FIRST ANNUAL REPORT

Contract #R7120840
Research Unit #141
Reporting Period: 1 April 1976-
31 March 1977
Number of Pages: 95

NORTON SOUND/CHUKCHI SEA OCEANOGRAPHIC PROCESSES (N-COP)

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31 March 1977

I. SUMMARY

The objective of this work unit is to relate oceanic advective and diffusive processes to potential pollution problems due to OCS petroleum activities. From data collected, processed and analyzed to date, the following can be concluded. An overall northward flow through the system on the order of 10^6 $m^3 s^{-1}$ (= 1 Sverdrup = 1 Sv) was occurring during late summer 1976.

The circulation in Norton Sound was analyzed from the cruise data of 26 September-6 October. The general flow in the western two-thirds of the Sound was cyclonic, and the bathymetry appears to be important in guiding the flow. There was inflow from the west near bottom in the two deeper troughs, and strong vertical mixing particularly in the northern trough off Nome where there was concentrated an intense westerly outflow. The line Cape Darby-Stuart Island"defines a relatively isolated eastern basin, which was filled in late summer with water relict from the previous winter. A two-layered density system reflected presence of upper and lower turbulent boundary layers. The pycnocline suppressed vertical heat flux, and in the eastern basin isolated the coldest bottom water. Water exchange with the western basin was very slow and appeared to be lateral diffusion rather than advection. Four anchored 24-hour stations including direct current measurements showed (1) the strong relationship between flow and the local winds and (2) internal waves on the pycnocline of 2-3 m amplitude and of tidal and higher frequencies.

Preliminary analysis of Kotzebue Sound showed similarities to Norton Sound. The shallow layer in the outer sound appears to participate in a cyclonic circulation which is isolated from both the lower layer and the eastern part of the Sound. Both the high stratification and the presence of cold and salty water, which must have been formed in winter, imply slow dispersion rates in much of the lower layer.

Cross sections from the Bering Strait region showed typical temperature and salinity values. There was a suggestion of small scale (< 50 km) baroclinic features north of Bering Strait.

II. INTRODUCTION

A. OBJECTIVE

The general objective of this work unit is to relate oceanic advective and diffusive processes to potential pollution problems due to OCS petroleum development. Specific goals are:

1. Verification of fluctuations in transport of the predominantly northward flow through the system;
2. Verification, and temporal and spatial description, of the bifurcation of northward flow which takes place west of Point Hope;
3. Definition of temporal and spatial scales of the eddies ubiquitous in the system, and acquisition of the data needed to contribute to a dynamical description; and,
4. Definition of circulation in Norton and Kotzebue sounds.

B. TASKS

The overall task is collection of field data to yield a description of the velocity field, improved understanding of mixing processes, and the relative importance of various driving mechanisms which cause and influence water motion. Specific tasks of the program are:

1. <u>Hydrographic data acquisition.</u> These allow computation of density fields and consequent baroclinic flow effects. Construction of vertical temperature and density sections will allow definition of spatial and temporal variations in the density field. Characterization of water masses by their temperature and salinity characteristics will allow estimation of advective and diffusive effects.
2. <u>Current meter data.</u> These will be used to establish the spatial and temporal flow variability at different locations in the study area. In combination with the density field, they can be used to define

barotropic vs. baroclinic flow and thus to identify possible driving mechanisms. In conjunction with sea level surface variation and surface wind field data, they can be used further in determining driving mechanisms.

3. Water level data. These will be used in conjunction with the systematic current flow variations in addressing driving mechanisms for the flow.

4. Atmospheric data. Surface pressure data will be compared with the water level data and flow variations. Wind data, both directly observed (where available) and geostrophic, may be obtained in certain cases. Both the surface pressure data and the wind data are necessary in analyzing driving mechanisms for flow, particularly in shallow waters such as the area under study.

C. APPLICATION TO PETROLEUM DEVELOPMENT HAZARD ASSESSMENT

Two distinct environmental problems can accompany petroleum development in a marine region, catastrophic spills and long-term or chronic leakage. This research unit addresses both of these problems. The eventual effect of a catastrophic spill depends upon where the spilled oil goes, *i.e.*, its trajectory, how long it takes to get there, and how much diffusion of the oil occurs along the trajectory. This study will provide estimates of the trajectories likely to be followed by spilled oil, and will furnish an indication of dispersion rates for such oil. Oil introduced into the environment via long-term or chronic leakage is more likely to be dispersed throughout the water column and, possibly, scavenged by suspended particulate matter. The problem now becomes one of understanding net transport of suspended matter, a process related to the advective and diffusive fields within the water column. An understanding of these processes requires, in turn, analysis of the velocity field and its driving mechanisms.

III. PRESENT STATE OF KNOWLEDGE

Prior to the present study, oceanographic knowledge of the Bering Strait region was summarized in a monograph by Coachman *et al.* (1975). They have used the results of oceanographic surveys carried out from 1922 until 1973 to define water masses and to estimate seasonal variations and transport of water through the system. The discussion below is abstracted from their work: the reader is referred to that work for additional detail.

A. CIRCULATION

The dominant circulation feature in the Norton-Chukchi region is the net northward flow. Transports measured through a section across Bering Strait are generally 1-2 Sv northward, though there have been a few documented cases of small (0.1-0.2 Sv) southerly transport. This northerly transport is driven by the sea level difference between the North Pacific and Arctic oceans. Significant short-term (< 1 week) fluctuations in the transport may, however, be brought about by regional wind stress variations and, possibly, atmospheric surface pressure fluctuations. Although seasonal variations are not well documented, there is no evidence for a winter decrease in north transport.

Details of the circulation are not well understood. Greater current speeds occur in Bering Strait than elsewhere, due to lateral constriction of the flow. Current speeds of 50-100 cm s^{-1} are not uncommon there, particularly at times when the mean north flow is augmented by southerly winds. Speeds are highest in the eastern near-surface part of the Strait. North of Bering Strait, there is a bifurcation of the north-flowing current in the region west of Cape Lisburne. One branch of the current flows northeast along the Alaskan coast. A general acceleration of flow to about 40 cm s^{-1} occurs in the near-shore region just off the Point Hope-Cape Lisburne peninsula. The other branch of the northerly current flows north-northwest, passing east of Wrangel Island off the Siberian coast. A southeast flow, the Siberian Coastal Current, passes inshore of the north-northwest flow along the Siberian coast and becomes entrained into the north flow just north of Bering Strait. South of Bering Strait, the passages east and west of St. Lawrence Island both contain accelerated north flow, required for continuity with flow through the Strait. A quiet area north-northeast of St. Lawrence Island is characterized by weak and variable flow, as the major north flow passes to the east and west of this region.

The circulation patterns in Norton and Kotzebue sounds are not well understood. There appears to be a tendency for weak cyclonic circulation in the western portions of both these embayments, but nothing is known of circulation in the eastern portions.

The regional tides are complex. In the Bering Strait region they are mixed, with the semidiurnal component being dominant. Net peak-to-peak current amplitudes observed north and south of the Strait are on the order of 10 cm s^{-1}. The regional tides are the result of confluence of tidal waves from the Arctic Ocean and the Bering Sea. There appear to be related amphidromic systems in Norton Sound, just south of St. Lawrence Island and in the Gulf of Anadyr.

B. WATER MASSES

Three water masses can be defined for the Bering Strait region; Anadyr, Bering Shelf and Alaskan Coastal waters, with the names reflecting origins. These water masses are defined on the basis of floating salinity, rather than fixed temperature-salinity, values to allow for large year-to-year variations. Temperature, highly non-conservative here, is not useful as a water mass parameter. Vertical stratification of water in the Bering Strait is primarily in temperature, the coldest water being the deepest. Horizontal gradients are primarily in salinity, with the most saline water (Anadyr Water) being to the west and the least saline (Alaskan Coastal Water) to the east.

The Anadyr and Bering Shelf waters originate south of St. Lawrence Island. Alaskan Coastal Water has some contribution from the south, but also a major contribution from Norton Sound. The sharp horizontal gradations between these water masses in Bering Strait suggest that little lateral mixing has occurred between them, hence that lateral mixing between St. Lawrence Island and Bering Strait may be small. North of Bering Strait, Anadyr and Bering Shelf waters mix to become Bering Sea Water, while Alaskan Coastal Water retains its identity and flows northeast along the coast.

Vertical mixing is in large part controlled by vertical stability, which in turn is subject to large seasonal variations. The Bering Sea shelf waters become markedly layered during summer due to fresh water input and solar insolation. The degree of stratification of Alaskan Coastal Water has been correlated with Yukon River discharge. Vertical salinity layering can become so pronounced that it severely restricts vertical heat transfer to the lower water strata. During winter, intense surface cooling and ice formation create vertically uniform water columns .

IV. STUDY AREA

The Norton Sound-Chukchi Sea oceanographic program encompasses the area roughly from St. Lawrence Island in the northern Bering Sea to Cape Lisburne in the Chukchi Sea (Figure 1). It includes Bering Strait, a major avenue for interchange of water between the Bering Sea and the Arctic Ocean, and two major embayments, Norton and Kotzebue sounds. The entire region is classified as continental shelf, and is typified by shallow bottom depths (∿ 20 m in Norton and Kotzebue sounds, increasing gradually to ∿ 50 m to the west).

The waters of the Norton-Chukchi region are subject to extremely harsh climatological conditions. Winter temperatures drop well below freezing and are often accompanied by high winds. These factors lead to formation of a seasonal ice cover which may reach 10/10 coverage during mid-winter, particularly in the Chukchi Sea.

Fresh-water input into the study region occurs via several large rivers, the Kobuk, Noatak and Yukon rivers along the Alaskan coast, the Anadyr River along the Siberian coast, and innumerable smaller streams. These rivers have highly seasonally variable flow rates, as exemplified by the Yukon which is the largest and attains maximum flows in June-July following melting of interior continental snowfalls (Figure 2).

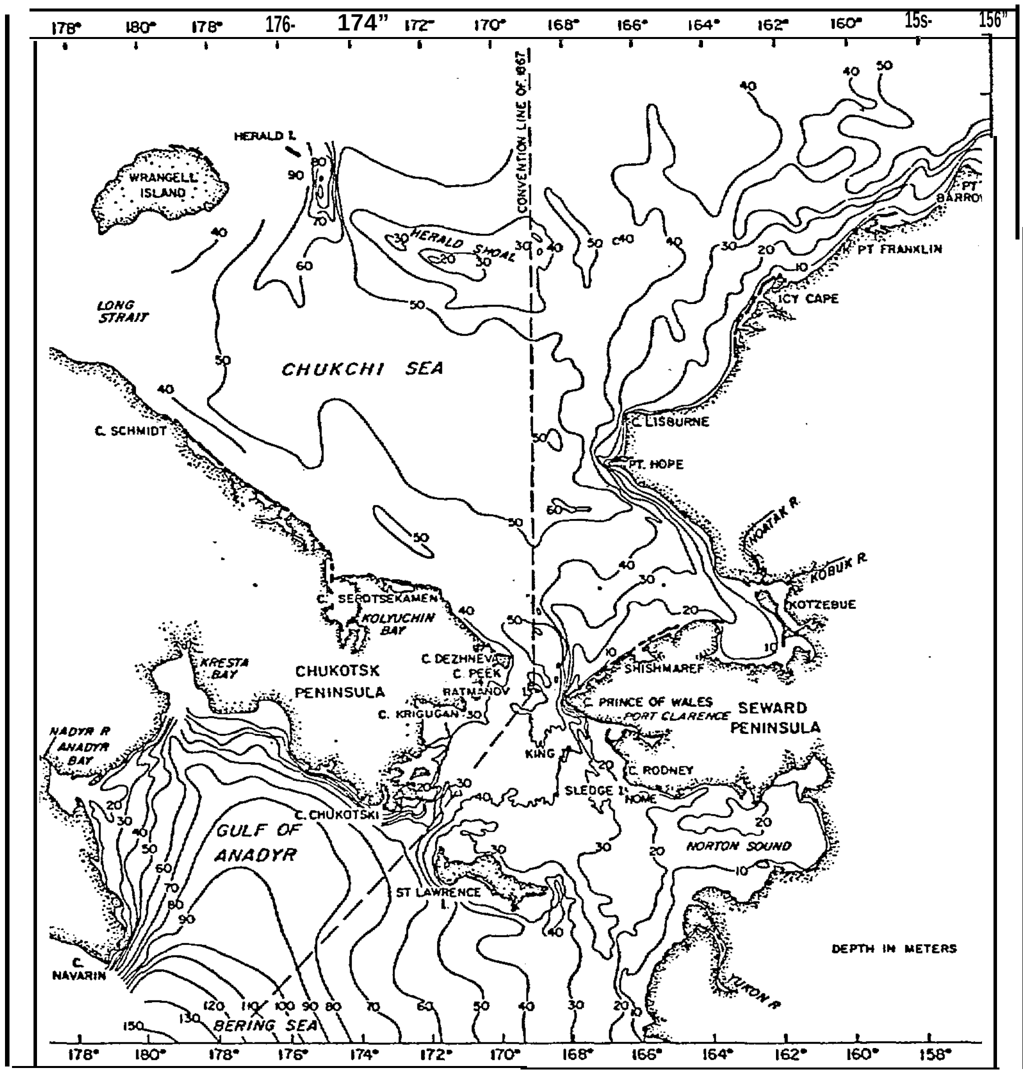

Figure 1. **Regional geography and bathymetry for the Norton Sound - Chukchi Sea study area (from Coachman et al., 1975).**

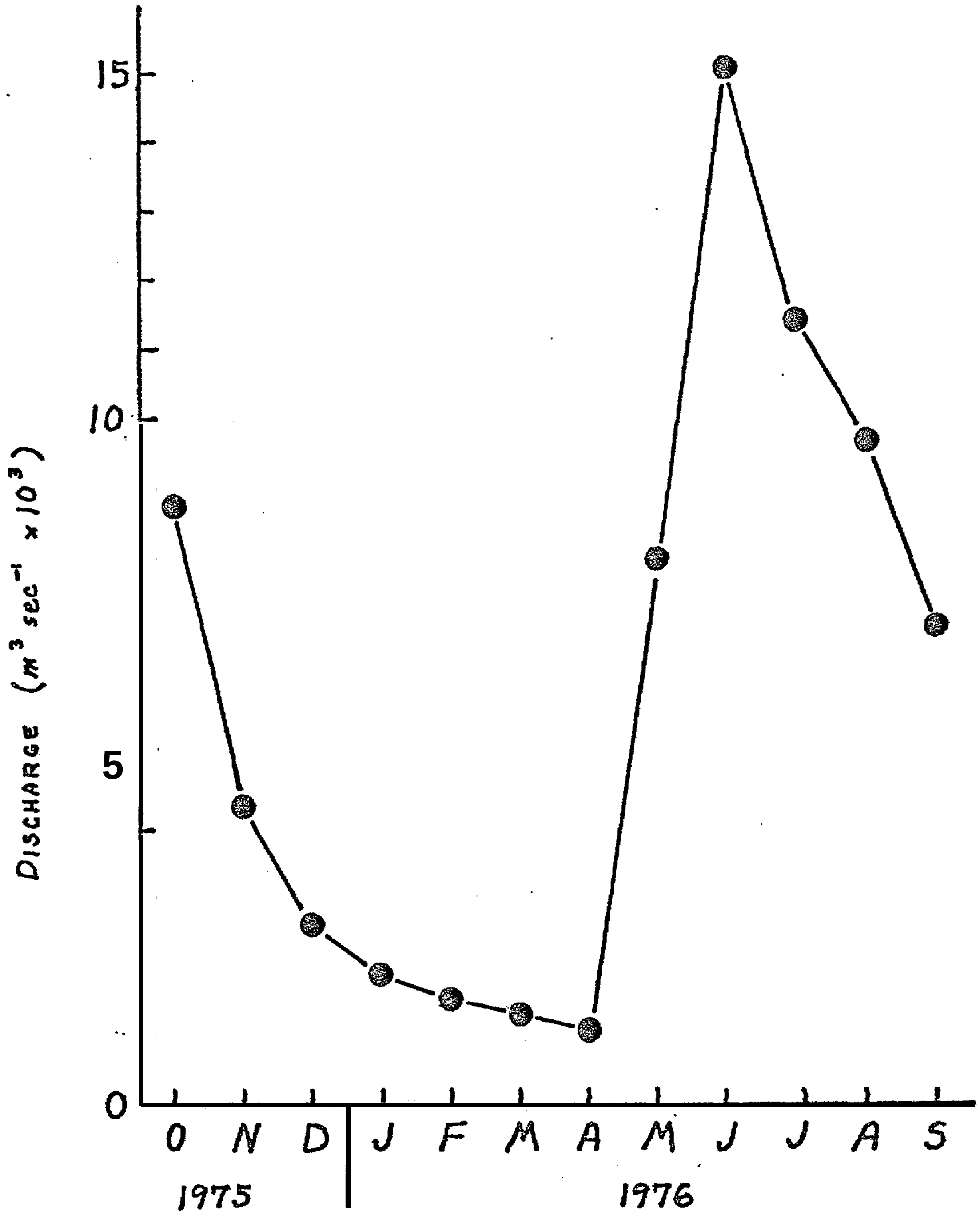

Figure 2. Monthly mean Yukon River discharge from ? October 1975 - 30 September 1976 as gauged at Pilot Station, about 180 km. upstream from the river mouth. (This was the first complete annual record from Pilot Station; previous discharge records are from Ruby, considerably farther upstream.)

V. PROGRAM RATIONALE AND METHODS OF DATA COLLECTION

In order to address the goals of this work unit, the following program was completed during the period 1 April 1976-31 March 1977.

Four field programs were completed during the period (Table 1). The first of these, during August-September 1976, obtained temperature and salinity data from the ice edge in the Arctic Ocean southward to the St. Lawrence Island region (Figure 3). Eighteen of the 19 regional moored current meter arrays were deployed during this cruise. The second cruise, carried out during early September 1976, obtained temperature and salinity data primarily from the Chukchi Sea and Kotzebue Sound regions (Figure 4) and carried out anchored current/CTD measurements. The third cruise, in September-October 1976, obtained temperature and salinity data and anchored current/CTD measurements from the Norton Sound region and deployed the remaining one of the 19 regional moored current meter arrays (Figure 5). The fourth field operation was carried out during February-March 1977 using helicopters as platforms; this operation is detailed under Section X of this report, "Summary of Fourth Quarter Operations: N-COP."

In addition to the oceanographic field work, weather data are being routinely collected, as detailed below.

Table 1

Summary of Oceanographic Field Work
During 1 April 1976-31 March 1977: N-COP

Date	Vessel	Chief Scientist	CTD Stations	Anchor Stations	Moorings
8/17/76-9/3/76	*Discoverer*	R. B. Tripp	151	0	18
8/31/76-9/17/76	*Moana Wave*	L. K. Coachman	83	52	0
9/26/76-10/6/76	*Discoverer*	R. D. Muench	45	5	1
1/30/77-3/2/77	Helicopters	R. B. Tripp	46	0	0

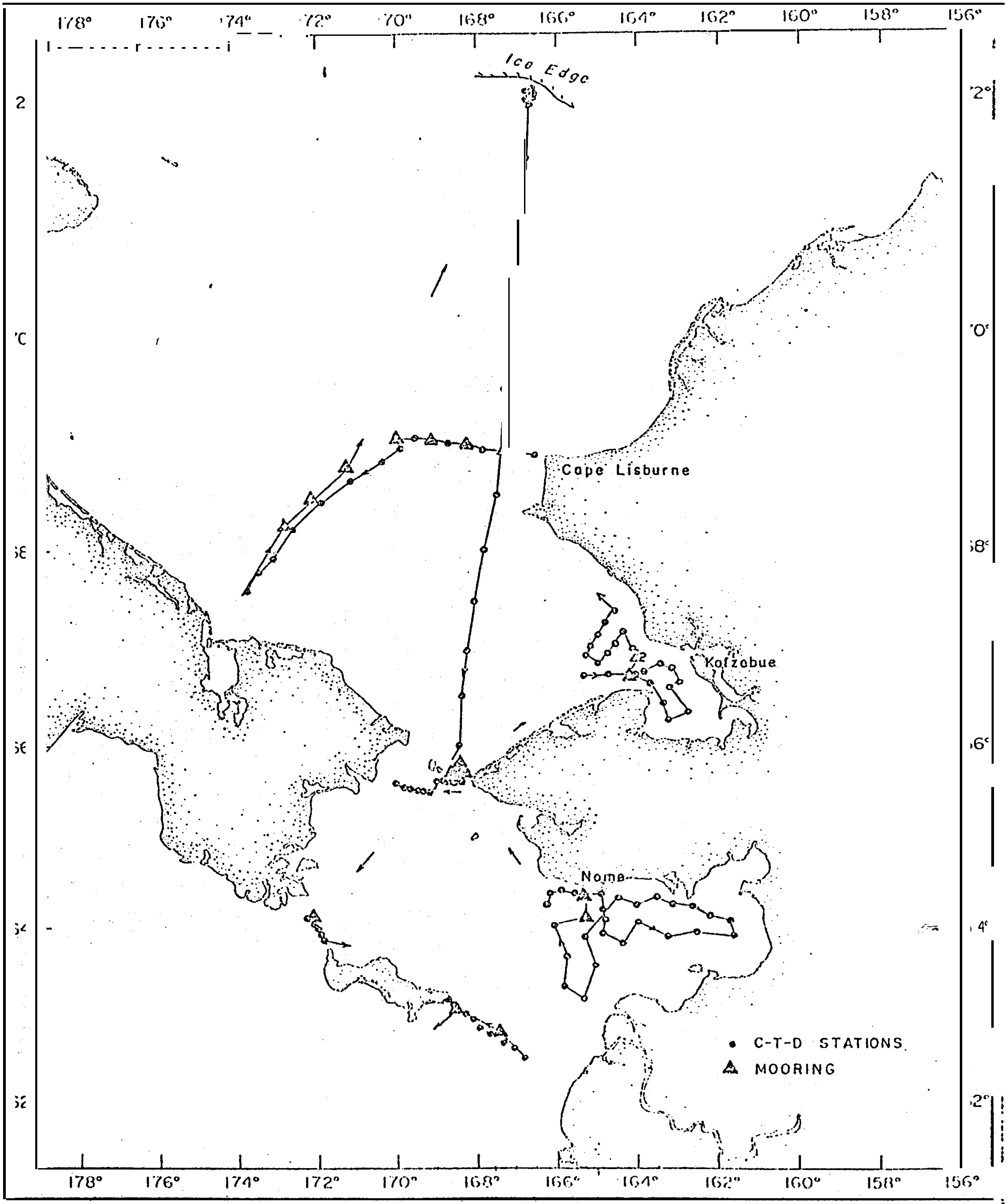

Figure 3. Oceanographic stations occupied during the 17 August-3 September 1976 cruise to the Norton Sound-Chukchi Sea region.

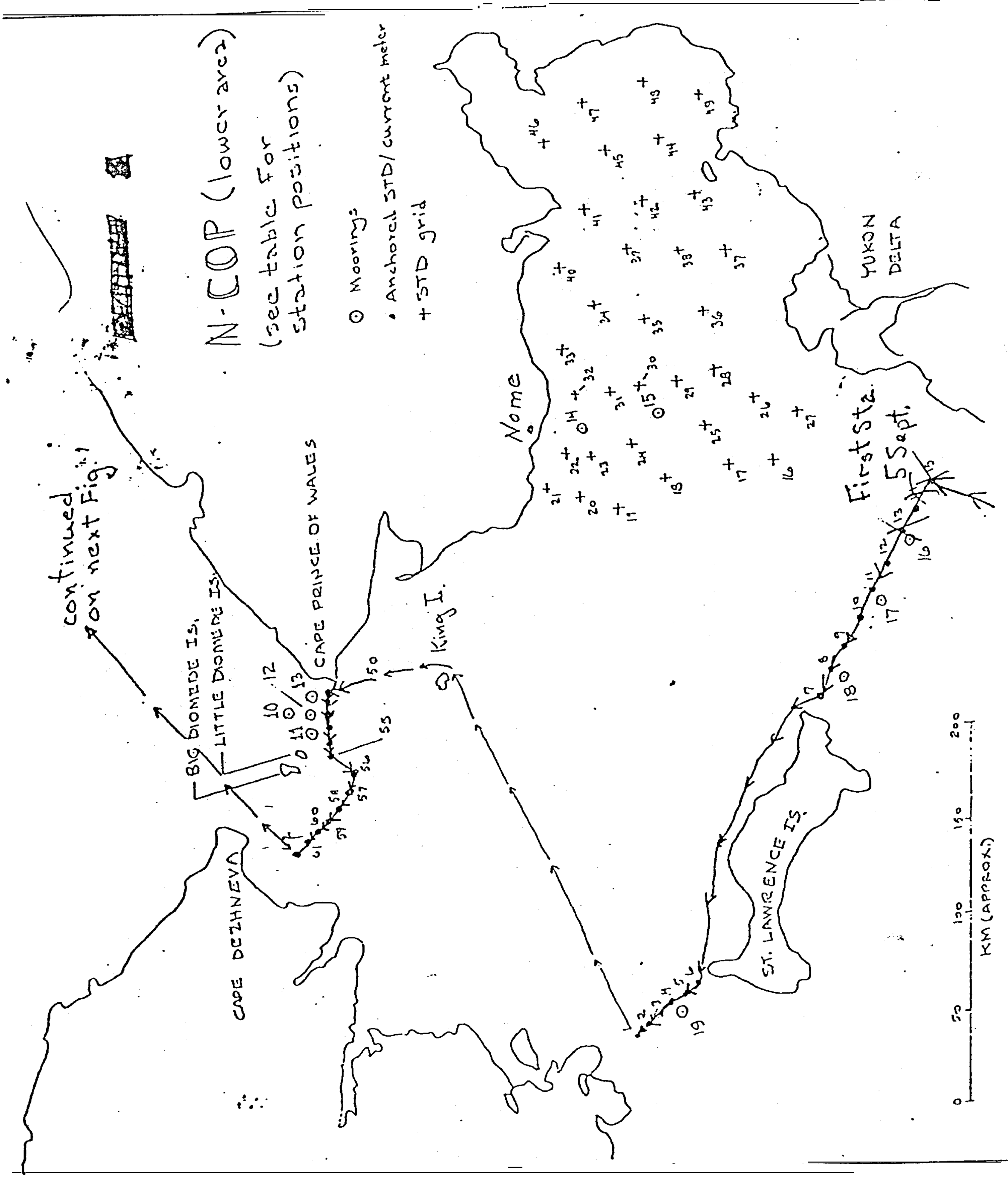

Figure 4A. Track of R/V *Moana Wave*, 5-14 Sept. **1976.**

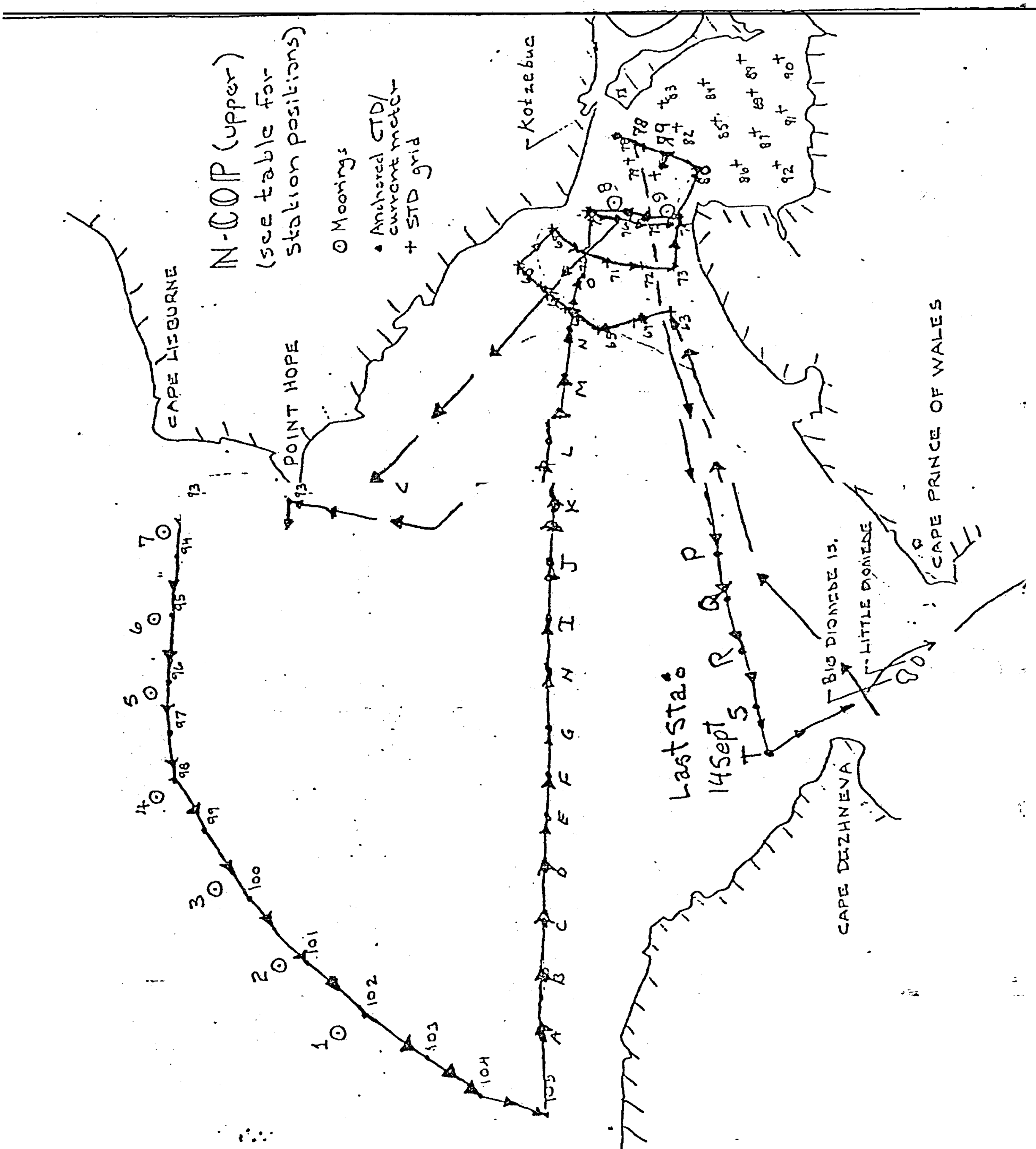

Figure 4B. Track of R/V *Moana Wave.*

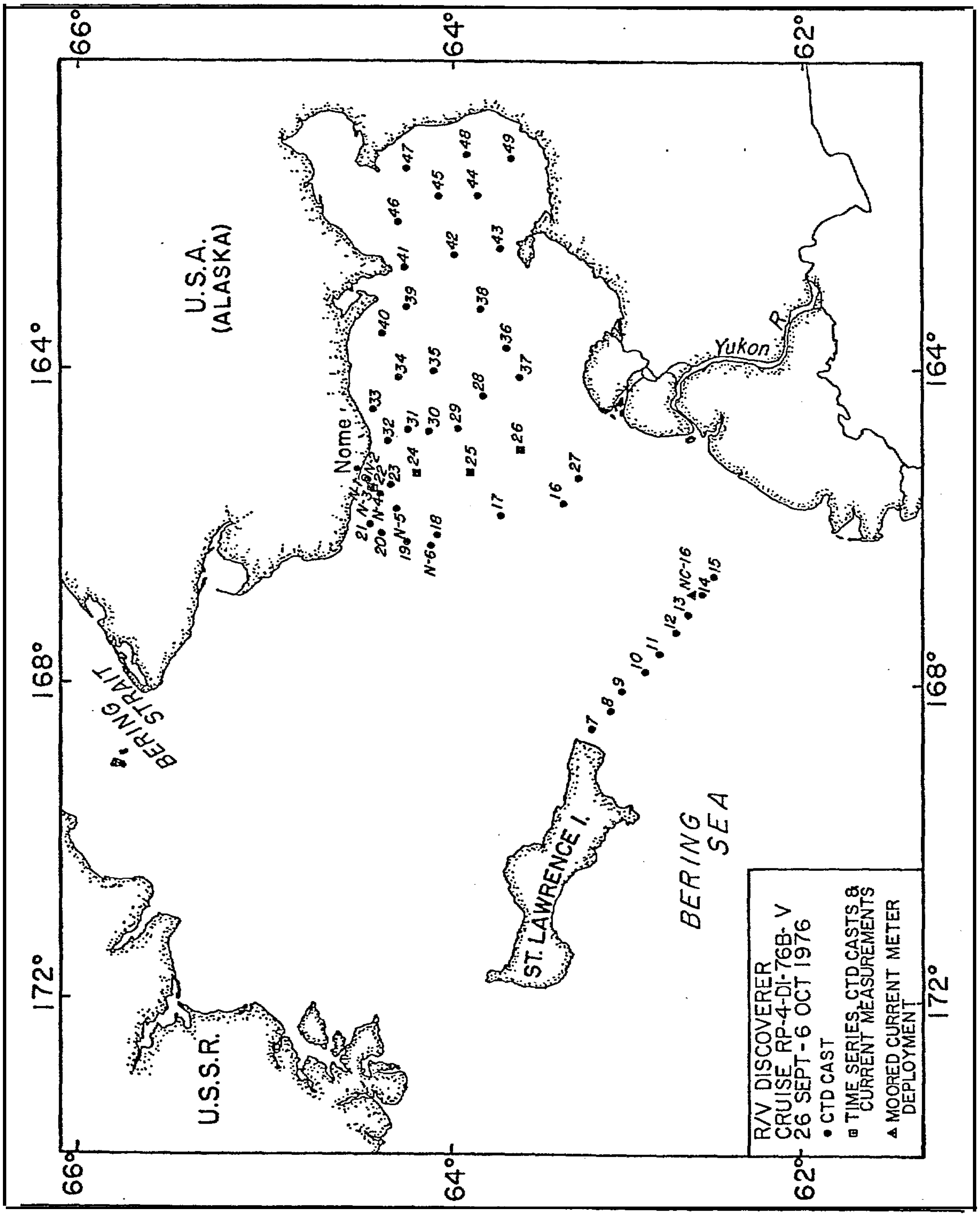

Figure 5. Oceanographic stations occupied during 26 September - 6 October cruise to the Norton Sound region.

A. TEMPERATURE AND SALINITY OBSERVATIONS

All temperature and salinity measurements except those from the February-March program were obtained using Plessey Model 9040 conductivity, salinity, depth (CTD) profiling instruments operating into Plessey digitizers and analog chart recorders. Of the vessels used, *Discoverer* and *Moana Wave,* only the former had the additional back-up recording capability for CTD data of a data acquisition system based on a PDP-11 computer (PODAS). In addition to providing back-up recording, this system also allowed near-real-time monitoring of the incoming temperature and salinity (as derived by the computer from temperature and conductivity) data. In one case, the September-October cruise, the back-up capability was needed as the Plessey digitizer malfunctioned during the latter part of the cruise. The capability of monitoring the data in near-real-time was also judged invaluable.

All data were acquired and processed on board ship according to the PMC manual. Calibration samples were obtained using a rosette or sample bottles on a minimum of every cast except during the Norton Sound time series stations obtained in September-October where every third cast was judged adequate. Salinities for calibration were run aboard the vessels. Raw data and calibration values were returned to the University of Washington (August and early September cruises) and the Pacific Marine Environmental Laboratory (September-October cruises) for final processing and analysis. All final temperature and salinity data products meet the OCSEAP standards for accuracy and format.

B. ANCHORED CURRENT MEASUREMENTS

During the August and September-October cruises to the Norton-Chukchi region, direct current measurements were made at approximately 5 m intervals throughout the water column at selected stations while the vessel was at anchor. These measurements were made using an Aanderaa Model RCM-4 current meter modified to be read out via a cable and deck read-out unit. At each station and depth, the reading was accepted and recorded only after it had been stabilized over a minimum period of 2 minutes to within about 1 cm s^{-1} and about 5° in directional variation. The individual measurements are felt to be accurate to within about 1 cm s^{-1} in speed and 5° in direction except for the near-surface measurements, which may have larger errors due to the uncertain effect of the nearby vessel's hull. It was hoped that waiting for the readings to stabilize would minimize errors due to lowering of the instrument and yawing of the vessel while at anchor. In regions of high current speeds where streaming of the meter may have occurred, observations of wire out, wire angle and the meter depth as obtained from the deck read-out unit were used to check on the true depth of the measurements.

The vessel used during both the August and September-October cruises, the *Discoverer,* was well suited to use of this deck read-out meter. The meter itself was suspended over the side using the port hydro winch just aft of the main oceanographic laboratory, with the electrical cable being fed out and retrieved by hand so that the hydro cable carried the weight of the meter. In this way, no strain was placed on the read-out cable. A 20-pound weight was placed under the meter to help prevent streaming in regions of high current speed. The read-out cable was fed into the oceanographic laboratory via a stuff tube, and the read-out unit thus located out of the weather at a convenient AC power source. Current speed and direction were computed from the read-out unit directly following each station in order to detect possible equipment malfunctions and to monitor the currents in real time. In general, malfunctions were minimal, the only one requiring attention involving apparent corrosion of the contacts where the meter joined the underwater cable. Both the equipment and the set-up aboard the vessel were extremely satisfactory.

C. MOORED CURRENT MEASUREMENTS

Long-term current measurements are presently being obtained via Aanderaa Model RCM-4 recording current meters deployed at 19 locations in the Norton-Chukchi study region (Figure 6). These moorings were deployed during August-September 1976 and will be retrieved during August 1977 to yield a full year of current records at each location.

Regional climatic considerations dictated some features of the moorings (Figure 7). In order to escape contact with surface winter ice, the subsurface floats were placed as deep as possible, about 10 m above the bottom. In regions where high current speeds were expected, Bering Strait, streamlined floats were used to minimize streaming of the arrays. Only a single meter was placed on each array, in anticipation of the vertical homogeneity of the water which obtains during a major part of the year and also for reasons of practicality. The meters themselves were modified to record for a full one-year period at 40-minute intervals. AMF acoustic releases are provided on each mooring for retrieval, and three of the moorings are provided with pressure sensors (Aanderaa) in addition to the current meters (Figure 6). In addition, a tide gauge was installed at Nome; technical difficulties, however, have prevented obtaining usable information from this gauge to date.

D. ATMOSPHERIC PRESSURE DATA

Atmospheric surface pressure data are being collected at the locations indicated on Figure 6. Eight of these stations were already operative prior to this project, five reporting data to the NWS, and barograph charts being obtained from the remaining three stations by special arrangement. In addition, two stations were supplied with barographs from which charts are now being received. The status of these weather"stations is indicated in Table 2.

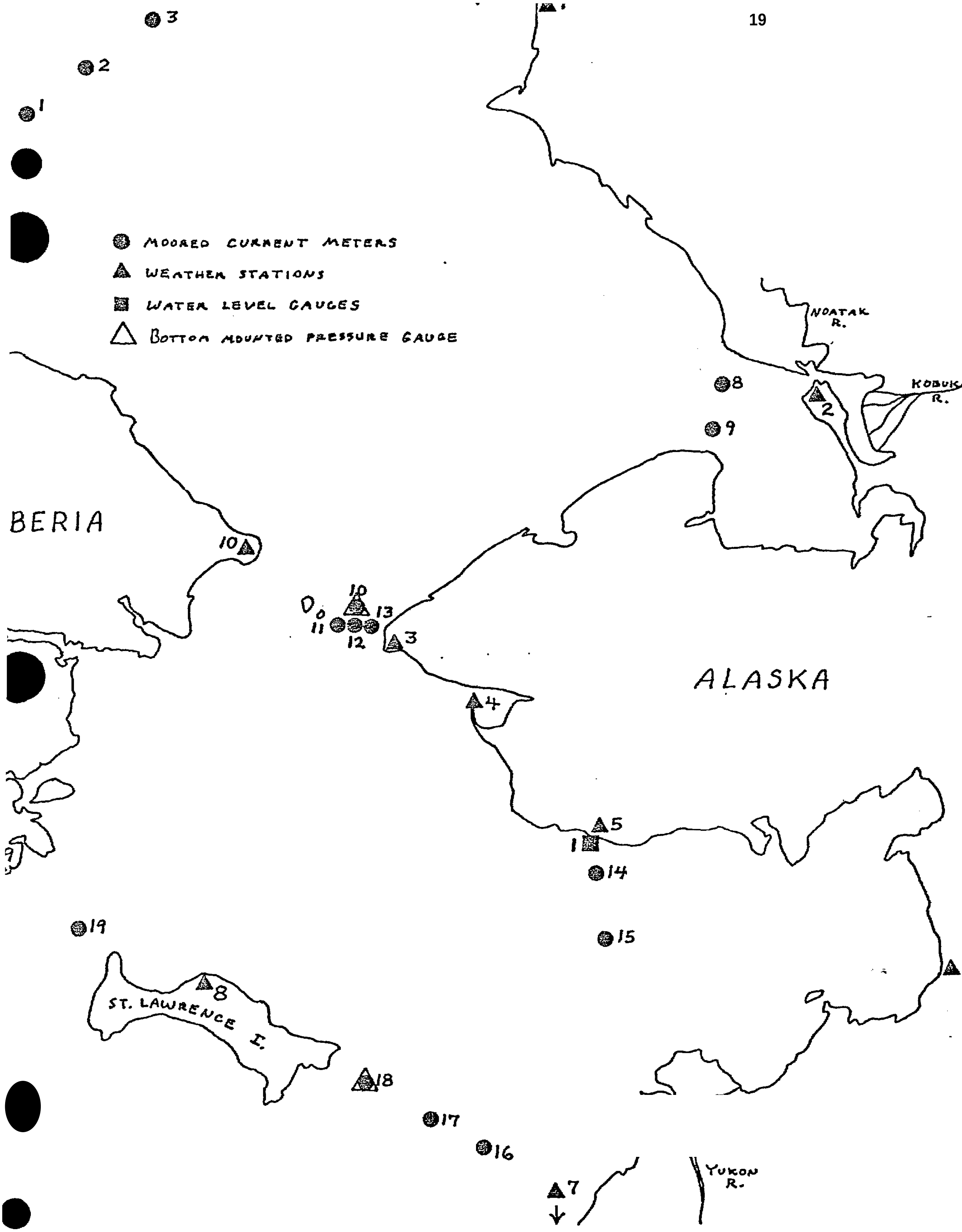

Figure 6. Locations of remote recording oceanographic instrumentation presently deployed in the Norton-Chukchi region.

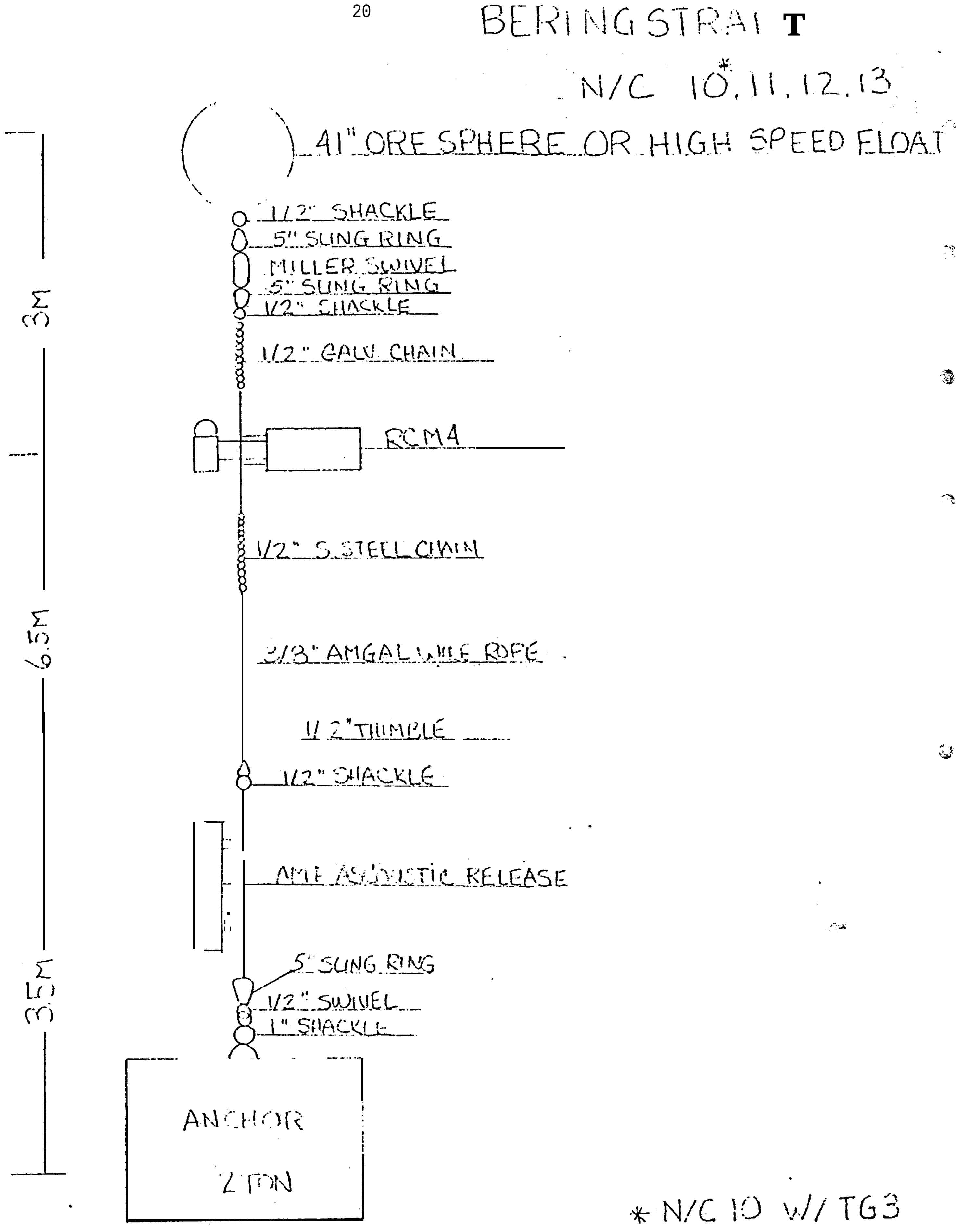

Figure "7. Example of the moored current meter configuration used in the Norton-Chukchi study region.

TABLE 2 N-COP WEATHER STATIONS (surface pressure data)

Number	Location	Dates	Comments
1	C. Lisburne	August 1976-pres.	Permanent USAF station; barograph charts sent to PMEL[1]
2	Kotzebue	Continuing	Permanent NWS station; current and historical data avail.[2]
3	Tin City	August 1976-pres.	Permanent USAF station; barograph charts sent to PMEL
4	Port Clarence	December 1976-pres.	Permanent USCG LORAN site; barograph charts sent to PMEL; barograph supplied by PMEL
5	Nome	Continuing	Permanent NWS station; current and historical data avail.
6	Unalakleet	Continuing	Permanent NWS station; current and historical data avail.
7	C. Romanzof	August 1976-pres.	Permanent USAF station; barograph charts sent to PMEL
8	Savoonga	December 1976-pres.	Wien Airlines office; barograph su plied by PMEL, and barograph charts sent to PMEL[3]
9	Kivak, USSR	Continuing	Current data available through NWS
10	Uelen, USSR	Continuing	Current data available through NWS

1. Each chart records over a one month period. Charts are sent monthly.

2. NWS data are received currently as surface pressure charts. Historical data are in the form of summaries and daily log sheets.

3. Pressure data from Savoonga are not calibrated, due to lack of a calibration facility there, but the records are adequate for detecting variations.

Barometric pressure data presently in hand are in the form of barograph charts, an example of which is shown in Figure 8. These charts will be digitized using a PDP-11 computer with graphics table; the requisite software is presently being developed. Continuous data coverage via barograph charts now on hand is given in Table 3. Pressure data from the remaining stations will be obtained from NWS as copies of daily weather log sheets.

Table 3

Continuous Atmospheric Pressure Data
(as Barograph Charts) Presently in Possession

Location	Dates
Cape Lisburne AFS, Alaska	16 June 1976-28 Feb. 1977
Cape Romanzof AFS, Alaska	2 Sept. 1976-31 Dec. 1976
Tin City AFS, Alaska	1 Aug. 1976-25 Feb. 1977
Port Clarence CGS, Alaska	18 Nov. 1976-1 Mar. 1977
Savoonga, Alaska	8 Dec. 1976-1 Mar. 1977

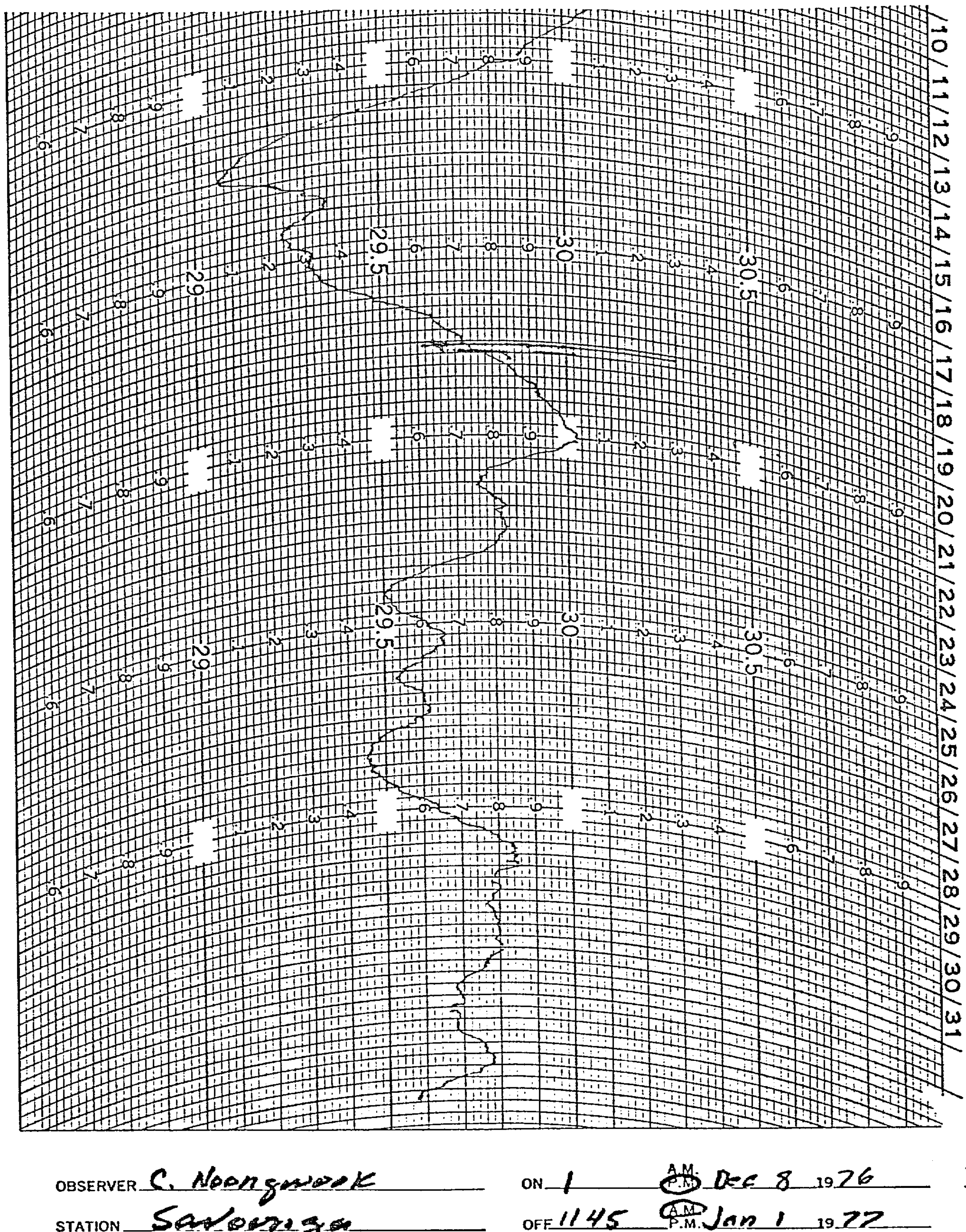

Figure 8. Example of atmospheric surface pressure record obtained via PMEL-provided barograph located at the Wien Airlines Office in Savoonga, St. Lawrence Island.

VI. RESULTS

A. THE SEPTEMBER-OCTOBER NORTON SOUND PROGRAM

Sufficient coverage was obtained in Norton Sound during the September-October cruise to yield insight into processes prevailing there. Figure 9 shows the station locations and the bathymetry in meters.

Distribution of density and temperature. Density and temperature derived from continuous vertical CTD profiles accurately reflect oceanographic conditions in Norton Sound. Density is the dynamically significant variable, while temperature is useful as a water mass tracer. Salinity exerts a dominant control over density at the temperatures encountered, and thus approximately duplicates the density distribution. Density is represented herein by sigma-t (σ_t).

Norton Sound was characterized by two well-mixed layers during September-October 1976 (Figures 10 and 11). Vertically well-mixed upper and lower layers were separated by a pycnocline which was more pronounced at the head (2.5 σ_t units m^{-1}) than at the mouth (1.5 σ_t units m^{-1}). A gradual seaward density increase (about 2 σ_t units) was present between station 42 and the mouth, but was absent from the eastern portion between stations 42 and 48 (Figure 10). There was, in fact, a reversal of this east-west gradient in the eastern third where water of $\sigma_t > 23$ was present. A weak south-north density decrease occurred above the pycnocline, while below the pycnocline density was nearly uniform (Figure 11). In western reaches of the Sound, density distribution exhibited considerable complexity particularly in the near-shore region off Nome. A layer of high density water ($\sigma_t > 24$) occurred along the bottom in the deep trough along the north coast, attenuating to the east until it was no longer present (cf. station 33). A band of low density water ($\sigma_t < 21$) was present along the coast off Nome, but did not appear to extend east or west for any great distance; it did not appear at station

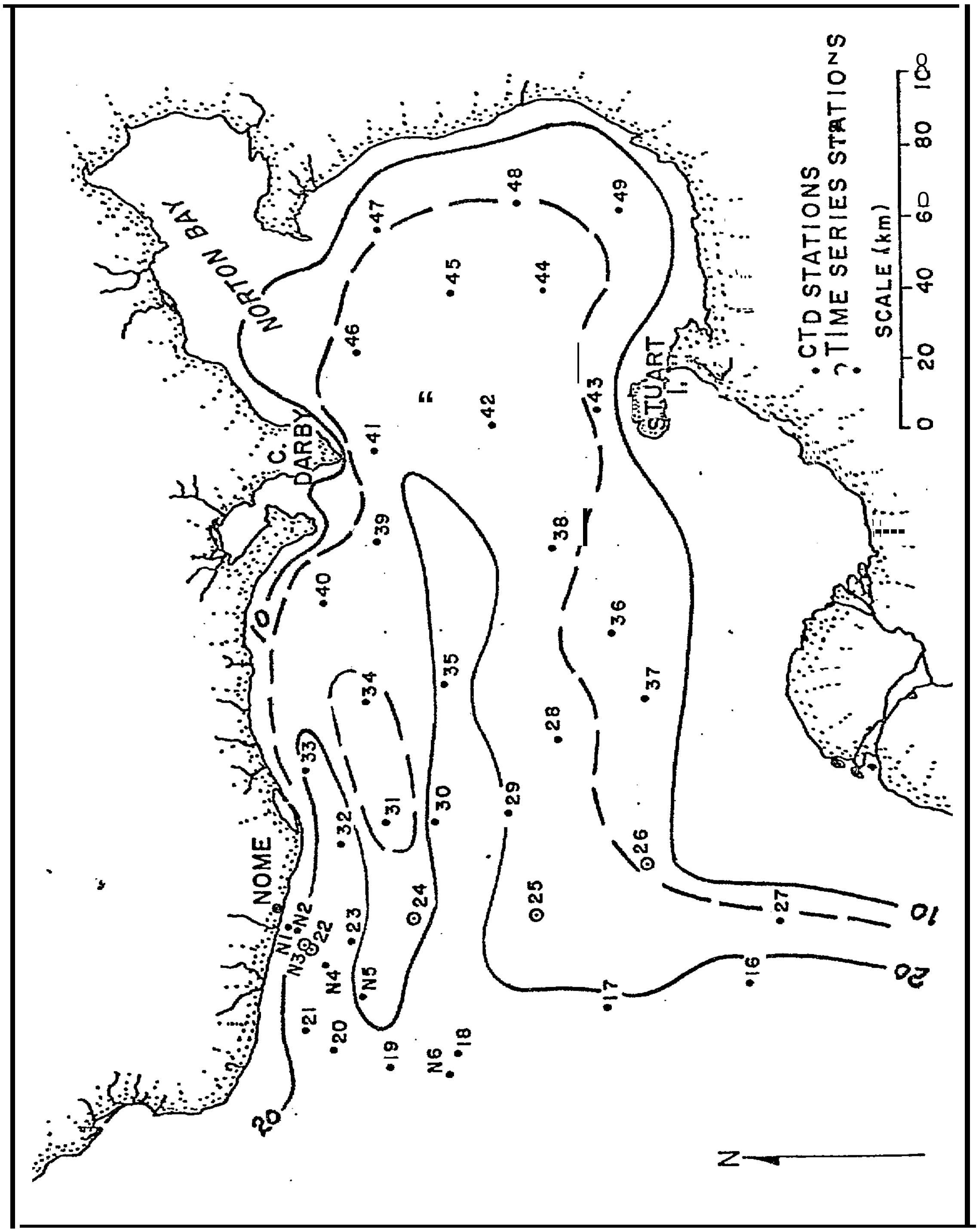

Figure 9. CTD and time series oceanographic stat ions occupied in Norton Sound during September-October 1976. Isobaths in meters, contoured from CEGS 9302.

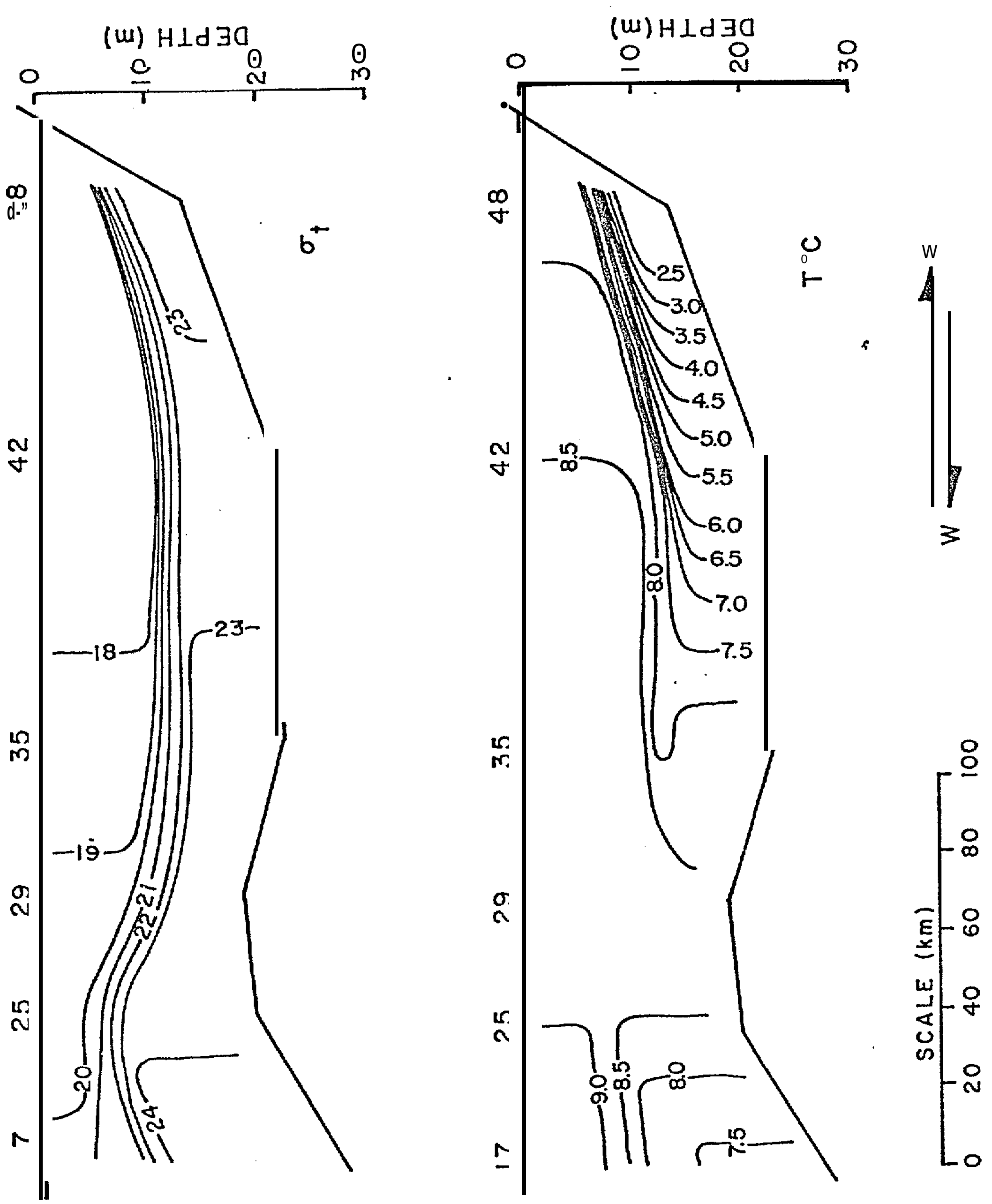

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Figure 10. Longitudinal density and temperature distributions in Norton Sound during September-October 1976.

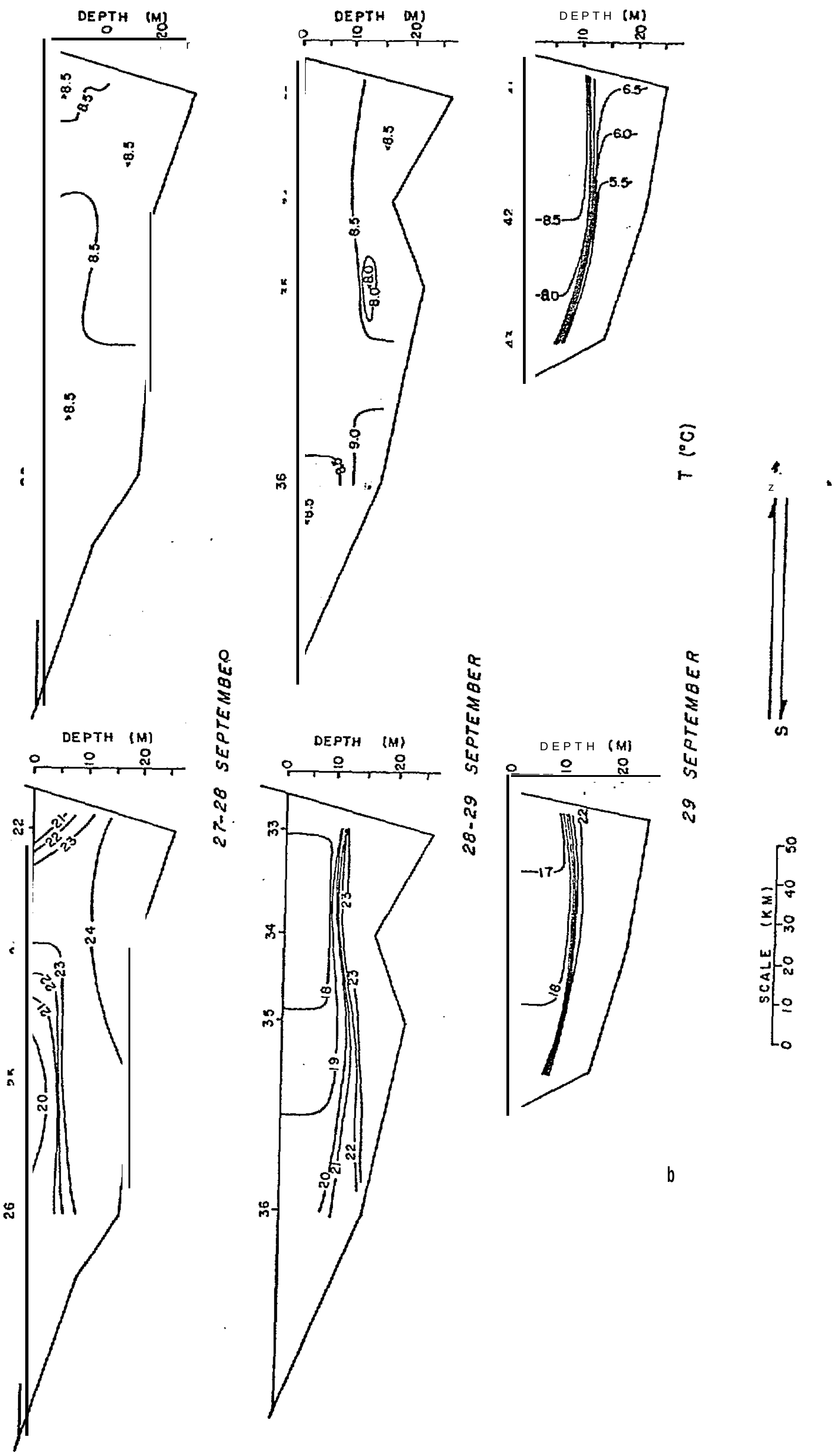


Figure 11. **North-south sections showing density and temperature distribution across Norton Sound during September-October 1976.**

33 to the east or 21 to the west. Near-shore stations obtained as part of a close-spaced section extending southwestward from Nome (Figure 12) detailed this feature and indicated densities down to σ_t = 19 in the near-shore band; the band was restricted primarily to the region above the pycnocline. High density water (σ_t > 23) occurred at stations 23 and 24 but was not present elsewhere. This high density area appeared between less dense water in the coastal band and in a shallow layer farther west at station 25 (Figure 11).

The temperature distribution bore little resemblance to density distribution except in the easternmost portion of the Sound, where temperature layering coincided with density layering (Figures 10 and 11). In the eastern and western portions temperatures near the surface were higher than near bottom, while in the central area (at station 29) temperatures were nearly homogeneous. Low near-bottom temperatures (< 2.5°C) at the head of the Sound are noteworthy because they do not show up elsewhere and because they require the existence of strong vertical gradients in a shallow region where vertical mixing might be expected to play an important role in controlling distribution. North-south temperature variations were irregular and less than 1°C, except for the section between Stuart Island and Cape Darby where there was a south-to-north increase in temperature (∿ 1°C) both above and below the pycnocline.

These north–south sections suggest that mean circulation in Norton Sound fell into two separate regimes. The western third of the Sound was characterized by well-defined east-west flows: a higher speed, concentrated coastal stream outward along the northern boundary and a broad, lower-energy flow into the Sound over the southern two-thirds of area. This structure is evident in both Figure 12 and the westernmost section of Figure 11. For the eastern Sound, mean flow was less well organized. There was a tendency for some inflowing water along the south to penetrate eastward before it turned north and eventually west to join the westerly

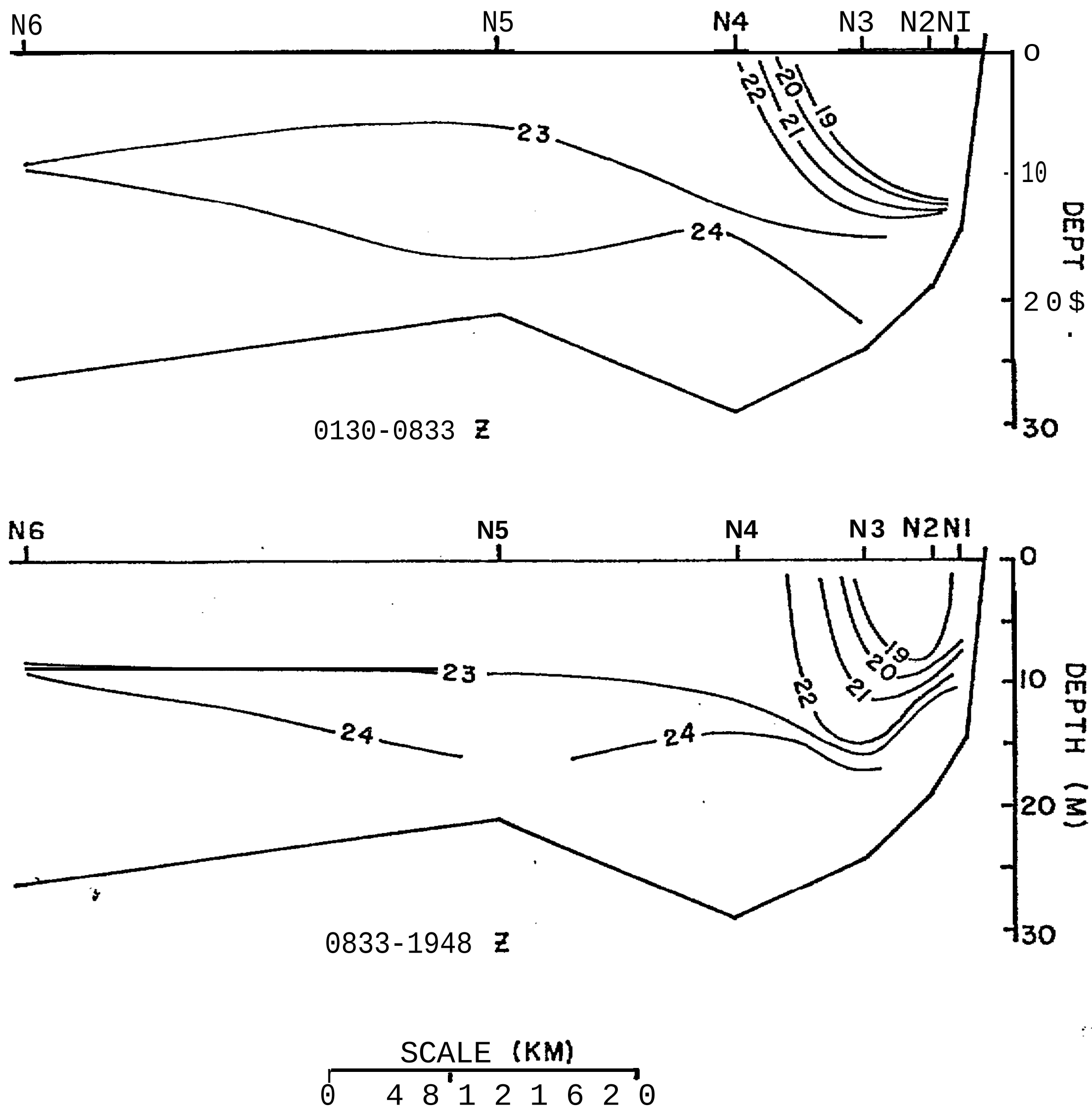


Figure 12. Sections showing density distribution off Nome during September-October 1976.

outflow. However, mean flow appeared sluggish in the eastern sections (Figure 11) and mostly northward (Figure 10).

The horizontal temperature distribution is summarized as a plot of temperature on the σ_t = 21 isopycnal surface (Figure 13). This isopycnal surface fell within the pycnocline, so the temperature distribution depicted is within the pycnocline. A warm tongue-like feature (8.5–9.5°C) extended eastward in the southern portion of the Sound, while a colder tongue (7–8.5°C) extended westward in the northern part. Presence of the strong pycnocline suggests a lack of vertical mixing. We feel that, despite the shallow depths, temperature in the pycnocline can serve as a qualitative water mass tracer because of this apparently weak vertical mixing. The temperature distribution can then be interpreted as reflecting cyclonic circulation in the western two-thirds of the Sound. East of the cul-de-sac formed by Stuart Island and Cape Darby, the pycnocline was too strong to allow clear definition of temperature on the σ_t = 21 surface.

There was bottom inflow along the two troughs which intrude the Sound from the west (cf. Figure 9). A clear indication of this is seen in the bottom salinity distribution (Figure 14). This water was then mixed upward and joined that of the general circulation. The upward mixing raises the salinity of the surface layer locally. Figure 15 shows the average salinity of the surface layer (~ upper 5m), and the strongest effects are noticeable at stations 24, 30, 35 and particularly at stations 22 and 21 west of Nome.

Density sections indicate that large variations in pycnocline depth occurred over the Sound; for example, it was about 5 meters shallower at station 25 than at 35 (Figure 10). Such variations are in part due to internal waves on the pycnocline. Figure 16 shows vertical density profiles at two of the five time-series stations. Each of the five time-series stations indicated vertical migrations in pycnocline depth on the order of 5 meters. Though the records are too short for

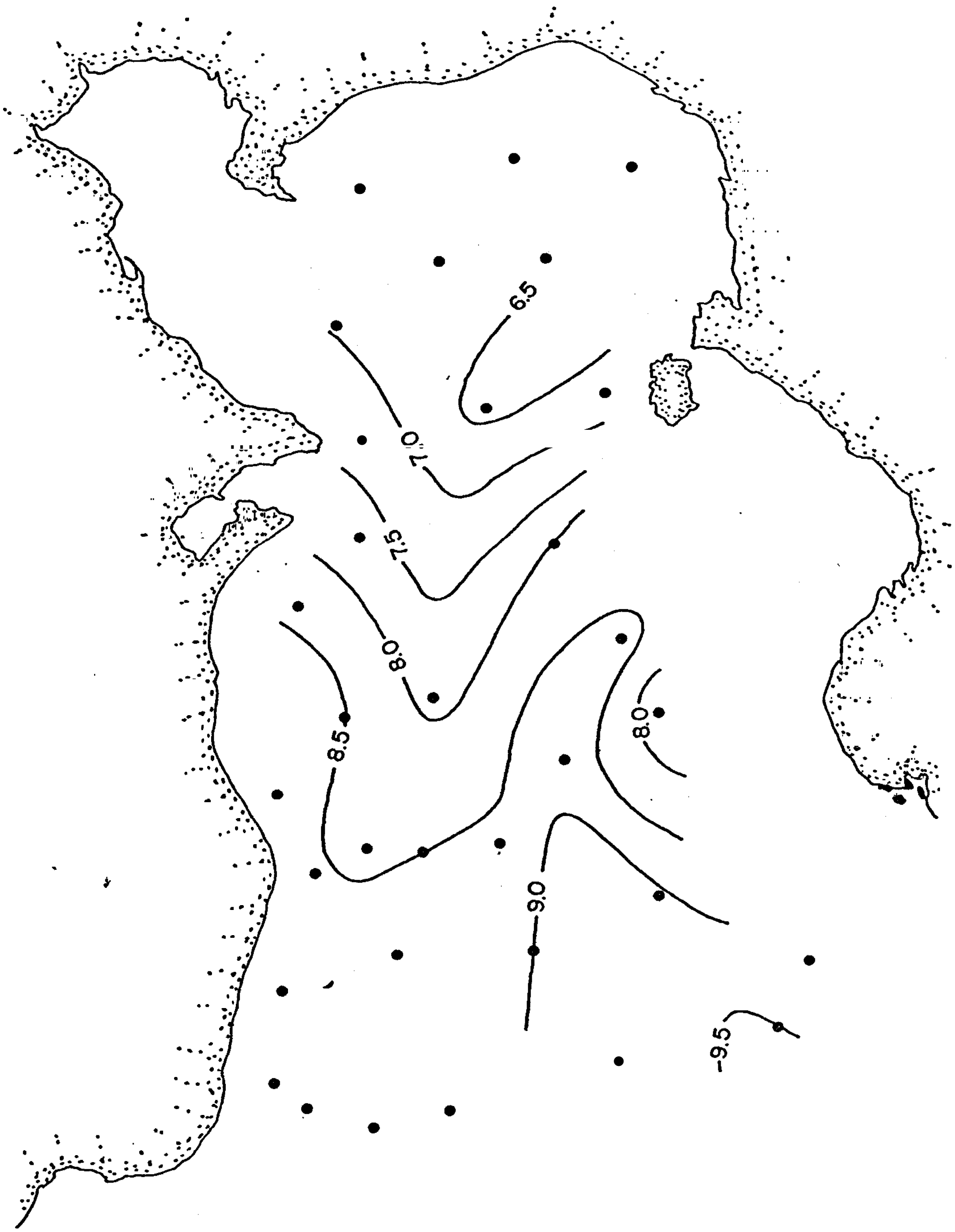


Figure 13. Temperature on the sigma-t = 21 surface in"Norton Sound.

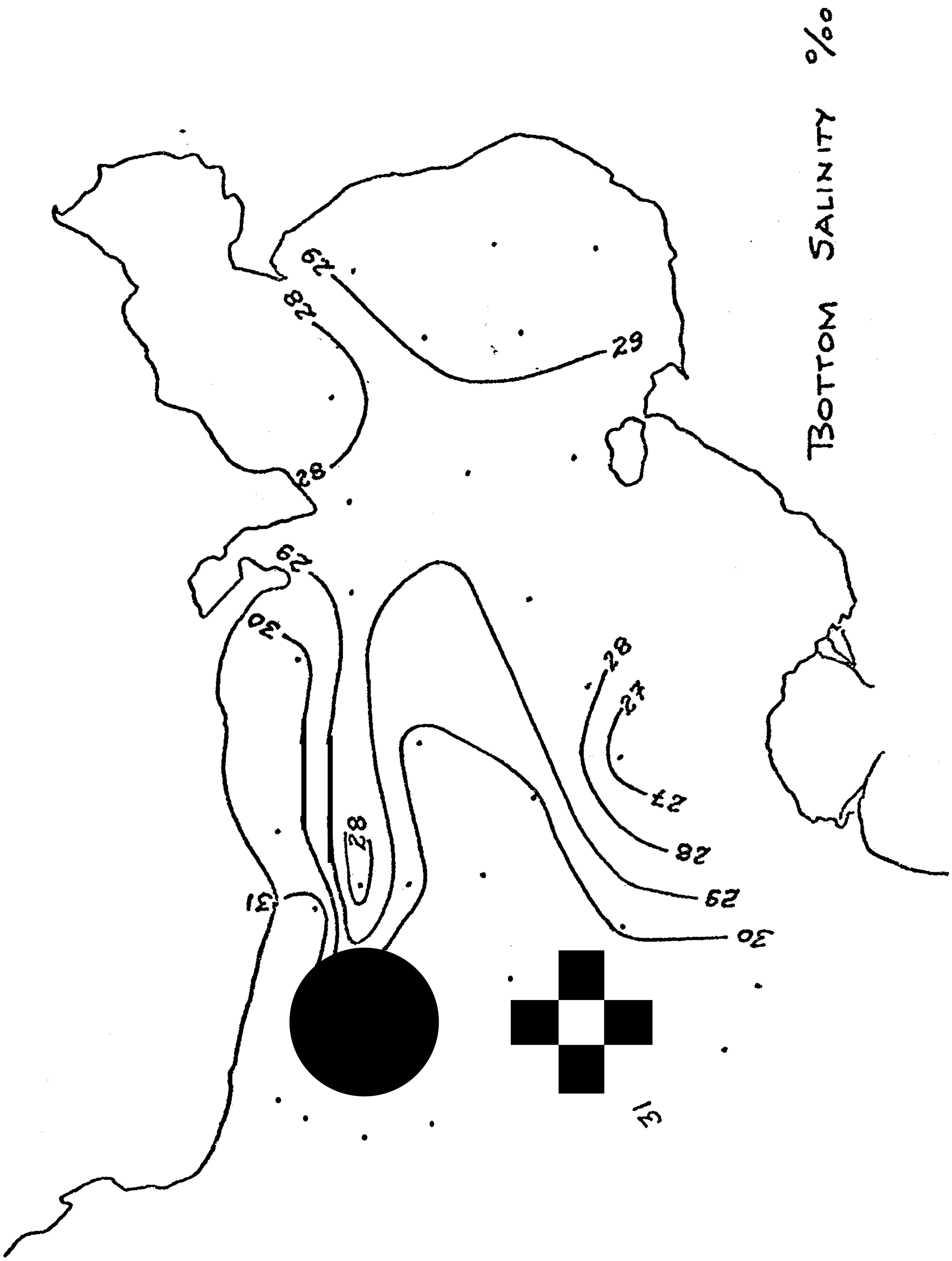


Figure 14. Salinity (‰) of the near-bottom layer.

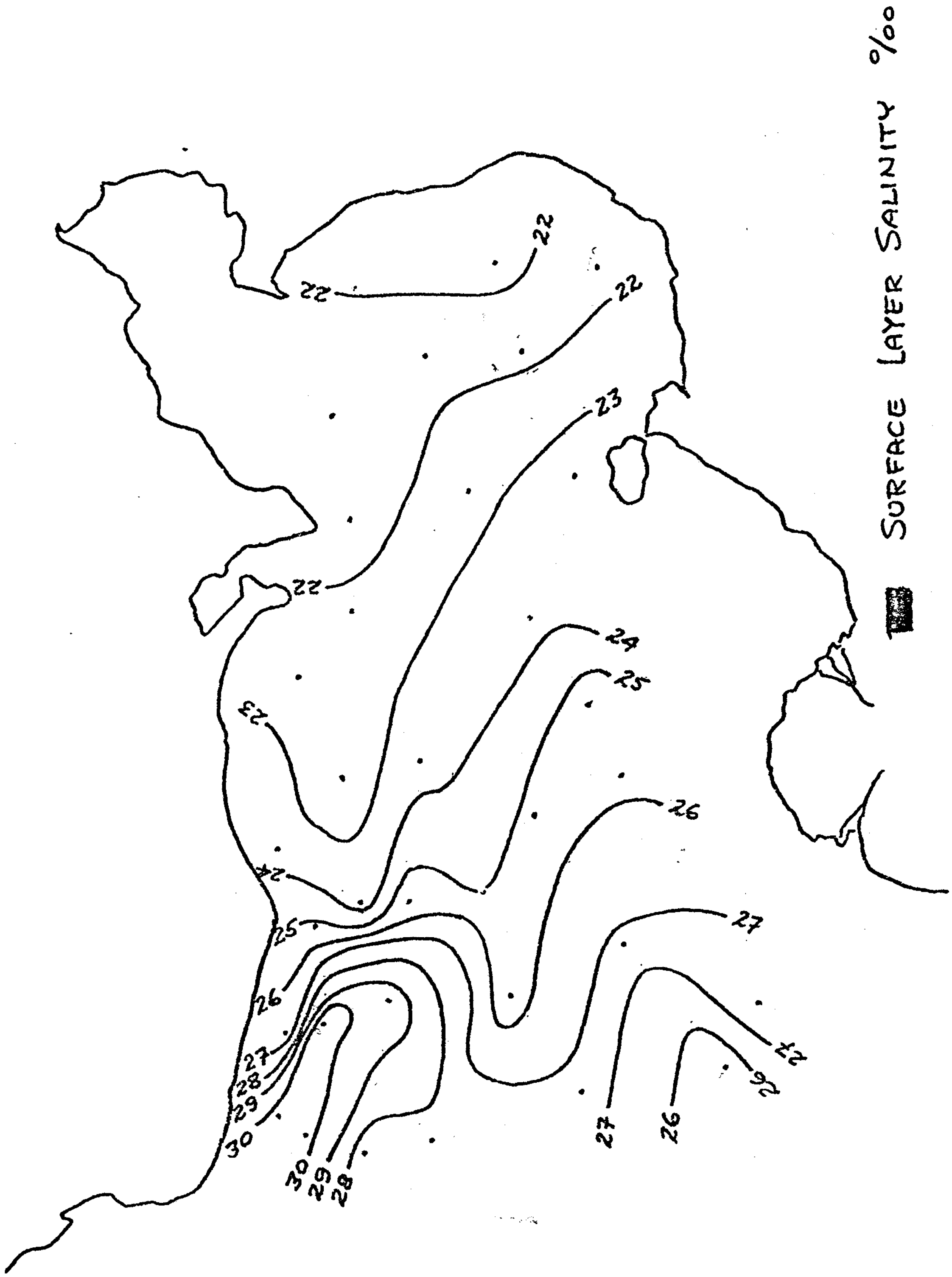


Figure 15. Salinity (‰) of the near-surface (∿ 5 m) layer.

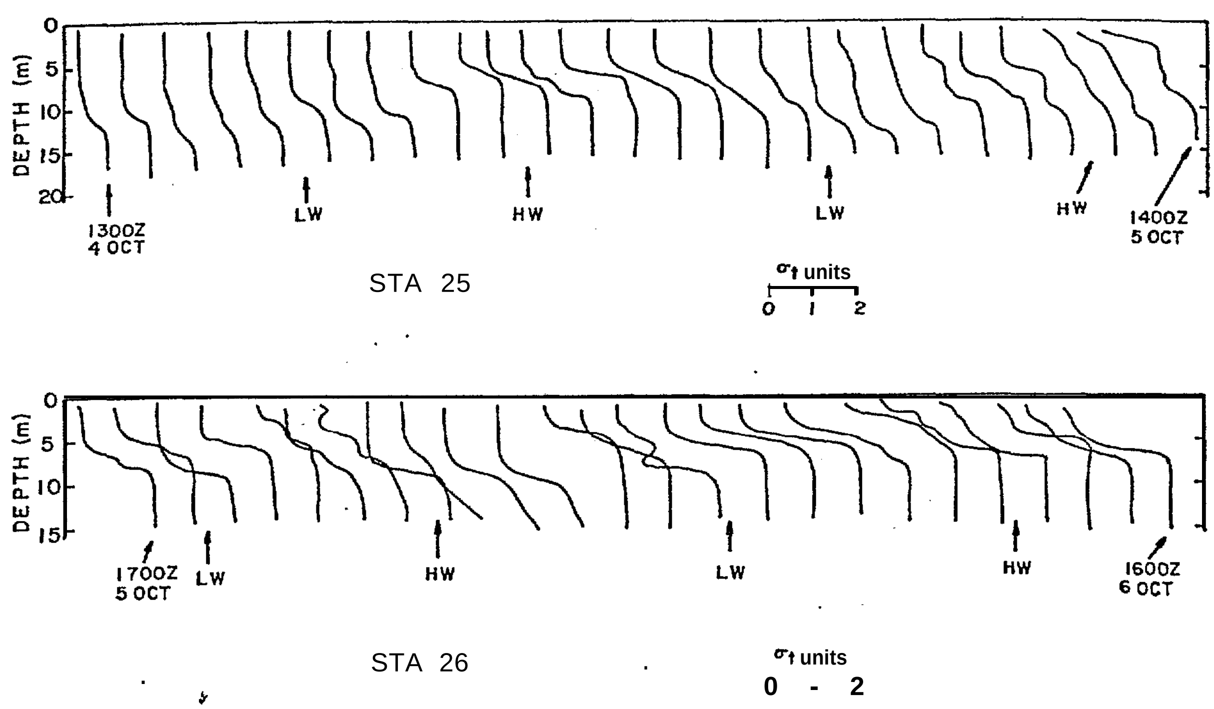


Figure 16. Examples of time variations in vertical density structure at two stations in Norton Sound.

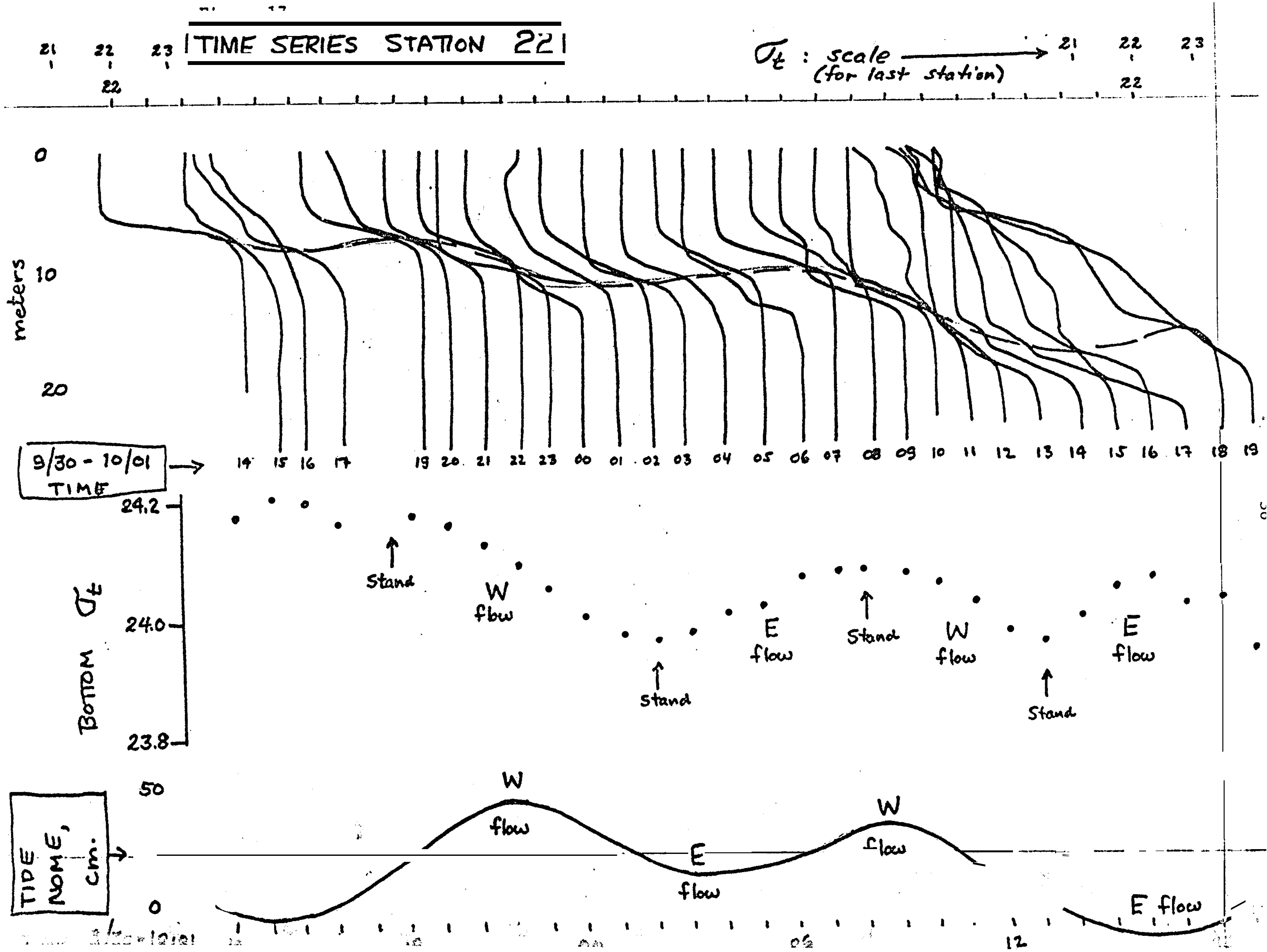
definitive analysis, the fluctuations might be composed of a basic tidal signal with some higher frequencies superimposed. The record at station 25 (Figure 16) appears to have a fairly clear tidal period signal as a dominant part of the fluctuation.

A closer connection between tides and time variations can be demonstrated for station 22, 15 km southwest of Nome. The predicted tides for stations around Norton Sound show the tide wave circulates cyclonically--thus off Nome the wave travels from east to west. Figure 17 plots the vertical σ_t profiles for time-series station 22 sequentially. Also plotted, on a time scale, are the bottom σ_t values and the predicted Nome tide. As the CTD stations were made at one-hour intervals, the σ_t offset between vertical profiles is the same scale as one-hour, so are visually equivalent in time,

The interpreted flows are as indicated. In a tidal progressive wave, the flow will be west at high water at Nome and east at low water. In the curve of variation of bottom σ_t, as the density increases to the west, a west flow will decrease σ_t and an east flow increase σ_t, as indicated. There is good correlation with the predicted tides. The fluctuations of the pycnocline also correlate--west flow brings *a* deepening of the pycnocline (which lies deeper to the east), and an east flow shallowing. The last few hours of the record become confused because of the intrusion of a less dense water parcel in the upper layers.

The time fluctuations of the other time-series stations cannot be so readily resolved in terms of the tides because the behavior of the tide wave in Norton Sound cannot be sufficiently resolved as yet. Tide table data show the times of high and low water to be progressively later from Kawanak Pass (Yukon Delta) to Stuart Island to Golovin Bay to Nome. Using the expression $c = f\,(gh)^{1/2}$ where c = wave speed, g = gravity, h = mean (effective) depth, and f = a factor accounting for the fact that tide waves in shallow shelf seas tend to move a little

TIME SERIES STATION 22



faster than $(gh)^{1/2}$ (Sverdrup, 1926), the speed and depths from Kawanak to Stuart to Golovin check very well with f ≈ 1.3. (In outer Kotzebue Sound f ≈ 1.5 [Coachman and Tripp, 1970].) Thus, a rotary wave cyclonic around outer Norton Sound with an amphidromic point somewhere in the outer central part of the Sound, is strongly suggested. However without further resolution we cannot locate stations 24, 25, and 26 with respect to the amphidromic point. It is hoped that the year-long current records from moorings NC-14 and NC-15 will help shed light on the tidal behavior.

Several density inversions were observed in the course of this study. These are believed to be real, and are qualitatively similar to those reported at greater depth in Bristol Bay by Coachman and Charnell (1977). Their treatment is beyond the scope of this paper.

Current and wind observations. Vector-averaged currents at each depth are shown along with vector-averaged surface winds at each of five stations in a transect south from Nome (Figure 18). The highest currents observed (∿ 50 cm sec^{-1}) occurred near the surface at station 22. Speeds at this station decreased with depth down to about 10 cm sec^{-1} near the bottom, while flow direction rotated slightly from northwesterly near the surface to west-southwesterly near the bottom. The currents at station 22 showed an onshore component which was maximum near the surface and decreased with depth to become slightly offshore near the bottom (Figure 19). Longshore currents were westerly throughout the water column and maximum near the surface, decreasing monotonically with depth.

The ten-hour time series (station N3), obtained about 2 km northeast of station 22 and about two days later, revealed an entirely different current regime than that observed at station 22 (Figure 19). Mean flow was southeasterly throughout the water column. A breakdown into components revealed that flow was offshore

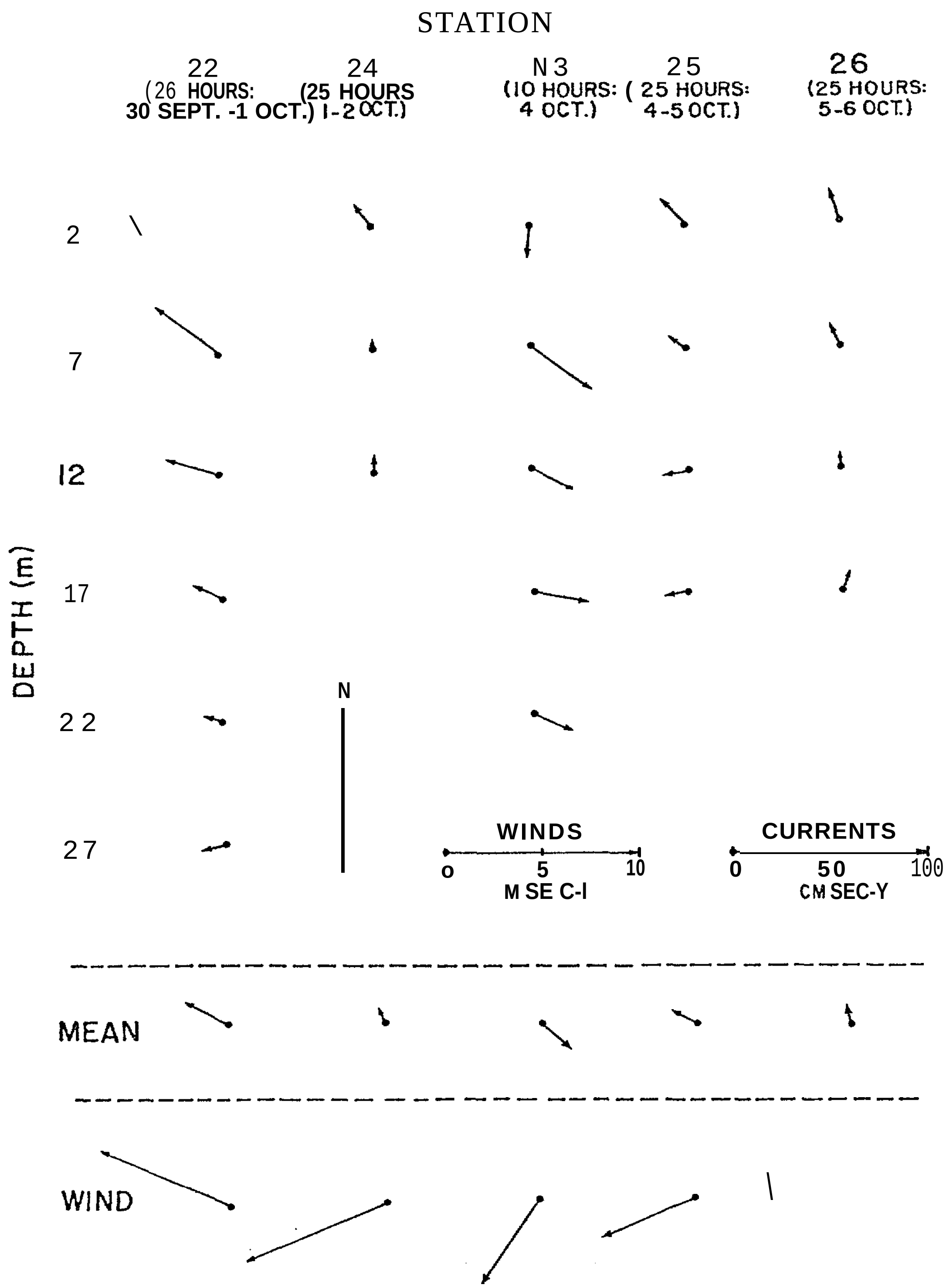


Figure 18 Mean currents and winds at the five time-series stations in Norton Sound.

except at 17 meters where a slight onshore component was present (Figure 17). The longshore component was easterly with a pronounced maximum at 7 meters.

Mean currents at stations 24, 25, and 26 were westerly to northerly through the water column and were maximum at the surface (12-18 cm sec^{-1}), becoming small ($\sim$ 5 cm sec^{-1}) near the bottom.

Individual hourly current records were generally characterized by short-term (on the order of a few hours) fluctuations (Figure 20). Only one of the five records is presented here because they all exhibited similar characteristics. There was no visual correlation between these fluctuations and fluctuations in the surface winds, although the apparent similarity in directions between the mean currents and winds (Figure 18) suggests that wind was a significant factor.

B. THE SEPTEMBER ANCHORED CURRENT MEASUREMENT PROGRAM

During the early September field program, anchored current measurements were obtained at each of the locations indicated in Figure 21. Interpretation of the results of these measurements (Table 4) is limited somewhat by the one-time-only nature of the measurements coupled with the natural variability of currents in the region. The measurements were however felt adequate to define large-scale regional circulation features.

Table 4

Observed Water Transports (Sv, 1 Sv = 10^6 $m^3 s^{-1}$)

Section	Date (s)	Transport	Comments
Bering Strait	September 8	0.70	Northerly flow with some southerly near-surface flow in western portion.
Cape Lisburne	September 10-11	0.72	Net northward flow.
		1.06	Southeasterly flow in Siberian Coastal Current (western part of section).
E. St. Lawrence	Septmber 6	0.73	Northward flow.
W. St. Lawrence	September 6-7	1.12	Northward flow.

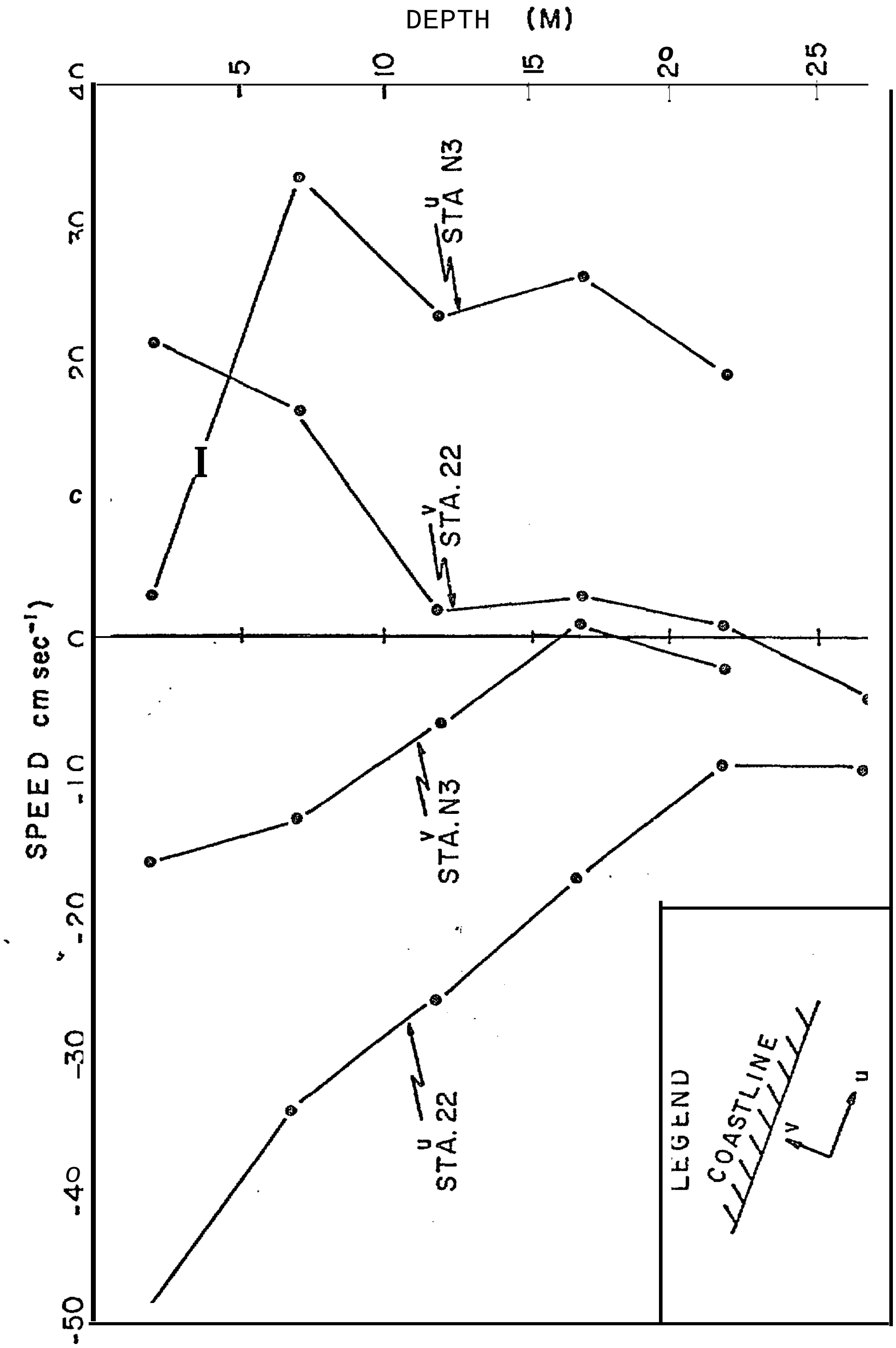


Figure 19. **On-offshore and** longshore **current structure off** Nome.

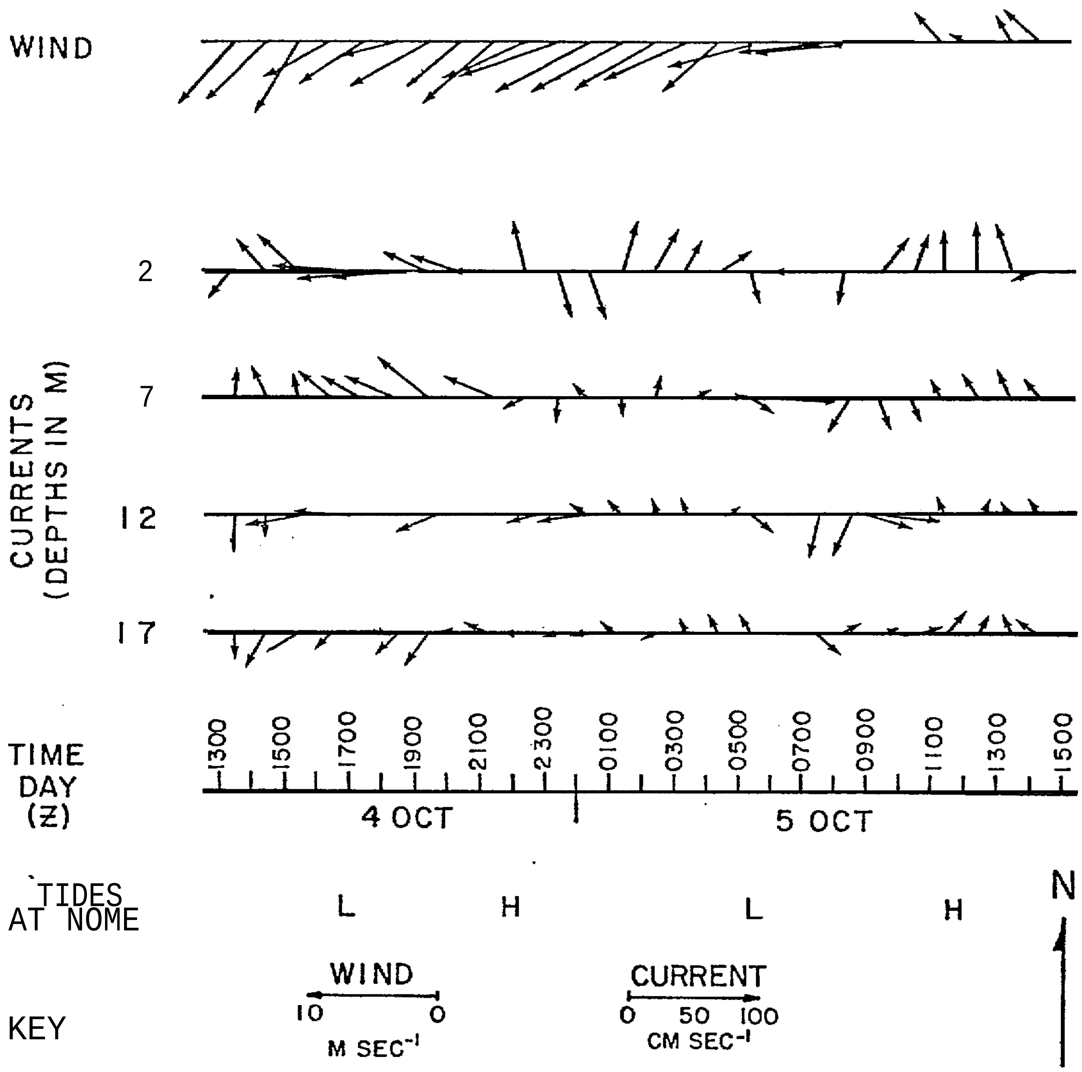


Figure 20. **Example showing short-term variations in** winds and water currents at station 25 **in Norton Sound,**

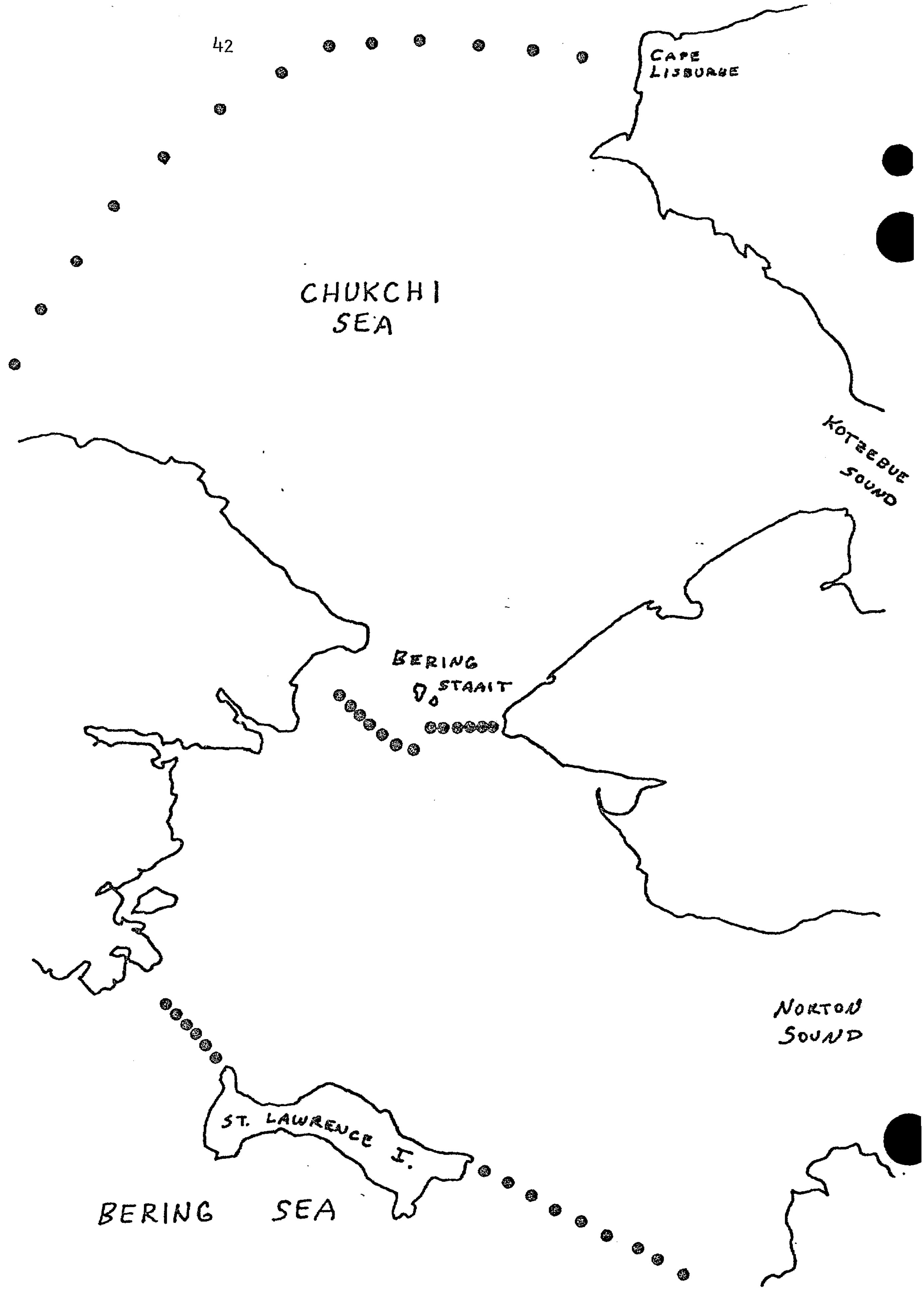


Figure 21. Locations of September 1976 anchored current stations in the Bering Strait region.

The measurements detected a northward flow of 0.70 Sv (1 Sv = 10^6 $m^3 s^{-1}$) through Bering Strait, in agreement with previous figures (see Coachman *et al.*, 1975). A relatively small (0.1 Sv) southward flow was present in the western near-surface portion of the Strait. Farther north off Cape Lisburne in the Chukchi Sea, a net northward transport of 0.72 Sv was the resultant of a northward 1.78 Sv flow through the eastern portion of the section and a southward 1.06 Sv flow through the western part of the section. The southward flow was a manifestation of the Siberian Coastal Current. The net northward flow past St. Lawrence Island in the northern Bering Sea was 1.85 Sv, about 65% of this through the passage west of the Island.

C. KOTZEBUE SOUND HYDROGRAPHY

We have begun examining the data from 26 hydrographic stations obtained in late August (Figure 22). Water depth varied from 31 m outside the Sound (station 66) to 14.5 m in the southeastern quadrant of the survey grid (station 88). Figures 23 *to* 31 illustrate our preliminary results.

Surface distributions (Figures 23 to 25) show that the shallow water in the Sound was warmer (11 C compared to 10 C) and fresher (26 compared to 30 g kg^{-1}) than the adjacent waters. There is a suggestion of an inflow of more saline water on the southern side of the entrance and an outflow of fresher water on the northern side: this circulation may bypass the easternmost part of the Sound.

Within Kotzebue Sound, bottom distributions (Figures 26 to 28) show some cold (<2 C) and salty (>32 g kg^{-1}) water which is a remnant of winter freezing. While inflow and outflow pattern similar to the shallow layer may be interpreted from these deeper distributions, the presence of relict winter water precludes a continuous cyclonic circulation within the deeper layer.

Stratification is very high in the northern and southeastern partsof the Sound (Figures 29 to 31): the Noatak River discharges into the Sound east of the

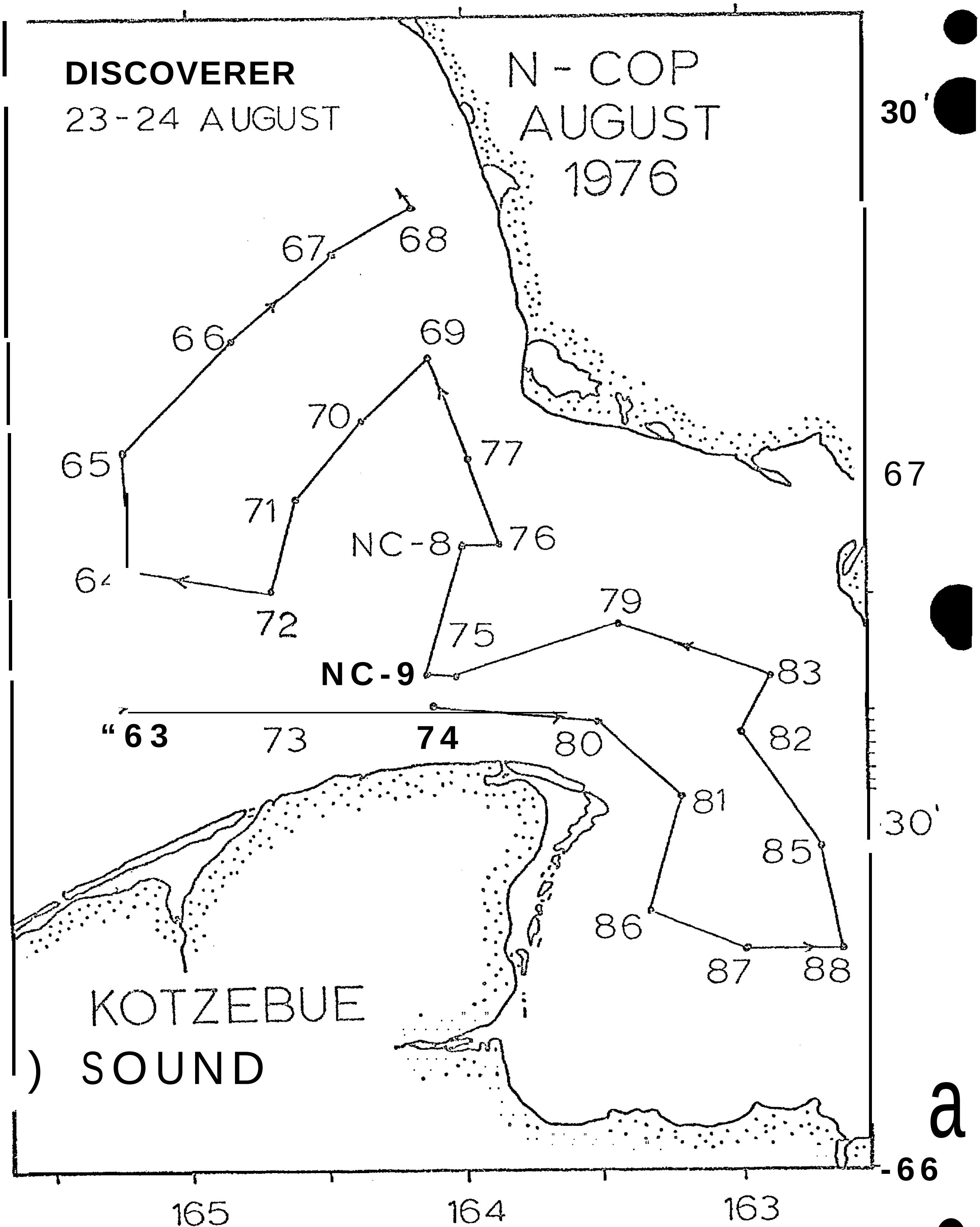


Figure 22. Track of NOAA ship *Discoverer.*

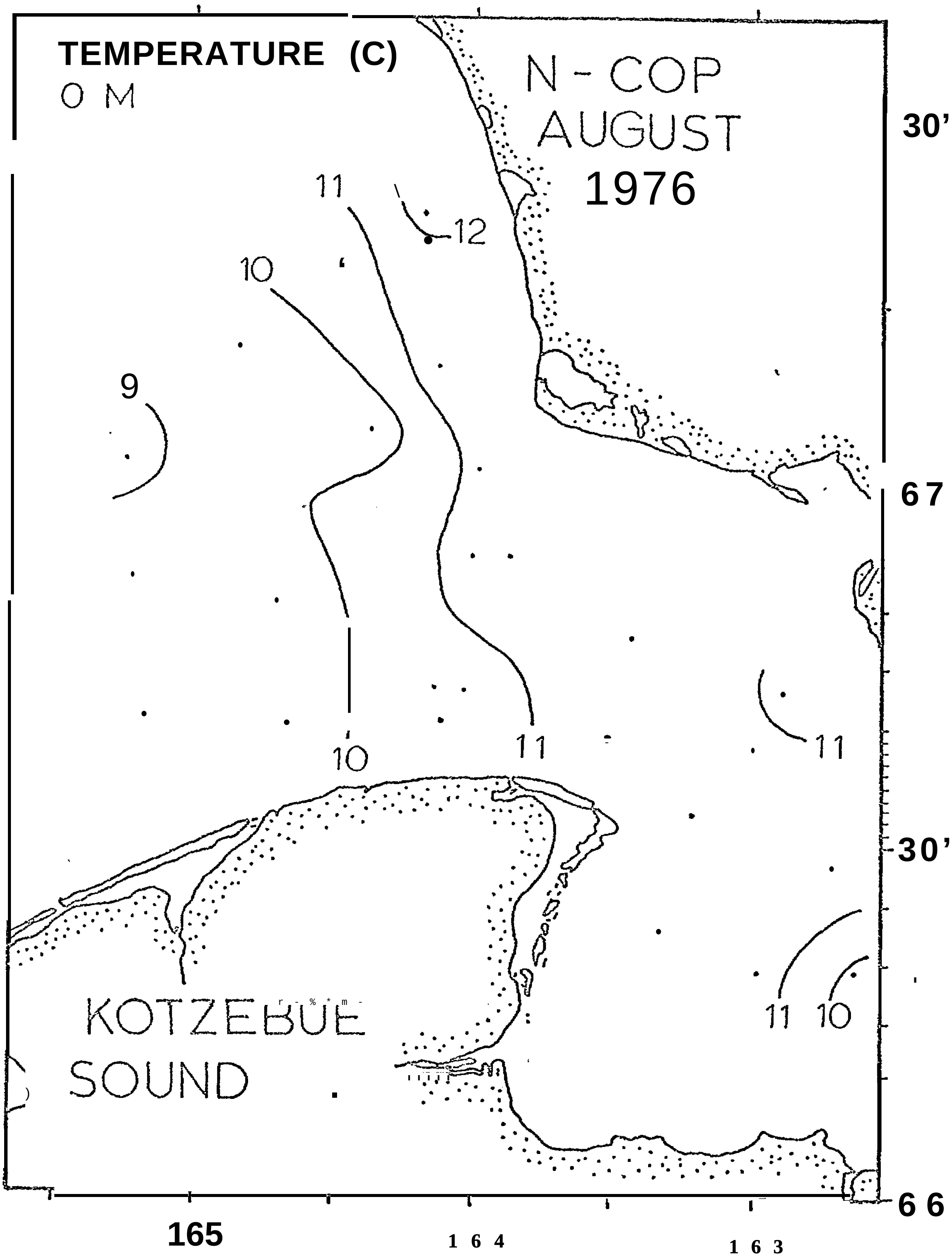


Figure 23. Surf ace temperature.

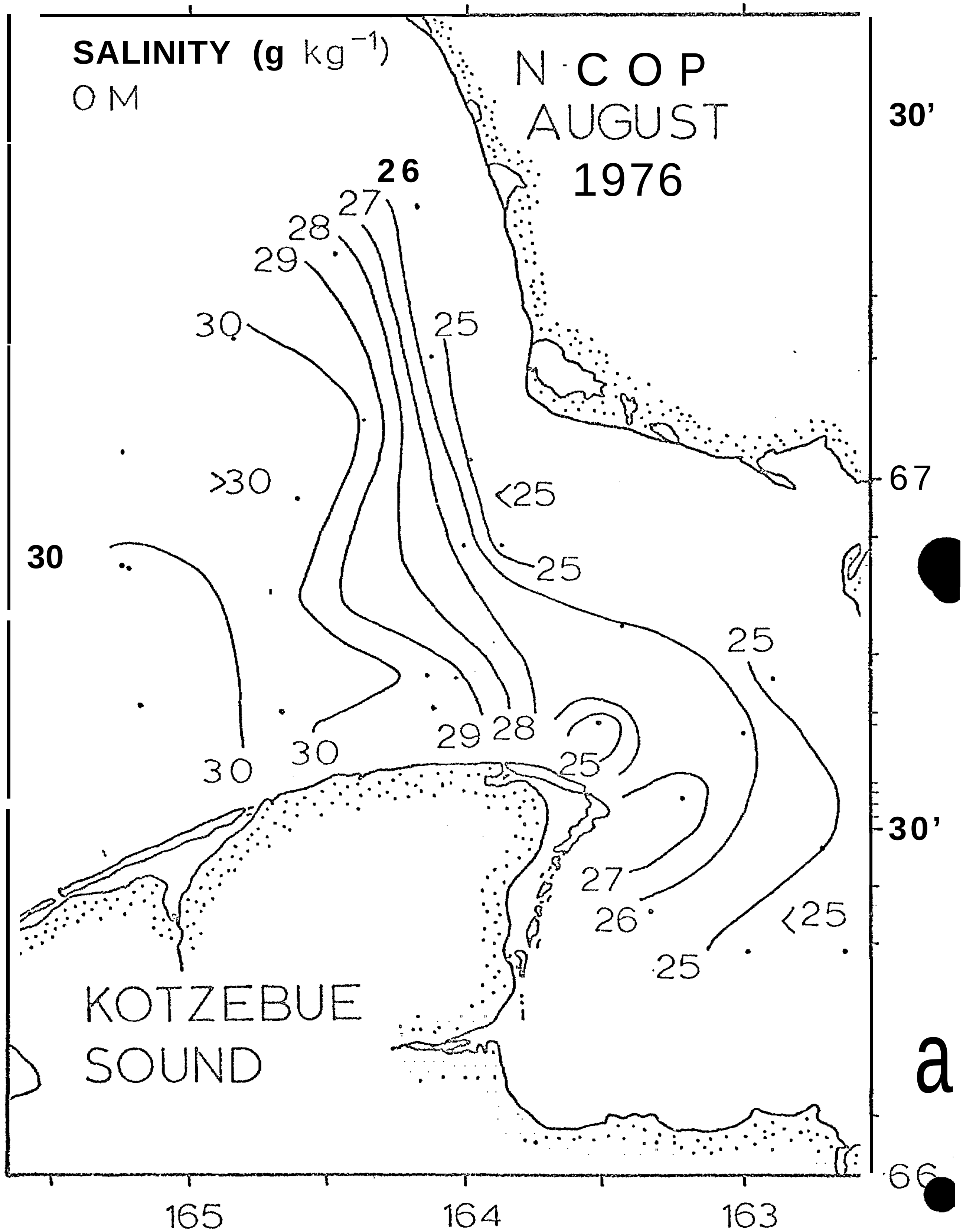


Figure 24. Surface salinity.

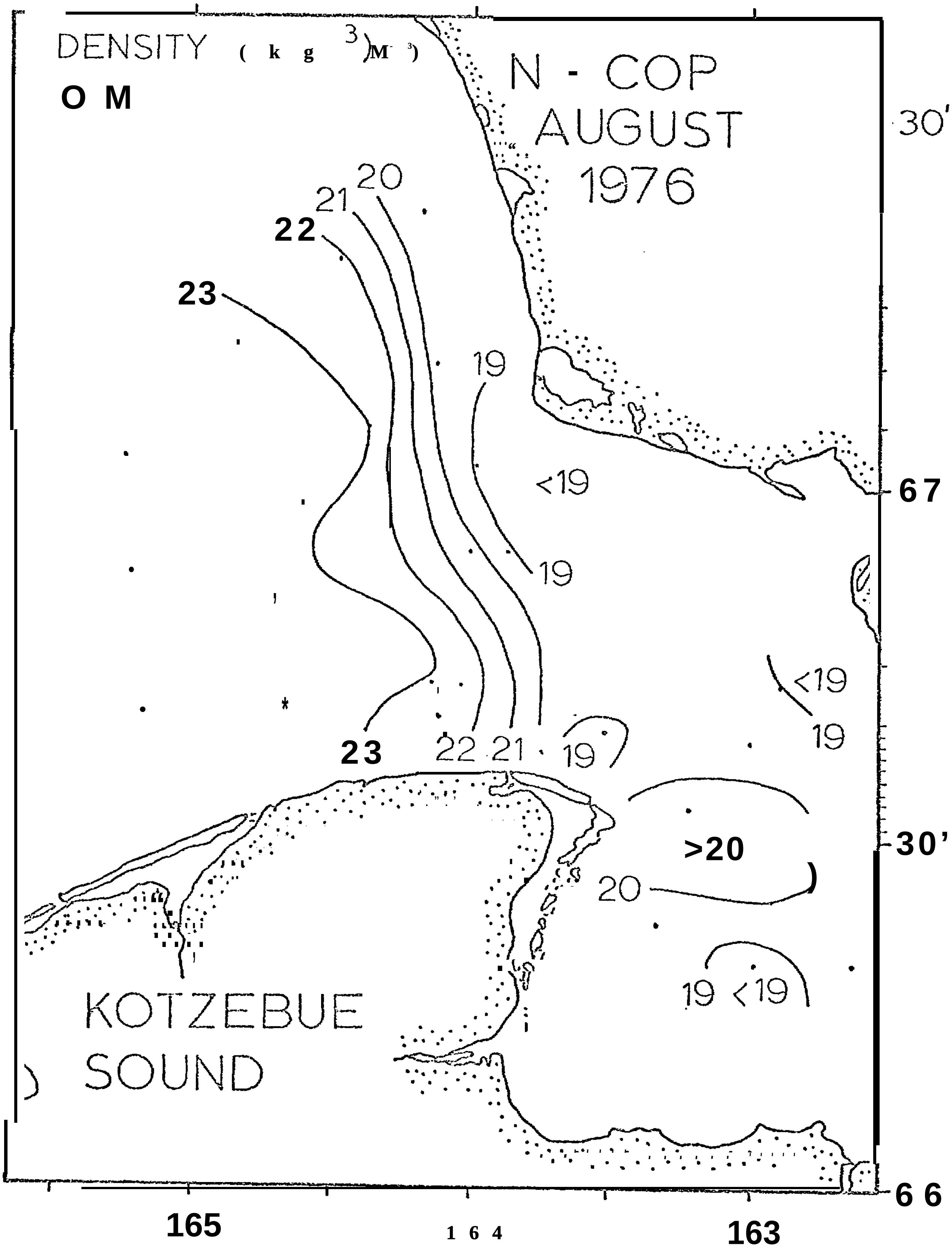


Figure 25. Surface density (σ_t).

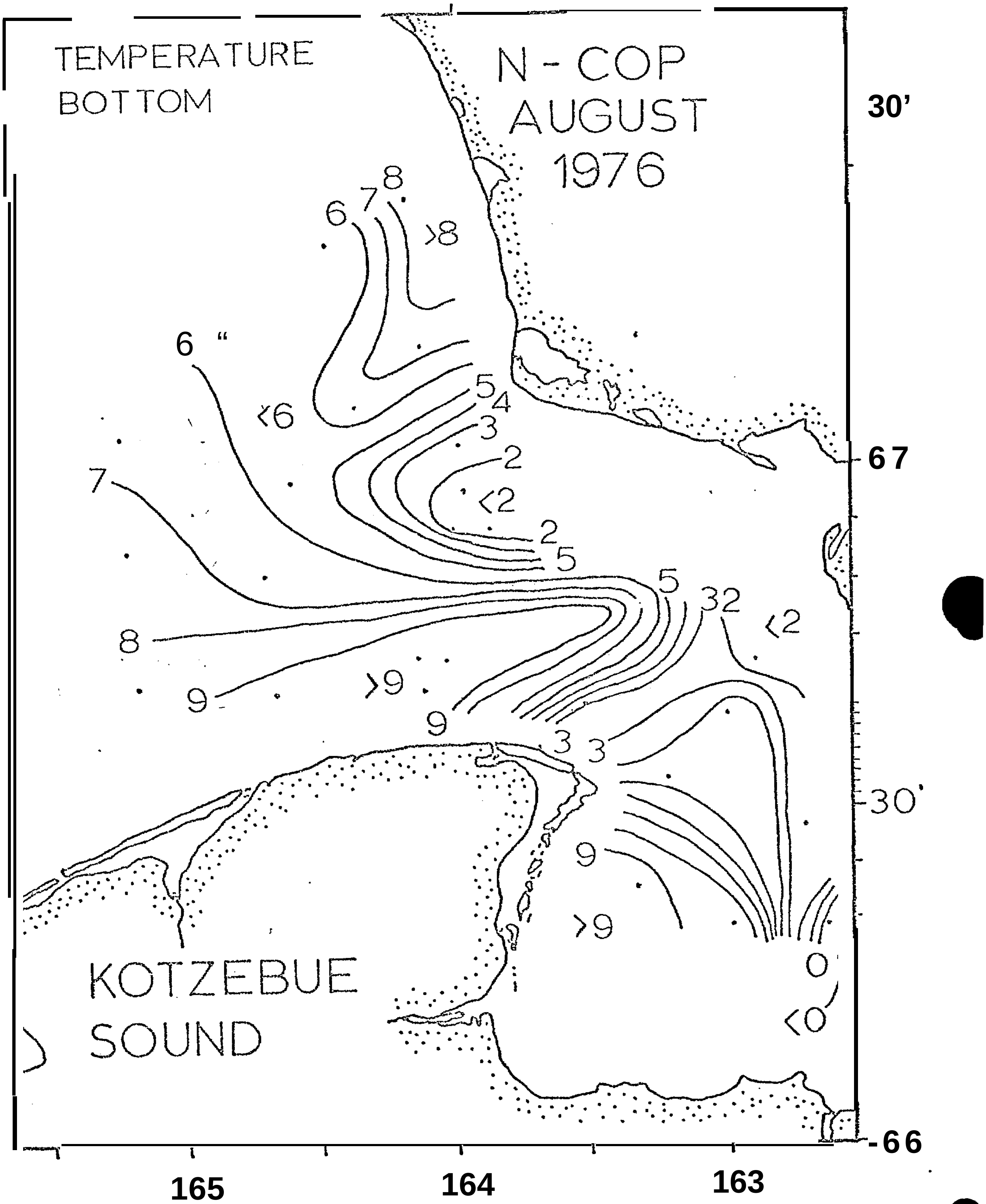


Figure 26. Bottom temperature.

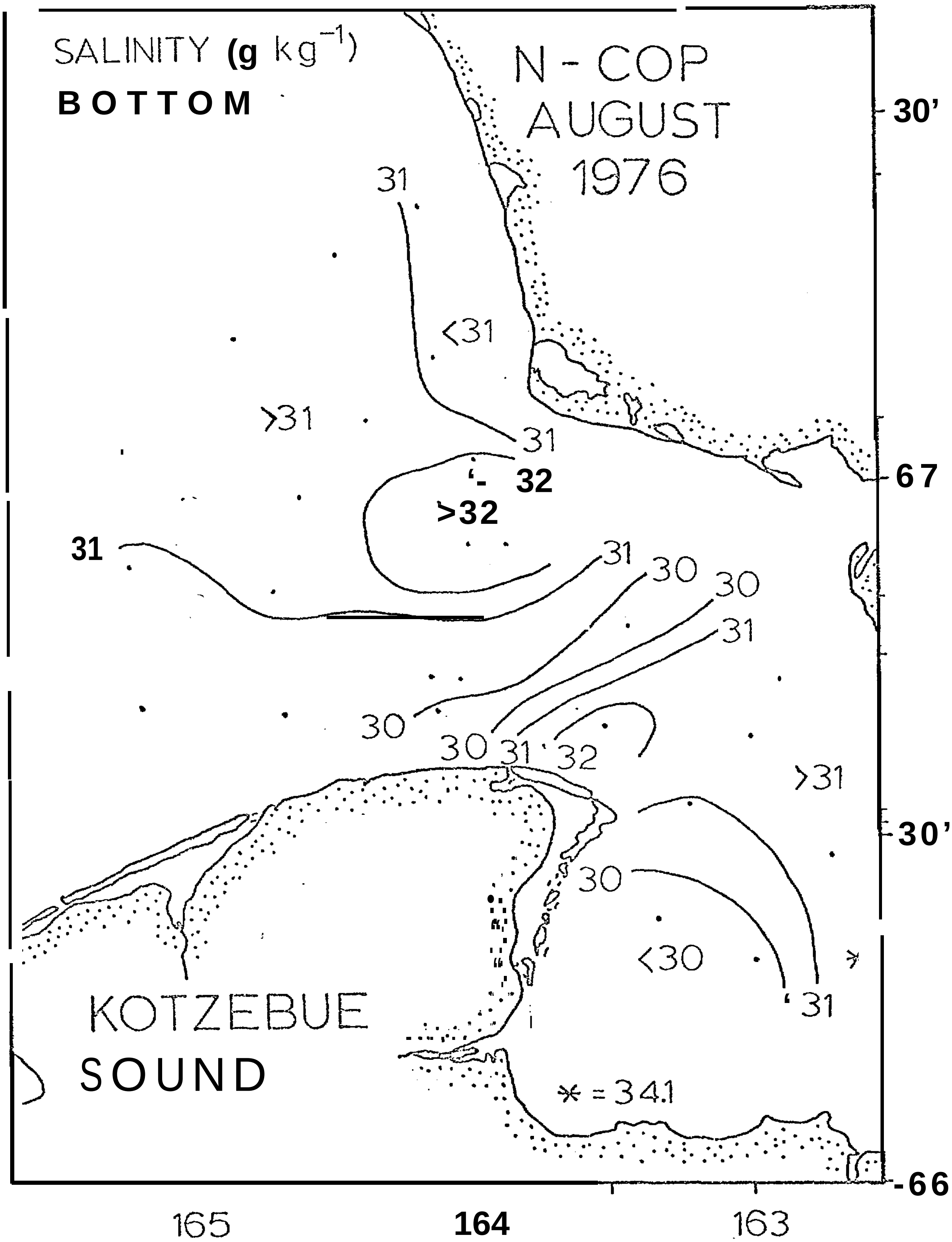


Figure 27. Bottom salinity.

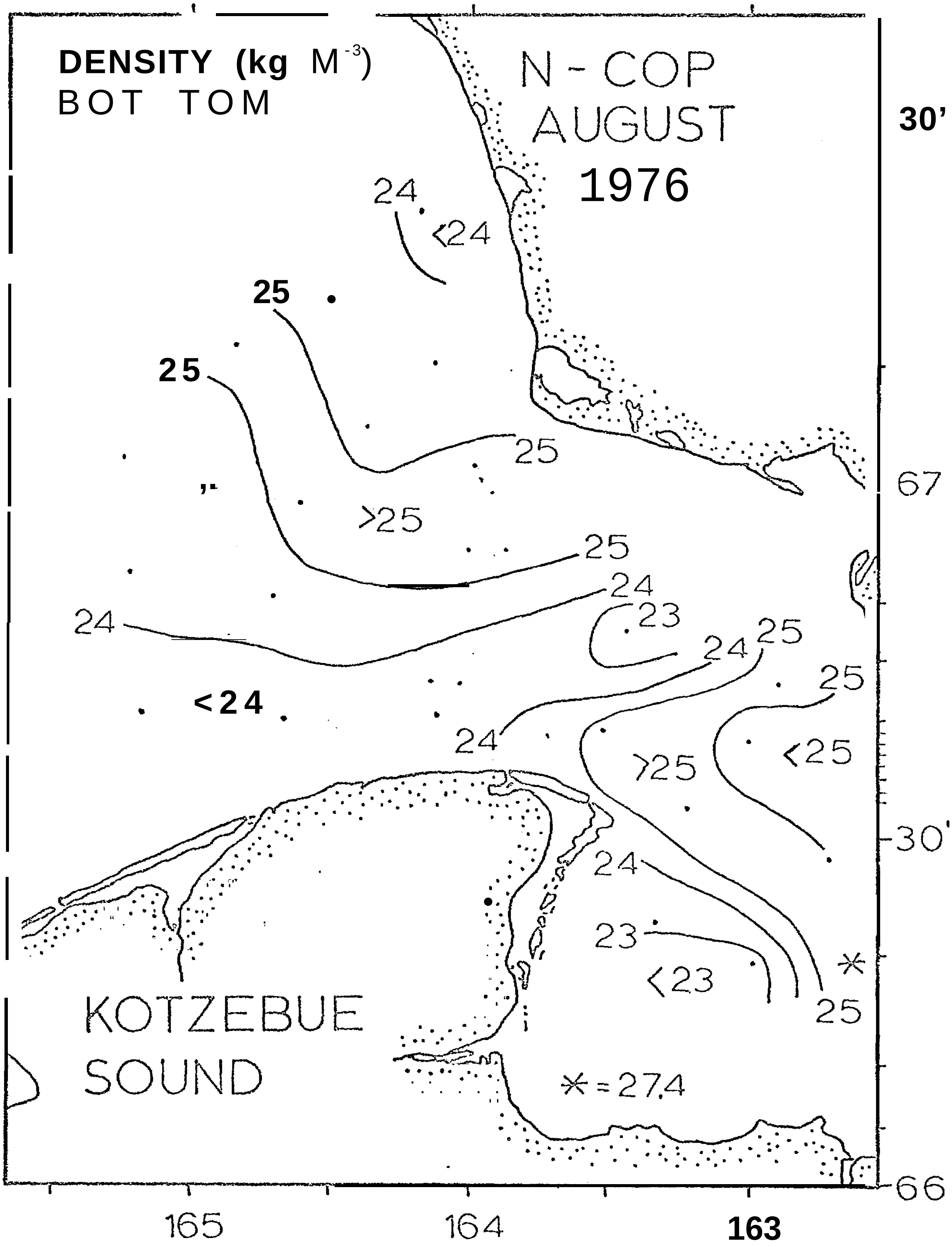


Figure 28. Bottom density (σ_t) .

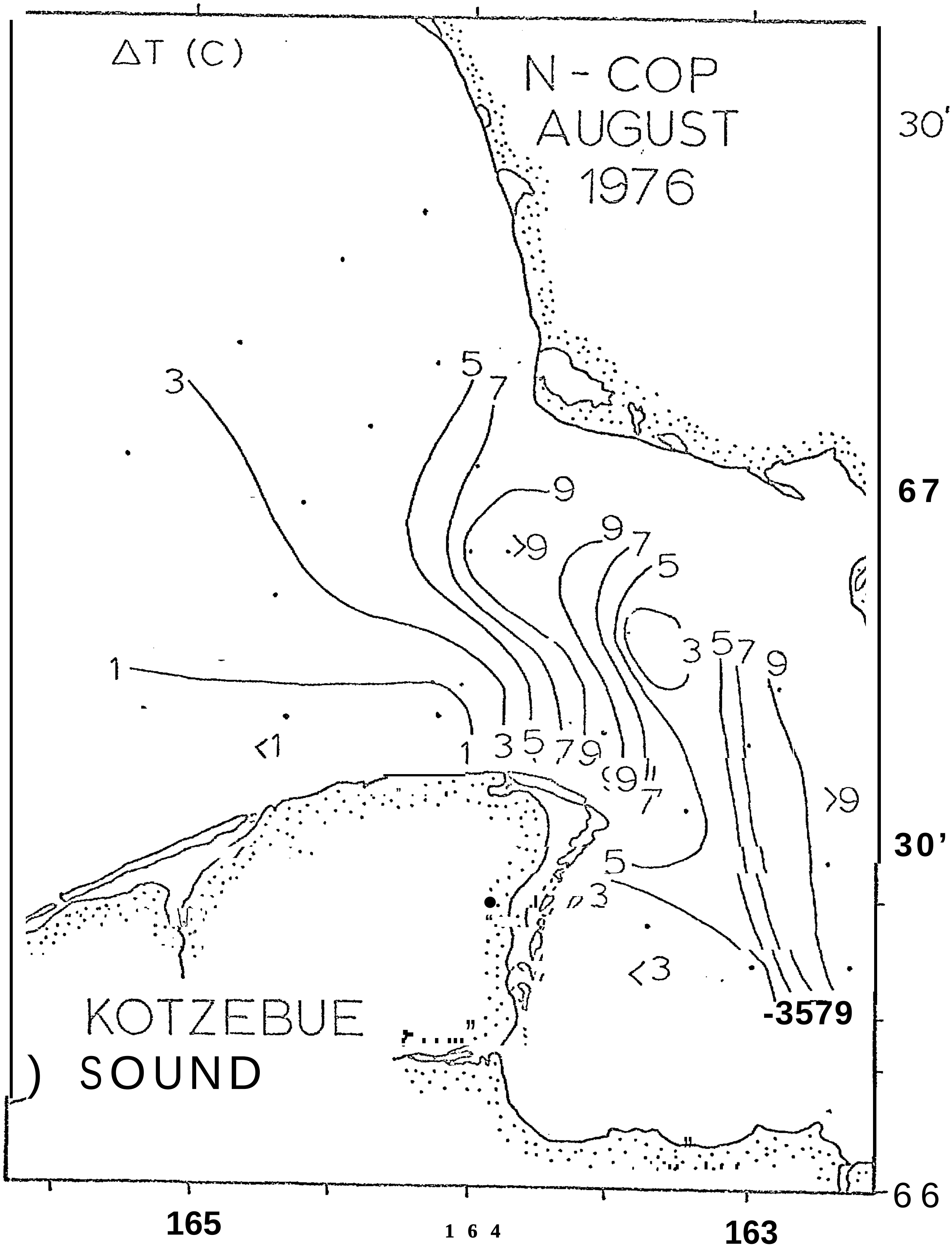


Figure 29. Temperature difference, surface minus bottom.

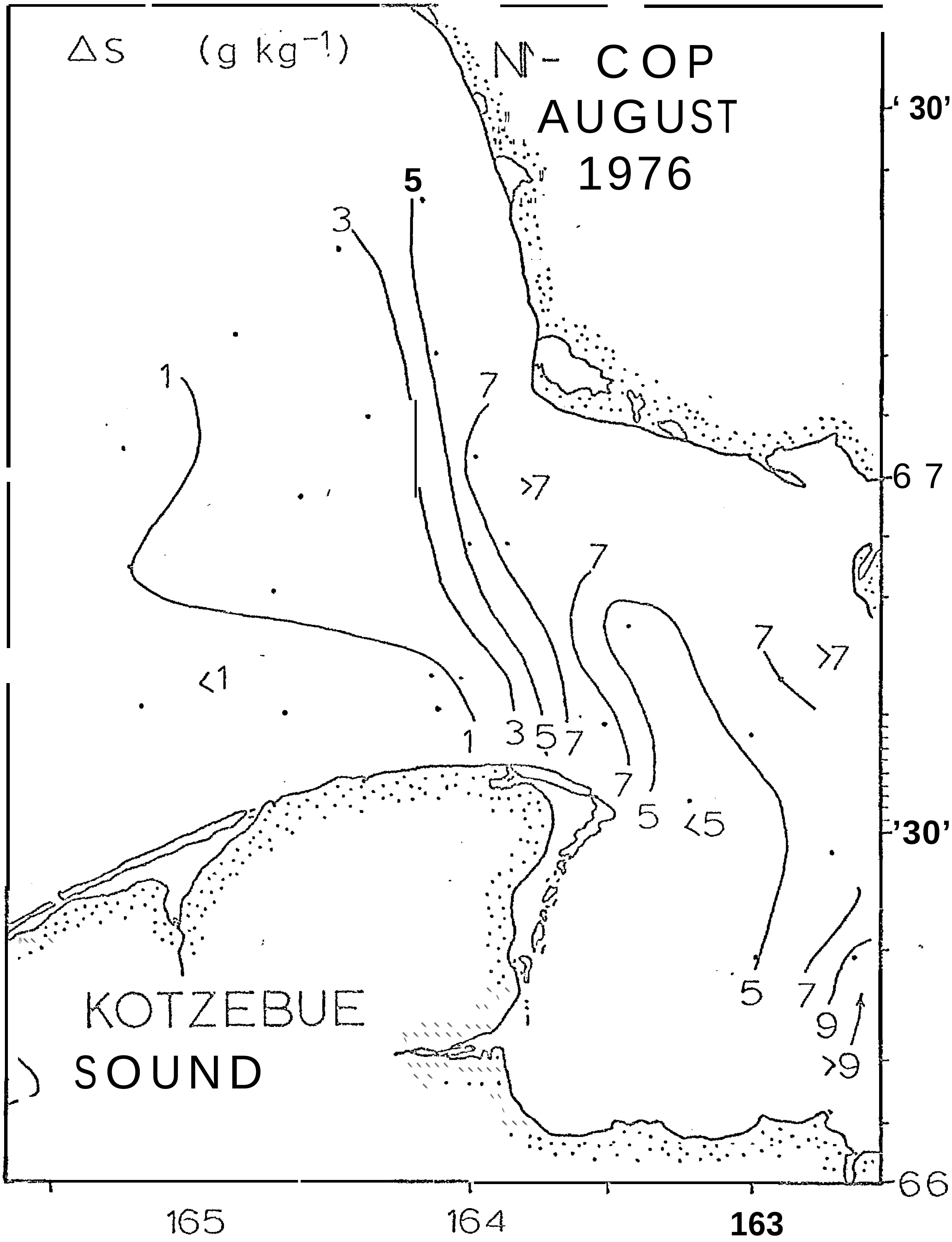


Figure 30. Salinity difference, bottom minus surface. .

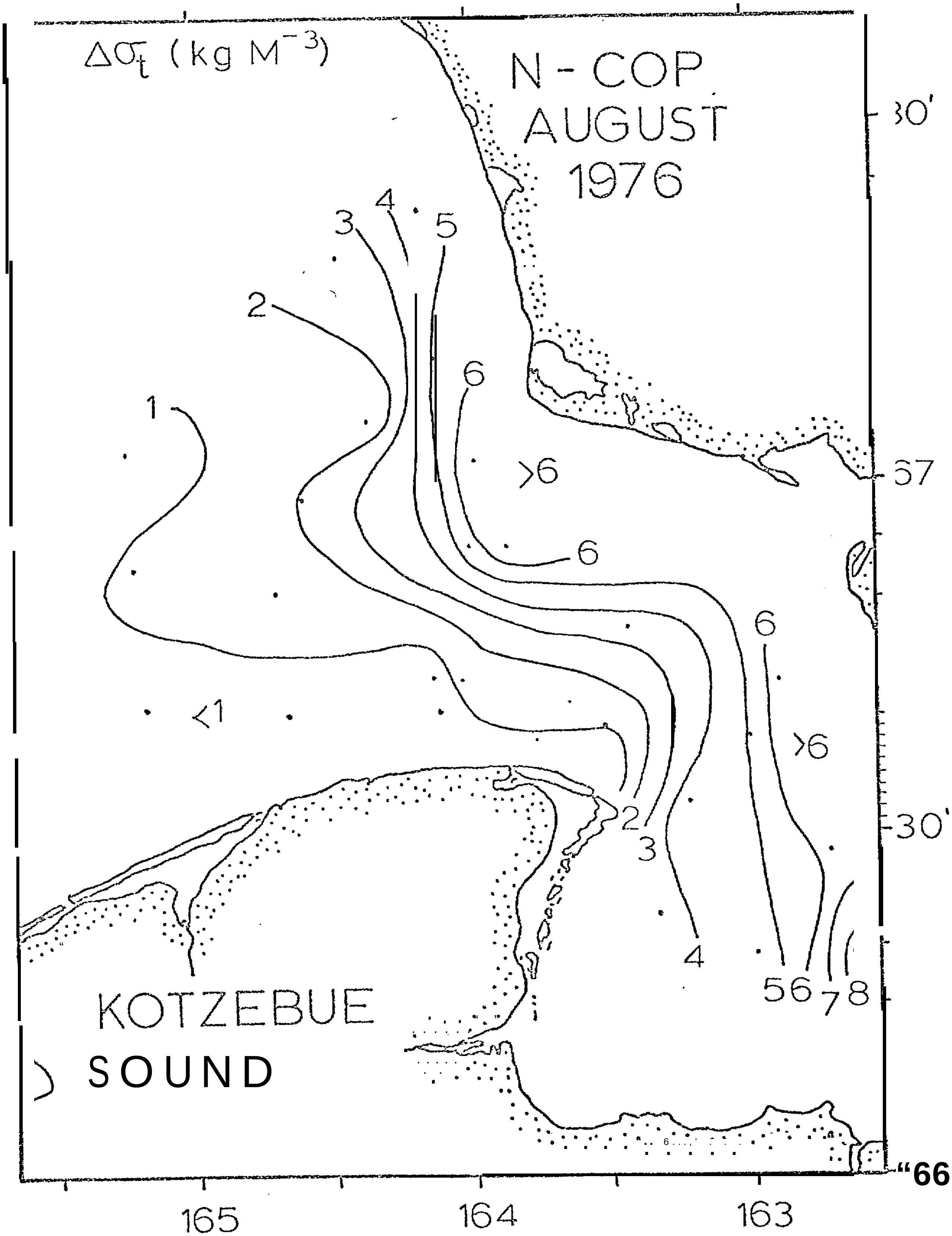


Figure 31. Density (σ_t) difference, bottom minus surface.

survey grid near 67N, and it markedly affects the stratification and surface salinity distributions.

The presence of the relict winter water and of the very high vertical stratification shows that the bottom water remains in place for periods of months. This means that:

1) Horizontal advection is too sluggish to flush out the Sound.

2) Horizontal diffusion (*i.e.*, processes with shorter periods than weeks, including tides and weather) is ineffective in renewing the bottom water.

3) Vertical mixing is insufficinet to overcome the buoyancy input from river runoff and insolation. This implies that tidal energy is low, and that in summer 1976 the winds were light.

By implication, pollutant dispersion in the lower layer would proceed slowly.

Finally, we emphasize that these results are preliminary. A more comprehensive report is in progress.

D. BERING STRAIT REGION HYDROGRAPHY

From the August 1976 cruise of the Discoverer (Figure 3), we have constructed hydrographic cross sections (Figures 32 to 43). These should be considered with the concurrent measurements of water velocity and the resulting transport calculations (section 2, Table 4).

Figures 32 to 34 show the section taken south of Bering Strait projected on a cross section of the Strait. Comparing this to the average late summer (20 August to 5 October) cross section of Coachman, Aagaard and Tripp (1975, Figure 31b), the eastern and shallow parts of the Strait are similar, butthe deeper and western portions were somewhat saltier and colder than average in 1976. This difference is in the direction of the early summer (5 July to 7 August) values, and may be typical.

The St. Lawrence sections (Figures 35 to 37) show very strong thermal stratification and a much less pronounced haline stratification. This may be caused by the noisy salinity record (thermal spiking): within the thermocline, the isohalines had to be estimated. Both the east and west passages have isopycnals sloping downward to the east, implying northward flow in agreement with the current measurements.

The Cape Lisburne sections (Figures 38 and 40) show some variability on a scale which is unresolved by the station spacing. The isopycnals imply northward flow near the center of the section and also near the Alaskan coast. At the southwestern end of the section the dilute, southward flowing, Siberian coastal current is clearly shown.

Figures 41 to 43 show the long section from the edge of the ice pack, south to Bering Strait. Near the ice edge, cold (< -1 C) and salty (> 33 g kg^{-1}) water resided in the bottom 15 m. This condition is normal as these cold temperatures and high salinities are characteristic of the winter Arctic shelf water. Particularly in the upper 10 m, the distributions show variability that is not fully resolved by the station spacing, in contrast to the sections across Bering Strait and near St. Lawrence Island.

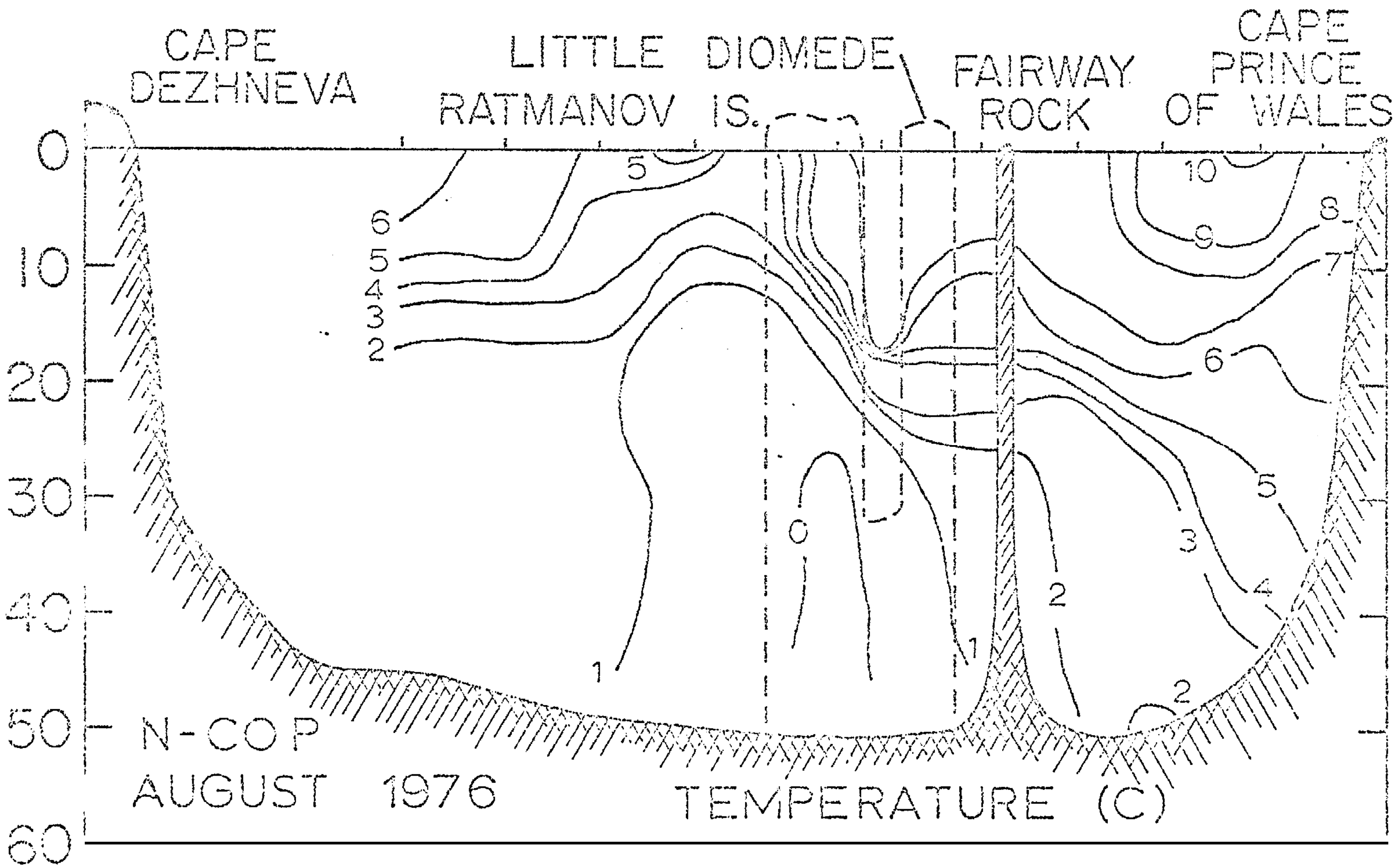


Figure 32. Temperature, Bering Strait section.

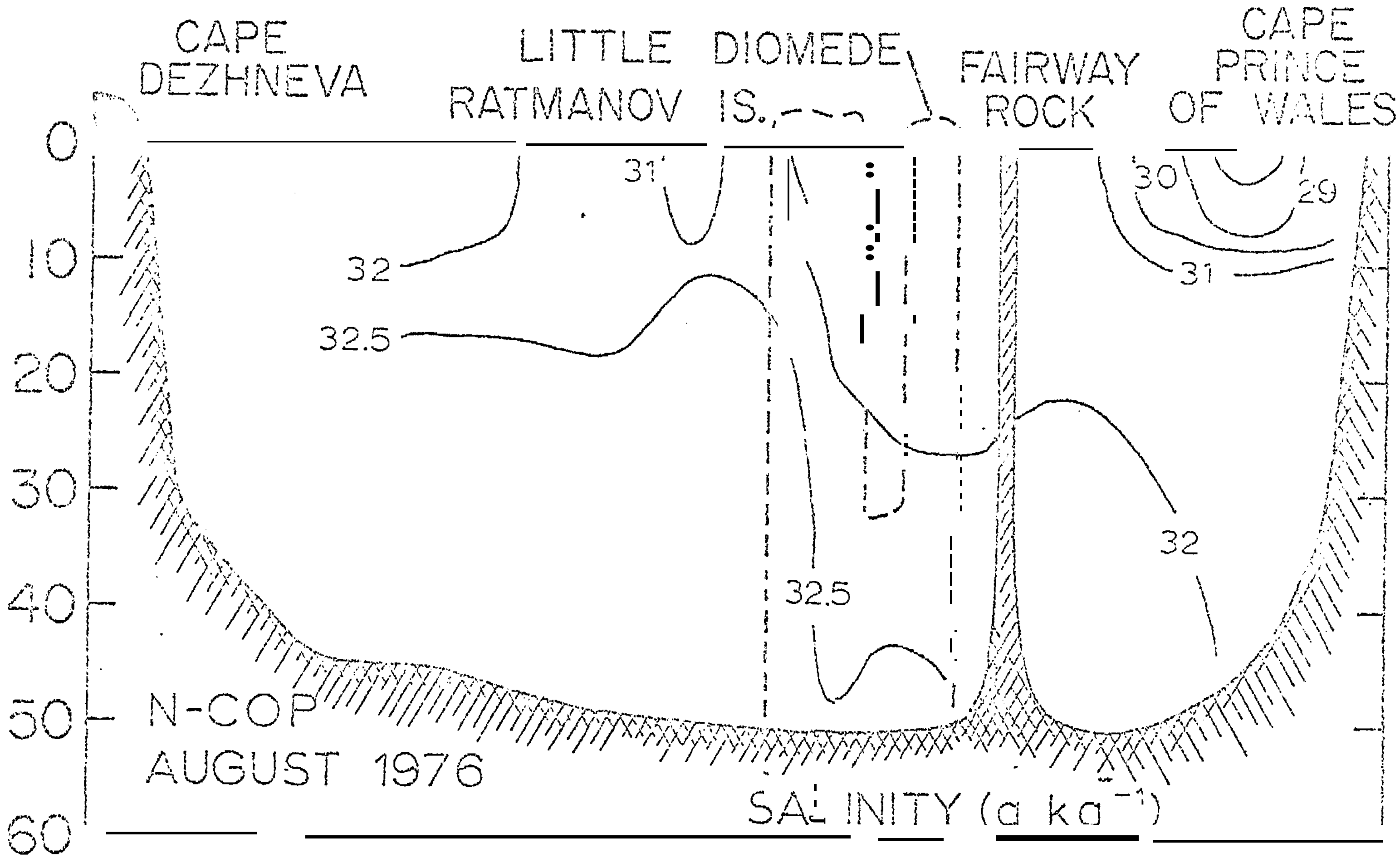


Figure 33. Salinity, Bering Strait section.

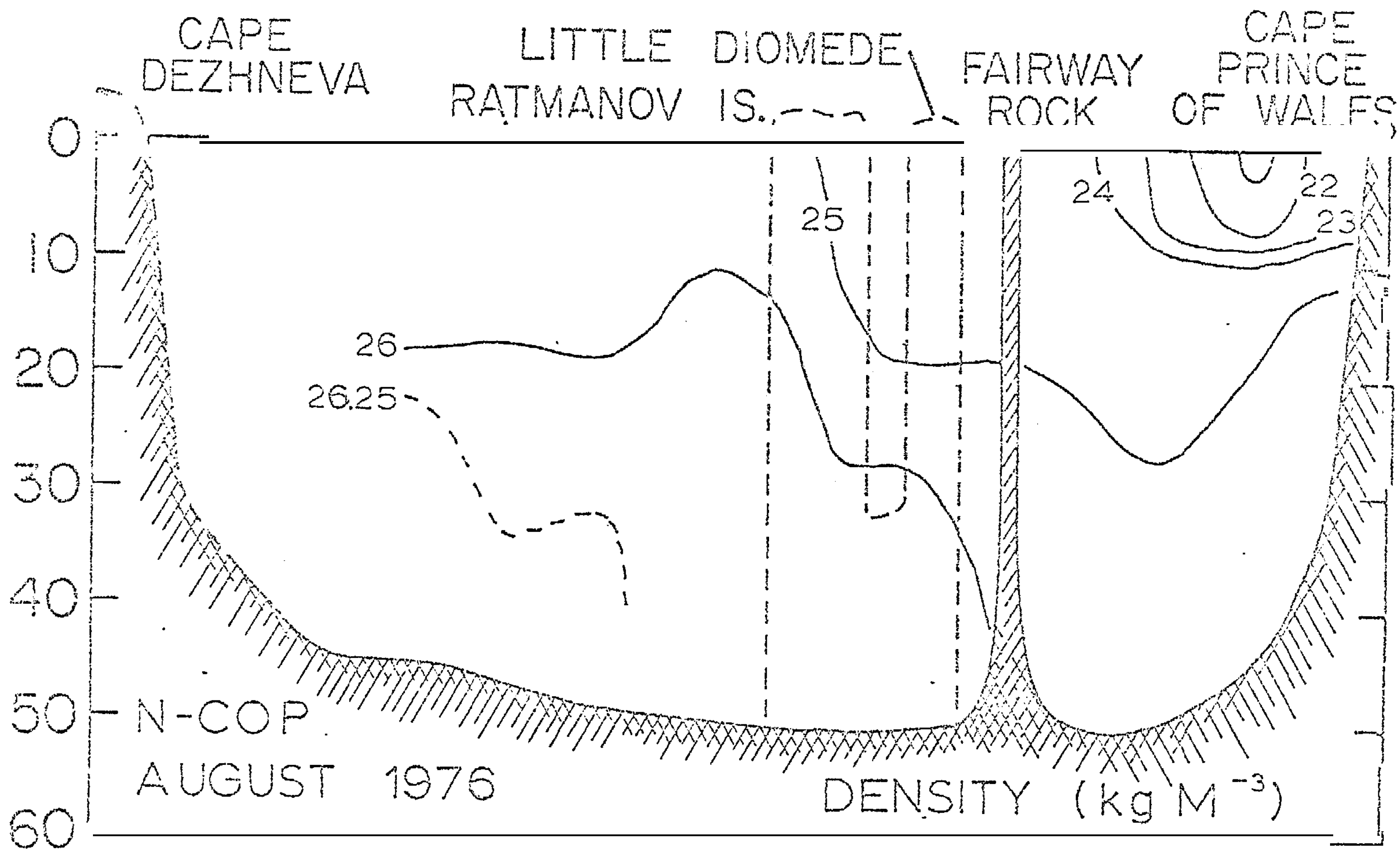


Figure 34. Density (σ_t), Bering Strait section.

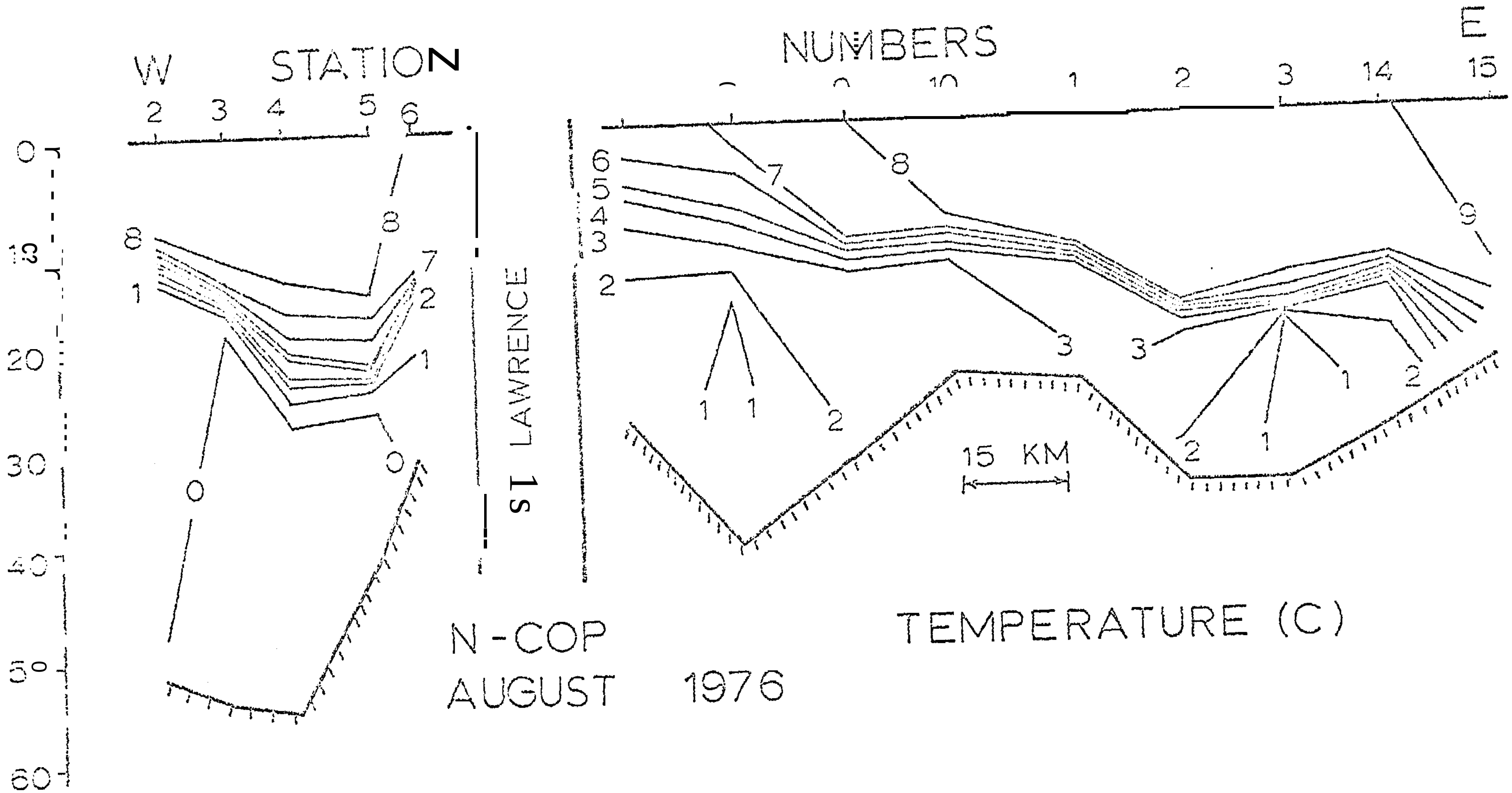


Figure 35. Temperature, St. Lawrence section.

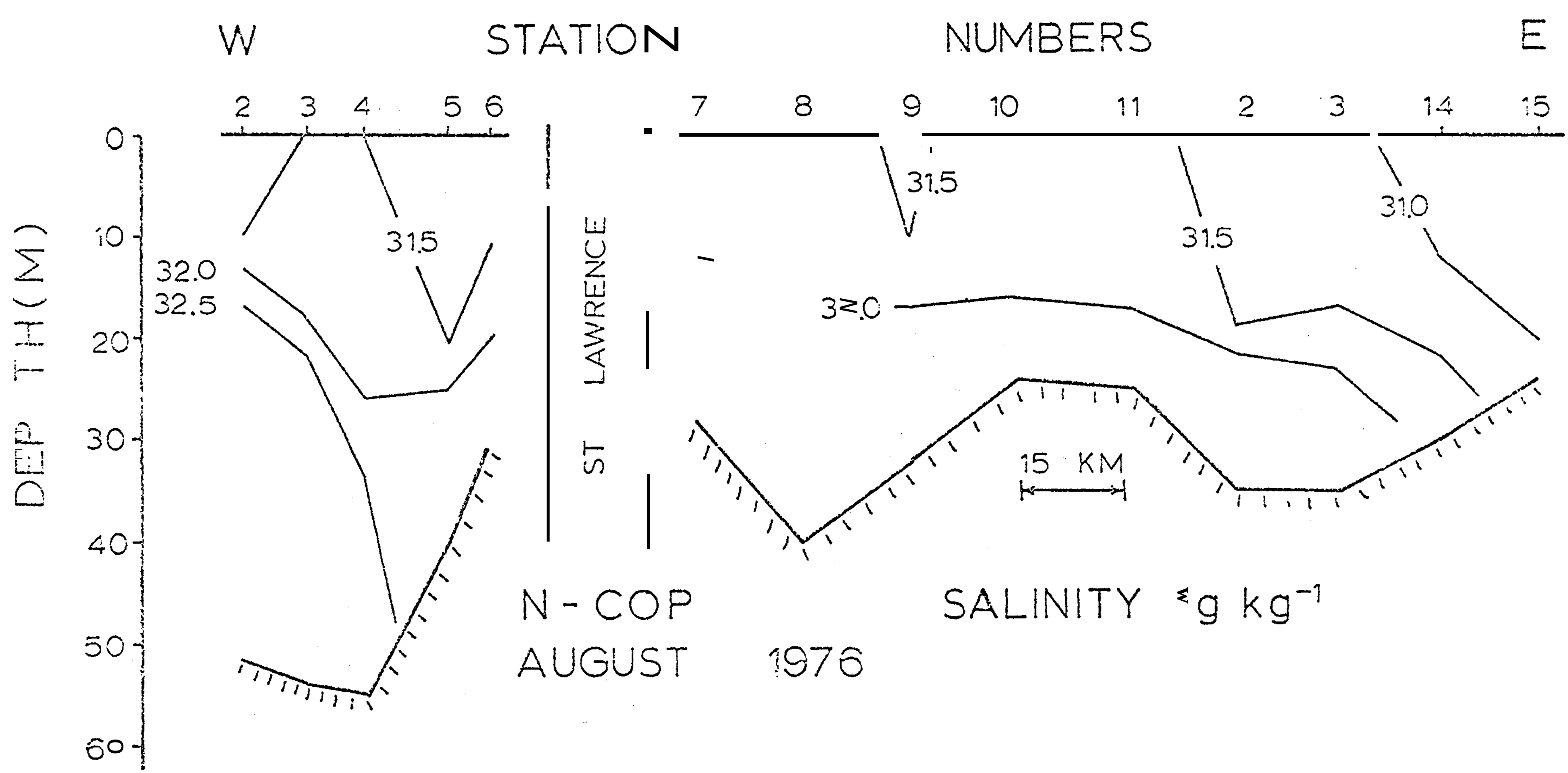


Figure 36. Salinity, St. Lawrence section.

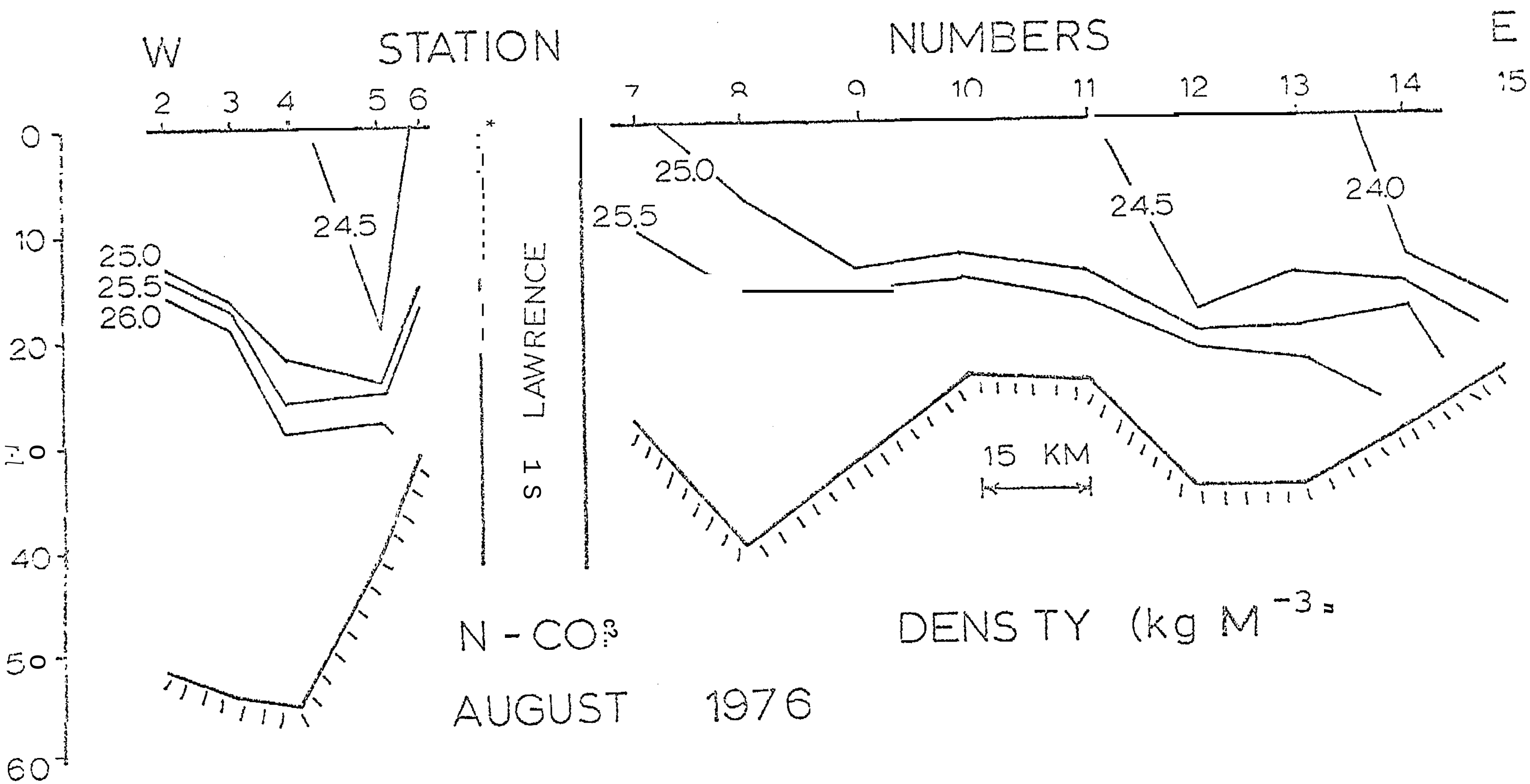


Figure 37. Density (σ_t), St. Lawrence section.

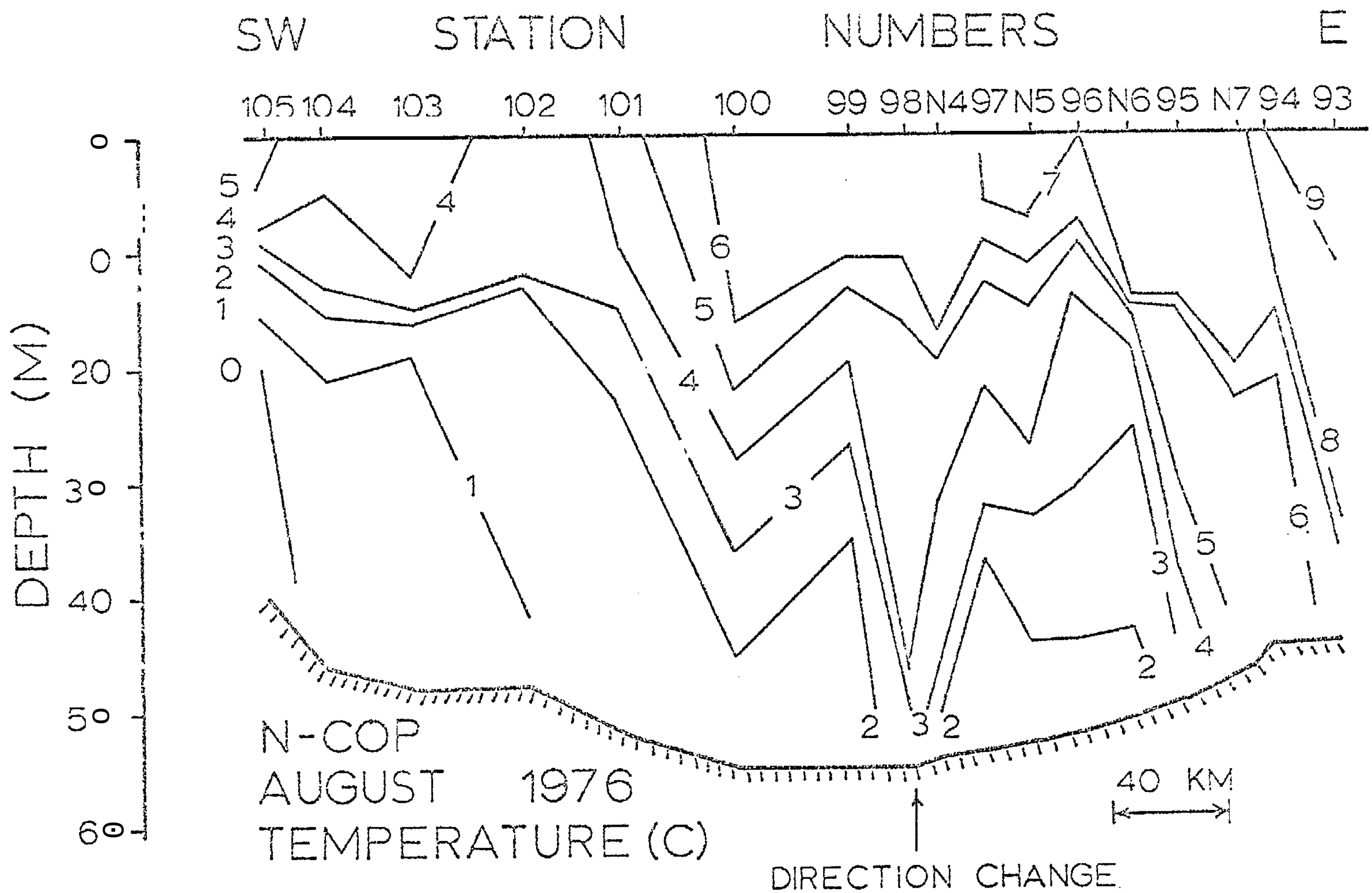


Figure 38. Temperature, Cape Lisburne section.

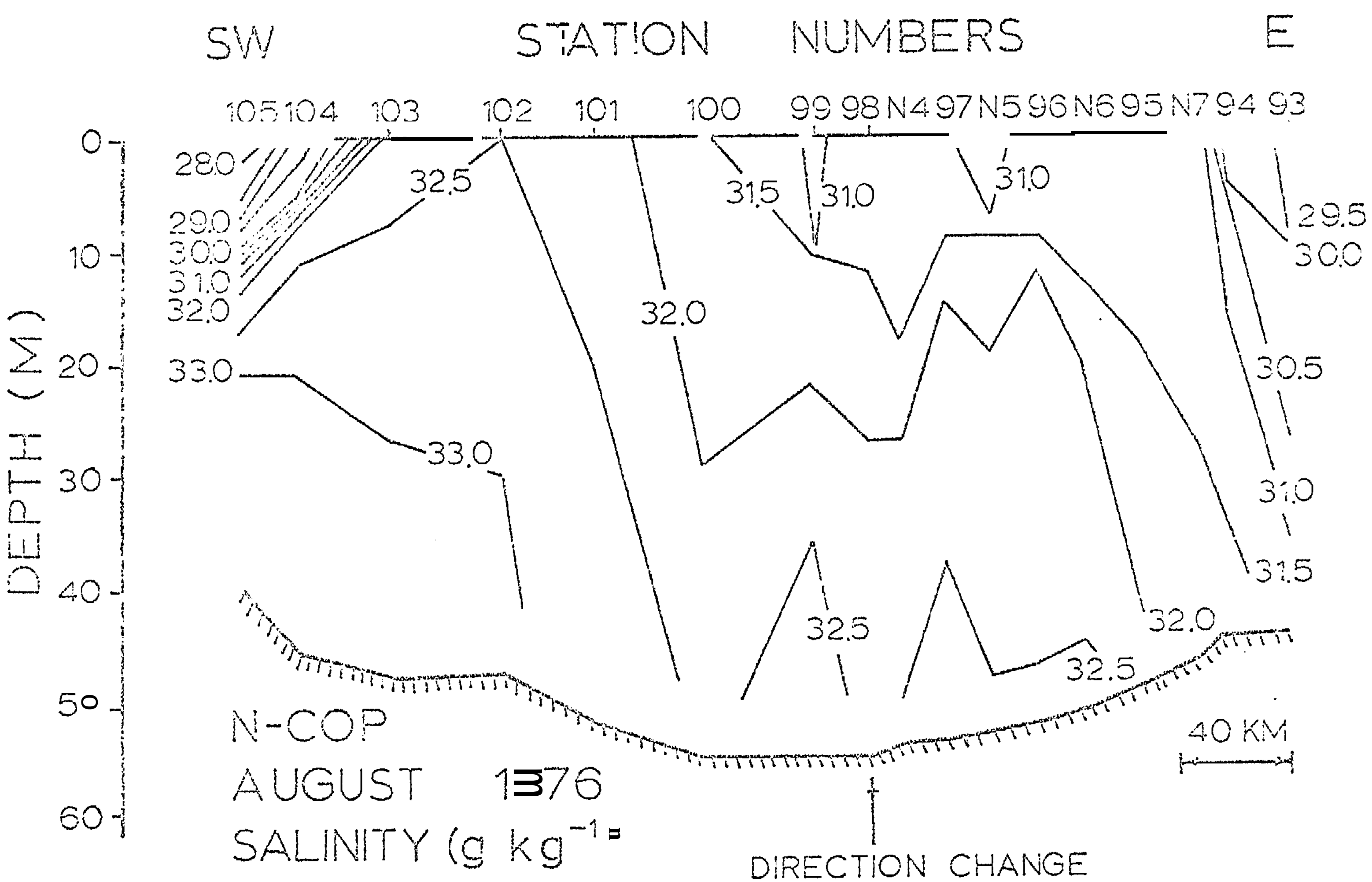


Figure 39. Salinity, Cape Lisburne section.

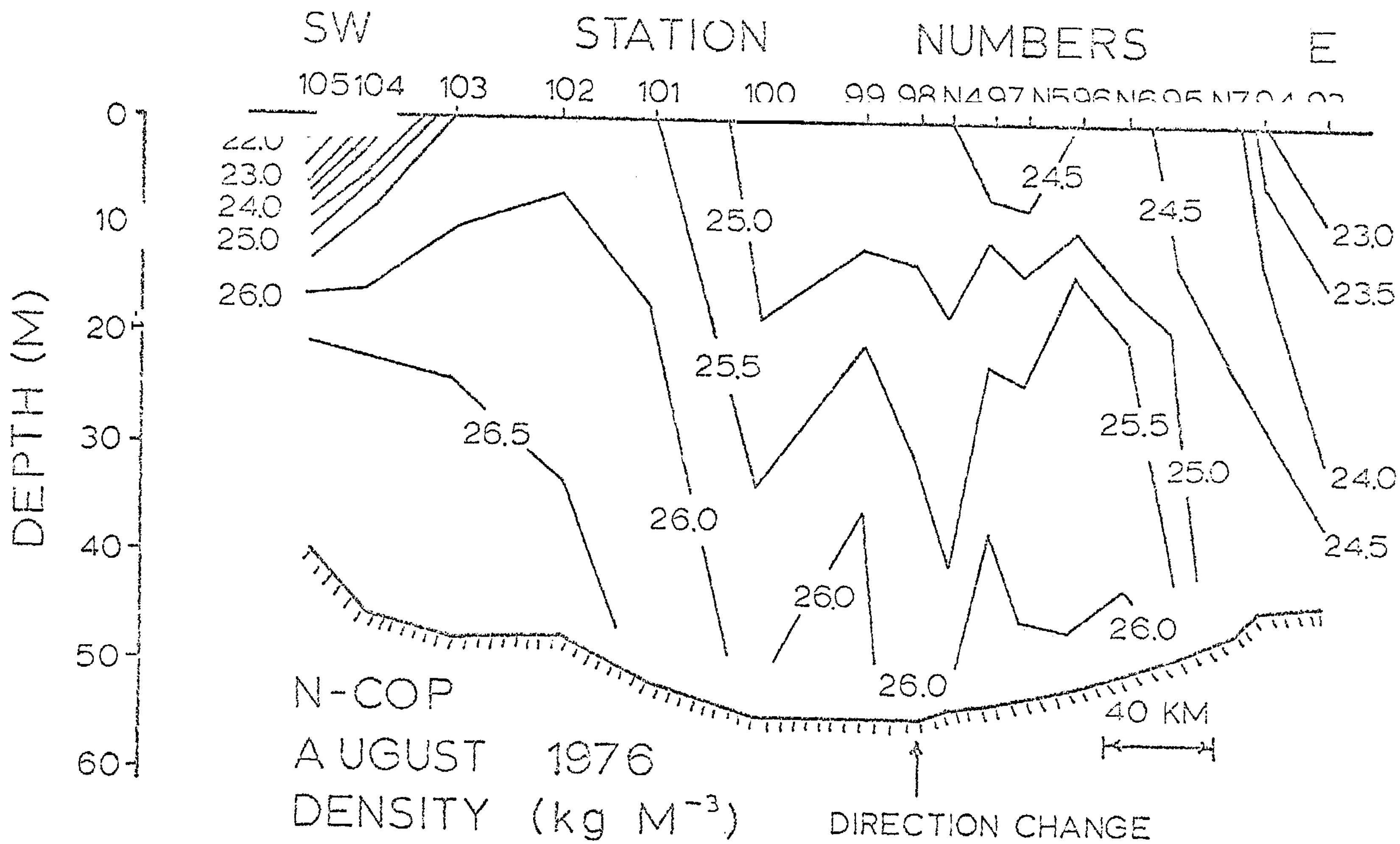


Figure 40. Density (σ_t), Cape Lisburne section.

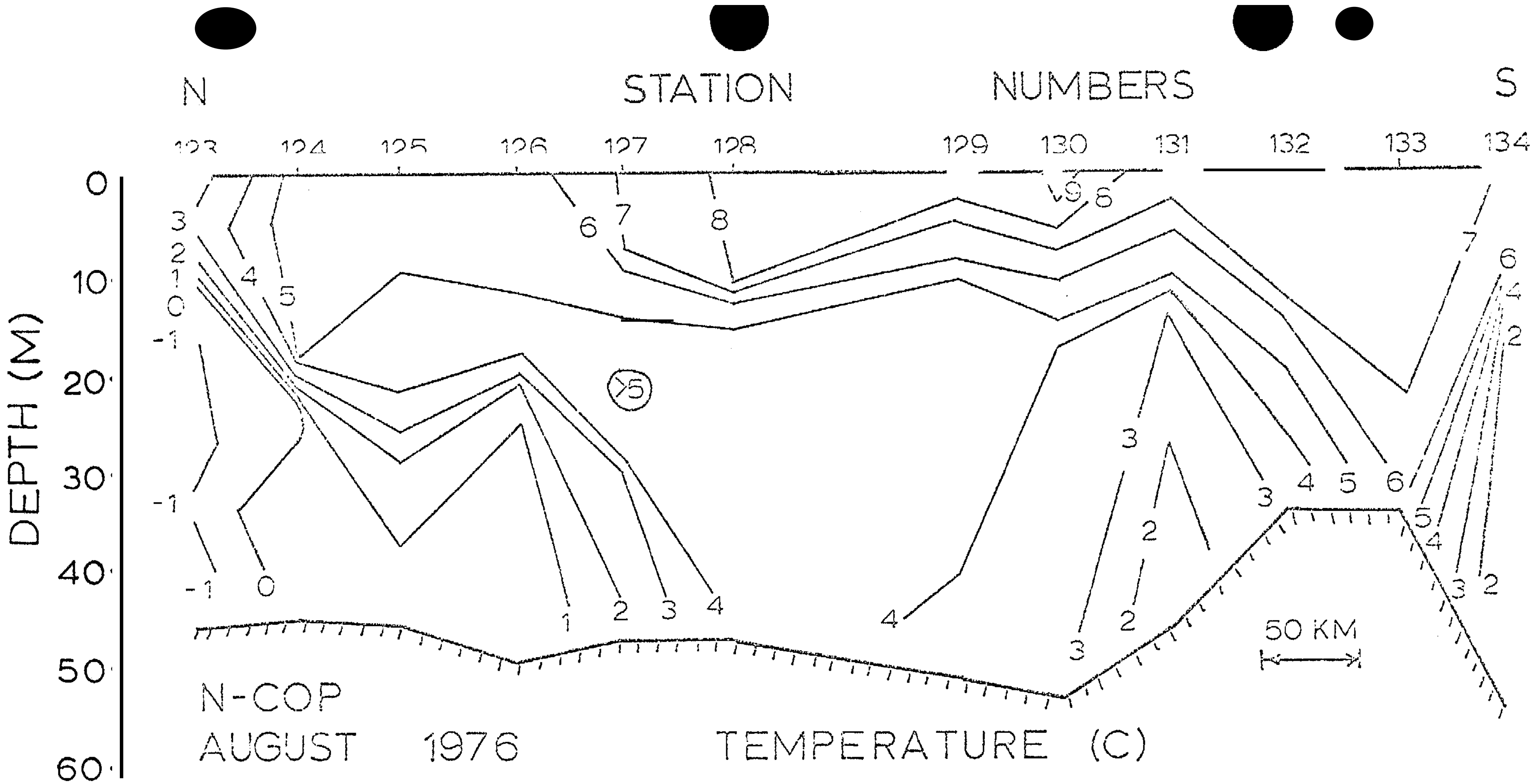


Figure 41. Temperature, ice edge to Bering Strait.

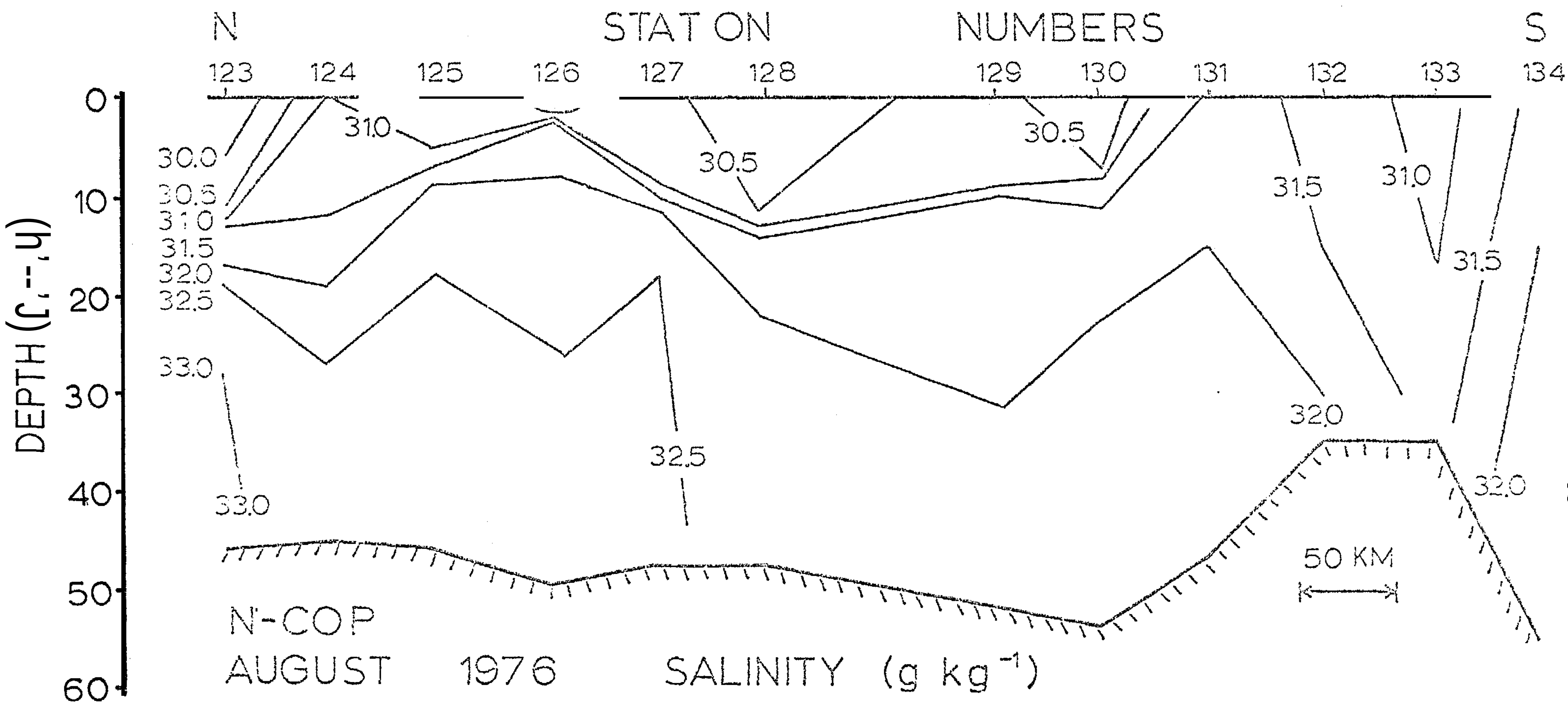


Figure 41. Temperature, ice edge to Bering Strait.

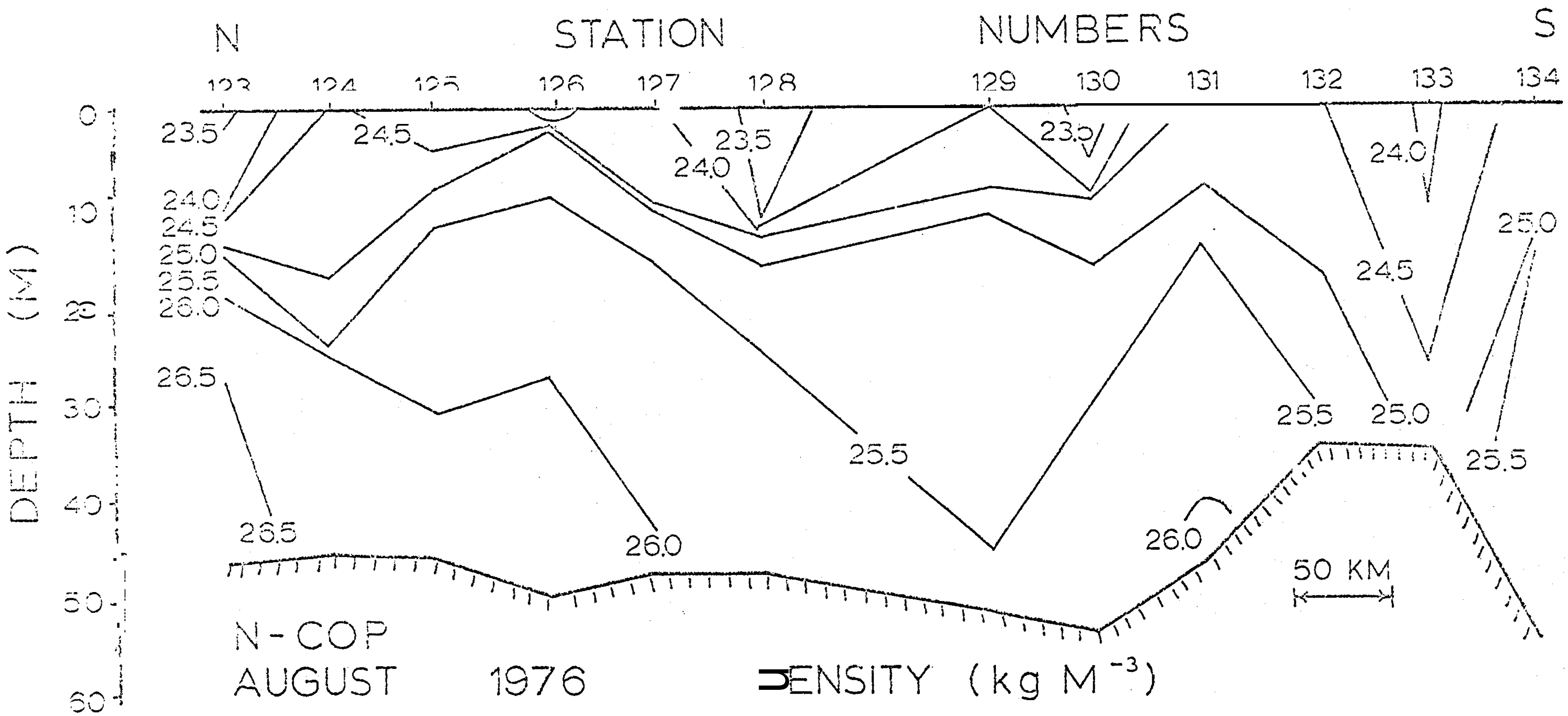


Figure 43. Density (σ_t), ice edge to Bering Strait.

VII. DISCUSSION

A. THE SEPTEMBER-OCTOBER NORTON SOUND PROGRAM

Geographic setting and morphology of Norton Sound suggest several features of the regional oceanographic processes: (1) transient wind-driven motions are large, (2) tidal motions are of only secondary importance, (3) sea-air heat and moisture exchange are dominant locally in conditioning water masses, (4) a south-north current across the mouth of the Sound may play a role in establishing mean circulation and (5) the bathymetry is important in guiding the circulation. The region has more of the character of a shallow sea than of a shelf due to its great horizontal extent, shallow depths, and lack of a shelf break. The shelf break exists, but is hundreds of kilometers to the southwest and effectively isolated from the Sound, if we consider the radius of deformation as an appropriate length scale.

The mean current measurements across the mouth of the Sound indicate a westward component of flow at each station except for the ten-hour series at N3 (Figure 16). Clearly such a flow, if steady-state, is impossible from continuity considerations, since it would result in a water level lowering within the Sound. These transports are of the proper direction and magnitude, except for station 22, to be due to surface winds. At station 22 it is necessary to consider the baroclinicity of the water column to account for the magnitudes of observed currents, but for the moment we concentrate on the wind-driven aspects. Transport at station 22was constrained by the coastline to a westerly direction, while transports farther offshore were to the right of the wind. Greater depths (stations 24 and 25) allowed a transport farther to the right of the wind than at the shallower depth (station 26) in accordance with Ekman drift *theory* (Neumann and Pierson, 1966).

Currents observed at station N3 were in marked contrast *to* those observed elsewhere in that they do not appear to be wind-driven. The lack of correlation between currents and tides for the other time-series stations suggests that tidal effects may be relatively insignificant, but we really don't know the tidal regime in sufficient detail to be able to relate events at specific locations. During occupation of this station, the wind had veered and had become more northerly than during the other measurements (Figure 18). This removal of *a* westward-directed wind stress allowed the previously established *sea* surface slope to force easterly flow throughout the water column. The distribution of longshore currents in the water column supports this (Figure 19); rather than maximum speed at the surface, as expected for a wind current, there was a subsurface maximum at 7 meters and only a slight decrease between there and the bottom. The current speed was small near the surface. Both this and the offshore near-surface flow were likely *a* response to the offshore winds. The small variation in longshore current speed with depth, except for a near-bottom decrease which was probably frictional, suggests a barotropic driving force.

Interpretation of water movement is made difficult by nonsynopticity of measurements. While a net westward flow component was observed at each of the 25-hour stations, there was a two-day break between stations 24 and 25 during which station N3 was occupied. It is possible that during this two-day period all water flowed eastward into the Sound. It is also possible that the boundary between east/west flow shifted to the north and put N3 in a typically south Sound regime; westward flow would occur only in a very narrow (15-20 km) band south of Nome.

These admittedly brief current measurements are, however, adequate to suggest that wind-driven currents play a dominant role in Norton Sound circulation. Because of shallow depths (less than half the estimated Ekman compensation depth), transports more nearly parallel the winds than in the deep ocean case where transports tend to be directed 90° to the right of the wind.

The strong pycnocline was a persistent feature of the Norton Sound water column. Measurements revealed no appreciable decoupling of currents across this feature in most cases. Only in the on-offshore component at station 22 was there a suggestion of decoupling (Figure 19); onshore flow above 10 meters was much greater (18-20 cm sec^{-1}) than below (2-3 cm sec^{-1}).

Both current and hydrographic measurements in the region just offshore from Nome revealed the presence of a strong coastal current consisting of a westward baroclinic current upon which was superposed a local wind-driven component. The baroclinic current, clearly evidenced as a band of low-density water, was restricted to within 15-20 km of shore (Figure 12) and was of uncertain east-west extent. The baroclinic component of this current was a consequence of dilution by runoff. Numerous small streams enter northern Norton Sound, particularly in the Norton Bay region. There are, however, no estimates available for freshwater input. More than sufficient freshwater enters the northern Bering Sea via the Yukon River to create such baroclinicity. Mean maximum runoff of the Yukon is on the order of 10^4 m^3 sec^{-1} (U.S.G.S. records) or on the same order as the entire flow of the coastal current during June and July, and was 5.6 x 10^3 m^3 sec^{-1} during the early portion of this fieldwork. The hydrographic data obtained in southwestern Norton Sound indicated, however, that Yukon water was not entering Norton Sound circulation in appreciable amounts at the time of this cruise (Figure 15). A small amount of Yukon water was probably entering the general circulation near Stuart Island and then moving north and west. It therefore appears that the baroclinic current was largely supported by local runoff along the north shore of the Sound.

The strongly two-layered structure is typical of shallow, near-shore regions subject to both tides and wind mixing. The upper mixed layer is due to the effects of wind, while the lower mixed layer is a result of turbulence generated by currents at the bottom. It is possible that high winds could mix the Sound completely to the bottom or that, in the absence of winds for a long period of time, the lower mixed layer could extend closer to the surface and result in effective thinning of the upper layer.

Tidal currents are responsible for the presence of a bottom mixed layer. The tides at Nome are of the semidiurnal mixed variety, with maximum tidal amplitudes on the order of 50 cm. While these might lead to significant excursion and associated currents in the western Sound, frictional damping would likely have caused attenuation of the wave by the time it reached the eastern Sound. While no measurements are available, it is probable that tides are small in the eastern Sound.

The presence of cold (< 2.5°C) near-bottom water in the eastern Sound presents an intriguing problem. A temperature–salinity plot of the waters in the Sound indicates that there was no external source for this cold water at the time of the cruise, which suggests that the cold water was most likely a remnant of water formed during the previous winter (Figure 22). That this water has persisted for some 4–5 months in a total water depth of about 20 meters and despite wind and tidal mixing and insolation suggests: (1) vertical mixing through the pycnocline was extremely small; (2) horizontal advection of bottom water into the eastern Sound was negligible; and, (3) solar insolation, particularly significant during the early summer because of 24-hour daylight, was unable to penetrate the bottom layer sufficiently to cause appreciable warming.

Neglect advection and heat sources and sinks. Assume that temperature of the bottom water at the end of the preceding winter was near the freezing point at -1.7°C, and that the temperature of the upper layer had reached 8°C by early August following a linear increase with time from early May when the ice first melted. These conditions require a vertical mixing coefficient *through* the pycno-cline of 2.5 x 10^{-2} cm^2 see-l. Though this may seem small for a vertical eddy coefficient, we believe it may be the right order for these conditions. Just wes a of Nome Coachman *et al.* (1975) estimated Kv's of order 10^{-1} where 10^8 Ewas order 200 m^{-1}. At stations in the inner sound (44,48) 10^8 E was order 2.5 x 10^5 m^{-1} over 2 to 3 m depth increments, an extreme stability. This unusually small vertical mixing may reflect abnormally mild weather during the preceding summer. Virtually no storms passed over Norton Sound during the two-month period preceding the cruise.

It is possible to estimate an advection rate using the temperature distribution in Figure 6 if we assume this distribution to be steady-state and to reflect a balance between horizontal advection and lateral diffusion. A horizontal length scale of **100** km, applied to the empirical findings of Okubo and Ozmidov(1970), yields a lateral eddy conductivity of 10^6 cm^2 see-l. Application of the method given by Proudman (1952) leads to estimates of an advection rate on the order of 1 cm see-l along the westward trending tongue of 7.0–8.5°C water. It is not clear why horizontal advection should be small in the eastern Sound. The promontories formed by Stuart Island on the south and Cape Darby on the north are apparently sufficient to deflect whatever easterly flow exists along the southern shore of the Sound to the north, preventing it from entering the eastern third. There is no sill between these promontories which might prevent interchange of the deeper waters. A cyclonic circulation, *as* suggested above, is apparently confined to the western portion of the Sound with the eastern end forming a relatively stagnant cul-de–sac.

There is, however, a water mass continuity between the inner Sound and the western part (cf. Figures 13 and 15). In the T-S diagram (Figure 44) a close association is noted between inner Sound waters through stations 42 and 43 to

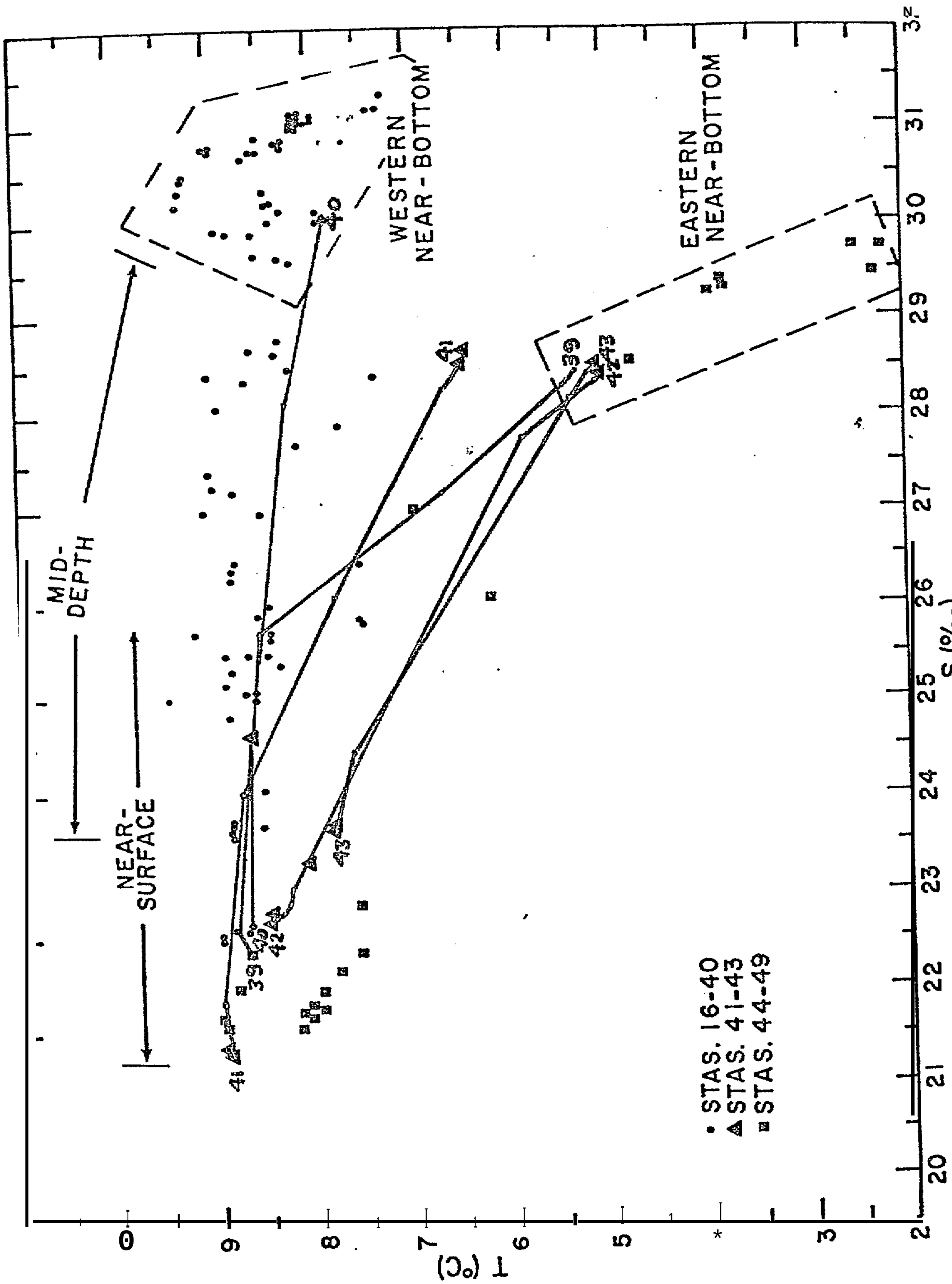


Figure 44. **Temperature-salinity characteristics** of **the water in Norton Sound during** late **September-early October** 1976. Complete **water 'ass** curves are shown for stations 39-43.

station 39. We conceive of the boundary not as one across which advection occurs, but rather a lateral diffusive flux boundary. The cyclonic circulation of the western Sound, passing north across the mouth of the inner Sound, in effect entrains some inner Sound water. We conclude that even though the inner Sound appears to be virtually isolated in the absence of strong storm conditions, and can retain relict water from the previous winter for many months, there is a slow diffusion out of the region.

Solar warming of the bottom layers might be expected. It is possible, however, that silt entering the Sound in freshwater would screen out a major portion of the solar radiation, resulting in more rapid warming of the upper layers and isolation of the bottom layer from warming influence. Silt carried by freshwater streams in this region is typically very fine and can remain suspended for long periods of time, particularly in the presence of wind mixing (personal observations and satellite photographs).

Based on the water mass distributions for 26 September-6 October, we have constructed a schematic diagram of the circulation (Figure 45). The short period current measurements do not necessarily reconcile with this scheme because of the demonstrated strong influence of local winds on the flow. The water mass properties suggest the longer-term or net circulation. With a strong and/or prolonged wind event, however, the circulation could be quite other than we have interpreted here from one data set. The circulation shown, however, may be generally representative because there were no strong wind events for at least two months prior to the survey.

The role of the northward circulation on the Bering shelf in inducing Norton Sound circulation is uncertain. Such a flow might: (1) create a south-north sea surface elevation difference across the mouth of the Sound which would then drive a circulation in the Sound as suggested for the Gulf of Maine by Csanady (1974); or (2) tend to follow bottom contours into the Sound, contributing to a cyclonic

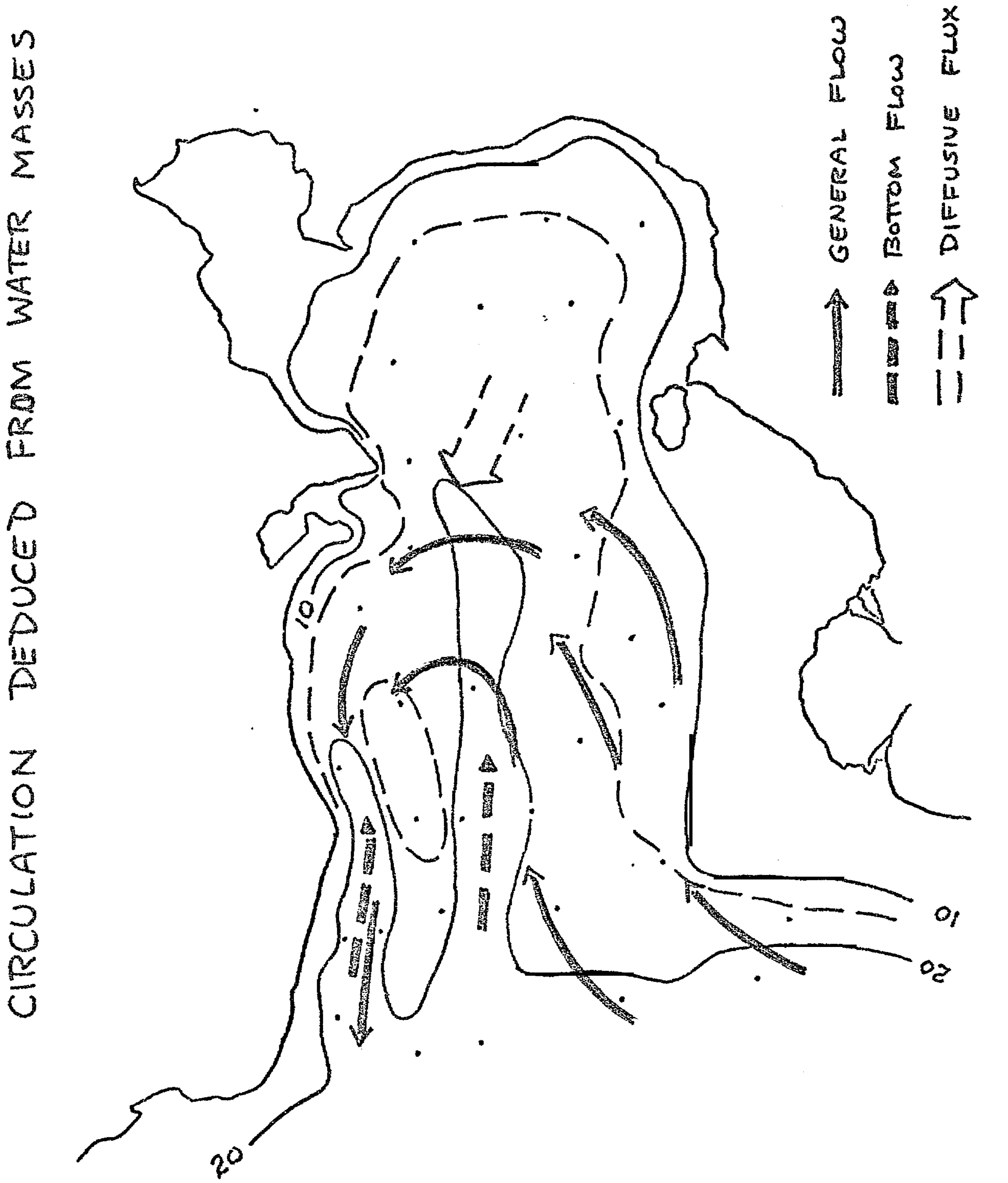


Figure 45. Schematic of circulation in Norton Sound based on September-October water mass data.

circulation there. Partial extension of this flow into the Sound was in fact suggested by northerly current components at the southern time-series stations 25 and 26 (Figure 16). This would, however, result in Yukon water entering the Sound; this was not observed. Such northerly flow would then veer to westerly at the northern coast of the Sound to satisfy both volume continuity and vorticity constraints. There was no evidence of a gyre-like flow as required by Csanady's model for the Gulf of Maine, but the current measurements would not have been adequate to define such a gyre were it present.

B. THE SEPTEMBER ANCHORED CURRENT MEASUREMENT PROGRAM

An attempt was made to apply the empirical equation of Coachman *et al.* (1975) relating transport through Bering Strait to sea-level atmospheric pressure at Nome. Daily atmospheric pressures from Nome are not available as yet, so two values were obtained by telephone from NWS Ashville, N.C. For the Bering Strait section, the predicted transport was 1.59 Sv rather than the 0.7 Sv observed. The pressure at Nome was, however, dropping rapidly at the time, suggesting non-steady conditions. Use of a sea level pressure value from Nome 18 hours later yields a predicted transport of 0.79 Sv. Coachman *et al.* noted that during periods of rapid change the correlation between Nome pressure and transport is improved by using a different time lag than the arbitrary one-day delay of the equation.

The much greater transport through the St. Lawrence Island section two days earlier appears to correlate well with the much higher atmospheric pressures of one and two days previously. Thus, we conclude that at the time of the 1976 measurements transport was northward through the system and in magnitude in agreement with previously documented flows.

C. KOTZEBUE SOUND HYDROGRAPHY

(See VI.)

D. BERING STRAIT REGION HYDROGRAPHY

(See VI.)

VIII. CONCLUSIONS

Norton Sound was characterized during field work in September-October as a strongly two-layered system. Current measurements obtained simultaneously with surface wind observations suggest that currents correlate well with the winds over time scales of about one day, but over hourly time scales they are not well-correlated. Both current measurements and temperature distribution support, qualitatively, a cyclonic water circulation in the Sound. The eastern third of the Sound formed a cul-de-sac having a sluggish circulation and low bottom temperatures due to residual water left from the previous winter. This situation may have been due in part to unusually mild summer weather during 1976, and may not be an annual feature, although the eastern Sound is certainly a lower energy region than the western portion.

The region off Nome was characterized by a 15–20 km wide coastal current system which was in part wind-driven and comprised a coastal downwelling regime, and in part baroclinic, driven by local runoff. This current was evidenced in the hydrographic structure by a low density coastal band of water, limited in east-west extent. Bottom scour off Nome suggests that. this current may be a common feature.

The entire Norton-Chukchi study region was characterized by a net. northward water transport on the order of 10^6 $m^3 s^{-1}$, measured values being from 0.70 to 1.85×10^6 m^3 s^{-1}. This flow was in agreement with previous measurements, suggesting that regional water transport was not abnormal during late summer 1976.

In analogy with Norton Sound, Kotzebue Sound was highly stratified. Within the upper layer, there appeared to be a cyclonic circulation in the western half of the Sound. Relict water from the winter showed that the lower layer and eastern half of the Sound were nearly stagnant: pollutant dispersion there would be slow.

IX. NEEDS FOR FURTHER STUDY

At this stage of the Norton-Chukchi oceanographic c program, with the year-round current arrays still deployed and summer 1977 field work still to be carried out, a list of detailed needs is somewhat premature. Nonetheless, it is possible to list several items which are not being addressed via the present program.

1. Winter oceanographic stations are needed in the northern Bering Sea to address seasonal variations. The winter 1977 field program obtained such data in the Chukchi Sea, but not in the Bering Sea (see Section X below). A winter program should seek to verify hypotheses concerning convective mixing and determine the effects of seasonal. ice cover upon circulation. It is planned to deploy 3 moored current meter arrays in the St. Lawrence Island-Norton Sound region overwinter 1977-78 to address these problems.
2. Lagrangian drift studies, such as those using the satellite-tracked drifters, are needed to define the circulation patterns through the channel east of St. Lawrence Island and into western Norton Sound.
3. Virtually no data are available from inside the 6 fm (11 m) contour off the Yukon delta or into the Yukon estuary itself. In consideration of the apparently weak-circulation in Norton Sound and the consequent possibility that a contaminant might remain off the Yukon mouth for some time, it is essential that information be acquired on the Yukon estuary, its dynamics and general nature.
4. Detailed studies are needed to determine the path and dynamics of the Yukon River plume. This plume, despite its probable prominence (projected from discharge figures), was not located during summer 1976 field work. A frontal zone study such as described for the Connecticut River plume by Garvine (1977) would be a suitable approach.

5. More closely-spaced stations, including more coverage in shallower water, are needed in Kotzebue Sound. It is important to define the extent of the water which remains in place during the summer, and also to determine how the summer weather affects this water and the circulation. This need will be addressed by work funded for summer 1977.

6. A closely-spaced hydrographic survey is required north of the Bering Strait to properly define the small-scale baroclinic structure suggested by the sections taken north of Bering Strait. This will be carried out, using available funds, during summer 1977.

In addition to these specific points, it is highly probable that analysis of the data to be retrieved from the year-round moorings during late summer 1977, in conjunction with new oceanographic cruise data to be obtained over that period, will raise new questions about the region.

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XII. SUMMARY OF FOURTH QUARTER OPERATIONS: N-COP

University of Washington

Department of Oceanography

Seattle, Washington 98195

Preliminary Report

University of Washington Participation in

NOAA UH-IH Helicopter Cruise W-26

Norton Sound/Chukchi Oceanographic Processes

30 January - 2 March 1977

by

Richard B. Tripp

NOAA Contract 03-5-022-67 TA 1

Approved by:

L. K. Coachman, Professor
Principal Investigator

K. Aagaard, Res. Assoc. Professor
Co-Principal Investigator

Francis A. Richards, Professor
Associate Chairman for Research

REF : M77-32

NORTON/CHUKCHI OCEANOGRAPHIC PROCESSES

1. Objectives

This cruise was to accomplish the winter physical oceanographic survey of Norton Sound, Kotzebue Sound, and the Chukchi Sea. This is a joint program between NOAA/PMEL and the University of Washington.

This program addresses the following questions: 1) verification of the fluctuations in the northward transport; 2) temporal and spatial description of the bifurcation of north flow which occurs off Point Hope; 3) provide data on temporal and spatial scales of eddies ubiquitous to the system; and 4) define the circulation of Norton and Kotzebue Sounds.

These data, when completed, will: 1) provide comprehensive environmental data on the Alaska Outer Continental Shelf; 2) define the probable ecological impact of petroleum exploration, production, storage, and transshipment on the continental shelf; and 3) refine our understanding of key ecological dynamic processes.

2. *Narrative*

The scenario of events is *as* follows:

30 January 1977
Clark Darnall and Jim Swift arrive Nome. Stayed in ADF&G bunkhouse. Quite inadequate for longer than overnight accomocation. No running water.

31 January 1977 Weather: winds NE 35 + 50.
R. Tripp arrives Nome. NOAA helicopter N57RF with Lt. D. Winter and G. Feld arrives Nome. The helicopter is expected to be down for maintenance for **a few clays.** Lodging is now at the Golden Nugget Hotel.

1 February 1977 Weather: winds NE 30+
Weather forecast poor. Large amount of open water off Nome. Helicopter down.

2 February 1977 Weather: winds NE 30+
Weather still poor. Helicopter down.

3 February 1977 Weather: winds NE 15, light snow.
Helicopter down. Parts arrived from Fairbanks in PM.

4 February 1977 Weather: winds ENE 15, blowing snow, light rime icing.
1100 BST 'Helicopter repaired and test flight completed.
1237 EST Helicopter recco flight east and west along the coast from Nome. A large amount of open water ∿20 miles off the coast.
1400 BST Recco flight in fixed wing aircraft to cover Norton Sound. The results of which indicate that there is little" suitable ice for landing present in Norton Sound. The only ice present is located in the southern half of Norton Sound.

5 February 1977 Weather: wind shifting ESE 15.
Blowing brash ice back towards Nome. However, ice not thick enough to fly over or land on.
1100 Helicopter recco along the coast. It is now obvious that the ice is not thick enough to accommodate the proposed helicopter survey. We are therefore going to attempt to use an 18′ aluminum boat to take some stations off Nome .

6 February 1977 Weather: snowing, poor visibility, winds W 13-17.
Cancelled boat attempt.

7 February 1977 Weather: fog, winds light.
Decided to cancel small boat venture as there is now enough slush ice to foul up motors. We are planning to transfer the operation to Kotzebue.

8 February 1977 Weather: cloudy, winds NNE 11, temp. -4°C.
0855 BST Helicopter departed for Kotzebue. Weather marginal at Kotzebue. Turned back due to icing and low clouds.
1120 BST Occupied CTD station on shore fast ice near Nome.
1300 BST Returned Nome.

9 February 1977 Weather: cloudy.
0910 BST Helicopter departed for Kotzebue. Weather bad 80 miles from Kotzebue.
1146 BST Returned Nome.

10 February 1977 Weather: cloudy, freezing drizzle.
Clark Darnall returned to Seattle. Weather marginal between OME/OTZ. Helicopter mechanic ill. Pilot has decided not to fly to Kotzebue due to weather.

11 February 1977 Weather: clear, temp. -3°C, light winds.
Winter and Feld departed for Kotzebue in helicopter N57RF. Tripp and Swift departed for Kotzebue on Wien Alaska flight.

12 February 1977 Weather: clear, temp. -28°C, winds calm.
1257 BST Departed Kotzebue for Kotzebue Sound survey area.
1620 BST Returned Kotzebue after occupying stations 2 and 3. A total of 13 hours of flight time was logged.

13 February 1977 Weather: partly cloudy, temp. -29°C, winds 295/15.
0919 BST Departed Kotzebue for survey area.
1545 BST Returned Kotzebue after occupying stations 4 through 9. A total of 2.0 hours of flight time was logged.

14 February 1977 Weather: cloudy, temp. -28°C, winds calm.
1025 BST Departed Kotzebue for survey area.
1538 BST Returned Kotzebue after occupying stations 10 through 14. A total of 2.3 hours of flight time was logged.

15 February 1977 Weather: cloudy, temp. -18°C, winds 010/6.
0955 BST Departed Kotzebue for survey area.
1600 BST Returned Kotzebue after occupying stations 15 through 23. A total of 2.3 hours of flight time was logged.

16 February 1977 Weather: cloudy, temp. -8°C, winds 100/15.
1015 BST Departed Kotzebue for survey area.
1537 BST Returned Kotzebue after occupying stations 24 through 28. A total of 2.5 hours of flight time was logged. This completed the survey of Kotzebue Sound (Fig. 1). Hydrographic station information is listed in Appendix A.

17 February 1977
Helicopter undergoing maintenance check. J. Swift had his sprained hand checked at hospital.

18 February 1977
0947 BST R. Tripp and D. Winter departed Kotzebue in fixed wing aircraft for recco flight of Cape Lisburne area.

Cape Krusenstern area: fresh leads and cracks. Ice was quite broken.

South Pt. Hope: general ice thickness 1-2'. Some 2'+. 7/8 oktas coverage. Some fairly large leads running E-W.

Line NW from Pt. Hope: general ice thickness 1-2' for 60 miles. Then ice thickness 2'+ to 120 miles and less broken up. some fresh leads running E-W.

120 mile point East to Cape Lisburne: same general pattern.

1405 BST Returned Kotzebue. A total of 4.3 hours of flight time was logged.

19 February 1977 Weather: overcast, snow, wind SW 20.
Salinity determinations. Packed all equipment for shipment to Cape Lisburne.

20 February 1977
Awaiting arrival of NARL twin otter for transport to Cape Lisburne.
1425 BST Winter and Feld departed Kotzebue in helicopter for Cape Lisburne.
1510 BST Helicopter returned Kotzebue due to severe icing conditions.

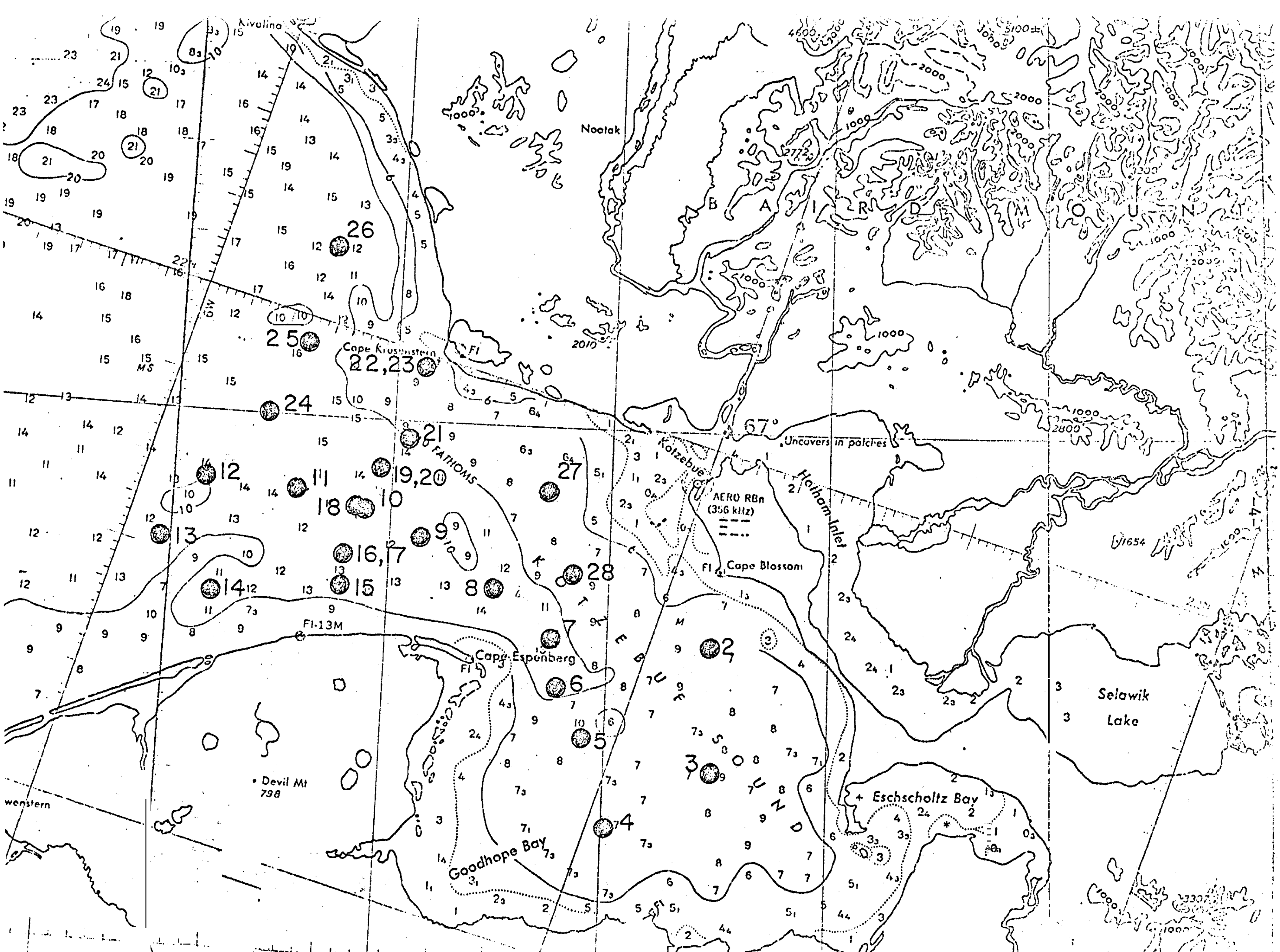
21 February 1977
Winter and Feld departed Kotzebue in helicopter and flew to Cape Lisburne. We are still waiting arrival of twin otter.

22 February 1977
Weather at Cape Lisbu-me and Barrow poor. No twin otter flight today.

23 February 1977
Helicopter N56RF (Barnhill and DeHart) arrived Cape Lisbume from Barrow.

24 February 1977 Weather: cloudy, winds SW 10.
1500 BST Tripp and Swift departed Kotzebue in NARL twin otter 127RL with all instrumentation and equipment.
1615 BST Arrived Cape Lisburne.

25 February 1977 Weather: overcast, visibility 1 mile, winds E 15.
Attempted to leave Cape Lisburne for the survey area but weather prevented us from leaving the area.



Kivalina
Nootak
Kotzebue
Hotham Inlet
Uncovers in patches
AERO RBn (356 kHz)
Cape Blossom
Cape Krusenstern
FATHOMS
Cape Espenberg
Fl-13M
Devil Mt 798
Goodhope Bay
Eschscholtz Bay
Selawik Lake
KOTZEBUE SOUND
BAIRD MOUNTAINS
67°

Figure 1

26 February 1977 Weather: cloudy, temp. -26° C, wind 120/9.
0926 AST Departed Cape Lisburne in helicopter N57RF (Winter and Feld) for survey area. Two Air Force personnel accompanied us on this trip (Fig. 2). Helicopter N56RF (Barnhill and DeHart) remain at Cape Lisbume in reserve.
1730 AST Returned Cape Lisburne after occupying stations 29 through 34. A total of 3.0 hours flight time was logged.

27 February 1977 Weather: partly cloudy, temp. -21°C, wind 140/9.
1000 AST Departed Cape Lisburne in helicopter N57RF (Winter and Feld) plus one Air Force person. Polars were sighted 23 miles and 35 miles west of Cape Lisbume.
1545 AST Returned Cape Lisburne after occupying stations 35 through 37. A total of 2.5 hours flight time was logged.

28 February 1977 Weather: partly cloudy, temp. -28°C, wind 100/6.
0954 AST Departed Cape Lisbume for Cape Beaufort area in Helicopter N57RF (Winter and FeId) and 1 Air Force person. Open water and light pancake ice from the shore fast ice to 70 miles normal to the coast prevented any landings. After taking one station we returned to the Cape Lisburne area.
1415 AST Returned Cape Lisbume after occupying stations 38 through 40. A total of 2.5 hours flight time was logged.

1 March 1977 weather: cloudy, temp. -33°C, winds calm.
0919 AST Departed Cape Lisburne in helicopter N57RF (Winter and Feld). For reaching the far end of the survey area the second auxiliary fuel tank was installed. Helicopter N56RF on standby to bring us fuel if necessary.
1710 AST Returned Cape Lisburne after occupying stations 41 through 46. A total of 3.6 hours of flight time was logged. This completed our survey off Cape Lisburne

2 March 1977
1428 AST Helicopters N56RF and N57RF departed Cape Lisbu-rne and flew to Barrow.
1655 AST R. Tripp and J. Swift departed Cape Lisburne in NARL C117 with all instrumentation and equipment
1930 AST Arrived Barrow.

Ice conditions encountered in the survey areas were as follows:

Norton Sound

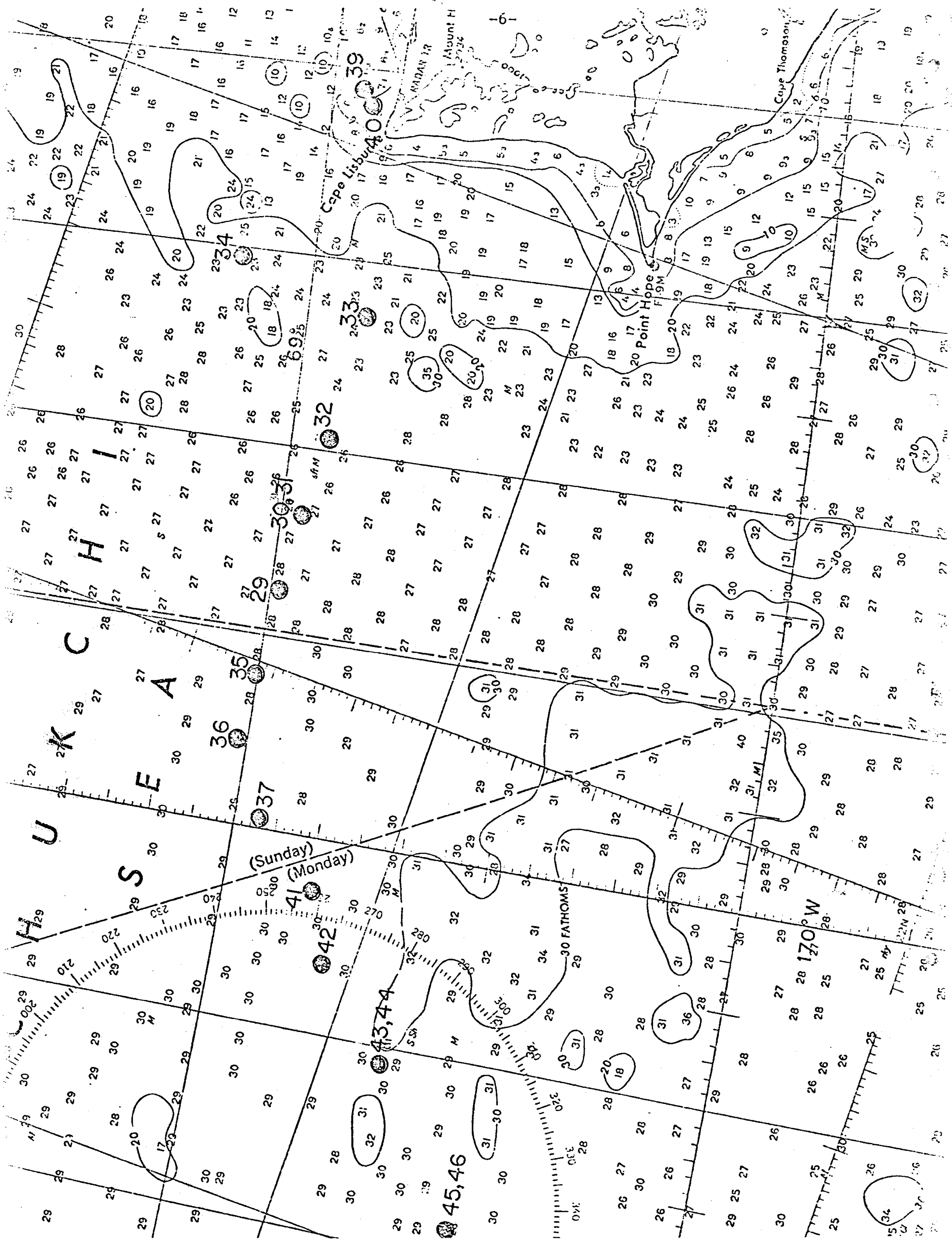
∿4/8 oktas coverage. Mostly new ice and young ice. Large amount of open water.

Kotzebue Sound

∿7/8 oktas coverage. First year ice 3-4′ thick off Kotzebue and in the shallower head of the Sound (< 7 fathoms). A mixture of young ice and first year ice off Cape Espenberg gradually changed to mostly new and young broken ice off Cape Krusenstern. There was more open water present near Cape Krusenstern than any other part of the Sound.

Cape Lisburne Area

The shore fast ice varied from 1-4 miles from Cape Lisbume to Cape Beaufort. A large amount of open water with new-ice forming extended 70 miles in an arc 70 miles from Cape Beaufort to Cape Lisburne.


CHUKCHI SEA
Cape Lisburne
Point Hope
Cape Thomson
(Sunday)
(Monday)
30 FATHOMS
170° W

West of Cape Lisburne

There was a large area of open water extending from Cape Lisburne westward for ~6 miles. This condition was quite normal as the winds were generally eastward during the survey period.

Longitude 166°45'1?

New ice which had been quite broken up. There were many leads present.

Longitude 167°01'W

A mixture of new, young and first year ice. Several leads in the area. The area was quite broken up and ridged.

Longitude 167°14'W

Mostly new and young ice with occasional pieces of first year ice. The area was quite broken up.

Longitude 167°56'W to 168°43'W

Mostly young and first year ice. The young ice was quite broken up and rafted.

Longitude 169°10'W to 169°56'W

Mostly first year ice. Several pieces of old ice in the area. A few small leads present. The area was quite compact and not as broken up as it was eastward of here.

Longitude 170°20.8'W to 171°49.4'W

Mostly compact first year and old ice. A few small leads present.

3. *Methods*

CTD casts were taken on each station utilizing a Plessey Model 9400 profiling system with a redesigned sensor package capable of permitting its deployment through an eight-inch auger hole. 110V power was supplied by a 2½ KW Onan portable generator. This operation worked quite satisfactorily out of the UH-IH helicopter. The data were stored on 7-track magnetic tape for reduction ashore. In order to determine field correction factors for the conductivity and temperature sensors, a water sample and temperature measurement were obtained from a Nansen bottle one meter above the sensors.

Salinity samples were analyzed at Kotzebue and Barrow utilizing a Hytech Model 6220 portable salinometer S/N 4917.

4. *Personnel*

R. B. Tripp	Principal Oceanographer	University of Washington
C. H. Darnall	Oceanographer	University of Washington (1/30-2/10)
J. Swift	Graduate Student	University of Washington
Lt. Don Winter	Pilot N57RF	NOAA
G. Feld	Mechanic N57RF	NOAA
Lt. Mike Barnhill	Pilot N56RF	NOAA (2/23-3/22)
R. DeHart	Mechanic N56RF	NOAA (2/23-3/22)

Acknowledgments

Mr. Feld and Lt. Winter's assistance in the collection of the data was greatly appreciated. The logistics and accommodations arranged for us by the Fairbanks project office were quite adequate. Captain Doug Dugan of the National Guard at Nome, Mr. Joe Walsh at Kotzebue, and. Major Eugene Culp USAF, Commander at Cape Lisburne and many others greatly assisted us and made us feel quite welcome. My thanks also go to the NARL flight operations who supplied us with fuel and transport when necessary.

APPENDIX A

CONS EC. NO.	DATE/TIME GMT 1977	LATITUDE N	LONGITUDE W	STD DEPTH M	WATER DEPTH M
		Norton Sound			
1	08-ii-2221	64-28.8	165-21.4	7	7
		Kotzebue Sound			
2	13-ii-0059	66-36.0	162-30.1	12	13
3	0205	66-21.7	162-30.0	10	11
4	2113	66-14.9	162-59.6	11	12
5	2213	66-25.9	163-06.3	13	14
6	2302	66-30.8	163-12.4	16	17
7	2354	66-36.4	163-17.1	22	23
8	14-ii-0053	66-41.5	163-31.7	21	22
9	0153	66-47.0	163-51.3	18	19
10	2219	66-50.4	164-07.8	22	23
11	2305	66-51.2	164-26.5	21	22
12	2355	66-53.0	164-49.4	23	24
13	15-ii-0046	66-44.9	165-01.6	20	21
14	0130	66-39.3	164-45.6	16	17
15	2i49	66-39.9	164-12.1	14	15
16	2228	66-45.1	164-10.8	19	20
17	2235	66-45.1	164-10.8	19	20
18	2318	66-50.7	164-08.5	22	23
19	2358	66-54.9	164-02.3	23	24
20	16-ii-0008	66-54.9	164-02.3	23	24
21	0052	66-57.9	163-53.7	19	20
22	0152	67-05.7	163-51.9	15	16
23	0200	67-05.7	163-51.9	15	16
24	2204	67-00.2	164-32.8	26	27
25	2319	67-07.9	164-24.1	27	28
26	17-ii-0003	67-19.4	164-16.3	22	23
27	0118	66-52.8	163-16.1	12	13
28	0158	66-43.6	163-09.9	13	14

Appendix A (cent'd)

CONSEC. NO.	DATE/TIME GMT 1'377	'LATITUDE N	LONGITUDE W	STD DEPTH M	WATER DEPTH M
		Cape Lisburne Area			
29	26-ii-2031	68-59.0	168-43.1	51	52
30	2133	68-57.1	168-21.2	48	49
31	2149	68-57.1	168-21.2	48	49
32	2306	68-54.8	167-56.2	47	48
33	27-ii-0015	68-53.2	167-14.2	42	43
34	0246	69-07.9	167-01.3	44	45
35	2101	69-00.3	169-10.4	49	50
36	2235	69-01.3	169-31.2	49	50
37	28-ii-0002	68-56.6	169-56.0	52	53
38	2055	69-03.4	164-09.4	10	11
39	2257	68-57'.0	166-08.4	10	11
40	2348	68-56.0	166-10.4	10	11
41	01-iii-2053	68-49.0	170-20.8	53	54
42	2203	68-46.6	170-38.2	52	53
43	2309	68-37.7	171-03.6	6	50
44	2357	68-37.7	171-03.6	49	50
45	02-iii-0051	68-25.0	171-49.4	48	49
46	0102	68-25.0	171-49.4	47	48

APPENDIX 1

Estimate of Funds Expended
by University of Washington
to 28 February 1977

TOTAL ALLOCATION (6/1/75-9/30/77)			**$204,500**
A.	Salaries - faculty, staff and students	7,839	
B.	Benefits	764	
C.	Expendable Supplies & Equipment	9,096	
D.	Permanent Equipment	19,811	
E.	Travel	4,752	
F.	Computer	3,825	
G.	Other Direct Costs	1,961	
H.	Indirect Costs .	3,433	
TOTAL EXPENDITURES			51,481
REMAINING BALANCE			$153,019

Underwater Meters

Ocean Currents Studied

NOAA scientists are taking the first systematic look at how ocean water moves beneath the Bering Sea ice pack.

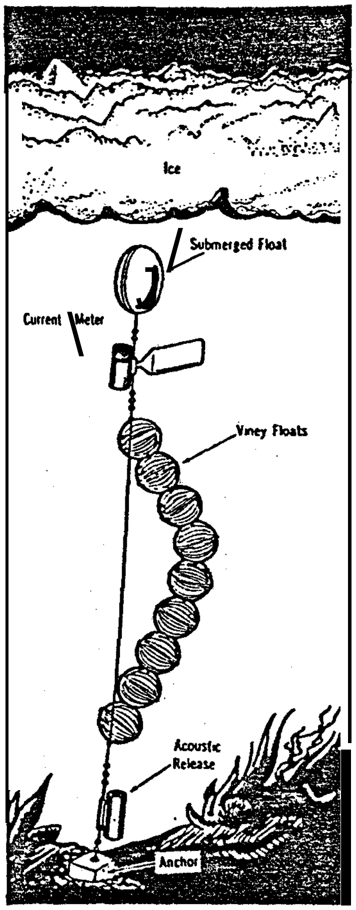
The unique measurements being mad e by submerged current meters are part of a sub-Arctic study by oceanographers with the Pacific Marine Environmental Laboratory in Seattle, and with the University of Washington.

According to Robert Charnell, the NOAA oceanographer leading the current study, little is known of water movement beneath the northern ice pack-or how water would transport oil spilled into the sub-Arctic marine environment.

"We know the water is driven by a large pressure gradient from the Bering Sea northward through the Bering Strait and into the Chukchi Sea, and there's been quite a lot of work on understanding what happens in the summertime. But up there, summer lasts *only* a month or two.

"That leaves the largest part of a year for which we have no information as to current speeds and direction, and what the water is doing under the ice. Clearly, if we had an oil spill therein winter we couldn't begin to prediet the spill's trajectory."

The present set of current-*met er* stations was deployed from the NOAA ship Discoverer



last summer, to form an array of 19 submerged meters. Each mooring consists of a cylindrical meter-about the sire of a loaf of bread-attached to a swivelled vane that senses the direction of water motion. The meter is suspended on a cable held taut by a buoyant, streamlined float, and anchored at the bottom by a heavy concrete weight. The cable is connected to the anchor by a coupling that can be acoustically triggered, permit ting a string of floats to raise the apparatus to the surface for retrieval.

Four current meters are set west of Cape Prince of Wales, the American side of the Bering Strait. Seven more are moored m the Chukchi Sea, in a shallow arc westward from Cape Lisburne, almost the northwest corner of Alaska. Two meters are installed at the mouth of Kotzebue Sound, and two more are in a line south of Nome in Norton Sound. Three are set along a southeastward line from St. Lawrence Island in the Bering Sea to the Yukon River delta, with a fourth meter northwest of St. Lawrence Island.

APPENDIX 3

Article from NOAA News, vol 2, no 5, March 4, 1977; p 3.