \approx 1{\cdot}5$ h. This is another hint that we are faced with an internal tide here.

There is another way to investigate if the measured fluctuations are due to internal waves: one computes the internal waves theoretically and tries to what extent the observed data can be represented by those waves.

THEORETICAL COMPUTATION OF INTERNAL WAVES AND COMPARISON WITH THE OBSERVED DATA

From the hydrodynamic equations of motion, the continuity equation, and the condition of incompressibility, one can derive the equation

$$\frac{d^2 W}{dz^2} + \Gamma \frac{dW}{dz} + \lambda\,\Gamma W = 0$$

where $W(z)$ is defined by $w(x, z) = F(x) \cdot W(z)$ and

$$\Gamma = \frac{1}{\bar{\varrho}}\frac{d\bar{\varrho}}{dz}, \; \lambda = \frac{g\,\varkappa^2}{\omega^2 - f^2} \quad \text{(Fjeldstad, 1933).}$$

$\varkappa$ is the horizontal wave number, ω the frequency and f the Coriolis parameter. We have solved the boundary value problem with the boundary conditions $W = 0$ at $z = 0$ and $z = H$ (depth to bottom) for the first five eigenvalues λ_n and eigenfunctions $W_n(z)$ at all stations. The distribution of $\bar{\varrho}$ we have used for that purpose is shown in Figure 6:3. The eigenfunctions (relative amplitudes) are shown in Figures 6:13–6:16. We have got the following eigenvalues λ_n [m^{-1}]:

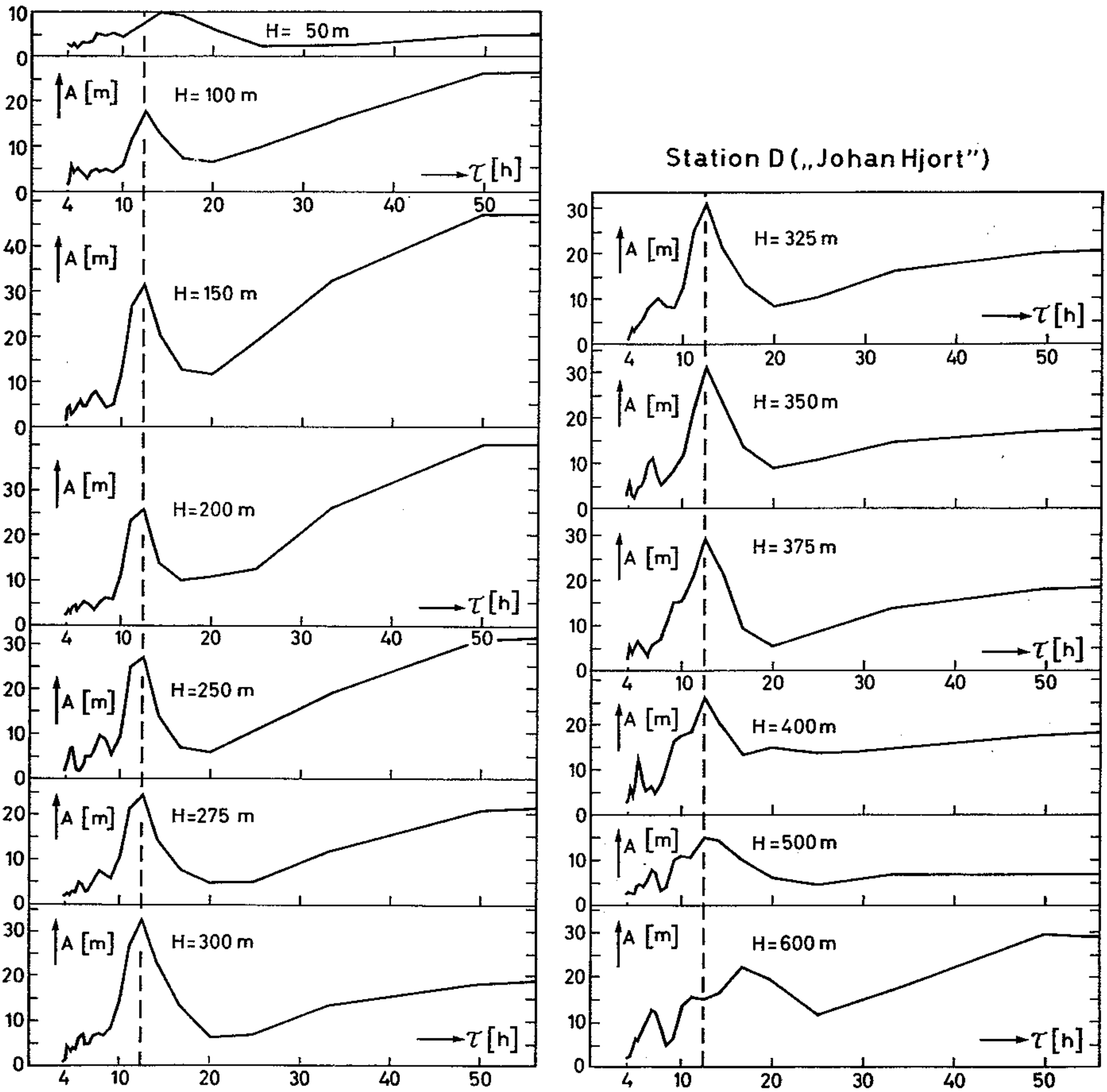

Figure 6:11. Amplitude spectrum of the ζ-distribution at station D (first permanent station only).

Station	λ_1	λ_2	λ_3	λ_4	λ_5
A	14·8	85·3	187	330	567
C	19·4	85·7	156	317	469
D	13·7	92·9	172	344	558
H	30·6	98·3	232	450	783

If we compute the wave number $\varkappa$ and the wave length $L = \frac{2\pi}{\varkappa}$ from λ neglecting the Coriolis parameter f we get for the first mode L_1 [km]: –

Station	L_1 (km)
A	36·4
C	31·8
D	37·8
H	25·3

From the ζ-distribution and the spectra we had

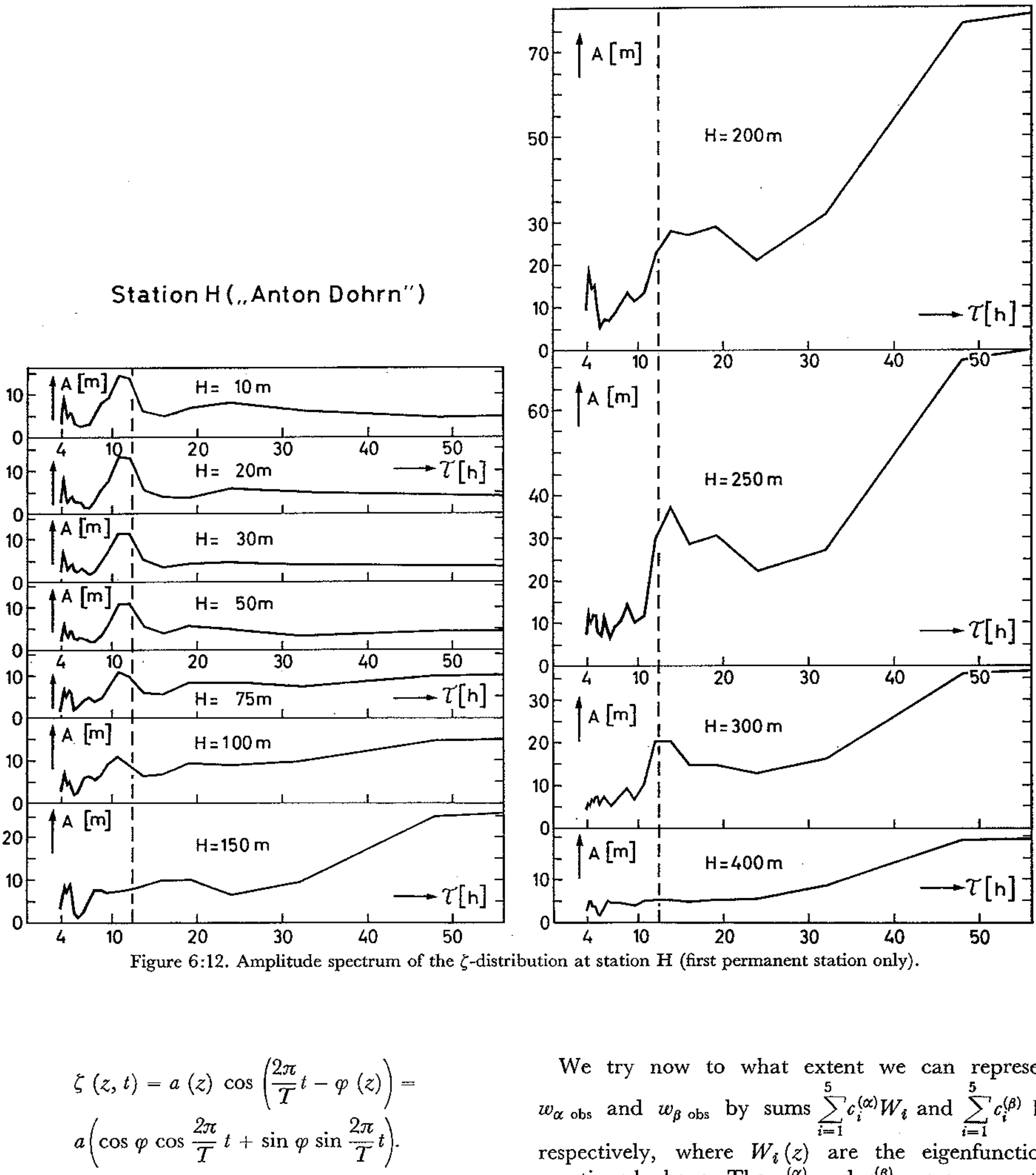

Figure 6:12. Amplitude spectrum of the ζ-distribution at station H (first permanent station only).

$$\zeta(z,t) = a(z)\cos\left(\frac{2\pi}{T}t - \varphi(z)\right) = a\left(\cos\varphi\cos\frac{2\pi}{T}t + \sin\varphi\sin\frac{2\pi}{T}t\right).$$

Hence

$$w(z,t) = w_{\alpha\text{ obs}}\cos\frac{2\pi}{T}t + w_{\beta\text{ obs}}\sin\frac{2\pi}{T}t$$

where

$$w_{\alpha\text{ obs}} = -\frac{2\pi}{T}a\sin\varphi \text{ and } w_{\beta\text{ obs}} = \frac{2\pi}{T}a\cos\varphi.$$

We try now to what extent we can represent $w_{\alpha\text{ obs}}$ and $w_{\beta\text{ obs}}$ by sums $\sum_{i=1}^{5} c_i^{(\alpha)} W_i$ and $\sum_{i=1}^{5} c_i^{(\beta)} W_i$ respectively, where $W_i(z)$ are the eigenfunctions mentioned above. The $c_i^{(\alpha)}$ and $c_i^{(\beta)}$ were computed by means of the method of least squares. Tables 6:1 –6:3 give the values $w_{\alpha\text{ obs}}$, $w_{\alpha\text{ comp}} = \sum_{i=1}^{5} c_i^{(\alpha)} W_i$ and the components $c_i^{(\alpha)} W_i$ and the same for $w_{\beta\text{ obs}}$ at stations C, D, H.

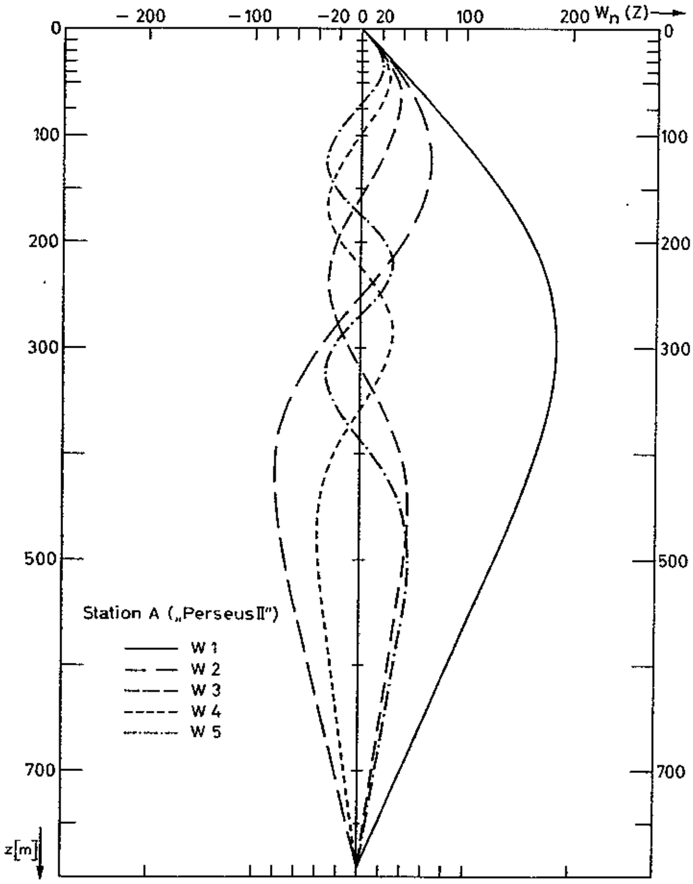

Figure 6:13. Eigenfunctions W_n (z) $(n = 1, 2, \dots 5)$ at station A.

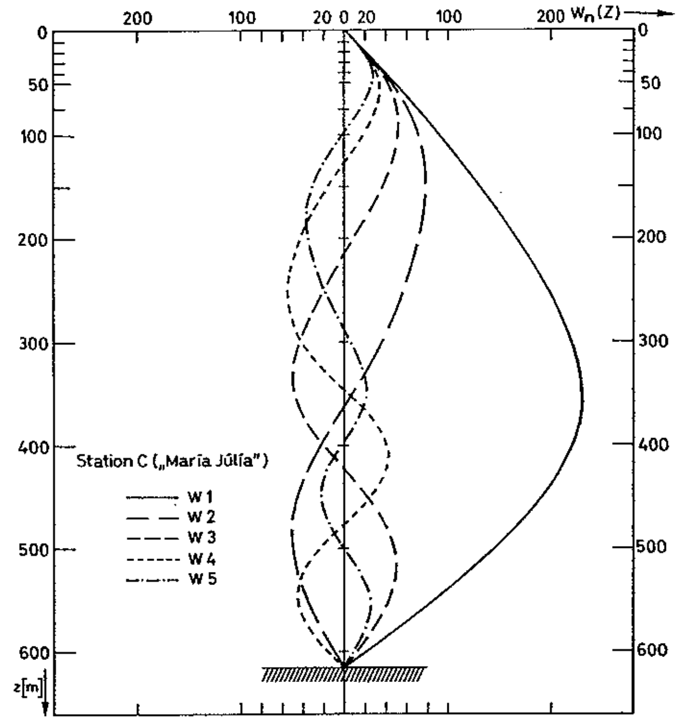

Figure 6:14. Eigenfunctions $W_n(z)$ $(n = 1, 2, \dots 5)$ at station C.

Good correspondence occurs at stations C (Table 6:1) and D (Table 6:2) whilst at station H (Table 6:3) we find some differences between $w_{\beta\,\mathrm{obs}}$ and $w_{\beta\,\mathrm{comp}}$. This indicates that at station H the movements of the water particles are not describable by internal waves only. That is understandable because of the currents on the southern slope of the Ridge. The analysis of stations C and D, however, show the important role which internal waves play in this area. Unfortunately the observations are not long enough and the distance between the stations is too large for a detailed analysis. The statement that the amplitudes vanish at station A does not necessarily mean that the observed internal tides are standing waves with a nodal line passing station A. Consider, for instance, the observed fluctuations at the position x_0 in a depth z_0 to be the result of a progressive internal wave, which consists of two modes: –

$$\zeta\ (x_0,\ z_0,\ t) = F_1\ (z_0)\ \cos\ (\omega_0 t - \varkappa_1 x_0)\ +\ F_2\ (z_0)\ \cos\ (\omega_0 t - \varkappa_2 x_0).$$

This may be written in the form

$$\zeta\ (x_0,\ z_0,\ t) = \sqrt{F_1^2 + F_2^2 + 2\,F_1\,F_2\ \cos\ [(\varkappa_1 - \varkappa_2)\ x_0]}$$
$$\cos \left\{\omega_0\,t - \varkappa_1\,x_0 + arc\,tg\,\frac{F_1\ sin\ (\varkappa_1 - \varkappa_2)\ x_0}{F_1 + F_2\ cos\ (\varkappa_1 - \varkappa_2)\ x_0}\right\}.$$

Table 6:3.

Comparison of observed and computed values (first five modes) for the vertical component of motion at station H ("Anton Dohrn")

w_α [mm sec.$^{-1}$]

Depth [m]	$w_{\alpha\,\mathrm{obs}}$	$w_{\alpha\,\mathrm{comp}}$	$c_1^{(\alpha)}\,w_1$	$c_2^{(\alpha)}\,w_2$	$c_3^{(\alpha)}\,w_3$	$c_4^{(\alpha)}\,w_4$	$c_5^{(\alpha)}\,w_5$
10	1·97	0·77	0·34	− 0·38	0·72	−0·53	0·62
20	1·88	1·48	0·67	− 0·75	1·42	− 1·04	1·18
30	1·65	2·04	1·00	− 1·11	2·05	− 1·44	1·54
50	1·60	2·10	1·62	− 1·68	2·71	− 1·46	0·91
75	1·42	1·05	2·28	− 2·02	2·14	− 0·11	− 1·24
100	1·31	0·93	2·82	− 2·02	0·70	1·39	− 1·96
150	1·10	1·88	3·79	− 1·74	− 2·57	3·84	− 1·44
200	2·81	2·84	4·76	− 1·46	− 5·84	6·29	− 0·91
250	3·75	3·30	5·65	− 1·11	− 8·32	7·18	− 0·10
300	2·55	2·68	6·39	− 0·66	− 9·08	5·29	0·74
400	0·70	0·71	6·98	0·40	− 2·62	−4·01	− 0·04

w_β [mm sec.$^{-1}$]

Depth [m]	$w_{\beta\,\mathrm{obs}}$	$w_{\beta\,\mathrm{comp}}$	$c_1^{(\beta)}\,w_1$	$c_2^{(\beta)}\,w_2$	$c_3^{(\beta)}\,w_3$	$c_4^{(\beta)}\,w_4$	$c_5^{(\beta)}\,w_5$
10	0·50	0·13	− 0·16	0·44	− 0·30	0·30	− 0·15
20	0·48	0·25	− 0·32	0·87	− 0·60	0·59	− 0·29
30	0·42	0·38	− 0·48	1·28	− 0·86	0·81	− 0·37
50	0·41	0·65	− 0·77	1·94	− 1·13	0·83	− 0·22
75	0·36	0·71	− 1·09	2·34	− 0·90	0·06	0·30
100	0·33	0·39	− 1·35	2·33	− 0·29	− 0·78	0·48
150	0·28	− 0·55	− 1·81	2·01	1·07	− 2·17	0·35
200	− 1·69	− 1·48	− 2·27	1·68	2·44	− 3·55	0·22
250	− 2·27	− 1·96	− 2·70	1·28	3·48	− 4·05	0·03
300	− 1·54	− 1·65	− 3·05	0·76	3·80	− 2·98	− 0·18
400	− 0·42	− 0·42	− 3·33	− 0·46	1·10	2·26	0·01

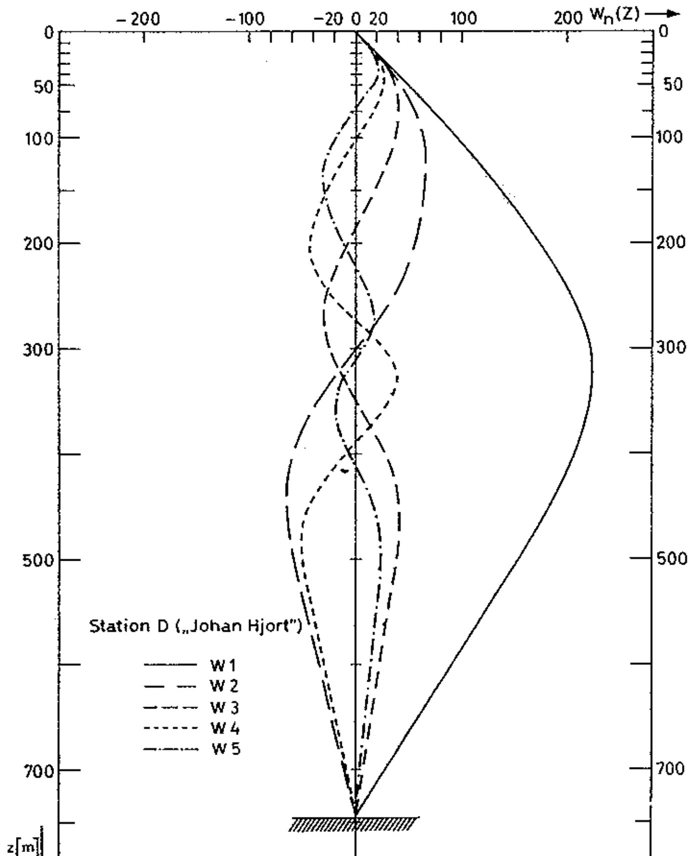

Figure 6:15. Eigenfunctions $W_n(z)$ ($n = 1, 2, \ldots 5$) at station D.

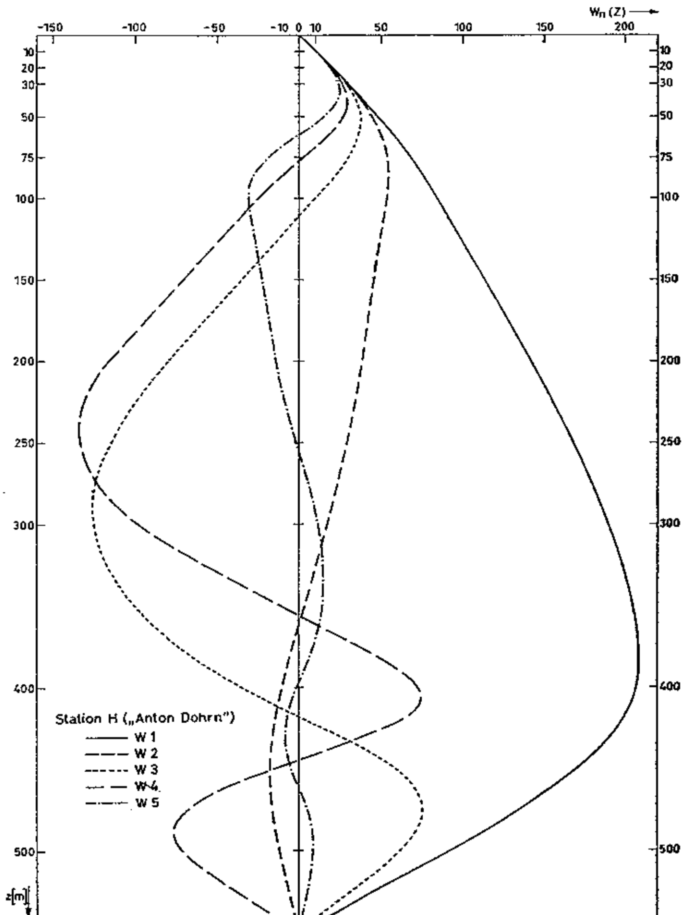

Figure 6:16. Eigenfunctions $W_n(z)$ ($n = 1, 2, \ldots 5$) at station H.

At the position x'_0, however, we find

$$\zeta\ (x'_0,\ z_0,\ t) = \sqrt{F_1^2 + F_2^2 + 2\,F_1\,F_2\ \cos\ [(\varkappa_1 - \varkappa_2)\ x'_0]}$$
$$\cos \left\{ \omega_0\, t - \varkappa_1 x'_0 + arc\ tg\ \frac{F_1\ \sin\ (\varkappa_1 - \varkappa_2)\ x'_0}{F_1 + F_2\ \cos\ (\varkappa_1 - \varkappa_2)\ x'_0} \right\}.$$

Therefore, at two stations, separated by the distance $(x'_0 - x_0)$ we find different amplitudes which can vary between $F_1 + F_2$ and $F_1 - F_2$. Drift station A may have such a distance from C and D that the amplitude vanishes there.

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CHAPTER 7 (I)

DISSOLVED OXYGEN IN THE WATERS OF THE ICELAND-FAROE RIDGE AREA, JUNE 1960

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Previously, HELLAND-HANSEN and NANSEN (1909) arrived at the conclusion that the cold near-bottom waters of the Norwegian Sea do not flow into the Atlantic Ocean over the Iceland-Faroe Ridge and other boundary ridges. They pointed out that these waters, coming in contact with overlying relatively warm waters, gradually mix with the latter and are carried out by the East Greenland Current through the Denmark Strait into the Atlantic Ocean. "The bottom waters of the Norwegian Sea, forming the floor of currents, remain practically unaltered for a very long period of years". H. MOSBY, (1959), in his recent investigations on the same question, has reached the same conclusion. He establishes almost complete homogeneity of the near-bottom waters of the Norwegian Sea, stating that only 14·5 $^0/_0$ of the volume of these waters is replaced every year due to the winter vertical circulation.

The collective work of the Soviet scientists VINOGRADOVA, KISLYAKOV, LITVIN and PONOMARENKO (1959), who studied the Iceland-Faroe area in 1955–1956 gives in general a good confirmation of the theory suggested by HELLAND-HANSEN and NANSEN (1909) but at the same time ascertains that the penetration of the highly transformed near-bottom waters of the Norwegian Sea into the Atlantic Ocean occurs also over the Iceland-Faroe Ridge through the channels crossing it. Nevertheless, the authors do not assume that the cold deep waters of the Norwegian Sea could easily, without great transformation, flow over the Ridge. They are checked in their course not only by the Ridge itself, as SHOKALSKY (1917) pointed out, but also by the waters of the East Icelandic Arctic Current running along the Ridge.

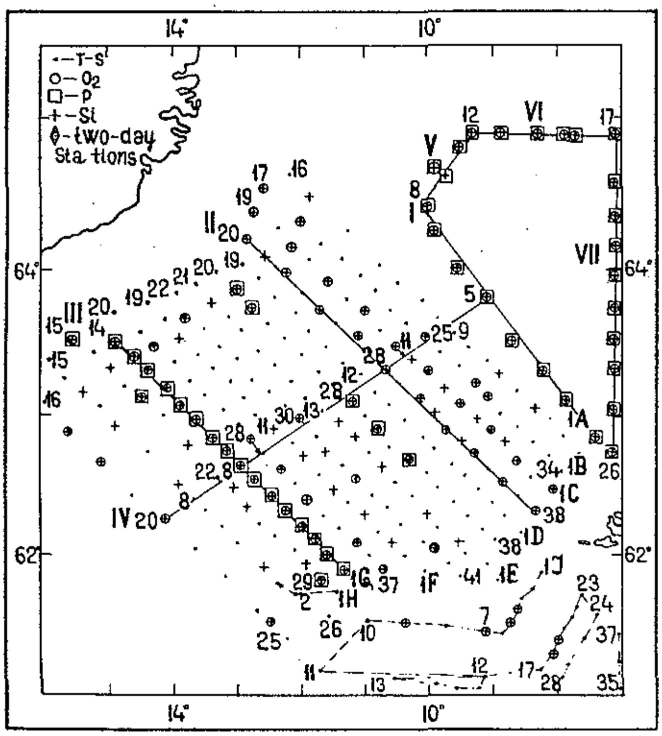
At the same time, some authors (COOPER (1955), ROBINSON (1952), and STEELE (1958)) interpret the presence of cold waters in certain depressions on the southwestern slopes of the Iceland-Faroe Ridge as a phenomenon of pure overflow of the cold bottom waters of the Norwegian Sea. This point of view is supported by the works of TAÏT (1957a, b, 1959), in which the author shows that the near-bottom waters of the Norwegian Sea (salinity about 34·92 $^0/_{00}$) at almost all times enter the deep Faroe-Shetland Channel, and from there sometimes emerge through the Faroe Bank Channel into the northeastern Atlantic Ocean along the southern base of the Iceland-Faroe Ridge. This idea has been confirmed most completely by long-term investigations carried out by English scientists. For instance, after the papers by ATKINS (1928, 1932), HARVEY (1925) and especially COOPER (1934, 1938, 1948, 1952) had been published, the fact became perfectly clear that, in the English Channel, quantitative variations in nutrient salt ultimately affecting the increment in length of commercial fish are caused by fluctuations in the inflow of deep Atlantic waters into this area. A hypothesis was formed that the overflow of the cold near-bottom waters of the Norwegian Sea occurs over the Iceland-Faroe submarine ridge. According to COOPER (1955), the level of these waters rises from time to time under tidal influence and as a result they flow into the Atlantic Ocean in the form of a gigantic "bolus", causing the lifting of oceanic waters rich in biogens and penetration of the latter into the Norwegian Sea and other shelf seas and areas. Hence the great importance for the prediction of the resources of oceanic fisheries of detailed investigations into this problem.

According to the decision of the Hydrographical Committee of ICES the author of this paper was asked to search for traces of the probable overflow in the distribution of dissolved oxygen, as one of the significant elements. The results of the work undertaken are given below.

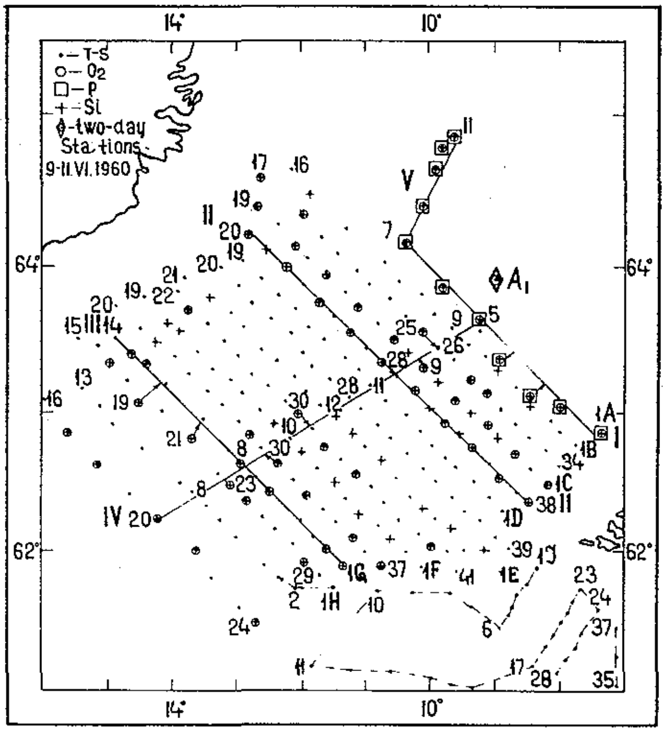
MATERIALS OF THE INVESTIGATION

All oxygen determinations on board the vessels of the International (ICES) Oceanographic Expedition of 1960 were done by the Winkler method. The results have been verified by the Hydrografic Committee and

1st SURVEY: 30. MAY–3. JUNE



2nd SURVEY: 6. MAY–9. JUNE



are used here without any additional control, except that the measurements by "Perseus II". have been carefully checked up also in the hydrochemical laboratory of Pinro. Preliminary study of the material showed that the qualitative aspect of the oxygen determinations and the determinations of other hydrochemical elements raises no question. The quantity of data obtained, however, does. The area investigated for oxygen is not covered by a uniform grid of stations (Figure 7:1), as would be desirable. At 300 stations where three surveys were carried out, 95 oxygen measurements were taken during the first survey, 63 during the second and 60 during the third. More complete oxygen observations were taken onboard the ships "Gauss" (Course C) and "Perseus II" (Course A). Less were taken by "Anton Dohrn" (Course G) and "Johan Hjort" (Course B), "Helland-Hansen" (Course F), "María Júlía" (Course E), "Explorer" (Course I), "Discovery II" (Course H) and "Ernest Holt" (Course D). Fortunately, the material on the most significant courses of the survey (Courses A, C and G) appears to be quite comparable. For some indispensable comparisons the oxygen determinations taken at the stations where the ships were anchored for 48 hours (Diamond stations H and A) were also used. At other stations of this type hydrochemical determinations were not carried out.

3rd SURVEY: 12. MAY–18. JUNE

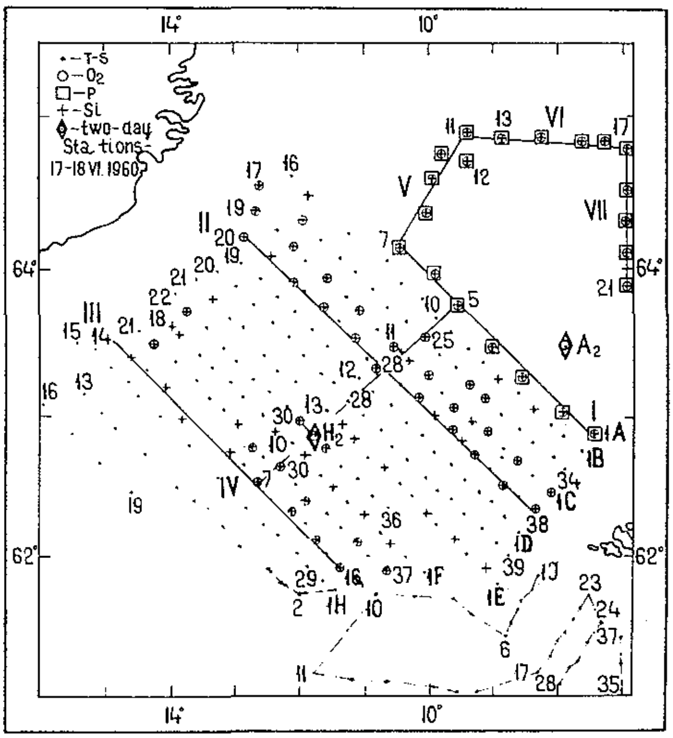


Figure 7 : 1. Charts of hydrographical and hydrochemical stations in the area of the Iceland-Faroe Ridge worked during the three surveys of the International Oceanographic Expedition in 1960.

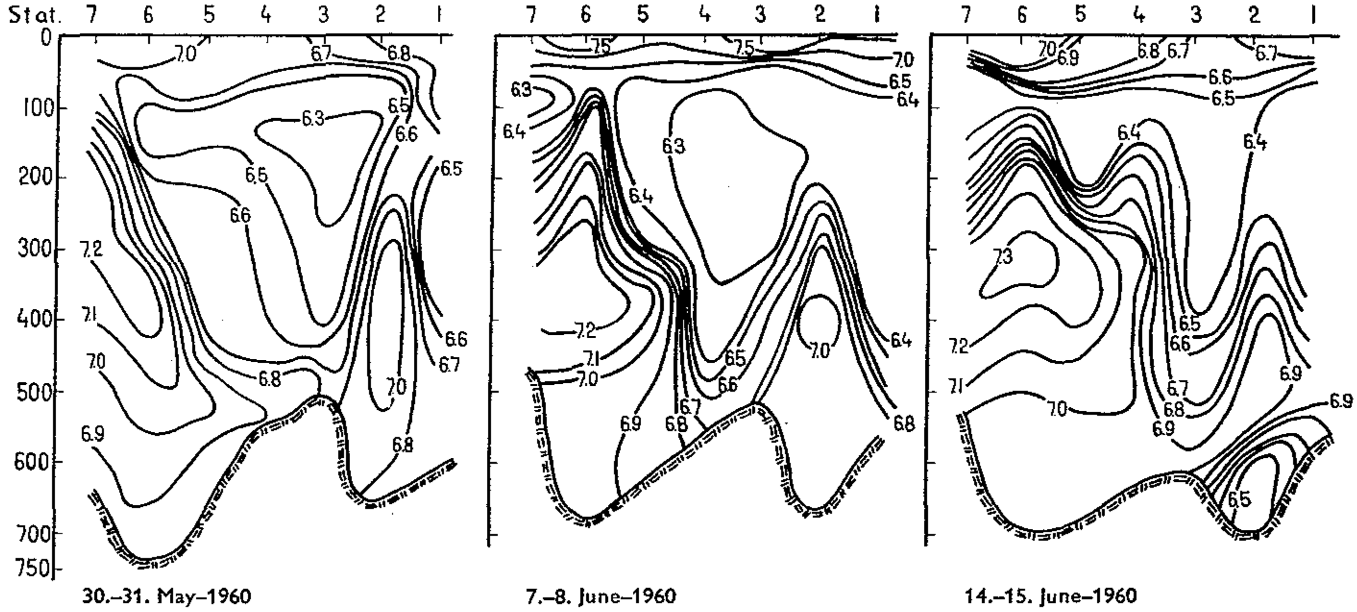


Figure 7:2. Isoxygens on Section I along Course A ("Perseus II") in ml O_2/l.

OXYGEN DISTRIBUTION ON THE SECTIONS

Preliminary investigations on the instrumental measurements of the velocities and directions of constant currents, as submitted by the participants of the expedition to the 48th Session of the ICES in September, 1960, do not solve the "overflow" problem. While at the two stations situated near C20 and C31 (Figure 7:1) JOSEPH found that residuals of the near-bottom currents were directed to the Atlantic, CARRUTHERS (1960), at the stations situated near E30 and F26 obtained quite different results. In both cases the authors observed that the temperatures of the moving water masses at these places greatly exceeded 2° C and JOSEPH states that this was because of the overflow of mixed waters, not of subarctic waters. As TAIT, the leader of the Expedition, showed in his report (1960), in the first half of June 1960, in the area of the Iceland-Faroe Ridge, the expedition had observed a recession of the relatively cold waters (temperature below 2° C) from the top of the Ridge and towards the Norwegian Sea, whence they had come earlier.

The conclusion drawn by TAIT agrees remarkably well with the distribution of dissolved oxygen on the sections. The analysis of the data gives the following picture. On Sections V–VI–VII (Figure 7:1) characterizing the waters of the East Icelandic Arctic Current, increased oxygen content was observed – over 8 ml O_2/l in the upper layers and about 7 ml O_2/l in the deep layers. Approaching the northeastern slope of the Ridge these waters tended to fill the northwestern deep (Figure 7:2) and partly the southeastern depression near Station A2 of Section I. On Section II ("Gauss") running over the very top of the Ridge (Figure 7:3) one cannot find the waters formerly rich in oxygen, excluding the limited elevated bottom areas where during the first and the second surveys these waters were still present. On this section, already during the first survey, counter movement of mixed waters with low oxygen content could be clearly traced which split up the stream of the Norwegian waters. On this section this process was especially well marked during the second survey. On the section worked during the third survey one could see two wedges with increased oxygen content and two wedges with decreased content of oxygen converging in one centre. At the stations situated over the southwestern slope of the Ridge we do not find traces of the water masses which were observed on Sections I and II. The waters of Atlantic origin, relatively poor in oxygen (oxygen content less than 6 ml O_2/l), intruded into columns of water with oxygen content of 6.4–6.7 ml O_2/l.

The limits of the water masses discussed above are well projected on Section IV running across the Ridge (Figure 7:4). During the first survey we observed the deep waters of the Norwegian Sea with high oxygen content approaching the top of the Ridge in the vicinity of Station C28 (this occurred on 1. June, 1960). Restricted from above and from the sides (on the Atlantic slope of the Ridge), these waters, during the second survey (7.–8. June, 1960), did not descend down the slope as they should according to theory, but rose to the surface near Station G8 and in part sank to the deep east of this area (Figure 7:3). On this section during the third survey we find noticeable intrusion of the Atlantic waters with rela-

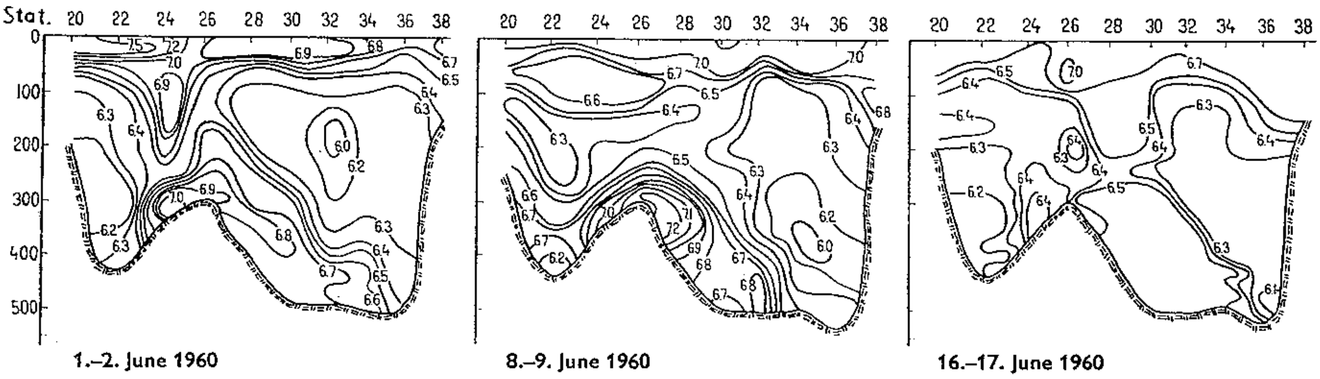


Figure 7:3. Isoxygens on Section II along Course C ("Gauss") in ml O_2/l.

tively low oxygen content and the formation of a patch of water with oxygen content less than 6 ml O_2/l on the Atlantic slope of the Ridge resulting from this process.

DISTRIBUTION OF OXYGEN NEAR THE BOTTOM, IN THE LAYERS OF MINIMUM AND MAXIMUM

Near-bottom isoxygens (Figure 7:5), which in this case reflect almost completely the picture of oxygen distribution in the mid-water layers as well, are in harmony with the near-bottom isotherm charts drawn by TAIT (1960). In all the surveys intrusion of the waters of the Norwegian Sea rich in oxygen is strongly pronounced, becoming somewhat weaker in the course of time. Under the pressure of the Atlantic waters, recession of the sub-Arctic waters occurred in the direction of the Norwegian Sea. During the first survey a patch of water with high oxygen content was especially distinctive on the chart in the channel between the Faroes and the Faroe Bank. (During the second and the third surveys oxygen determinations were not taken there). This phenomenon confirms the data collected by TAIT (1957a, 1957b, 1961), JACOBSEN (1943), HERMANN (1952, 1955, 1958) and ANDERSEN (1953, 1957) on the penetration of cold near-bottom waters of the Norwegian Sea through the Faroe-Shetland Channel into this area. But it is noteworthy that these intrusions of the near-bottom waters on the Atlantic slope of the Ridge disperse very quickly and leave no noticeable traces.

A remarkable phenomenon which throws some light on the problem is that of oxygen minimum and maximum due to which the curves of vertical oxygen distribution here, as in many other ocean areas, have the S-form. As a role, in these cases oxygen content drops from maximum values on the surface and in the near-surface layer to a definite minimum at a certain depth; then a more or less sharp increase occurs in the midwater layers, followed by a decrease in oxygen content down to the bottom. According to JACOBSEN (1916) and WÜST (1935), dynamic processes are the basis of the formation of oxygen minima and maxima. Evidently, the reason is the enrichment of moving water masses with oxygen. SEIWELL (1937) assigns the greatest role in the formation of these layers to biological processes. The observations by SCHMIDT mentioned in the book by HARVEY (1925) confirms this. An assumption also existed that the layer of oxygen minimum could form due to oxydation of sinking detrital matter. But DIETRICH (1937) disproved this, showing that absorption of oxygen by detrital matter occurs evenly along the whole vertical line. Later REDFIELD (1942) made a similar statement. SVERDRUP's attempt (1938) to find an explanation of the phenomenon of the oxygen maximum also failed.

Oxygen distribution in the area of the Iceland-Faroe Ridge showed that the layers of maximum and minimum are determined there by dynamic processes as observed by MUSINA (1960) for central Arctic areas. While Atlantic waters with relatively low oxygen content tend to wedge up into the upper layers, deep water masses of the Norwegian Sea rich in oxygen which move in the opposite direction are forced downwards and disperse in the midwater layers of the Atlantic Ocean before they reach the bottom. Taking into consideration the fact that the uppermost layer of the sea is permanently enriched with oxygen from the atmosphere and due to photosynthesis and that in the near-bottom layers oxygen is spent on oxydation processes and the respiration of animals, one can understand the character of the curve of vertical oxygen distribution.

The position of the surface of oxygen minimum and maximum and the course of isoxygens on them give a good illustration of what is said above. (Figure 7:6)[1].

[1] The observations taken in the southern part of the area being scarce, the analogous schemes for the second and third surveys are not given though they also conform to the conclusions drawn (A.M.).

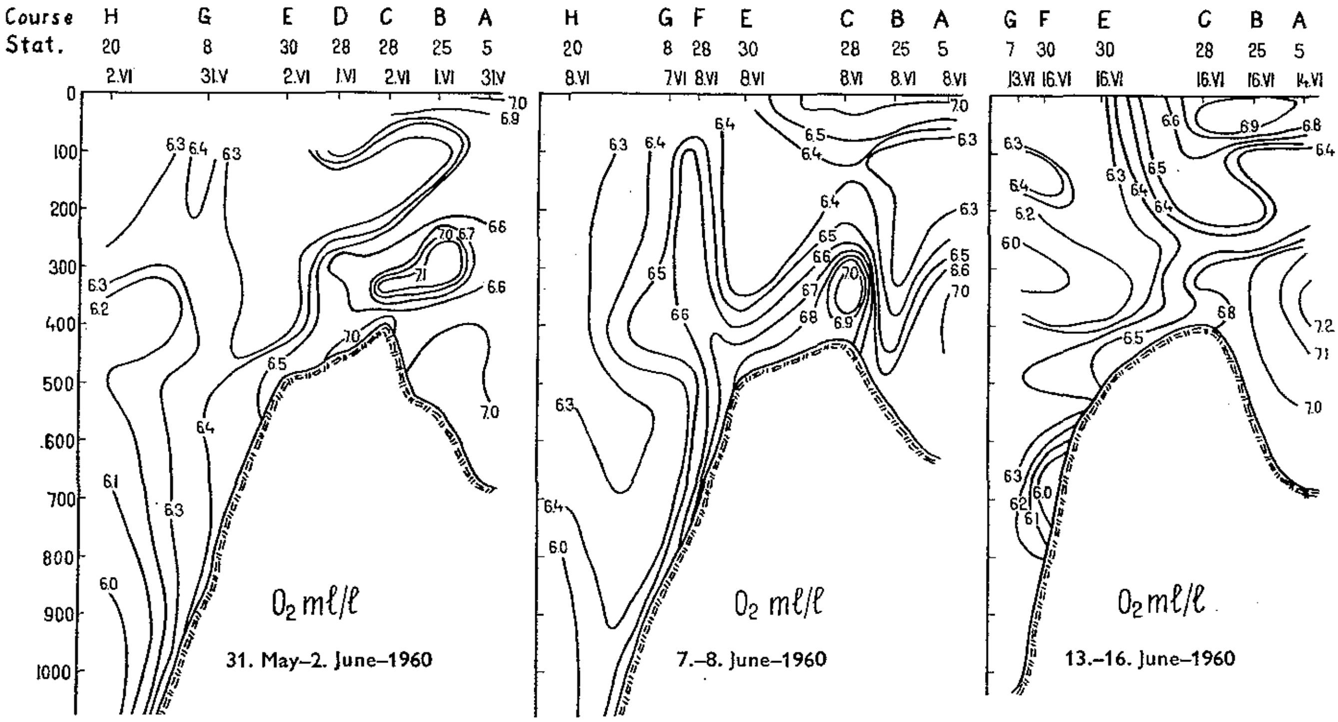


Figure 7:4. Isoxygens on Section IV across the Ridge (Figure 7:1) in ml O_2/l.

In fact, the layers of oxygen minimum and maximum are conjugated with each other. Both are inclined in the direction of the Atlantic and their oxygen content decreases in the same direction.

The analysis of oxygen minima and maxima at Stations A_1, A_2, and H_2 (Figure 7:1) where the work was carried out for 48 hours does not reveal any correlation between their positions during different hours of observation and tidal phenomena. This is impeded, evidently, by the horizontal migrations of water masses caused by other factors.

CORRELATION BETWEEN OXYGEN DISTRIBUTION AND DISTRIBUTION OF OTHER ELEMENTS

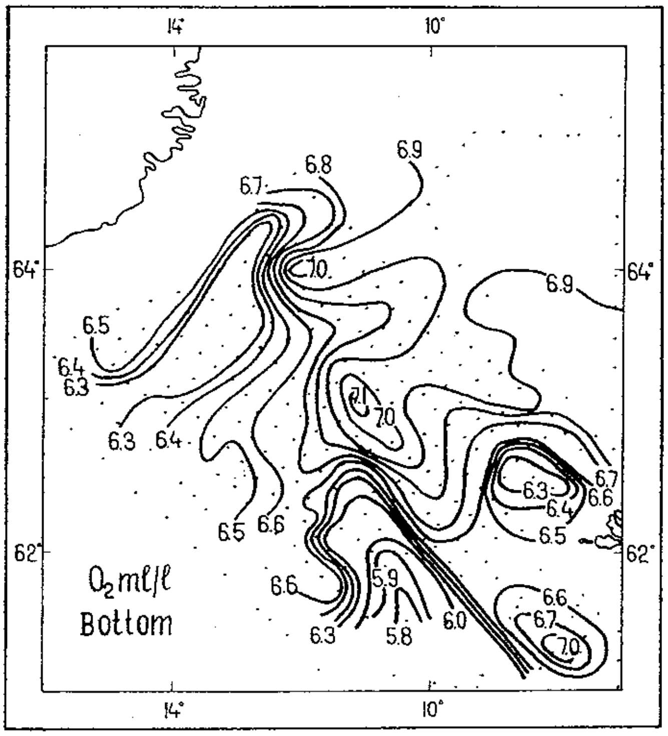
When analysing temperature and salinity distributions we find that very close correlation exists between these elements. For instance, for the complexes of the surface layer the correlation coefficient $TS = +0{\cdot}904 \pm 0{\cdot}010$, $n = 311$. For the complexes of the near-bottom layer the correlation coefficient appears to be $+0{\cdot}933 \pm 0{\cdot}007$, $n = 306$. The corresponding correlation coefficients for midwater layers can be

Table 7:1

Correlation coefficients between the distribution of oxygen in ml/l and that of other elements in the area of the Iceland-Faroe Ridge in June, 1960

Elements, complexes and time	Survey	n	r	σ_r	$\lvert r\rvert\sqrt{n-1}$
T° and O_2 of surface	1	46	− 0·814	0·059	5·4
T° and O_2 of 100 m bottom layer	1	492	− 0·788	0·018	17·1
T° and O_2 of 100 m bottom layer	2	312	− 0·673	0·031	11·8
T° and O_2 of 100 m bottom layer	3	337	− 0·778	0·021	14·4
T° and O_2 of 100 m bottom layer	1+2+3	1140	− 0·820	0·010	27·6
S°/₀₀ and O_2 ml/l of surface	1	47	− 0·850	0·041	5·8
S°/₀₀ and O_2 of 100 m bottom layer	1	516	− 0·843	0·013	19·1
S°/₀₀ and O_2 of 100 m bottom layer	2	327	− 0·750	0·024	13·5
S°/₀₀ and O_2 of 100 m bottom layer	3	344	− 0·833	0·016	15·5
P µg-at/l and O_2ml/l of 100 m bottom layer	1	142	− 0·121	0·083	1·4
Si µg-at/l and O_2ml/l of 100 m bottom layer	1	368	− 0·073	0·052	1·4

1st SURVEY



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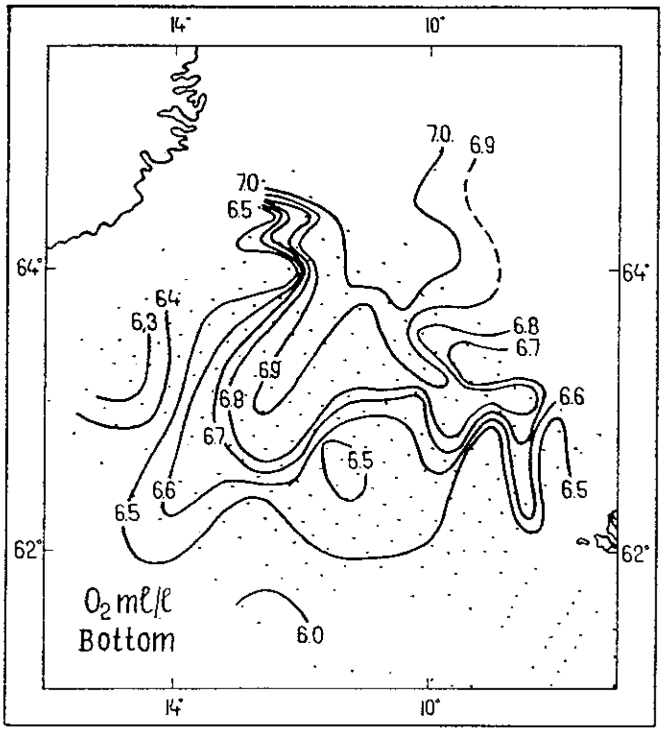

still better. For example the correlation coefficient for the 500 m layer = $+0{\cdot}984 \pm 0{\cdot}002$, $n = 192$.

Thus, the temperature-salinity regime of this area depends chiefly on the ratio between the water masses of the Atlantic Ocean and those of the Arctic Ocean. If at any given point the Atlantic component increases, temperature and salinity have to increase too, and vice versa – if the component of the Arctic Ocean increases, temperature and salinity have to decrease. But, as the difference between the oxygen content of the Atlantic waters and that of the water masses of the Arctic Ocean is very great, according to Harvey (1925), we must admit that the oxygen regime on the borderline of the intermixing of these two initial water masses must depend upon their proportion at the location in question. Therefore, if at the same time as we use the correlation equation we find the deviation of dissolved oxygen content from "normal" at every point of observation, we will be able to determine the origin of these waters. For instance, the author has solved the problem of the origin of cold near-bottom waters over the West Greenland grounds (Adrov, 1960, 1961, 1962). Moreover, as oxygen, unlike temperature and salinity, is influenced by congregations of animals and especially by concentration of fish schools, it is possible to contour areas of this

3rd SURVEY

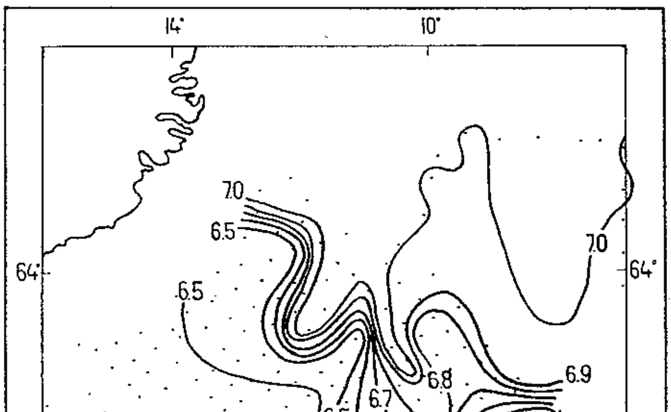

Figure 7: 5. Near-bottom isoxygens according to the three surveys in ml O_2/l.

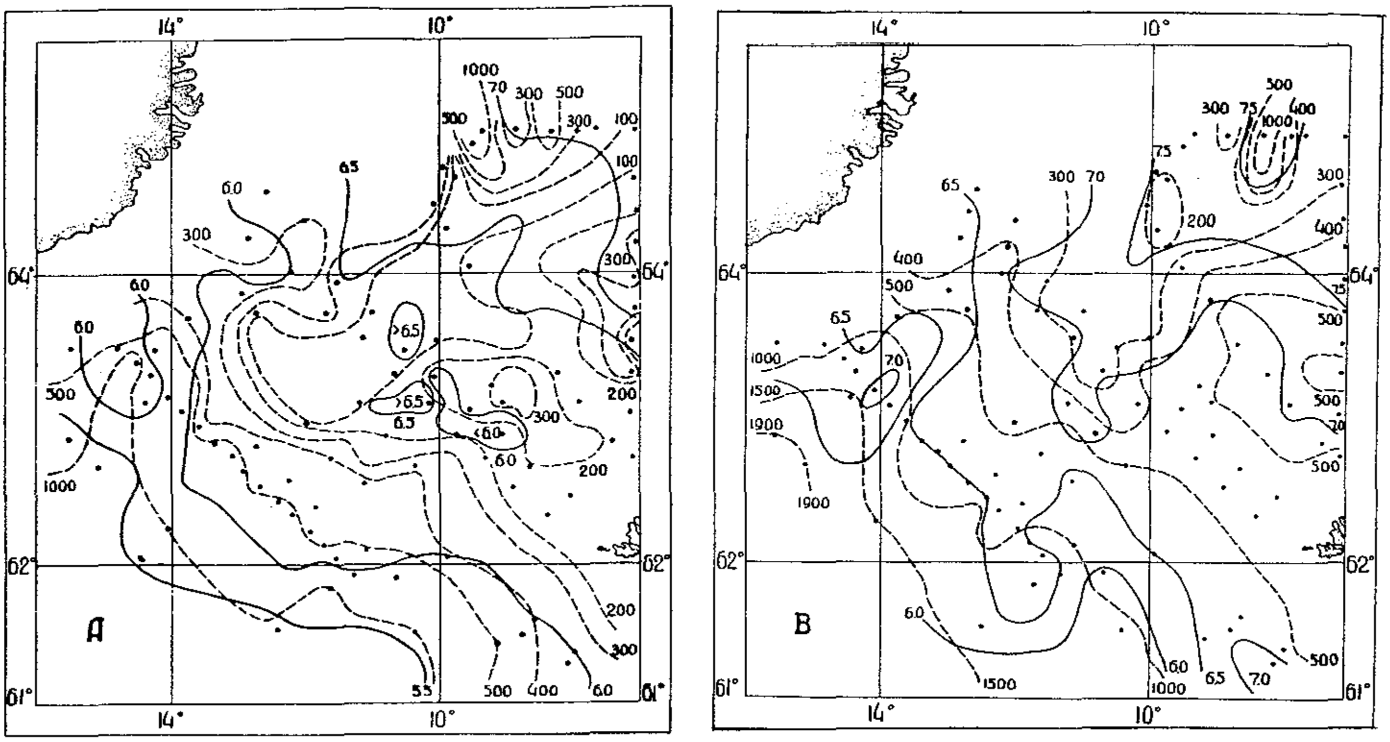

Figure 7:6. Isoxygens in ml O_2/l (continuous lines) and isobaths (broken lines) of the layer of minimum (A) and that of maximum (B) according to the data of the first survey of the International Oceanographic Expedition, 1960.

kind (Adrov, 1957; Yelizarov, 1959; Pakhorukov, 1959), which is both of theoretical and of certain practical interest.

Employing this method in the investigation of our material from the area of the Iceland-Faroe Ridge we first of all correlated oxygen content at certain points of observations with temperature, salinity and the content of biogenous elements and represented the results obtained in Table 7:1.

Very high negative coefficients of correlation between the distribution of temperature and salinity and that of oxygen in the area in question reveal very close inverse correlation between these elements. It is obvious from the fifth column that this correlation is quite real. As soon as the Atlantic waters are characterized by higher content of biogenous elements compared with the waters of the Norwegian Sea we should expect the same inverse correlation between oxygen and biogenous elements. This correlation seems to exist in reality, but coefficients of correlation between these elements appeared to be too small and not normative. Despite Cooper's supposition it proves quite clearly that the Atlantic deep waters are not the only main source of nutrient salts for the Norwegian Sea. Evidently in this same area, there is another source of nutrient salts of equal importance, and as this source is situated in relatively cold waters, the correlation between oxygen and biogenous elements proved to be about nil. The investigations by Zhukova and Fedosov (1961) suggest the same idea, showing that the regeneration of nutrient salts in the sea can occur due to bacterial processes in the bottom sedimentations of detrital matter. This supposition perfectly agrees with the high plankton production in the central parts of the Norwegian Sea (Pavshtics (1960)) and the high content of biogenous elements in the deep areas of the sea as Soviet investigations have shown (Alekseev, Istoshin and Ponomarenko (1961), and Fedosov and Ermachenko (1961)).

On the basis of the results obtained a correlation equation was worked out connecting the distribution of temperature and salinity in the 100 m-bottom layer if $n = 1140$. It is as follows: $\overline{O}_2 = -0{\cdot}091\,T^0 + 7{\cdot}05$ where $\overline{O}_2$ is the amount of dissolved oxygen and T^0 is the water temperature at the given point. The character of oxygen isanomals determined as the differences between the observed and the computed values in ml/l conforms to that of isoxygens on the sections mentioned above. For example, on Section IV (Figure 7:7) the Atlantic waters relatively poor in oxygen but with positive anomalies, are well marked. Like a wall of water they block the way of the mixed water masses covering the top of the Ridge. Very intensive intermixing occurs in these water masses which form a complete boundary zone with anomalies approaching 0·0 ml. O_2/l. This process is well represented on the

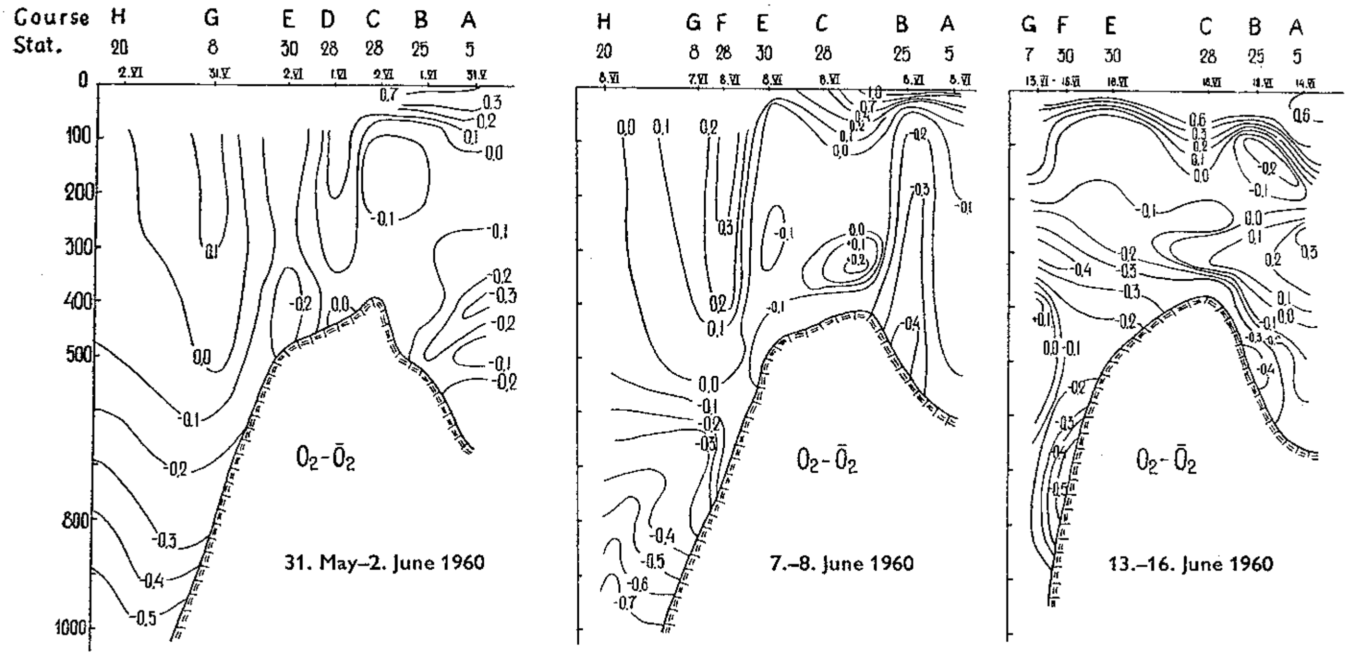

Figure 7:7. Oxygen isanomals in ml O_2/l on Section IV (Figure 7:1).
Method of calculation is given in the paper.

diagram of vertical distribution observed during the third survey where one can see that the water masses with zero oxygen anomaly raised to the upper layers travel in the direction of the Norwegian Sea.

SEARCH FOR THE TRACES OF "OVERFLOW"

Judging from the works by ALEKSEEV (1959) and YAROGOV, (1959) water masses of the East Icelandic Arctic Current of the Faroe-Shetland Channel and the deep cold waters of the Norwegian Sea should be regarded as a single whole. Evidently, the cold near-bottom waters of the central part of the sea originate not only and not so much from the water masses of the Jan Mayen area, but also and perhaps to an even greater degree from the waters of the North Iceland Deep which are carried out by the East Icelandic Arctic Current into the Faroe-Icelandic area and the central part of the Norwegian Sea. It follows that, under the influence of internal waves, as TAIT points out (1960), the cold and relatively heavy waters can flow over the Iceland-Faroe Ridge in mixed if not in pure condition, as JOSEPH admits.

To check up this supposition, we utilise the method of graphic correlation between the deficiency in oxygen saturation calculated according to the tables compiled by Fox (1907) and the conventional density σ_t of the water under question. In our opinion, JOHNSTON (1960) succeeded in using this method when he carried out investigations into the origin of the near-bottom waters of the eastern deep of the North Atlantic.

It is obvious from the σ_t $(0_2–0'_2)$ diagram (Figure 7:8) that the deep cold waters of the Norwegian Sea (dots on the diagram) have nothing in common with the deep waters of the Atlantic slope of the Ridge (crosses on the diagram). Assuming that the overflow of already mixed waters takes place there, the fact remains unexplained why the disappearance of such great deficiency of oxygen did not occur. Only on the diagram of the third survey a few measurements reveal deep waters with oxygen deficiency less $-0{\cdot}5$ ml $0_2/1$, but these values refer here to the uppermost limit of the layer investigated. As to the four crosses which on the diagram of the first survey coincided with the dots, this can be explained by the fact that on the diagram values were plotted referring to Stations I 4, I 5, I 18 and I 31 situated in the channel between the Faroes and the Faroe Bank where the deep cold waters from the Norwegian Sea had been observed. These facts suggest an idea that in this case great oxygen deficiencies in the relatively warm near-bottom waters of the Atlantic Ocean result from biological processes, not from the penetration of cold deep waters high oxygen content into them (the deficiency is to disappear due to such intermixing). This conclusion is confirmed by other facts. For instance, according to

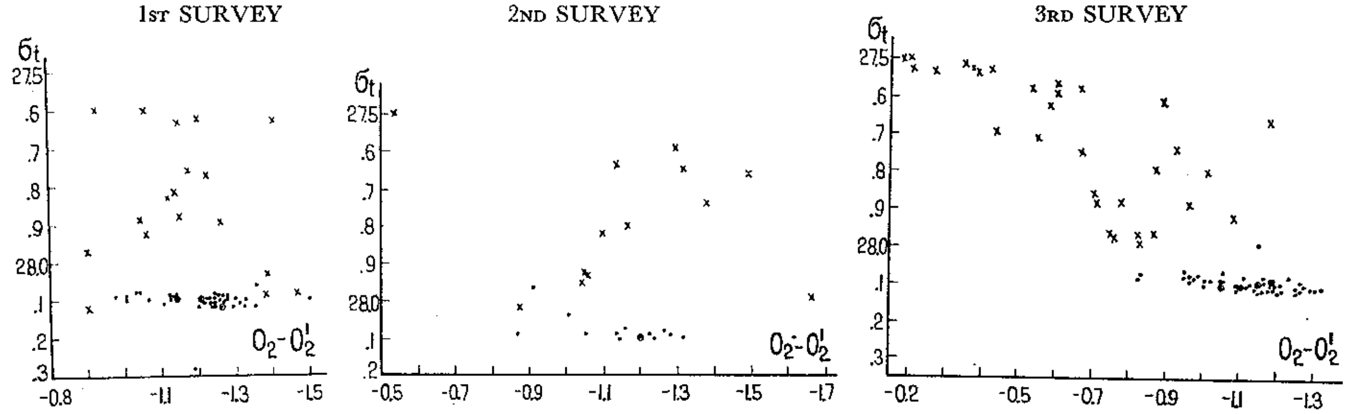

Figure 7:8. Diagram of correlations between the deficiency in oxygen saturation of the water (according to Fox's (1907) tables and the values of conventional density δ_t in the 500 m-bottom layer north of the Ridge (dots) and south of it (crosses).

the above mentioned paper by Johnston (1960), in the eastern deep of the North Atlantic where, as the works by Riley (1951) and Hermann (1958) show, the temperature of near-bottom waters exceeds 2·5° C, great oxygen deficiencies are observed. This could not take place if the influence of the deep waters of the Norwegian Sea had spread there. Therefore it is no mere chance that applying Worthington's formula (1958) Johnston (1960), despite his own views, showed that the near-bottom waters of the eastern part of the North Atlantic are "younger" than the near-bottom waters of the Norwegian Sea and that therefore there is no direct relationship between both waters.

ON THE DISTRIBUTION OF OXYGEN IN CONNECTION WITH VERTICAL STABILITY OF WATER LAYERS

The distribution of dissolved oxygen in the water column is directly connected with the processes of intermixing and the interaction of water masses of different origin. But, as Ivanov-Frantskevich (1953) showed, the distribution of indices of the vertical stability of water layers is connected with the same processes. Therefore it is advisable to compute the values of the vertical stability E·10⁸ of separate layers on the selected sections using the tables by Zubov, N. (1957) and to compare the distribution of these indices with the distribution of dissolved oxygen.

Our calculations and comparisons showed that in a number of cases at the stations situated in the area of the Iceland-Faroe Ridge oxygen minima coincide with maximum values of vertical stability and, conversely oxygen maxima with minimum values of vertical stability (Figure 7:9). The area with homogeneous water layers is characterized by almost parallel vertical distribution of minimum oxygen values (for this area) and almost zero values of vertical stability (see Station A17, Figure 7:9). In the area where the near-bottom waters of the Norwegian Sea penetrate through the Faroe-Shetland Channel (Station 19-I), increased stability and maximum values of dissolved oxygen are observed. Certainly, not in all the cases was there a similar distinct connection between the distribution of vertical stability of the layers and the content of dissolved oxygen, as this is impeded by the processes of intermixing between separate interacting water masses which take place in the water column continuously, but the cases we do observe show that the phenomena of oxygen minima and maxima can be very closely correlated with biological and dynamic processes operating simultaneously in the water column.

The presence of a great number of vortices in the streams of different origin creates in this area a very complicated and very alternating picture of the distribution of values of vertical stability of the water layers. For instance, on Section II along Course C (Figure 7:10) the character of the $E\cdot10^8$ isoline resembles that of the oxygen on the same section (Fig. 7:3). During all three surveys vast areas with stability less than 100 $E\cdot10^8$ units were contoured off the Icelandic and the Faroese slopes. These are the areas of minimum oxygen values. They were formed due to the penetration of the Atlantic water masses. The near-bottom waters covering the most elevated part of the section are characterized by the least stability. These are the waters with high oxygen content which have come from the Norwegian Sea as shown above. It is obvious both from the isolines of stability and the isoxygens that these waters slip down the slope to the right to fill the deep west of the Faroes. Other $E\cdot10^8$ isolines show that the Atlantic water masses of small stability and small values of dissolved oxygen penetrating there near the Icelandic slope break the counter-currents of the Norwegian Sea. Thus, factors of quite different origin give one and the same picture of complex movement of the water masses in the area of the Iceland-Faroe Ridge.

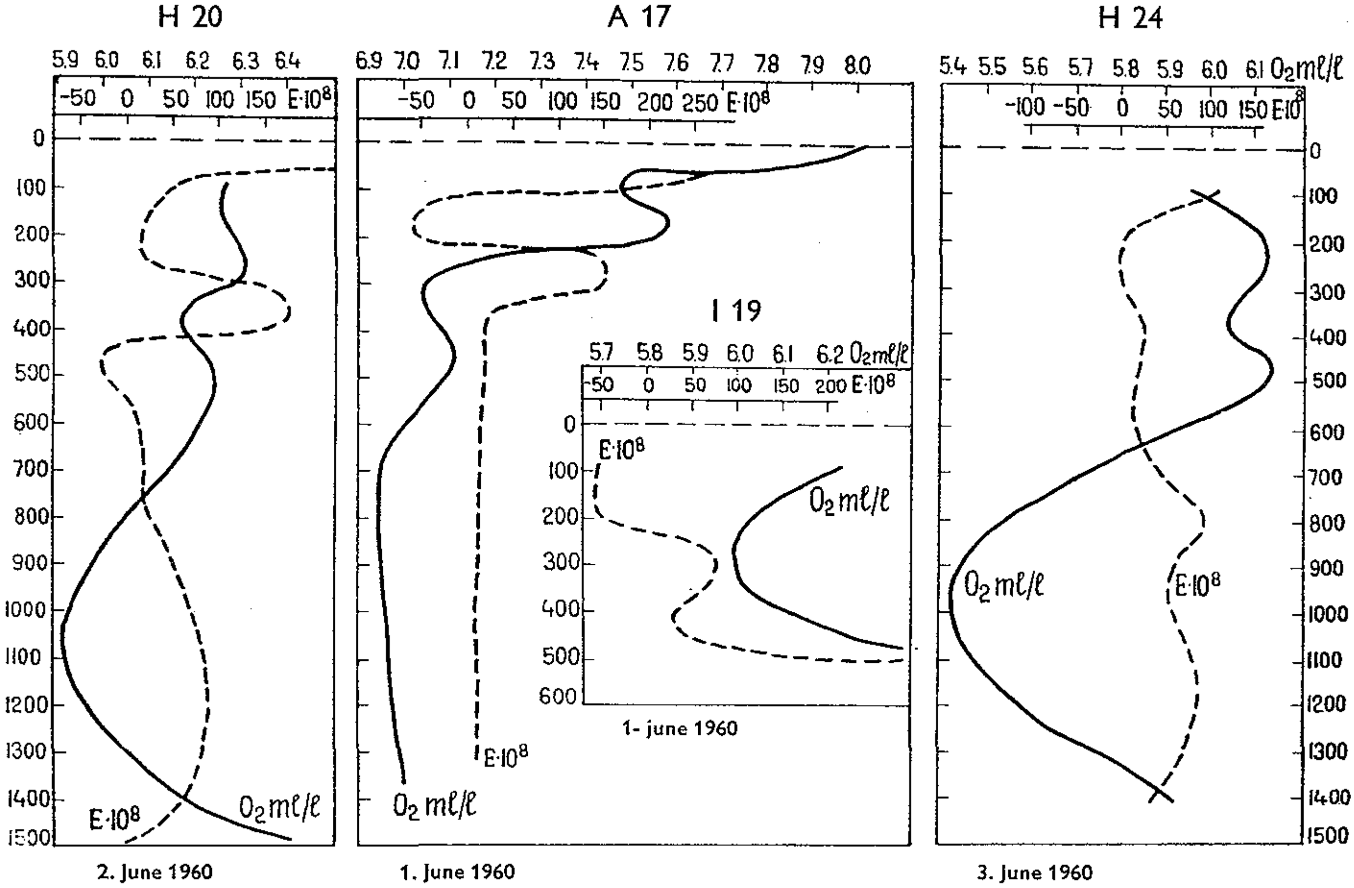

Figure 7:9. Curves of vertical oxygen distribution in ml O_2/l and those of the indices of stability of the water layers E·10^8 at several stations worked during the 1st survey of the International Oceanographic Expedition, 1960.

Comparing the distribution of absolute value of oxygen content with the distribution of oxygen anomalies on Section IV (Figure 7:4 and 7:7) we have found the lifting of water masses between Stations F28 and E30. The vertical distribution of E·10^8 stability indices at the same stations (Figure 7:11) exhibits the same. For instance, if according to JOSEPH (1960), near Station E30 deep waters move in the direction of the Atlantic, it follows that the deep waters at Station F28 are none other than the transformed waters from Station E30. But as it is evident from the density and stability curves, very stable and highly stratified deep water masses, after having covered some 30 miles from Station E30 to Station F28, acquire uniform density and become quite unstable along the whole vertical from 100 m to 500 m. Under this layer stratified layers of greater stability are situated. Hence it is clear why the isoxygens in this part of the section take the shape of a tongue which protrudes upwards. It can also be understood why in this area JOSEPH observed a constant surface current moving in the direction of the Norwegian Sea. Obviously, in this case we dealt with a vortex with horizontal axis.

CONCLUSION

The analysis of the distribution of dissolved oxygen in the waters of the Faroe-Iceland area according to the materials of the three surveys carried out during the ICES International Oceanographic Expedition in June 1960, has revealed no traces of the hypothetical flow of cold deep waters of the Norwegian Sea into the Atlantic over the Iceland-Faroe submarine Ridge. These waters coming from the northeast into the depressions of the Ridge and following them in the direction of the Atlantic Ocean mix to a great extent with the surrounding water masses which flow in the opposite direction and then, being transformed, penetrate into the midwater ocean layers, stipulating the existence of the layer of oxygen maximum there. In their turn, the Atlantic water masses of low oxygen content approaching the relatively cold mixed waters of the Ridge constantly wedge up to the surface and form a layer of oxygen minimum at corresponding depths. The layers of minimum and maximum are conjugated with each other and inclined in the direction of the Atlantic, the absolute oxygen values in both layers increasing in general in the same direction.

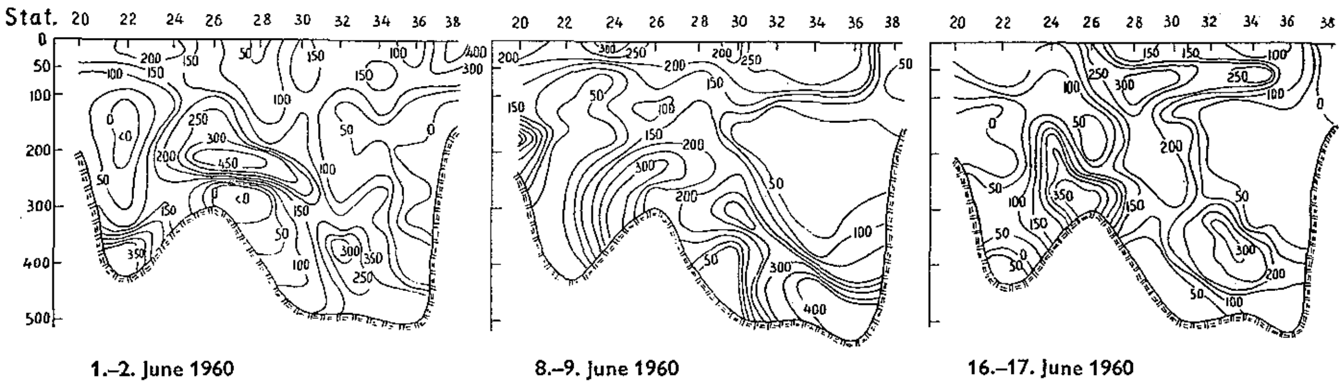

Figure 7 :10. Isolines of the indices of the vertical stability of the water layers E·10⁸ on Section II along Course C ("Gauss").

There is a close correlation between dissolved oxygen content, temperature and salinity, which indicates a predominating role of the water exchange between the Atlantic Ocean and the Norwegian Sea in the fluctuations of the hydrological conditions in the boundary area. The simultaneous absence of correlation between oxygen on the one hand and biogens (phosphorus and silicon) on the other, does not permit us to consider the deep layers of the Atlantic Ocean as the sole main source of nutrient salts for the productive layer of the Norwegian Sea and other northern seas and areas. Evidently, in the Norwegian Sea there is another main source of these salts which is confirmed by direct hydrochemical observations.

A very complicated and alternating distribution of oxygen in the waters of the Iceland-Faroe Ridge is revealed which shows great turbulence in the velocity field there and indicates the existence of a complex and alternating system of circulation of the water masses of different origin. This conclusion is confirmed also by the distribution of indices of vertical stability in the water layers.

The conclusion drawn by HELLAND-HANSEN and NANSEN (1909), that overflow of the cold near-bottom waters (in pure condition) of the Norwegian Sea through any of the ridges separating this Sea from the Atlantic Ocean does not take place must be considered to be correct in the light of the data on oxygen analysed in the present paper.

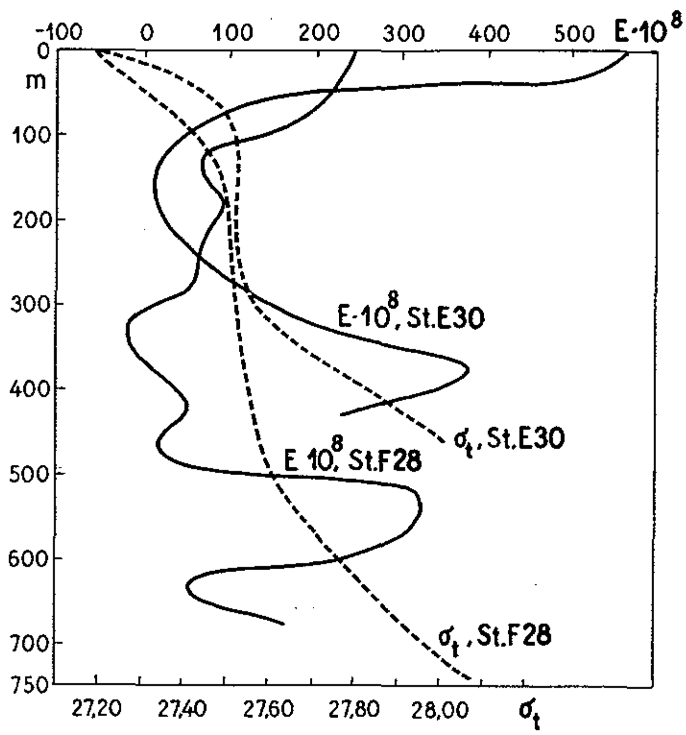

Figure 7 :11. Curves of vertical distribution of the vertical stability indices $E \cdot 10^8$ in the water layers and those of conventional density δ_t at Stations 30E and 28F during the 2nd survey of the International Oceanographic Expedition in 1960.

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CHAPTER 7 (II)
HYDROCHEMICAL CHARACTERISTICS OF WATER MASSES AND WATER EXCHANGE BETWEEN ICELAND AND FAROES

(HYDROGRAPHICAL SURVEYS IN JUNE 1960)

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Elevation of the bottom between Iceland and the Faroes forms a sea shallow with minimum depths of below 300 metres on the Rosengarten Bank and delimited in its entire length by 500-metre isobaths (Figure 7:13). This shallow or ridge is a considerable obstacle for water exchange through the region between the Norwegian Sea and the Atlantic Ocean.

The cross-sectional area of the Ridge is about 125 km^2. According to observations collected mainly during the International Geophysical Year and also during the ICES expedition of 1960, it was found by the dynamic method (G. N. ZAITSEV, 1962), that the resultant water exchange in this region (in the direction of the Norwegian Sea) was on the average 1·44 km^3 per hour. According to the same calculation it was found that each of two constituents of this water exchange is ten or eleven times greater than the above resultant value. Further analysis of the calculated values showed that water exchange was most intensive in the upper 50-metre photic layer (Figure 7:12), reaching 3·76 km^3 per hour. In the lower layer of 50 m to 300 m, the intensity of water exchange in both directions was almost one half of that in the upper layer; and in this layer the movement of waters of the Atlantic into the Norwegian Sea predominated. Two-way water exchange occurred in the deepest area of the submarine ridge in its southeastern part where deep waters of both types were observed. (M. V. FEDOSOV and I. A. ERMACHENKO, 1962). The values obtained show that the dynamic of the water masses in this border region of the two oceans is somewhat high, the resulting water exchange, however, being at least 20 times less than the total exchange. Investigations carried out in June 1960 according to the programme of the ICES Hydrographical Committee allowed for the collection of various synchronous data including hydrochemical observations characterising the seawater column over the area investigated.

Salinity was determined by a method of electrometric registration of changes in the electroconductivity of water samples in a created electric field, yielding very precise data. Determination of dissolved molecular oxygen was made by WINKLER's method on samples collected by seawater sampling bottles.

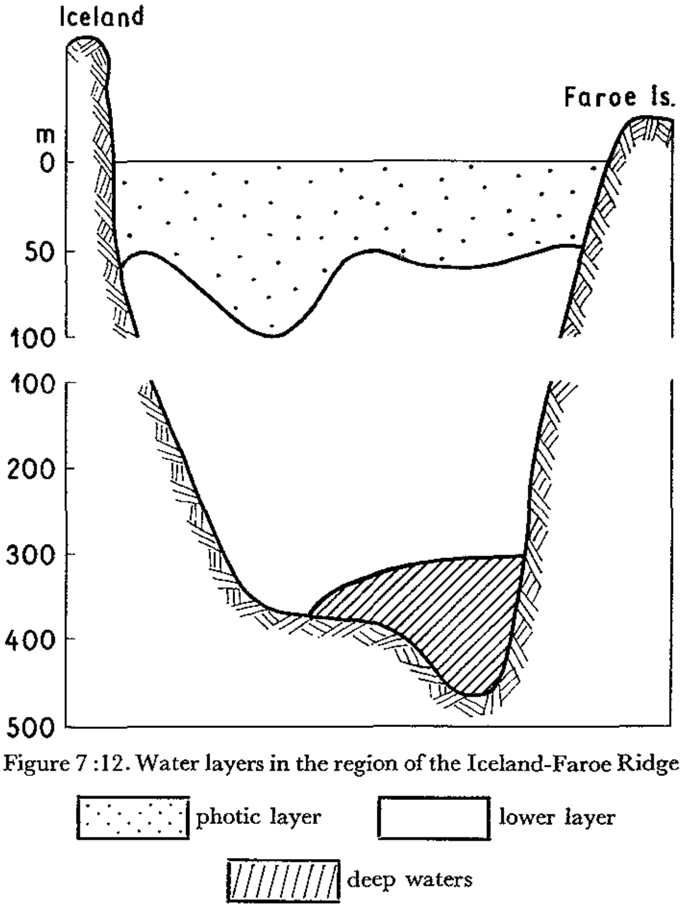


Figure 7 :12. Water layers in the region of the Iceland-Faroe Ridge

Dissolved silicium was determined on water samples collected in polythene bottles. Before commencing operations, silicium standard solutions were compared with each other, and in control analyses gave the same results. Colorimetric determination of silicium was carried out with a blue modification of the method

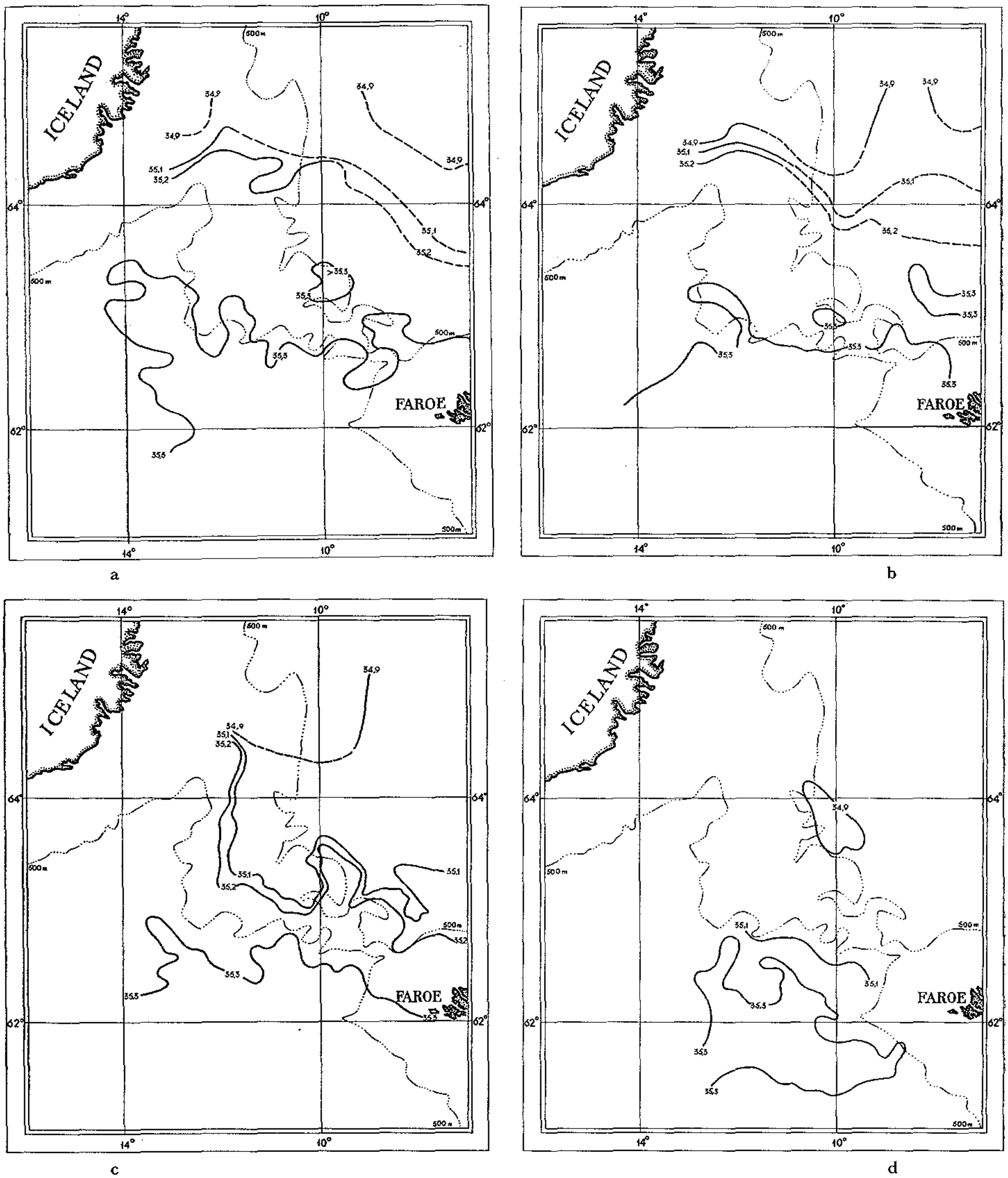


Figure 7:13. First Survey. Distribution of water masses of different salinity:
a) at surface; b) at 100 m; c) at 300 m; d) at 500 m.
$\geqq$ 35·3 $^0/_{00}$ = Atlantic waters
$\leqq$ 34·9 $^0/_{00}$ = Norwegian Sea waters
35·1 $^0/_{00}$ = waters of equal admixture (1 :1)
of Oceanic and Norwegian Sea types.

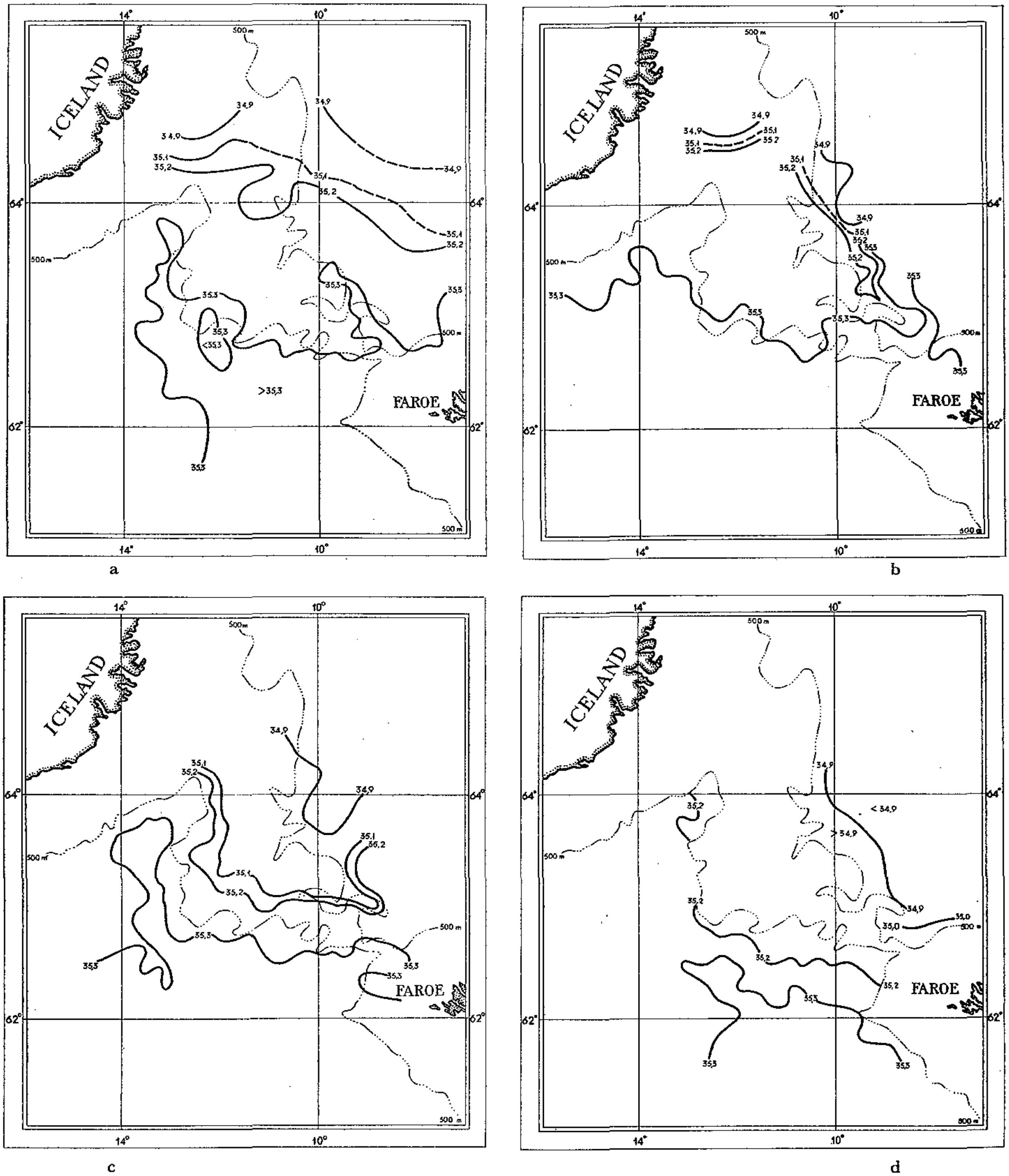


Figure 7:13. Second Survey. Distribution of water masses of different salinity:
a) at surface; b) at 100 m; c) at 300 m; d) at 500 m.

$\geqq 35{\cdot}3\,^0/_{00}$ = Atlantic waters
$\leqq 34{\cdot}9\,^0/_{00}$ = Norwegian Sea waters
$35{\cdot}1\,^0/_{00}$ = waters of equal admixture (1:1) of Oceanic and Norwegian Sea types.

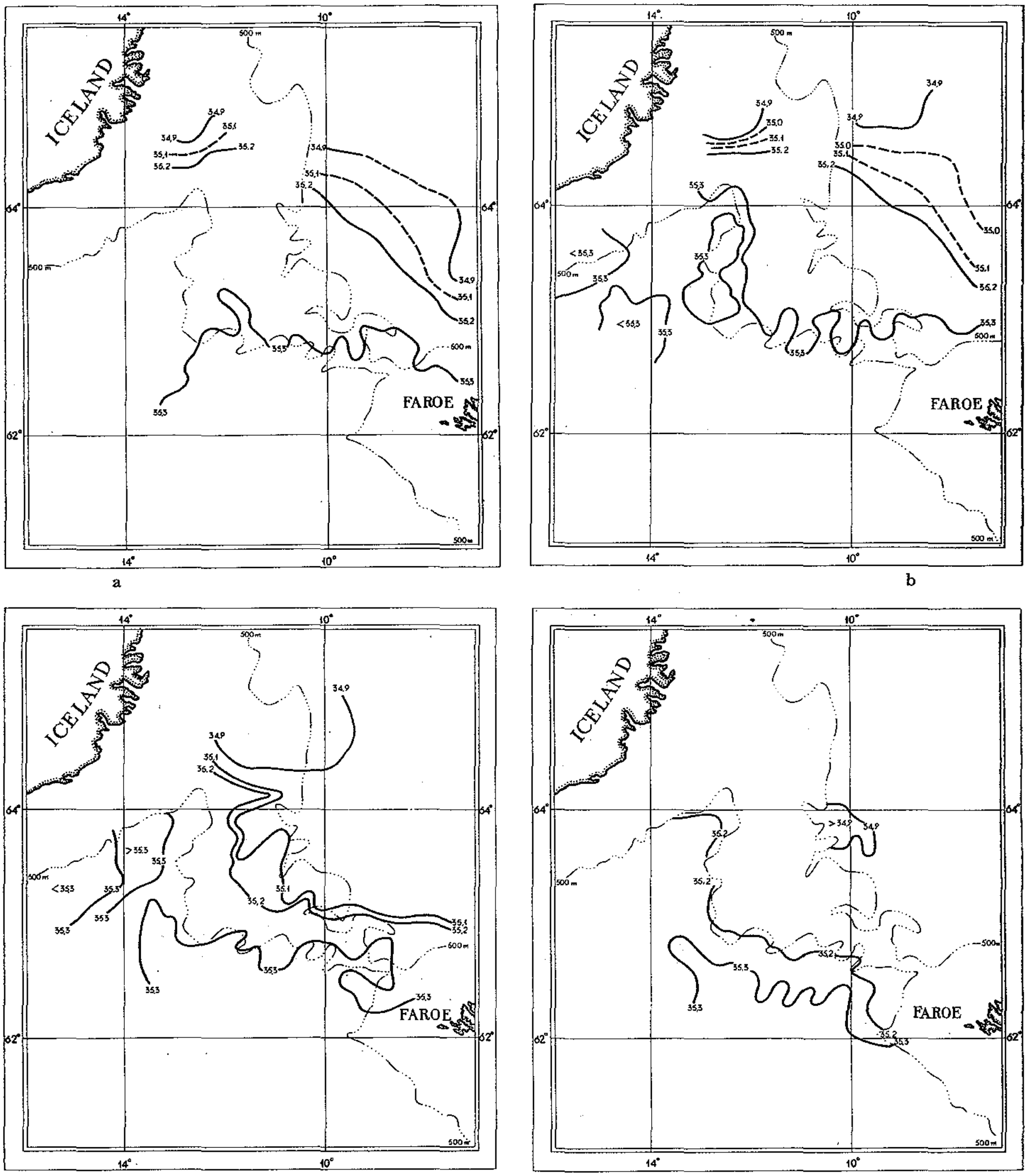
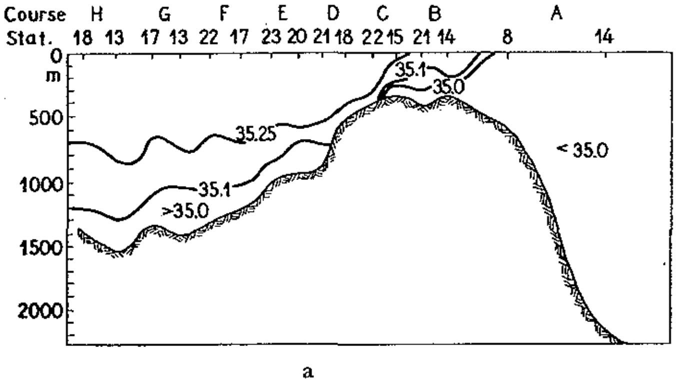


Figure 7:13. Third Survey. Distribution of water masses of different salinity:
a) at surface; b) at 100 m; c) at 300 m; d) at 500 m.
$\geqq$ 35·3 ‰ = Atlantic waters
$\leqq$ 34·9 ‰ = Norwegian Sea waters
35·1 ‰ = waters of equal admixture (1:1)
of Oceanic and Norwegian Sea types.



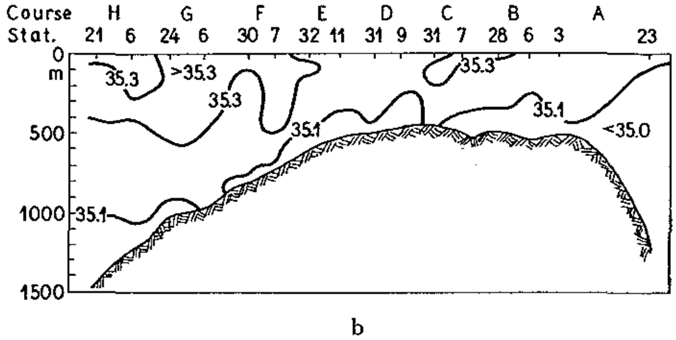


Figure 7 :14. Distribution of salinities on sections transverse to the Ridge: H – A courses. (a) Z section (b) V section.

of silicium-molybdenum complex. Determination of phosphates was carried out according to a modern variant of the well-known method of Denigès-Atkins, using comparison standards made of seawater. Aboard R. V. "Perseus" experiments were carried out on the assessment of biochemical oxygen consumption in natural samples of seawater in four main layers down to 500 metres. Incubation of the samples was carried out in a water thermostat. On additional water samples collected from R. V. "Perseus II" analyses were made under laboratory conditions to determine the concentration of organically combined phosphorus and nitrogen, employing the method of combustion with sulphuric acid for mineralization of dissolved organic and suspended matter. To get precise results of the colorimetric determination of the quantities of phosphorus – nitrogen and ammonia-nitrogen in treated samples of seawater, comparison standards of seawater treated in a similar way and previously standardized were used. Existing hydrochemical data characterize the water masses in the Faroe-Iceland area coming from either side of the Ridge: from the Norwegian Sea on the one hand and the Atlantic Ocean on the other. The properties of the mixed waters in the area of the underwater ridge then help to analyse questions of water exchange in the shallower parts of the region investigated. The area between the two aquatic reservoirs. Proceeding from already known systems of hydrodynamic processes and the relative volumes of the water masses adjacent to the Ridge, one should consider (as a number of investigations have shown) the dynamic of water masses of the North Atlantic as a primary impulse of the water exchange with the Norwegian Sea. Hydrochemical data collected during the expedition clearly show the existence of an intensive water head from the Atlantic Ocean in the area of the Ridge (Figures 7 :13 and 7 :14).

In the long run this leads to the formation of an oppositely-directed head of water masses from the side of the Norwegian Sea. The main water exchange of the Arctic Ocean occurs in a watershed of the Atlantic and partly in the Faroes-Icelandic area. The two-way water exchange through a section of this strait is only a little more than $0{\cdot}7\,^0/_0$ of the value of the water exchange of the whole Norwegian-Greenlandic Basin, which allowed Mosby (1962) to disregard it while estimating water balance. However, the intensity of the water exchange through this section between the Atlantic and the Norwegian Sea is equivalent to the average intensity of the water exchange of the whole Norwegian-Greenlandic Basin in all its outside sections and depths and is about 2×10^3 km^3/km^2 per year in two-way exchange.

Waters of Atlantic origin with salinity from $35{\cdot}00\,^0/_{00}$ to over $35{\cdot}30\,^0/_{00}$ move toward the north, i.e. over the

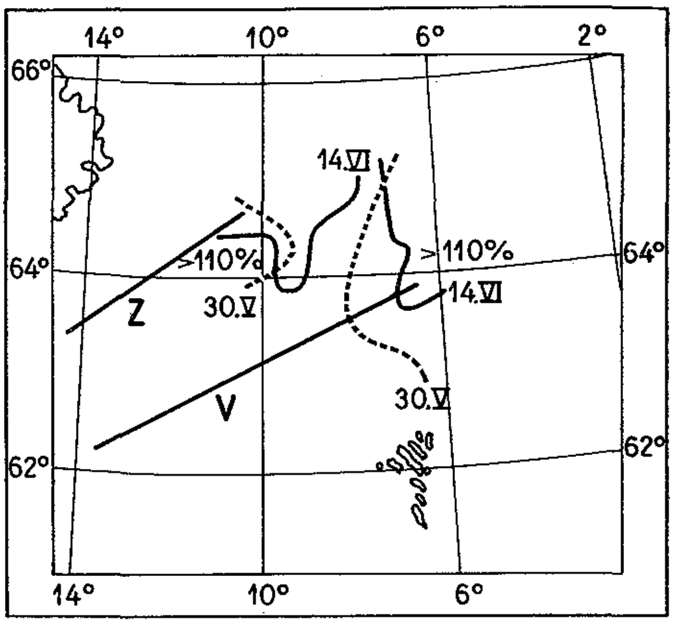
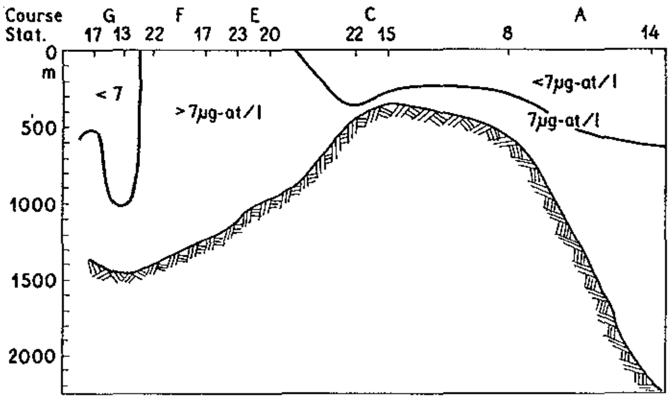
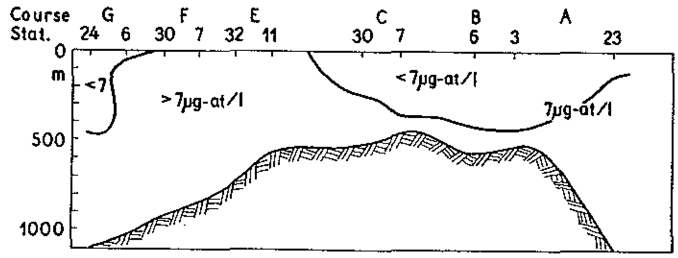


Figure 7 :15. Displacement of water layer (for the period from the first to the third surveys) oversaturated with oxygen and showing the directions of the Z and V sections.



a



b

Figure 7:16. Distribution of silicium on Z and V sections transverse to the Ridge: G – A courses. (a) Z section (b) V section.

"summit" of the Ridge, as delineated on the figures accompanying this paper. If we take the salinity of Northeastern Atlantic waters as 35·3 ‰ and above, then one can see that the diluting effect of waters coming from the Norwegian Sea with salinity of 34·9 ‰ and less, occurs mainly on the northern slope and along the middle line of the Iceland-Faroe Ridge. Only a few data show that 50 % diluted waters penetrate south of the summit of the Ridge. The salinity of these equally mixed oceanic and northern waters is 35·1 ‰ (50 % of water with salinity of 35·3 ‰ and 50 % of water with salinity of 34·9 ‰). With 25 per cent of Atlantic water the salinity of the mixed water is 35·0 ‰, and with 10 per cent Atlantic water the salinity of the mixed water is about 34·94 ‰.

Waters of this salinity in the uppermost 500-metre water layer cross the Ridge towards the Norwegian Sea.

Hence, it can be deduced that water exchange between the Atlantic and the Norwegian Sea through the Iceland-Faroe Ridge area takes place with intensive water mixing.

Taking into account that the volume of the water mass over the Ridge is approximately 30,000 km^3, the intensity of the water exchange in this area (~ 30 km^3 per hour) is 0·1 per cent per hour.

Such intensity of water exchange means the renewal of the whole water mass over the Ridge between eight and nine times in the course of a year at speeds expressed in multiples of one-tenth of a knot.

$$\left(\frac{30\ \text{km}^3\ \text{per hour}}{125\ \text{sq. km}} = 0{\cdot}24\ \text{km per hour}\right)$$

Collected during a number of voyages, mainly by the research vessels "Anton Dohrn" and "Perseus II", data on the distribution of phosphates showed that water masses to the south of the Ridge contained more phosphates in all layers as compared with those lying to the north.

Data on the content and distribution of dissolved silicium point to a difference between the content of silicium in waters of Atlantic origin and those of the Norwegian Sea. At the same time physico-chemical conditions of dissolution of scarcely soluble compounds

Table 7:2

Content of phospate-phosphorus (in µg-at./l) in the waters of the Iceland-Faroe Ridge, June 1960

Salinity	Course G		Course A	
35·25 ‰	0–100 m	0·94	0–50 m	0·50
	100–500 m	1·16	100–300 m	0·81
35·15–35·25 ‰	–	–	0– 50 m	0·48
	–	–	100– 200 m	0·76
	700– 800 m	1·29	–	
35·05–35·15 ‰	–	–	200– 300 m	0·77
	1000–1500 m	1·23	–	–
34·9 –35·05 ‰	–	–	0– 25 m	0·53
	–	–	100– 500 m	0·85
	1100–1600 m	1·29	500–1500 m	0·97
34·9 ‰	–	–	0– 25 m	0·42
	–	–	50– 300 m	0·77

Table 7:3
The content of silicium (in μg-at./l) in waters of the Iceland-Faroe Ridge, June 1960

	Course G		Course F		Course E				Course D		Course B				Course A		
Salinity	Over depth of the Atlantic		Over the southern slope		Over the southern slope		Over the Ridge		Over the Ridge		Over the Ridge		Over the northern slope		Over the northern slope		Over de of the N wegian S
‰	m		m		m		m		m		m		m		m		m
35·25	0–50	3·6	–	–	–	–	–	–	0–50	4·6	–	–	–	–	0–50	4·6	0–50
	100–800	6·4	400	16·8	300	10·4	300	11·2	100–400	6·4	–	–	–	–	50–300	6·0	50–100
35·15–	–	–	–	–	–	–	–	–	0–50	4·3	–	–	–	–	–	–	0–50
35·25	700–1000	7·4	400	17·4	–	–	–	–	50–500	6·8	–	–	300	5·4	50–300	6·05	100–300
35·0 –	–	–	–	–	–	–	–	–	0–50	5·7	–	–	–	–	–	–	0
35·15	800–1600	9·3	900–1200	19·9	600	11·8	–	–	50–400	6·8	–	–	–	–	100–300	6·6	100–300
34·9–	–	–	–	–	–	–	–	–	–	–	25–100	5·7	–	–	–	–	0–50
35·0	–	–	700–900	18·8	600	11·0	500	11·4	300–500	7·5	–	–	300–500	7·5	100–500	6·6	–
34·9	–	–	–	–	–	–	–	–	–	–	25–100	5·2	–	–	–	–	0–50
	–	–	–	–	–	–	–	–	–	–	100–400	6·0	–	–	–	–	50–300

of silicum influence the content of silicum in the seawaters investigated to a far greater extent than a change in concentration due to mixture of various water masses. Data obtained from the research vessels "Perseus II" and "Johan Hjort" show the silicium content of the Norwegian Sea waters in June, 1960. Data collected by "Anton Dohrn" and "María Júlía" on the southern slope of the Ridge testify to the content of silicium in waters of Atlantic origin; similar data were collected by the research vessel "Gauss" in the same waters, but over a shallow part of the Ridge.

It is known that in natural water scarcely soluble compounds of silicium are subject to the influence (apart from other factors) of an active reaction of the aquatic environment which regulates a rate of solubility of these compounds. During the expedition, data on this active reaction were not obtained, but some information earlier collected on this subject clarifies the question of the distribution of silicium in these waters.

Saturation of seawaters with compounds of dissolved silicium acid in deep waters is higher than that in surface waters.

Table 7:4
Active reaction of seawater

		pH	
Photic layer, southern area of Norwegian Sea ..	0– 50 m	8·20–8·41	Δ = 0·21
Lower layer	100–500 m	7·95–8·13	Δ = 0·18
Deep water layers	500 m	7·60–8·07	Δ = 0·47

As the pH value diminishes, the limits of solubility of the less insoluble magnesium and calcium salts of monosilicate expand.

From the research vessel "Perseus II" water samples were collected which were later analysed for organic compounds of phosphorus and nitrogen. While comparing the values obtained with those that had earlier been worked for an area of shallow water over the Ridge and for an area which was close to Iceland, it was found that the former were characterized by a poorer content of nitrogen, which pointed to the availability of a larger part of a relatively younger organic matter in the waters of the Norwegian Sea:

Data on the oxygen content in the photic layer (June 1960) show that the most intensive formation of phytoplankton tock place in waters of the Norwegian Sea which were enriched by Atlantic waters. Photosynthesis in the upper layer of water went on intensively and provided for oversaturation in oxygen by 8–10 to above 20 per cent.

The above observations point to a great dynamism of the waters which was observed during the expedition.

It was noticed that the geographic disposition of the water layers in the zone through stations A1, A2, A3, etc. corresponded with the distribution of areas of most intensive photosynthesis. After two weeks, iso-oxygens of 110 % moved considerably from the A1, A2, A3 course toward the east (Figure 7:15).

The distribution of oxygen, phosphate and silicium point to an upheaval of deep waters into a shallow-water area (Figure 7:16).

Sharp fluctuations in the phosphate and silicium contents which occur within a few hours also point to a rapid displacement of the water column in the surface layer.

During the investigations of 1960, besides an elaborate programme of observations, determinations were made on board "Perseus" of the consumption of oxygen in seawater in the area A between Iceland

Table 7:5

Organic compounds of phosphorus and nitrogen (in μg-at./l)

Depth in metres	Waters of area A June 1960		Waters over summit of the Ridge		Waters closer to Southeastern Iceland	
	N	P	N	P	N	P
0–100 m	22·92	2·07	10·00	2·42	7·35	2·10
100–340 m	–	–	9·21	1·87	–	–
100–800 m	20·21	1·74	–	–	–	–

and Faroes. In the uppermost layer biochemical consumption of oxygen was on the average 0·025 mg O_2/l per day. In the photic layer biochemical consumption of oxygen was 0·053 mg O_2/l per day. On the 100-metres section the consumption was 0·056 mg O_2/l per day and in the 500-metre lower layer, 0·049 mg O_2/l per day.

The month of June during which observations of the biochemical consumption of oxygen were made, is one of the month of the vegetative period, when seawater contains much labile "fresh" organic matter which is subject to intensive dissociation. Indeed, according to materials collected during the International Geophysical Year, when observations were made in different seasons of the year, biochemical consumption of oxygen in the surface layers of the North Atlantic waters flowing through the Icelandic-Scandinavian watershed, was from 0·03 to 0·07 mg O_2/l per day and in lower layers (500 m) from 0·004 to 0·1 mg O_2/l per day. In the waters of the Norwegian Sea, biochemical consumption of oxygen in the surface layer varied from 0·04 to 0·12 mg O_2/l per day and in a lower layer (500 m) from 0·06 to 0·10 mg O_2/l per day.

The values of biochemical consumption of oxygen which were obtained in June 1960 enable us to calculate the most probable average value of oxygen consumption in these waters for the period of the expedition. The value in question was 0·75 mg/l (0·05 mg O_2/l per day for 15 days).

Data obtained on the oxygen content permit the inference that an upper photic layer (in the present case op to 50 metres of water column) is continuously enriched from the atmosphere due to photosynthesis. This keeps the oxygen content in the above layer at a level of 6·5 ml/l (June). At the same time, with such intensive consumption, the oxygen content of the lower layer of the water column can be kept unchanged only by horizontal and vertical mixing of the water layers. For the period from the first to the third surveys, an average reduction of the oxygen content of the lower layer (up to 500 metres) was only 0·06 ml/l. Due to such fluctuations the content of oxygen in deep waters was 0·08 and 0·12 ml/l. For this reason it can be supposed that, due to mixing, the intensity of aeration in the lower layer is $1^1/_2$ to 2 times greater than in deep waters. If the average concentration of oxygen in the photic layer is taken as 6·73 ml/l, and that in the lower layer as 6·43 ml/l, then we should find that the intensity of mixing of the photic layer with the lower one (which is required in order to keep the observed average oxygen content at the same level) is, per 15 days, from 10% to 15% of the volume of the water masses which take part in the mixing.

The above calculations were made according to the mixing formulae: –

$$\frac{A}{B} = \frac{\frac{c-b}{a-b}}{\frac{a-c}{a-b}} = \frac{c-b}{a-c}$$

where A and B are the amounts of the mixing water, a, b, c the concentration of components; $a > c > b$ points to the fact that vertical renewal of the water column of the lower layer (the layer from 100 to 500 metres) occurred twice or thrice, which, for oceanic reservoirs, is highly intensive mixing that is observed only at high latitudes in the ocean or in sea shallows.

Characterizing the oceanic and Norwegian Sea water layers on the basis of the average amount of molecular oxygen in them, one can determine also the distribution of the main water masses in the Faroe-Iceland area. In order to eliminate the influence of photosynthesis and atmospheric oxygen we examine

Table 7:6

Fluctuations in phosphate-phosphorus and silicium contents in the uppermost 0-25 metres layer through "Perseus" stations on each of the three surveys

Nos. of stations	Si (μg-at./l)			P (μg-at./l)		
	1st Survey	2nd Survey	3rd Survey	1st Survey	2nd Survey	3rd Survey
1	3·8	1·2	0	0·60	0·19	0
3	5·2	0	2·1	0·67	0·17	0·40
5	3·8	1·5	0	–	0·27	0·54
7	0	0	0	0	0·22	0·17
9	3·8	0	0	0·55	0·18	0
11	4·2	0	0	0·57	0·00	0·25
13	6·4	–	2·3	0·60	–	0·38

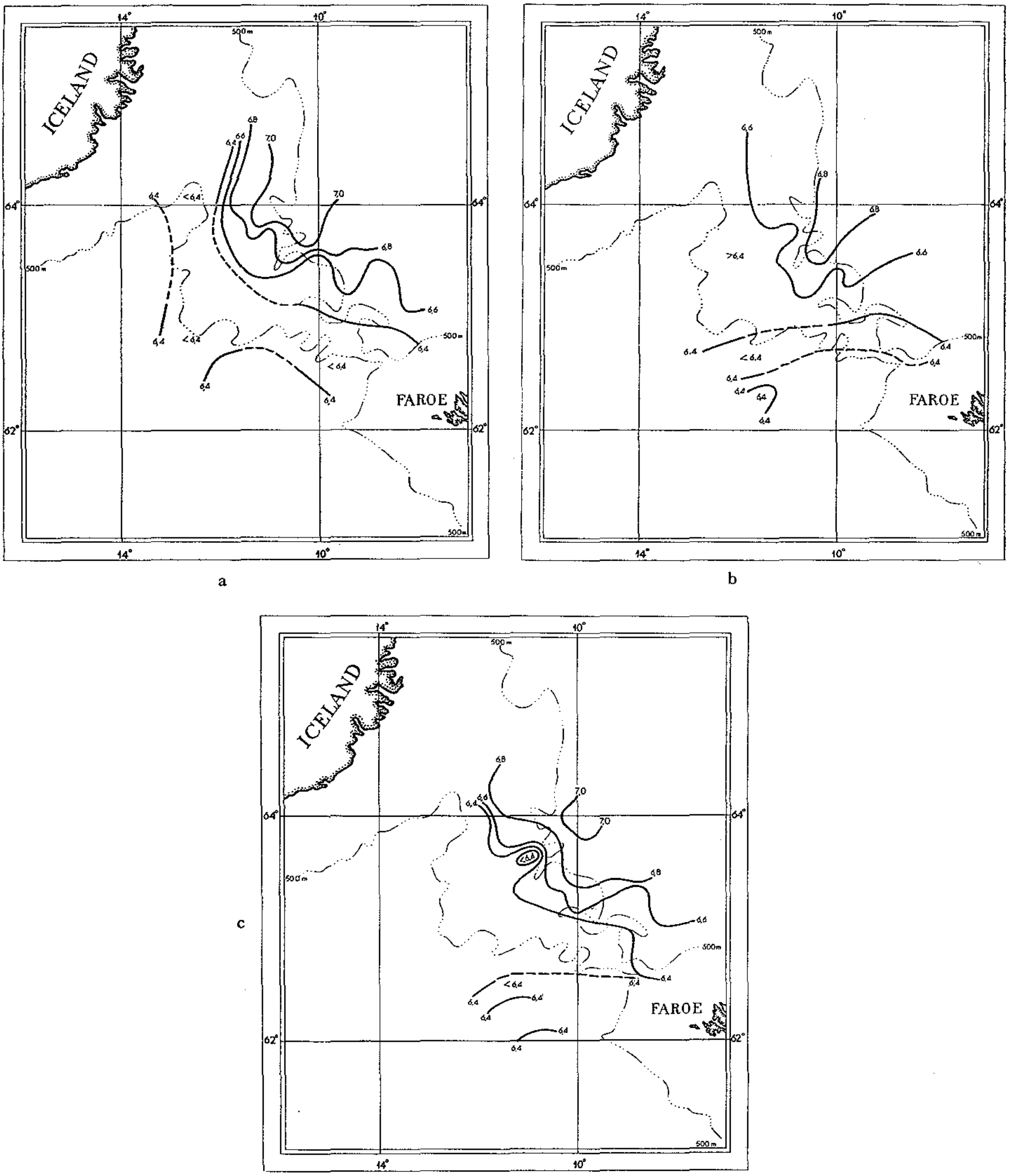


Figure 7:17. Distribution of oxygen (in ml O_2/l) in the 200–500 m layer of the Iceland-Faroe Ridge area (O_2 ml/l).
a) = 1st Survey
b) = 2nd Survey
c) = 3rd Survey
6·4 ml O_2/l = Atlantic waters
7·0 ml O_2/l = Norwegian Sea waters

waters lying below the photic layer to depths typical of the Ridge.

In the south, on the side of the Atlantic (below a selected water layer of 200–500 m) along the total length of the G_1 and G_2 sections, the water mass contains oxygen in amounts of less than 6·4 mg²/l, except at the stations Nos. 13 and 12, and 19 and 20, the two latter being situated in the same southwest area where reduction of oxygen takes place in depths below 600 metres.

In the 200–500 metre layer, excluding stations 7 and 8 of the G_1 section, there are a few values of less than 6·4 ml O_2/l. It was found during the first and the third surveys that the stations Nos. 7 and 8 in the centre of the section, are situated where waters with a small oxygen content move further towards the Iceland-Faroe Ridge. On the C_2, C_1 and B_2 sections, oxygen content of less than 6·4 ml/l was noted in the southeast and northwest parts of these sections lying mostly over the Ridge. In the central part of these sections the oxygen content was more than 6·6 ml/l to 7·0 ml/l and above. A detailed examination of the charts (Figure 7:17) of dissolved oxygen distribution in the Iceland-Faroe Ridge area shows that in the 200–500 metre layer, waters of Atlantic origin with oxygen content of 6·4 ml/l and less go from the south in the centre of the area and reach the Ridge from two sides, from near Iceland on the one hand and near the Faroes on the other. Over the Ridge, there occurs an intensive mixing of these waters, with waters coming from the Norwegian Sea which contain considerably more dissolved oxygen, namely, 7·0 ml/l and above.

Judging from the average amount of molecular oxygen in the two main water masses, an area of fifty per cent mixing lies also to the north of the Ridge.

CONCLUSIONS

An analysis of hydrochemical samples collected by the research vessels participating in the ICES "Overflow" Expedition in the shallow water area between Iceland and the Faroe Islands in June 1960, furnishes some characteristics of the water masses involved in the overflow problem, and permits the following summary of the results obtained.

The distribution of salinity observed in June 1960 in the region of the submarine ridge between Iceland and the Faroes and calculation of the rate of mixing of the two water masses characteristic of this area – the one of the Atlantic origin (salinity 35·5 ‰ and over), the other of Norwegian Sea origin (salinity 34·9 ‰ and below) confirms the phenomenon of water exchange in this region.

Water with salinity of 35·1 ‰ and above are those resulting from the mixing of the basic water masses in equal volumes (50 % + 50 %).

Distributions of salinity, oxygen, phosphates and silicates in the water column indicates an upheaval of waters from along the slope on the side of the Atlantic on to the shallow area of the Ridge. Distribution of the above components also confirms the existence of a head of currents of the Gulf Stream system upon the boundary zone of the Norwegian Sea and the Atlantic, and points to the important part this head plays in the water exchange of the area.

The water mass characteristics (salinity, oxygen, phosphates, silicium) show a difference in composition of the water masses which take part in the water exchange.

Waters of Atlantic origin contained (June, 1960) more phosphates than Norwegian Sea waters (29–36 μg P/l as against 16–25 μg P/l).

Additional hydrochemical data (R. V. "Perseus II") of the content of phosphorus and nitrogen of organic compounds of seawater, together with data collected in this area during the International Geophysical Year, showed that in waters from the Norwegian Sea side of the Ridge there is more organic matter than in those of the Atlantic.

A change in the location of areas of seawater oversaturated with oxygen (for the period from the first to the third surveys), revealed dynamism of the waters in the area investigated and their displacement to the east during this period.

Calculation of the intensity of oxygen consumption (data obtained from on board the research vessel "Perseus II") and penetration of oxygen into water layers due to hydrodynamical processes (taking into account the oxygen content actually observed in the water), showed that renewal of the water column in a less active layer was 10–15 per cent for the period of the observations, which conformed to twice – thrice mixture of this layer per year. Such intensity of mixture is observed in waters of sub-polar zones.

The foregoing investigations organized by the Hydrographic Committee of ICES, and conducted by a group of vessels in June 1960, showed advantages of method in that important results were obtained within a short period and without considerable expense incurred by the countries participating.

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CHAPTER 8 (I)

OBSERVATIONS OF THE DEPTH OF VISIBILITY, VERTICAL TEMPERATURE AND TURBIDITY RECORDINGS IN THE SEA AREA BETWEEN ICELAND AND THE FAROES DURING THE ICES ICELAND-FAROE RIDGE EXPEDITION, MAY-JUNE 1960

By

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During the above expedition observations of the depth of visibility were made aboard the vessels "Johan Hjort", "Gauss", "Ernest Holt", "María Júlía", "Helland-Hansen", and "Explorer". Besides this, synchronous vertical temperature and turbidity recordings were obtained on board "Gauss" in the Sections C_1 and C_2 (see Figure 0:1, p. 6) from the surface down to the bottom. This paper gives a summary of these measurements.

OBSERVATIONS OF THE DEPTH OF VISIBILITY

The depth at which a white disc disappears from sight in the sea is only a rough indicator of the absorption of daylight in seawater. Only mean values of a long series of observations can be used for scientific purposes (JOSEPH, 1952). We have therefore not compiled single observational values and their positions, but mean values. Table 8:1 gives an idea of the number (n) of the depths of visibility measured by the individual research vessels along the profiles (P) of Figure 0:1 of the Introduction (p. 6), their mean values ($\bar{s}$) and their scattering ($\pm \Delta s$).

The mean values of each profile are represented in the lower part of Figure 8:1.

These values vary between 7 and $8^1/_2$ m. This average is so to say an optical section perpendicular to the Iceland-Faroe Ridge ranging from SW to NE. The observations, moreover, were summarized in strips 20 nautical miles apart from each other and perpendicular to the Iceland-Faroe Ridge. The corresponding mean values are given in the right hand part of Table 8:1 and in the upper part of Figure 8:1. They represent a section parallel to the Iceland-Faroe Ridge, the distance from the shore of the Faroes in nautical miles serving as horizontal scale.

When averaging the observations, those of the vessel "Explorer" were left out as they were collected somewhat outside the central area of investigation and differ considerably from the other data.

The mean value derived from the other 302 obser-

Table 8:1

VESSEL	P	n	$\bar{s}$	$\pm \Delta s$	n	$\bar{s}$	nm	n	$\bar{s}$	$\pm \Delta s$
"Johan Hjort"	B_1	27	8·3	2·2	72	8·1	32	27	8·1	2·4
	B_2	45	8·0	2·0			48	30	8·1	2·1
"Gauss"	C_1	24	7·0	2·2	50	7·1	64	29	7·5	1·6
	C_2	26	7·1	1·9			81	27	7·7	1·8
"Ernest Holt"	D_1	16	8·2	1·4	33	7·7	99	33	8·3	1·6
	D_2	17	7·2	0·9			117	33	8·3	1·5
"María Júlía"	E_1	59	8·4	1·7	113	8·3	135	33	8·1	1·7
	E_2	54	8·2	1·3			153	32	7·5	1·3
"Helland-Hansen"	F_1	23	8·3	1·5	34	8·0	172	25	7·5	1·6
	F_2	11	7·3	1·0			192	21	8·2	1·9
"Explorer"	I_1	6	9·6	–	9	10·4	$\sum$	302	8	1·8
	I_2	3	12	–						

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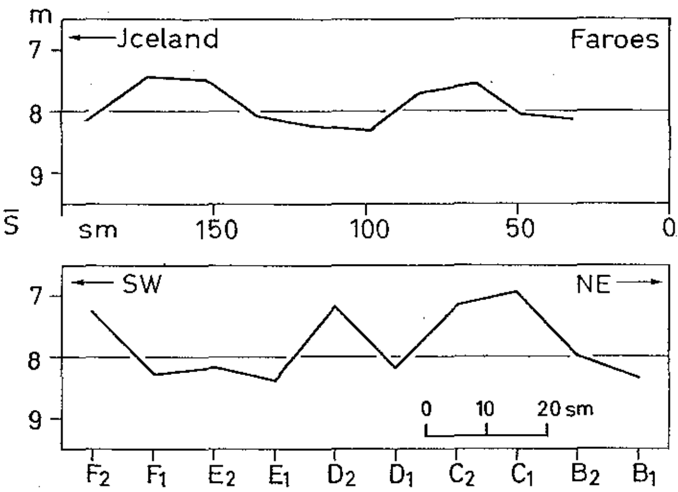

Figure 8 :1. Mean values of the depths of visibility.

vations is 8 m, its scattering $\pm$ 1·8 m. This depth of visibility corresponds to a vertical Extinction Coefficient of almost $0{\cdot}1\,m^{-1}$ in the decadic system and $0{\cdot}3\,m^{-1}$ referred to the basis e. The intensity of daylight in a 10 m thick surface layer can therefore be estimated in the period of observation by the relation:

$$\mathcal{J}\,(z) = \mathcal{J}_0\, e^{-0{\cdot}3z}$$

where z = depth in metres and $\mathcal{J}_0$ = intensity of daylight at the surface.

VERTICAL TEMPERATURE AND TURBIDITY RECORDINGS IN THE SECTIONS C_1 AND C_2

During the several C_1 and C_2 runnings 117 vertical temperature and turbidity records were obtained onboard "Gauss" from surface to bottom. A transparency

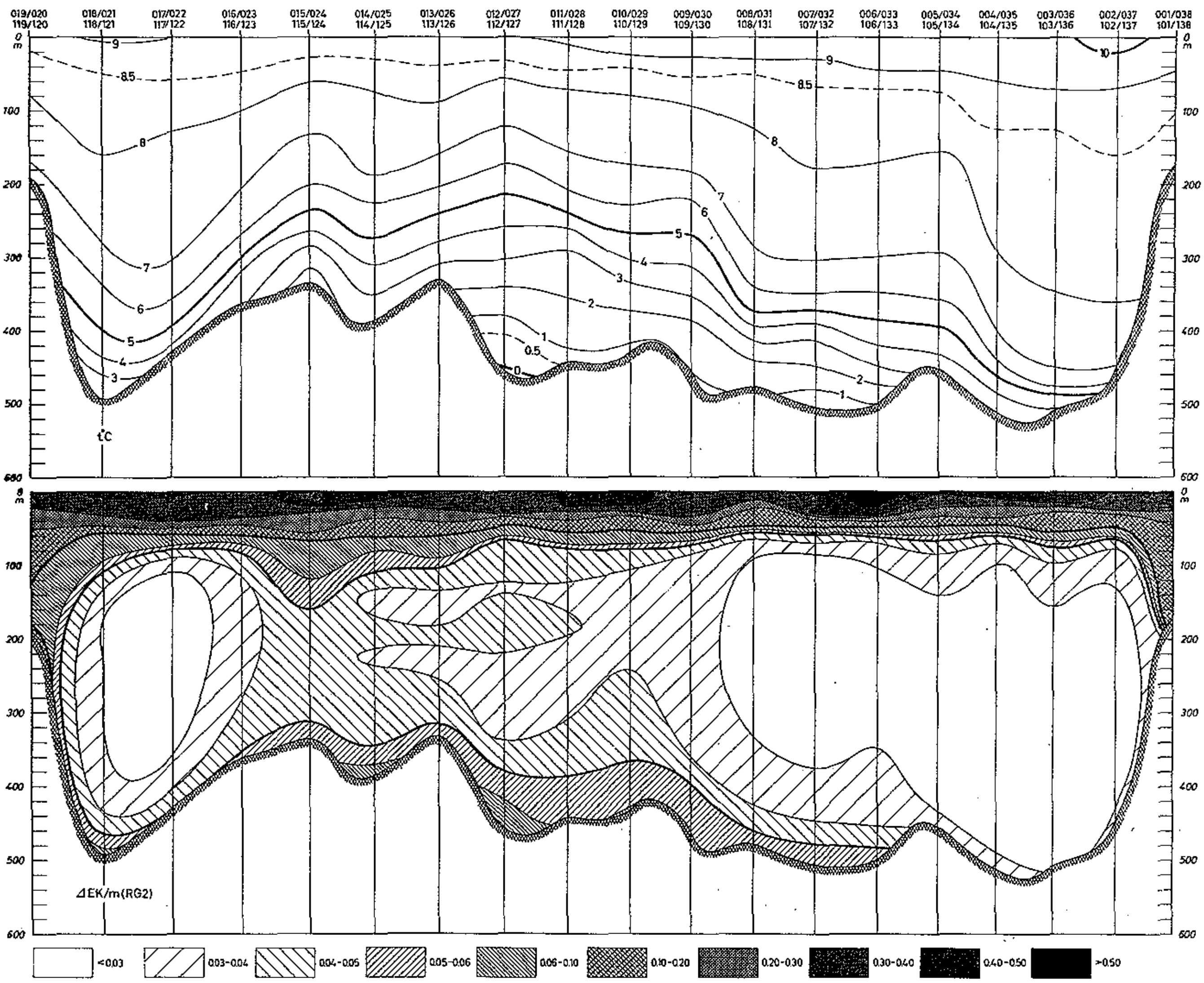

Figure 8:2. Mean temperature and turbidity distribution along the sections C_1 and C_2 derived from 117 vertical temperature and turbidity recordings.

measuring device with a resistance thermometer were used in these measurements. Device and method have earlier been described in detail (JOSEPH, 1959). We will thus repeat only the most important facts:

The transparency of the water was recorded over a horizontal distance of 2m in the red end of the spectrum (Schott filter R 62). The results were transformed by the formula

$$\Delta\,\mathrm{EK} = \frac{1}{2} \log \frac{J_0}{J}$$

to differences of the decadic Extinction Coefficients (Δ EK) of a 1m thick water layer (JOSEPH, 1955) and referred to the intensity of the purest water observed (J_0). The Δ EK values are a measure of the additional absorption by the organic matter (plankton) during the observations and probably also by inorganic matter near the bottom. Whether a quantitative connection exists between the presence of plankton and the Δ EK values, perhaps in form of linear relation, could not be ascertained as no plankton samples were taken.

The temperatures were measured by means of a resistance thermometer and recorded with the values of the turbidity during the veering of the instrument.

The temperature and Δ EK values of 117 stations were plotted on diagrams represented in Figure 8:5 (pp. 210–22). The upper abscissa gives the temperature scale, the lower one the Δ EK scale, and the ordinate the depth scale. Time and position are also given.

The cloud-like form in which plankton appears and the motion of the water caused by the tidal streams result in a strong scattering of the turbidity values, especially in the surface layer. Single records are therefore of little practical value. In order to get an idea of the mean conditions, the turbidity records, and for comparative purposes, also the corresponding temperature records, were first averaged station by station. Then the stations opposite to each other and 10 nautical miles apart in the sections C_1 and C_2 were summarized. This procedure seems to be particularly appropriate in view of the fact that the main direction of the tidal streams tends nearly perpendicular to the sections and also because the water masses are continuously moving to and fro between the sections.

Every 10m mean values were derived, once from the surface and once from the bottom. The procedure made it possible to point out special features of the turbidity and temperature conditions near the bottom, as for example the bottom turbidity, despite the fact that the depths of the summarized stations had been averaged. The curves averaged from the surface as well as from the bottom easily joined at medium depth.

The results are given in Figure 8:2.

The abscissa represents the averaged stations, the ordinate the depths. The vertical recordings are

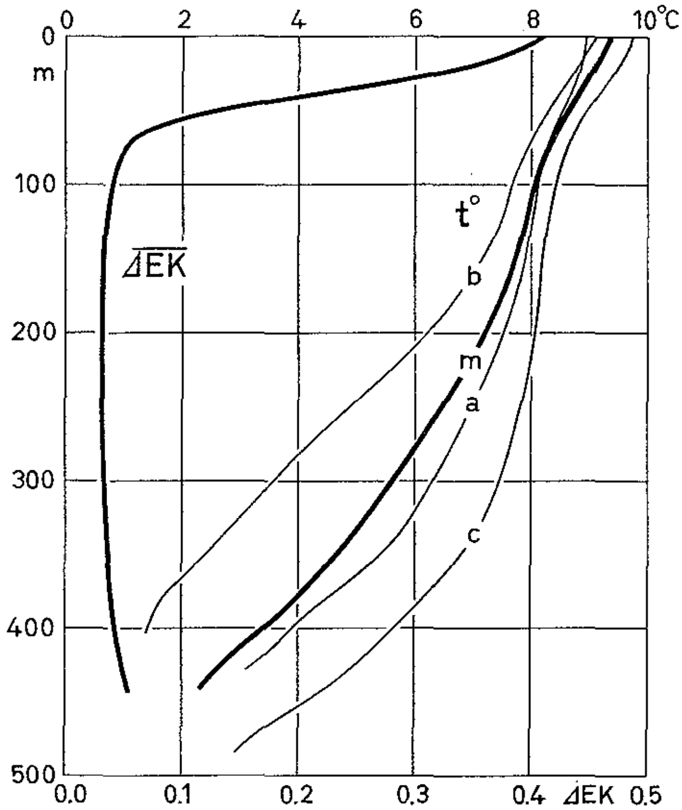

Figure 8:3. Mean vertical turbidity (ΔEK) and temperature distribution (m), mean temperature distribution in the western (a), the middle (b), and eastern part (c) of the sections C_1 and C_2.

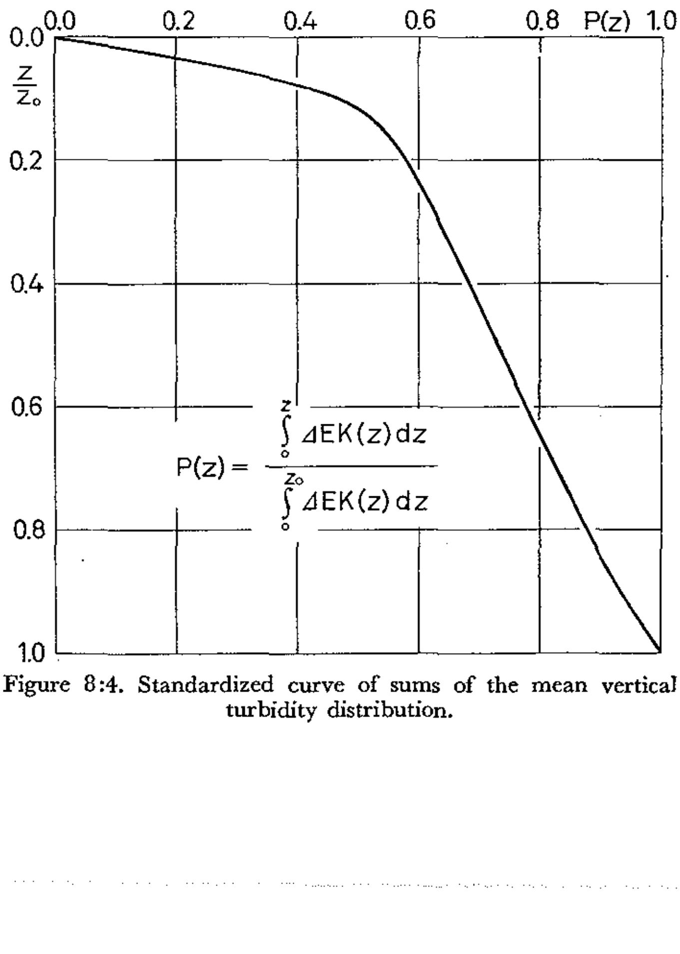

Figure 8:4. Standardized curve of sums of the mean vertical turbidity distribution.

represented by a straight line. The lower part of the figure shows the mean turbidity distribution along the section C. We have a 50–70 m thick plankton surface layer. Below this, bodies of pure water are distinctly outlined in the eastern and western part of the section, while a stronger stratification obviously prevailed in the middle part. The characteristic feature of this part is a stronger bottom turbidity to be seen also from the single recordings. We can assume that this is due to the tidal streams. The upper part of the figure represents the mean temperature distribution along the sections C_1 and C_2 as ascertained by the records obtained during the expedition. The coldest bottom water was traced at the stations C12 and C27. In order to underline the differences in the vertical temperature distribution, the recordings were once again split into the following groups:

(a) (western part): Stations 16–18 and 21–23
(b) (middle part) : 9–15 and 24–30
(c) (eastern part) : 2–8 and 31–37

Moreover, the mean vertical distribution at the stations 2–18 and 21–37, *i.e.* at all stations except the shallow continental shelf stations, was computed for the ΔEK and temperature values (m). The results are given in Figure 8:3.

They once again clearly demonstrate that the presence of plankton is restricted to the upper 50–70 m and that the purest water can be found at a depth of 200–300 m. In the middle part of the section the water is at all depths colder than in the western part and the still warmer eastern part. We have a mean temperature difference between surface and bottom of ca. 7°C. In Figure 8:4 the mean vertical turbidity distribution is given in the form of a curve of sums.

The ordinate gives the relation between the measured depth z and the water depth z_0, the abscissa the relation between the quantity of suspended matter down to the depth z and the total amount of suspended matter down to the bottom. This definition is, however, only true provided the amount of suspended matter can be given as approximately proportional to the ΔEK values. This way of representation has the advantage that vertical turbidity distributions of sea areas differing in depths and in the intensity of turbidity can be compared. The curve represents the standardized vertical turbidity distribution averaged from 68 vertical records obtained along the sections C_1 and C_2. Half of the suspended matter effective in increasing the absorption can be traced in the upper tenths of the total depth.

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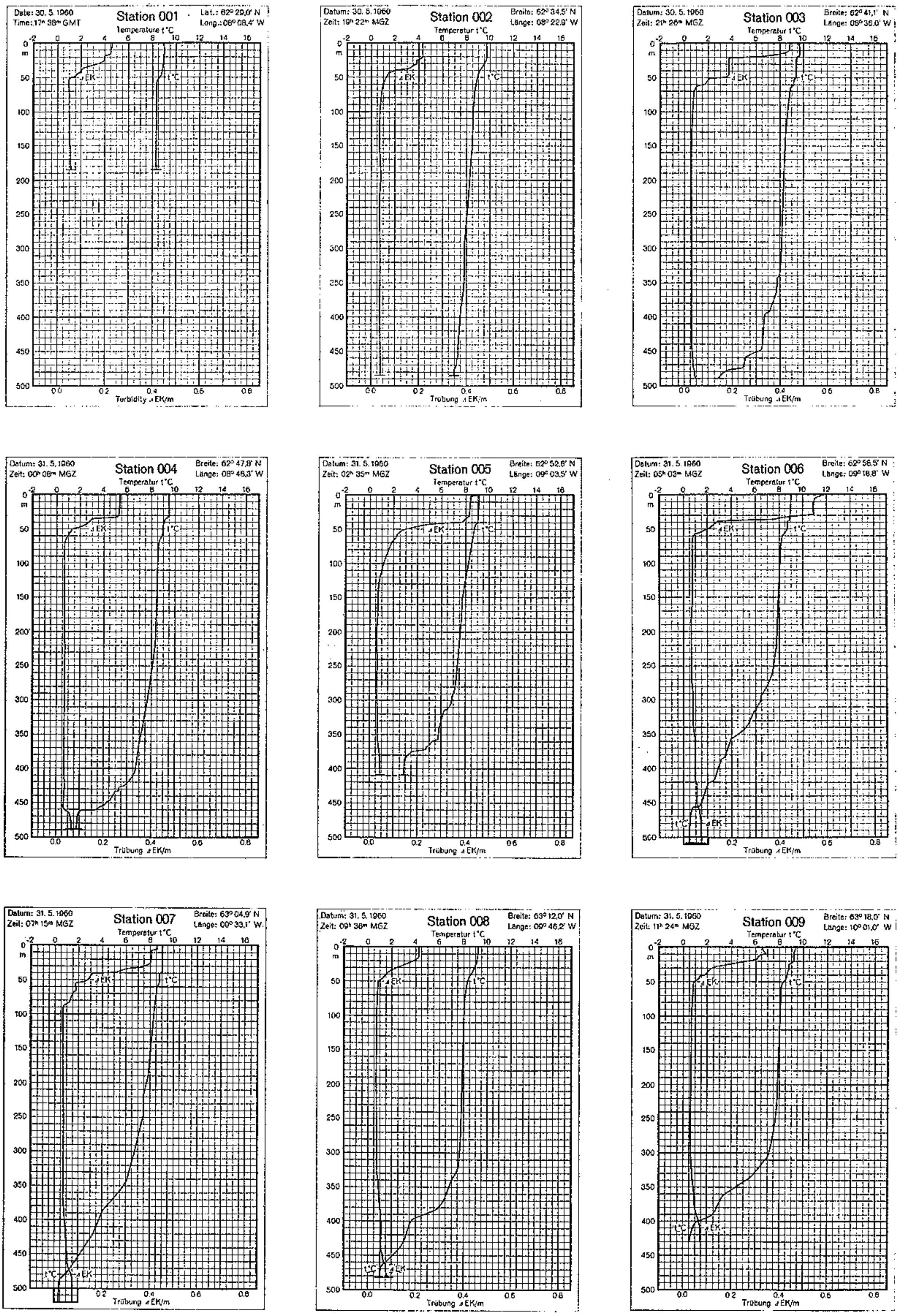

Figure 8:5. Vertical temperature (t° C) and turbidity (ΔEK) records on Course C, Stations 001–009. (cont.)

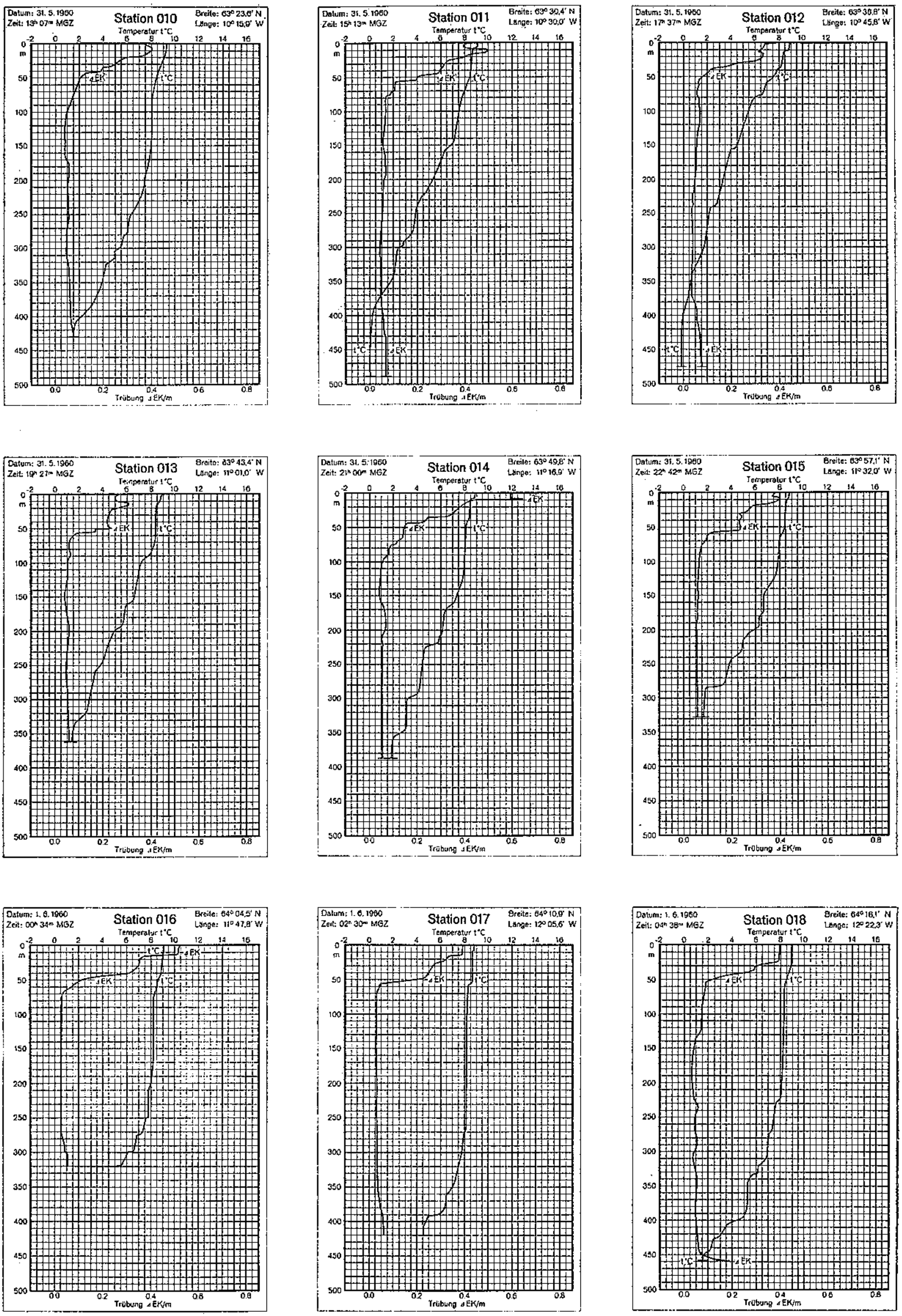

Figure 8:5 Vertical temperature (t° C) and turbidity (ΔEK) records on Course C, Stations 010–018. (cont.)

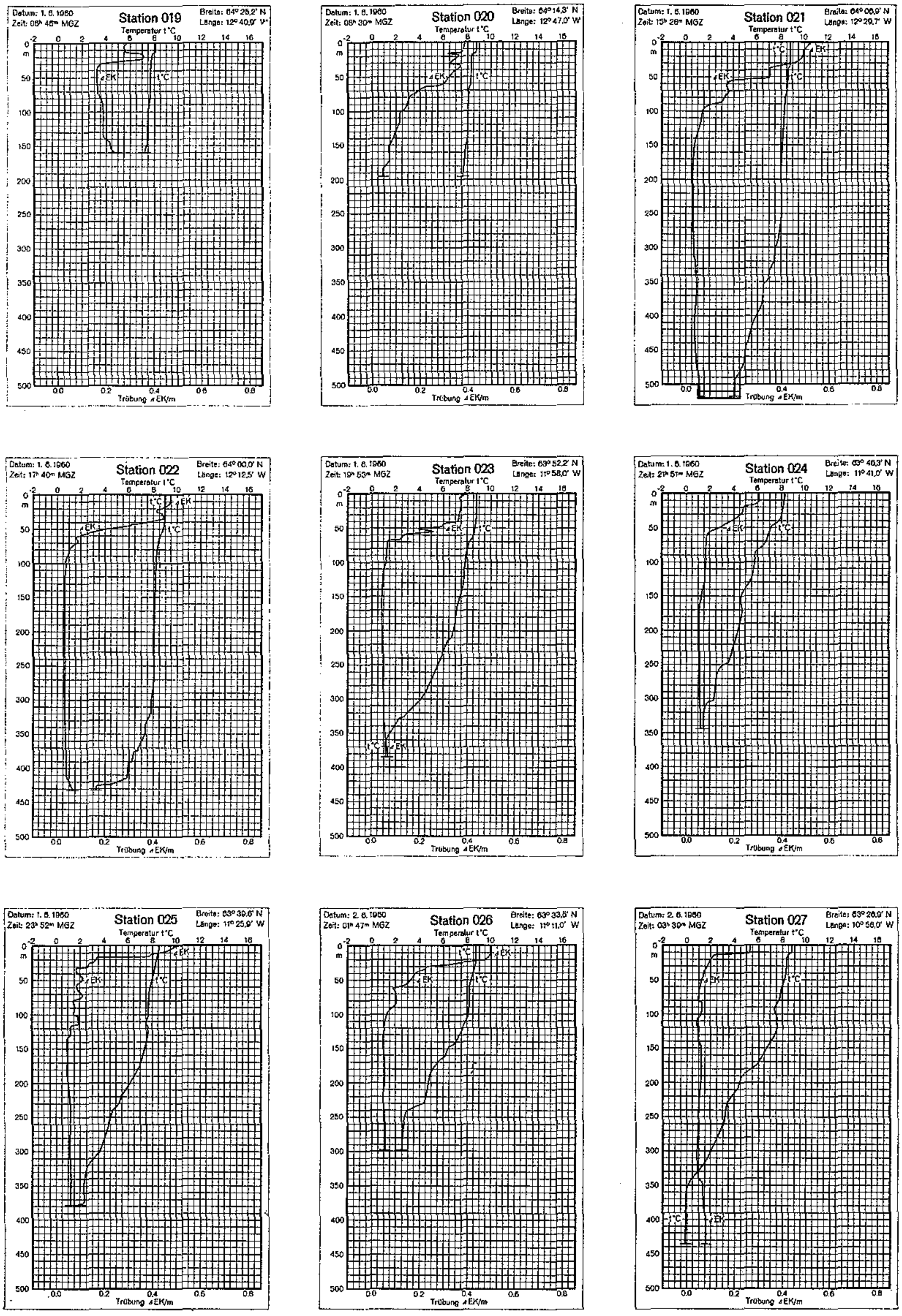

Figure 8:5. Vertical temperature (t° C) and turbidity (ΔEK) records on Course C, Stations 019–027. (cont.)

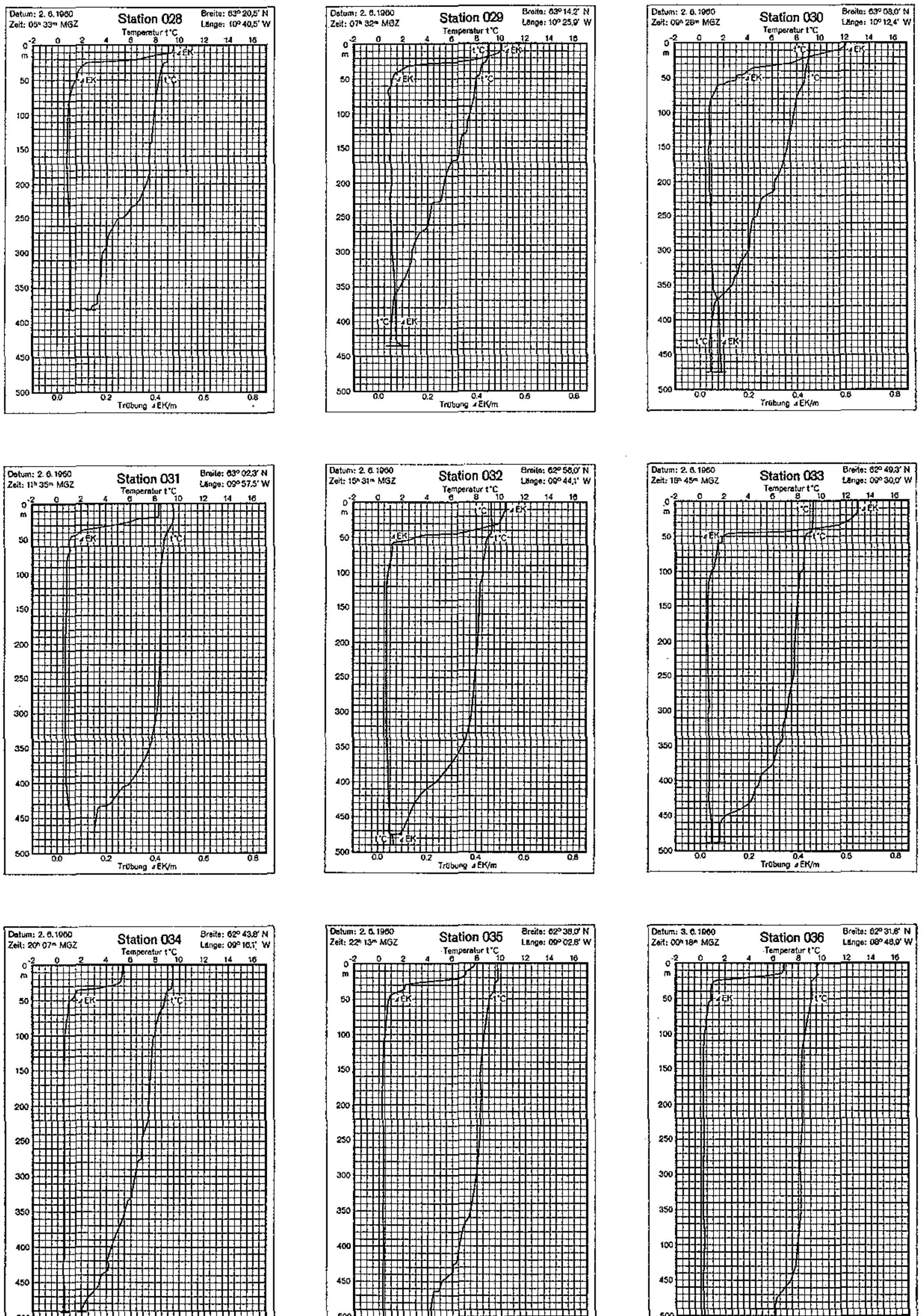

Figure 8:5. Vertical temperature (t° C) and turbidity (ΔEK) records on Course C, Stations 028–036. (cont.)

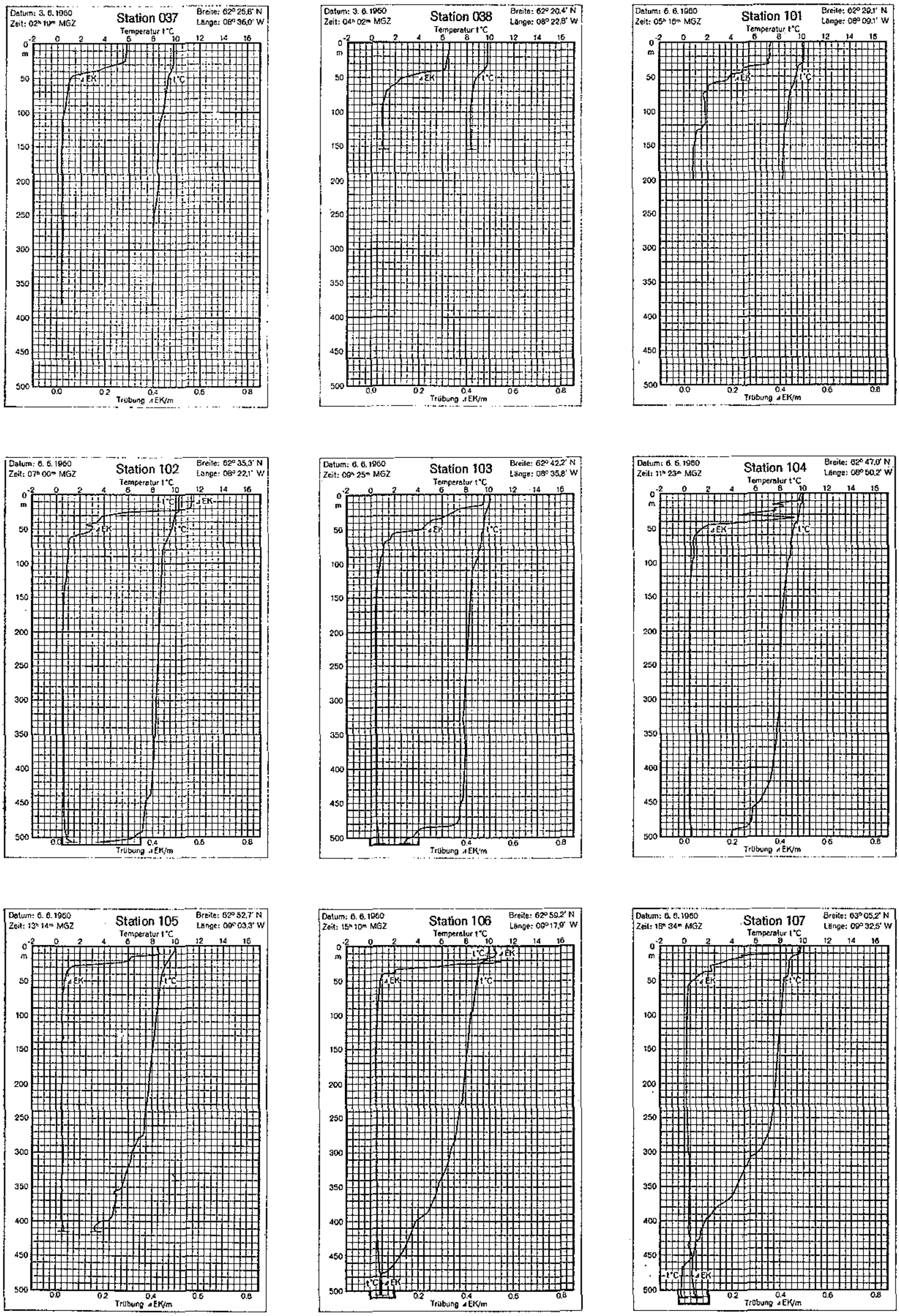

Figure 8:5. Vertical temperature (t° C) and turbidity (ΔEK) records on Course C, Stations 037–038 and 101–107. (cont.)

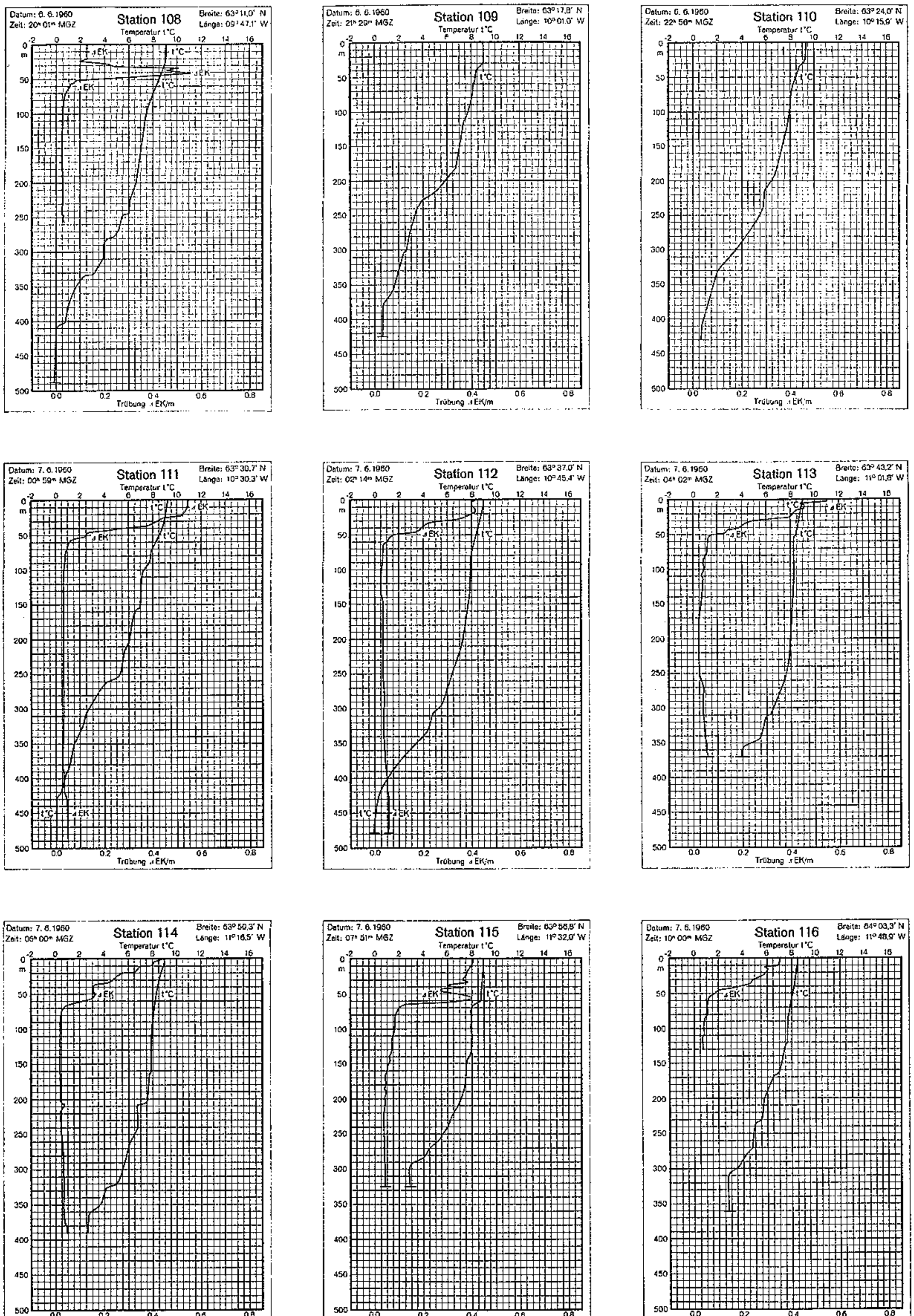

Figure 8:5. Vertical temperature (t° C) and turbidity (ΔEK) records on Course C, Stations 108–116. (cont.)

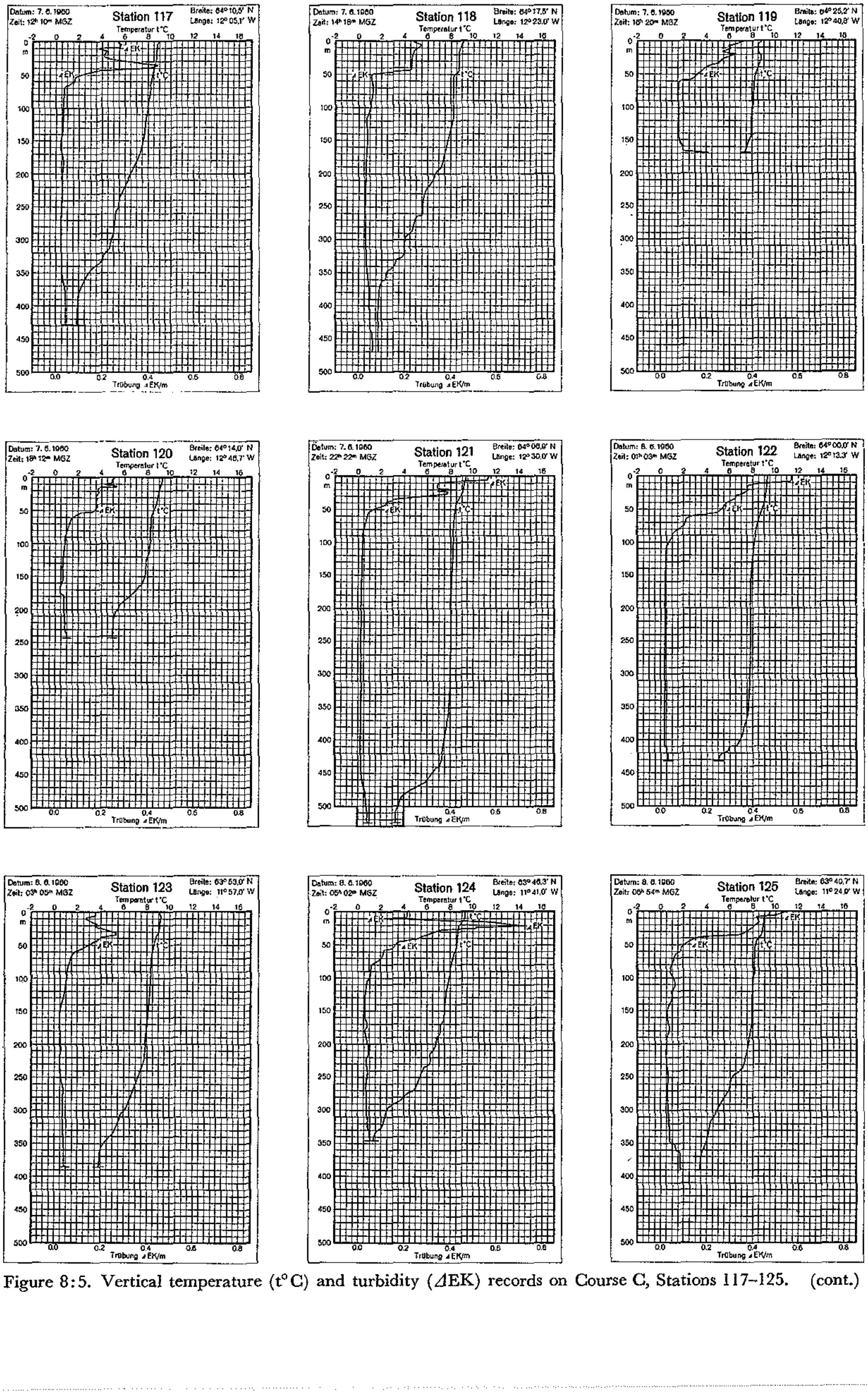

Figure 8:5. Vertical temperature (t°C) and turbidity (ΔEK) records on Course C, Stations 117–125. (cont.)

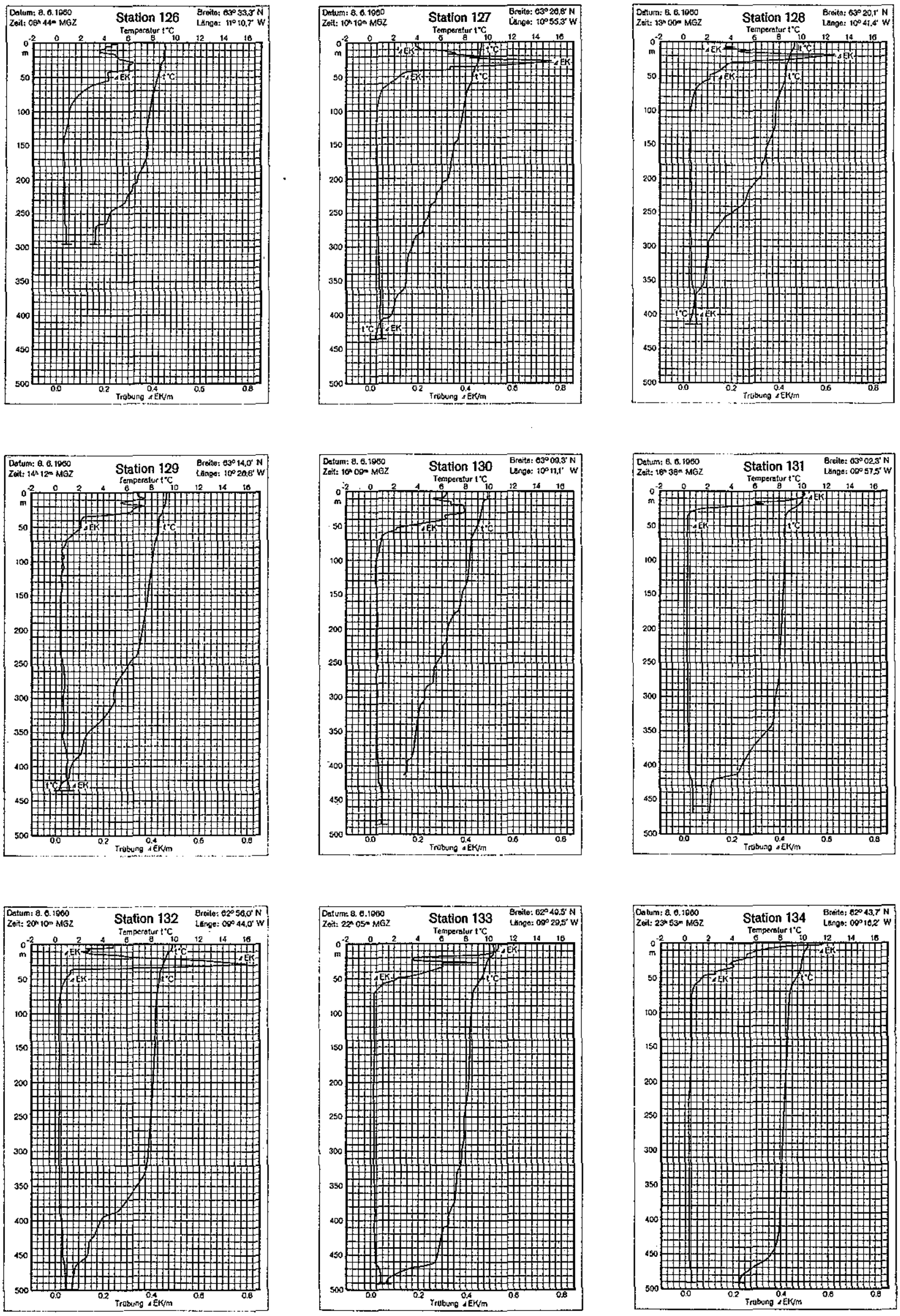

Figure 8:5. Vertical temperature (t° C) and turbidity (ΔEK) records on Course C, Stations 126–134. (cont.)

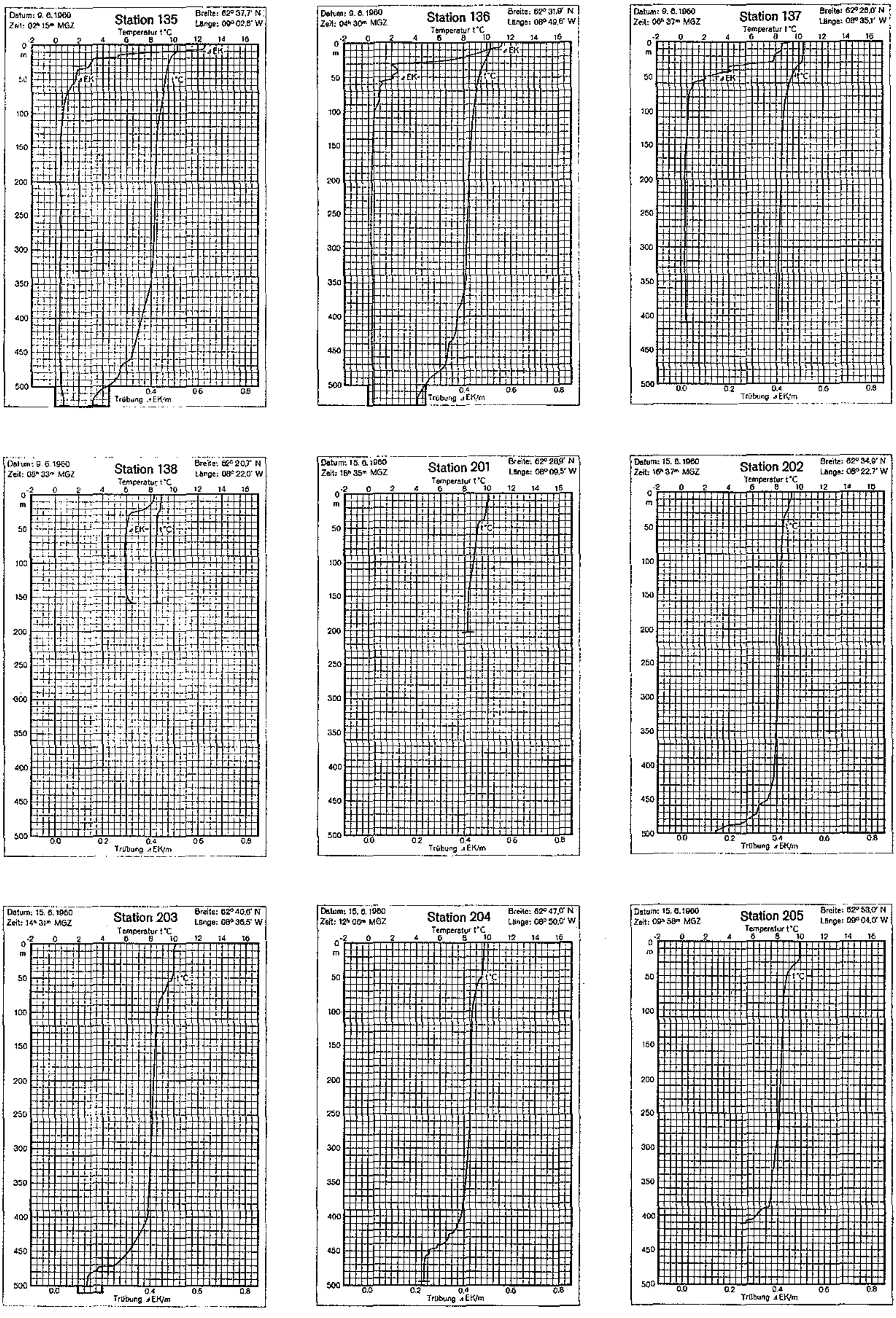

Figure 8:5. Vertical temperature (t° C) and turbidity (ΔEK) records on Course C, Stations 135–138 and 201–205. (cont.)

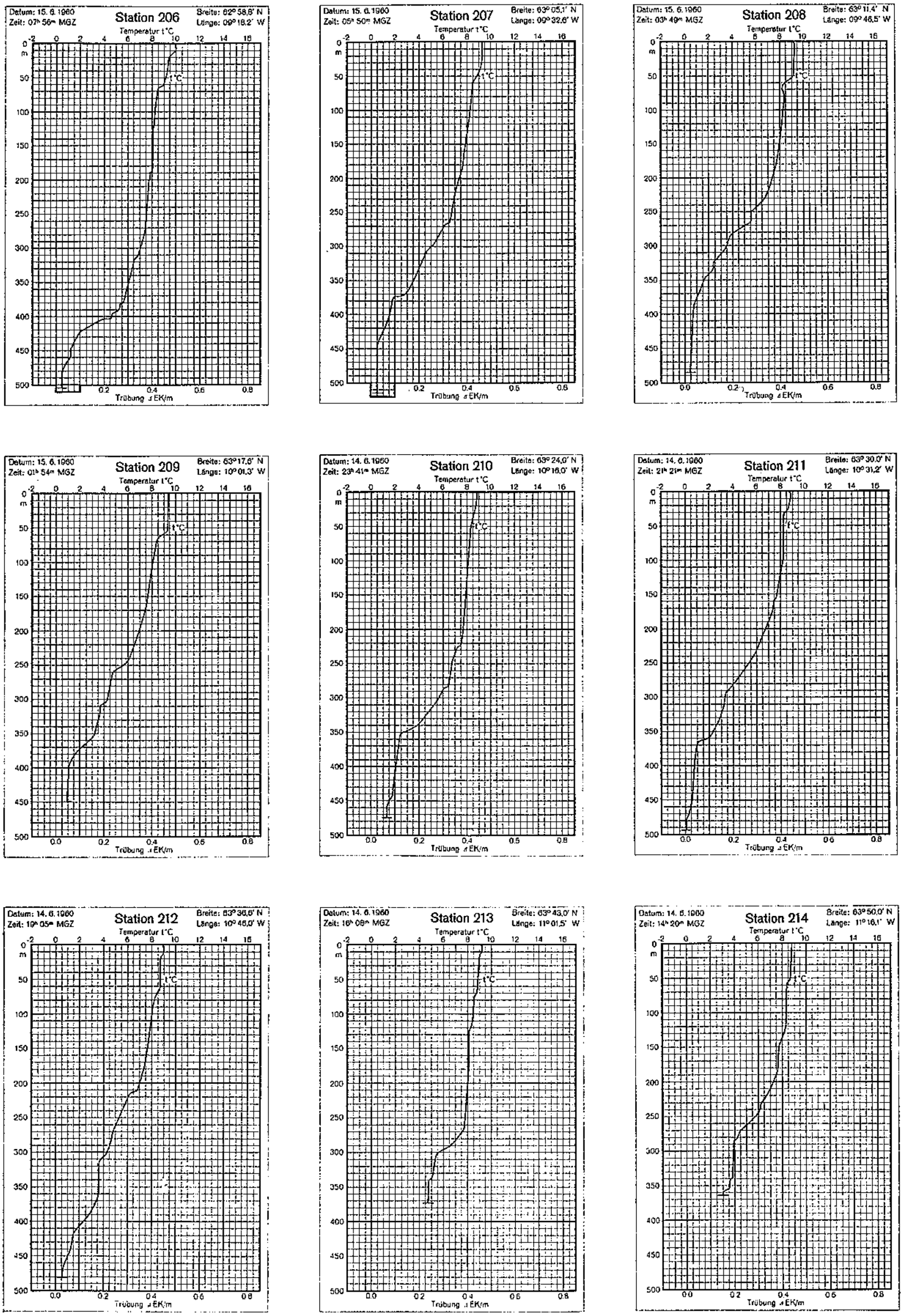

Figure 8:5. Vertical temperature (t° C) records on Course C, Stations 206–214. (cont.)

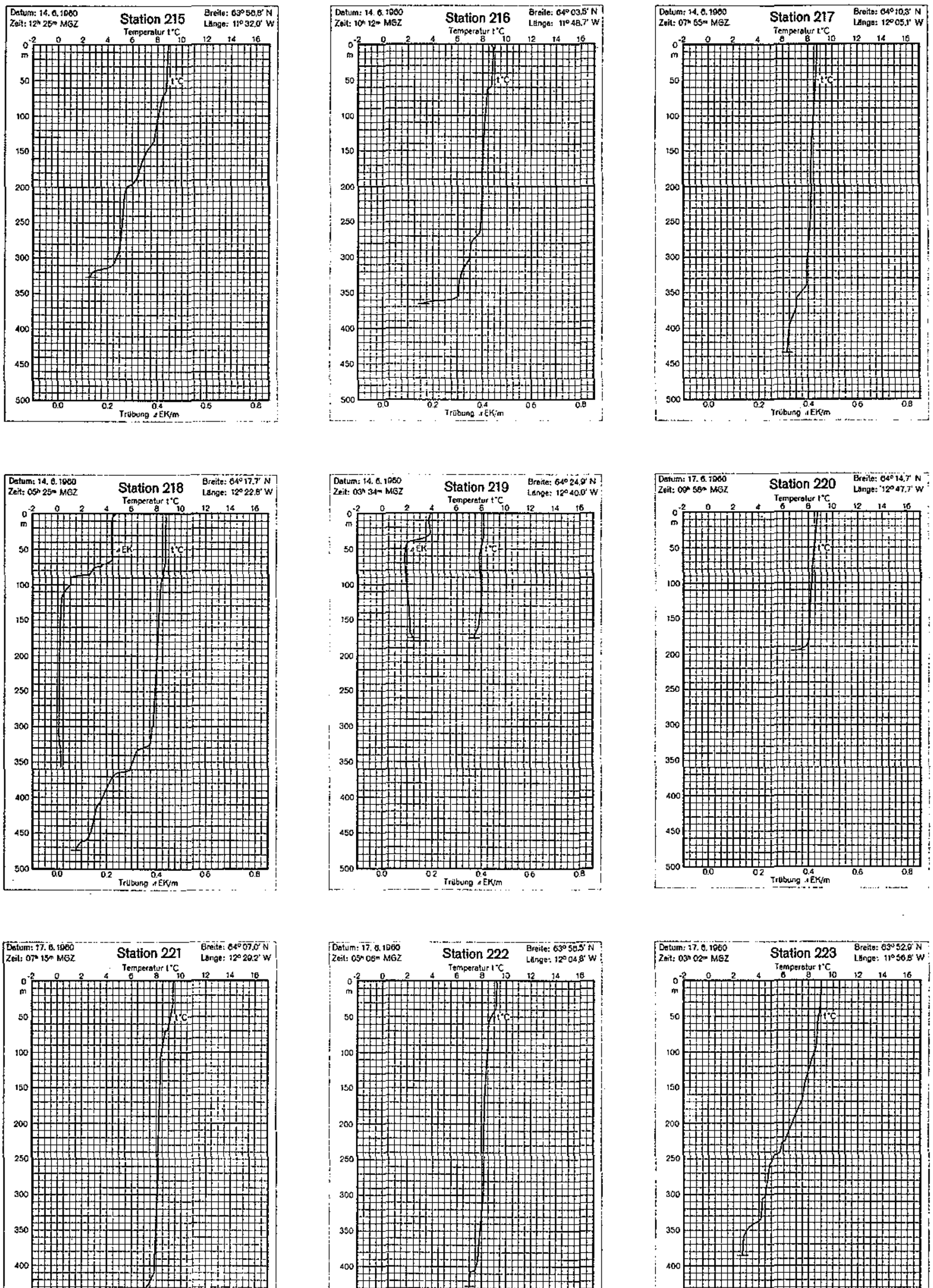

Figure 8:5. Vertical temperature (t° C) and turbidity (ΔEK) records on Course C, Stations 215–223. (cont.)

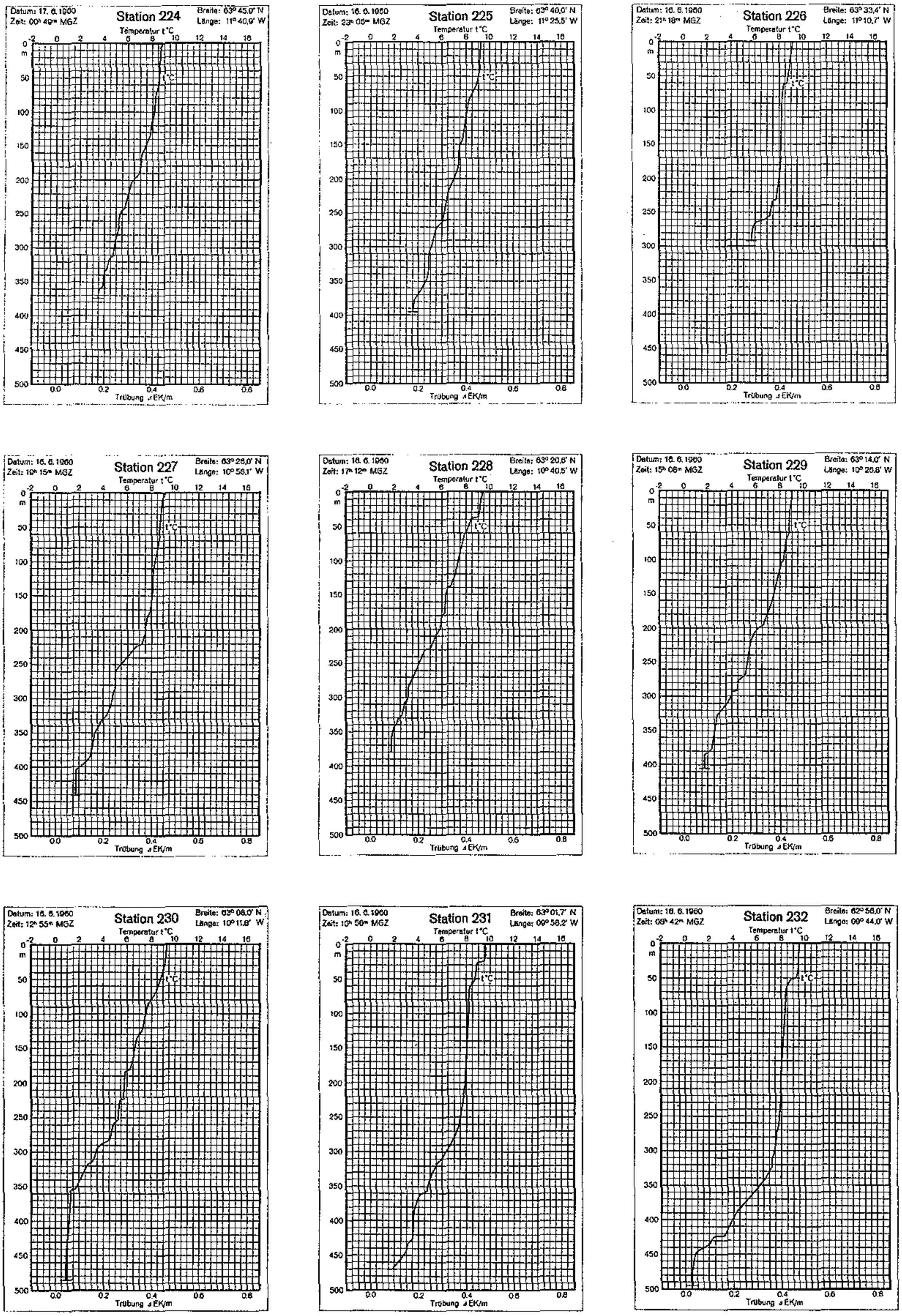

Figure 8:5. Vertical temperature (t° C) records on Course C, Stations 224–232. (cont.)

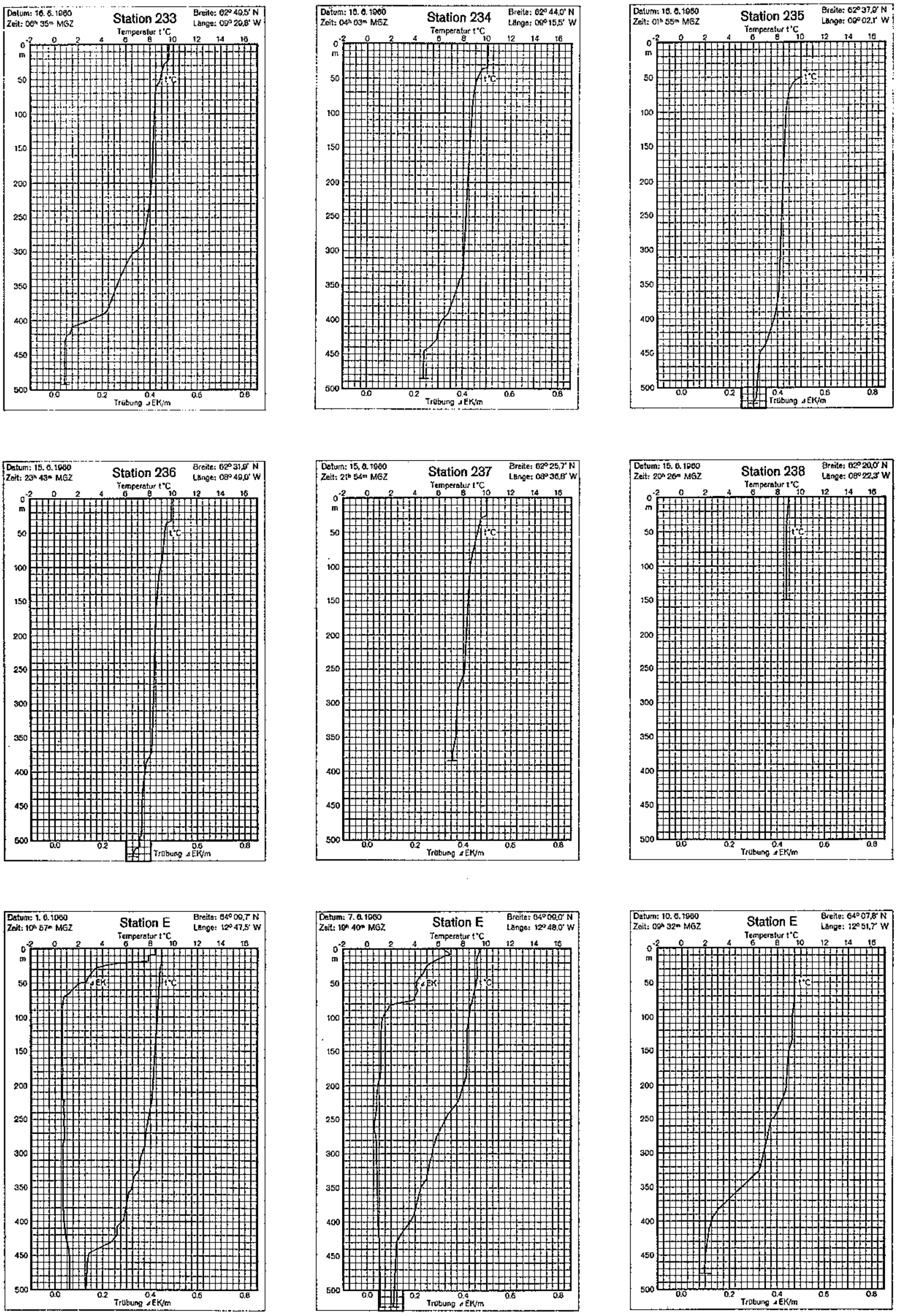

Figure 8:5. Vertical temperature (t° C) and turbidity (ΔEK) records on Course C, Stations 233–238 and on Diamond Station E.

CHAPTER 8 (II)
TEMPERATURE-DEPTH RECORDS BY THE RESEARCH VESSEL "ERNEST HOLT"

By

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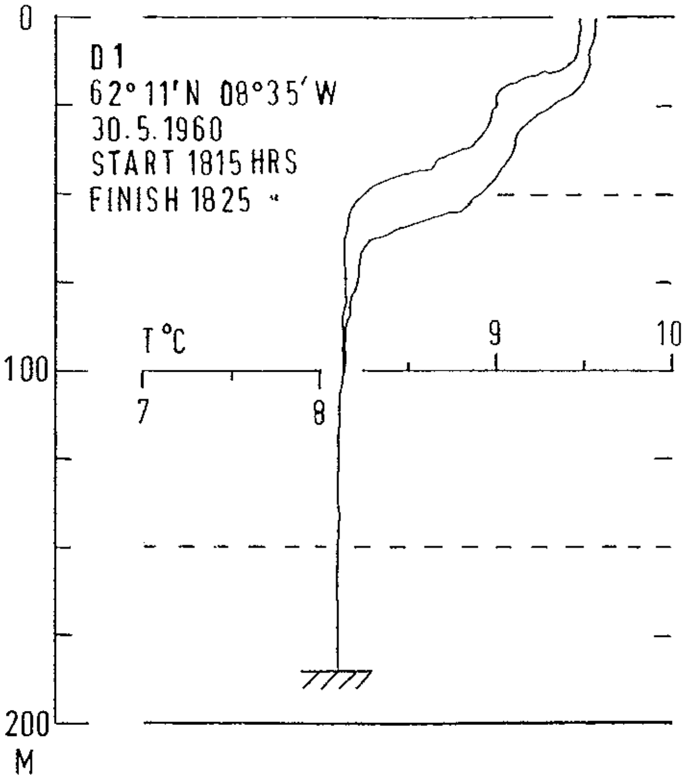

Figure 8:6a.

The Research Vessel "Ernest Holt" used the MAFF[1] Temperature-Depth Recorder described by BOOKER (1961). This allows vertical temperature profiles to be obtained between the surface and 500 m depth. The records obtained by R. V. "Ernest Holt" contained a certain amount of noise at times owing to the fact that the recorder was being used at an early stage in its development. Where necessary this noise has been removed by fitting a line by eye to the centre of the record. Copies of all the records obtained and treated in this way are shown in the figures. The recorder was on the whole used only at those stations on the Iceland-Faroe Ridge where the depth was sufficiently shallow for the sensing head to reach the bottom. At most stations two records were obtained, a DOWN record during the lowering of the sensing head and UP record during the hoisting operation. Both records are shown on the same figure and the differences between them are considered to be mainly due to (a) the fact that the ship was drifting during the lowering and hoisting operations and these took up a total of 40

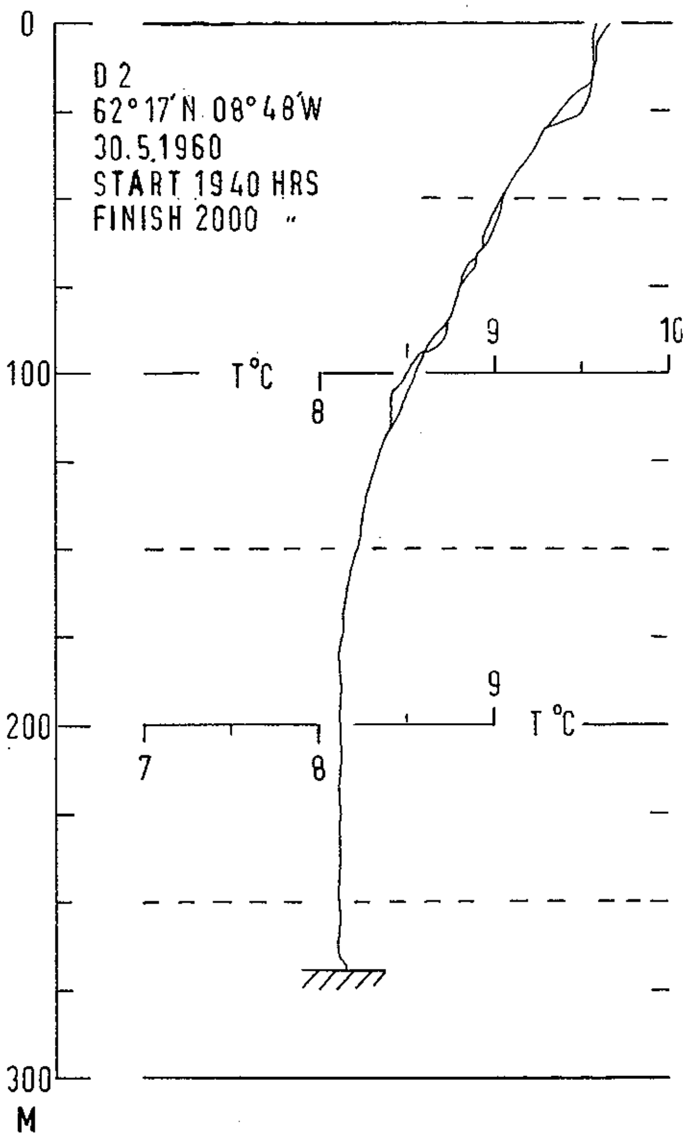

Figure 8:6b.

[1] Ministry of Agriculture, Fisheries, and Food.

minutes (b) internal waves (c) hysteresis in the instrument. The effect of (c) is considered to be small since the magnitude of the differences between the UP and the DOWN record varies from station to station, and since for any particular station at depths shallower than 270 m the differences are the same as those between the UP and DOWN records given by a conventional bathythermograph, which was lowered at the same time as the MAFF Temperature-Depth Recorder was being used.

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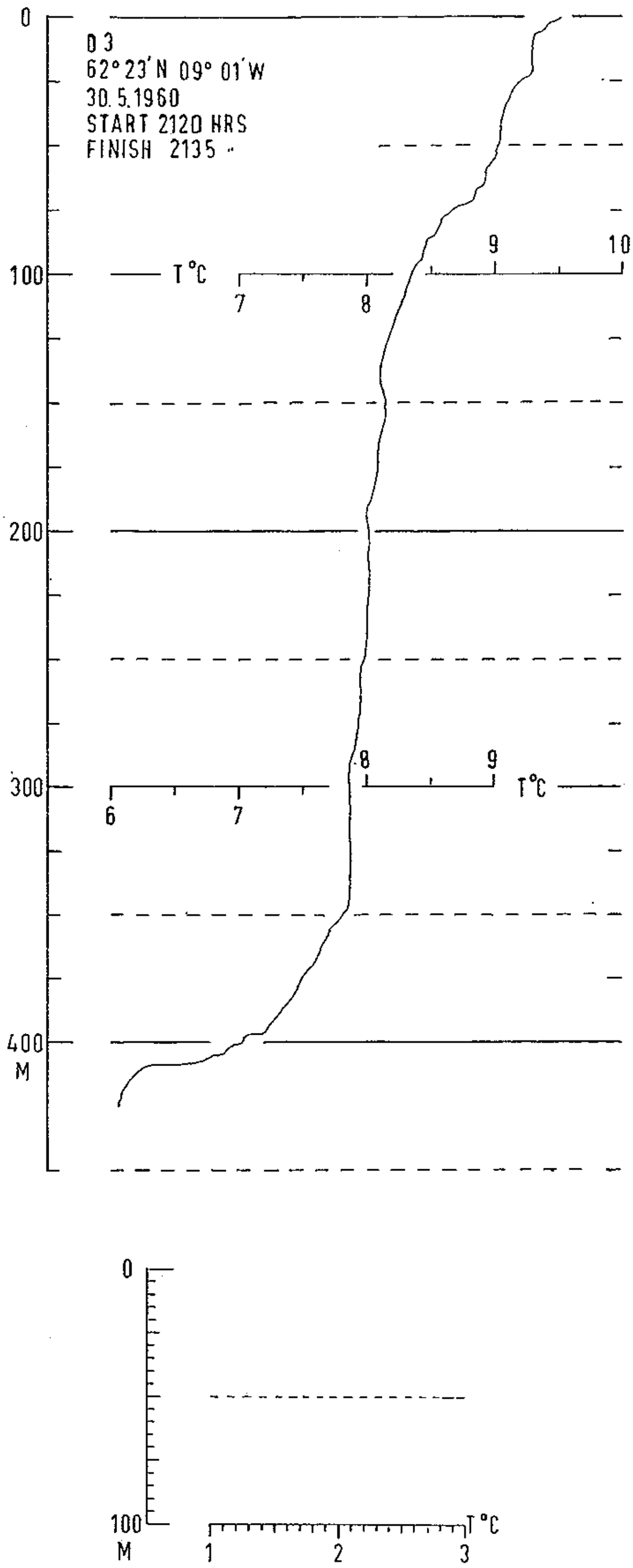
Figures 8:9–8:35 are reproduced on pp. 225–237.



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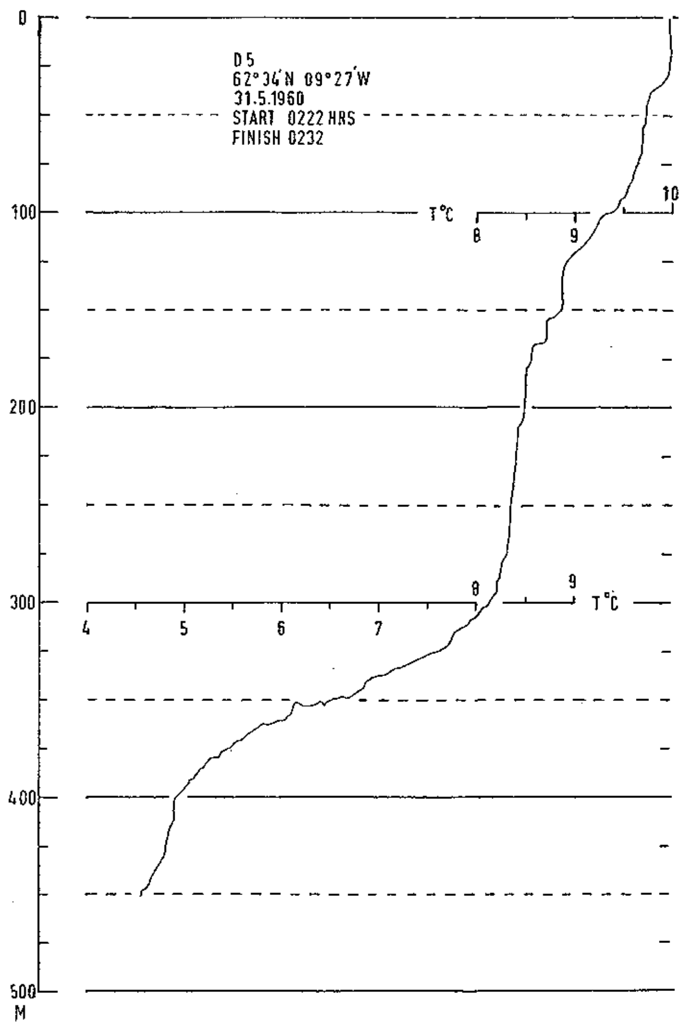

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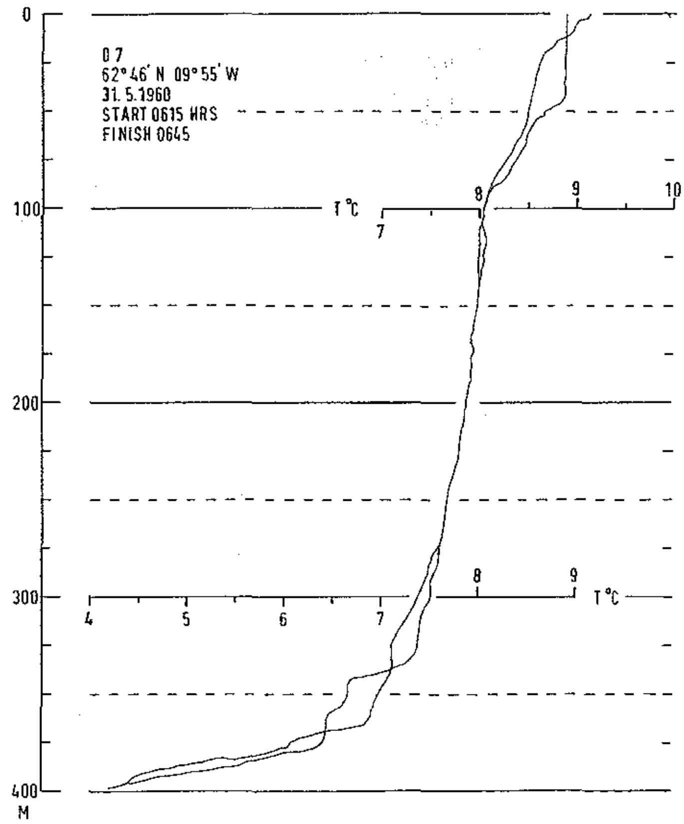

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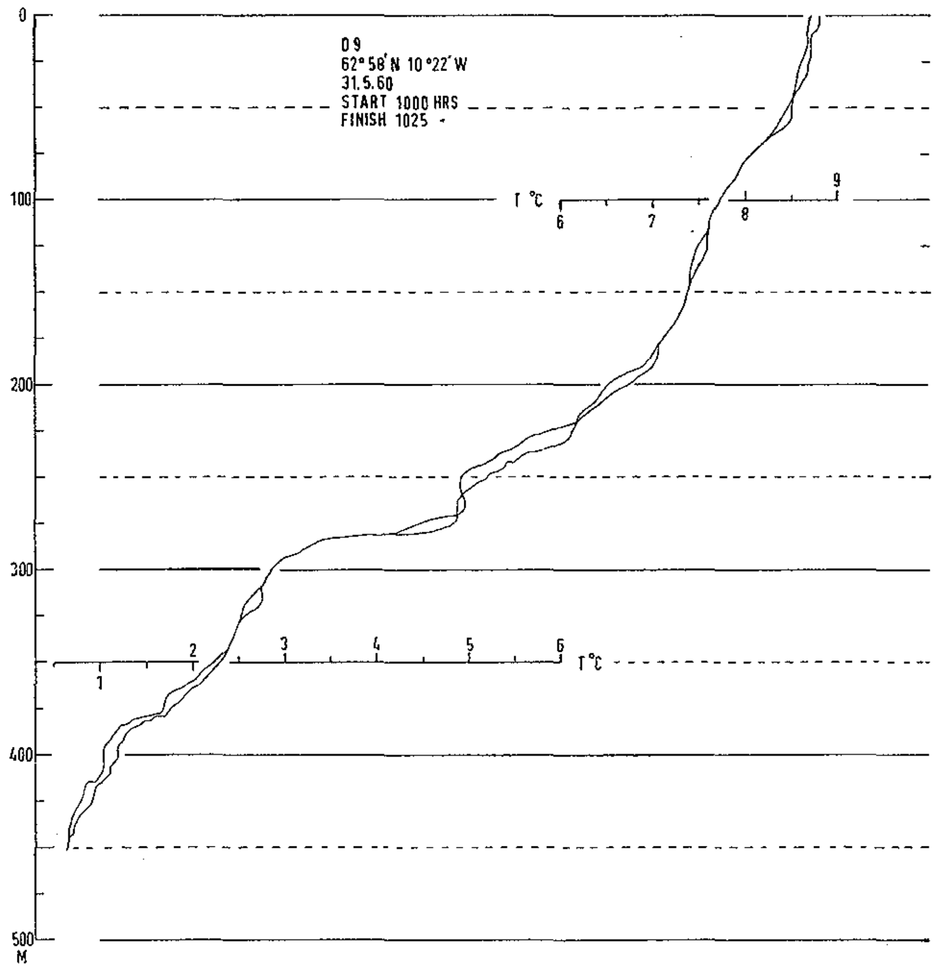

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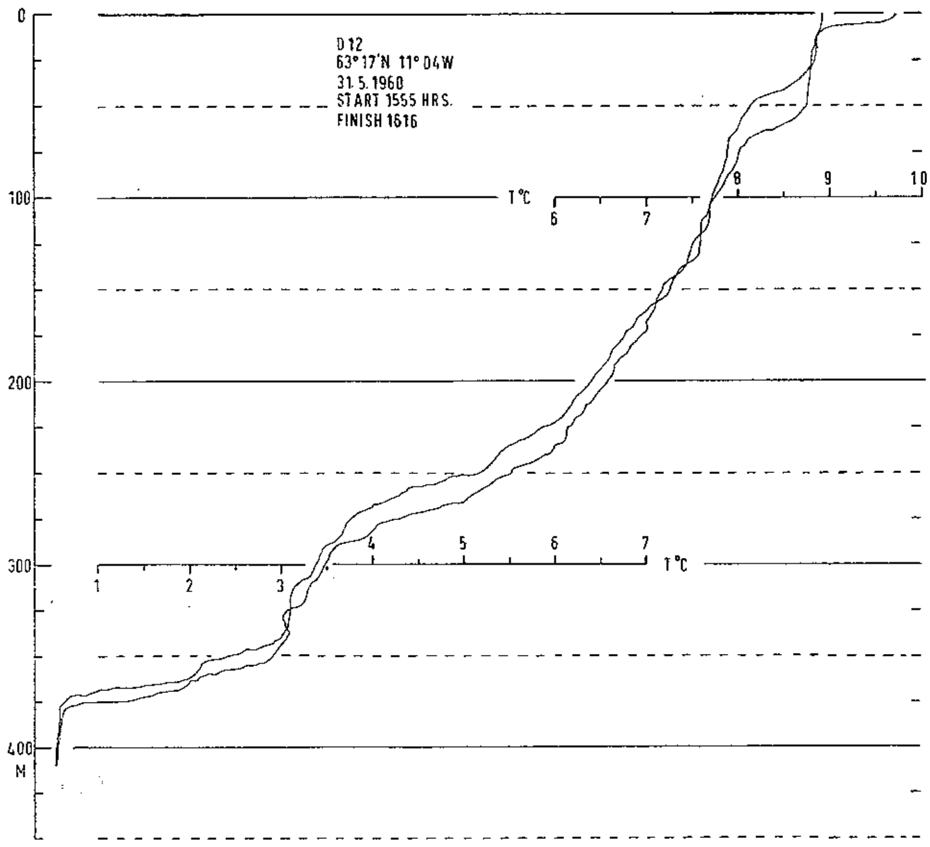

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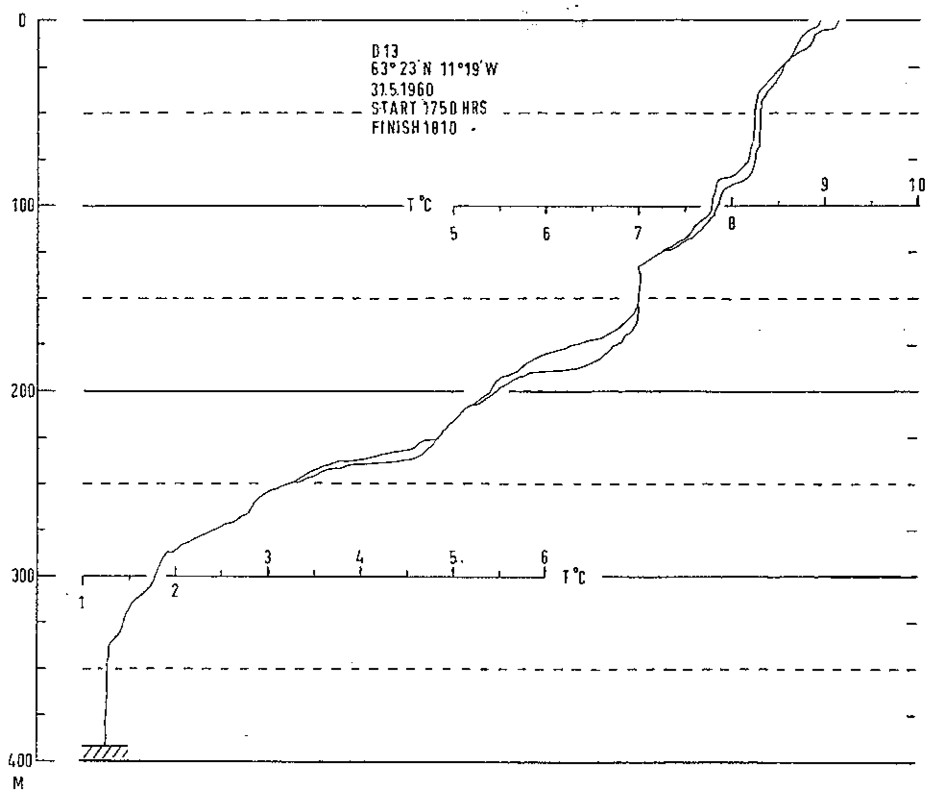

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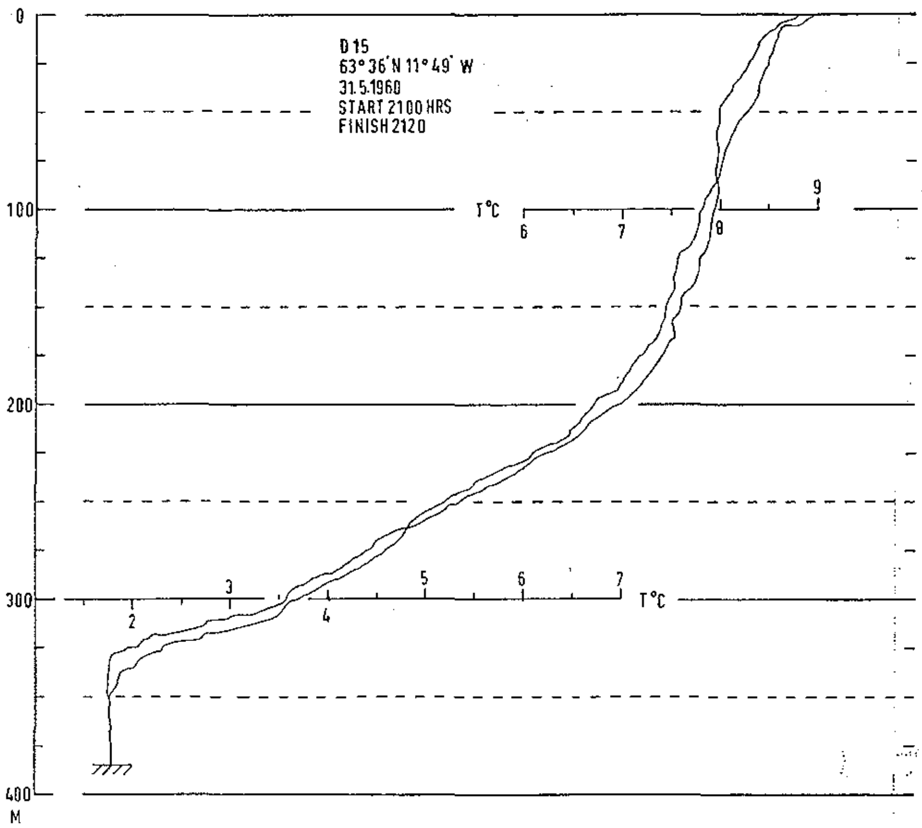

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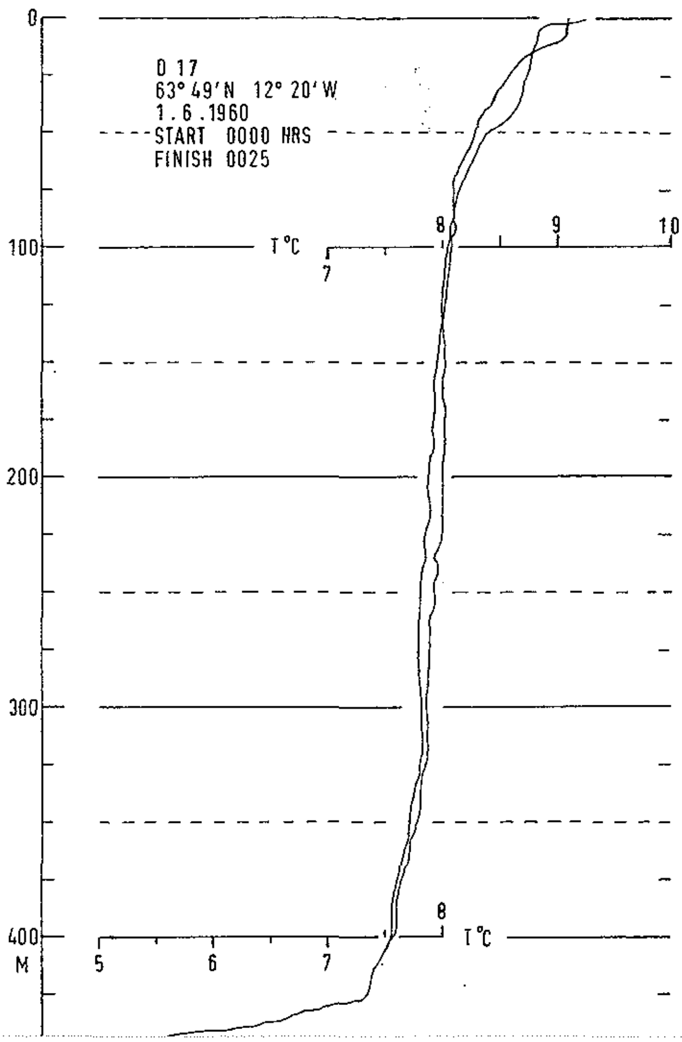

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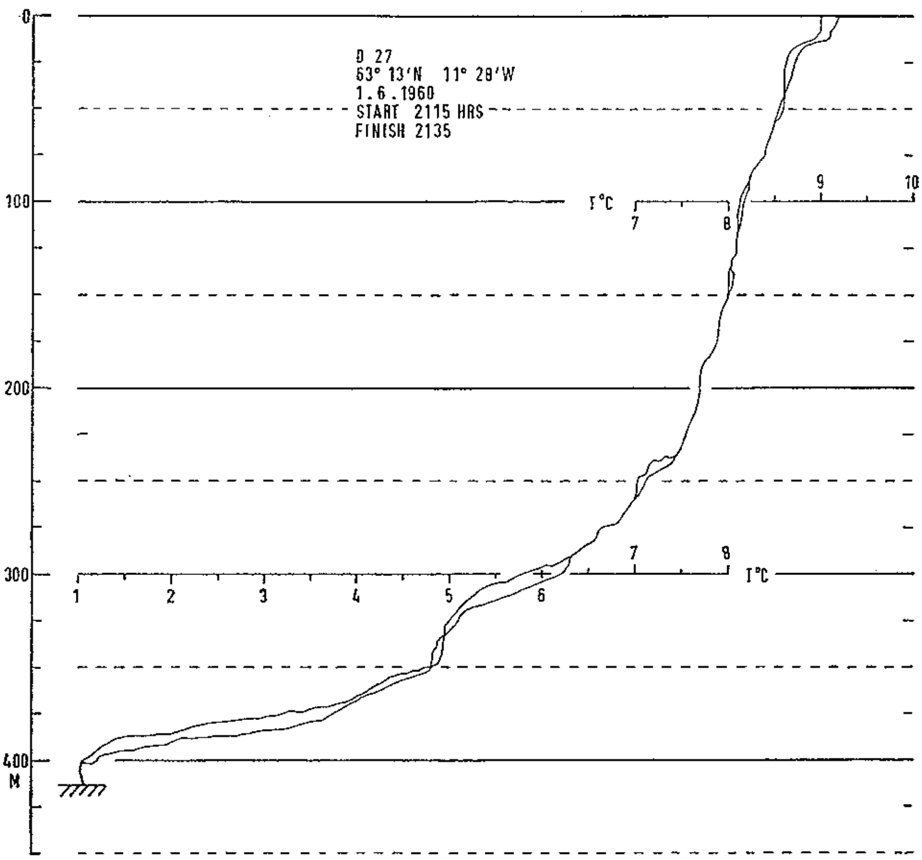

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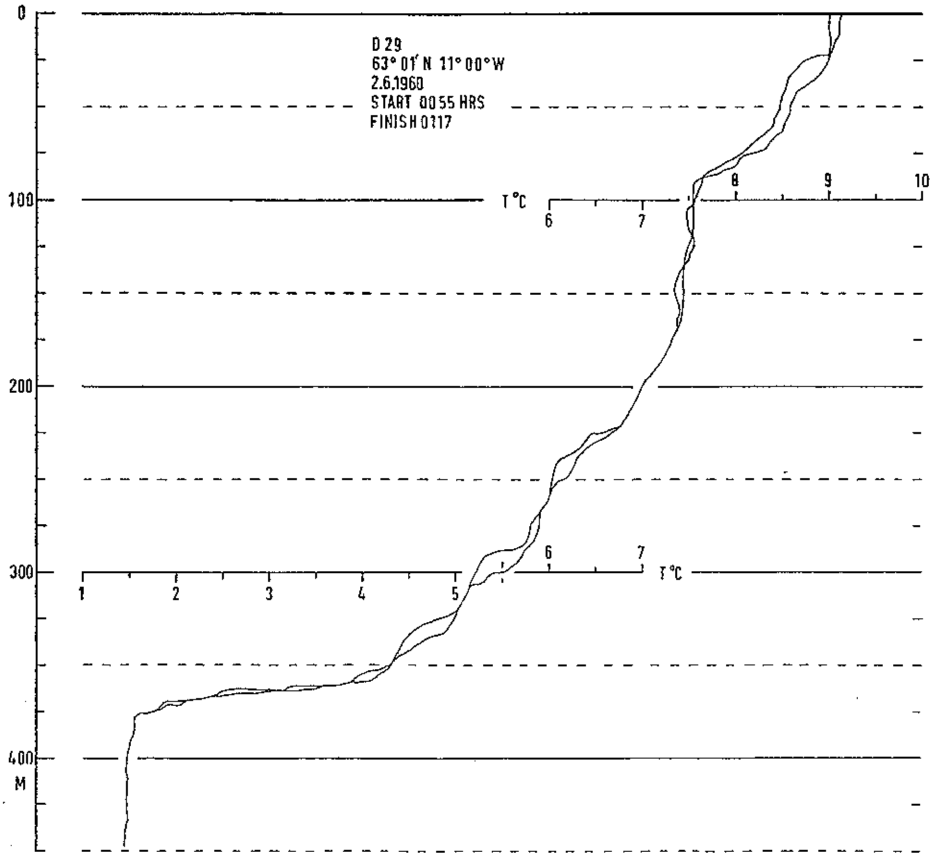

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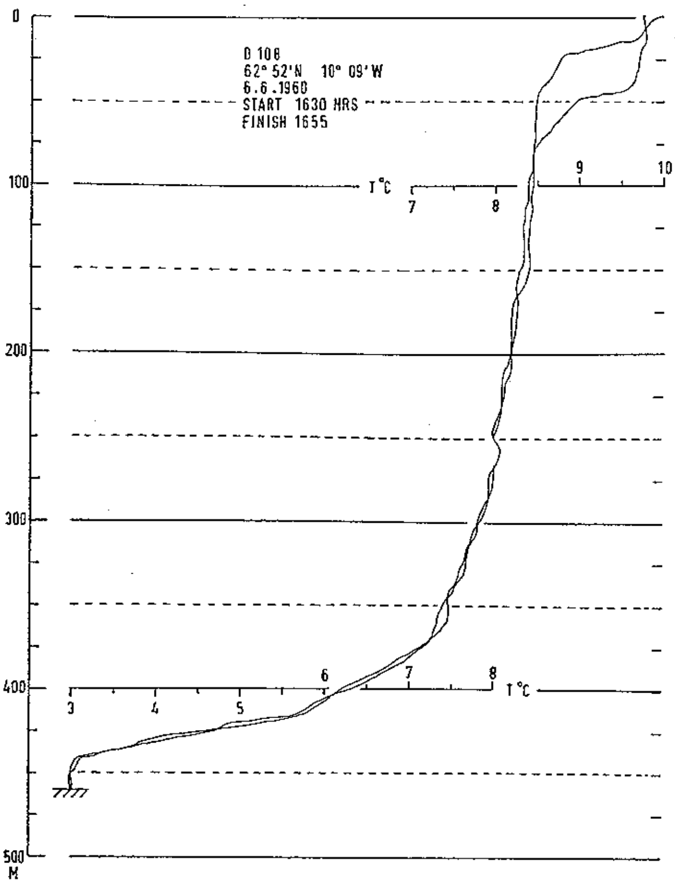

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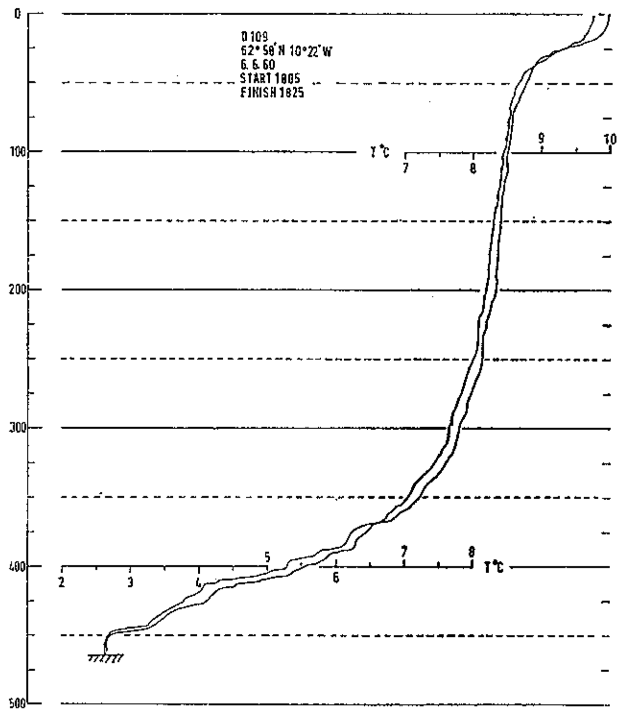

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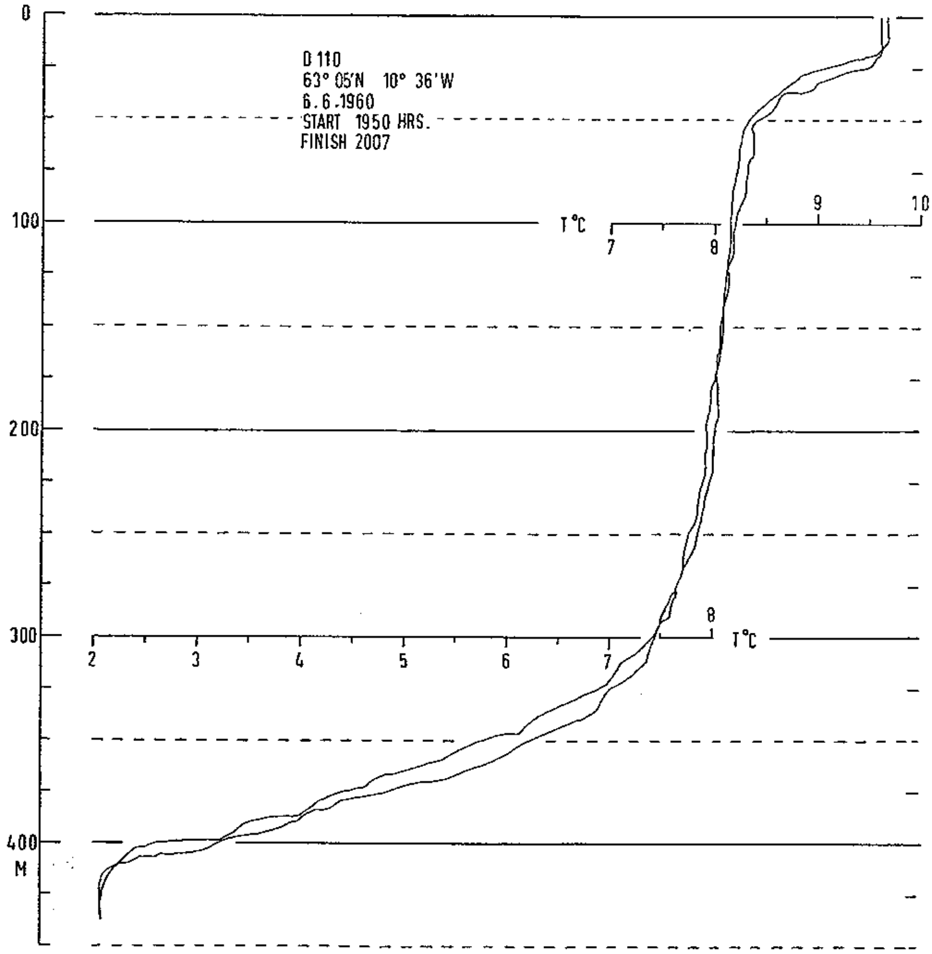

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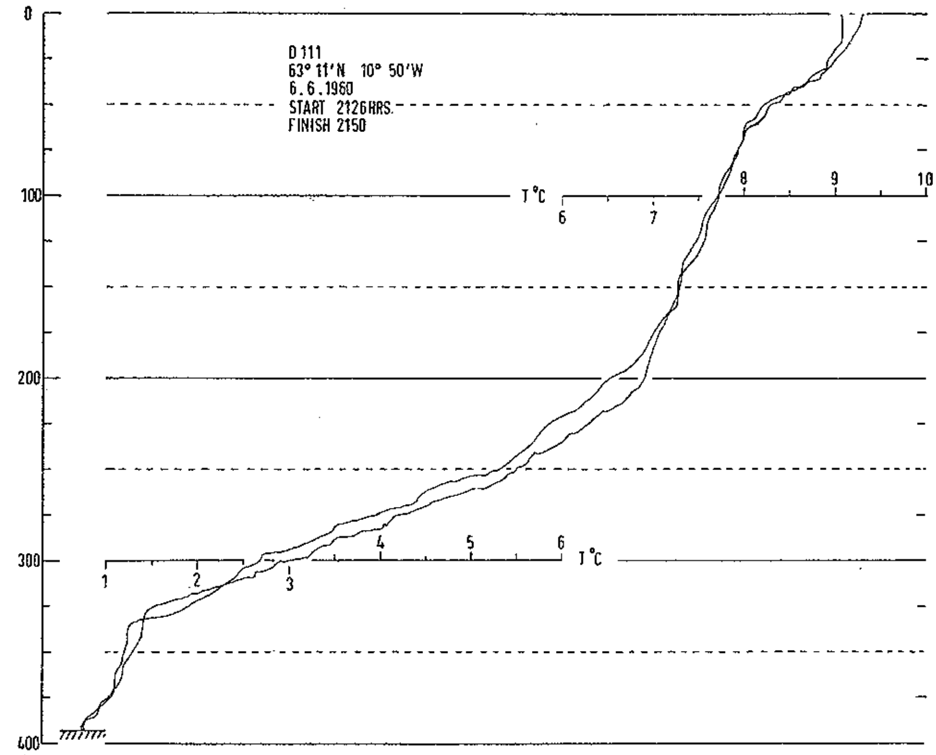

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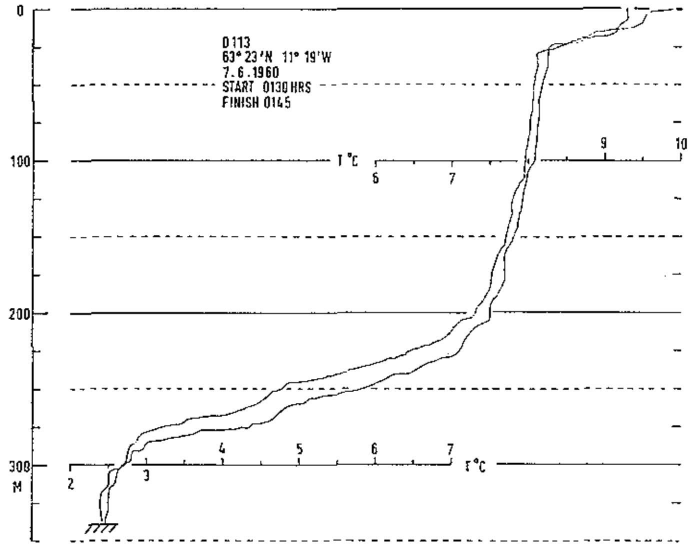

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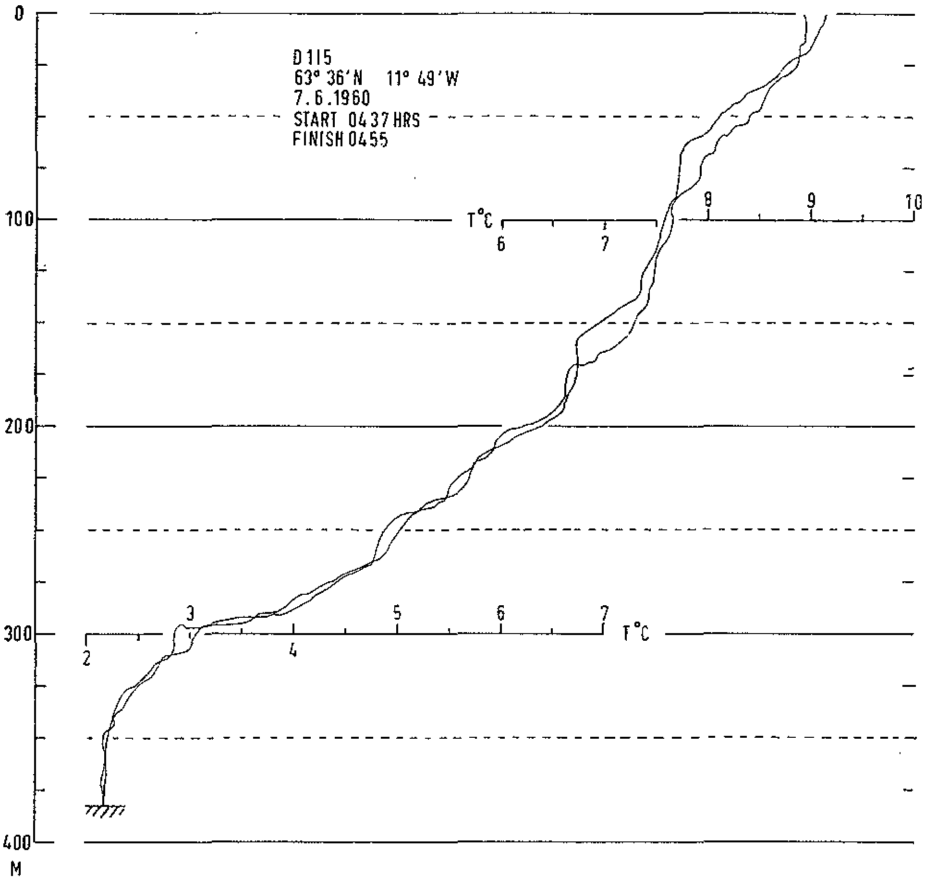

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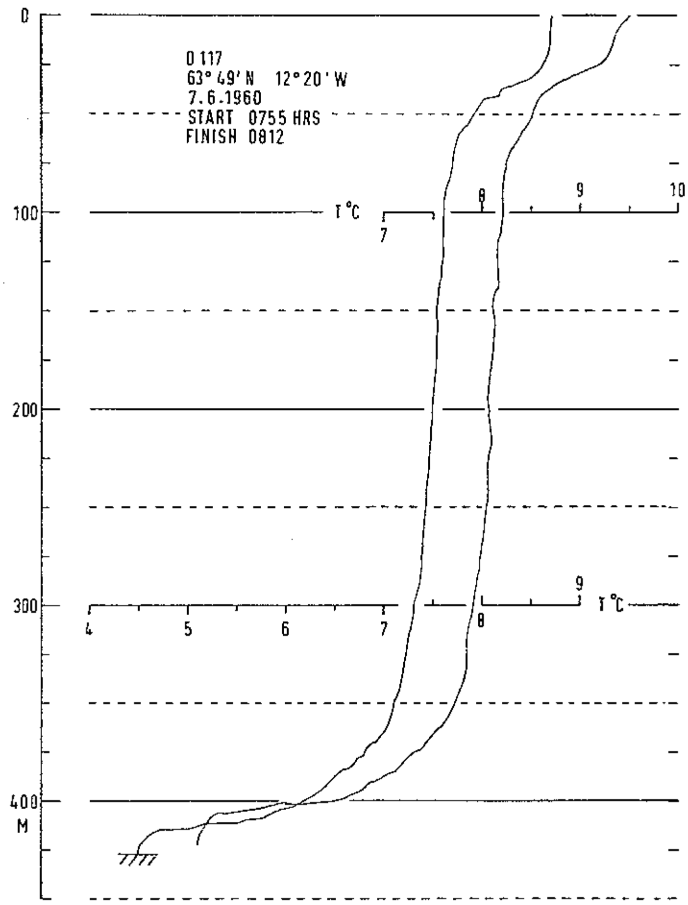

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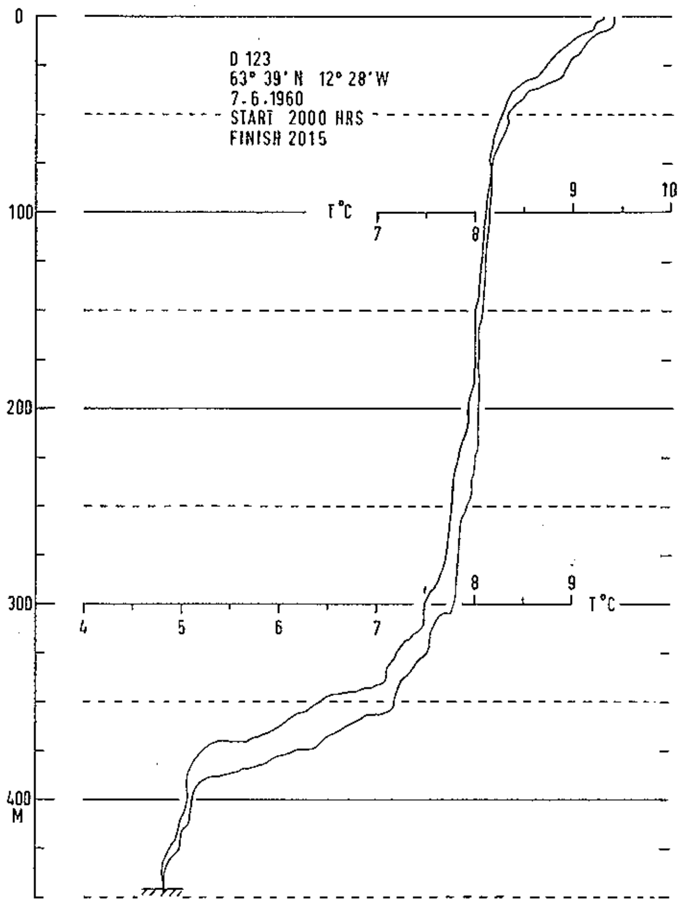

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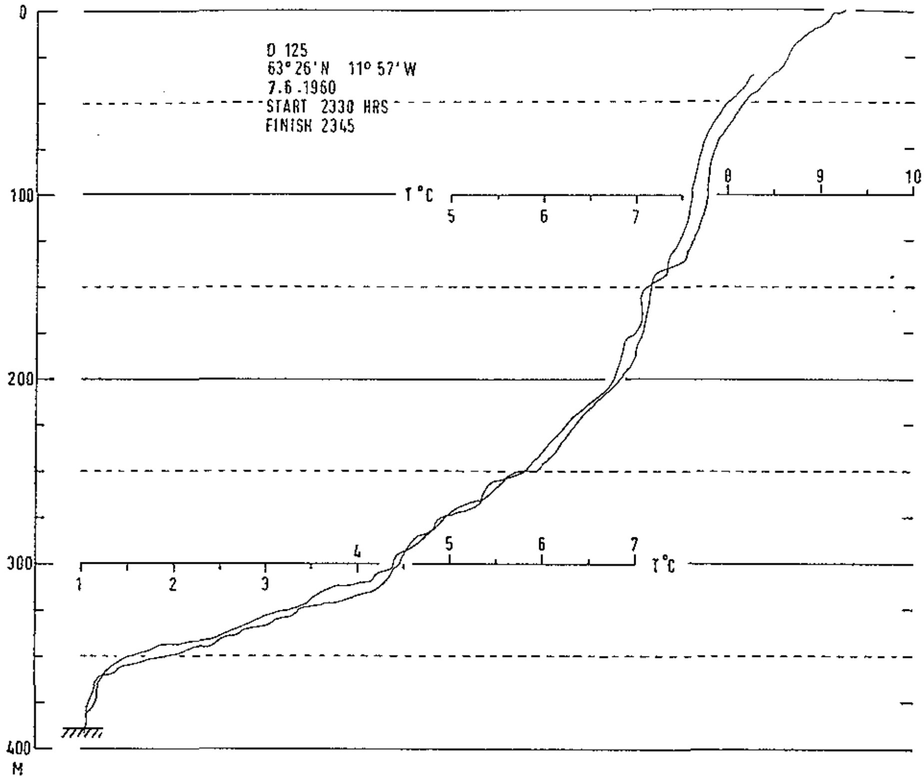

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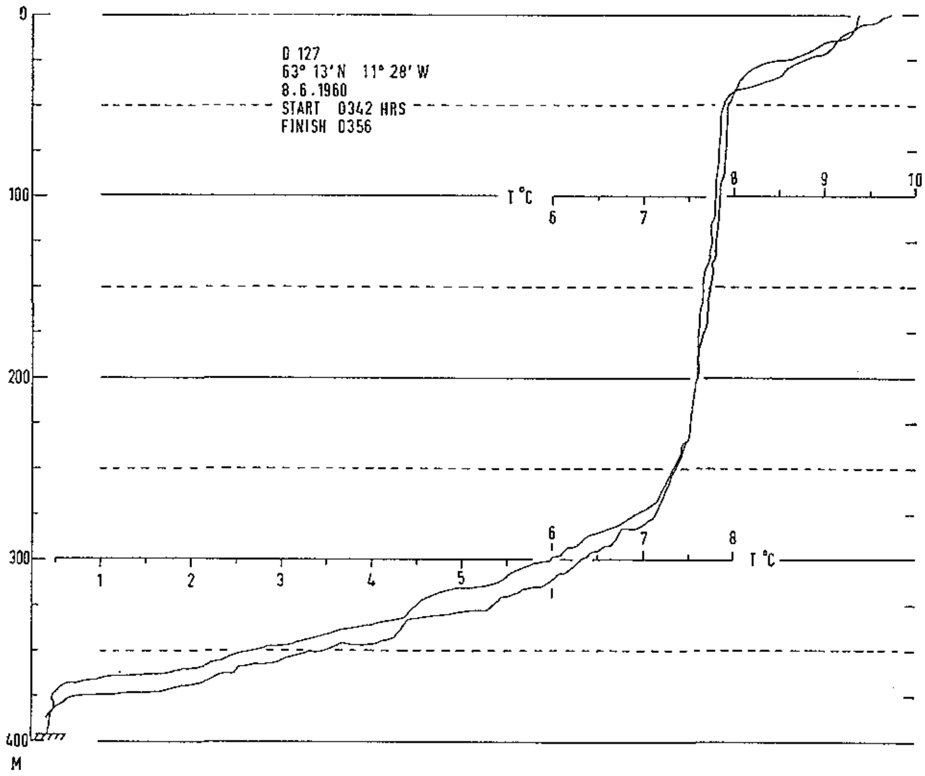

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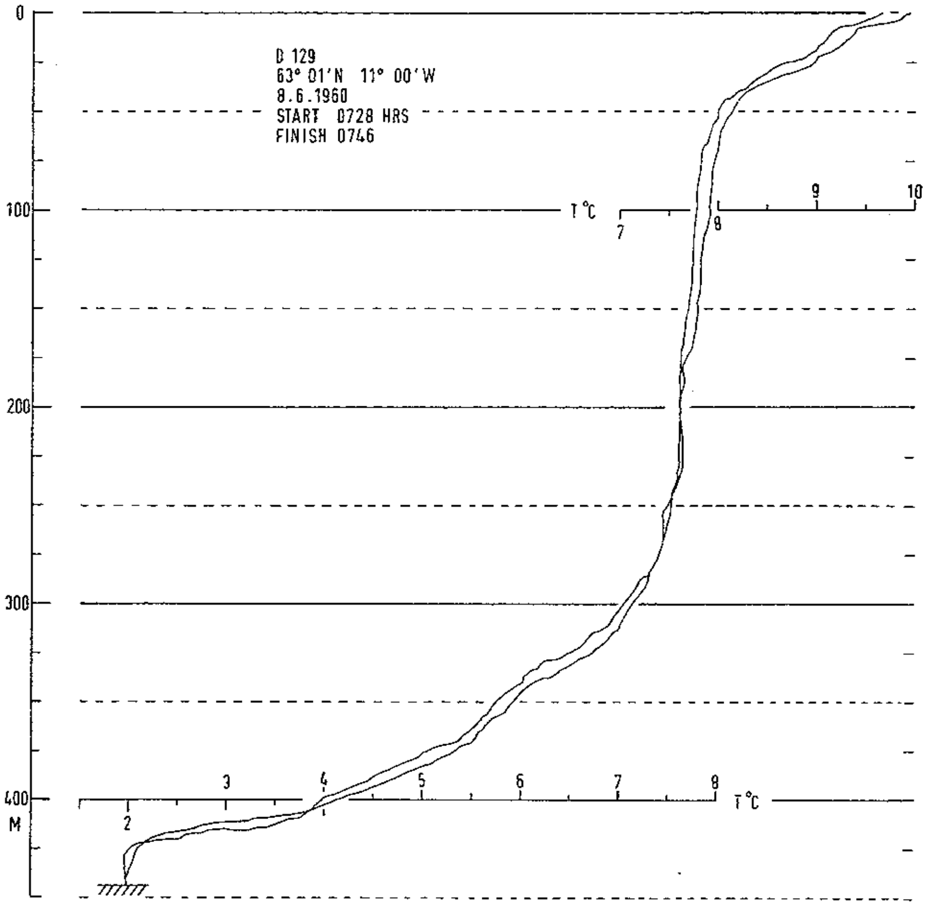
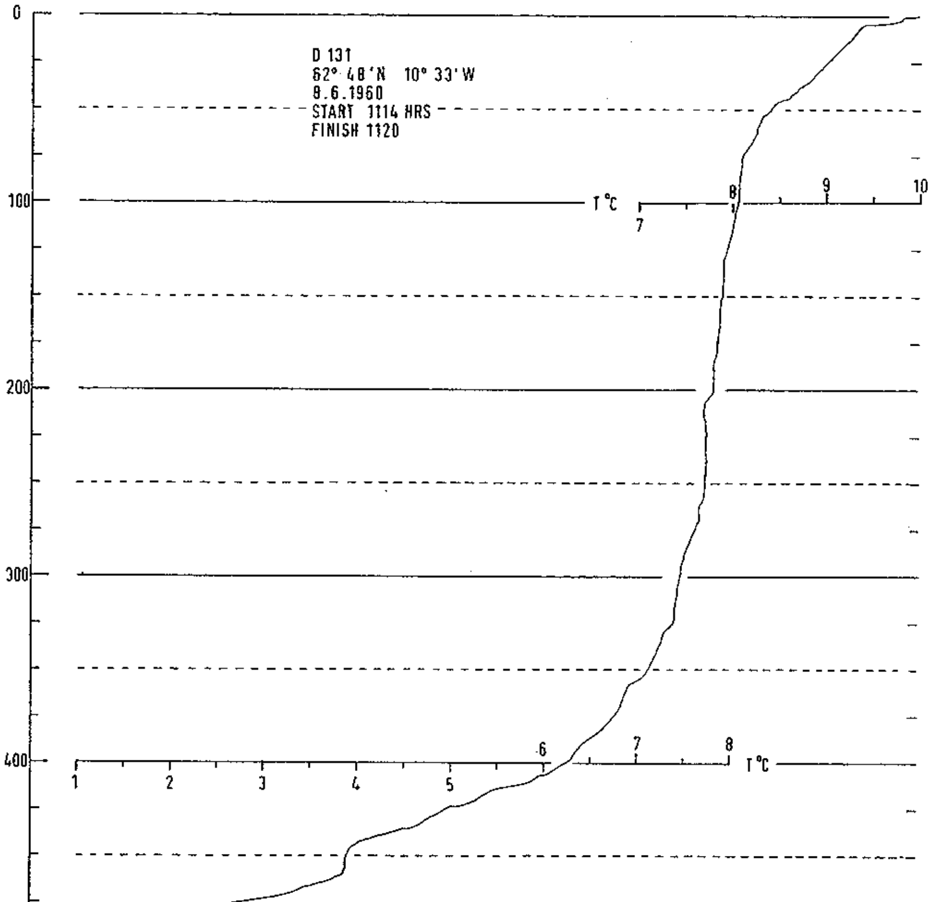
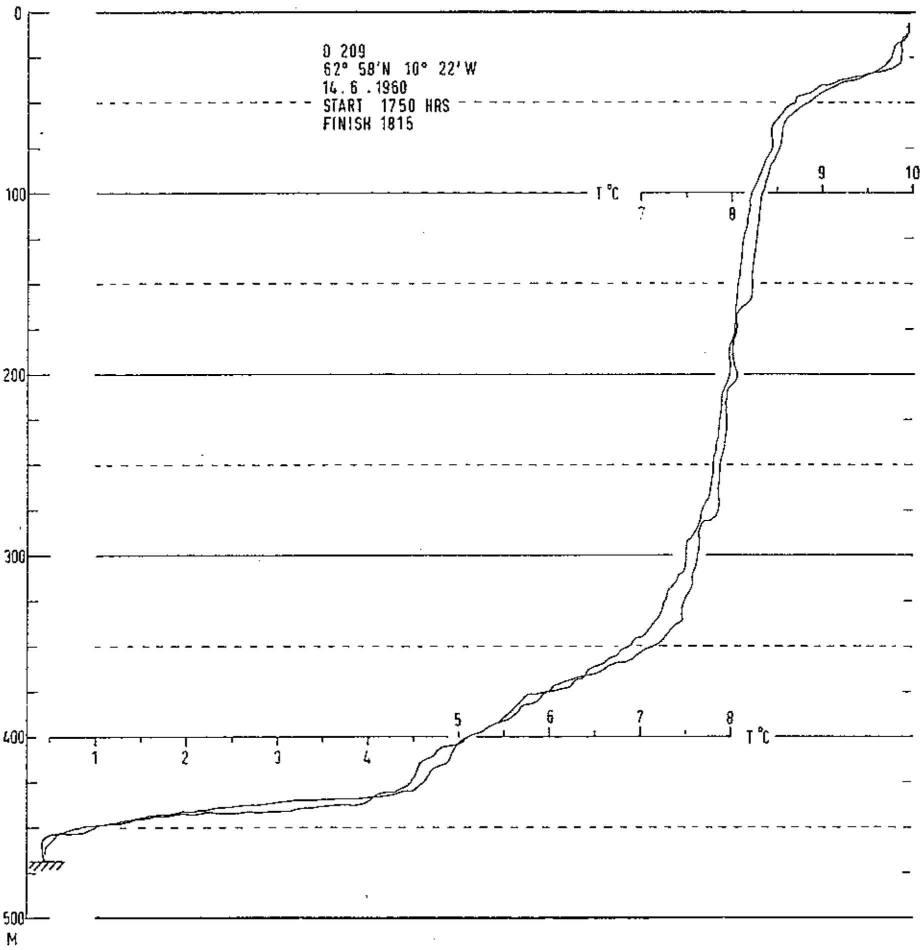

D 129
63° 01'N 11° 00'W
8.6.1960
START 0728 HRS
FINISH 0746
T °C
M

Figure 8:27.


D 131
62° 48'N 10° 33'W
8.6.1960
START 1114 HRS
FINISH 1120
T °C



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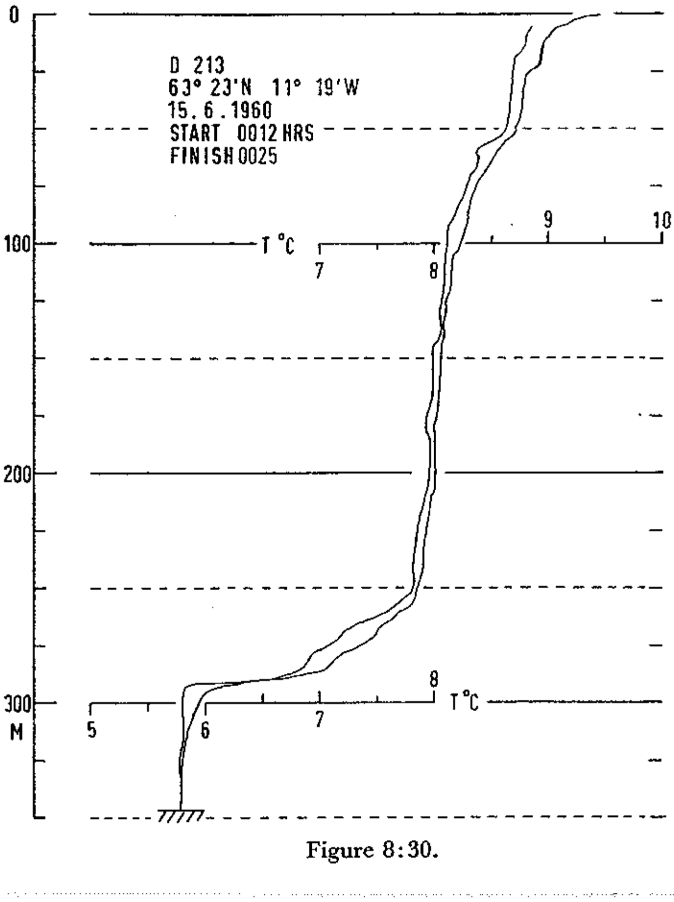

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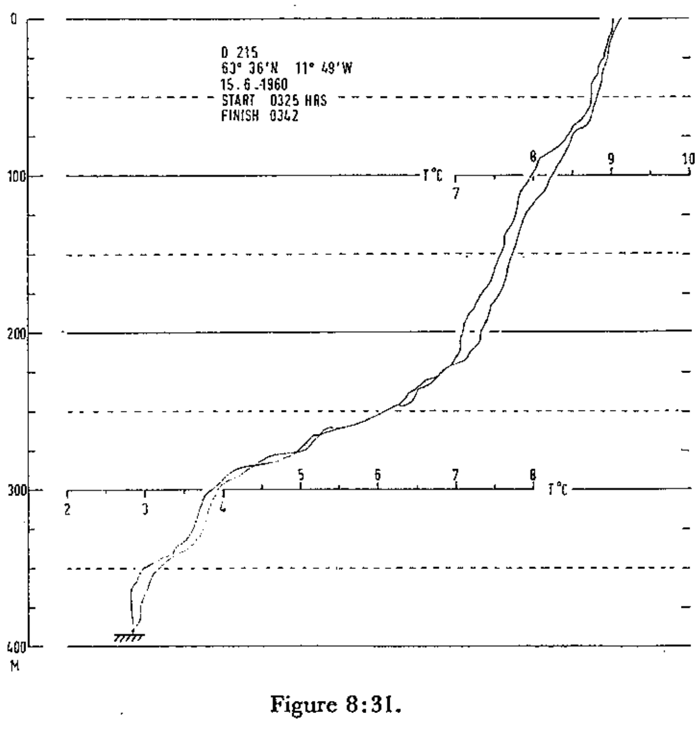

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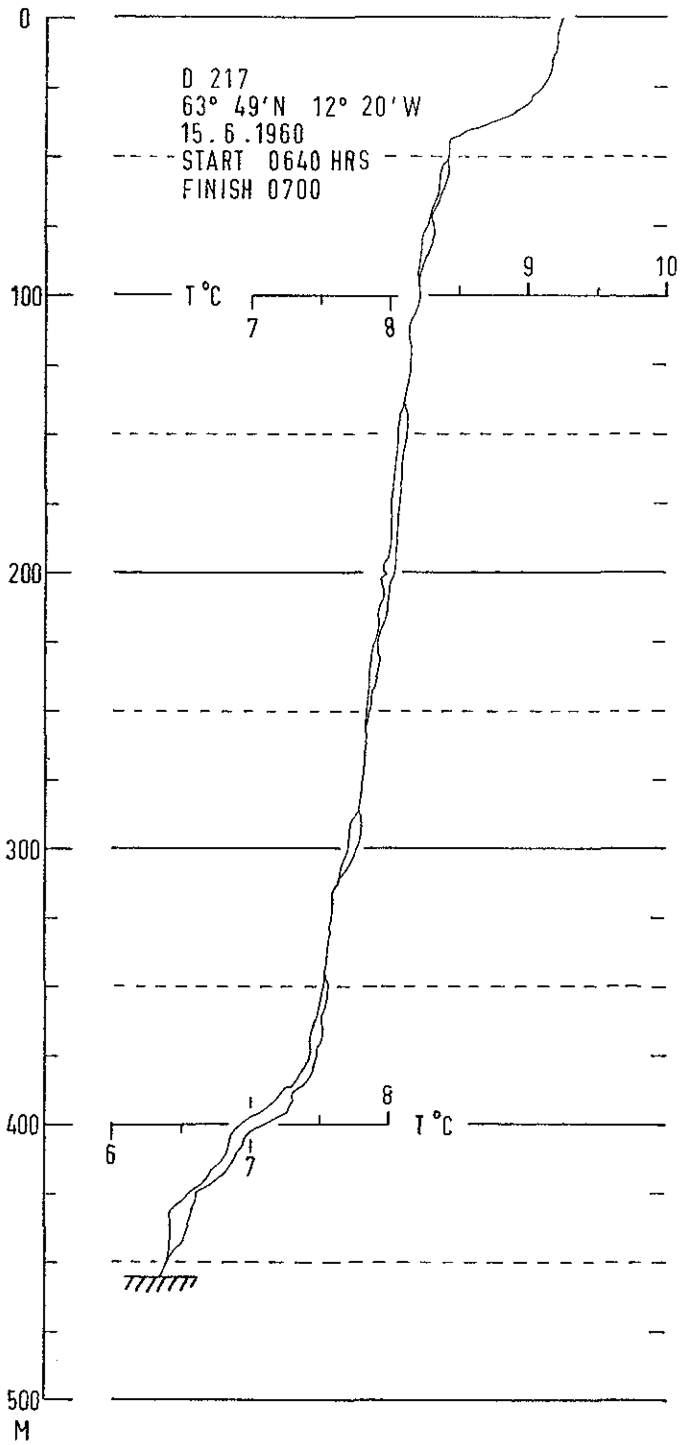

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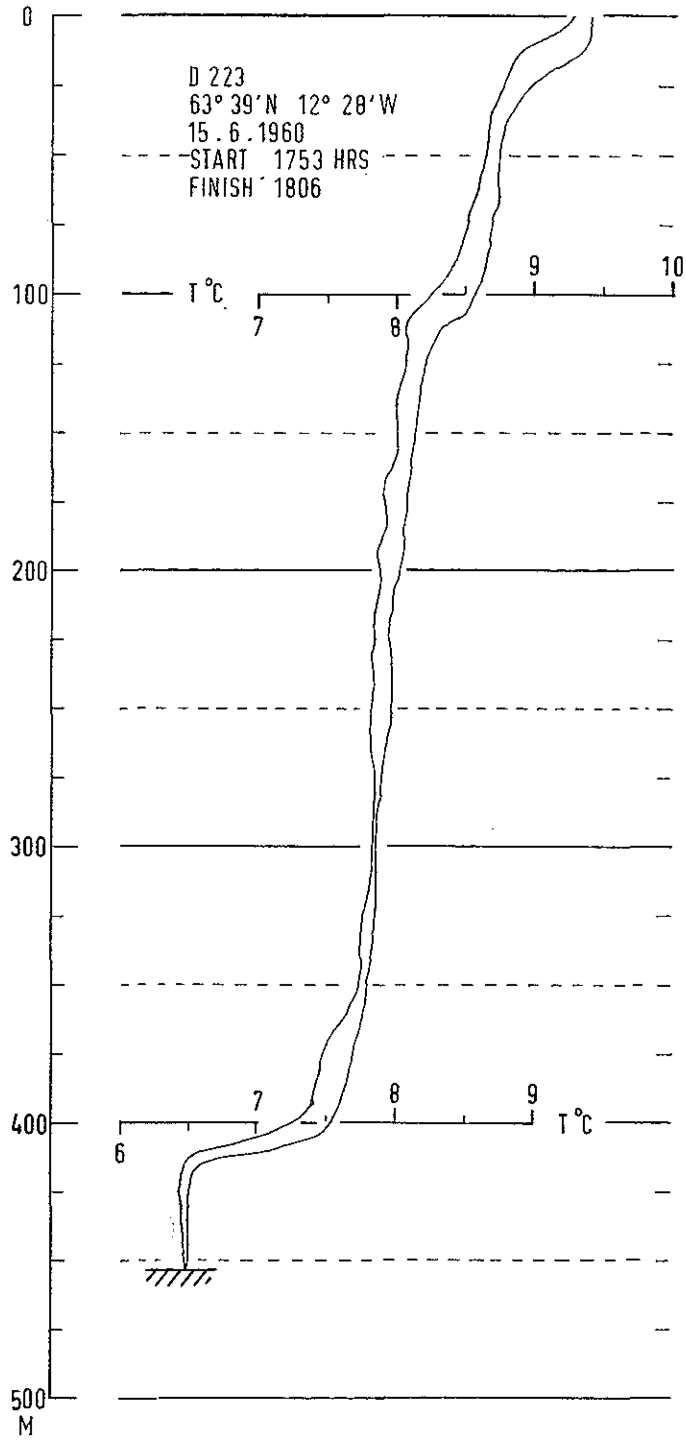

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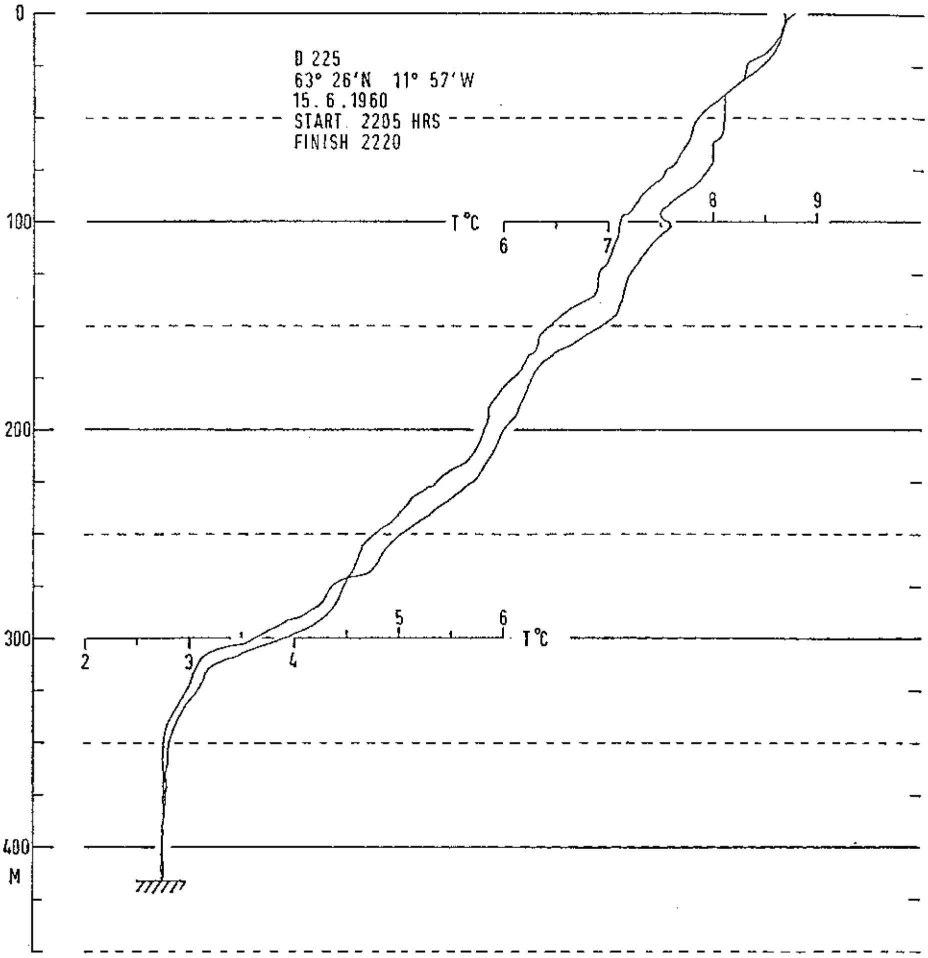

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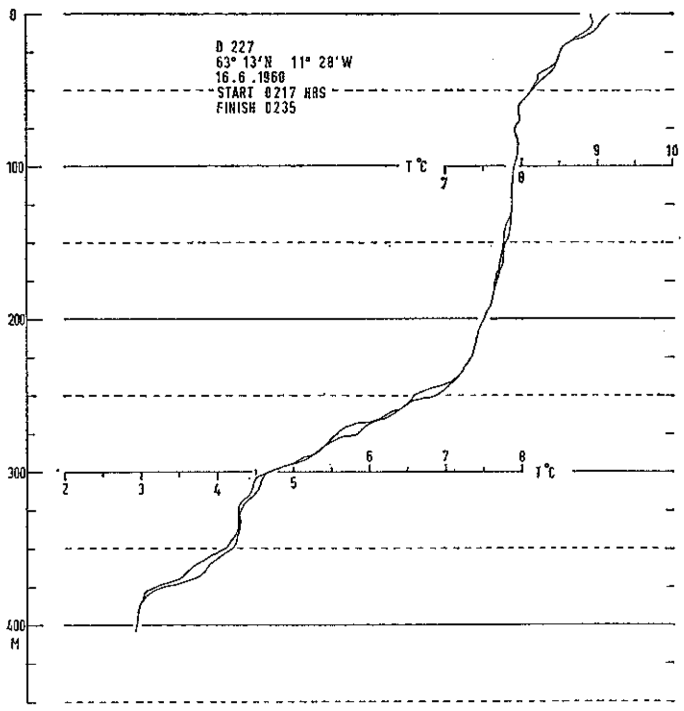

Figure 8:35.

CHAPTER 9
OBSERVATIONS ON THE DISTRIBUTION OF DEMERSAL FISH ON THE ICELAND-FAROE RIDGE IN RELATION TO BOTTOM TEMPERATURES AND DEPTHS

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INTRODUCTION

Since the days of Sir JOHN MURRAY, scientists have well understood how significant is the chain of submarine ridges – part of which is formed by the Iceland-Faroe Ridge – as a barrier between the bottom fauna of the Atlantic and that of the Arctic. The sharp differences in temperature on either side of the Ridge are reflected by equally sharp differences in their fauna, that of the Norwegian Sea being a very peculiar one. Of the 433 species of animals listed by MURRAY (*vide* N. B. MARSHALL: Aspects of Deep Sea Biology: 357, 1954) on one or other side of the Ridge, only 48 have been found on both sides. The fauna of the Ridge itself, on the contrary, might consist of a mixture of both Atlantic and Arctic elements, with a marked predominance of eurythermic forms. This should be especially true for sedentary and slow-moving animals. If we assume that the phenomenon of the overflow of cold Arctic water across the Ridge is confined to some special passages determined perhaps by the topography of the Ridge, then this phenomenon might cause a much more differentiated pattern of distribution of the invertebrate bottom fauna. Unfortunately, a detailed survey relevant to this question has not yet been undertaken.

A pulsating overflow with rapid temperature changes near the bottom on one side of the Ridge ought to be paralleled by similar changes in the distribution of the more active, faster-moving animals. In the commercial fisheries on the northern side of the Ridge, such phenomena have sometimes been observed by our trawlermen; rapid changes in the availability of redfish have occurred at the same location within a few hours. Long-term variations have also been observed. Earlier research vessel cruises to the "Rosengarten" have also shown a rather complex distribution pattern of ichthyofauna. The patterns of distribution of Atlantic and Arctic forms were often rather irregular but, on the whole, followed more or less distinctly a dividing line along the top of the Ridge. Both hydrographical and topographical factors may be involved in the formation of this peculiar pattern.

The "ICES-Overflow-Programme" offered a welcome chance to learn something more about the factors governing the distribution of fish living at or close to the bottom of the area. Therefore, immediately after completing the third hydrographical survey in the same area (19.–22. June, 1960), it was decided to spend a few more days with R. V. "Anton Dohrn" in getting some information concerning the relationship between fish distribution, water temperature, and depth. It was assumed that bottom temperatures would not have changed significantly within the few days and so further observations were made only at one station (AD 759/1960). Here, according to the chart prepared by Dr. TAIT for the third survey, the temperature ought to have been between 0° and 1° C. However, the actual bottom temperature when fishing was started at this station was found to be $-0{\cdot}02°$ C. Thus the bottom temperatures seem to change more rapidly than was expected. With this information in mind, one cannot be sure of the degree to which the temperatures used from Dr. TAIT's chart for the preparation of our distributional charts are reliable.

For that reason, and since only 18 hauls could be made in the time available, there is included in this report the larger and more detailed information obtained in a cruise the year before (28. April–6. May, 1959), which covered nearly the same area and in some cases even the same stations. During this cruise bottom temperatures were measured immediately before fishing commenced at each station. However, due

Table 9:1

List of trawl stations. "Anton Dohrn" cruises April/May 1959 and May/June 1960

Station No.	Data	Position N. lat.	Position W. long.	Depth m.	Bottom temp. °C[1]	Fishing time	Remarks
A. *1959 Cruise.*							
3218	28. April	64°20′	12°25′	450–460	2·8	19·20–19·50	
3223	29. „	63°40′	12°30′	450	5·1	06·45–07·15	
3224	29. „	63°35′	12°29′	440–460	5·1	08·30–10·30	Commercial fishery
3225	29. „	63°37′	11°39′	350	5·4	14·10–14·40	
3226	29. „	63°40′	10°45′	430–450	2·7	17·55–18·25	
3229	30. „	63°19′	09°37′	450	1·1	06·45–07·15	
3230	30. „	63°30′	11°10′	310	5·6	12·45–13·15	
3231	30. „	63°12′	11°40′	400	4·1	15·50–16·20	
3232	30. „	63°24′	12°38′	500–510	3·8	21·00–21·30	
3236	1. May	63°35′	12°30′	450	–	06·30–08·30	Commercial fishery
3237	1. „	63°46′	12°25′	430	–	10·00–11·40	Commercial fishery
3238	1. „	63°43′	13°00′	650	3·6	14·30–15·00	
3252	2. „	63°00′	08°36′	440	–	23·50–00·20	
3253	3. „	63°02′	10°35′	450	1·9	06·50–07·20	
3254	3. „	63°00′	12°17′	470–480	4·7	17·10–17·40	
3255	3. „	63°09′	13°18′	735–760	4·2	22·40–23·40	Trawl heavily damaged
3267	6. „	61°15′	08°05′	750–805	–0·2	13·40–14·30	Came fast; net damaged
B. *1960 Cruise.*							
751/60	19. June	64°11′	12°13′	445	6	10·50–11·20	
752/60	19. „	64°20′	12°23′	450	1–2	13·25–13·55	Came fast; net lost
754/60	19. „	63°53′	12°27′	466	6	18·55–19·05	Came fast; net undamaged
755/60	19. „	63°53′	11°50′	370	2–3	20·55–21·25	Came fast; net damaged
756/60	20. „	63°36′	12°30′	450	6	07·20–07·50	
757/60	20. „	63°37′	12°15′	400–410	6	08·50–09·20	
758/60	20. „	63°36′	11°27′	320–330	3–4	11·45–12·15	
759/70	20. „	63°37′	10°46′	480	0–1[2]	14·40–15·10	
761/60	20. „	63°23′	10°40′	410	1–2	19·50–20·20	
762/60	20. „	63°20′	10°40′	320	1–2	21·20–21·50	
763/60	21. „	63°23′	11°37′	400	3	06·50–07·20	
764/60	21. „	63°22′	12°33′	500	5	11·50–12·05	Came fast; net damaged
765/60	21. „	63°10′	12°43′	500	5–6	13·50–14·20	
766/60	21. „	62°58′	12°22′	490–500	4–5	18·20–18·50	
767/60	21. „	63°00′	11°45′	480	4	20·45–21·15	
768/60	22. „	63°01′	10°47′	450	3–4	06·45–07·15	
769/60	22. „	63°00′	09°50′	480–500	2	09·40–10·10	
771/60	22. „	62°46′	09°09′	470	4–5	14·50.15·05	Came fast; net undamaged

[1] The bottom temperatures for the 1960 cruise were abstracted from a chart of the third survey prepared by Dr. Tait.
[2] The actual bottom temperature was stated to be $-0{\cdot}02$° C.

to time-consuming racial investigations on redfish, it was not always possible to work up the catches in detail, i.e. the precise numbers of specimens of the different species are not always available. In such instances the numbers of individuals to each "Korb" (basket) were estimated; reliable factors for such a computation were available. The number of trawl stations on the 1959 cruise was 17.

Generally, standard hauls of 30 minutes duration were made in both years. In some cases, such as when the net came fast, the fishing time was shorter, and in others, when fishing for commercial purposes during the 1959 cruise for instance, it was extended up to two hours.

Some comments may be made concerning the term "demersal fish" as applied in this report. In addition to the "true" bottom fish, a few other species are included which may spend their lives partially in mid-water rather than at the sea-bed. Such species are e.g. the greater silver smelt, *Argentina silus* (Ascanius) and the blue whiting, *Micromesistius poutassou* (Risso). Both of these species may occasionally be taken by hook and line even close to the surface; however, the main habitat at least of *Argentina* is on or close to the bottom, where according to Cohen (1958), it seems to prefer the edge of the Continental Shelf, thus often sharing the grounds with the redfish, which is, likewise, not a true bottom-dweller. Most likely the blue whiting is in its habit much more a midwater fish than *Argentina*. It is, however, very commonly encountered in catches of

Table 9:3

Ranges and weighted mean values of depths and bottom temperatures for demersal fish species (Numbers of specimens converted from table 9:2 A and 9:2 B according to "standard hauls"; 1959 and 1960 cruises combined)

Species	Number of specimens	Depth (m) Range	Depth (m) Mean	Bottom temperature °C Range	Bottom temperature °C Mean
Centroscyllium fabricii	23	450–760	662	2·8–5·5	3·9
Centroscymnus coelolepis	1	735–760	–	4·2	–
Raja radiata	78	400–500	452	–0·02–6·0	2·5
Raja fyllae	26	310–760	465	1·5–5·6	3·9
Raja spinicauda	6	430–805	586	–0·2–4·2	2·1
Raja hyperborea	1	750–805	–	–0·2	–
Argentina silus	938	310–510	454	1·5–6·0	4·9
Notacanthus phasganorus	3	450–760	617	2·8–4·2	3·5
Coryphaenoides rupestris	533	400–760	640	1·1–4·2	3·5
Macrourus berglax	5	450–760	513	2·8–4·2	3·1
Gadus morhua	48	310–445	331	1·5–6·0	3·0
Melanogrammus aeglefinus	1	310	–	5·6	–
Pollachius virens	27	310–500	385	1·5–6·0	5·3
Micromesistius poutassou	2628	310–760	431	–0·02–6·0	3·7
Molva dypterygia	42	320–805	439	–0·2–6·0	3·5
Brosme brosme	40	310–500	407	1·9–6·0	4·6
Gaidropsarus argentatus	5	750–805	–	–0·2	–
Lepidion eques	8	500–760	625	3·6–5·0	4·0
Ammodytes lancea marinus	6	470	–	4–5	–
Aphanopus carbo	1	735–760	–	4·2	–
Anarhichas minor	21	320–460	412	1·5–6·0	3·9
Anarhichas denticulatus	6	430–450	445	1·1–2·7	2·2
Lycodes esmarkii	26	400–760	496	–0·02–5·5	2·6
Lycodes eudipleurostictus	12	400–805	492	–0·2–4·1	0·6
Lycodes pallidus pallidus	9	735–805	773	–0·2–4·2	0·3
Sebastes viviparus	5	320–760	545	3·5–5·1	4·2
Sebastes marinus, type *marinus*	272	320–650	378	1·5–6·0	3·4
Sebastes marinus, type *mentella*	2978	320–760	449	1·5–6·0	4·6
Sebastes marinus, type intermediate	479	320–650	363	–0·02–6·0	2·7
Sebastes marinus, type giants	16	320–470	423	3·5–6·0	4·4
Artediellus atlanticus	16	450–480	463	–0·02–3·5	0·9
Cottunculus microps	28	320–805	481	–0·2–6·0	2·1
Cottunculus thomsonii	1	735–760	–	4·2	–
Careproctus reinhardtii	3	450–805	571	–0·2–4·0	2·2
Paraliparis bathybii	1	750–805	–	–0·2	–
Hippoglossus hippoglossus	2	320	–	1–2	–
Reinhardtius hippoglossoides	180	400–805	449	–0·2–4·5	1·6
Hippoglossoides platessoides	72	310–500	417	1·5–6·0	4·1
Lophius piscatorius	2	500	–	5·0	–

the otter-trawl, and it is obviously very rarely caught in situations where the bottom temperature is lower than 2·5°C, even if the midwater layers may show temperatures suitable for its occurrence. Therefore, it seems to be justified to conclude that the bulk of the trawl-caught specimens has been taken close to the bottom.

During both cruises many examples of true bathypelagic and even pelagic fishes were found in the stomachs of various species of "bottom fish", a situation which suggests that the bottom fish may either temporarily feed off the bottom, or that the midwater fish, limited to a certain minimum depth perhaps by factors such as pressures, may possibly "strand" at the edges of the Ridge and then are eaten by the bottom fish. These midwater fish are not included in our report.

MATERIAL AND METHODS

The stations worked during the two cruises are listed in Table 9:1. Tables 9:2 A and 9:2 B show the numbers of demersal fish caught at the different stations of the respective cruises according to their families, and give their size range and their mean lengths. Furthermore,

Table 9:4

Bt.°C	*Cottunculus* No. of specimens	(No. of hauls)	*Reinhardtius* No. of specimens	(No. of hauls)
< 0	7	(2)	19	(2)
0–1	5	(1)	11	(2)
1–2	7	(3)	105	(3)
2–3	4	(1)	31	(3)
3–4	–	(–)	5	(1)
4–5	2	(2)	7	(3)

the letters "b" (= boreal), "ba" (= boreo-Arctic), and "a" (= Arctic), following the scientific name of each species, give a hint as to the ichthyogeographic components to which the species are referred. In the headlines of these tables the serial number of each station, the depth, the bottom temperature, and the duration of the haul (trawl at the bottom) are given.

The number of species was 34, in 1959 and 23 in 1960; altogether 36 species were caught. Immediately after capture, the fish were identified (the non-commercial species by the junior author) and measured to the cm below. Examples of most of the species were preserved and are stored in the collections of the "Institut für Seefischerei", Hamburg.

The vertical distribution of the species and their relation to the bottom temperatures are listed in Tables 9:3 and 9:5. The geographic distribution is mapped on Figures 9:1 to 9:8, those of the 1960 cruise (signed with "B") showing also the thermic situation at the bottom according to the third hydrographic survey of the "Overflow-Programme". For the 1959 cruise (signed with "A"), a cover page[7] gives the bottom temperatures so far actually measured. A second cover page for all the maps shows the topography of the Iceland-Faroe Ridge.

The symbols for the individual species are of different sizes according to the number of specimens caught. When the duration of a haul exceeded the usual 30 minutes, the numbers of fish actually caught have been converted to the standard haul in order to make the figures on the maps comparable. Some exceptions, however, were made for some rare species. In Figure 9:6 the composition of the redfish catches is shown according to "types".

Finally, the composition of the individual hauls was investigated according to the ichthyogeographic elements of which they were composed. This is shown in Table 9:6 as well as in the Figures 9:9A and 9:9B and thoroughly discussed in the following section.

[7] For Cover Pages 1 and 2 see pocket in the cover of this volume.

THE ICHTHYOFAUNA OF THE ICELAND-FAROE RIDGE AND ITS DISTRIBUTION

The demersal fish community of the Iceland-Faroe Ridge comprises at least three major faunal elements, viz. a boreal, a boreo-Arctic, and an Arctic component.

The first component may be further subdivided into a species group typically inhabiting the deeper parts of the Continental Shelf and the offshore banks and into another group whose species characteristically inhabit the Atlantic slopes, where they occupy a much wider geographical range than do the bankfish.

The group of boreal bankfish represented in our catches is made up of the following seven species: the gadoid fishes *Gadus morhua* Linnaeus, *Melanogrammus aeglefinus* (Linnaeus), *Pollachius virens* (Linnaeus), the sandeel *Ammodytes lancea marinus* Raitt, the lesser redfish *Sebastes viviparus* Krøyer, the long rough dab *Hippoglossoides platessoides* (Walbaum), and the monkfish *Lophius piscatorius* Linnaeus.

Atlantic deep-water species are: the dogfishes *Centroscymnus coelolepis* Bocage & Capello and *Centroscyllium fabricii* (Reinhardt), the spiny eel *Notacanthus phasganorus* Goode, the grenadierfish *Coryphaenoides rupestris* Gunnerus, the morid fish *Lepidion eques* Günther, the black scabbardfish *Aphanopus carbo* Lowe and the cottunculid *Cottunculus thomsonii* (Günther), i.e. equally 7 species. Four other boreal species link the two sub-groups together to some degree; these are *Argentina silus* (Ascanius), the blue whiting *Micromesistius poutassou* (Risso), the blue ling *Molva dypterygia* (Pennant), and the torsk *Brosme brosme* (Ascanius), the first two of which are indeed semi-pelagic and therefore perhaps show a wider range in their bathymetric distribution.

Turning to the boreo-Arctic element, we encounter an ecological group of fish, most species of which show a rather unorthodox relationship to the depth, their distribution being mainly governed by temperature. According to Saemundson (1949) and others we might regard the following eight species as boreo-Arctic: the rajids *Raja radiata* Donovan and *R. fyllae* Lütken, the grenadier *Macrourus berglax* Lacépède, the

(Continued on p. 262)

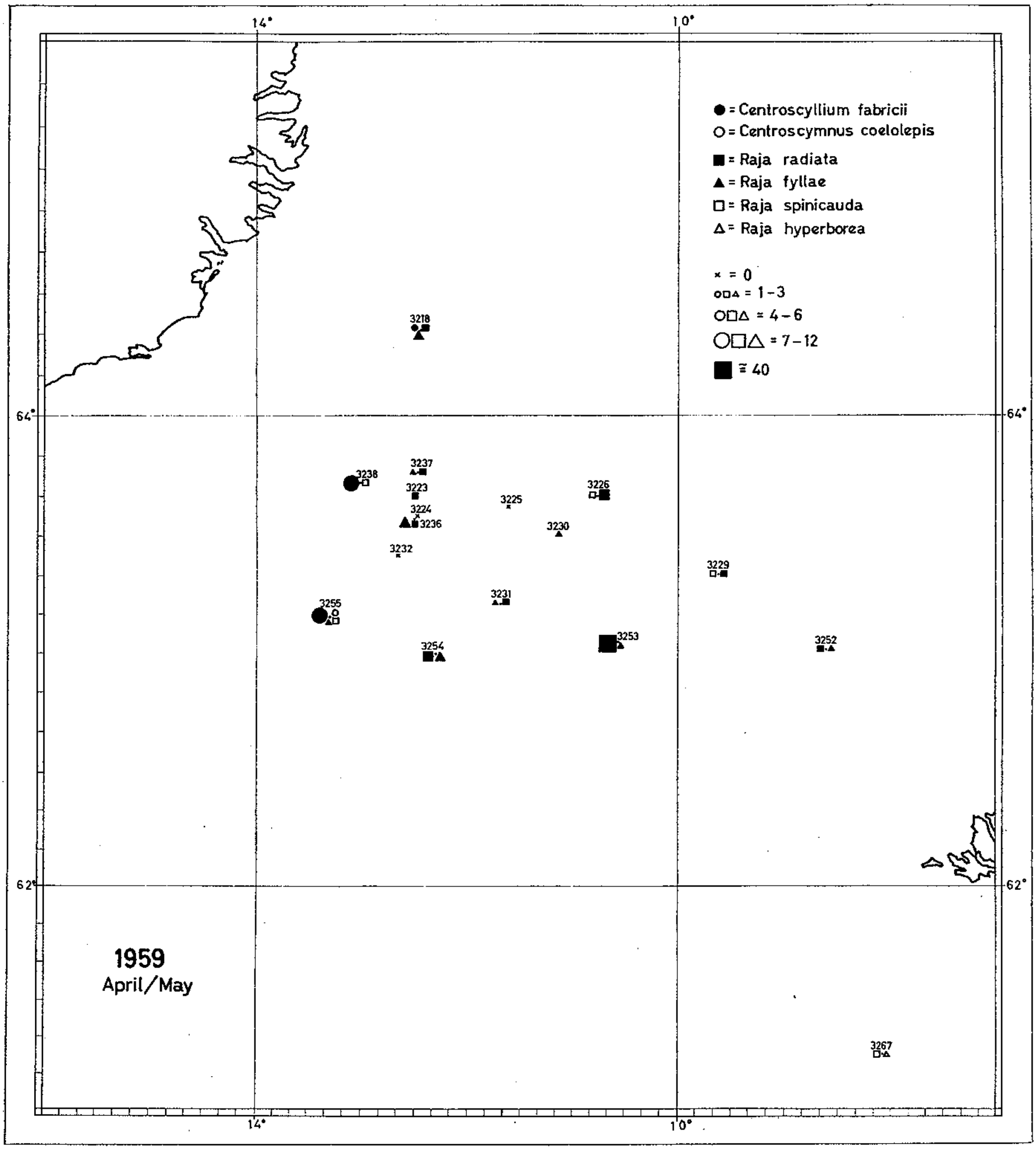

Figure 9 : 1 A. Distribution of Elasmobranch catches, 1959 cruise.

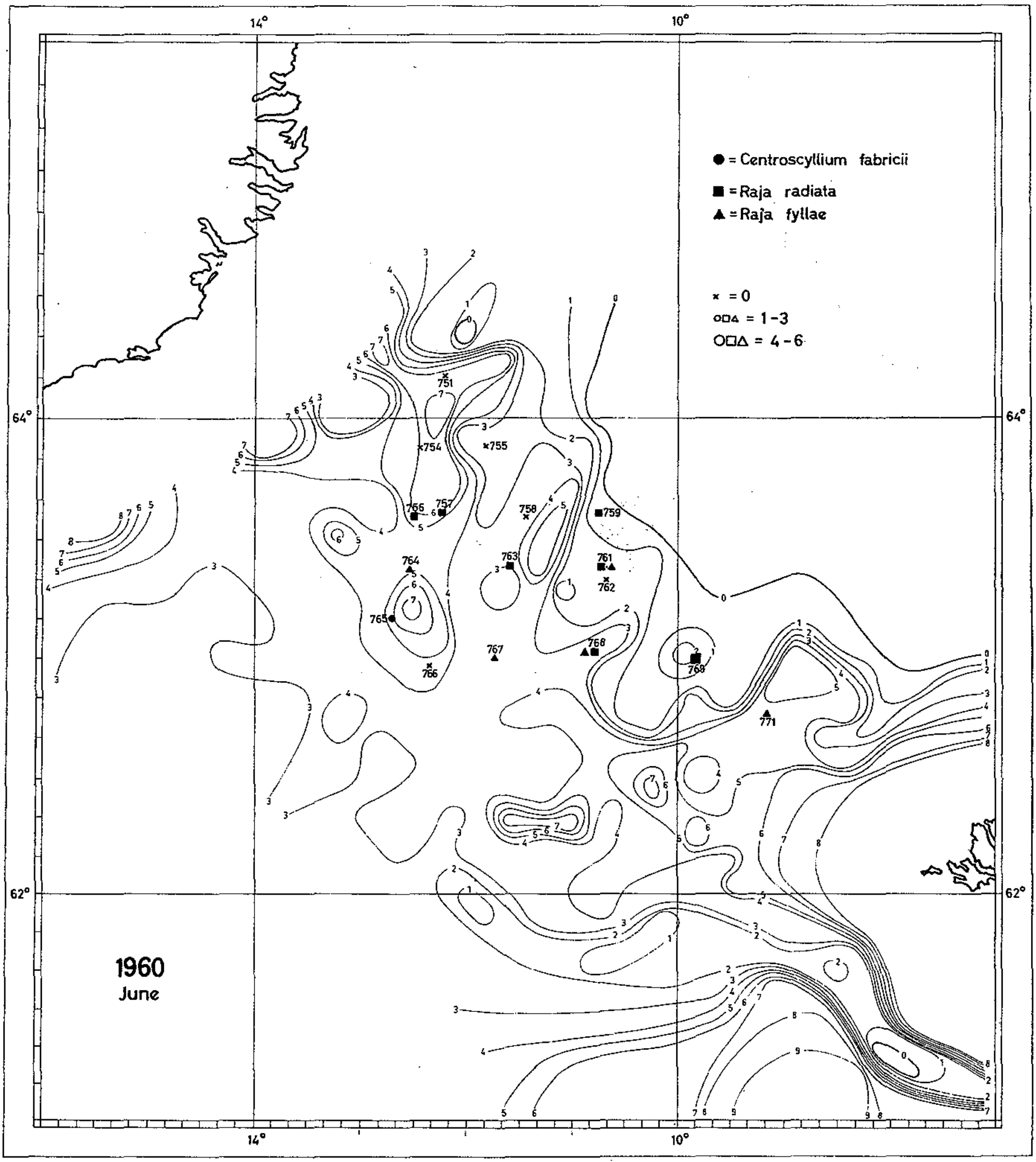

Figure 9:1 B. Distribution of Elasmobranch catches, 1960 cruise.

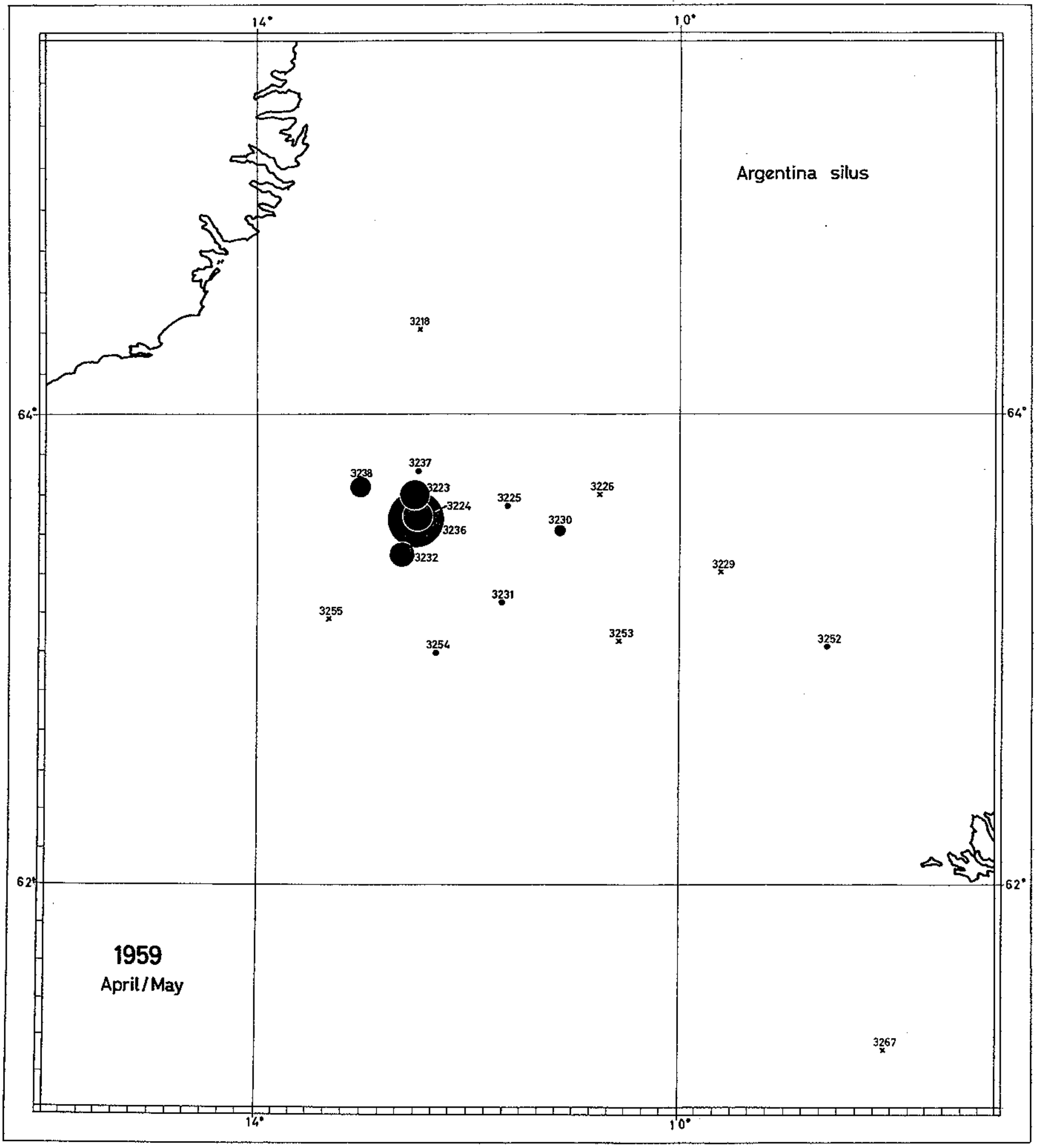

Figure 9:2 A. Distribution of catches of *Argentina silus*, 1959 cruise.

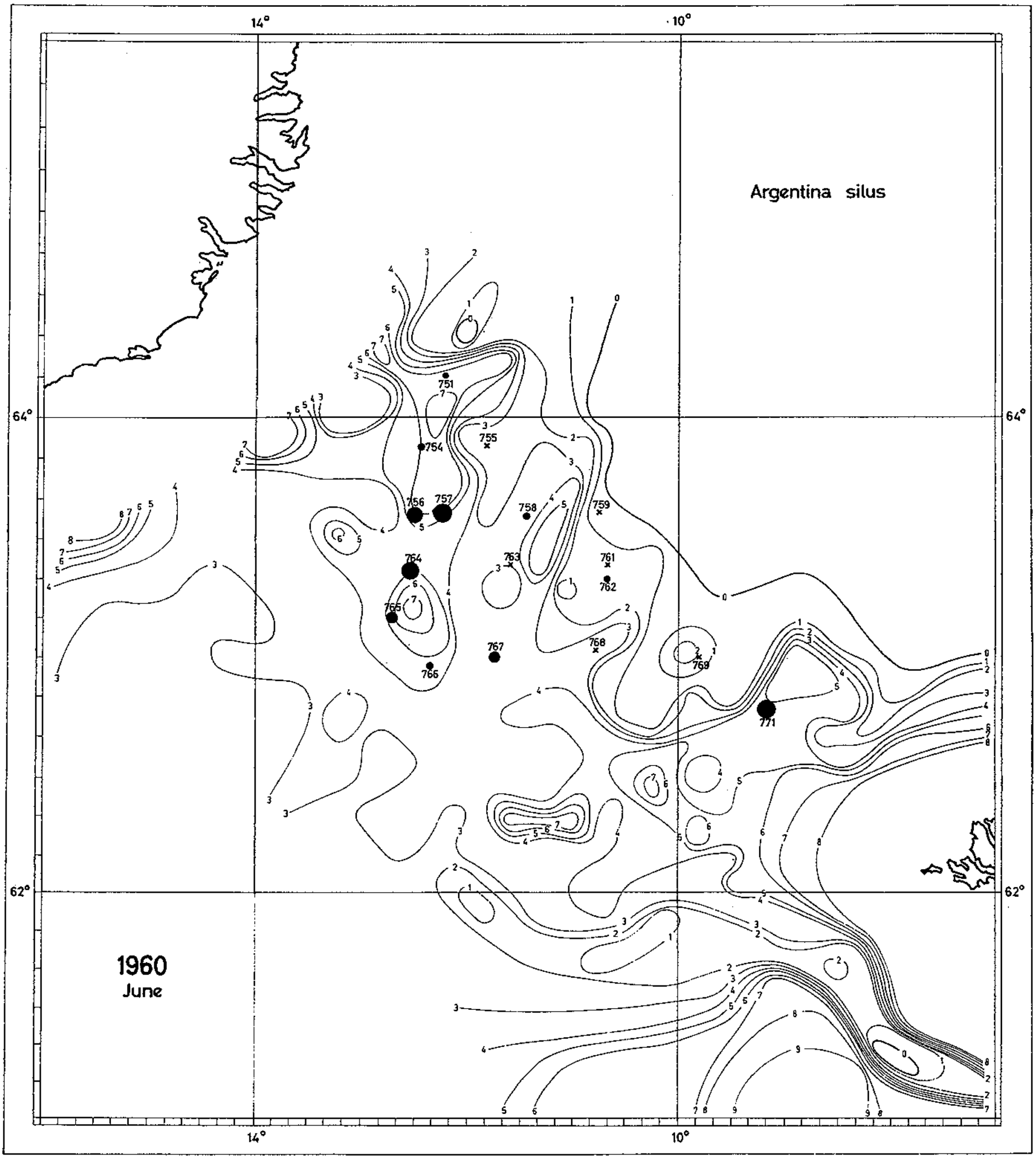

Figure 9:2 B. Distribution of catches of *Argentina silus*, 1960 cruise.

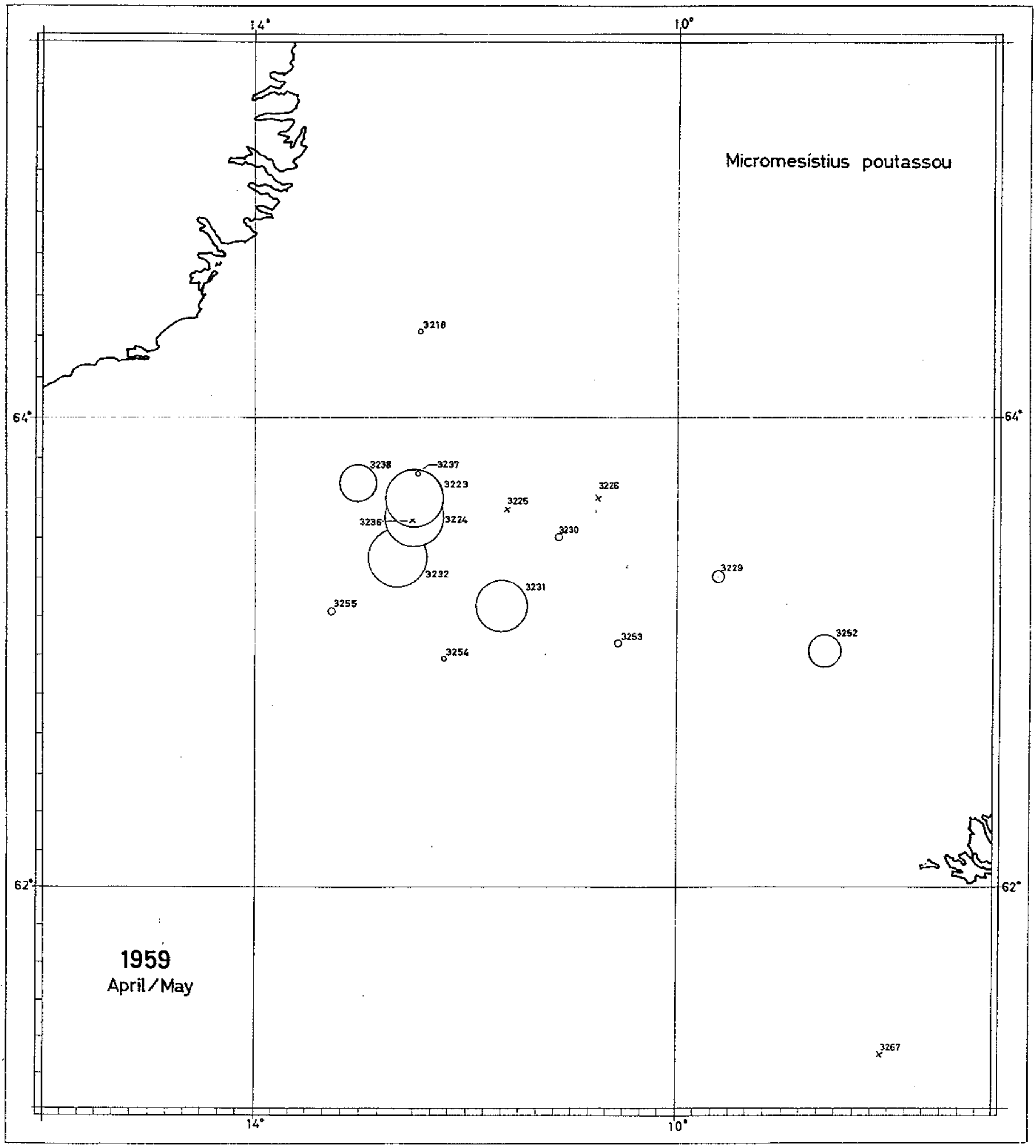

Figure 9:3 A. Distribution of catches of *Micromesistius poutassou*, 1959 cruise.

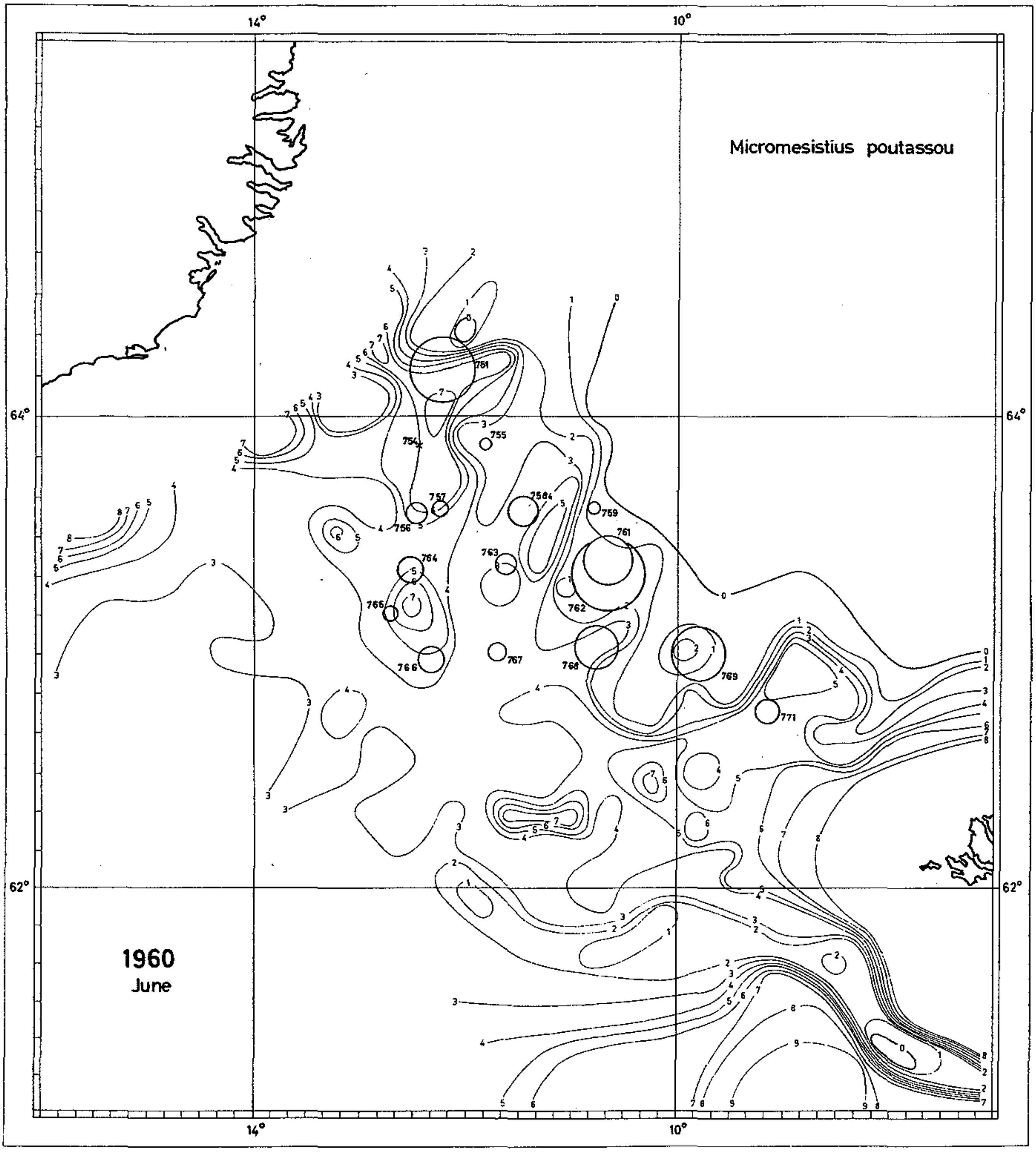

Figure 9:3 B. Distribution of catches of *Micromesistius poutassou,* 1960 cruise.

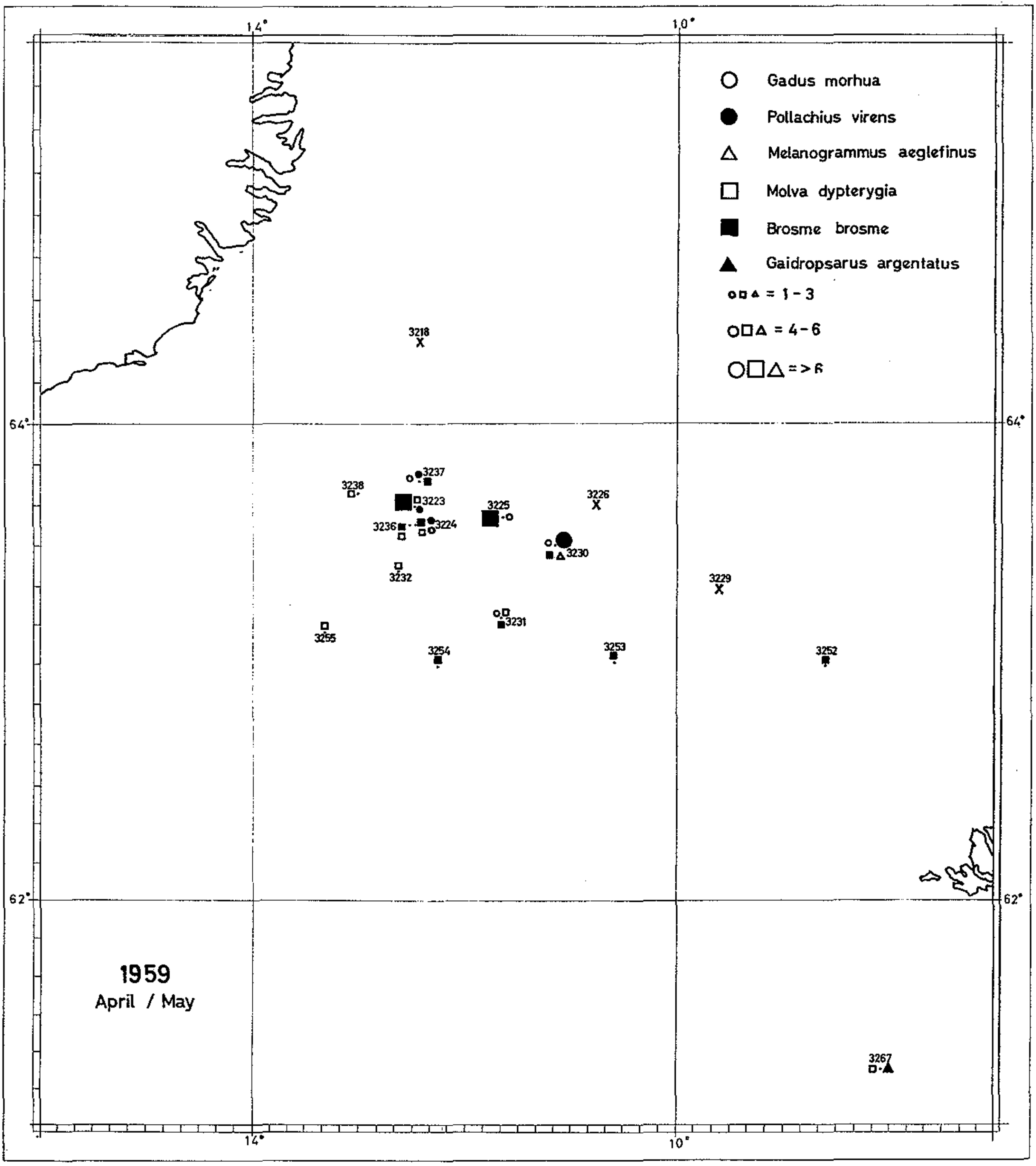

Figure 9:4 A. Distribution of Gadoid catches (except *Micromesistius*), 1959 cruise.

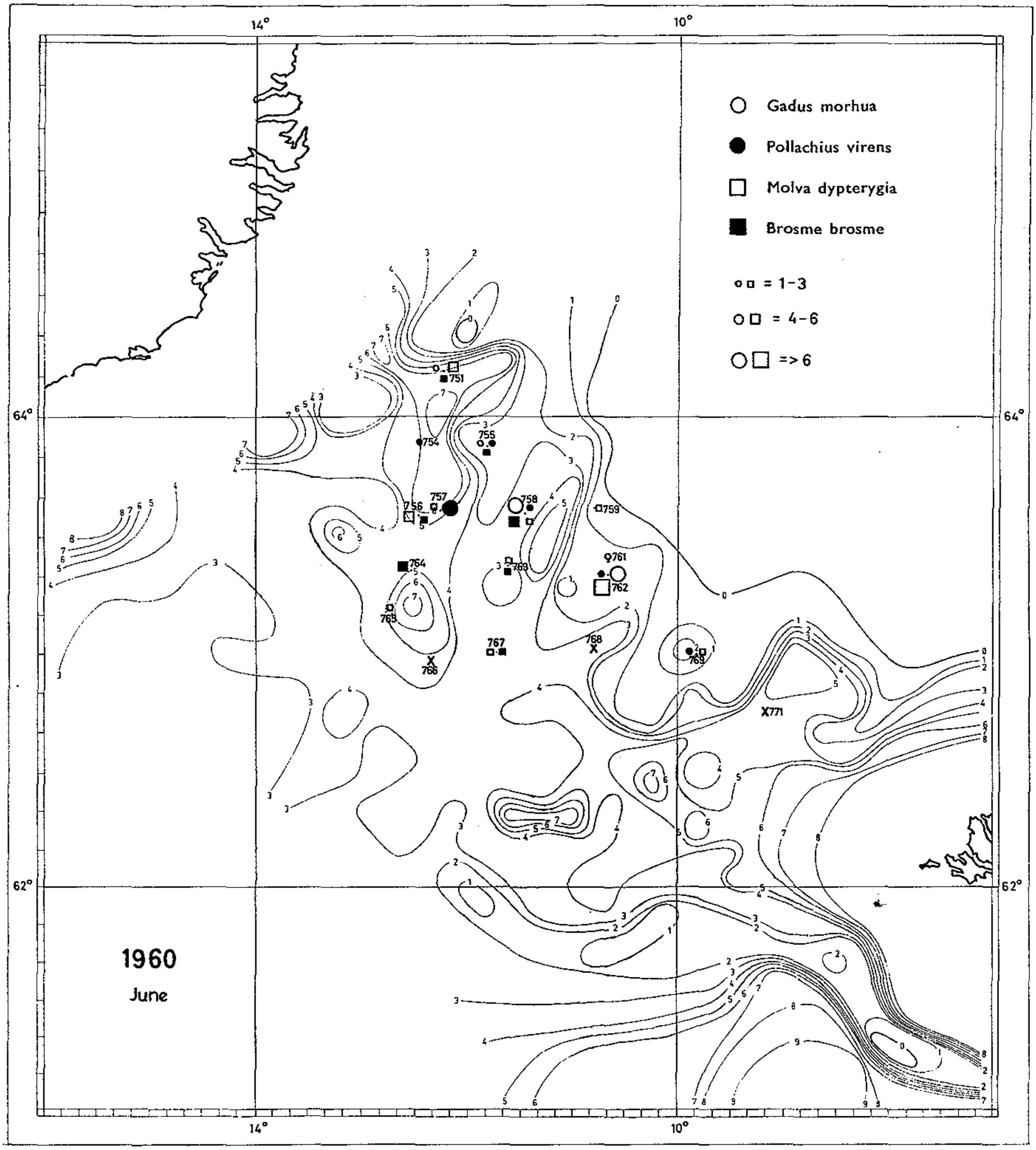

Figure 9:4 B. Distribution of Gadoid catches (except *Micromesistius),* 1960 cruise.

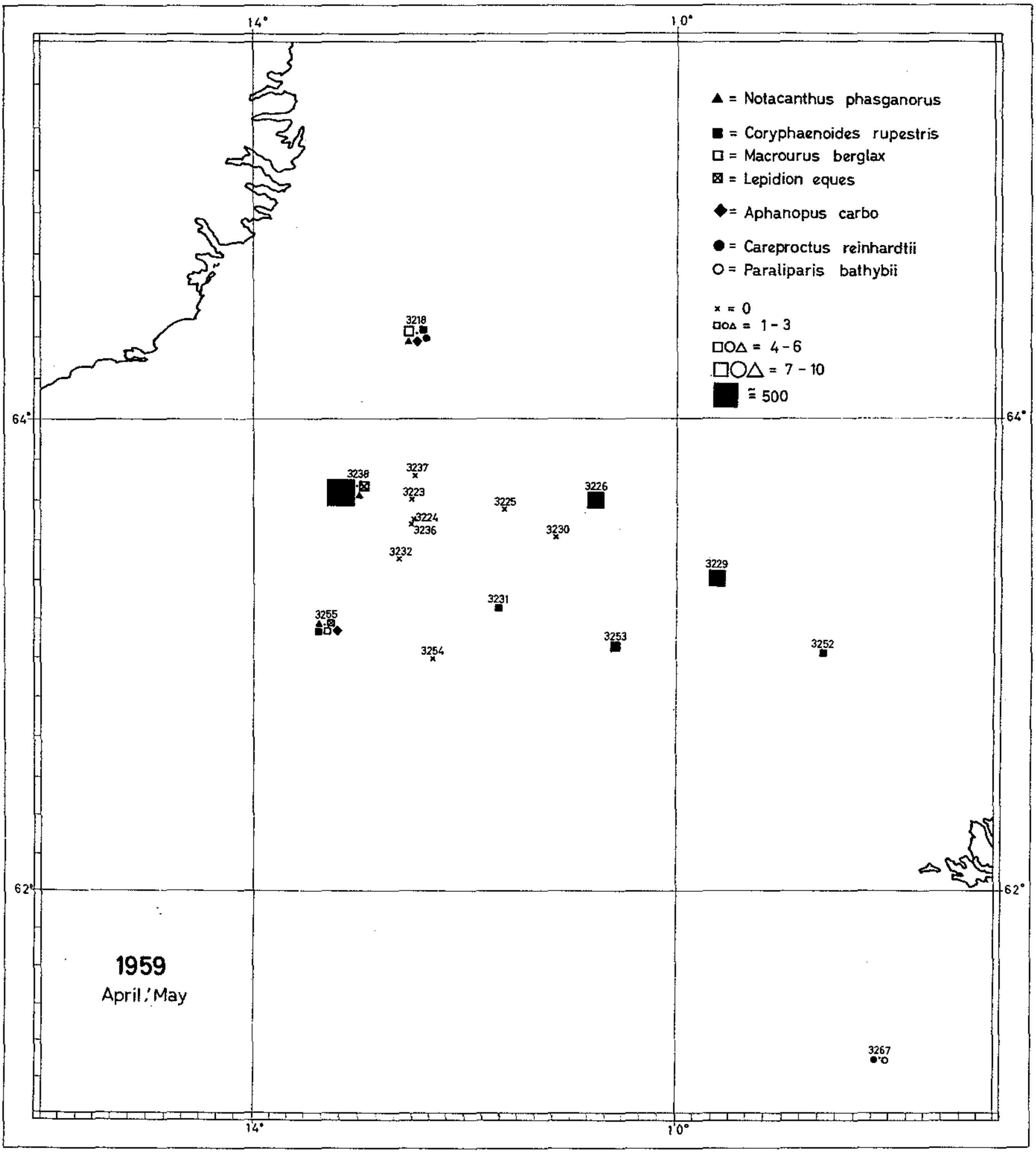

Figure 9:5 A. Distribution of catches of Notacanthidae, Macrouridae, Moridae, Ammodytidae, Trichiuridae, Liparidae and Lophiidae, 1959 cruise.

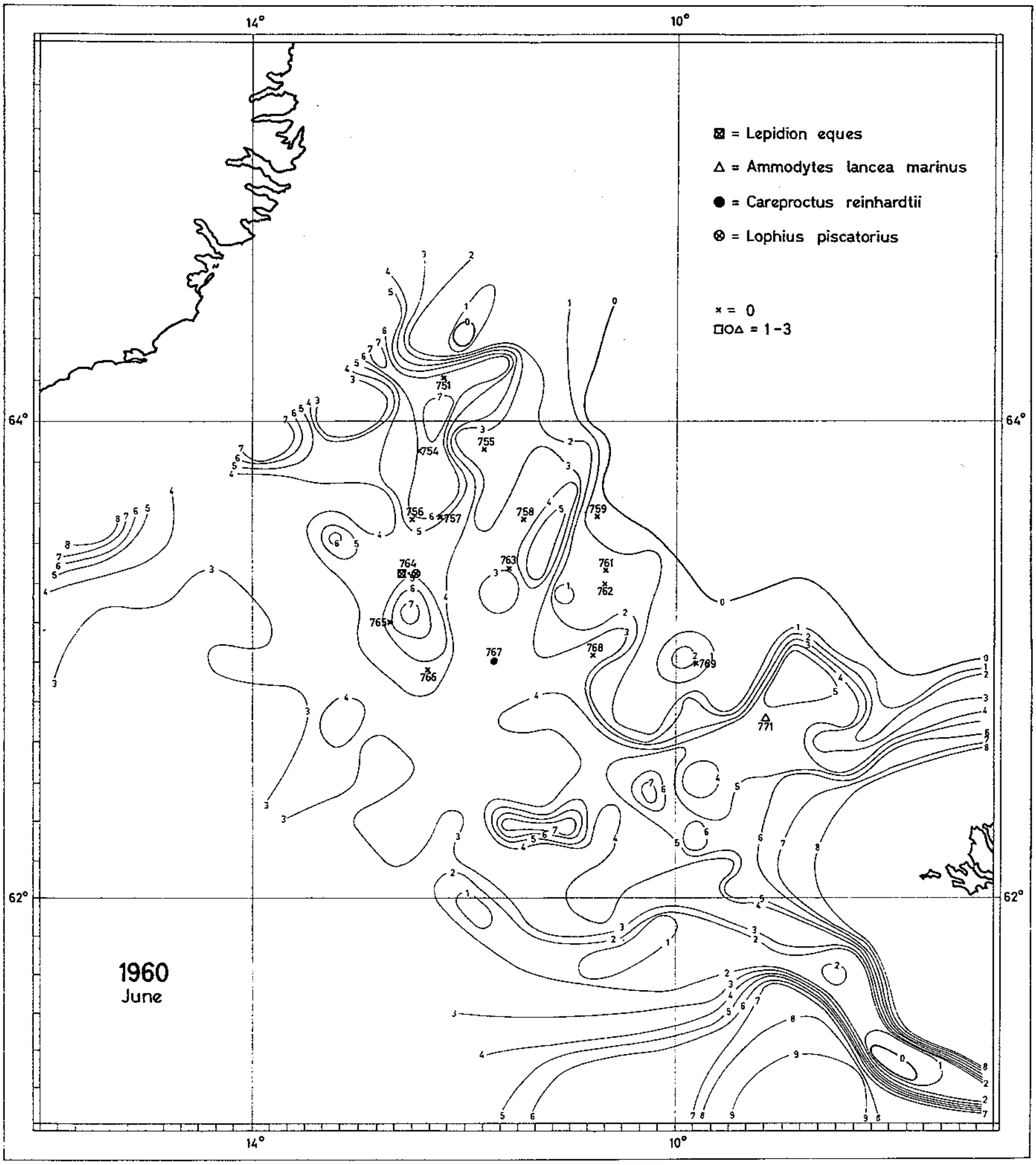

Figure 9:5 B. Distribution of catches of Notacanthidae, Macrouridae, Moridae, Ammodytidae, Trichiuridae, Liparidae and Lophiidae, 1960 cruise.

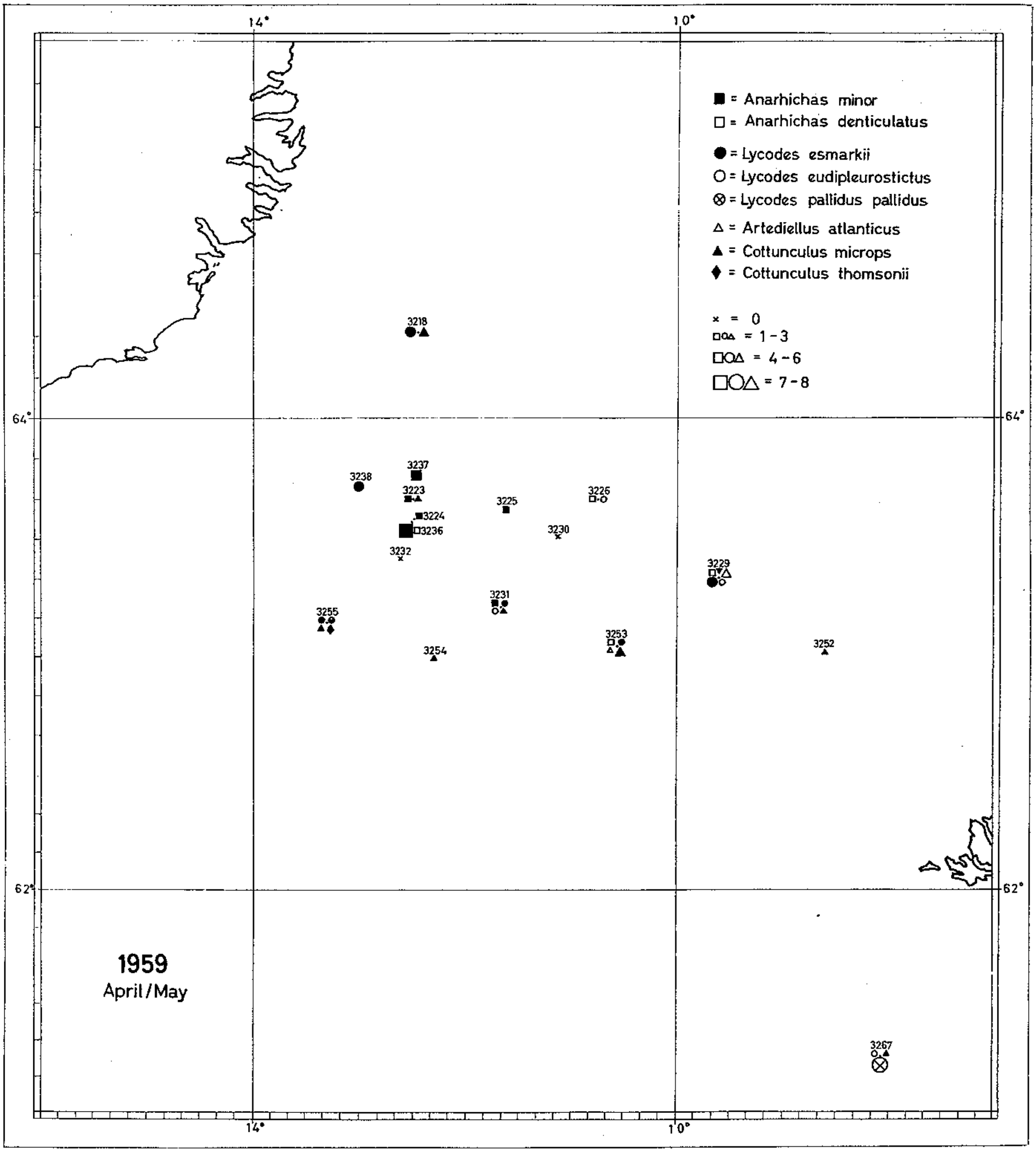

Figure 9:6 A. Distribution of catches of Blennioidea, Cottidae and Cottunculidae, 1959 cruise.

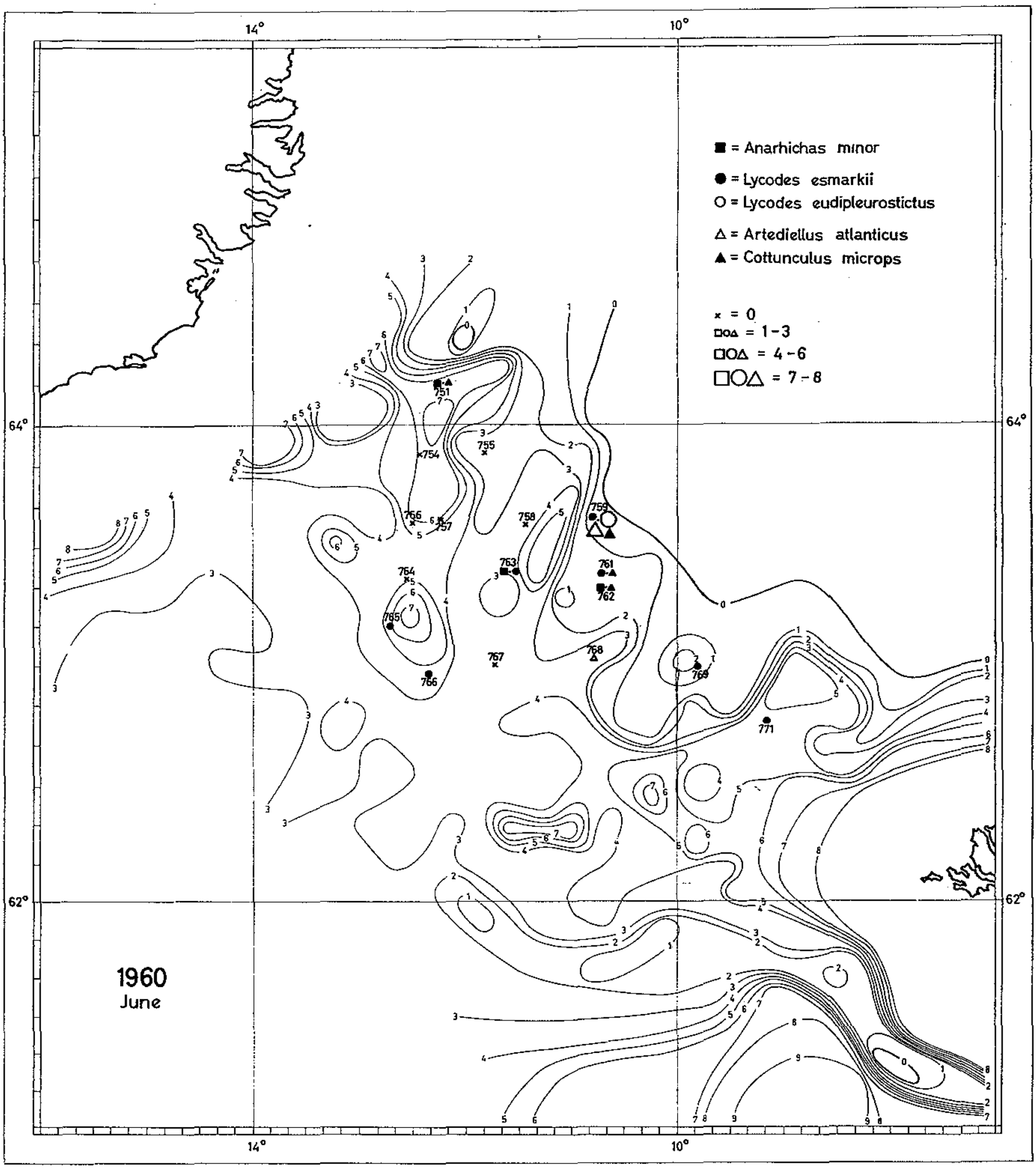

Figure 9:6 B. Distribution of catches of Blennioidea, Cottidae and Cottunculidae, 1960 cruise.

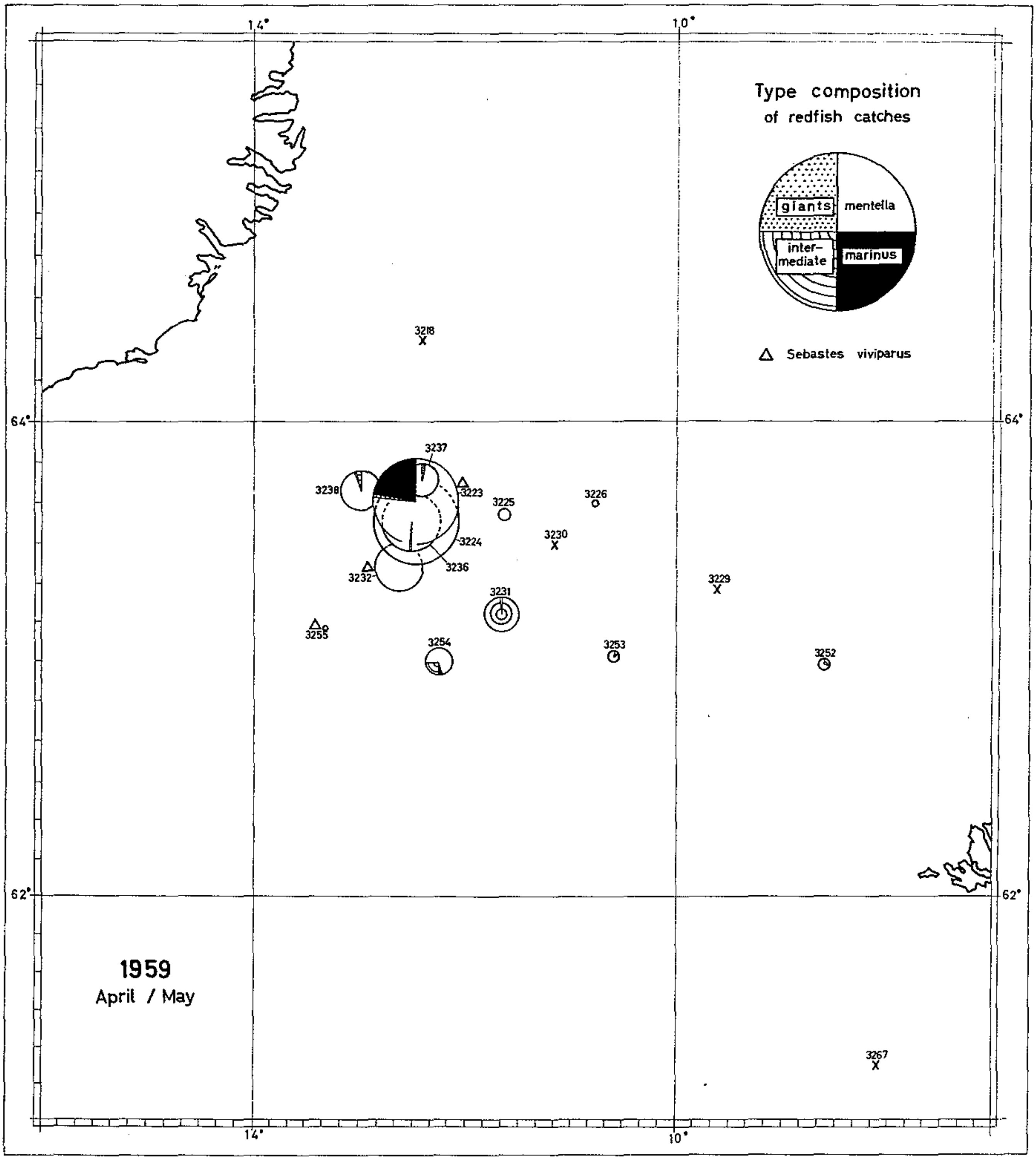

Figure 9:7 A. Distribution of Redfish catches, 1959 cruise.

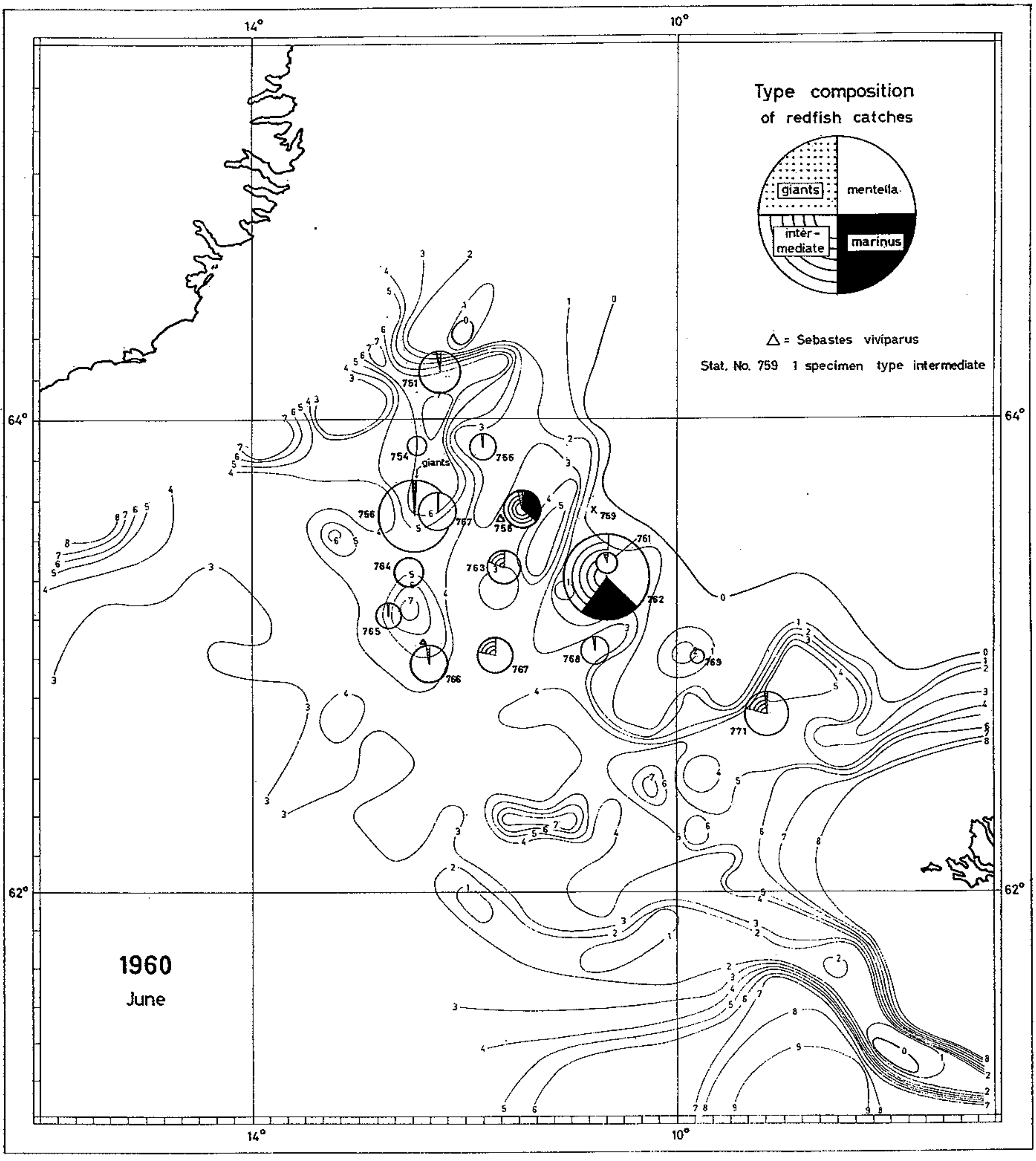

Figure 9:7 B. Distribution of Redfish catches, 1960 cruise.

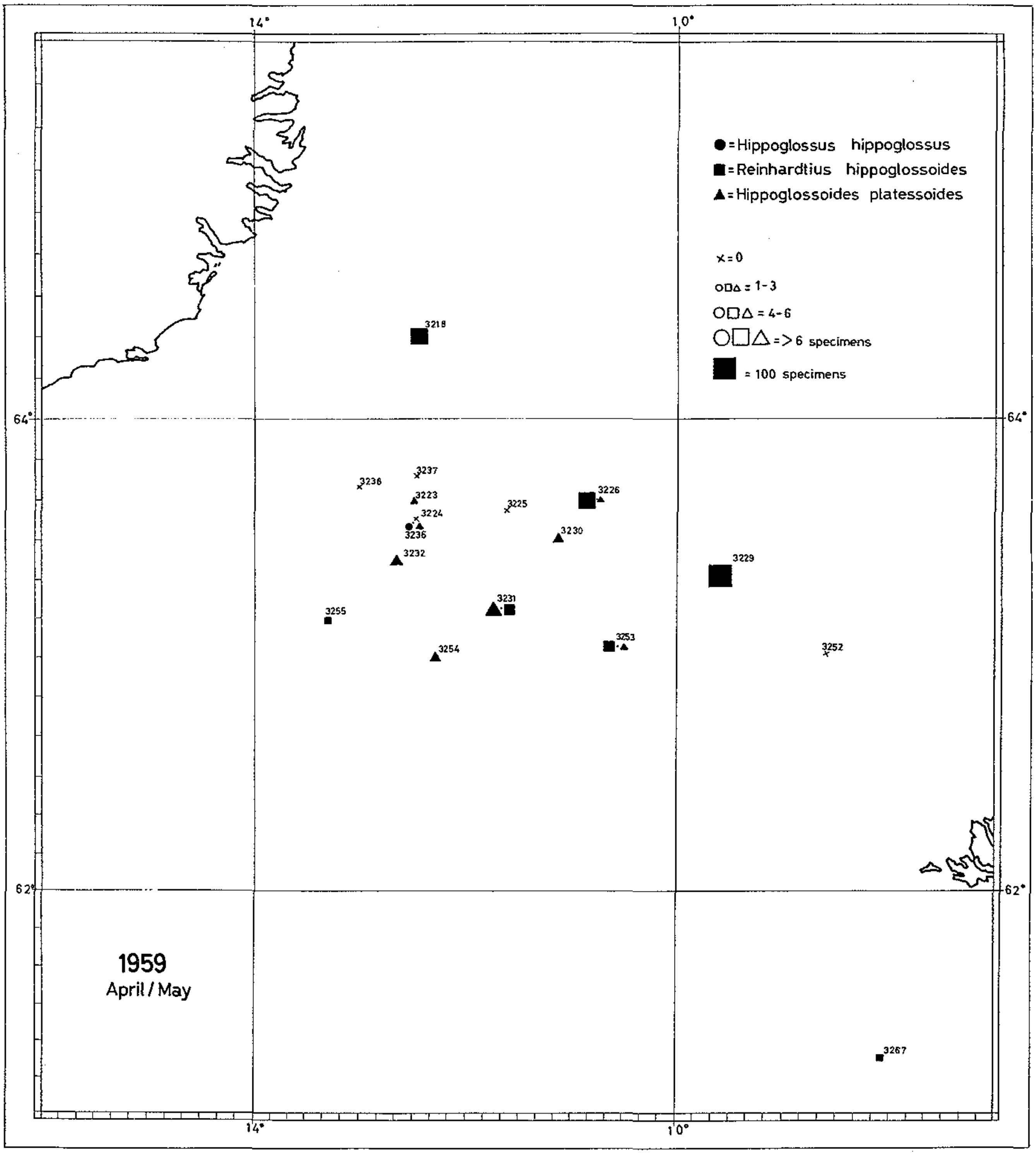

Figure 9:8 A. Distribution of Pleuronectid catches, 1959 cruise.

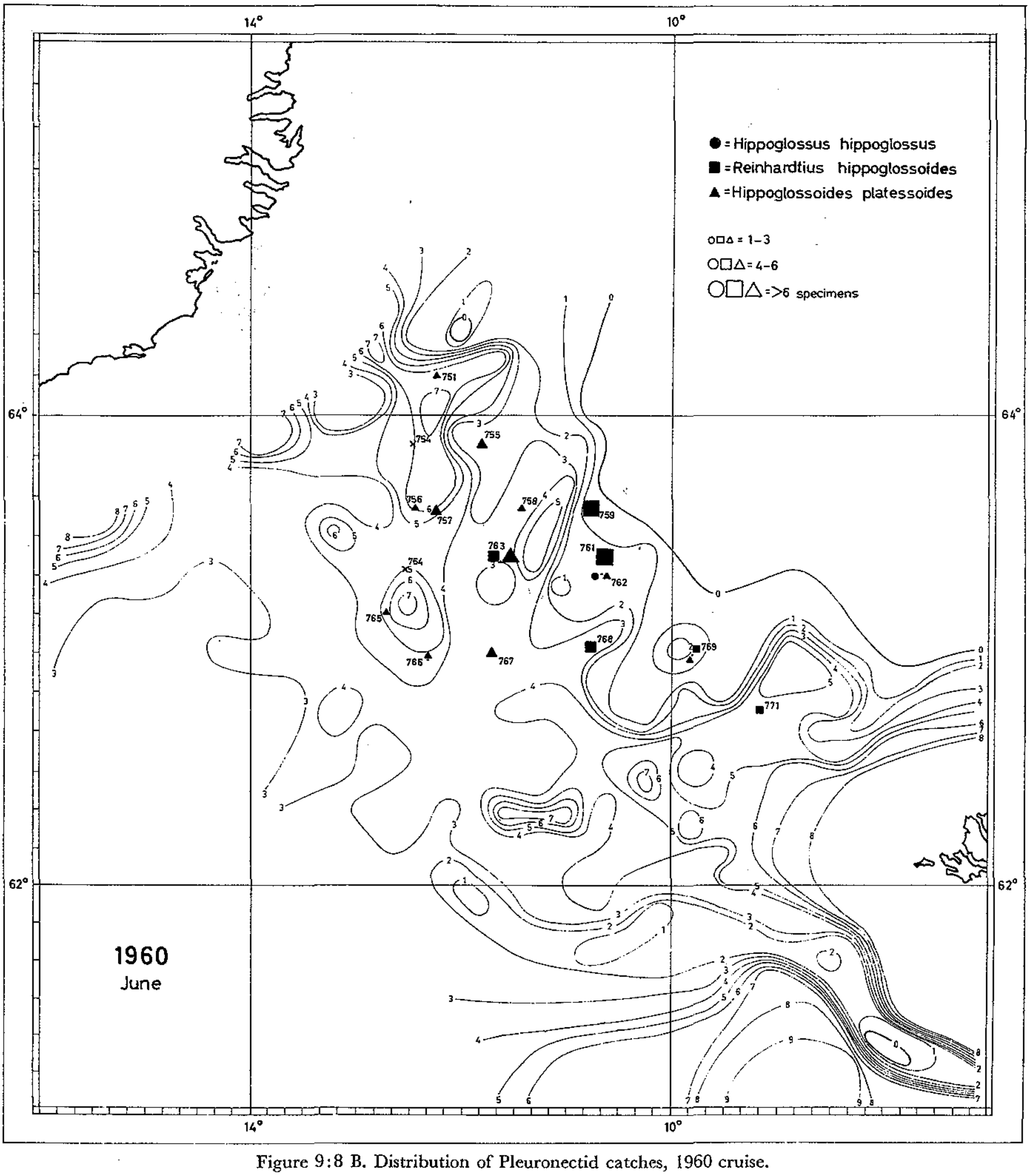

Figure 9:8 B. Distribution of Pleuronectid catches, 1960 cruise.

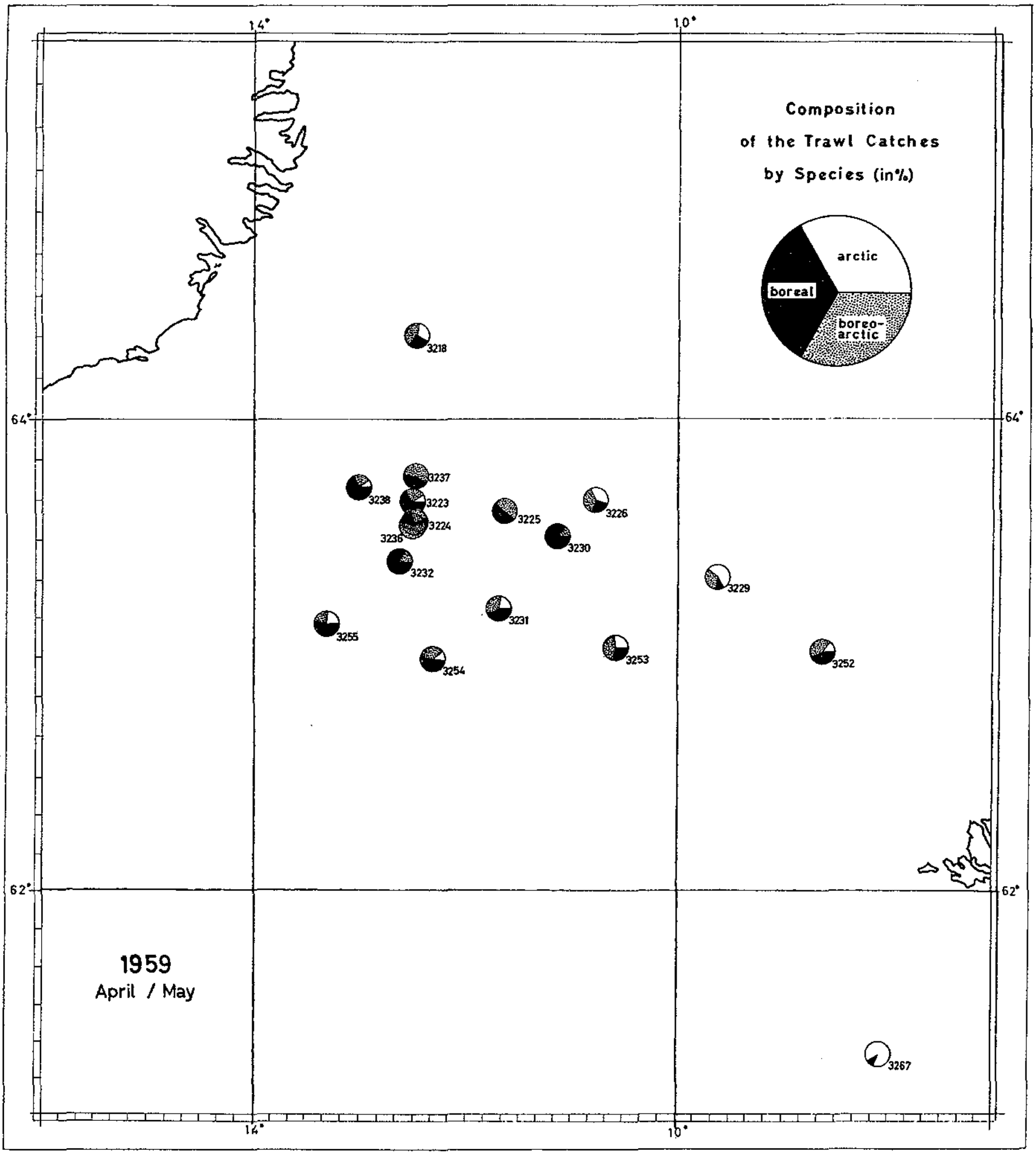

Figure 9:9 A. Ichthyogeographic composition of the trawl catches as percentages of species caught, 1959 cruise.

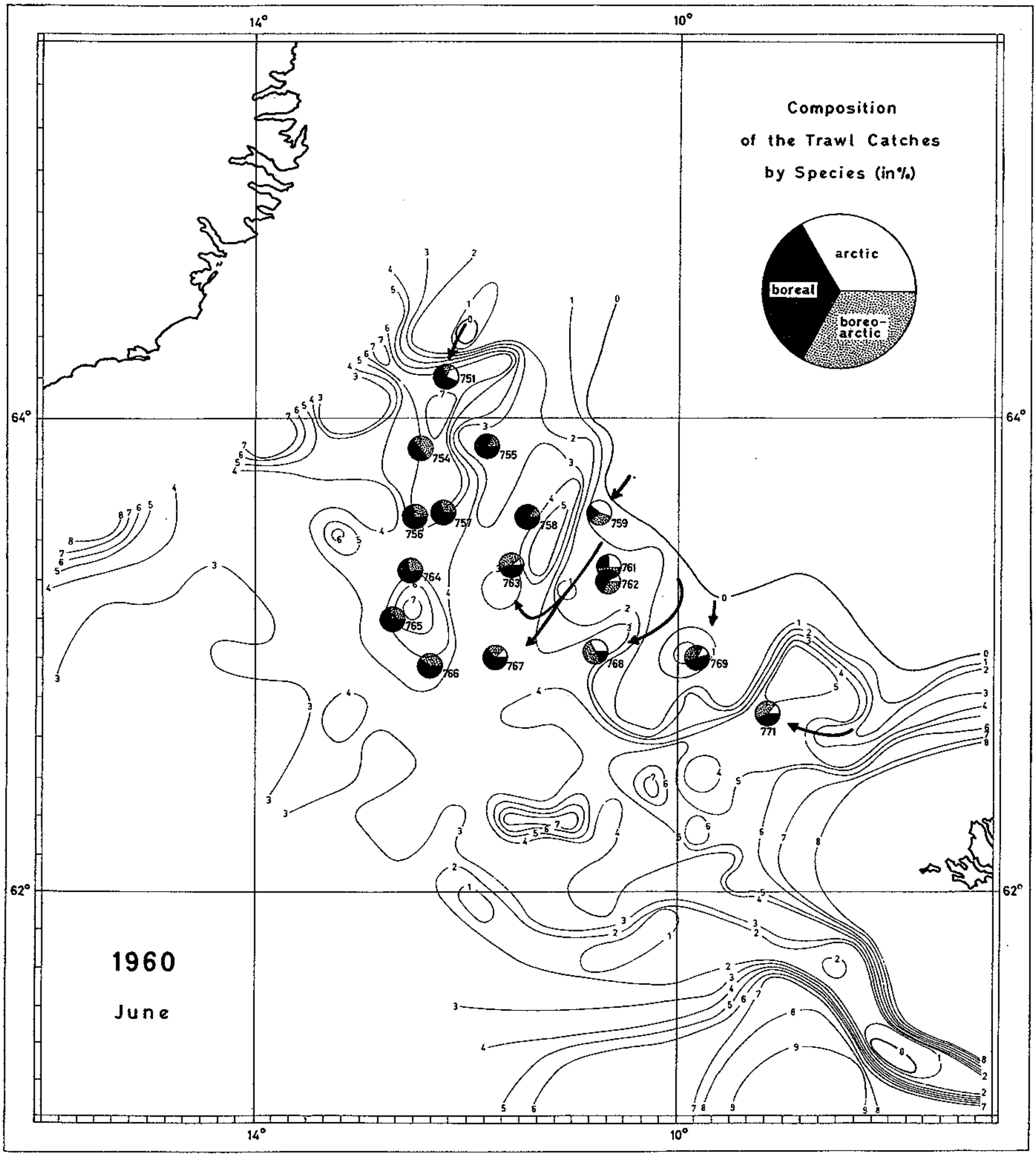

Figure 9:9 B. Ichthyogeographic composition of the trawl catches as percentages of species caught, 1960 cruise.

wolffishes *Anarhichas minor* Olafsen, *A. denticulatus* Krøyer and *Lycodes esmarkii* Collett, the redfish *Sebastes marinus* Linnaeus (including the mentella-form) and the halibut *Hippoglossus hippoglossus* (Linnaeus).

The Arctic element is represented by the skates *Raja spinicauda* Jensen and *R. hyperborea* Collett, the gadoid fish *Gaidropsarus argentatus* (Reinhardt), the wolffishes *Lycodes eudipleurostictus* Jensen and *L. p. pallidus* Collett, the small cottid fish *Artediellus atlanticus* Jordan & Evermann, in spite of the fact that it is taken as "boreo-Arctic, coastal"(!) by SAEMUNDSON (l.c.), the cottunculid fish *Cottunculus microps* Collett, the two liparids *Careproctus reinhardtii* Krøyer[8] and *Paraliparis bathybii* Collett, and the Greenland halibut *Reinhardtius hippoglossoides* (Walbaum) – altogether ten species showing a more or less distinct preference for deep water.

Some remarks should be made concerning the use of the term "Arctic". The species lumped together here as a group certainly reveal differences with regard to their adaptation to environmental conditions, e.g. some of them being much more eurythermic than others. Thus *Raja spinicauda*, *Reinhardtius hippoglossoides* and especially *Cottunculus microps* are able to sustain rather high temperatures for a period long enough at least to survive a temporary warming of their habitats. Others, as e.g. *Artediellus*, seem to have successfully established populations adapted to a boreal environment at the southern edge of their habitats. Since, however, all these species reach their maximum abundance in the cold water and since they not only tolerate but seem to prefer much lower temperatures than the boreo-Arctic fish, we include them here in the group called as a matter of convenience "Arctic", though the term "sub-Arctic "might seem to be more adequate for at least some of them.

According to BARANENKOVA, PONOMARENKO & SEREBRYAKOV (1962), the Greenland skate ought to be taken as a "warm" water fish rather than an Arctic species. However, the catches of the species in Newfoundland waters of between $+0{\cdot}65°$ and $-1{\cdot}5°$C as well as its occurrence together with *R. hyperborea* in the Faroe Channel at negative temperatures exclude to our minds the Greenland skate from the boreo-Arctic group.

In Table 9:4 the numbers of *Cottunculus* and *Reinhardtius* are shown in relation to the temperatures observed during the two cruises.

The temperature range between 0° and 2° C seems to be the preferred one in both species.

[8] According to the characters lined out by BURKE (1930) the specimens of the Iceland-Faroe Ridge would fall under *C. longipinnis* Burke, 1912. However, as long as the taxonomic status of the Greenlandic *Careproctus* appears to be uncertain, we prefer the more conservative attitude in referring the specimens to *reinhardtii* Krøyer.

In summary, the ichthyogeographical analysis of the demersal fish caught on the Iceland-Faroe Ridge reveals the following composition:

A. Boreal	18	species
1) "Bankfish"	7	,,
2) Atlantic deep water fish	7	,,
3) "Connecting species"	4	,,
B. Boreo-Arctic	8	,,
C. Arctic deep water fish	10	,,

In Table 9:5 the mean values for the distribution of the species according to depth and bottom temperatures as observed during the two cruises of "Anton Dohrn" are shown. Where a species was caught at one station only, the values for depth and temperature of this station are given instead of a mean. In spite of the scarcity of available data, we arrived in this manner at results fitting very well to the expected distribution. Thus the boreal species are listed on the left, i.e. in the relatively "warm" half of the table, the "bankfish" occupying the upper left quarter, the deep-water species the lower one. In a similar way the Arctic species are found on the "cold" right half of Table 9:5, whereas the boreo-Arctic fish are widely scattered over both sides of its upper half.

On the other hand, considering the species-composition of the different stations, no single location is occupied by one faunal element only. This is certainly due to the fact that all of the stations were situated within the border-area between the boreal Atlantic and the Arctic Norwegian Sea, and the deepest hauls suggest what would have been found farther down the slope on either side of the Ridge. Thus, at the wesernmost station at a depth of between 735 and 765 mtand with a bottom temperature of 4·2° C (stat. 3255) the catch comprised a boreal assemblage composed of such typical Atlantic deep-water representatives as *Centroscyllium*, *Centroscymnus*, *Notacanthus*, *Coryphaenoides*, *Lepidion*, *Aphanopus*, and *Cottunculus thomsonii*. In contrast, the easternmost haul (stat. 3267), which took place in the Faroe Channel at depths of between 750 and 805 m and at a temperature of $-0{\cdot}2°$C, reveals a highly Arctic community with *Raja hyperborea*, *R. spinicauda*, *Gaidropsarus argentatus*, *Lycodes eudipleurostictus*, *L. p. pallidus*, *Cottunculus microps*, *Reinhardtius hippoglossoides*, *Careproctus reinhardtii* and *Paraliparis bathybii*.

The Ridge itself – that is, the commercially fished areas between the 300 m and 500 m isobaths, known to the German fishermen as the "Rosengarten" – is the typical habitat of a mixed fauna consisting mainly of boreo-Arctic species, with the redfish, the main objective of the commercial fishery there, being the "Leitform" (dominating species). The species comprising this community are either eurythermic – the true bottom fish – and adapted to sustain rather rapid

Table 9:5.
Mean distribution of demersal fish species according to depth and bottom temperatures (1959 and 1960 cruises combined)

Bt. °C / Depth m.	5–6	4–5	3–4	2–3	1–2	0–1	>0
300–350	*Melanogrammus aeglefinus*		*Gadus morhua*		*Hippoglossus hippoglossus*		
351–400	*Pollachius virens*		*Sebastes marinus*, type *marinus*	*Sebastes marinus*			
401–450		*Brosme brosme* *Sebastes marinus*, type *mentella* and giants *Hippoglossoides platessoides*	*Micromesistius poutassou* *Molva dypterygia* *Anarhichas minor*	*Anarhichas denticulatus*	*Reinhardtius hippoglossoides*		
451–500	*Lophius piscatorius*	*Argentina silus* *Ammodytes lancea marinus*	*Raja fyllae*	*Raja radiata* *Lycodes esmarkii* *Cottunculus microps*		*Lycodes eudipleurostictus* *Artediellus atlanticus*	
501–550		*Sebastes viviparus*	*Macrourus berglax*				
551–600				*Raja spinicauda* *Careproctus reinhardtii*			
601–650			*Notacanthus phasganorus* *Lepidion eques* *Coryphaenoides rupestris*				
651–700			*Centroscyllium fabricii*				
701–750		*Centroscymnus coelolepis* *Aphanopus carbo* *Cottunculus thomsonii*					
751–800						*Lycodes pallidus*	*Raja hyperborea* *Gaidropsarus argentatus* *Paraliparis bathybii*

changes in bottom temperatures, or are semi-pelagic, and therefore able to avoid such changes by rising to a more suitable water layer. Most of the species involved show a vast geographical distribution, with a particular community forming a characteristic belt of varying width marking the borders between the boreal and the Arctic fish fauna along the submarine ridges and the edges of the continental shelves in the North Atlantic area. This belt coincides rather closely with the known distribution of *Sebastes marinus* s.l.

The phenomenon of the "overflow" might, we think, be mirrored by the distribution of the demersal fish in the area investigated. If the distribution of the Arctic species west of the Ridge could be discovered, perhaps some clues could be found as to the routes of the Arctic water, as well as to the manner in which it may pass

Table 9:6

Zoogeographic components of the ichthyo-fauna of the Iceland-Faroe Ridge by stations

Station No.	Depth m	Bt° C	Species caught: Boreal Nos.	Boreal °/₀	Boreo-Arctic Nos.	Boreo-Arctic °/₀	Arctic Nos.	Arctic °/₀	Characterization of the station
					1959				
3218	450–460	2·8	3[9]	30·0	4	40·0	3	30·0	boreo-Arctic
3223	450	5·1	7	63·6	3	27·3	1	9·1	boreal
3224	440–460	5·1	6	75·0	2	25·0	–	–	boreal
3225	350	5·4	2	50·0	2	50·0	–	–	boreal/boreo-Arctic
3226	430–450	2·7	2	25·0	3	37·5	3	37·5	boreo-Arctic/Arctic
3229	450	1·1	1	11·1	3	33·3	5	55·6	Arctic
3230	310	5·6	6	87·5	1	14·3	–	–	boreal
3231	400	4·1	6	42·8	5	35·7	3	21·4	boreo-Arctic
3232	500–510	3·8	5	83·3	1	16·7	–	–	boreal
3236	450	–	4	40·0	6	60·0	–	–	boreo-Arctic
3237	430	–	3	42·9	4	57·1	–	–	boreo-Arctic
3238	650	3·6	7	70·0	2	20·0	1	10·0	boreal deep water
3252	440	–	3	42·9	3	42·9	1	14·3	boreal/boreo-Arctic
3253	450	1·9	3	27·3	5	45·4	3	27·3	boreo-Arctic
3254	470–480	4·7	4	50·0	3	37·5	1	12·5	boreal/boreo-Arctic
3255	735–760	4·2	9	53·0	4	23·5	4	23·5	boreal deep water
3267	750–805	–0·2	1	10·0	–	–	9	90·0	Arctic deep water
					1960				
751	445	6	5	62·5	2	25·0	1	12·5	boreal
754	466	6	1	50·0	1	50·0	–	–	boreal[10]
755	370	2–3	5	83·3	1	16·7	–	–	boreal
756	450	6	5	71·4	2	28·6	–	–	boreal
757	400–410	6	5	71·4	2	28·6	–	–	boreal
758	320–330	3–4	7	87·5	1	12·5	–	–	boreal
759	480	–0·02	2	22·2	3	33·3	4	44·5	Arctic
761	410	1–2	2	25·0	4	50·0	2	25·0	boreo-Arctic
762	320	1–2	5	55·6	3	33·3	1	11·1	boreal/boreo-Arctic
763	400	3	4	44·4	4	44·4	1	11·2	boreo-Arctic
764	500	5	5	71·4	2	28·6	–	–	boreal
765	500	5–6	5	71·4	2	28·6	–	–	boreal
766	490–500	4–5	3	60·0	2	40·0	–	–	boreal
767	480	4	5	62·5	2	25·0	1	12·5	boreal
768	450	3–4	1	16·7	3	50·0	2	33·3	boreo-Arctic
769	480–500	2	4	50·0	3	37·5	1	12·5	boreal/boreo-Arctic
771	470	4–5	3	42·8	3	42·8	1	14·4	boreo-Arctic

[9] Only samples of more than 10 specimens of the semipelagic *Argentina* and *Micromesistius* are included, the smaller numbers presumably being caught pelagically.
[10] Only 10 minutes trawled; net damaged.

the Ridge, and as to its extension which may enable the Arctic fishes to extend their ranges. From the species captured by R. V. "Anton Dohrn", the following are listed by Murray and Hjort (1912) as being among the principal "coldwater" fish of the deep Norwegian Sea: *Raja hyperborea, Lycodes pallidus, L. eudipleurostictus, Cottunculus microps, Careproctus reinhardtii* and *Paraliparis bathybii*. To these fish we may add *Raja spinicauda, Gaidropsarus argentatus, Artediellus atlanticus,* and *Reinhardtius hippoglossoides*. According to Saemundsson (l.c., Table II) none of these species has ever been captured in the warm water to the south or west of Iceland, except *Raja spinicauda*, which is said to be very rare in the south of this island, and the Greenland halibut, also very rare to the west of it. The Arctic fish species found on the Iceland-Faroe Ridge therefore certainly have immigrated from the slope of the Norwegian Sea. So far as the number of species is concerned, it represents 27·8 °/₀ of the total demersal fish fauna, the number of specimens indeed being a very small one; this, however, may be related to the well-known fact that most of the species involved, when compared with either boreal or boreo-Arctic species, occur only in small numbers.

Table 9:6 and Figures 9:9A and 9:9B show the percentages of the species composition at the individual stations from the faunal point of view. A striking similarity can be seen at once in the distribution of the Arctic component when comparing the two cruises. It then appears that in both years the Arctic species which are found in the deeper grounds to the east as well as to the west of the "top" of the Ridge, with one exception only, did not inhabit the shallowest parts of the Ridge (within the 400 m-contour). The percentage of Arctic species decreases from east to west, but in the west apparently it increases again with increasing depth (1959). Figure 9:9B illustrates a rather satisfying relationship between the distribution of these species and the isotherms. Bearing in mind the fact that the hydrographical situation shown on the map was drawn up some days before the fishery stations were done, a close parallelism may not be expected. Nevertheless, the stations where Arctic species were captured are situated either inside or somewhat in front of the indentations of the isotherms where the cold water is pushing southwestwards or westwards. The fish distribution therefore could suggest a somewhat advanced phase of the hydrographical situation in which the cold water masses have been progressing on their way across the Ridge. However, there is also the possibility that the Arctic species might be more or less stationary, their distribution rather closely linked with fixed passages of cold water. Not only is the fact that the similarity in the distribution of these fish between the two cruises favours the last mentioned possibility, but also the fact that none of the species involved is a powerful swimmer except possibly the Greenland halibut. Moreover, some of the more eurythermic species such as the Greenland skate, *Cottunculus microps*, and the Greenland halibut were encountered actually at rather high temperatures in some instances during the 1959 cruise.

In order to find the extent of the role hydrography plays in the distribution pattern of fish, the sketches of the isotherms close to the sea bottom (prepared on board during the two previous surveys of the "Overflow-Programme") were compared with the final chart of the third survey (prepared by Dr. Tait) and also with the temperature chart for 1959. Despite the quantitative differences in the distribution of the cold water on the Ridge, a rather clear trend can be seen as to the directions and the passages in which the phenomenon of the overflow proceeds. The overflow seems to be closely related to the topography of the Ridge, the cold water, depending upon its weight, being forced on its way across the Ridge to follow the slopes of the two plateaus outlined by the 400 m contour and forming the top of the Ridge. The shallow furrow between the two plateaux as well as the extensive southeastern slope appear to be the main passages where the cold water advances in a generally southwesterly direction. In addition, there is the deep Faroe-Bank Channel where the water flows permanently to the northwest only in the lowest depths.

Table 9:7.
Observed bottom temperatures for "Arctic fish-stations"

Station No.	Bottom temperatures in °C. Survey No. 1	Survey No. 2	Survey No. 3	measured in 1959
3218	3	2	1–2	2.8
3223	4.5	3.5	5–6	5.1
3226	≈0	0–1	0–1	2.7
3229	≈1.2	–0.25	<0	1.1
3231	2–3	≈1	3	4.1
3238	≈5	3–4	3–4	3.6
3252	≈1.5	2–3	3	–
3253	0–1	>2	3	1.9
3254	3–4	4	4–5	4.7
3255	>4	2	3–4	4.2
3267	≈0	≈0	≈0	–0.2
751	≈5	2	6	–
759	<0	0–1	0–1[11]	–
761	≈2	0–1	1–2	–
762	≈2	0–1	1–2	–
763	1–2	2–3	3	–
767	1–2	1	4	–
768	≈1	2–3	3–4	–
769	1–2	1–2	2	–
771	1–2	4–5	4–5	–

[11] Actually measured – 0·02° C.

Table 9:7 shows the bottom temperatures met with during the three surveys of the ICES Expedition for those stations of the two respective cruises where Arctic species were found and the actual measurements obtained during the 1959 cruise.

It is shown that six of the twenty stations involved always had bottom temperatures of less than 2° C, five up to 3° C, four up to approximately 4° C, three up to 5° C, and two up to 6° C. For the first 6 stations the respective numbers of Arctic fish were 10 species with 196 specimens, for the next five stations they were 6 species with 50 specimens. The four stations with a temperature range up to about 4° C gave 7 species with 17 specimens, the next three up to 5° C, 3 species with 5 specimens, and the two stations with the warmest temperatures 2 specimens of *Cottunculus microps* only. Six of the eleven first-mentioned stations are situated along the eastern slope of the Ridge, one in the Faroe-Bank Channel, one on the northern slope and two on the southern, leaving only one station in the middle of the Ridge itself. The four stations showing a variation in temperature of up to 4° C are the western or southwestern ones, except for station No. 768, which is near the southern slope, where two of the stations of the next group are also to be found, leaving one (No. 3238) on the northwestern slope. The two warmest stations are northern and northwestern respectively.

From the picture drawn from the fish distribution, it can be concluded that the Arctic species tend to follow closely the cold water on its way across the Ridge to the western side, where they are able to find suitable conditions on the rather steep slope. This slope represents the narrow westernmost fringe of the distribution area of some of the Arctic species, where, on their way down they meet with the easternmost outposts of the boreal deep water species, as can be seen from the trawl catches at stations No. 3238 and No. 3255. In such situations an increase in the number of Arctic fish can be observed below 700 m depth, the fish apparently becoming crowded by the environmental conditions.

The routes by which Arctic fish apparently do cross the Ridge are indicated in Figure 9:9B by black arrows. It is further concluded that although some of these species at least are able to tolerate somewhat greater variations in temperatures, the main direction and the main passages of the "Overflow" must be rather constant and that this phenomenon takes place in relatively short intervals because every investigation of the Iceland-Faroe Ridge reveals the existence of the Arctic fish element at almost the same localities.

ACKNOWLEDGEMENTS

The authors are indebted to Dr. J. B. Tait of the Marine Laboratory, Aberdeen, by whose permission the bottom chart for the third hydrographic survey of the "Overflow-Programme" could be used, and to Dr. G. Tomczak of the Deutsches Hydrographisches Institut, Hamburg, who made available some preliminary charts of the first two surveys, prepared on board the R. V. "Gauss". Miss F. W. Crouse helped in revising the English wording.

SUMMARY

Immediately after the third hydrographic survey of the "ICES-Overflow-Programme", the R. V. "Anton Dohrn" undertook a trawling survey in order to get some information concerning the relationship between fish distribution, water temperatures and depth. The results of this and a similar survey made in 1959 are reported and discussed. Distribution charts of the individual fish species as well as of the ichthyogeographic components are given for both cruises.

The fish fauna of the Iceland-Faroe Ridge is composed of three major elements, viz. a boreal, a boreo-Arctic, and an Arctic component. As a whole 36 species of demersal fish were caught during the two cruises. Eighteen of these are boreal fish, which can be further subdivided into 7 species of "Bankfish", 7 Atlantic deep-water and 4 "Connecting species". Eight species belong to the boreo-Arctic group, and 10 are Arctic or semi-Arctic respectively.

Since the authors believe that the influence of the "Overflow" on the distribution of demersal fish can best be understood by studying the exact locations of Arctic species, they have dealt primarily in this paper with the habitat pattern of these species. A striking similarity in the distribution of the Arctic fish can be observed when a comparison of the two cruises is made. Furthermore, a close relationship appears to exist between the movement of the cold water, the distribution of the Arctic fish species and the topography of the Ridge. The cold water, according to its weight, seems to be forced on its way across the Ridge to follow the slopes of the two plateaux forming the summit of the Ridge. The shallow furrow between these plateaux as well as the extensive southeastern slope appear to be the main passages for both the cold water and the Arctic fish species. Most of the stations involved, especially those showing a rather high proportion of Arctic fish were found to be immersed in cold water almost every time they were investigated. In other cases only those species which are more eurythermic were caught at somewhat higher bottom temperatures.

Since most of the Arctic fish are rather slow and presumably unable to avoid sudden changes in temperatures by active emigration, the phenomenon of the overflow must take place in relatively short intervals and mainly by the same passages in order to enable the Arctic fish species to establish their habitats on the Ridge. The steep western slope of the Iceland-Faroe Ridge seems to represent the westernmost fringe of the distribution area of the Arctic fish fauna. Here they are crowded in by the environmental conditions and therefore increase in numbers again at a depth of more than 700 m, where they build up a peculiar community with the easternmost outposts of the boreal deep-water species.

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LIST OF DEMERSAL FISH SPECIES CAUGHT BY F. R. V. ANTON DOHRN ON THE ICELAND-FAROE RIDGE IN 1959 AND 1960

Family Squalidae – the Picked Dogfishes
1) *Centroscyllium fabricii* (Reinhardt), 1825
2) *Centroscymnus coelolepis* Bocage & Capello, 1864

Family Rajidae – the Rays and Skates
3) *Raja radiata* Donovan, 1808 – the Starry Ray
4) *Raja fyllae* Lütken, 1887
5) *Raja spinicauda* Jensen, 1914 – the Greenland Skate
6) *Raja hyperborea* Collett, 1878

Family Argentinidae – the Silver Smelts
7) *Argentina silus* (Ascanius), 1775 – the Greater Silver Smelt

Family Notacanthidae – the Spiny Eels
8) *Notacanthus phasganorus* Goode, 1881

Family Macrouridae – the Grenadiers
9) *Coryphaenoides rupestris* Gunnerus, 1765
10) *Macrourus berglax* Lacépède, 1802

Family Gadidae – the Cod Family
11) *Gadus morhua* Linnaeus, 1758 – the Cod
12) *Melanogrammus aeglefinus* (Linnaeus), 1758 – the Haddock
13) *Pollachius virens* (Linnaeus), 1758 – the Coalfish
14) *Micromesistius poutassou* (Risso), 1826 – the Blue Whiting
15) *Molva dypterygia* (Pennant), 1784 – the Blue Ling
16) *Brosme brosme* (Ascanius), 1772 – the Torsk
17) *Gaidropsarus argentatus* (Reinhardt), 1838

Family Moridae
18) *Lepidion eques* (Günther), 1887

Family Trichiuridae – the Hair-tails
19) *Aphanopus carbo* Lowe, 1839 – the Black Scabbardfish

Family Ammodytidae – the Sand Eels
20) *Ammodytes lancea marinus* Raitt, 1934

Family Anarhichadidae – the Wolffishes
21) *Anarhichas minor* Olafsen, 1772 – the Spotted Wolffish
22) *Anarhichas denticulatus* Krøyer, 1844

Family Zoarcidae – the Eel Pout Family
23) *Lycodes esmarkii* Collett, 1880
24) *Lycodes eudipleurostictus* Jensen, 1902
25) *Lycodes pallidus pallidus* Collett, 1879

Family Scorpaenidae – the Rockfishes
26) *Sebastes viviparus* Krøyer, 1845 – the Lesser Redfish
27) *Sebastes marinus*, type *marinus* (Linnaeus), 1758 – the Redfish
Sebastes marinus, type *mentella* Travin, 1951 – the Redfish
Sebastes marinus, type "intermediate" – the Redfish
Sebastes marinus, type "giants" – the Redfish

Family Cottidae – the Bull-heads
28) *Artediellus atlanticus* Jordan & Evermann, 1898

Family Cottunculidae
29) *Cottunculus microps* Collett, 1875
30) *Cottunculus thomsonii* (Günther), 1882

Family Liparidae – the Sea-snails
31) *Careproctus reinhardtii* Krøyer, 1862
32) *Paraliparis bathybii* Collett, 1879

Family Pleuronectidae – the Flounders
33) *Hippoglossus hippoglossus* (Linnaeus), 1758 – the Halibut
34) *Reinhardtius hippoglossoides* (Walbaum), 1792 – the Greenland Halibut
35) *Hippoglossoides platessoides* (Fabricius), 1780 – the Long Rough Dab

Family Lophiidae – the Angler Family
36) *Lophius piscatorius* Linnaeus, 1758 – the Monk

CHAPTER 10
THE INTERNATIONAL "OVERFLOW" EXPEDITION (ICES) OF THE ICELAND-FAROE RIDGE, MAY-JUNE 1960

A REVIEW

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The Iceland-Faroe Ridge is part of the Greenland-Scotland Ridge, the main barrier between the European Arctic and sub-Arctic seas together with the North Polar Sea on one side and the open Atlantic on the other side. Nearly all the water entering the northern seas by crossing the main ridge is bound to leave them through the same passage. When the International "Overflow" Expedition (I.O.E.) started in 1960, it was known from previous investigations that the northgoing water over the Greenland-Scotland Ridge is concentrated in three currents (Northeast-Atlantic Current between Faroe and Shetlands, current west of Faroe, Irminger Current west of Iceland) and is balanced by five currents (East Greenland Current, East Iceland Current and three bottom currents). The bottom currents are controlled by the bottom topography: one by the cross channel of the Greenland-Iceland Ridge, another by the Faroe-Bank Channel between Faroe and Faroe-Bank, the third spills over the plateau of the Iceland-Faroe Ridge. The first mentioned channel is broad with a sill depth of about 615 m (G. Dietrich, 1957). The overflow through this channel forms the cold bottom water of the Labrador Sea. The Faroe-Bank Channel is narrow with a sill depth of 820–830 m (J. Harvey, 1965, confirming the first hint by A. H. W. Robinson, 1952). Cold deep water of the Norwegian Sea flows through this channel and contributes together with the overflow of the Iceland-Faroe Ridge to the bottom water of the Northeast Atlantic. This ridge is a broad sill with no distinct cross channel. Therefore the overflow fluctuates not only in time, but also, as results of former studies show, in space (summarized by G. Dietrich, 1960).

The investigation of the overflow of the Greenland-Scotland Ridge is an important problem in oceanography not only because of its scientific interest, but also to European fisheries. It requires international cooperation of several research ships, and even then the area is too wide for a single multiple ship programme. When planning the expedition it seemed to be worthwhile to concentrate the effort on one part of the whole ridge. Many reasons were decisive in the selection of the Iceland-Faroe Ridge.

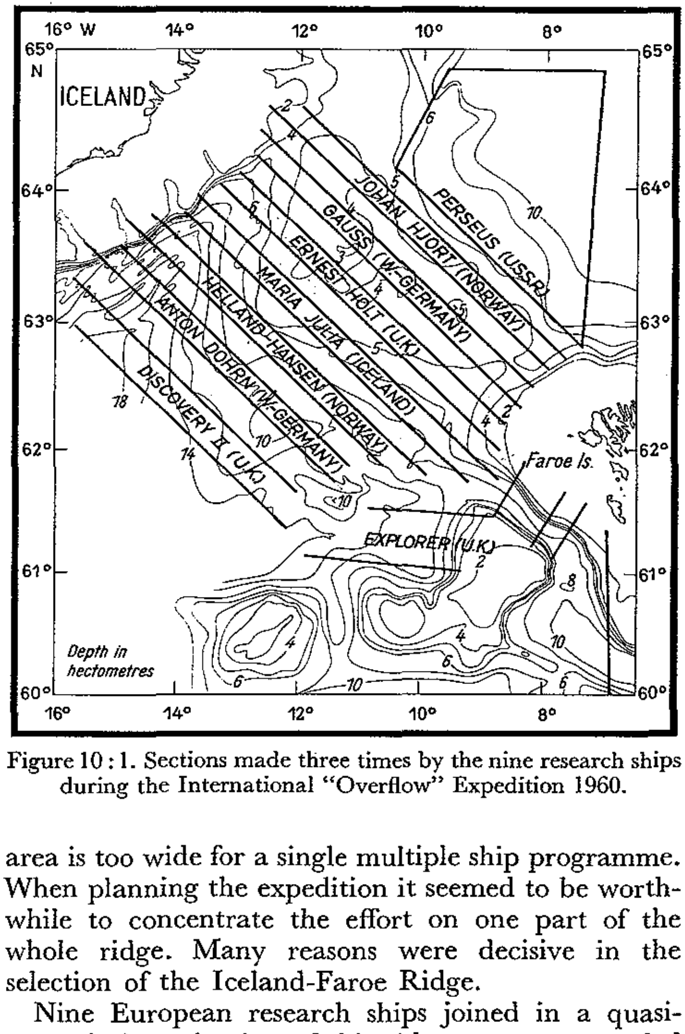

Figure 10 : 1. Sections made three times by the nine research ships during the International "Overflow" Expedition 1960.

Nine European research ships joined in a quasi-synoptic investigation of this ridge, as recommended by the ICES which accepted responsibility for this survey. The Hydrographical Committee of the ICES constituted a sub-committee which coordinated the cruises under the chairmanship of J. B. Tait. The ships and their scientific leaders were as follows: UK:

Table 10:1

Examples for tidal currents and residual currents near the surface and the bottom in the vicinity of the Icelandic Shelf[1]

(64°10'N, 12°47'W)

Period of analysis	Depth of measurements m	Phase h min	Main direction °	Velocity in main direction cm/sec	Rotation -cum sole	Ratio of axes	Residual current direction °	Residual current velocity cm/sec
12. June, 07^h–12. June, 19^h . .	20	+ 2 36	229	46·9	–	0·35	37	38·3
	476	+ 2 08	191	20·2	+	0·60	214	26·6
12. June, 20^h–13. June, 08^h . .	20	+ 1 50	197	54·0	–	0·41	19	21·6
	476	+ 2 35	182	16·8	+	0·58	215	22·1
13. June, 09^h–13. June, 21^h . .	20	+ 1 49	211	49·5	–	0·50	338	7·0
	476	+ 1 55	189	18·7	+	0·39	214	19·4
17. June, 21^h–18. June, 10^h . .	20	+ 3 03	204	27·9	–	0·16	35	33·3
	476	+ 5 29	128	12·5	+	0·96	212	22·9

[1] J. JOSEPH, p. 164 this volume.

"Ernest Holt" (A. J. LEE), "Discovery II" (H. HERDMAN), "Explorer" (J. B. TAIT); F. R. Germany: "Anton Dohrn" (G. DIETRICH), "Gauss" (J. JOSEPH); Norway: "Helland-Hansen" (O. SÆLEN), "Johan Hjort" (J. EGGVIN); Iceland: "María Júlía" (U. STEFÁNSSON); USSR: "Perseus II" (M. M. ADROV). A survey of the nine ships on a narrow station net of about 300 stations on 18 sections was made from 30th May to 2nd June 1960. It was repeated twice with about one week's interval: 6th to 9th June and 13th to 16th June 1960. Figure 10:1 shows the courses of the sections made by the nine research ships. These three surveys gave one basis for the investigations of the overflow and its changes in time and space. The second basis consisted of repeated observations for about 3 days at selected positions made after the second and third surveys, completed by deep current measurements with anchored instruments. It may be added that the I.O.E. was the first survey to take advantage of the modern methods of long-term recording by anchored instruments in deep water. But in those years the number of instruments available was small. The longest record was 11 days in 476 m depth, a further two were 8 days, and at 7 other positions the measurements were shorter than three days.

This expedition is remarkable with respect to several points of view:

1. It was an optimal coordination of 9 research ships in a small region to reach a maximum of synoptic work.
2. It was an optimal intensification of measurements with the same methods.
3. In oceanography it was the starting point of current measurements in deep water by self-recording anchored instruments.

The representation of the observations and its discussion in this volume contains a lot of new general and special results. It is difficult to mention all of them. Since one or other result is not in correspondence with the whole, it seems preferable to restrict the discussion to the main features. The observational material strongly forces one to recognize the great variability in the sea, especially in the frontal zones of different water masses in the Iceland-Faroe region as the outstanding feature. For the description and explanation of the processes governing this variability self-recording instruments anchored for long periods are of course necessary. The results mentioned in the following call for further study by such methods.

The meteorological situation in the Overflow area (M. RODEWALD and F. KRÜGLER, this volume, pp. 18–37) in the months of May and June 1960 compared with the monthly means for the period of 1900–1940 showed special anomalies. The normal westerlies had an additional southeasterly component influencing mean temperatures of the air and of the surface water. Both were 1·0 to 1·5° C warmer than average. The actual weather conditions were variable not only in time, but also over the region considered. Sometimes the wind velocity reached more than 21 knots from southwest to southeast directions. But the strong winds connected with rapidly moving fronts did not last for more than $^1/_2$ to 1 day. Between 11.–13. June we had in most parts a northeast gale with speeds about 25–30

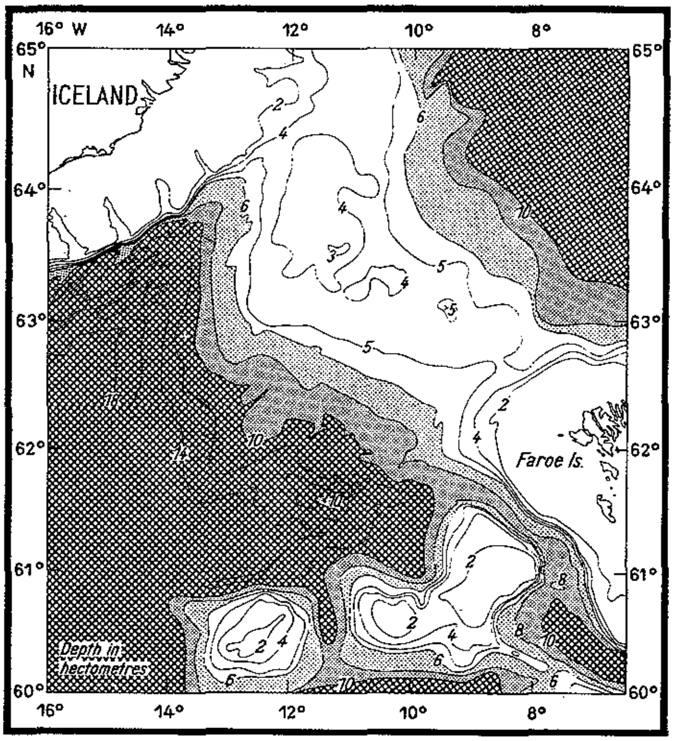

Figure 10:2. Generalized bottom topography.

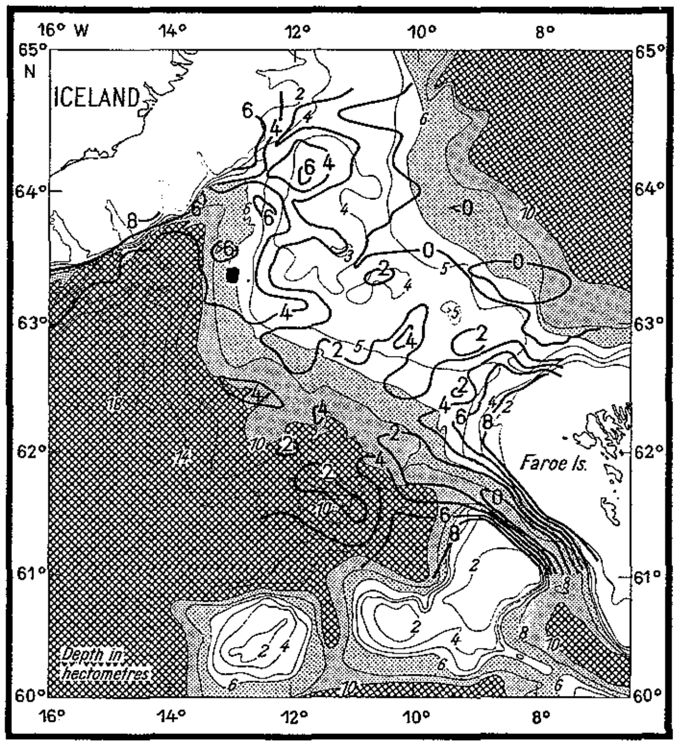

Figure 10:3. Generalized distribution of bottom temperature on the first survey 30. May to 2. June 1960.

knots. On the whole the weather conditions during the expedition were relatively unstable in the overflow area. A part of the special synoptic weather maps prepared by the meteorological station of "Anton Dohrn" and based on the International Weather Broadcast but supplemented by the observations of the research ships shows the details. Even the intensive oceanographical observations of this expedition seem relatively poor compared with the meteorological observations.

A new bathymetric chart of the Iceland-Faroe Ridge on the scale 1:500.000 (J. JOSEPH, this volume, p. 17) based on the echogrammes of the research ships shows no systematic deviations from former maps (G. DIETRICH, 1956). The Ridge has a broad flat crest which is everywhere shallower than 500 m depth. There are no distinct channels, only indistinct depressions in the plateau; one near the Iceland Shelf, another near the Faroe Shelf and three more between them. The deepest sill depth of these five reaches 490 m, the shallowest part about 300 m. The generalized bathymetric chart in Figure 10:2 shows the principal features.

The main effort of the I.O.E. 1960 was the detection and delineation of cold deep-water overflow from the Norwegian Sea into the North Atlantic Ocean. But the measurements were not restricted to the deep water alone. The unique systematic investigation involved the whole water mass from surface to bottom and therefore the frontal zone of relatively warm and saline North Atlantic water on one hand and cold, less saline sub-Arctic water, on the other. The distribution of temperature and salinity is shown in detail in 84 figures. One set of 21 figures (J. B. TAIT, this volume, pp. 38–63) refers to the horizontal distribution at the surface, 100, 300, 400 and 500 metres and on the bottom on each of the three surveys. Another set of 27 figures (J. B. TAIT, this volume 64–100) shows the vertical distribution of temperature and salinity on each of the sections of the nine research ships. A third set of 36 figures (A. J. LEE, this volume, pp. 100–135) represents the temperature and salinity distributions on five sections normal to the Ridge and one along the axis of the Faroe-Bank Channel. Additional T-S analyses of the water masses (F. HERMANN, this volume, pp. 139–49) and of the overflowing North Icelandic water (U. STEFÁNSSON, this volume, pp. 135–9) complete the discussion of the data. Figure 10:3 shows the temperature distribution on the bottom during the first survey. It is a generalized example combined with the bathymetric chart. Comparing Figure 10:3 with one of the vertical sections (Figures 10:4 and 10:5), it can be seen that the cold bottom water is relatively thin on the summit and the southern shoulder of the Ridge, mostly less than 100 m thick. It is evident that in stormy weather during the expedition the research vessels could not always measure with reversing thermometers very near to the bottom. A main result of the survey is, that the cold overflow water is found nearly everywhere on the Ridge where the depth exceeds

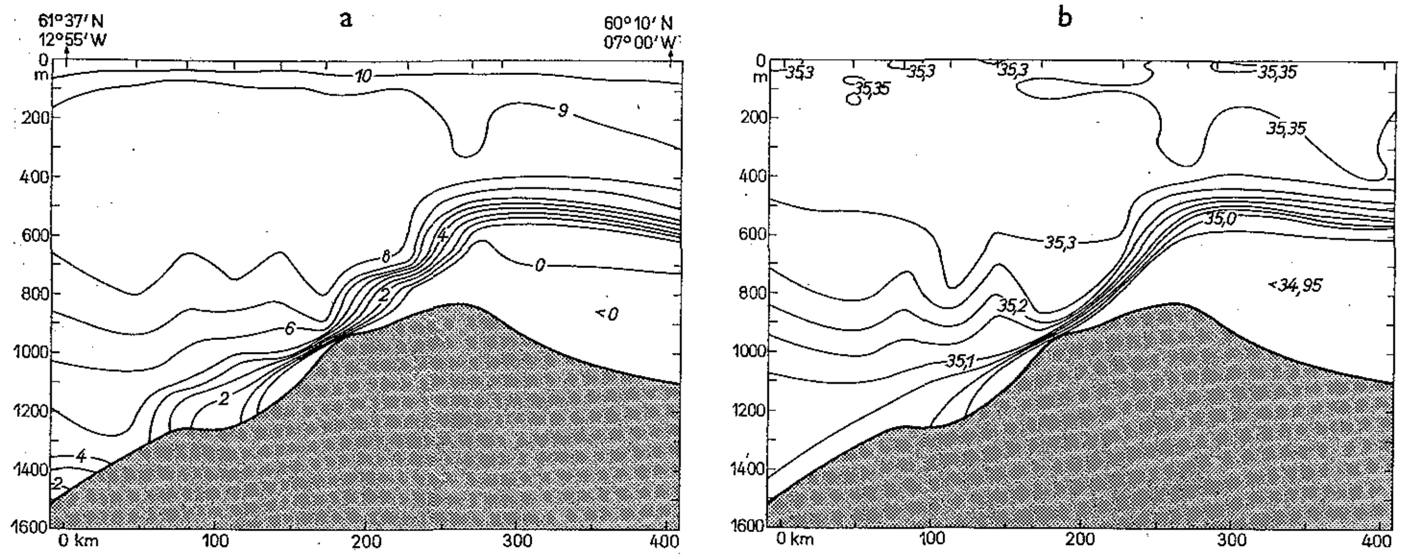

Figure 10:4. Section of a) temperature and b) salinity along the Faroe-Bank Channel on the second survey 6. to 9. June 1960.

300 m. It is, however, far from evenly distributed over the Ridge and is mainly concentrated in four branches.

Analyses of all the T-S diagrams from the stations in the three overflow surveys distinguish the following water types as the most important ones:

NA	North Atlantic water	9·0° C	35·33 ‰
AI	Irminger Sea water	3·5° C	34·93 ‰
NI	North Icelandic winter water	2·5° C	34·88 ‰
NS	Norwegian Sea Deep water	–0·5° C	34·92 ‰

The tongues rich in NS-water are shown in Figure 10:6. The highest percentage was found in the outlet of the Faroe-Bank Channel. The course of these tongues indicates the main direction of the overflow current during the period of the three surveys. When the overflow has crossed the summit of the Ridge, it seems to be deflected to the right and runs nearly parallel to the isobaths, in agreement with the results of the direct current measurements (J. Joseph, this volume, pp. 157–72) as shown in Figure 10:7. Calculation of the total volume transport in the four branches crossing the Ridge gives about $1{\cdot}1\times10^{6}$ m^3/sec, the outflow of the Faroe-Bank Channel $1{\cdot}4\times10^{6}$ m^3/sec. The main contribution to the North Atlantic originates from the Faroe-Bank Channel.

The discussion of the hydrochemical data brings no outstanding new information. The water on both sides and in all layers is relatively high in oxygen, so that it seems that this factor is not as good an indicator as temperature for delineating water motions. The

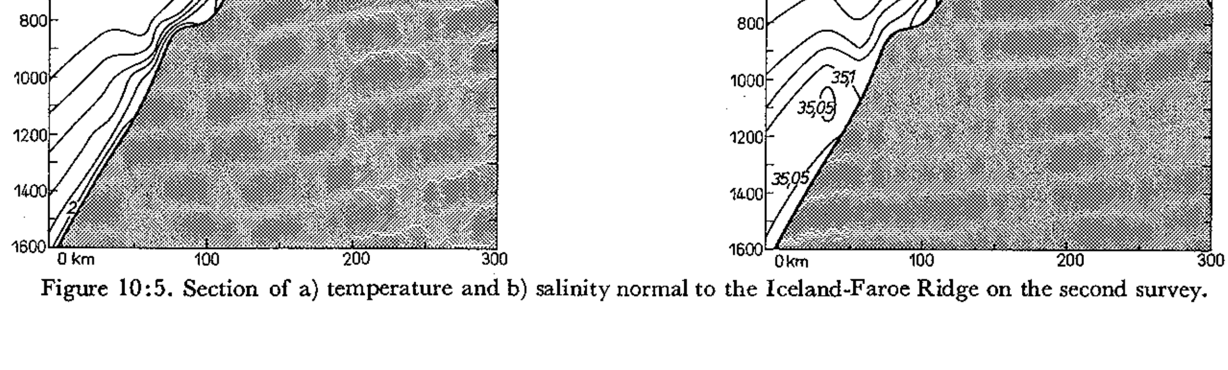

Figure 10:5. Section of a) temperature and b) salinity normal to the Iceland-Faroe Ridge on the second survey.

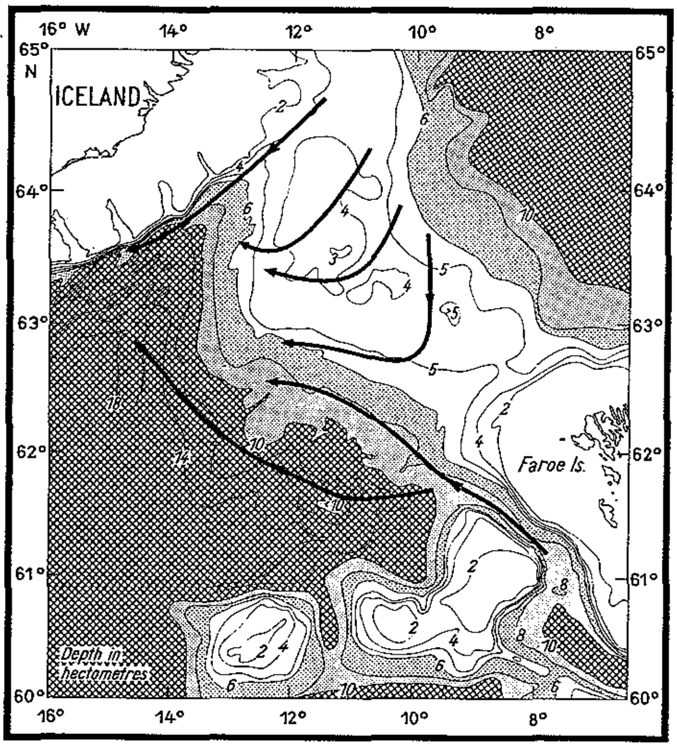

Figure 10:6. Cores of the main overflow branches.

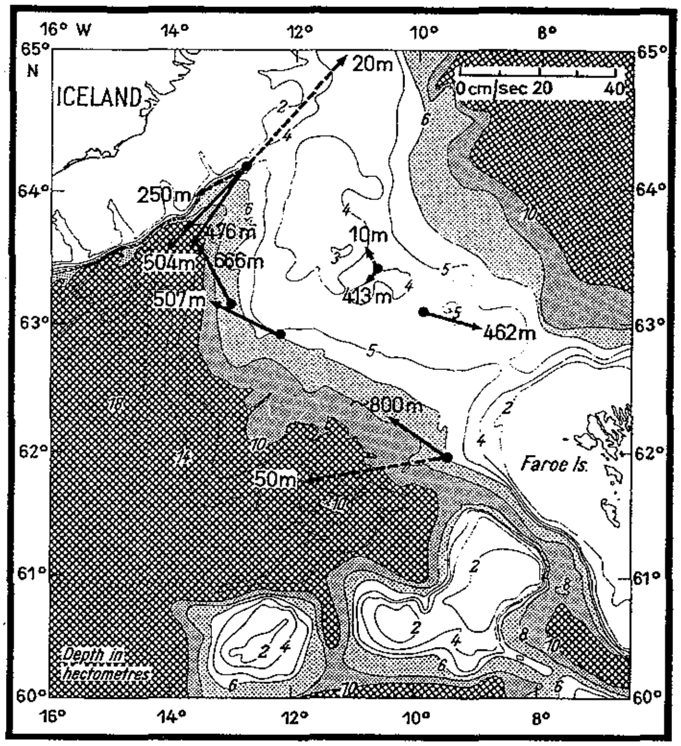

Figure 10:7. Residual currents in the surface and bottom layer based on current measurements 9. to 12. June 1960.

developed features (M. M. Adrov, this volume, pp. 184–95) are not in contradiction to the temperature and salinity distribution. Additional hydrochemical data (phosphate, silicate) show (M. V. Fedosov and I. A. Ermachenko, this volume, pp. 196–205) more differences in the composition of the distinct water masses. The number of observations is much less than of temperature and salinity but the general picture given by the T-S analysis is confirmed.

In Figure 10:6 is shown a simplification of the situation. The changes in time are threefold in nature: pulsations, tidal effect and internal waves. By the repetition of the sections in the second and third survey such pulsations are evident, but a correct synchronisation is not possible. In general there was an increase of the overflow between survey 1 and 2 in the northern part, but a decrease of the outflow of the Faroe-Bank Channel at the same time.

From ten positions where current measurements were carried out, three gave continuous records for more than three days. In one period (9. to 12. June 1960) 7 current meters worked simultaneously so that the residual current could be determined (Figure 10:7). This current was predominantly directed to the North Atlantic, in general not normal to the Ridge, but following the isobaths. The velocity of the tidal currents near the bottom were of the same order of magnitude as that of the residual current. In contrast selected examples of "Gauss" recordings show some remarkable characteristic features: The phase of the tidal current ellipses at surface and bottom are the same as in the direction of the major axis of the tidal ellipses, but the velocity of the tidal current in this direction is much lower near the bottom than near the surface. Especially remarkable is the sense of rotation of the tidal currents, which is the opposite at the surface than it is at the bottom. The residual current on the bottom is relatively stable in direction and velocity but at the surface it is variable and mainly opposite in direction: on the bottom it is directed to the North Atlantic, at the surface to the Norwegian Sea. This station is the only one where measurements are given at two levels for a long period. The conditions are so complicated by the superposition of strong tidal and non-tidal currents that single current measurements in this area are of low value.

This impression is confirmed where the internal waves are taken into consideration (L. Magaard and W. Krauss, this volume, pp. 173–83). Four permanent stations with hourly observations over about three days could be analysed; three stations in a triangle on the northern slope of the Ridge ("Perseus II", "María Júlía", and "Johan Hjort") and one on the southern slope ("Anton Dohrn"). At one station of the triangle amplitudes of internal waves vanish, but the other two stations show high amplitudes with tidal periods. This indicates

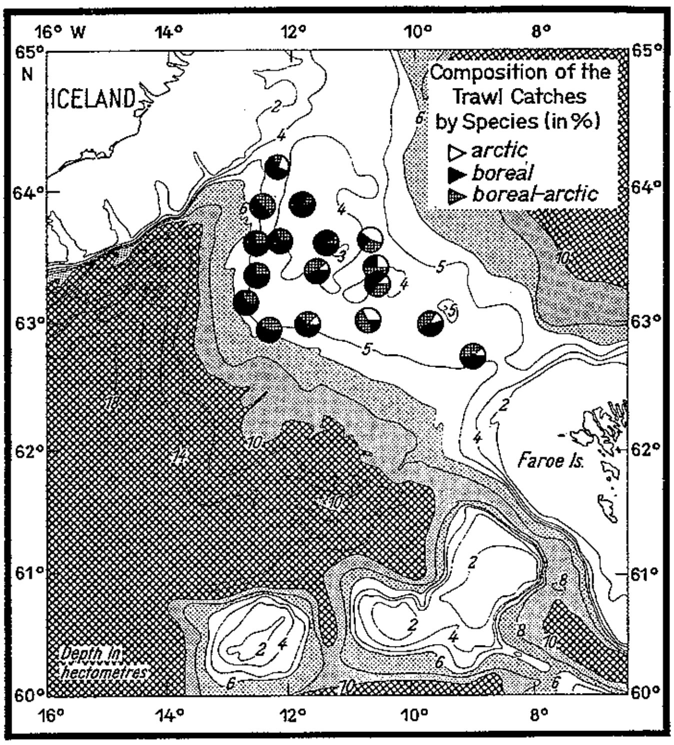

Figure 10:8. Composition of the "Anton Dohrn" trawl catches made in June 1960.

an internal tidal wave with a nodal line. The theoretical computation of internal waves to the fifth mode based on the mean vertical density distribution gives good correspondence between observation and calculation. The important role of internal waves with amplitudes up to 50 m shows how careful one has to be in interpreting single sections and stations.

These internal waves and the lack of a well defined level of no motion may be the reason why the common dynamic methods for calculation of water movement and water transport (M. A. Bogdanov, G. N. Zaitsev and S. I. Potaichuk, this volume, pp. 150–6) bring no further insight into the processes in the Ridge region.

Six of the research vessels made measurements of the depth of visibility with the Secchi disc. The results are very uniform. This depth is between 7 and 8·5 m. More information was given by the records of the vertical distribution of transparency, combined with recordings of temperature from the surface to the bottom. These measurements were made by "Gauss" at 117 stations. The results (J. Joseph, this volume, pp. 206–22) show the high concentration of turbidity in the surface layer down to about 50 m caused by plankton: the clearest water lies between 200 and 300 m and near the bottom the turbidity increases.

The relationship between fish distribution, water temperature and bottom topography was studied immediately after the third survey of the "Overflow" Expedition on 18 hauls made by the "Anton Dohrn". The results of these catches and a further 17 hauls made in 1959 are discussed (A. Kotthaus and G. Krefft, this volume, pp. 238–67). The bottom fish fauna of the Iceland-Faroe Ridge is composed of three major elements: a boreal, a boreo-Arctic and an Arctic. 36 different species of demersal fish were caught: 18 boreal, 8 boreo-Arctic and 10 Arctic. High proportions of Arctic fish were found in cold water (Figure 10:8). As most of the Arctic fishes are rather slow and presumably unable to avoid sudden changes in temperature by active emigration, the distribution of Arctic fishes gives an idea as to which way the average overflow proceeds. The fish distribution indicates that variations of the overflow in time are not accompanied by great changes in space. The distribution of Arctic fishes is not in contradiction in the more detailed lines of the actual overflows shown in Figure 10:6.

The International "Overflow"-Expedition of the Iceland-Faroe Ridge, May–June 1960 was a first step towards a systematic investigation of the Greenland-Scotland Ridge. Some problems could be solved, others are open. The need for continuous recordings is evident. But in consideration of the stormy region and the fishery, the mooring of buoys in the Iceland-Faroe area is a difficult task. Submerged recording systems that can be commanded to come to the surface for recovery as required are essential.

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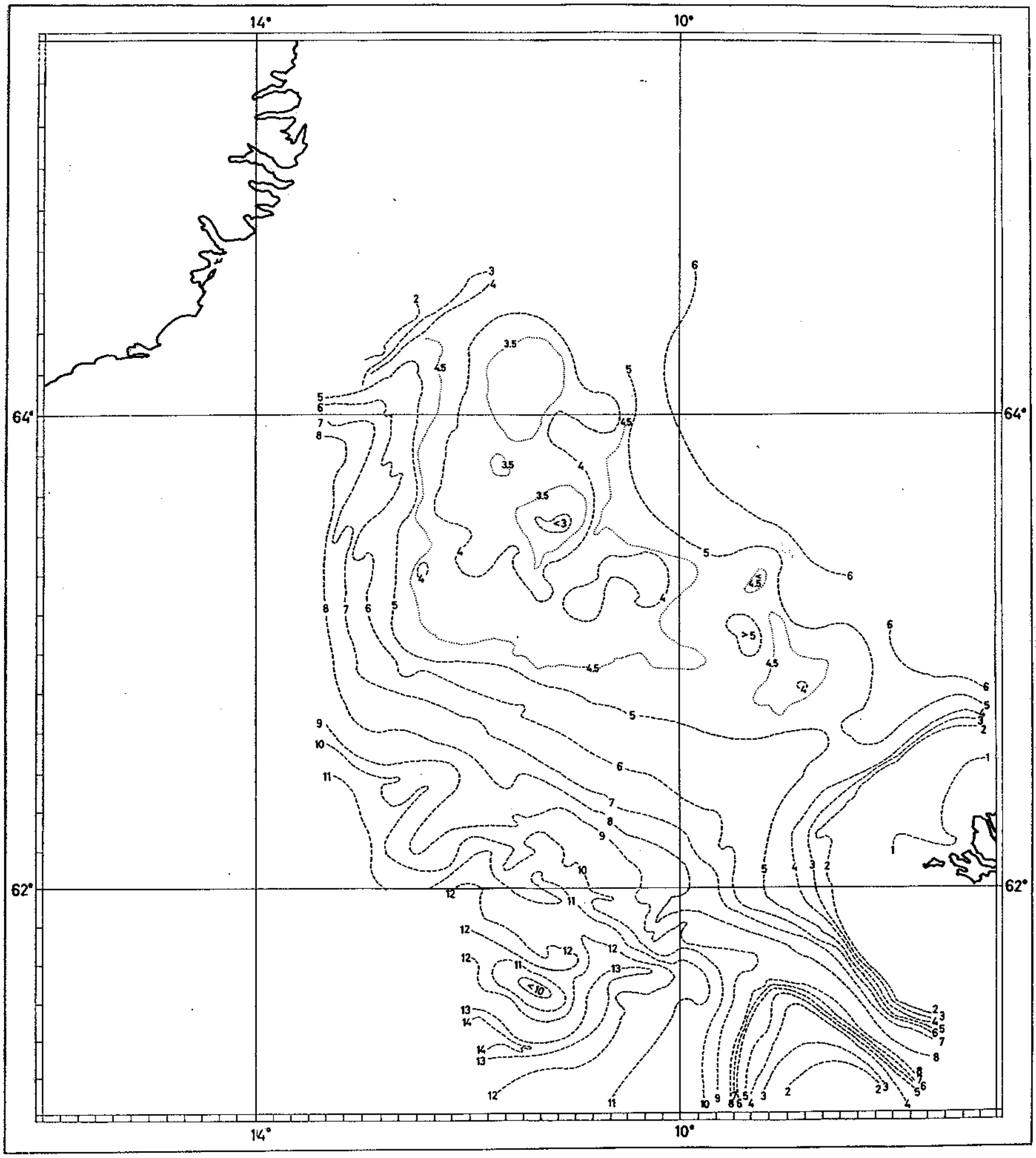
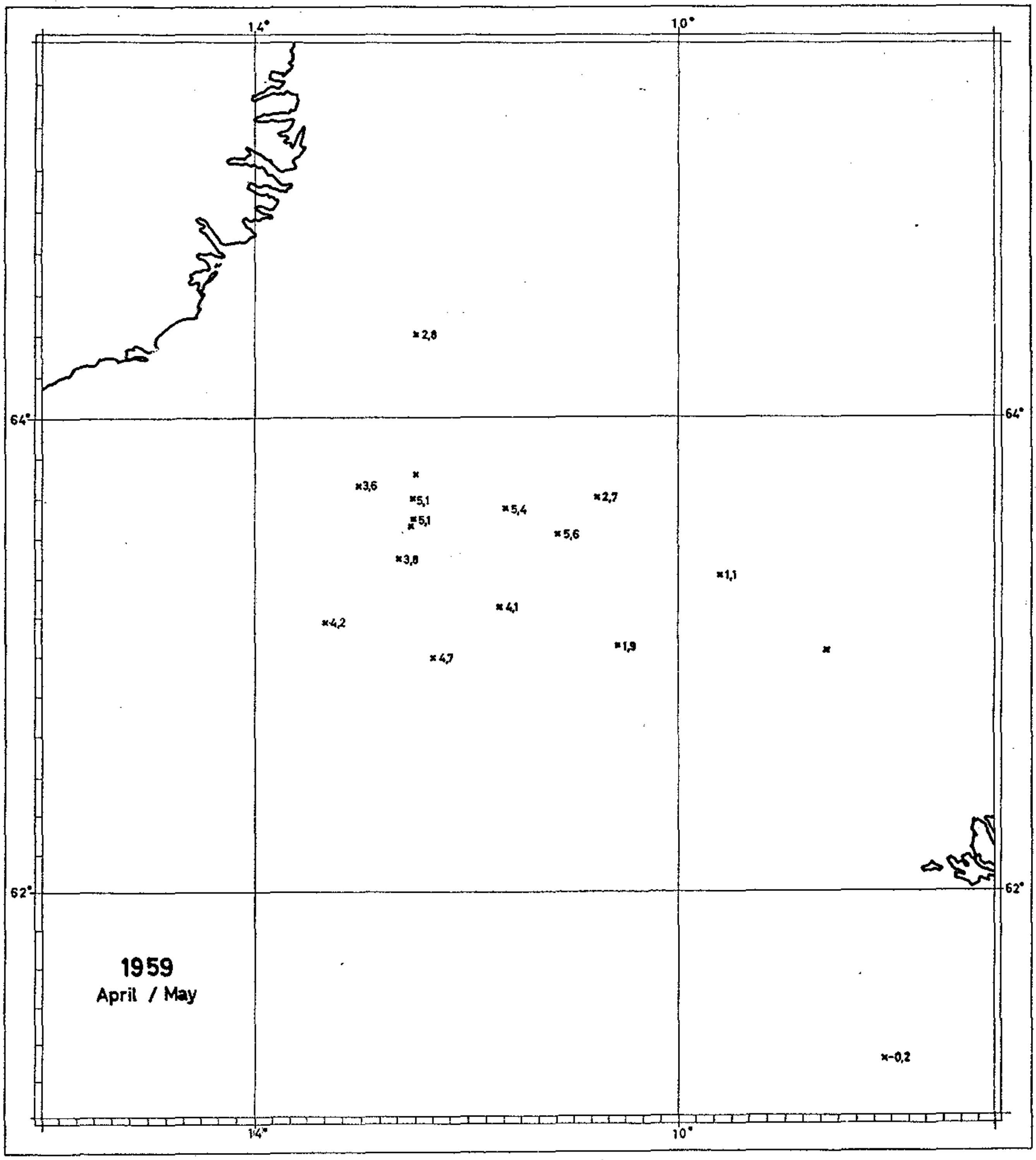


Cover page 2. Bathymetric chart of the Iceland-Faroe Ridge (by hectometres).



Cover page 1. Bottom temperatures actually measured during the 1959 cruise.