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UNITED STATES NAVAL POSTGRADUATE SCHOOL

THESIS

STUDY OF THE OCEANIC POLAR FRONT IN THE DENMARK STRAIT

by

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December 1968

STUDY OF THE OCEANIC POLAR FRONT

IN THE DENMARK STRAIT

by

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Submitted in partial fulfillment of the
requirements for the degree of

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from the

NAVAL POSTGRADUATE SCHOOL
December 1968

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ABSTRACT

A computer program is utilized to examine the effect on sound propagation of the oceanic polar front in the Denmark Strait and along the Southeastern coast of Greenland. Ray traces are computed with the source in both the cold and warm current areas for surface thermal gradients of 0.036 C/KM to 1.68 C/KM. These gradients are created by varying horizontal distances between actual oceanographic stations. The results indicate greater trapping angles with the source in cold water. A relationship is reported between the surface thermal gradient and the change in trapping angle difference for pairs of runs.

The location of the oceanic polar front and the effects of environmental influences on its strength and seasonal movement are described.

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I. INTRODUCTION

A. Statement of the Problem

The term "oceanic polar front" has been used by Norwegian oceanographers for over a half century; however, the term "front" to describe oceanic boundaries came into use in the United States only within the last two decades. Fuglister (1954) referred to a frontal zone as separating relatively permanent adjacent currents and Cromwell and Reid (1956) attempted to formalize a definition for small scale thermal fronts. As late as 1961, LaFond proposed a more general definition of a front as "the leading edge of a border separating unlike water masses...." The definition reported by Dietrich (1964) and used during the Polar Front Survey conducted during the International Geophysical Year 1957-1958 will be utilized here. This specifies an oceanic polar front as the boundary separating cold, sub-polar water of low salinity from a water mass composed of warm, highly saline water originating in sub-tropical regions.

Other than the west wall of the Gulf Stream off the east coast of the United States, very few of the oceanic frontal zones have been thoroughly examined. Even the "Gulf Stream wall" has not been subjected to the precise synoptic sampling required and there is still much we do not know about its structure and dynamics.

As may be inferred from the definition above, a frontal zone is an area of very complex temperature and salinity structure. The large horizontal gradients found in these regions greatly affect the behavior of sound waves in both the vertical and horizontal planes, and oceanic "abnormalities" such as temperature inversions and sub-thermocline ducts frequently are found at the fronts.

Since the oceanic fronts are convergence zones between two currents with different physical, chemical and biological properties, changes in water color, wave action and other physical parameters often may be observed at the boundaries from either aircraft or surface vessels.

Abundant marine life often is found in the frontal regions and the zonal boundaries usually will mark the limit of distribution of certain species. The production of phytoplankton is usually high at the fronts. Furthermore, there is also an accumulation of zooplankton, partly brought about by the transport of organisms by the converging currents. As a result, frontal areas provide a large percentage of the feeding areas of commercially important fish species in the northern seas (Shpaykher, 1964).

Due to the biologic activity and the complex water mass structure, the effectiveness of hull-mounted sonars may be degraded in these regions and false targets will abound. Thus the importance of the fronts is twofold:

first, the effect of fronts relative to commercial fisheries; and second, the effect of increased difficulty of detection in the military Anti-Submarine Warfare problem.

The purpose of this study is to examine the hydrography of the water masses comprising the oceanic polar front in the Denmark Strait and to determine frontal effects on sound propagation across the frontal axis.

The hydrography of the area as reported in the literature has been compared with seven oceanographic sections taken across the polar front in 1955 and 1958.

In order to examine the frontal effects on sound propagation, an assumption was made for each section that the two stations lying across the front represented the boundary of a different water mass. Sonar ray trace programs were then run for each section using assumed horizontal separations of ten, six and four kilometers between the stations. The bottom was assumed level at 400 meters in four of the sections, level at 230 meters in two of the sections and level at 300 meters for the final section. The ray traces were computed using a source depth of 25 feet simulating hull-mounted sonar. Two sets of traces were computed for each section. In the first instance, the source was placed on the warmer side and ray traces were computed looking into cold water. For the second set, the source was then moved to cold water and runs made toward the warmer profile.

The ray traces were completed using a two-dimensional ray trace program on the Control Data Corporation Model 6500 computer at Fleet Numerical Weather Central, (FNWC), Monterey (Ayres, et al. 1966), and are described in detail in Section IV. For each individual station used in the ray trace program, temperature and salinity profiles are shown. Selected ray traces and their sound velocity profiles are also illustrated (Figures 12 to 15).

B. The Data

Since the problem deals with an ocean area containing severe horizontal temperature and salinity gradients, the technique of long-term data averaging did not appear to offer a solution. As an alternative approach, it was decided to employ quasi-synoptic sections taken across the frontal zone in an attempt to describe the structure of the front on a seasonal basis. The sections utilized were obtained from FNWC, Monterey, and comprise those contained in the FNWC Ocean History Information Retrieval Systems (FOHIRS) from the ocean area delineated in Figure 1, for the years 1955 to the present (Griswold, et al. 1968). Only seven usable sections from the area of interest were contained in the data bank. Even though the sections, as shown in Figure 2, provide good coverage of the Strait, it would be desirable to have seasonally repetitive data for the same location.

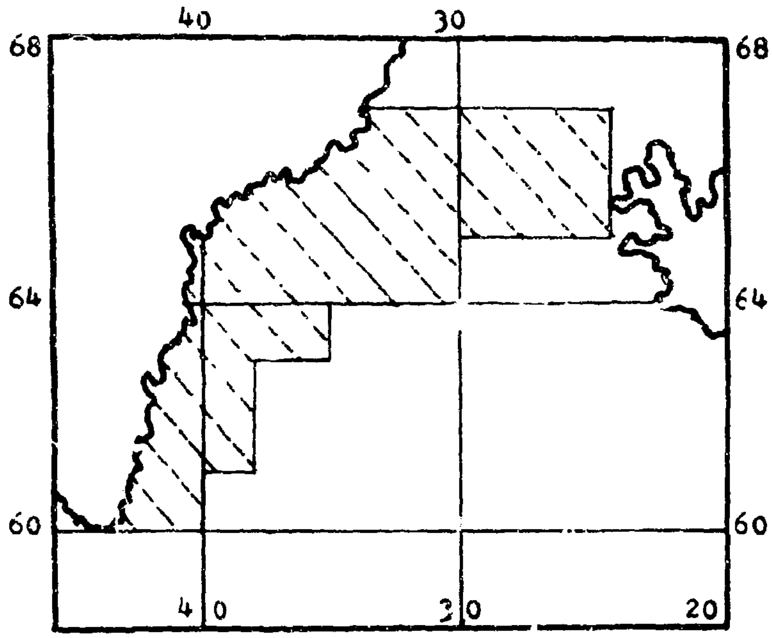

Figure 1. Area of data search

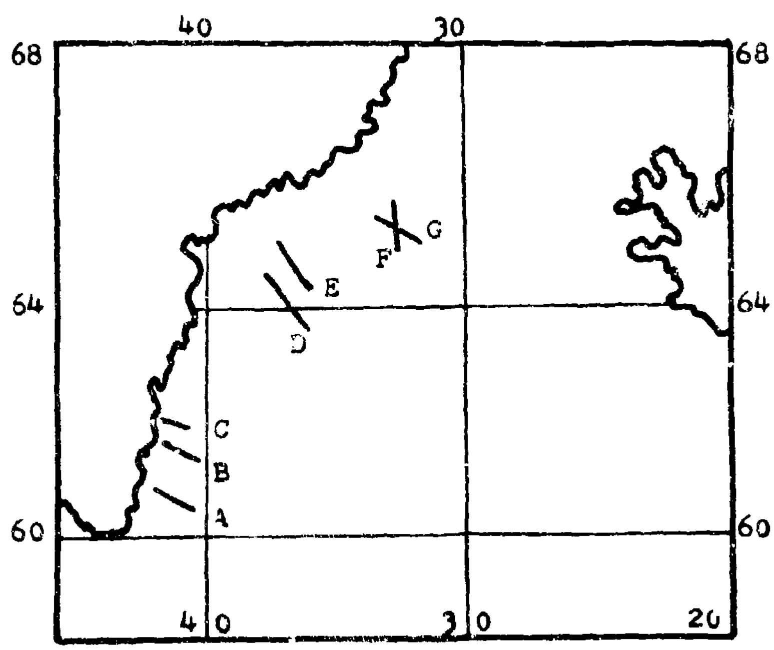

Figure 2. Location of the sections

The seven sections obtained from FNWC, Monterey, provide seasonal coverage as follows:

Winter	January-March	1
Spring	April-June	4
Summer	July-September	2
Fall	October-December	0

Five of the sections were taken in 1955 and the remaining two in 1958. For each section used, temperature and salinity profiles are shown in Figure 3.

The current structure at the front in 1955 was characterized by above-average development of the East Greenland Current and a more weakly-developed Irminger Current (Hermann, 1959). Conversely, in 1958 the Irminger Current showed its greatest intensification in many years while the East Greenland Current was weak (Hermann, 1960).

These observations are confirmed by Smed (1965) who shows that the yearly anomalies of the surface temperature in the area reached their highest value in fifteen years during 1958 while 1955 was the second coldest year of the decade, 1950-1959.

Due to the varying position of the sections, seasonal influence, and frontal meander, no direct correlation with annual variations is possible from the sections. For the same reasons, seasonal correlation was not feasible although the two September sections, C and E, do show the lowest surface salinities.

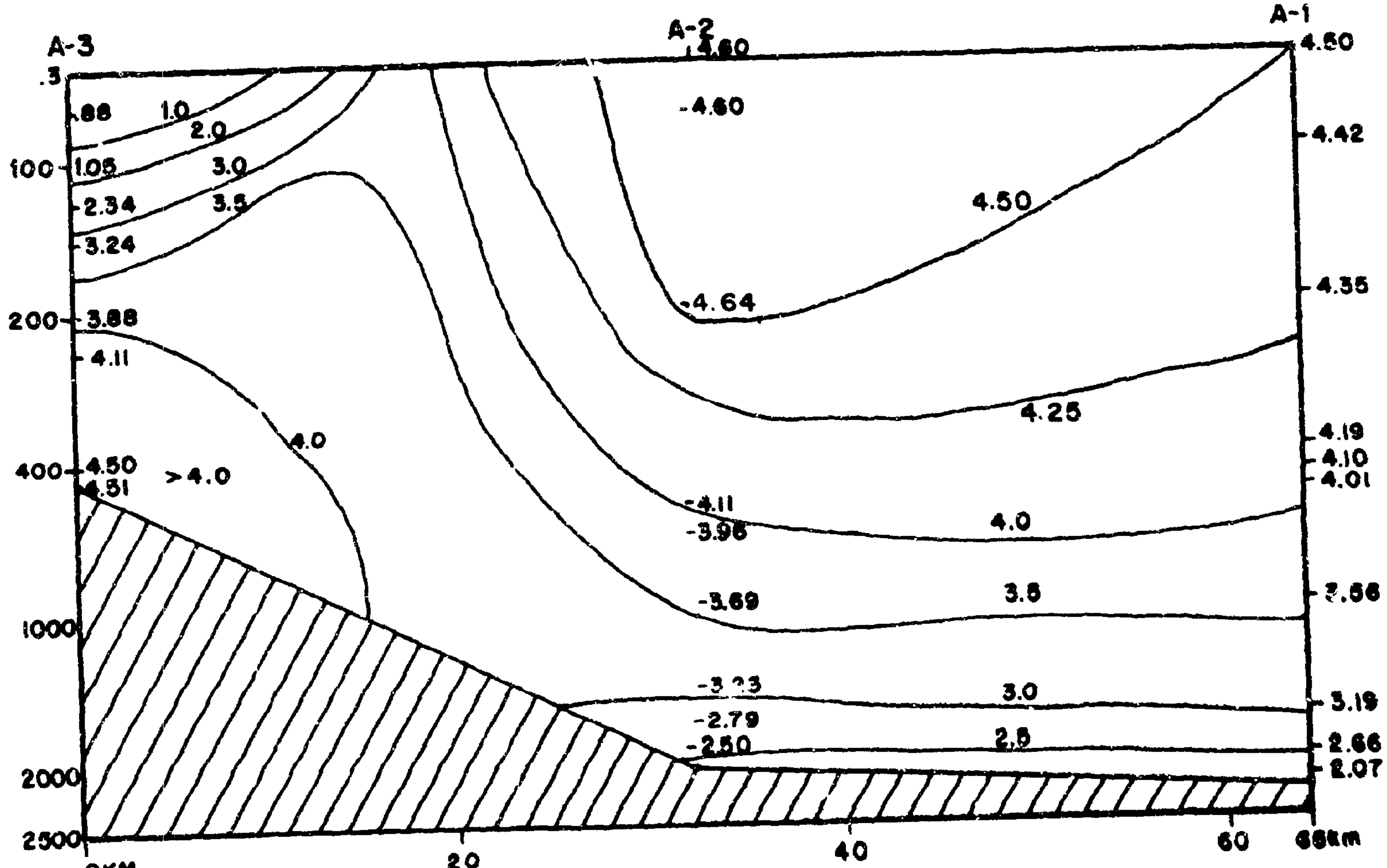

FIGURE 3.a.1 SECTION A TEMPERATURE (°C)

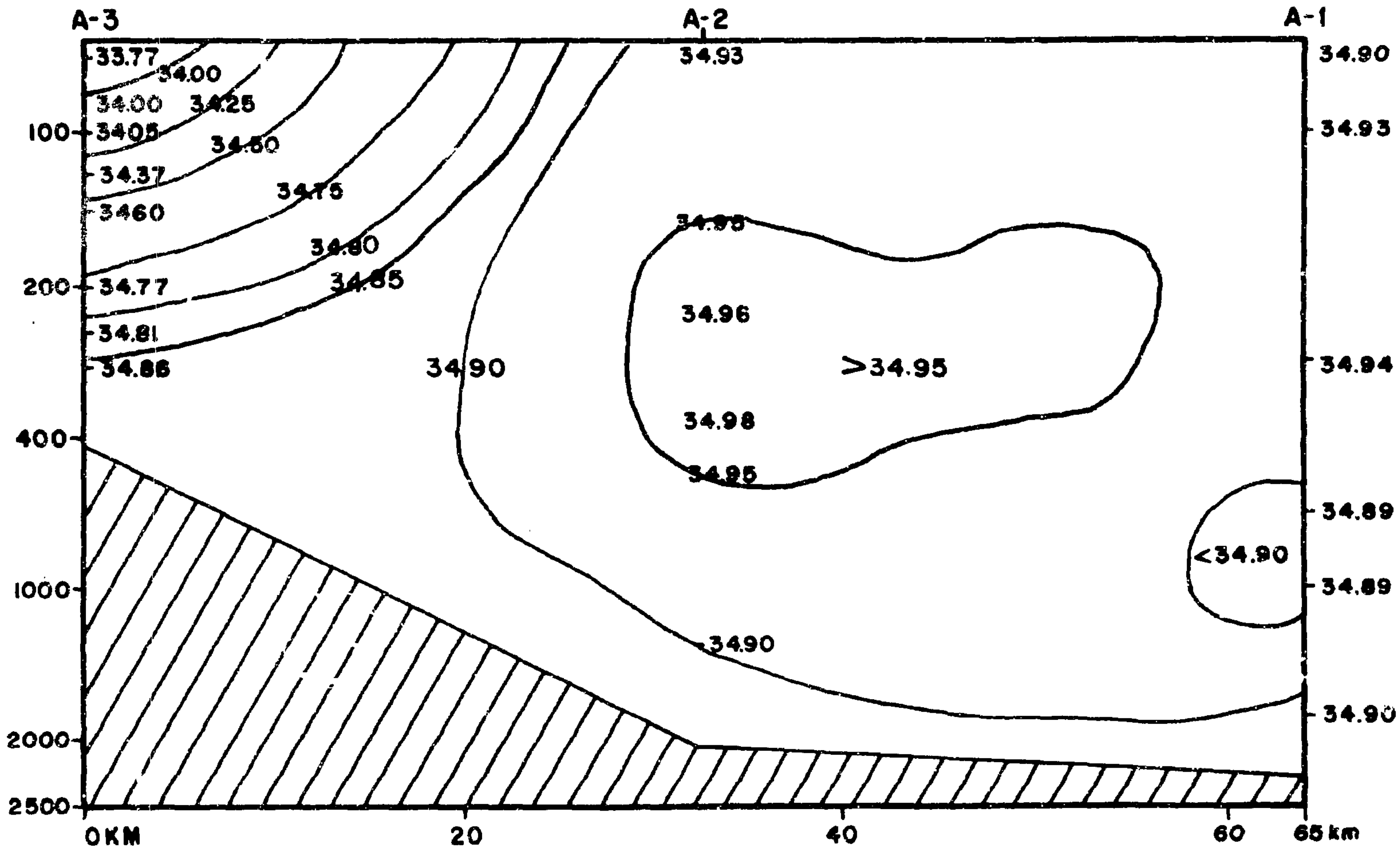

FIGURE 3.a.2 SECTION A SALINITY (‰)

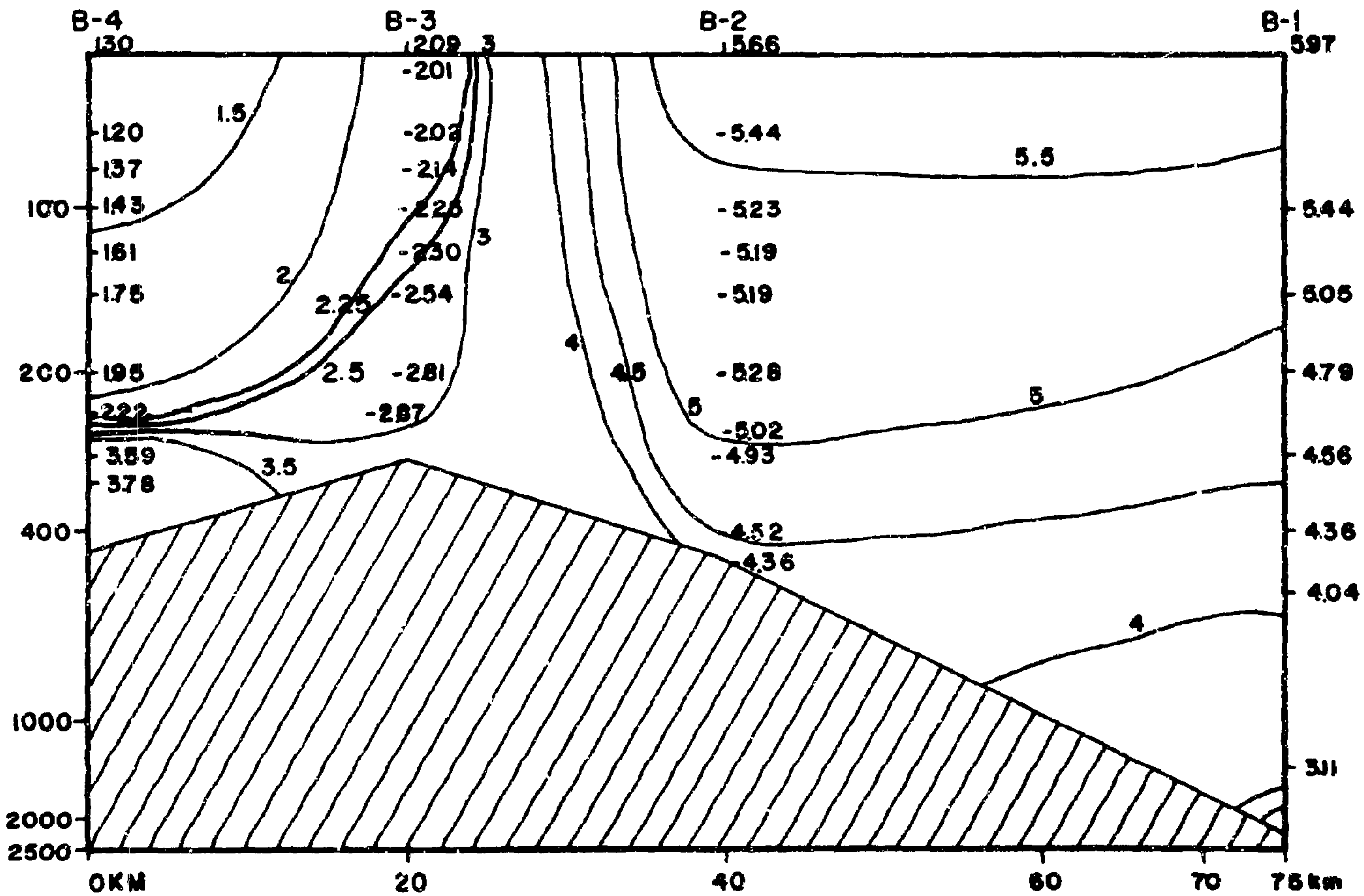

FIGURE 3.b.1 SECTION B TEMPERATURE (°C)

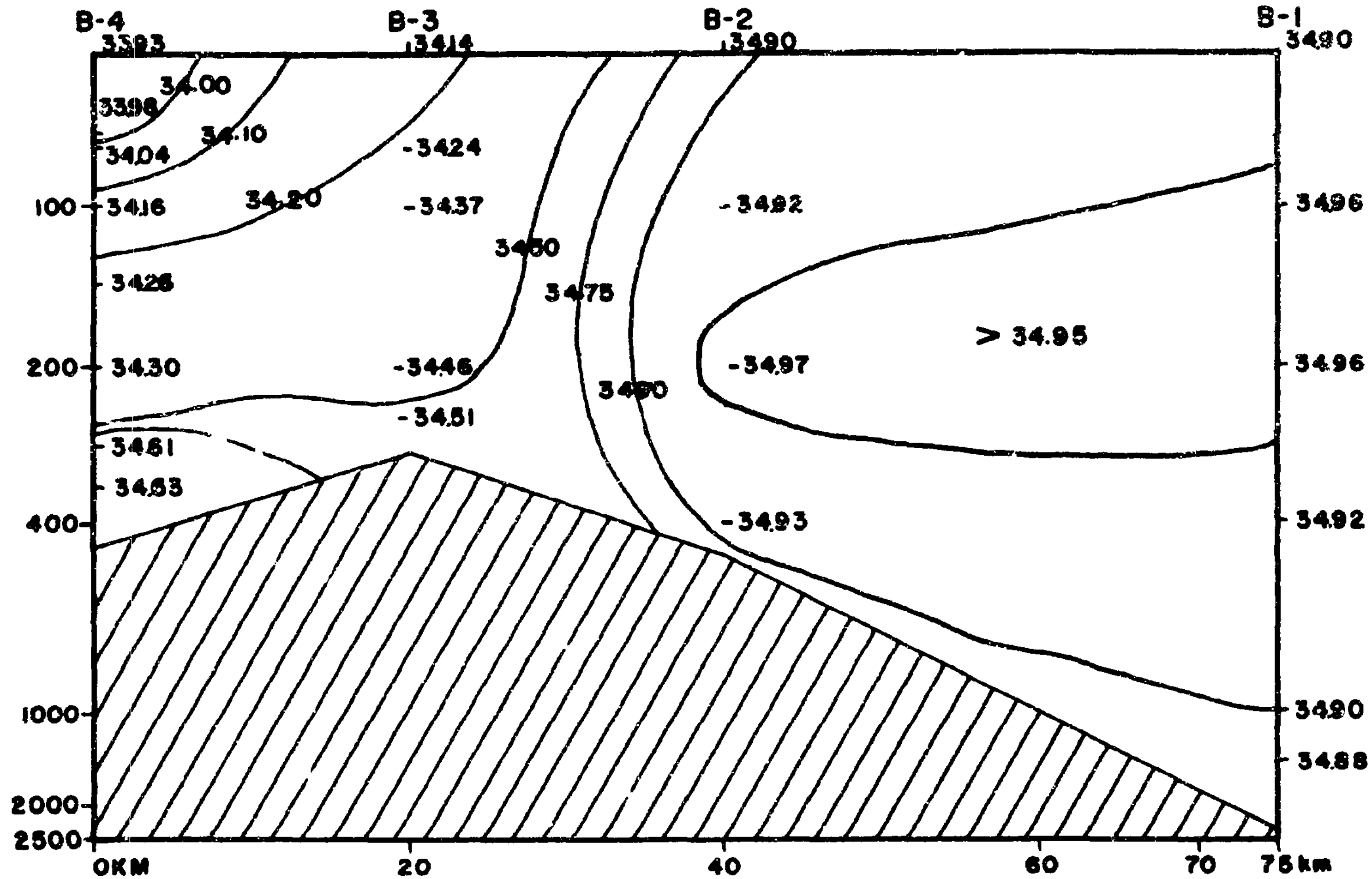

FIGURE 3.b.2 SECTION B SALINITY (°/oo)

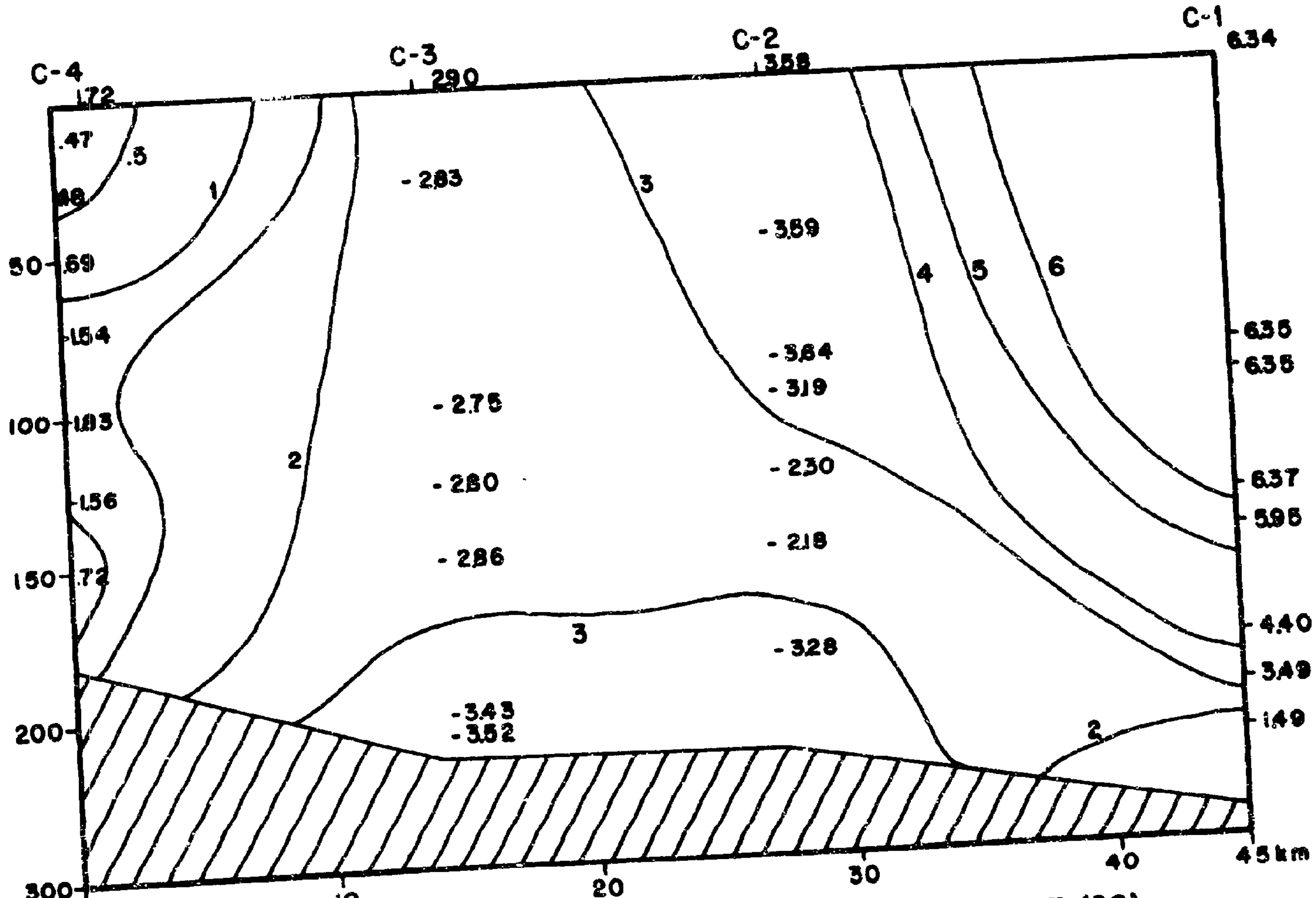

FIGURE 3.c.1 SECTION C TEMPERATURE (°C)

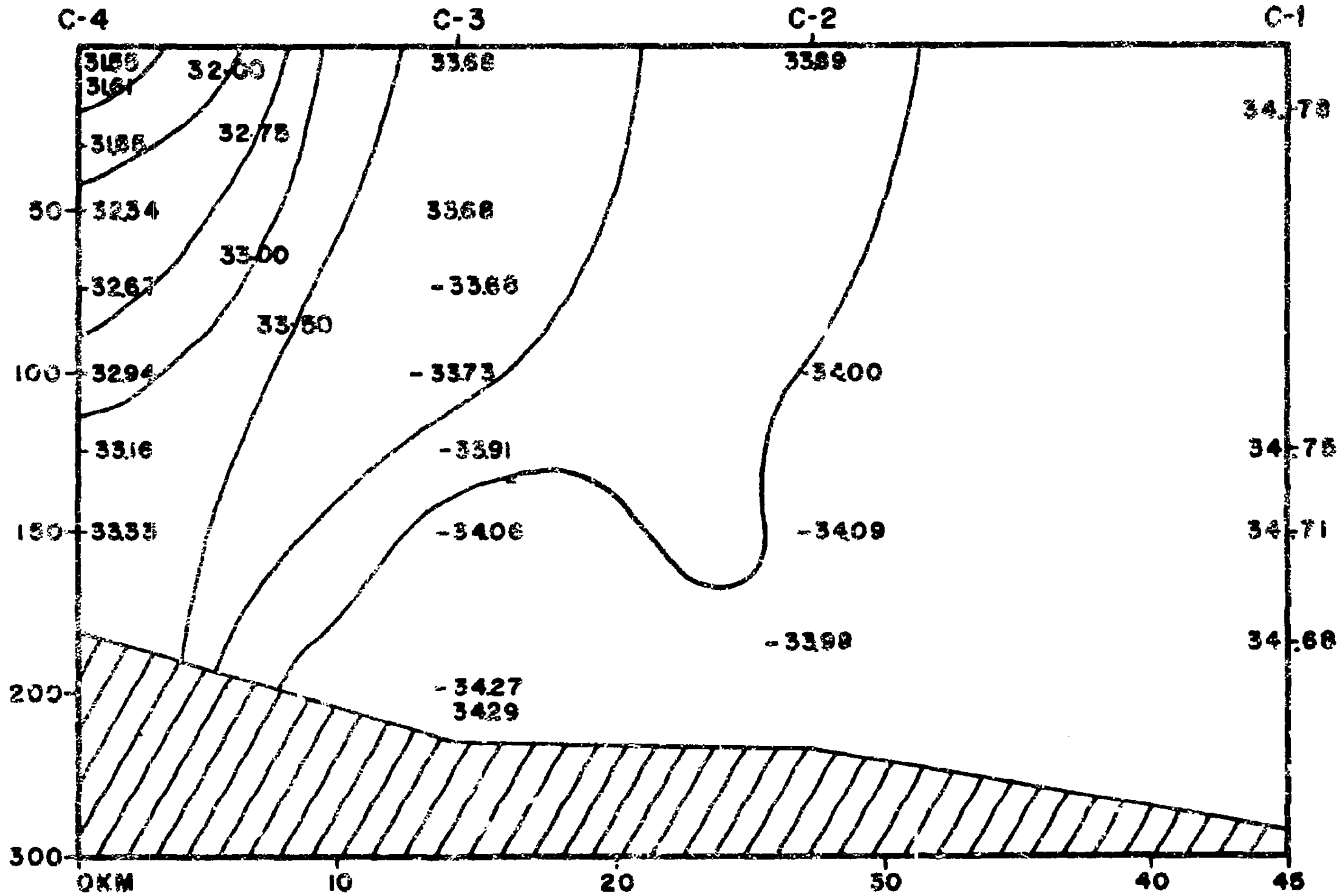

FIGURE 3.c.2 SECTION C SALINITY (‰)

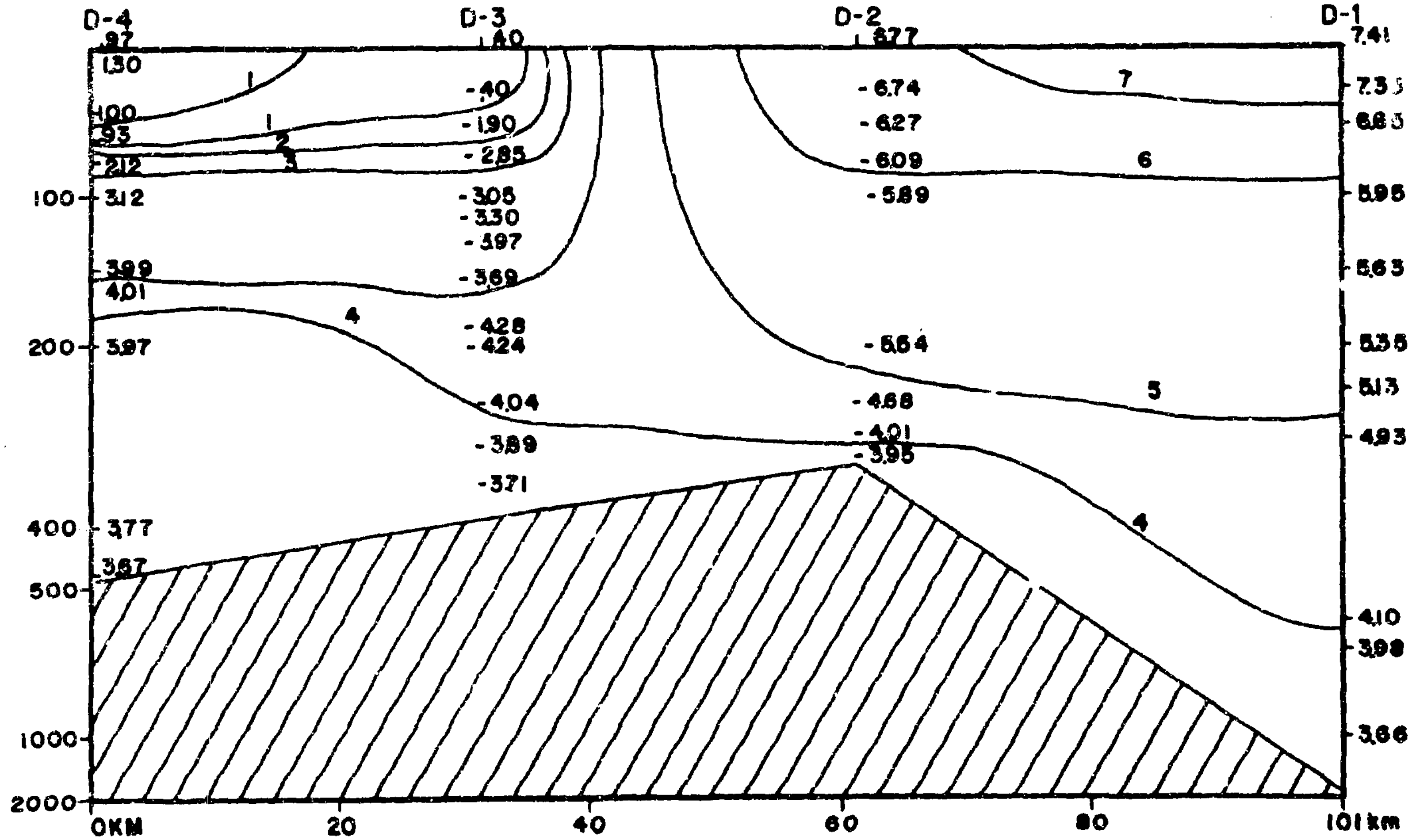

FIGURE 3.d.1 SECTION D TEMPERATURE (°C)

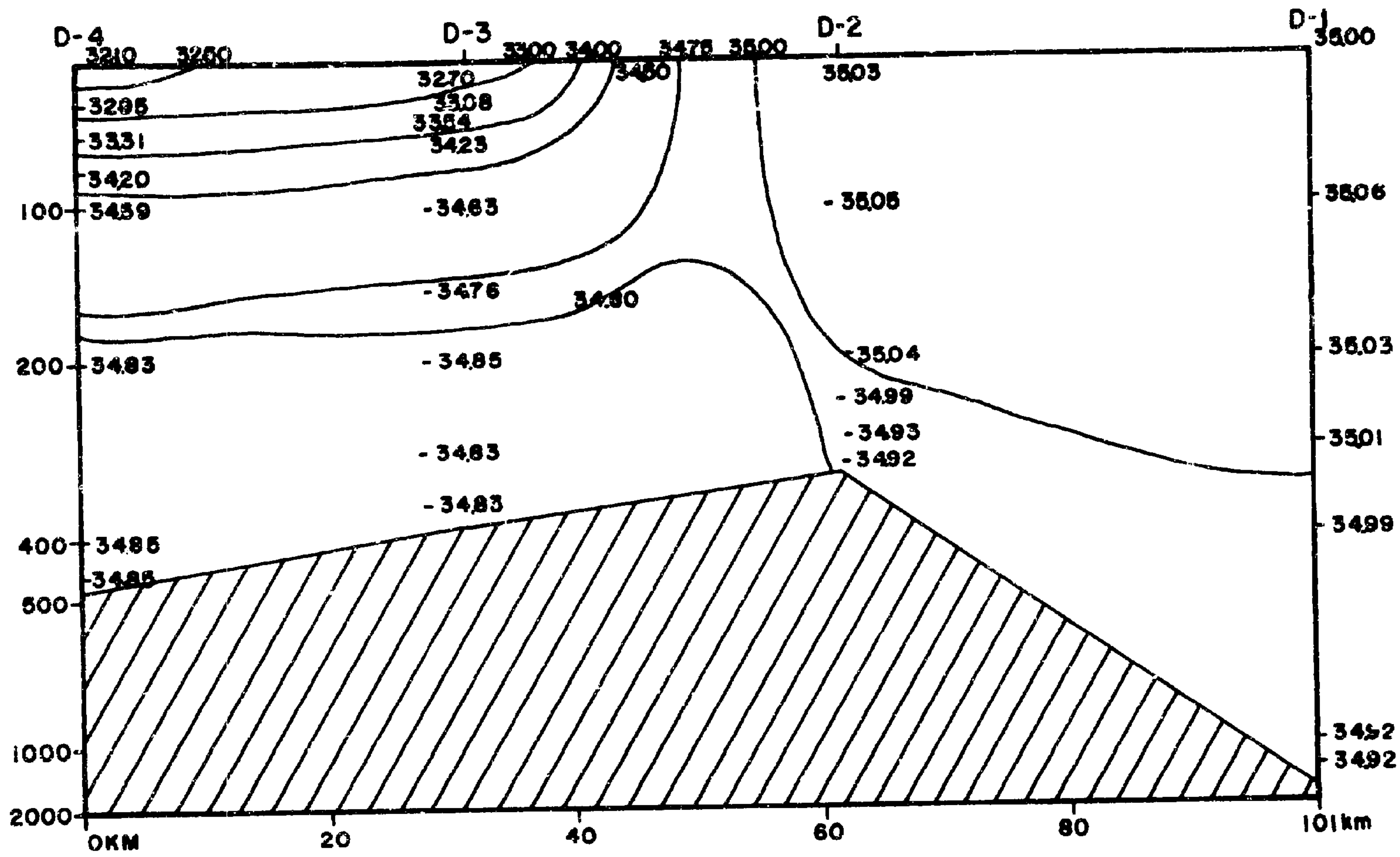

FIGURE 3.d.2 SECTION D SALINITY (°/oo)

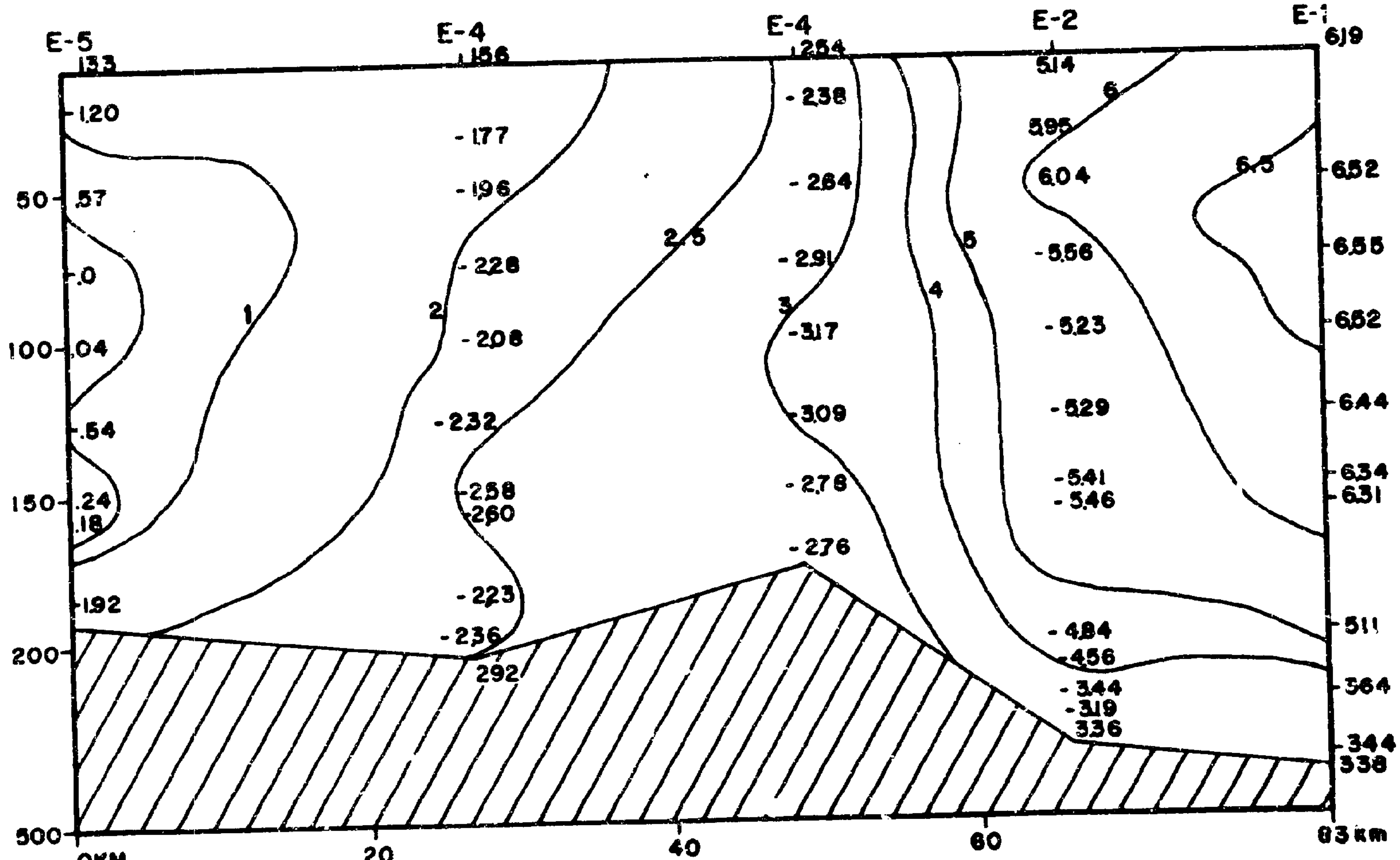

FIGURE 3.e.1 SECTION E TEMPERATURE (°C)

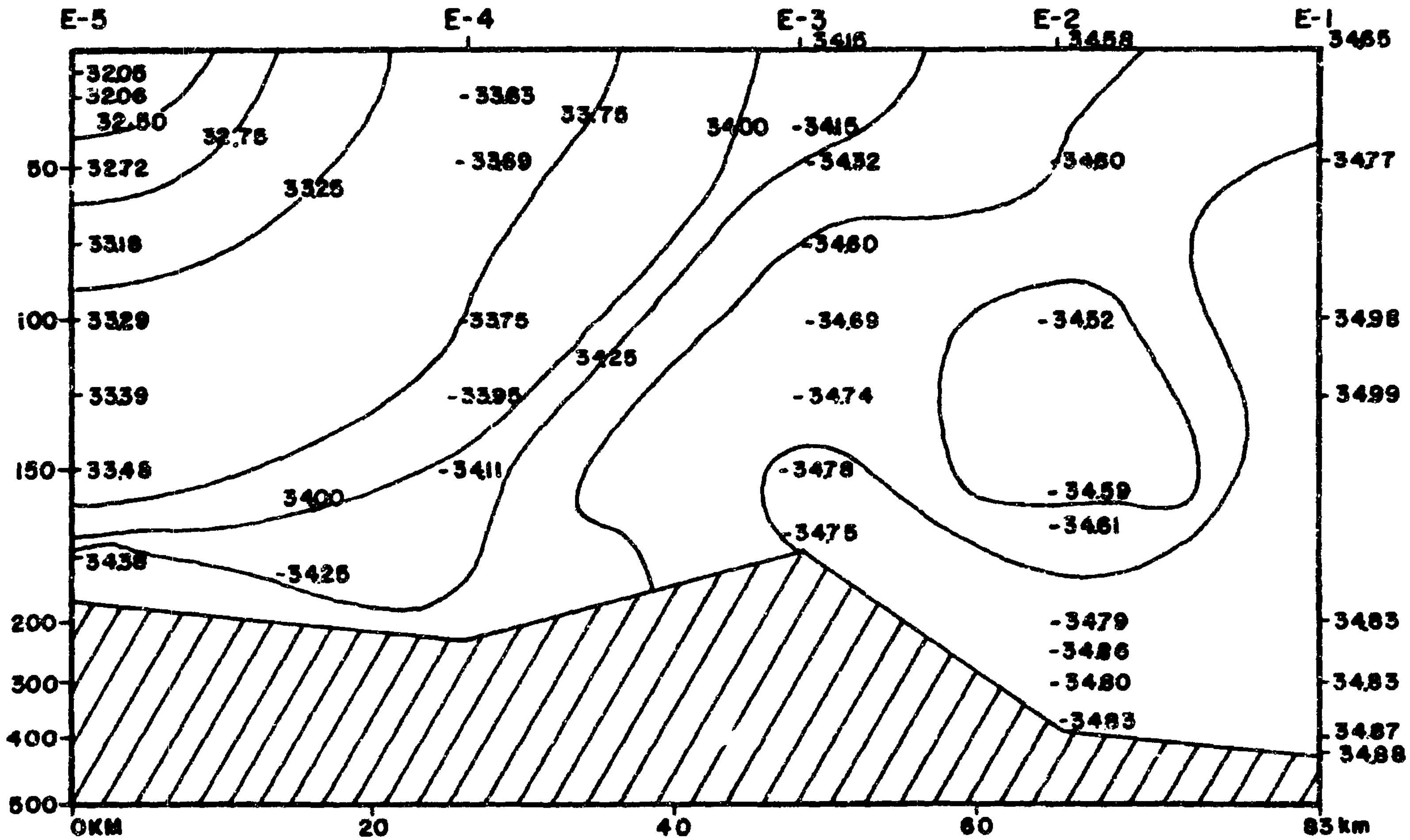

FIGURE 3.e.2 SECTION E SALINITY (‰)

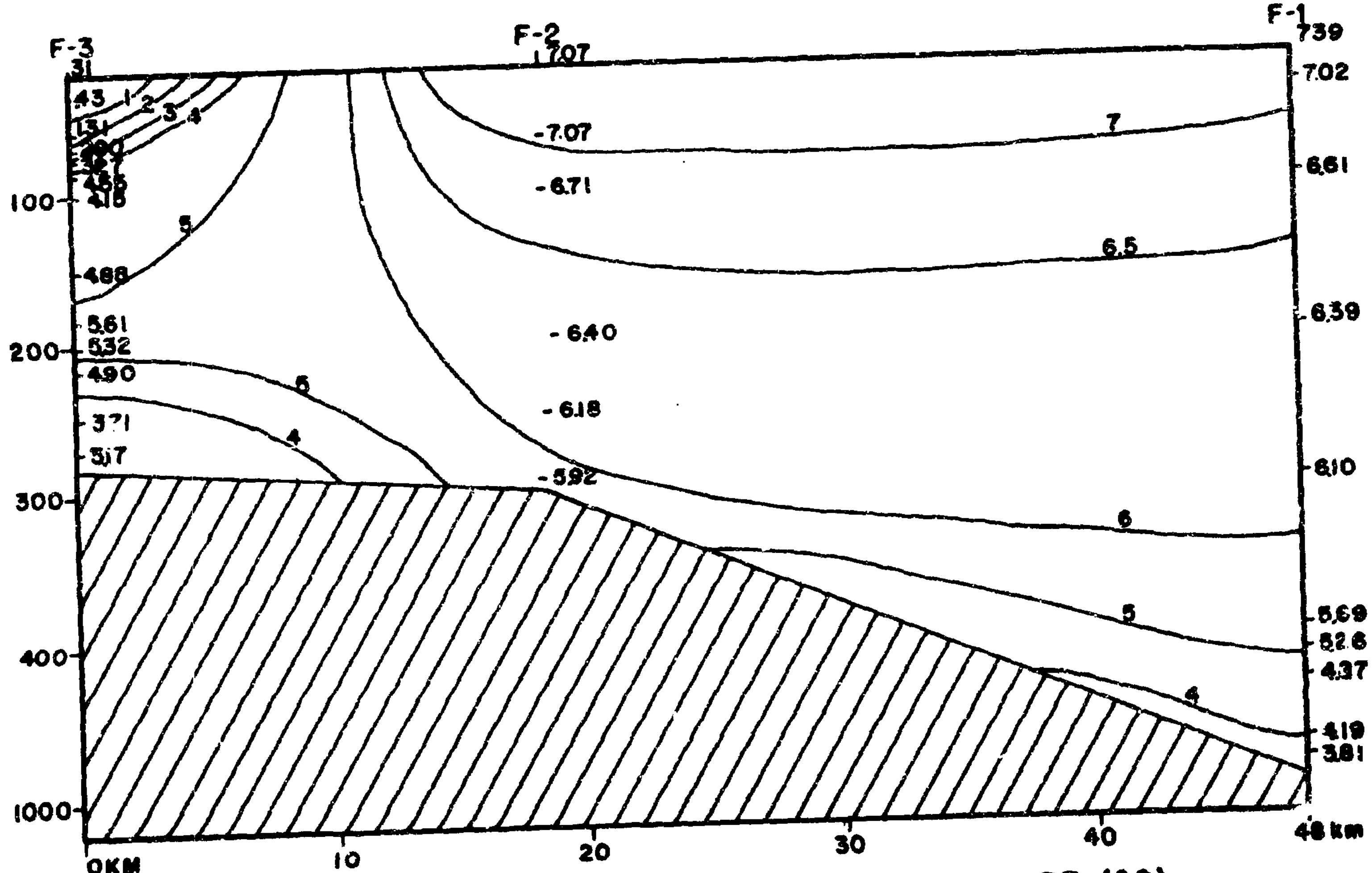

FIGURE 3.f.1 SECTION F TEMPERATURE (°C)

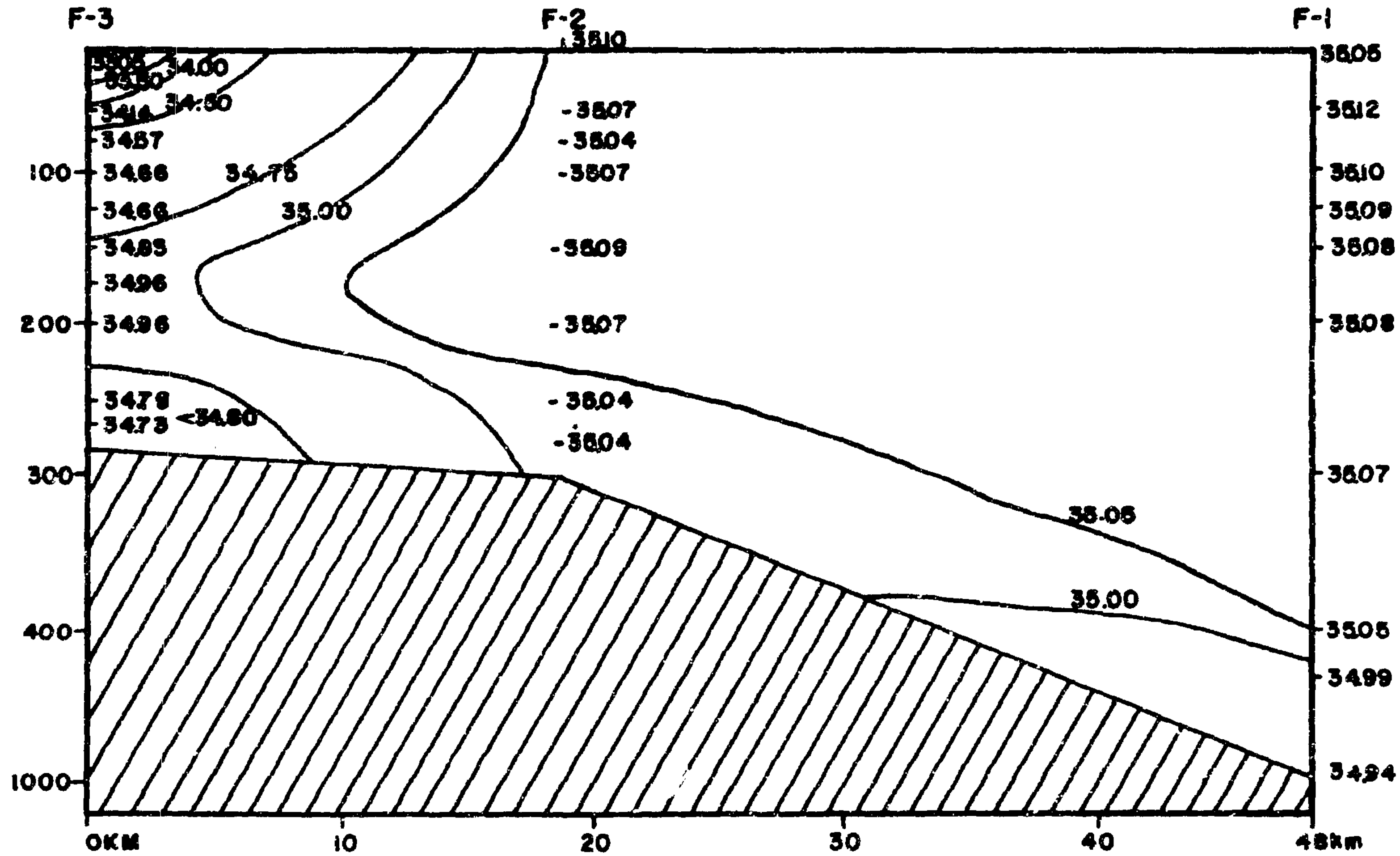

FIGURE 3.f.2 SECTION F SALINITY (°/oo)

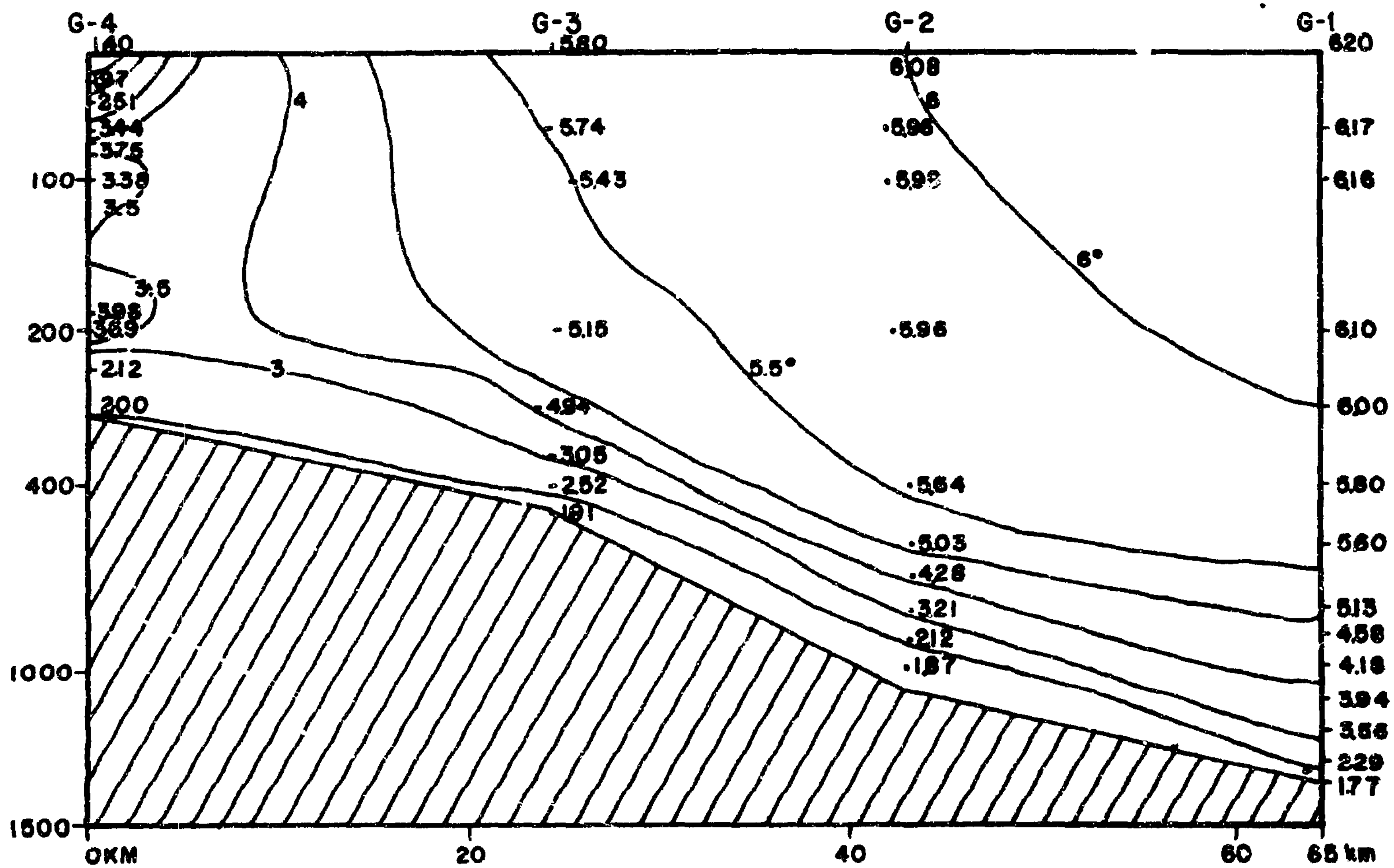

FIGURE 3.g.1 SECTION G TEMPERATURE (°C)

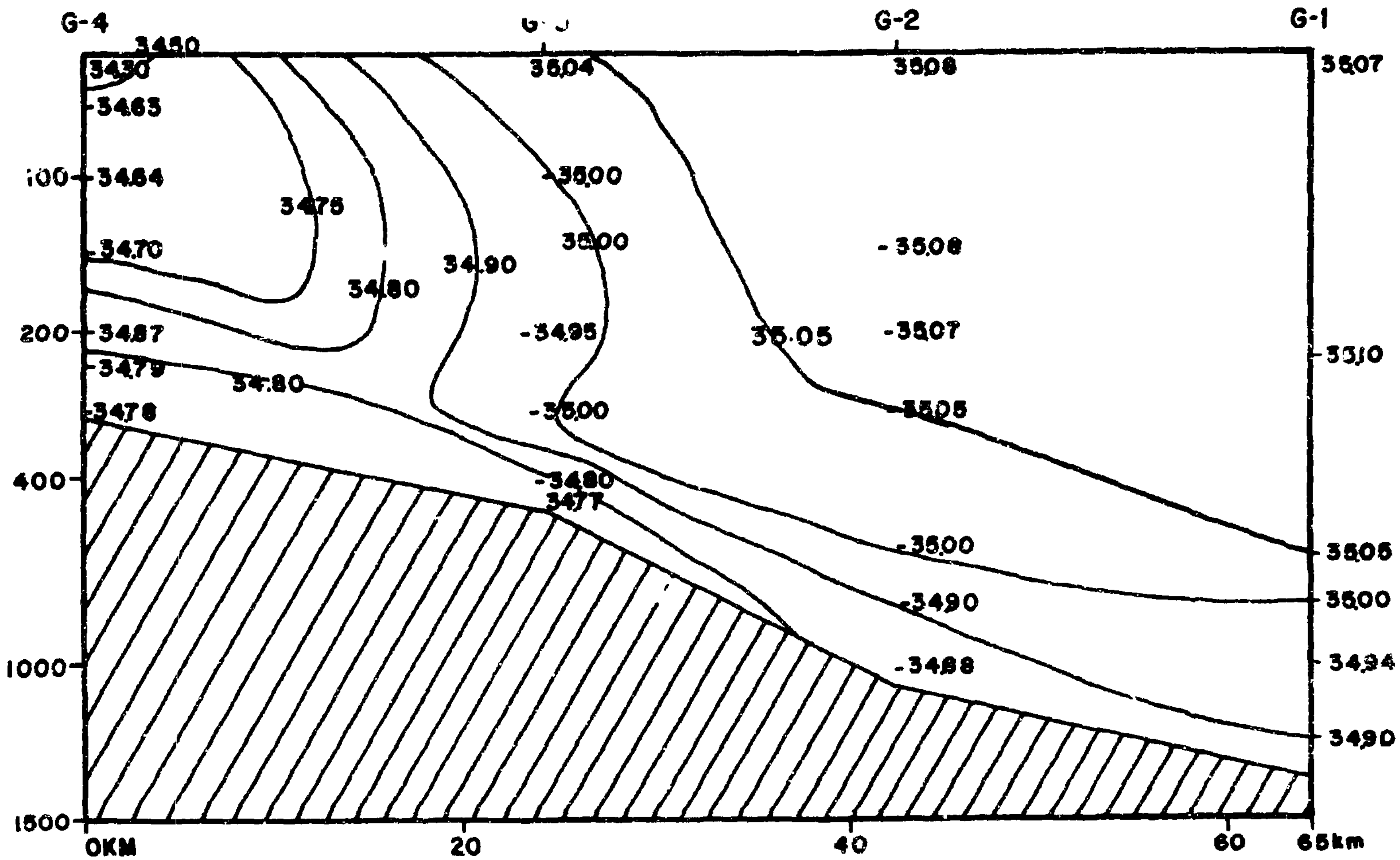

FIGURE 3.g.2 SECTION G SALINITY (°/oo)

A problem encountered in attempting to deal with a narrow frontal zone concerned the horizontal distance between the individual stations which comprise each section. These ranges average ten to fifteen miles and provide, at best, a rough description of a zone in which surface temperatures may differ by as much as 6 C across a distance of only three nautical miles (Krugler, 1952).

An examination of this area using closely spaced Experimental Bathythermograph (XBT) drops or a thermistor chain would be desirable but unfortunately has not been accomplished. Mazeika (1968), in his work across the Gulf Stream, has demonstrated that excellent approximations can be made using non-continuous data.

II. THE CHARACTERISTICS OF THE WATER MASSES

A. The Currents

The East Greenland Current flows in a southerly direction on or near the continental shelf of the eastern coast of Greenland (Figure 4). It may be traced from the straits between Northern Greenland and West Spitzbergen as far south as Cape Farewell, a distance of approximately 3000 km. It is composed, at origin, largely of water from the Arctic Basin and may have a characteristic temperature as low as -1.72 C with salinities from 31.00 o/oo to 33.5 o/oo depending largely on the influence of mixing and ice thaw or freeze. As the current moves to the south, it forms a narrow, shallow band of cold water lying against the western edge of the warmer and more saline Greenland Sea. According to Chaplygin (1959), the upper boundary of the East Greenland Current is always within 55 meters of the surface and at no time is it thicker than 210 meters.

To the north of the Greenland-Iceland Ridge, the East Greenland Current is underlain by what several authors refer to as the Return Atlantic Current (Figure 5). This current forms the western side of the counterclockwise gyre in the Norwegian/Greenland Sea area and is usually found at depths between 200 and 300 meters with a temperature near 2 C and a salinity of 34.75 - 34.90 o/oo (Lee, 1963).

According to Chaplygin, it is a slow current flowing at only 1-2 cm sec^{-1}, while Sverdrup (1942) gives a figure of

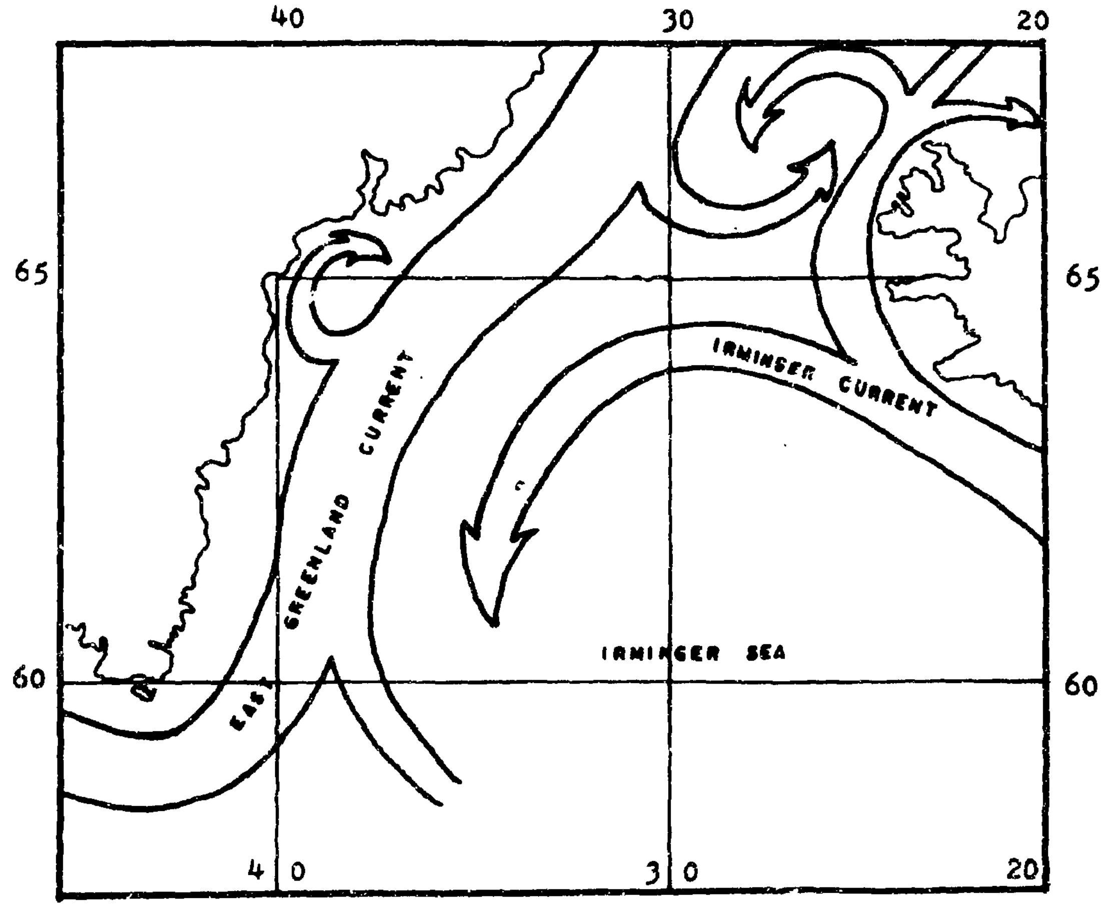

Figure 4. The surface current system
(after Hastings, 1960)

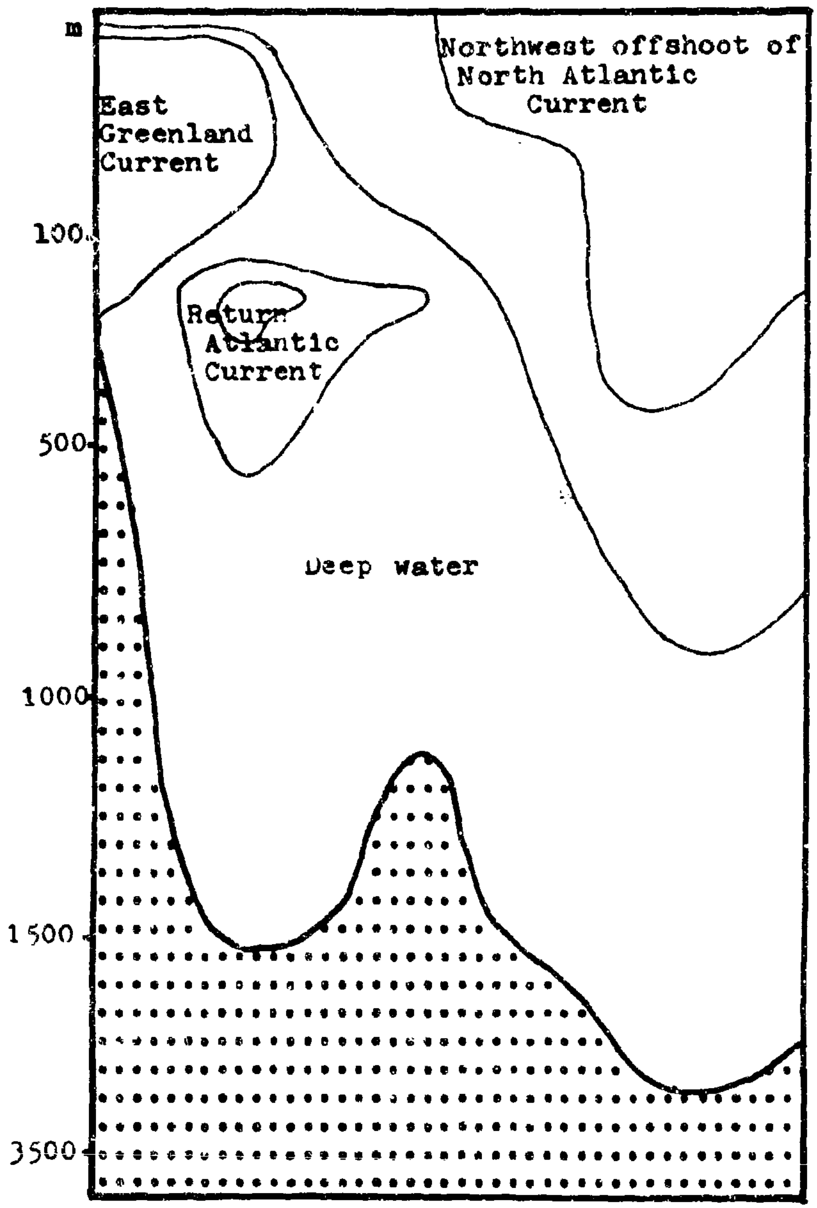

Figure 5. Current profile north of the Greenland-Icelandic Ridge (after Gladfelter, 1964)

25-35 cm sec^{-1} for the core of the more rapid East Greenland Current.

A major portion of the slow Retur . Atlantic Current, or undercurrent, is turned toward the East in an area to the north of the Greenland-Iceland Ridge and flows along the north coast of Iceland. South of the Greenland-Iceland Ridge, the East Greenland Current is bordered and underlain by the Irminger Current water as it proceeds toward Cape Farewell.

To further complicate the thermohaline structure near the bottom, there is evidence of intermittent overflow of cold deep water across the Greenland-Iceland Ridge. This flow, formed by winter cooling in the Norwegian Sea (Harvey, 1961), is defined by Cooper (1955a) as "a series of self-contained, cold, heavy balls or boluses of water". Harvey (1961) reports a decrease in temperature at the bottom of the Denmark Strait in August, 1960 from 2.5 C to 0.1 C with a sampling interval of 20 hours. The measured bottom current increased from 0.3 kts to a range of 0.54 kts to 1.4 kts, flowing in a southwesterly direction roughly parallel to the trough through the Greenland-Iceland Ridge.

The Irminger Current is a branch of the North Atlantic Drift Current, a part of the Gulf Stream System, and brings warm saline water into the Irminger Sea. As the Irminger Current approaches the southwest corner of Iceland, it splits into two branches. The major portion of the water moves to the southwest and flows alongside and in the same direction as the East Greenland Current while a much smaller amount courses around the Northern coast of Iceland toward the Faroe-Iceland Ridge. The Irminger Current water may vary seasonally, but many authors assign a temperature of 8-10 C and a salinity of 35.20 o/oo (See for example Cooper, 1955b) as average values. This water also has been referred to as North Eastern Atlantic Water (Holzkamm, et al. 1964).

The Irminger Current is driven by the wind system of the Icelandic atmospheric low as will be shown later. This low has large year-to-year-variations in its mean intensity. Thus, relatively large changes may be expected in the volume of flow of the Irminger Current as well as in the position of its boundaries.

B. The Vertical Structure

As may be seen in the section profiles (Figure 3), the vertical gradients are usually very gentle in the warm region. Upon entering the colder zone however, the vertical gradients of both temperature and salinity increase sharply due to the shallow extent of the East Greenland Current and the mass of warmer, more saline water which underlies it.

Of note is the frequency of occurrence of sub-thermocline ducts found at stations on both sides of the front. A preferred depth for these ducts appears to be 75 to 100 meters; their presence suggests that Variable Depth Sonar might be used with excellent efficiency in this region.

III. INFLUENCES ON THE STRENGTH AND LOCATION OF THE FRONT

The strength of the horizontal gradients in the frontal area is a function of several interacting environmental processes. The major parameters considered in this study are:

a) meterological influences (wind currents at the surface causing oceanic current convergence),

b) ice (affecting the convergence of both wind and thermohaline circulation) and

c) bottom topography.

These parameters, with the exception of c), vary daily as well as seasonally or annually.

A. The Meterological Influence

As indicated in the Local Area Forecasters Handbook for Keflavik, Iceland (1963), the area south of Greenland and southwest of Iceland is a junction for three diverse air masses:

1) the warm maritime air masses moving northward from the central North Atlantic,

2) arctic air from the Arctic Ocean or the Greenland ice cap and

3) continental air masses moving eastward from North America.

These air masses frequently interact to form an atmospheric polar front lying on or near the axis of the oceanic polar front. Figure 6 shows the mean seasonal positions of the

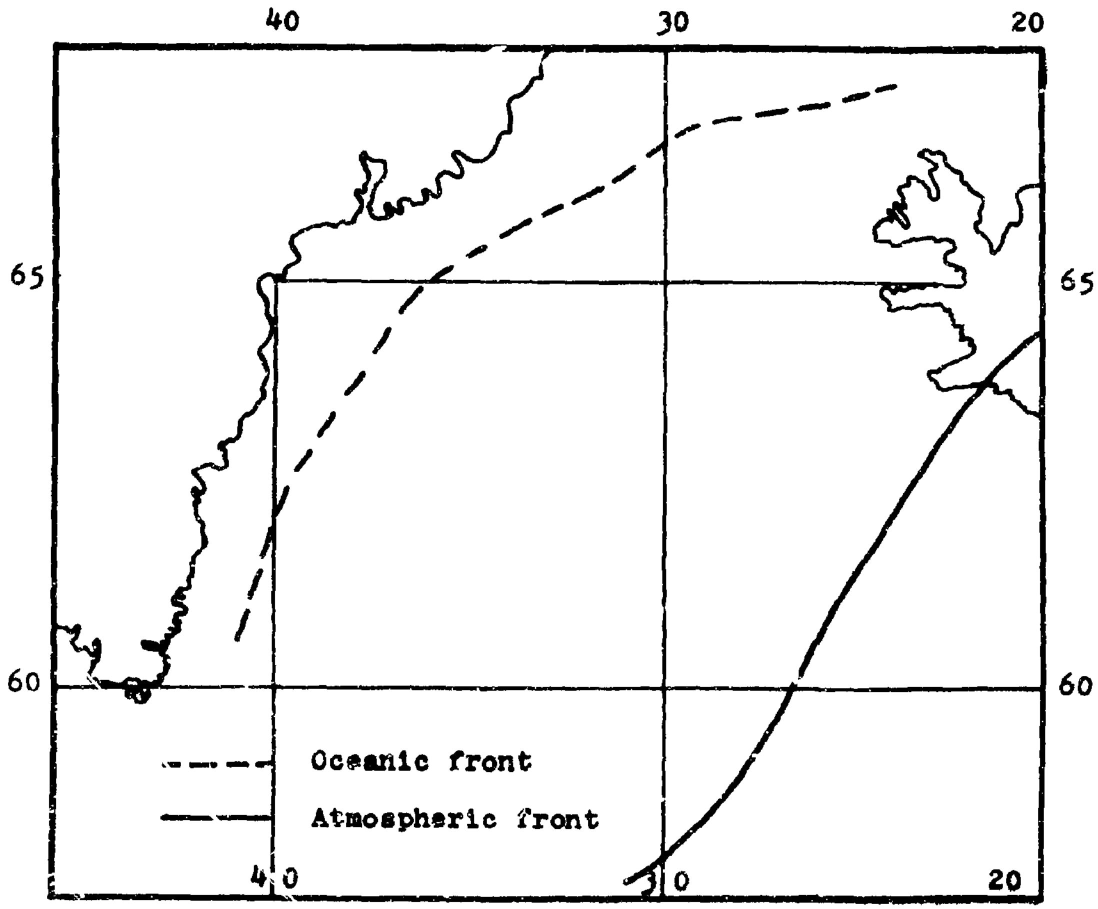

Figure 6a. Mean seasonal position of the atmospheric and oceanic Polar Fronts - Summer (after Petterson, 1958 and Dietrich, 1964)

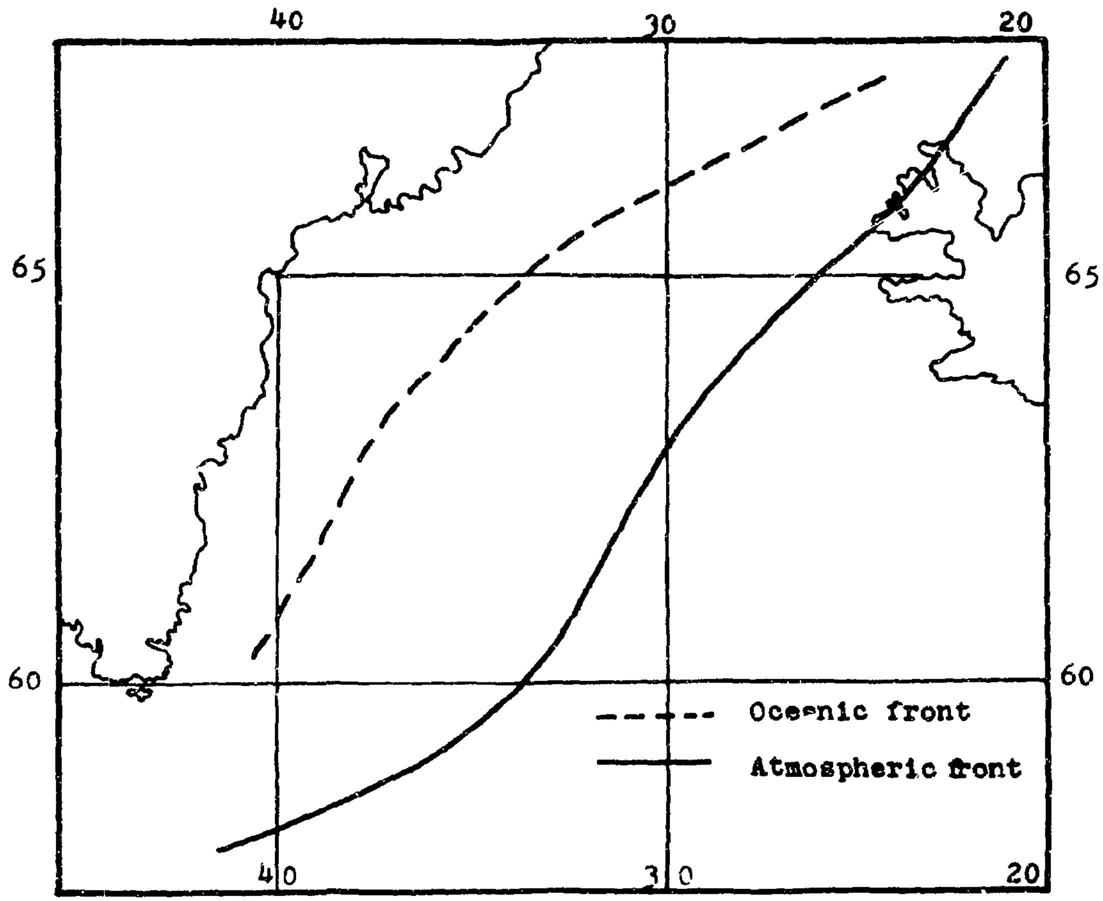

Figure 6b. Mean seasonal position of the atmospheric and oceanic Polar Fronts - Winter (after Petterson, 1958 and Dietrich, 1964)

two fronts. The atmospheric polar front exhibits large fluctuations with time and the location shown is subjective.

It is difficult to state a causal relationship between the fronts, but one may conclude that the surface currents which make up the oceanic polar front are greatly affected by the wind system. By extension then, we may postulate that the position of the oceanic polar front is directly related to that of the atmospheric polar front and that it reacts seasonally to atmospheric changes.

B. Ice and Its Influence

The seasonal distribution of ice along the coasts of Greenland and through the Denmark Strait is shown in Figure 7 (Climatological and Oceanographic Atlas for Mariners, 1959). The ice distribution may vary greatly from year to year and even day to day. Meyer (1965) has shown that during light ice years, the atmospheric high pressure system over Greenland is highly developed and the Icelandic low shifted to the south of its long term mean position. Conversely, heavy ice years show the Icelandic low shifted to the north. According to Meyer, the ice field moves onshore and becomes closely packed as a result of northerly, northeasterly, and easterly winds and will be pushed well off the coast as a result of westerlies. Figure 8 from Meyer shows an example of the rapid changes possible. On 21 April 1960, the ice edge was 56 miles from the coast. Eleven days later, after a period of northeasterly and

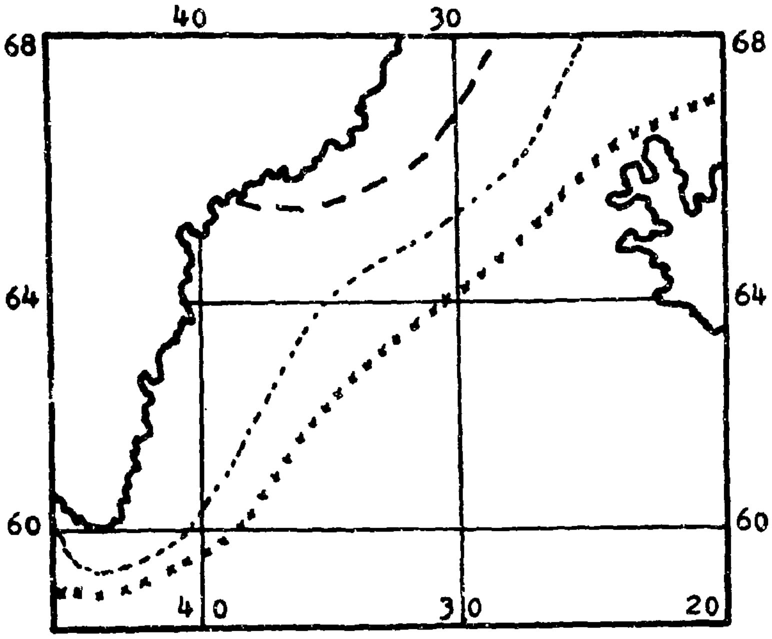

Figure 7 a. Average ice conditions in May
(after Climatological and Oceanographic
Atlas for Mariners, 1959)

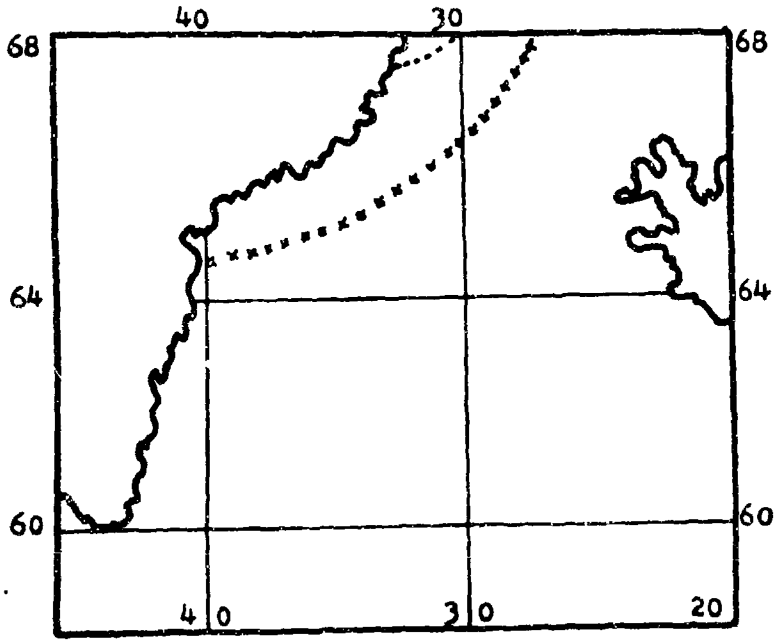

Figure 7 b. Average ice conditions in September
········ Mean ice concentration 0.8-1.0
— — — Minimum extent, concentration 0.5 or greater
xxxxxxxx Maximum extent, concentration 0.5 or greater

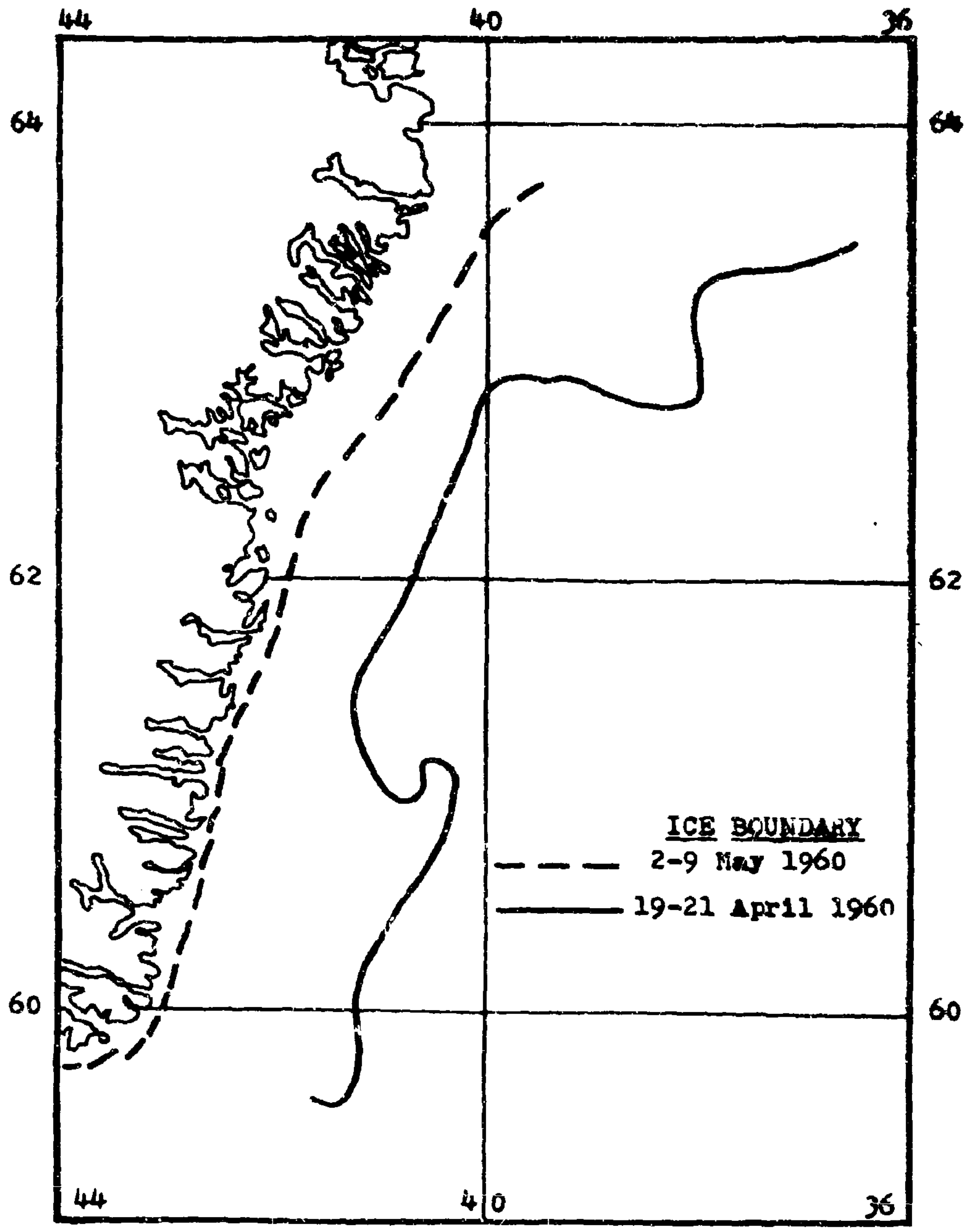

Figure 8. Rapidly changing ice boundaries off the S.E. coast of Greenland (after Meyer, 1965)

easterly winds, the ice edge was only 4-6 miles from the coast. Meyer further states that the ice edge is rarely driven beyond the border of the continental shelf. It will be shown in the next section that the oceanic polar front normally lies along the edge of the shelf. Since only the most massive ice floes and large bergs could exist for any length of time in the warm Irminger Current, it would appear the ice distribution strengthens the hypothesis of front location along the shelf edge.

C. The Bottom and Its Influence

The bottom topography of the Denmark Strait and Southeastern Greenland is varied. The Greenland-Iceland Ridge connects the shelves of Greenland and Iceland at depths of 200-300 m, but is cut along its NE-SW axis by a 600 M channel. The shelf off SE Greenland is twenty to fifty miles wide and is heavily glaciated with a discernible line of terminal moraines found near the break in slope. The slope is precipitous, falling from depths of 400 to 1000 meters in four or five miles, and then more gradually deepening to 3000 meters in the Icelandic and Labrador Basins (See Figure 9).

Along the Greenland-Iceland Rise, the oceanic front is more diffuse than on either side of the Rise. It is believed by the author that this is due partly to the more easterly position of the Irminger Current in this region

Figure 9. Bottom morphology of the North Atlantic (after Dietrich, 1964)

partly to the topographic deflection of the majority of the Return Atlantic Current.

South of the Greenland-Iceland Ridge, the center of the frontal zone tends to lie along the 1000 m contour. This is demonstrated by Dietrich and Gieskes (1966) and Dietrich (1958). As presented in cross-section by Hermann (1959, 1960) and reproduced in Figure 10, the front is seen to lie directly over the 1000 m contour. The close proximity of the 400 m contour to the edge of the slope and the surface thermal gradient shown in Figure 11 indicate that the shoraward edge of the front closely follows the 400 meter level along the south-eastern coast of Greenland. The depths assumed for the ray trace programs were based on this postulation.

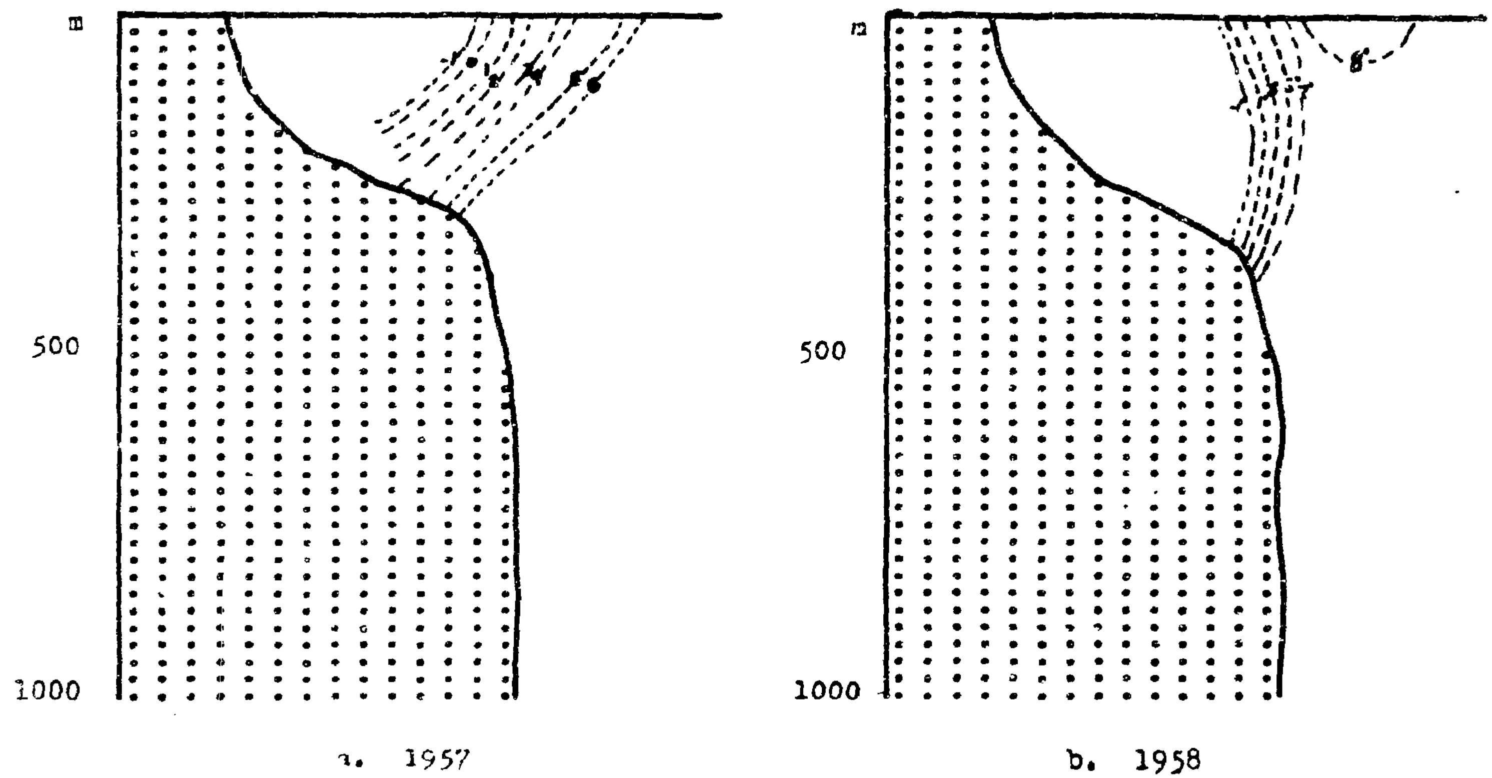

Figure 10. Cross sections off Cape Farewell
(after Hermann, 1959, 1960)

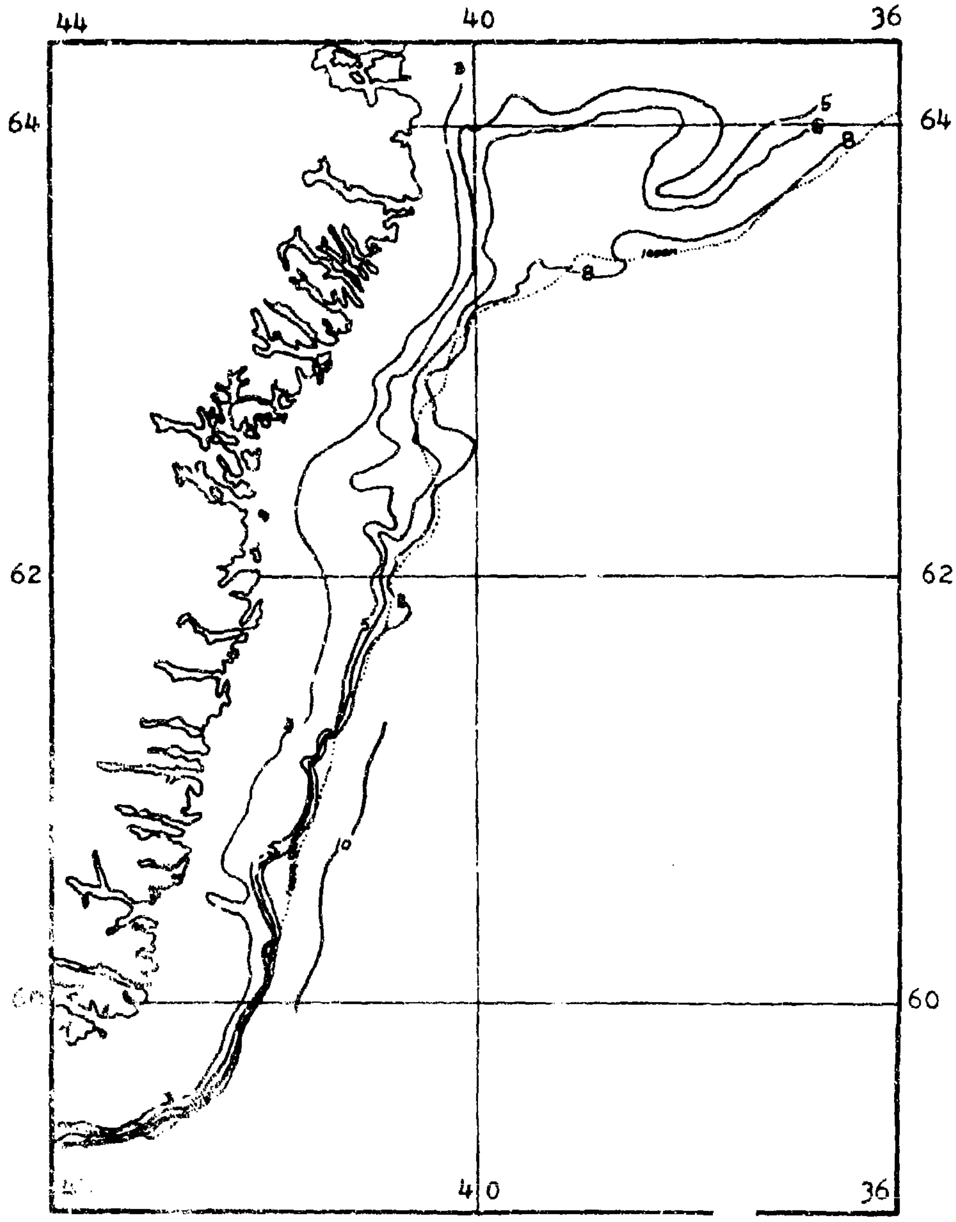

Figure 11. Temperature along the S.E. Greenland Slope, 1966 (after Dietric and Geiskes, 1968)

IV. FRONTAL EFFECTS ON SOUND PROPAGATION

A. The Computer Program

As indicated in part I.B., sonar ray traces were utilized to investigate frontal effects on sound propagation. The ray trace method was employed since other approaches, such as the normal mode technique, would cause insurmountable difficulties in this highly complex region. No precedents for this study have been found in the literature.

The ray traces were computed using the high precision computer program developed at FNWC (Ayres, et al., 1966). This program computes the ray position every 1/128th of a second of travel or less. As a ray approaches the surface or bottom, the time step is reduced so that the actual contact point is computed. Additionally, the program corrects for earth curvature (Wolff, et al.). Inputs required for each run are:

a) temperature and salinity at selected depths, surface to bottom,

b) range of each profile from sound origin,

c) bottom configuration,

d) source depth and

e) angles of propagation.

Input depths were selected to provide the computer with information on changes in temperature and salinity gradients and tend to be clustered about points of maximum change.

Output data permitted location of the ray in range and depth from the source at 60, 150, 300 and 500 feet from the surface and whenever the ray touched the surface or bottom or executed a maximum depth or minimum depth turn. These data are tabulated for each set of profiles in Tables 1-7.

B. Assumptions

The principal assumption made in this study of the effect of the oceanic polar front on sound propagation is that the stations lying on opposite sides of the front properly represent the water masses found there and that by compressing the profile spacing we are duplicating thermohaline gradient conditions which may be found in the environment but for which no data presently exist. The justification for this compression is the high surface thermal gradient reported by Krugler (1952), Dietrich, et al., (1961), and others. These gradients were not found in data available to the author, but do exist. There is no technique for precisely locating the front on any section and the thermohaline structure present at any station justifiably may be assumed to continue toward the boundary for some distance, thus increasing the gradients and reducing the compression required.

Compression of the stations ranged from 1.4/1 for the 10 KM run for Section C to a maximum of 8/1 for the 4 KM run of Section A. Compressed surface temperature gradients ranged from .036 C/KM in the 4 KM run of Section F. The maximum gradient of 1.68 C/KM exceeds the surface gradient reported by Krugler (1952) of 6 C in 3 NM (which converts to approximately 1 C/KM), but is much smaller than the gradient reported by Dietrich et al., (1961) of "7 C over a distance of a few hundred metres".

As previously stated, the bottom was assumed level for each of the sections, but a depth representative of its location was assigned to each. This was done to permit comparison of frontal effects from section to section to be made without the variable influence of bottom topography.

C. Results

The compilation of results in Tables 1-7 presents the section designator, date, season, and station numbers used in the ray trace programs with their locations, charted depths and assumed depths. The actual horizontal distance between profiles is given, as well as the difference in measured surface temperature, ΔT (SURFACE). Assumed separations of 10, 6 and 4 KM were divided into ΔT (SURFACE) to obtain the DT/DX gradient information.

The angle trapped is defined as the angular distance in degrees between the horizontal or zero degree ray and the angle which first touches bottom within the range of consideration.

SECTION: A　　DATE: 8 APRIL 1958　　SEASON: SPRING

STATION	LOCATION	CHARTED DEPTH (m)	ASSUMED DEPTH (m)
A-2	60-42N 41-02W	2055	400
A-3	60-54N 41-35W	438	400

ACTUAL SEPARATION: 32 KM　　ΔT (SURFACE): 4.30°C

ASSUMED SPACING		10 KM		6 KM		4 KM	
DT/DX (C/KM)		.43		.72		1.07	
DIRECTION OF SOUND PROPAGATION		COLD TO WARM	WARM TO COLD	COLD TO WARM	WARM TO COLD	COLD TO WARM	WARM TO COLD
ANGLE TRAPPED		10.40	6.40	10.20	7.00	10.40	8.00
	ø	x y z	x y z	x y z	x y z	x y z	x y z
NUMBER OF SURFACE BOUNCES (x)	0°	6/6/0	6/6/0	4/4/0	3/4/0	2/3/0	2/3/0
	1°	6/6/0	6/6/0	4/4/0	3/4/0	2/3/0	2/3/0
	2°	6/6/0	2/3/0	3/4/0	1/2/0	2/3/0	1/1/0
MAX DEPTH TURNS (y)	3°	3/4/0	1/2/0	2/2/0	0/1/0	1/1/0	0/1/0
	4°	2/2/0	2/2/0	1/1/0	1/1/0	0/1/0	0/1/0
	6°	2/2/0	0/1/0	1/1/0	0/1/0	1/1/0	0/1/0
MIN DEPTH TURNS (z)	8°	1/2/0	BOTTOM	1/1/0	BOTTOM	0/1/0	BOTTOM
	10°	0/1/0	"	0/0/0/	"	0/0/0	"
	ø						
MAXIMUM DEPTH OF RAY (FT.) AND RANGE (KYDS)	0°	33/8.2	30/1.4	33/4.9	27/1.0	33/3.3	26/.8
	1°	55/10.9	65/1.2	44/5.1	61/1.1	44/3.6	57/.9
	2°	81/10.9	184/2.8	69/5.4	168/2.5	74/4.1	153/2.2
	3°	142/10.9	368/3.7	107/6.5	360/3.9	135/4.3	328/3.9
	4°	182/1.9	416/2.5	230/6.5	401/2.3	198/2.2	393/2.3
	6°	578/10.9	1117/7.4	532/6.5	854/5.4	402/1.8	647/3.7
	8°	602/6.9	BOTTOM	522/6.5	BOTTOM	528/2.4	BOTTOM
	10°	1065/6.2	"	1280/6.5	"	845/4.4	"

Table 1. Tabulation of ray trace data.
Section A

SECTION: B

DATE: 7 JUNE 1955

SEASON: SPRING

STATION	LOCATION	CHARTED DEPTH (m)	ASSUMED DEPTH (m)
B-3	61-25N 41-23W	320	400
B-4	61-28N 41-47W	450	400

ACTUAL SEPARATION: 20 KM

△T (SURFACE): .71°C

ASSUMED SPACING		10 KM		6 KM		4 KM	
DT/DX (C/KM)		.071		.11		.18	
DIRECTION OF SOUND PROPAGATION		COLD TO WARM	WARM TO COLD	COLD TO WARM	WARM TO COLD	COLD TO WARM	WARM TO COLD
ANGLE TRAPPED		8.80	7.80	8.60	8.10	8.80	8.80
	Ø	x y z	x y z	x y z	x y z	x y z	x y z
NUMBER OF SURFACE BOUNCES (x)	0°	0/3/3	0/3/3	0/2/0	0/2/2	0/1/1	0/1/1
	1°	3/4/0	3/4/0	2/2/0	2/2/0	1/2/0	1/2/0
	2°	1/2/1	4/4/0	1/2/0	2/3/0	0/1/1	1/2/0
	3°	2/2/0	2/2/0	1/1/0	1/1/0	0/1/0	0/1/0
MAX DEPTH TURNS (y)	4°	1/2/0	1/2/0	1/1/0	0/1/0	0/1/0	0/1/0
	6°	1/1/0	1/1/0	0/1/0	0/1/0	0/0/0	0/0/0
	8°	1/1/0	BOTTOM	0/1/0	0/0/0	0/0/0	0/1/0
MIN DEPTH TURNS (z)		BOTTOM	"	BOTTOM	BOTTOM	BOTTOM	BOTTOM
MAXIMUM DEPTH OF RAY (FT.) AND RANGE (KYDS)	Ø						
	0°	29/3.3	31/5.5	30/5.1	31/4.2	29/2.0	31/1.3
	1°	68/1.3	61/10.7	66/1.2	56/3.9	60/1.5	60/4.2
	2°	213/7.9	125/10.9	192/2.3	115/6.3	202/2.5	84/3.0
	3°	262/7.7	249/2.5	261/2.4	247/2.6	261/2.4	245/2.6
	4°	414/9.7	397/3.4	401/3.1	390/3.3	408/3.2	383/3.1
	6°	787/4.8	771/5.0	796/5.1	766/4.9	786/4.4	755/4.4
	8°	1000/10.9	BOTTOM	1075/5.0	1309/6.3	1173/4.3	1024/4.0
	10°	BOTTOM	"	BOTTOM	BOTTOM	BOTTOM	BOTTOM

Table 2. Tabulation of ray trace data.
Section B

SECTION: C DATE: 18 SEPT. 1955 SEASON: SUMMER

STATION	LOCATION	CHARTED DEPTH (m)	ASSUMED DEPTH (m)
C-3	61-56N 41-30W	230	230
C-4	62-00N 41-45W	180	230

ACTUAL SEPARATION: 14 KM ΔT (SURFACE): 2.18°C

ASSUMED SPACING		10 KM		6 KM		4 KM	
DT/DX (C/KM)		.21		.36		.56	
DIRECTION OF SOUND PROPAGATION		COLD TO WARM	WARM TO COLD	COLD TO WARM	WARM TO COLD	COLD TO WARM	WARM TO COLD
ANGLE TRAPPED		6.60	5.20	6.60	6.00	7.00	4.40
	Ø	x y z	x y z	x y z	x y z	x y z	x y z
NUMBER OF SURFACE BOUNCES (x)	0°	4/4/0	5/5/0	2/3/0	3/3/0	2/2/0	2/2/0
	1°	3/3/0	2/3/0	1/2/0	1/2/0	1/1/0	1/1/0
	2°	2/2/0	3/3/0	1/1/0	1/2/0	1/1/0	1/1/0
MAX DEPTH TURNS (y)	3°	3/3/0	2/3/0	1/2/0	2/2/0	1/1/0	1/1/0
	4°	3/3/0	0/2/1	2/2/0	0/1/0	1/1/0	0/0/0
	6°	1/2/0	BOTTOM	1/1/0	BOTTOM	0/1/0	BOTTOM
MIN DEPTH TURNS (z)	8°	BOTTOM	"	BOTTOM	"	BOTTOM	"
	10°	"	"	"	"	"	"
	Ø						
MAXIMUM DEPTH OF RAY (FT.) AND RANGE (KYDS)	0°	37/10.9	SOURCE	31/5.1	SOURCE	28/2.4	SOURCE
	1°	63/7.5	107/2.6	61/4.3	99/2.2	72/4.4	92/2.0
	2°	163/10.9	191/2.2	152/6.6	177/2.0	113/1.6	165/1.8
	3°	179/7.6	307/3.6	177/4.6	244/2.0	179/4.4	224/1.8
	4°	265/10.9	664/9.5	184/1.1	701/6.2	248/4.4	654/4.4
	6°	519/10.1	BOTTOM	462/6.6	BOTTOM	316/2.3	BOTTOM
	8°	BOTTOM	"	BOTTOM	"	BOTTOM	"
	10°	"	"	"	"	"	"

Table 3. Tabulation of ray trace data.
Section C

SECTION: D | DATE: 11 JUNE 1955 | SEASON: SPRING

STATION	LOCATION	CHARTED DEPTH (m)	ASSUMED DEPTH (m)
D-2	63-54N 36-50W	335	400
D-3	64-08N 37-18W	395	400

ACTUAL SEPARATION: 30 KM

ΔT (SURFACE): 6.63°C

		10 KM		6 KM		4 KM	
ASSUMED SPACING		10 KM		6 KM		4 KM	
DT/DX (C/KM)		.66		1.11		1.66	
DIRECTION OF SOUND PROPAGATION		COLD TO WARM	WARM TO COLD	COLD TO WARM	WARM TO COLD	COLD TO WARM	WARM TO COLD
ANGLE TRAPPED		10.20	3.00	10.20	4.40	10.80	6.00
	Ø	x y z	x y z	x y z	x y z	x y z	x y z
NUMBER OF SURFACE BOUNCES (x)	0°	3/4/0	3/4/0	2/2/0	2/3/0	1/2/0	1/2/0
	1°	4/4/0	4/5/0	2/3/0	2/3/0	1/2/0	2/2/0
	2°	4/5/0	2/3/0	2/3/0	3/3/0	2/2/0	2/2/0
MAX DEPTH TURNS (y)	3°	4/5/1	BOTTOM	3/3/0	1/2/0	2/2/0	1/1/0
	4°	5/5/0	"	3/3/0	0/0/0	2/2/0	0/1/0
	6°	4/5/0	"	2/3/0	BOTTOM	2/2/0	BOTTOM
MIN DEPTH TURNS (z)	8°	2/2/0	"	1/2/0	"	1/1/0	"
	10°	1/1/0	"	0/0/0	"	0/0/0	"
	Ø						
MAXIMUM DEPTH OF RAY (FT.) AND RANGE (KYDS)	0°	33/9.7	SOURCE	35/6.5	SOURCE	30/3.1	SOURCE
	1°	62/10.9	69/1.4	54/5.6	66/1.2	50/3.0	63/1.1
	2°	90/9.7	334/3.9	83/5.0	167/2.0	78/2.8	124/1.5
	3°	172/10.9	BOTTOM	172/6.6	375/2.9	130/4.4	273/2.6
	4°	311/10.9	"	257/6.6	1104/6.6	213/4.4	570/4.0
	6°	362/10.5	"	210/4.7	BOTTOM	174/2.4	BOTTOM
	3°	547/10.9	"	379/5.1	"	345/4.4	"
	10°	803/10.9	"	1200/6.5	"	1002/4.4	"

Table 4. Tabulation of ray trace data.
Section D

SECTION: E | DATE: 16 SEPT. 1955 | SEASON: SUMMER

STATION	LOCATION	CHARTED DEPTH (m)	ASSUMED DEPTH (m)
E-4	65-10N 36-17W	230	230
E-5	65-22N 36-41W	190	230

ACTUAL SEPARATION: 27 KM

ΔT (SURFACE): .36°C

ASSUMED SPACING		10 KM		6 KM		4 KM	
DT/DX (C/KM)		.036		.06		.09	
DIRECTION OF SOUND PROPAGATION		COLD TO WARM	WARM TO WARM	COLD TO WARM	WARM TO COLD	COLD TO WARM	WARM TO COLD
ANGLE TRAPPED		7.10	7.50	7.60	7.70	7.40	7.90
	Ø	x y z	x y z	x y z	x y z	x y z	x y z
NUMBER OF SURFACE BOUNCES (x)	0°	1/4/2	1/3/1	1/2/1	2/2/0	1/2/0	1/1/0
	1°	3/4/0	4/[illegible]/0	2/2/0	2/2/0	1/2/0	1/2/0
	2°	1/2/0	4/4/0	1/1/0	2/2/0	0/1/0	1/2/0
MAX DEPTH TURNS (y)	3°	1/2/0	1/3/1	1/1/0	1/2/0	0/1/0	0/0/0
	4°	1/2/0	1/2/1	1/1/0	0/1/1	0/1/0	0/1/0
	6°	2/2/0	1/2/0	1/1/0	1/1/0	0/1/0	0/1/0
MIN DEPTH TURNS (z)	8°	BOTTOM	BOTTOM	BOTTOM	BOTTOM	BOTTOM	BOTTOM
	10°	"	"	"	"	"	"
MAXIMUM DEPTH OF RAY (FT.) AND RANGE (KYDS)	Ø						
	0°	46/10.7	50/1.4	46/3.8	49/1.4	52/3.7	49/1.5
	1°	60/ALL	62/9.3	60/ALL	60/ALL	60/ALL	62/3.7
	2°	395/3.3	142/10.9	386/3.5	109/6.6	371/4.0	88/3.1
	3°	517/3.2	264/9.9	514/3.4	369/6.4	500/3.5	300/4.4
	4°	551/8.0	361/7.5	5[illegible]/2.5	317/6.6	539/2.8	296/3.6
	6°	662/7.2	544/3.1	598/2.2	530/2.6	629/2.7	526/2.5
	8°	BOTTOM	BOTTOM	BOTTOM	BOTTOM	BOTTOM	BOTTOM
	10°	"	"	"	"	"	"

Table 5. Tabulation of ray trace data.
Section E

SECTION: F | DATE: 13 JUNE 1955 | SEASON: SPRING

STATION	LOCATION	CHARTED DEPTH (m)	ASSUMED DEPTH (m)
F-2	65-40N 32-30W	300	300
F-3	65-50N 32-25W	280	300

ACTUAL SEPARATION: 18 KM

ΔT (SURFACE): 6.73°C

	Ø						
ASSUMED SPACING		10 KM		6 KM		4 KM	
DT/DX (C/KM)		.67		1.12		1.68	
DIRECTION OF SOUND PROPAGATION		COLD TO WARM	WARM TO COLD	COLD TO WARM	WARM TO COLD	COLD TO WARM	WARM TO COLD
ANGLE TRAPPED		10.00	4.00	10.80	4.80	10.80	5.60
	Ø	x y z	x y z	x y z	x y z	x y z	x y z
NUMBER OF SURFACE BOUNCES (x)	0°	4/5/0	4/5/0	3/3/0	3/3/0	2/2/0	2/2/0
	1°	4/4/0	3/4/0	2/3/0	2/2/0	1/2/0	1/2/0
	2°	4/4/0	5/5/0	2/3/0	3/3/0	1/2/0	2/2/0
MAX DEPTH TURNS (y)	3°	5/5/0	0/3/2	3/3/0	3/3/0	2/2/0	1/2/0
	4°	5/5/0	BOTTOM	3/3/0	1/2/0	2/2/0	0/1/0
	6°	6/6/0	"	3/3/0	BOTTOM	2/2/0	BOTTOM
MIN DEPTH TURNS (z)	8°	4/5/0	"	3/3/0	"	2/2/0	"
	10°	BOTTOM	"	1/1/0	"	0/1/0	"
MAXIMUM DEPTH OF RAY (FT.) AND RANGE (KYDS)	Ø						
	0°	SOURCE	SOURCE	SOURCE	SOURCE	SOURCE	SOURCE
	1°	53/8.7	66/1.6	56/6.4	64/1.5	52/3.5	62/1.3
	2°	99/10.9	133/1.8	108/6.2	119/1.4	98/3.4	111/1.2
	3°	127/8.5	347/4.2	118/4.5	165/1.2	112/2.5	158/1.1
	4°	156/8.5	BOTTOM	150/4.4	478/3.1	145/2.6	453/4.2
	6°	445/10.9	"	331/6.5	BOTTOM	311/4.4	BOTTOM
	8°	474/7.6	"	633/6.5	"	533/4.4	"
	10°	BOTTOM	"	520/6.5	"	521/2.5	"

Table 6. Tabulation of ray trace data.
Section F

SECTION: G DATE: 20 MAR. 1958 SEASON: WINTER

STATION	LOCATION	CHARTED DEPTH (m)	ASSUMED DEPTH (m)
G-3	65-33N 32-12W	497	400
G-4	65-46N 32-34W	313	400

ACTUAL SEPARATION: 25 KM ΔT (SURFACE): 4.40°C

ASSUMED SPACING		10 KM		6 KM		4 KM	
DT/DX (C/KM)		.44		.73		1.1	
DIRECTION OF SOUND PROPAGATION		COLD TO WARM	WARM TO COLD	COLD TO WARM	WARM TO COLD	COLD TO WARM	WARM TO COLD
ANGLE TRAPPED		8.00	3.50	7.80	4.20	8.80	6.00
	ø	x y z	x y z	x y z	x y z	x y z	x y z
NUMBER OF SURFACE BOUNCES (x)	0°	9/10/0	4/6/2	5/6/0	3/4/1	4/4/0	1/3/1
	1°	9/9/0	8/9/0	5/6/0	5/5/0	3/4/0	3/4/0
	2°	8/8/0	6/6/0	4/5/0	3/4/0	3/3/0	2/3/0
MAX DEPTH TURNS (y)	3°	7/7/0	1/2/0	4/4/0	0/1/0	2/3/0	1/1/0
	4°	6/6/0	BOTTOM	3/4/0	0/0/0	2/2/0	0/1/0
	6°	3/3/0	"	1/2/1	BOTTOM	1/1/0	BOTTOM
MIN DEPTH TURNS (z)	8°	BOTTOM	"	BOTTOM	"	0/0/0	"
	10°	"	"	"	"	BOTTOM	"
	ø						
MAXIMUM DEPTH OF RAY (FT.) AND RANGE (KYDS)	0°	48/10.9	SOURCE	37/5.5	SOURCE	33/3.1	SOURCE
	1°	44/9.3	53/1.0	50/6.3	50/.9	41/3.5	48/.8
	2°	62/9.4	115/1.4	59/5.5	107/1.3	69/4.4	98/1.2
	3°	88/9.3	518/4.5	92/6.6	498/4.6	77/3.3	194/2.2
	4°	115/8.8	BOTTOM	120/5.7	1156/6.6	130/4.4	549/3.5
	6°	467/10.9	"	214/6.6	BOTTOM	317/4.4	BOTTOM
	8°	BOTTOM	"	BOTTOM	"	1010/4.4	"
	10°	"	"	"	"	BOTTOM	"

Table 7. Tabulation of ray trace data.
Section G

For each depression angle (Ø), 0, 1, 2, 3, 4, 6, 8, and 10 degrees, the number of surface bounces (x), number of maximum depth turns (y) and number of minimum depth turns (z) are recorded in the columns below the corresponding letter.

The final tabulation gives the maximum depth attained by the ray (in feet) and the horizontal range from the source (in kiloyards) at which this depth is reached.

Upon examination of these data in Tables 1-7, several points of interest became apparent:

1) In all runs where the assumed surface thermal gradient was greater than 0.20 C/KM (36 runs) the cold-to-warm propagation tended to produce more surface bounces than the warm-to-cold runs. The ray density is greater in the near-surface layers in the cold-to-warm runs. This is further demonstrated by the maximum depths attained by the rays, in that the rays from cold-to-warm were more shallow than the corresponding warm-to-cold ray. This comparison is illustrated in Figure 12.

2) Conversely, in those cases where the assumed surface thermal gradient was less than 0.2 C/KM, the warm-to-cold propagation produced more surface bounces and the cold-to-warm rays reached a greater depth. Propagation of this type is shown in Figure 13.

3) The angle between the zero degree ray and the first ray to touch bottom (trapping angle) was greater in

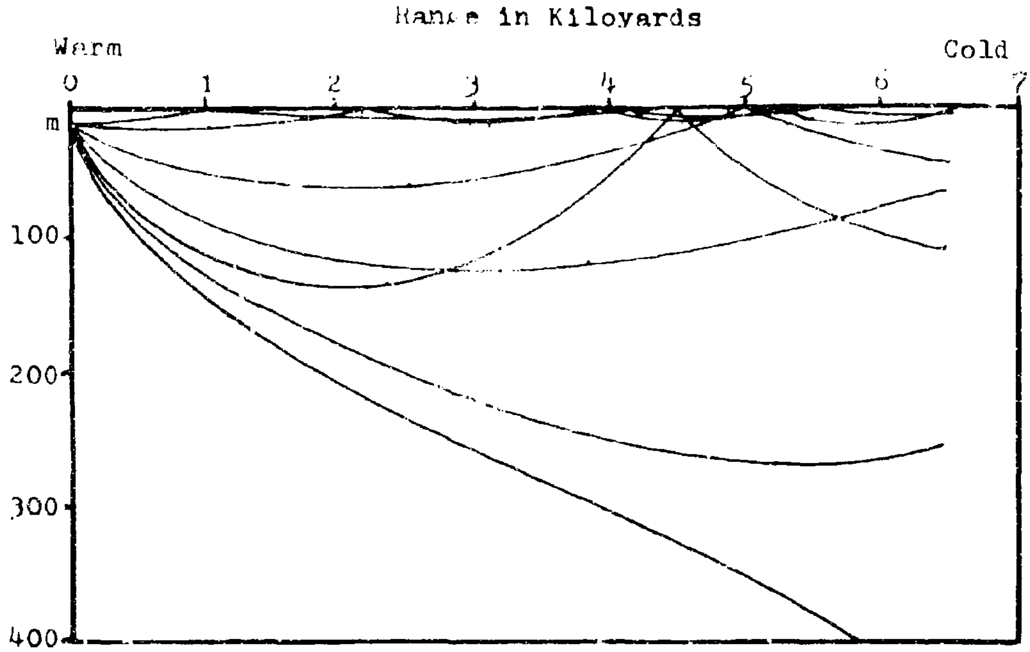

Figure 12a. Ray trace diagram
Section A, 6 KM. profile spacing
Warm to cold

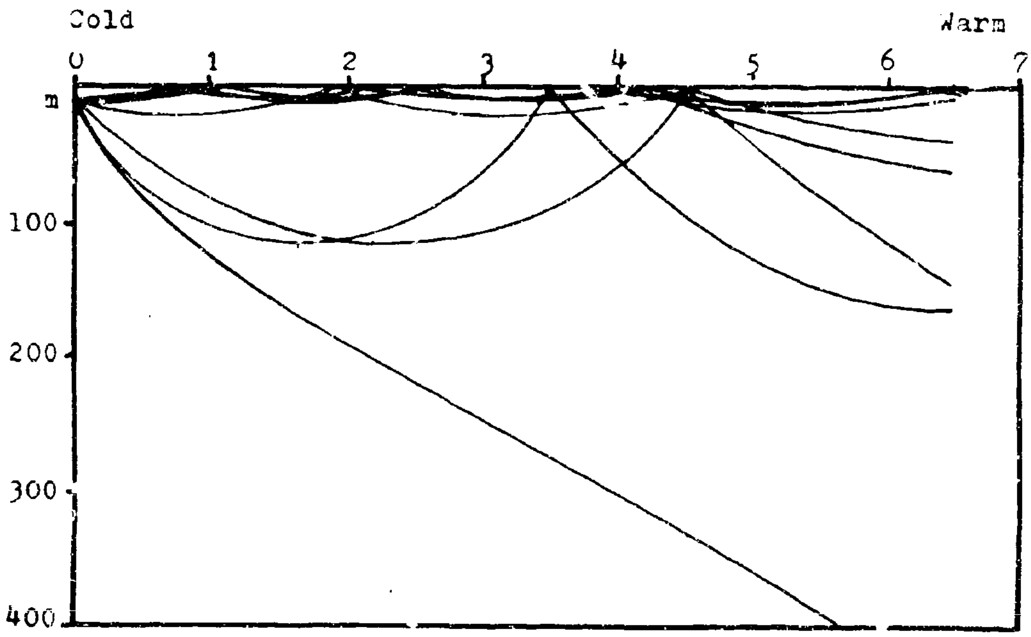

Figure 12b. Ray trace diagram
Section A, 6 KM. profile spacing
Cold to warm

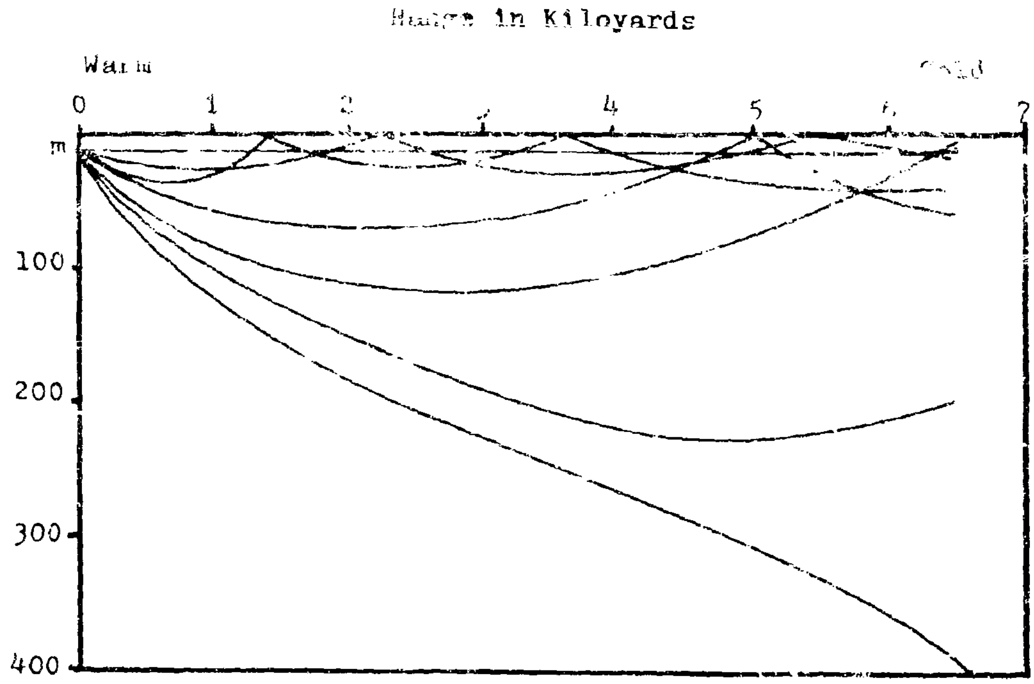

Figure 13a. Ray trace diagram
Section B, 6 KM. profile spacing
Warm to cold

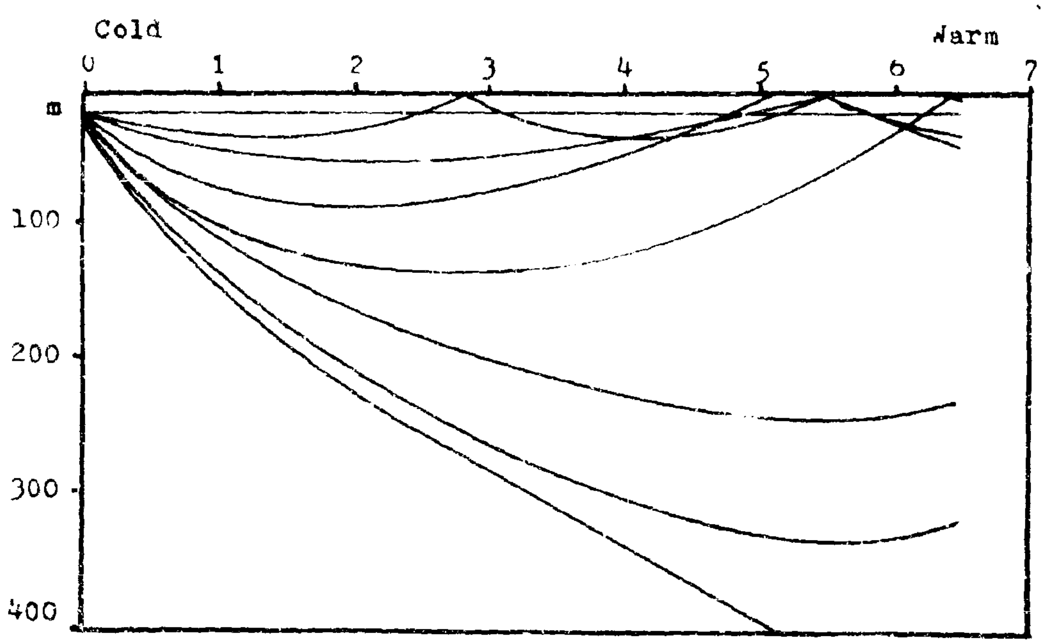

Figure 13b. Ray trace diagram
Section B, 6 KM. profile spacing
Cold to warm

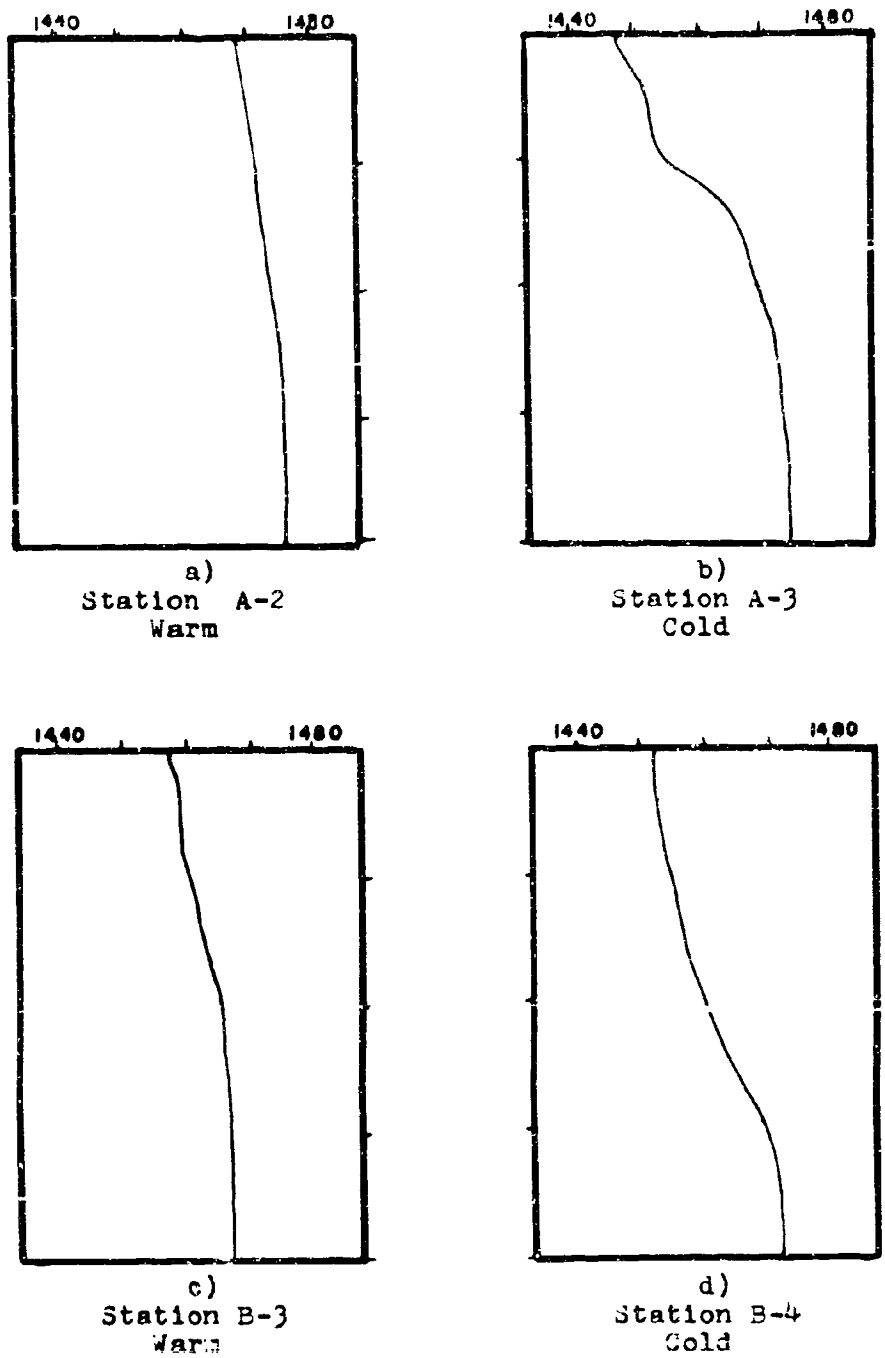

Figure 14. Sound velocity profiles for Sections A and B

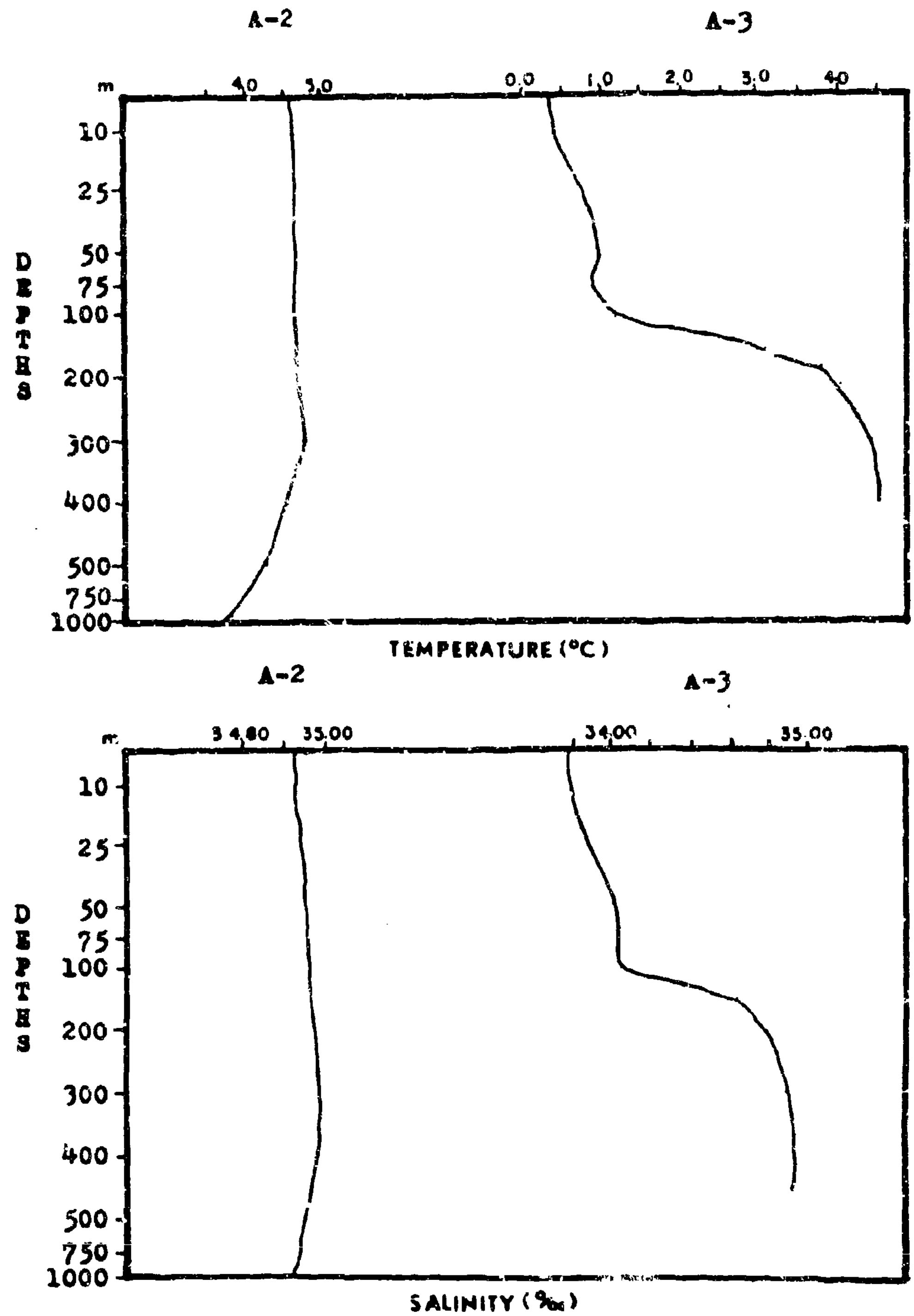

FIGURE 15a. TEMPERATURE/SALINITY PROFILES
SECTION A

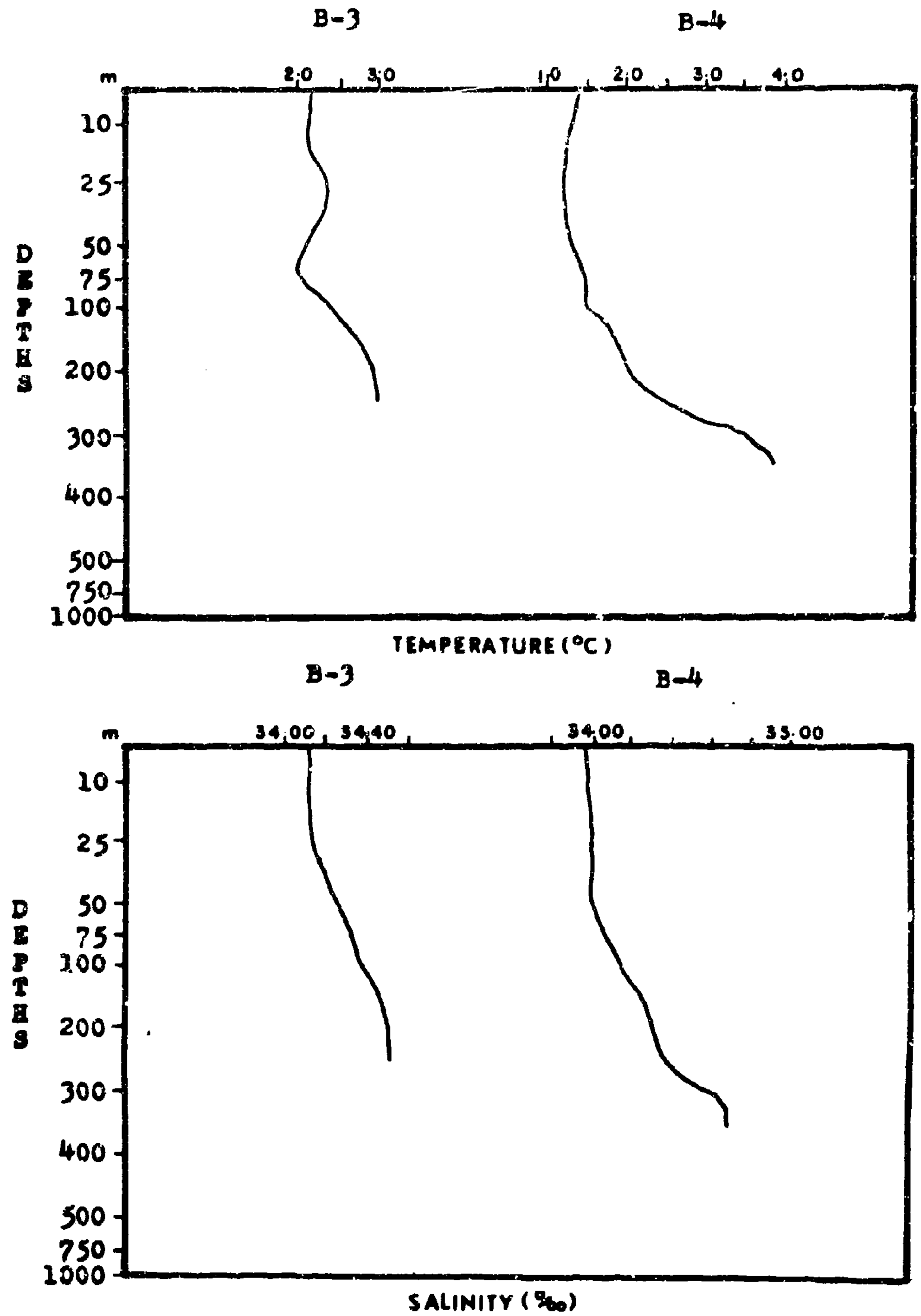

FIGURE 15b. TEMPERATURE/SALINITY PROFILES SECTION B

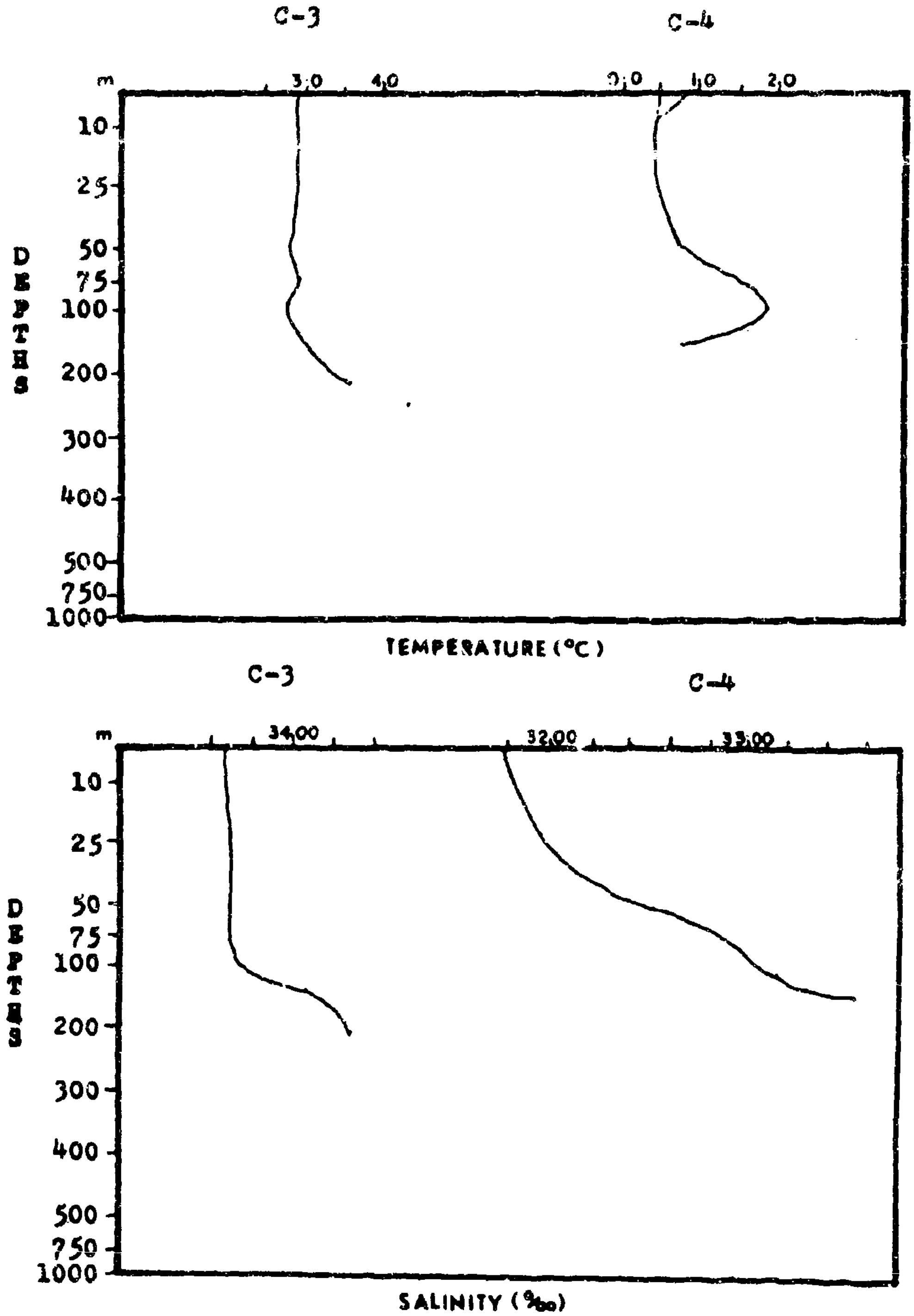

FIGURE 15c. TEMPERATURE/SALINITY PROFILES
SECTION C

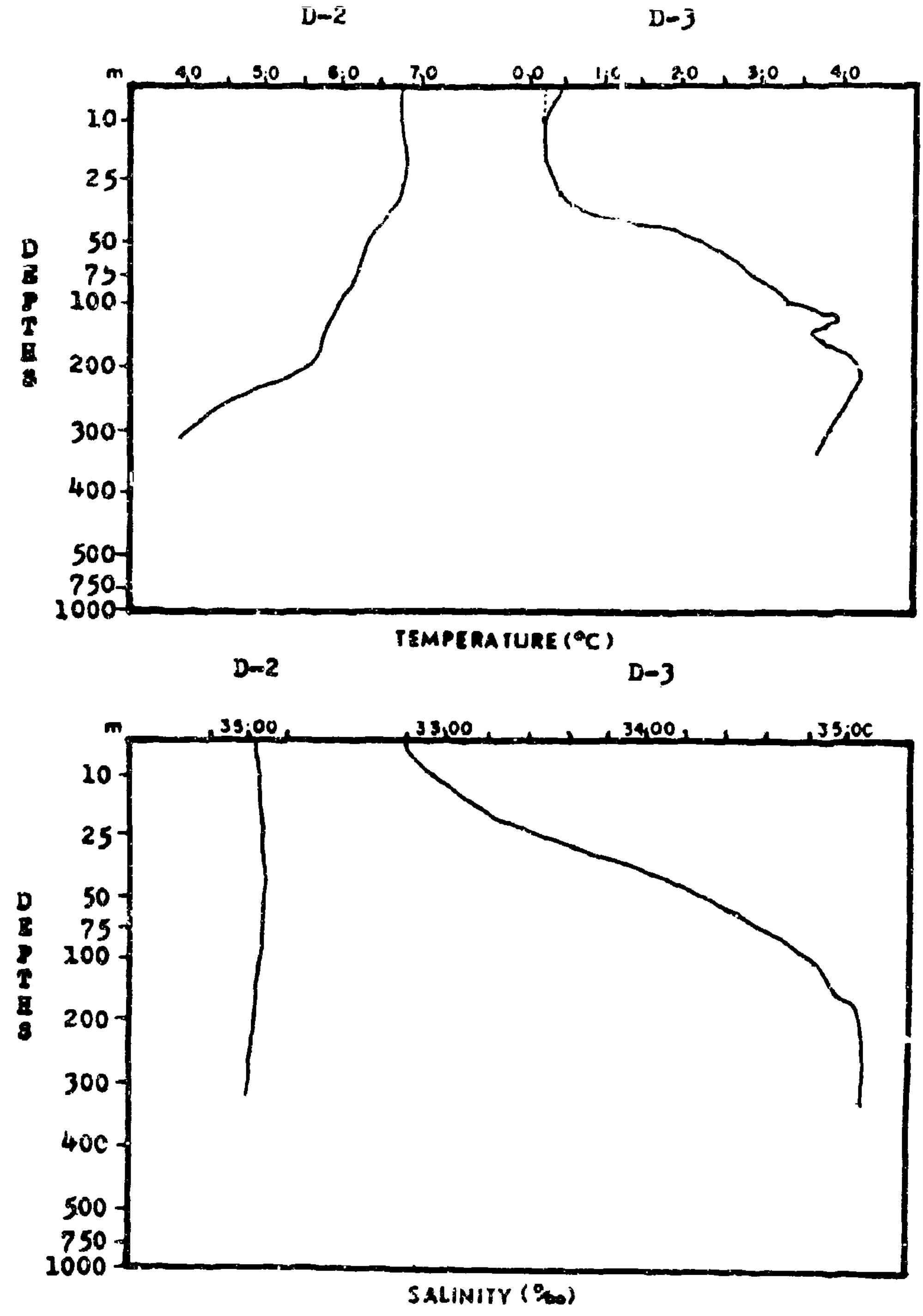

FIGURE 154. TEMPERATURE/SALINITY PROFILES SECTION D

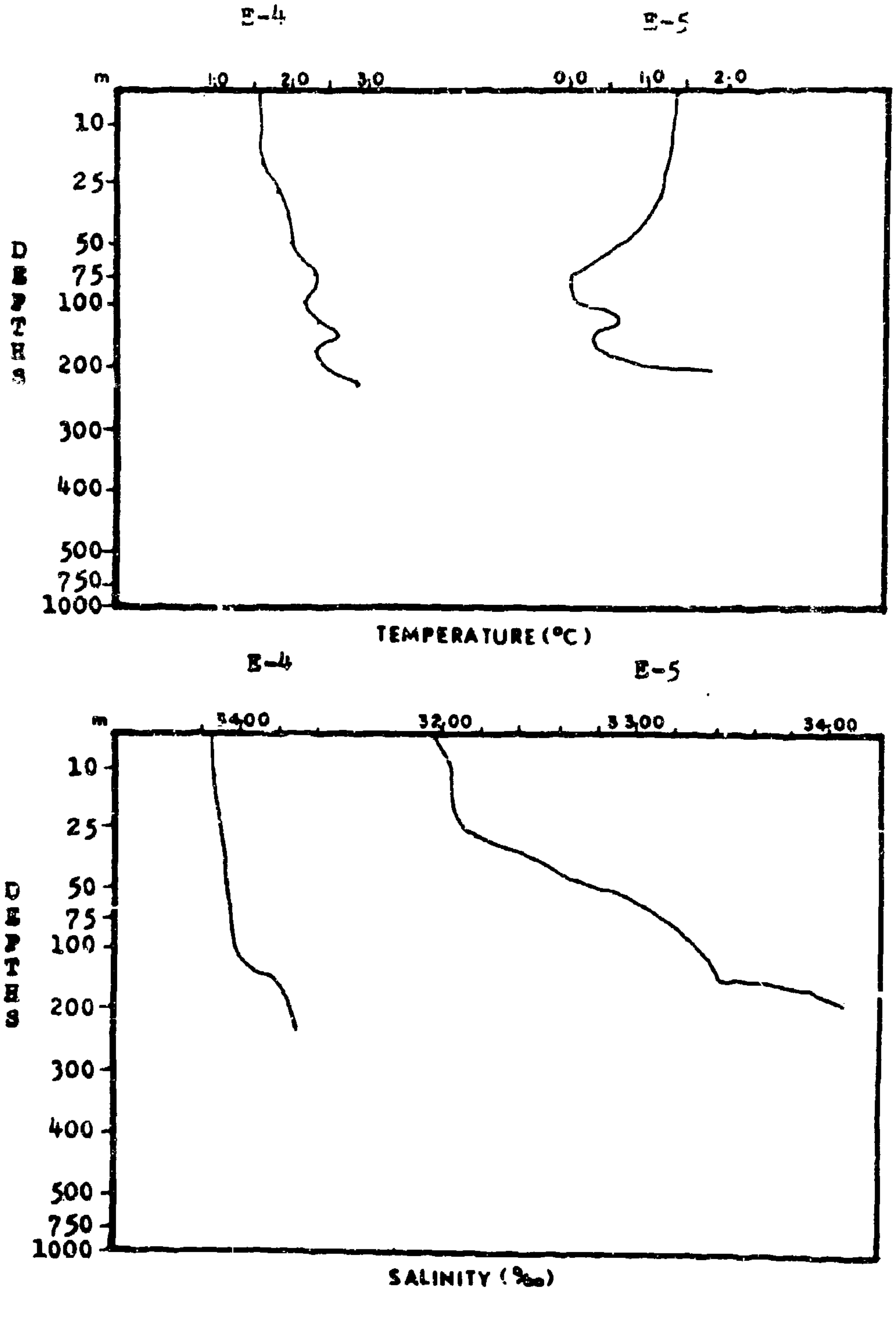

FIGURE 15e. TEMPERATURE/SALINITY PROFILES SECTION E

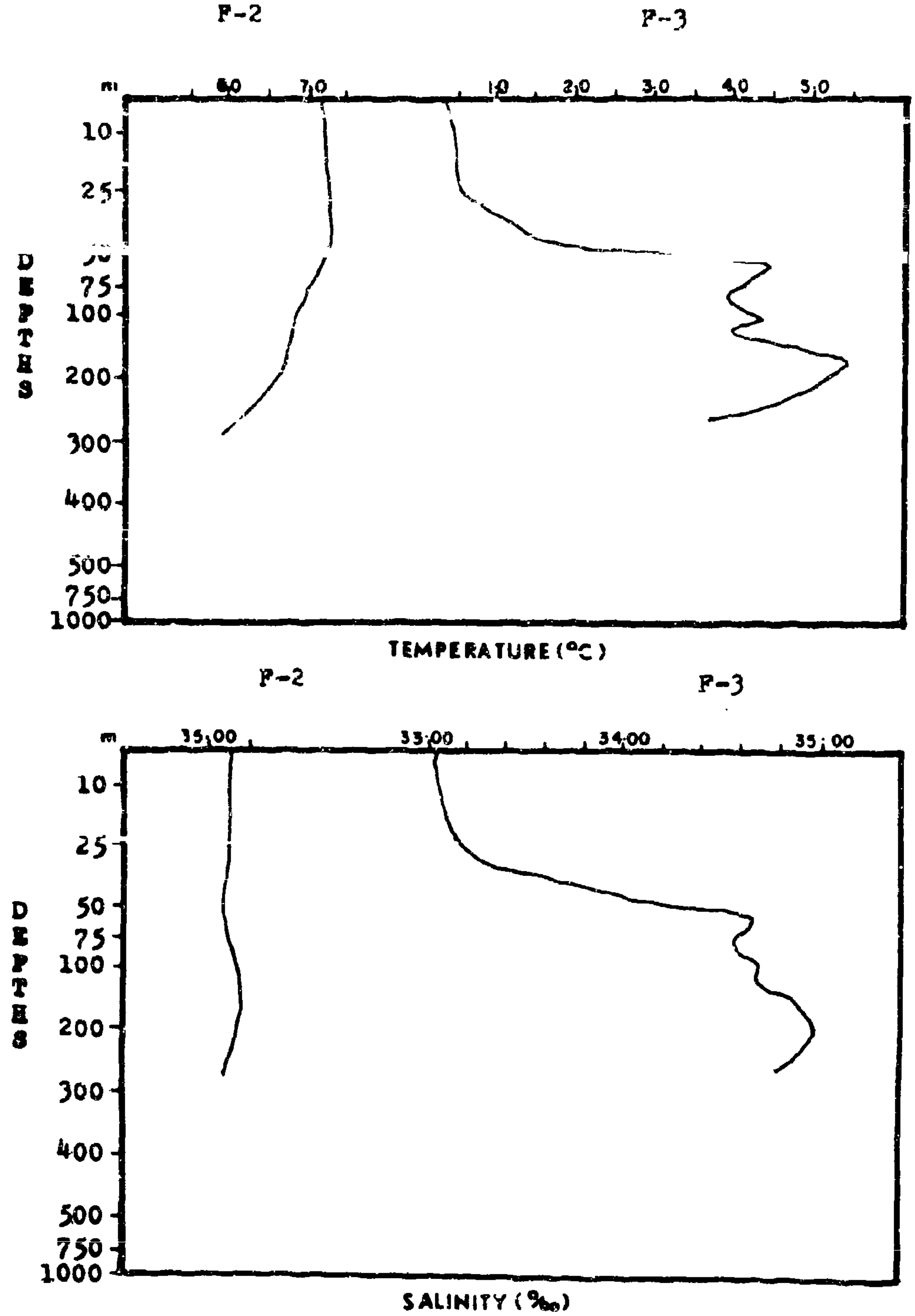

FIGURE 15f. TEMPERATURE/SALINITY PROFILES
SECTION F

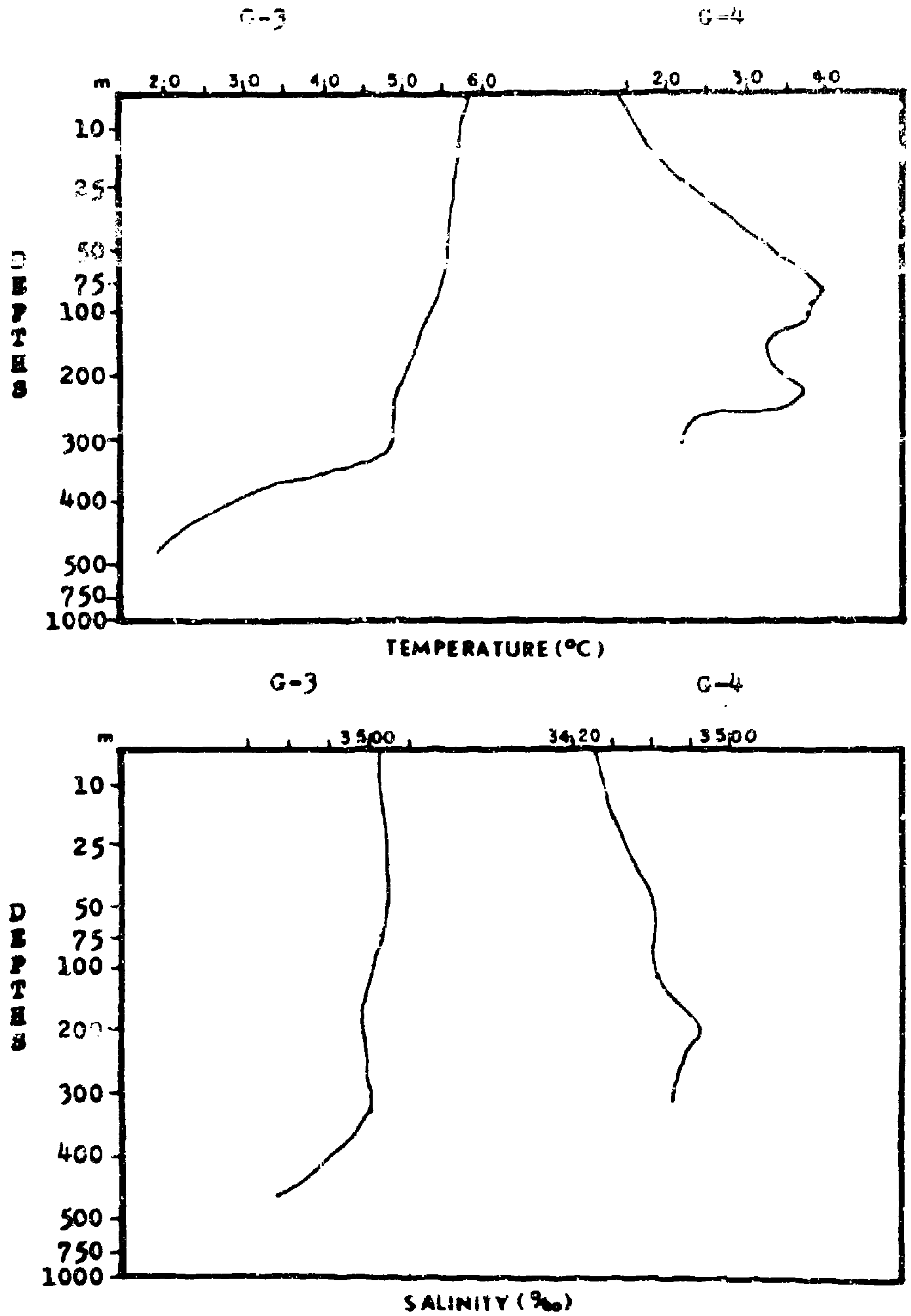

FIGURE 15g. TEMPERATURE/SALINITY PROFILES SECTION G

the cold-to-warm direct'on in 18 out of the 21 pairs of ray traces which were computed. The exceptions were the 3 pairs of runs from Section E which had the smallest surface thermal gradient of any of the sections.

4) A large percentage of rays propagated in the cold-to-warm direction attain their maximum depth at or near the maximum range of the run. This indicates that the cold-to warm rays are diving deeper and deeper with increasing range.

5) As the surface thermal gradient is increased, ray traces in opposing directions become more similar in both surface bounces and ray depth. This is primarily a result of the interpolation of sound velocity from one profile to another.

Of particular interest are the curves of Figure 16. The surface thermal gradient is plotted versus the difference in angle trapped for each pair of runs in opposite directions. The convention used is that the angle obtained by subtracting the trapping angle of the warm-to-cold run from the trapping angle of the cold-to-warm run is considered to be positive. These curves, drawn for each of the assumed profile spacings, indicate that the difference in angle trapped tends to increase as the surface gradient increases for each of the three distances examined. At first glance, the decrease in the d fference as the spacing of the sections decreases from 10 to 6 to 4 KM appears to be in contradiction to the basic premise that the difference

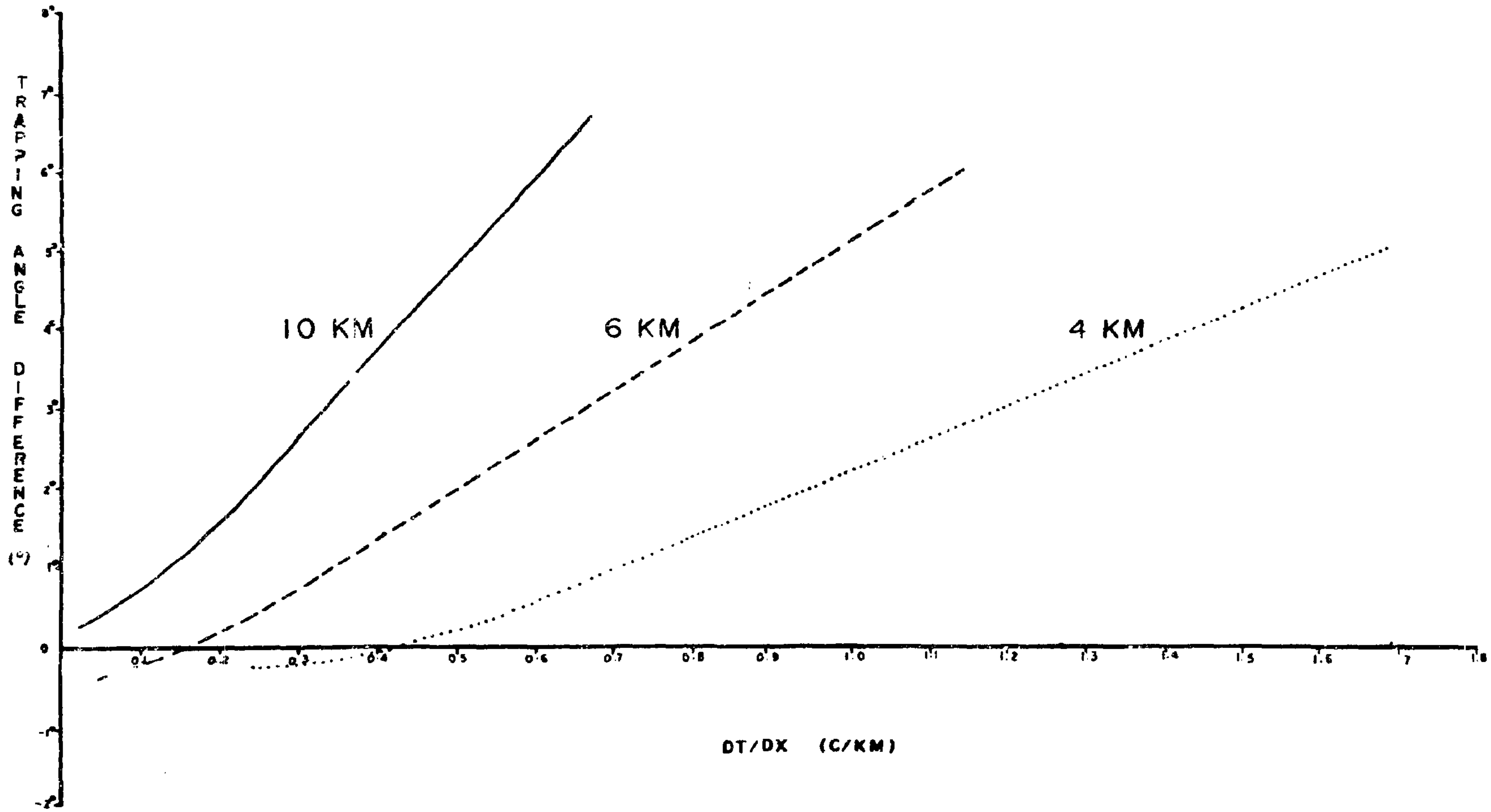

Figure 16. Relationship between surface thermal gradient and trapping angle differences for 10, 6 and 4 KM. profile spacing

in trapping angle increases as the surface gradient increases. However close examination of the angles trapped shows that as the profiles are moved more closely together, the trapping angle in the warm-to-cold direction of propagation increases. It then more closely approaches the cold-to-warm trapping angle which remains relatively stable. This occurs in six of the seven sections examined. Only Section C does not exhibit this tendency at a profile spacing of 4 KM. It has not been determined why this pair of runs is inconsistent with the remainder of the data.

Thus, Figure 16 points to the possibility of preparing operationally useful nomograms for estimating sonar efficiency in frontal regions. These nomograms would require the collection of more closely spaced synoptic observations than were available to this author but could be of immense operational use in oceanic frontal zones.

V. CONCLUSIONS

Computation of sonar ray traces across the oceanic polar front in the Denmark Strait region and along the southeastern coast of Greenland and an examination of the hydrography of the area lead to the following conclusions:

1) The position of the oceanic polar front may vary widely from day to day, but generally is found along the edge of the continental shelf.

2) While local influences may temporarily alter the gradient structure, conditions on an annual basis result from the effect of atmospheric wind systems which drive the Irminger and East Greenland Currents.

3) The angle of propagation trapped by sonar rays propagating across the front is larger when the sound source is in cold water, compared to conditions with the source in warm water.

4) As the gradient increases, the angle trapped by propagation from the warm side increases. Gradient has little effect on the cold-to-warm trapping which varies only slightly.

5) A relationship can be demonstrated between the surface thermal gradient and the change in angle trapped with change in direction of propagation for each assumed profile spacing.

VI. RECOMMENDATIONS FOR FURTHER RESEARCH

A requirement exists for a thorough examination of this frontal zone by towed thermistor chain or closely spaced XBT profiles.

Repetitive sections should be taken in the same locations as often as possible, but at least once during each season. This would provide an excellent data base for the construction of the sonar efficiency nomograms mentioned in Section IV.

An additional objective should be clarification of the relationship of the strength and position of the oceanic polar front to the atmospheric polar front.

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13. ABSTRACT

A computer program is utilized to examine the effect on sound propagation of the oceanic polar front in the Denmark Strait and along the Southeastern coast of Greenland. Ray traces are computed with the source in both the cold and warm current areas for surface thermal gradients of 0.036 C/KM to 1.68 C/KM. These gradients are created by varying horizontal distances between actual oceanographic stations. The results indicate greater trapping angles with the source in cold water. A relationship is reported between the surface thermal gradient and the change in trapping angle difference for pairs of runs.

The location of the oceanic polar front and the effects of environmental influences on its strength and seasonal movement are described.

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