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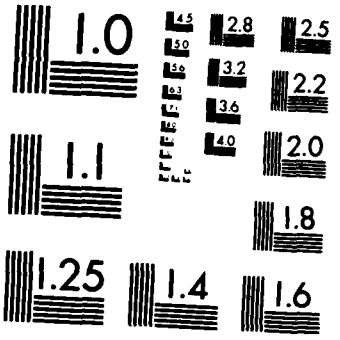

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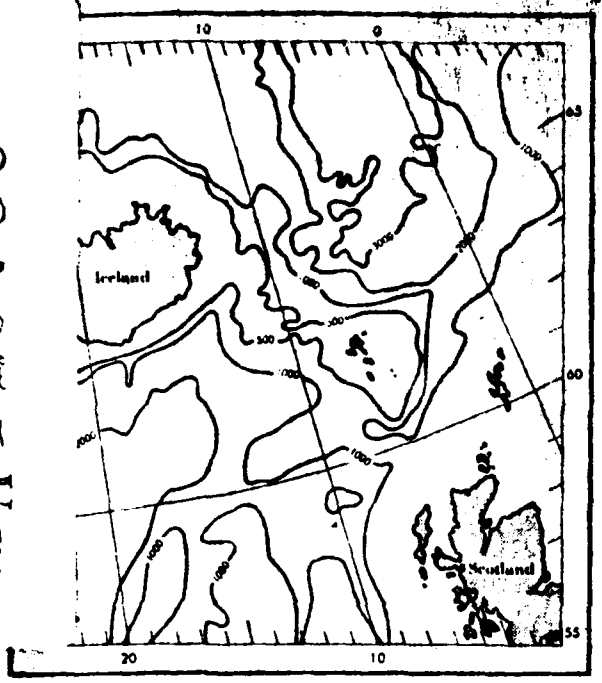

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ROBERT B. LORENS
GERALD M. LEONE

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PREPARED BY
COMMANDING OFFICER,
NAVAL OCEANOGRAPHIC OFFICE
NSTL STATION, BAY ST. LOUIS, MS 39522

PREPARED FOR
COMMANDER
NAVAL OCEANOGRAPHY COMMAND
NSTL STATION, BAY ST. LOUIS, MS 39529

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FOREWORD

Since 1976, the Naval Oceanographic Office has been involved in a program to establish an environmental baseline for trace metals in the open ocean. This report provides results of such an investigation for copper, mercury and supportive biological nutrients in the Iceland-Faroe Ridge region. By using supportive physical parameters (salinity, potential temperature and density), information as to water mass movement in an unique oceanographic environment can be correlated to differences in metal concentrations.

C. H. BASSETT

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

A suite of water samples was collected in the Iceland-Faroe Ridge area and was analyzed for copper and, to a lesser extent, for mercury. Two sample sets (one for copper and the other for mercury) were collected at a depth of 50 m with a horizontal spacing of 15 m. Horizontal variations in copper concentration were negligible; the mean concentration was 77 ± 9 ng Cu/kg. Patches of water with high (102 ± 23 ng Hg/l) and low (9.4 ± 4 ng Hg/l) mercury -

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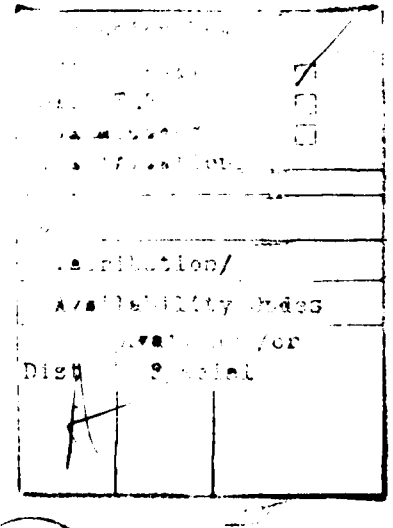
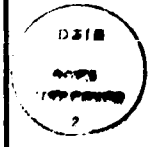
20. Abstract, cont.

concentrations were separated by horizontal distances of 15 to 50 m. These samples were collected at the base of the mixed layer, which may account for the sharp transition in mercury concentration. Four vertical profiles between 50 and 300 m, all taken within 13 minutes, showed no significant changes in copper concentration. Nine other profiles were obtained in the region to define the distribution of copper. Water at the Arctic Front (112 ± ng Cu/kg) was enriched in copper with respect to adjacent North Atlantic water (85 ± 11 ng Cu/kg). Lobes of water with high copper concentration (100 to 140 ng Cu/kg) protruded into Norwegian Sea water (80 to 90 ng Cu/kg). An eddy-like feature north of the Arctic Front was identified. The copper concentration of the core was similar to the concentration found at the front.





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INTRODUCTION

Ocean fronts, boundary zones where mixing occurs between water masses, are often characterized by sharp gradients in temperature and salinity. At frontal zones these physical parameters often have a high degree of temporal and spatial variability. This variability results from meanders in the front location and from eddies which separate from the frontal zone and migrate into adjoining water masses (Hansen and Meincke, 1979). There is however a paucity of data describing the distribution of non-physical parameters at ocean fronts. It is likely that sharp gradients in the physical parameters may induce local circulation and regeneration patterns that intensify the concentrations of biological and chemical parameters at these boundary zones.

During late September and early October, 1980, the U.S. Naval Oceanographic Office (NAVOCEANO), aboard the USNS ELISHA KENT KANE (Cruise #270980), occupied a series of stations in the North Atlantic, the Iceland-Faroe Ridge area, and the Norwegian Sea (figure 1). An ocean front situated over the Iceland-Faroe Ridge separates North Atlantic water from Norwegian Sea water. The literature is confusing with regard to front nomenclature in the arctic and polar areas; this front has sometimes been referred to as the Polar Front, as have other fronts further to the north. In this report, according to the convention of Swift and Aagaard (1981), the front, which separates the Atlantic domain from the Arctic domain, will be referred to as the Arctic Front. This report discusses the distribution and variability of copper, and to a lesser extent mercury, in the Iceland-Faroe Ridge area, where the dominant oceanographic feature is the Arctic Front.

SAMPLE COLLECTION

Seawater samples were collected using either a 12-bottle or a 25-bottle rosette at stations shown in figure 1. When weather conditions and sea state permitted, a General Oceanics 24-bottle rosette capable of handling 10-ℓ bottles was deployed. This rosette was equipped with plastic-coated lead weights, a painted aluminum frame, an anodized aluminum termination, and a plastic-coated steel cable. A combination of 2.5 and 10-ℓ Go-Flo bottles manufactured by General Oceanics was deployed with the 24-bottle system. During poor weather conditions, a General Oceanics 12-bottle rosette was used. This rosette could carry only 2.5-ℓ bottles and was equipped with a stainless steel termination, galvanized shackles, and a galvanized steel cable. A stainless steel Neil Brown CTD and a urethane-coated stainless steel pinger were mounted on each rosette. The 24-bottle rosette was deployed at stations 015, 023, and 026 for vertical profiles and at stations 012, 015, and 018 for special profiles which are described below. Station coordinates are listed in the data table captions in Appendices A, B, C, and D.

At nine stations, CTD data were collected on the down-cast and Go-Flo bottles were tripped on the up-cast. Bottle sampling depth was determined from the up-cast CTD pressure reading; salinity and temperature data for that pressure were read from the CTD down-cast record. At two stations, 012 and 015, the 24-bottle rosette was towed at 50 m to collect samples for mercury and copper, respectively. CTD data were collected before and after each sequence of bottle firings. At station 018, the rosette was cycled four times, within 13 minutes, between 50 and 300 m. Samples were collected on each cycle at 50-m intervals.

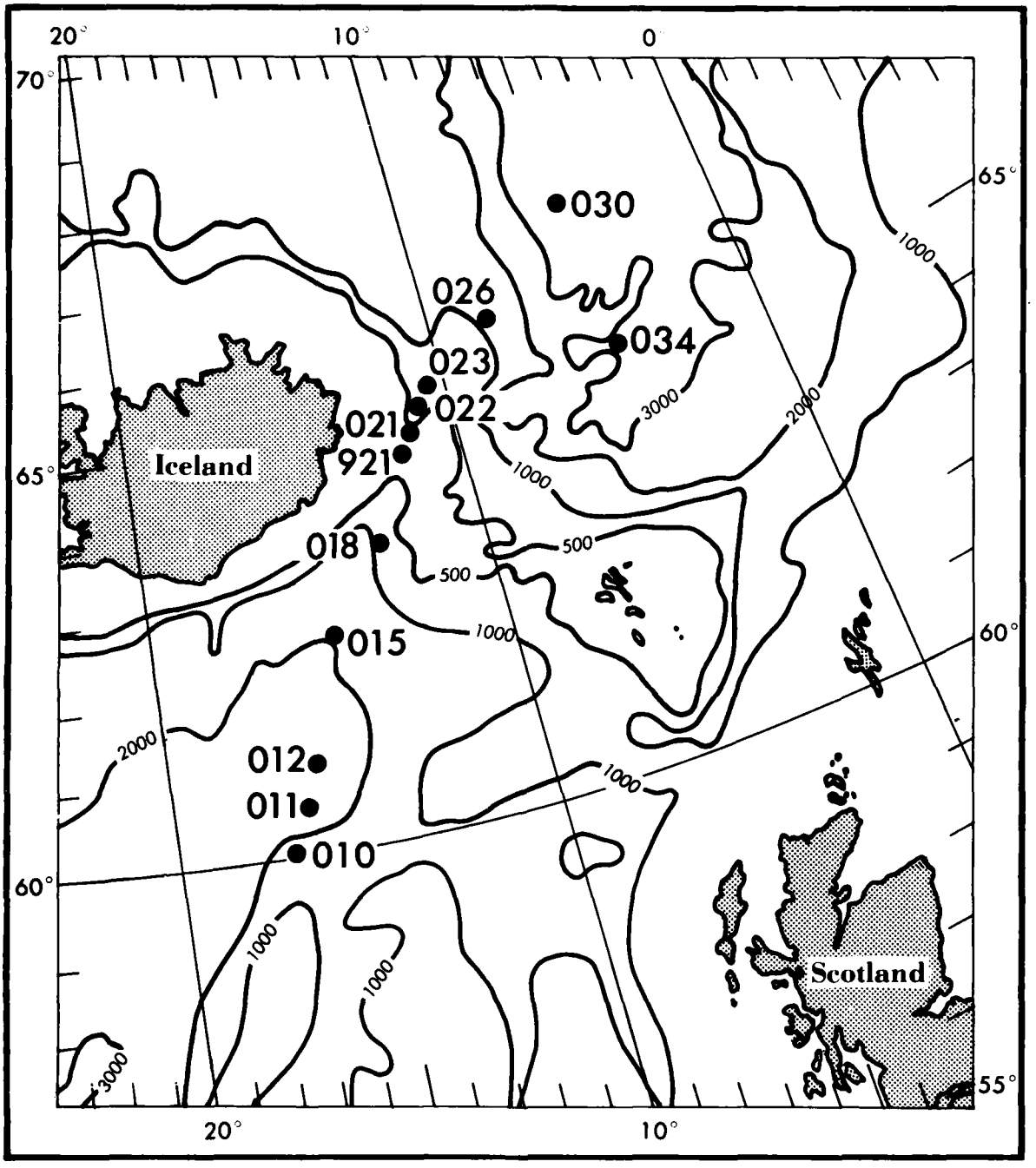

Figure 1. Station locations (bathymetry from Dietrich, 1969).

Before the cruise, each Go-Flo bottle was rinsed with MICRO detergent, 0.1 N HCl and Milli-Q water (18 megohm-cm water produced by a Milli-Pore Corporation deionization system). The Go-Flo bottle interiors had been teflon coated, and the normal push-pull valves were replaced with threaded teflon plug valves. Nutrient and dissolved oxygen samples were collected directly from this valve. Samples to be analyzed for copper were collected in 1-ℓ conventional polyethylene (CPE) bottles via a teflon valve and tube system which was connected to the Go-Flo bottle. The 1-ℓ CPE bottles were uncapped, attached to the sampling apparatus, acidified, and recapped in a laminar flow, clean-air bench. Before each sample, the teflon sampling apparatus was rinsed with Milli-Q water.

Samples for mercury analysis were collected in pre-cleaned 250-ml, screw-capped, glass bottles containing 2 ml of concentrated nitric acid. The mercury samples were drawn from the Go-Flo bottles mounted on the rosette as it rested on the ship's fantail. A stiff aft wind carried effluent from the ship's stacks toward the starboard bow while the samples were being drawn.

ANALYTICAL METHODS

Seawater samples were analyzed for nutrients and dissolved oxygen after each station. Nutrients were determined with a Technicon Auto Analyzer II using procedures detailed by the manufacturer and some modifications suggested in Folkard (1978) and Froelich et al., (1977). Dissolved oxygen was determined by the Winkler Method as modified by Carpenter (1965).

Each 1-ℓ seawater sample was preserved with 4 ml of 6 N double distilled HCl. These samples were analyzed for copper within 12 months of collection. Extraction/preconcentration procedures were adopted from Bruland et al., (1979) incorporating the following modifications. One ml of 11 M acetate buffer was added to 200 g of acidified seawater to obtain a pH of 4. The back extraction into 7.5 M HNO_3 was eliminated. Instead, the organic phase from both forward extractions was drained into a 30-ml, Oak-Ridge, FEP teflon, centrifuge tube followed by the addition of 500 µl of quartz-distilled HNO_3 (Q-HNO_3). The mixture was heated to approximately 50° C to evaporate the organic phase without boiling; it was then heated to 90° C to digest the remaining organic material and evaporate the Q-HNO_3. A followup digestion and evaporation was made after a second addition of 500 µl of Q-HNO_3. The extracted metals were then dissolved in 2 ml of 0.1 N Q-HNO_3 and transferred to a 7-ml, linear polyethylene vial. Two procedural blanks were run with each day's samples using previously extracted samples. The blanks were dissolved in 1 ml of 0.1 N Q-HNO_3.

Initially, chloroform was used as the organic solvent in the above procedure. However, replicate analyses of samples using chloroform resulted in high values with very poor precision. In place of chloroform, freon (1, 1, 2 - trichloro - 1, 2, 2 - trifluoroethane) was substituted. On a bulk sample of seawater six replicate extractions with chloroform and with freon gave the following: the mean using chloroform was 125 $\pm$ 38 ng Cu/kg, whereas the mean using freon was 86 $\pm$ 4 ng Cu/kg. (Except where indicated otherwise, in this report deviations from mean values are one standard deviation.) On the basis of these results, freon was selected as the organic solvent to use in the preconcentration step.

The preconcentrated samples were analyzed for copper using a Perkin Elmer 603 atomic absorption spectrophotometer equipped with an HGA-2100 graphite furnace and an AS-1 auto sampler. Deuterium-arc background correction was applied to all samples. Pyrolytically-coated carbon rods and an argon purge gas were used in the graphite furnace. Standards were prepared in 0.1 N Q-HNO_3 from Fisher 1000 ppm A.A. standards. All instrument settings were as recommended by Perkin Elmer. A standard curve was run before and after each set of 18 samples and a mid-range standard bracketed each sample. Signal output was adjusted for baseline drift, and the bracket standards were used to compensate for minor variations in carbon rod response.

Blanks were determined daily with each set of samples processed. The mean of 96 blank determinations was 1.4 ± 1.0 ng Cu. The highest blank value was 6.4 ng; the lowest blank value was 0.1 ng Cu. A 200-g water sample with a 1.4 ng copper procedural blank had a 7 ng Cu/kg blank correction.

The efficiency of the extraction procedure and the succeeding analyt l steps was evaluated using the method of standard additions. Five ℓ of se water were mixed and divided into five 1-ℓ samples. Four of the samples : e spiked with known amounts of copper. Each of the five samples was extrac and analyzed in triplicate. Means with standard deviations are plotted i figure 2; a regression line through the data gave a sample concentration c 95 ng Cu/kg. Routine analysis of the sample gave the essentially identical value of 98 ± 3 ng Cu/kg.

In addition to the regular seawater samples and blanks processed in duplicate, each day two samples, drawn from an acidified bulk seawater reservoir maintained in the laboratory, were carried through the procedure. The day-to-day variation in the apparent copper concentration of the bulk sample was used as an index of the analytical precision. Three batches of bulk seawater were used and table 1 gives the mean copper concentration and standard deviation of each. In the table, n is the number of days for which data on each batch is available.

Table 1

Bulk Seawater	n	Copper, ng/kg
A-2	4	87.0 ± 2.7 (± 3%)
A-3	23	93.9 ± 5.9 (± 6%)
A-4	14	89.7 ± 1.9 (± 2%)

The worst case, 6% error at the 90 ng/kg level, is assumed to be representative of the precision of the copper data listed in this report.

This level of precision, although representative of the laboratory procedure, does not include any error that was introduced during sampling in the field. At two stations, numbers 023 and 026, multiple 1-ℓ samples were drawn from each of nine 10-ℓ Go-Flo bottles. The mean per cent deviation for these samples was ± 5%, with a low of ± 2% and a high of ± 9%. This indicates that sampling procedures did not significantly influence analytical precision and that ± 6% is probably a good estimate of the overall precision of the data set. Even so, individual samples with concentrations that were substantially different from those of adjacent samples were suspect. For example, at

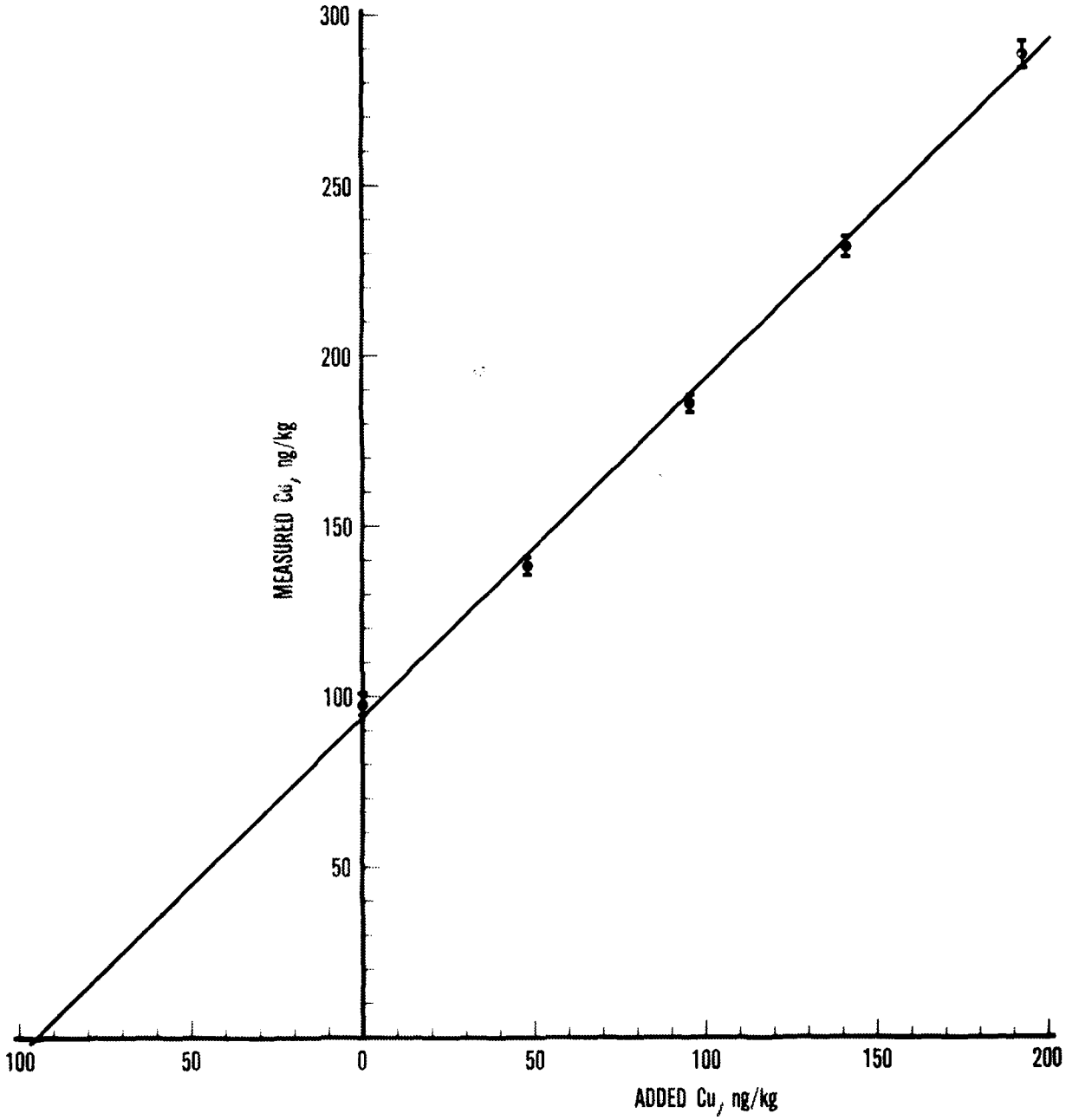

Figure 2. Standard additions to bulk seawater sample. Sample concentration estimated from regression line is 95 ng cu/kg. Sample concentration determined using routine procedure is 98 $\pm$ 3 ng cu/kg.

station 011 two Go-Flo bottles were tripped at 500 m; one sample had a concentration of 80 ng Cu/kg, the second had a concentration of 221 ng Cu/kg and was probably contaminated. Other solitary samples with high concentrations were probably contaminated.

Sample accuracy is difficult to assess in light of the lack of an established seawater standard at these concentration levels. Although there are no comparable data in the literature for this location, other open ocean areas have similar copper concentrations (Boyle et al., 1977; Moore, 1978; and Bruland, 1980).

Seawater samples were analyzed for mercury at the University of Rhode Island using a gold amalgamation procedure (Mukherji and Kester, 1979; Fitzgerald and Gill, 1979). Blanks on the order of 22 ng Hg/l were subtracted from the data reported here. The analytical error reported for individual values in appendix D results from imprecisions in the calibration curve.

RESULTS AND DISCUSSION

Station data are listed in appendix A. Potential temperature and salinity data were transcribed from the CTD down-cast record. Copper, nitrate-plus-nitrite, and phosphate data for each depth at a station are plotted to a depth of 800 m in figures 3 through 11.

At stations 012 and 015 samples from horizontal tows of the rosette were collected. Appendix B lists the copper data and mean concentrations from duplicate analyses. These means are plotted against tow distance in figure 12. Pressure, salinity, and temperature data derived from the CTD record for the copper tow are plotted in figure 13. At station 018, four cycles of the rosette were made between 50 and 300 m; the data are listed in appendix C and plotted in figure 14. The data from the horizontal mercury tow are listed in appendix D and illustrated in figure 15. Pressure, salinity, and temperature data for the mercury tow are plotted in figure 16.

Rosette tows and repetitive rosette cyclings were undertaken to obtain some information about short term sample variability in near surface water. For the tows, coincident CTD and water sample data were not obtained, so precise sample position within the area of consideration is only approximately known. Supporting temperature and salinity data for each sample set were available only for the time before and after the set of sample bottles was tripped.

Only minor variations in copper concentrations were found in the 350-m long horizontal profile at station 015. The mean concentration of these samples, collected at approximately 15-m intervals at a depth of 50 m, was 77 $\pm$9 ($\pm$ 12%) ng Cu/kg. This deviation is larger than the expected analytical precision of $\pm$6%, indicating the variation observed may be significant. However, the quantity of data was not sufficient to define any meaningful trends (figure 12). Samples collected at station 18 were analyzed for copper and show no significant variation with successive cycles, except at 100 m (figure 14). At 100 m there was a 59 ng Cu/kg drop in concentration from the first through the fourth sample. Variation in sample concentrations at

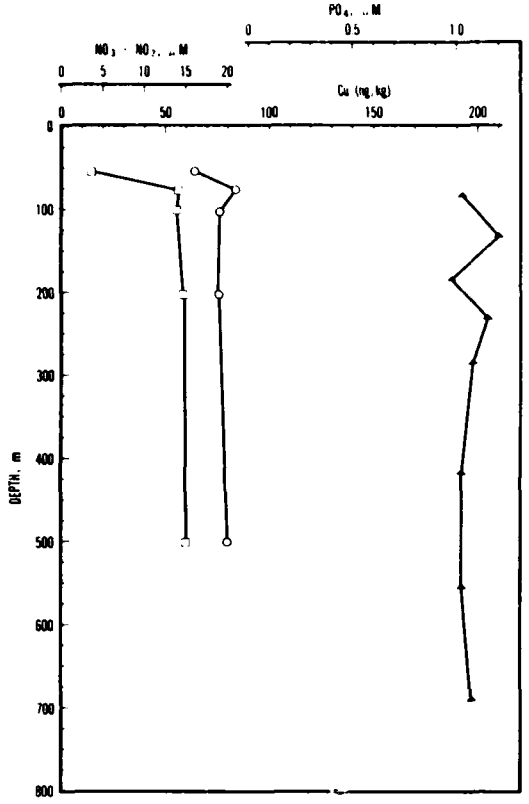

Figure 3. Station 011 vertical profiles showing copper (O) and nitrate-plus-nitrite (□). Phosphate (▲) profile is from nearby Station 010.

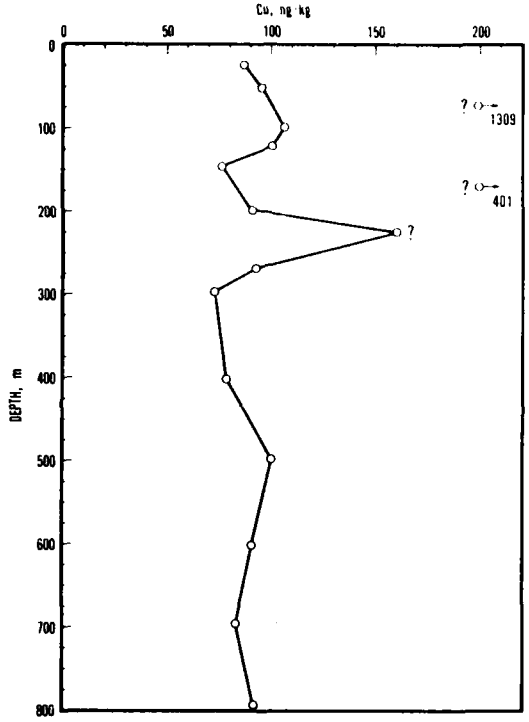

Figure 4. Station 015 vertical profile showing copper (O). Potentially contaminated samples marked with "?".

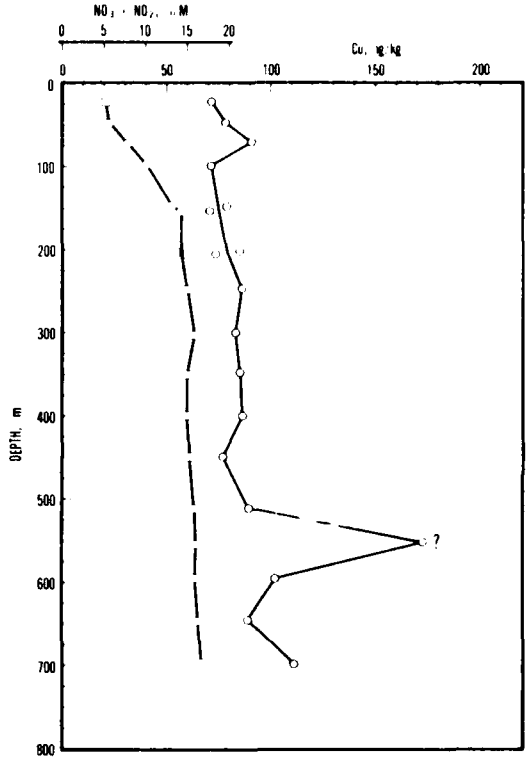

Figure 5. Station 018 vertical profiles showing copper (O) and nitrate-plus-nitrite (□). Potentially contaminated samples marked with "?".

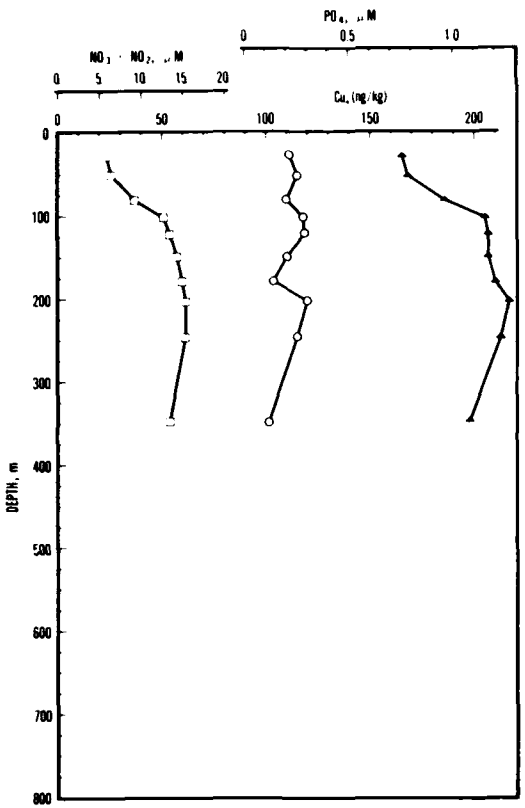

Figure 6. Station 921 vertical profiles showing copper (O), nitrate-plus-nitrite (□), and phosphate (▲).

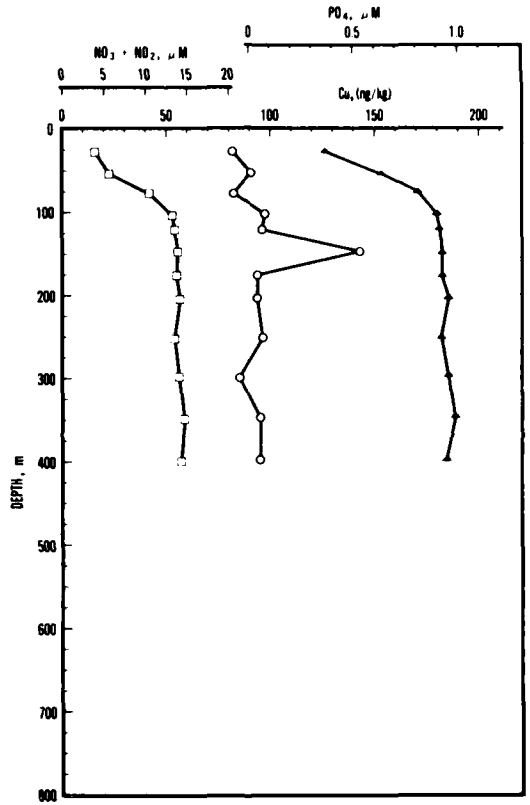

Figure 7. Station 021 vertical profiles showing copper (O), nitrate-plus-nitrite (□), and phosphate (▲).

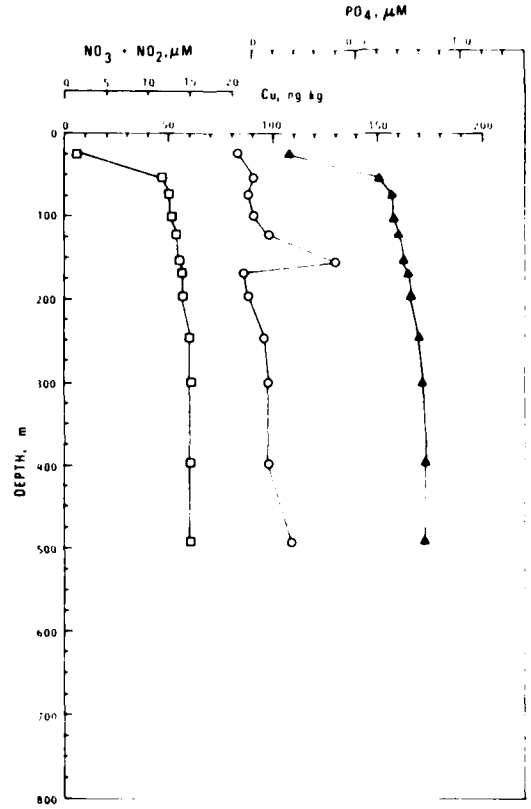

Figure 8. Station 022 vertical profiles showing copper (O), nitrate-plus-nitrite (□), and phosphate (▲).

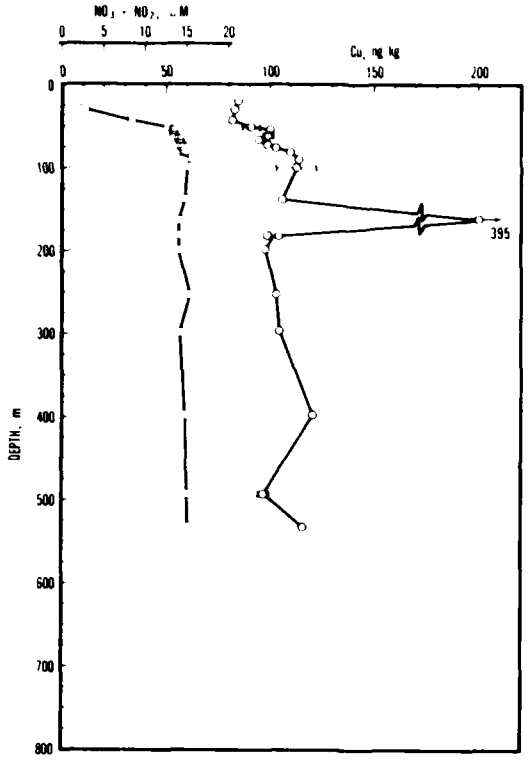

Figure 9. Station 023 vertical profiles showing copper (O), and nitrate-plus-nitrite (□).

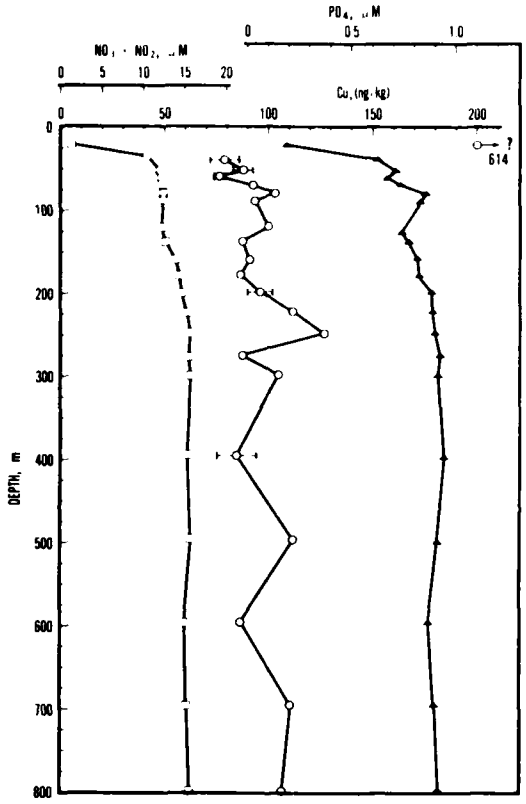

Figure 10. Station 026 vertical profiles showing copper (O), nitrate-plus-nitrite (□), and phosphate (▲). Potentially contaminated samples marked with "?".

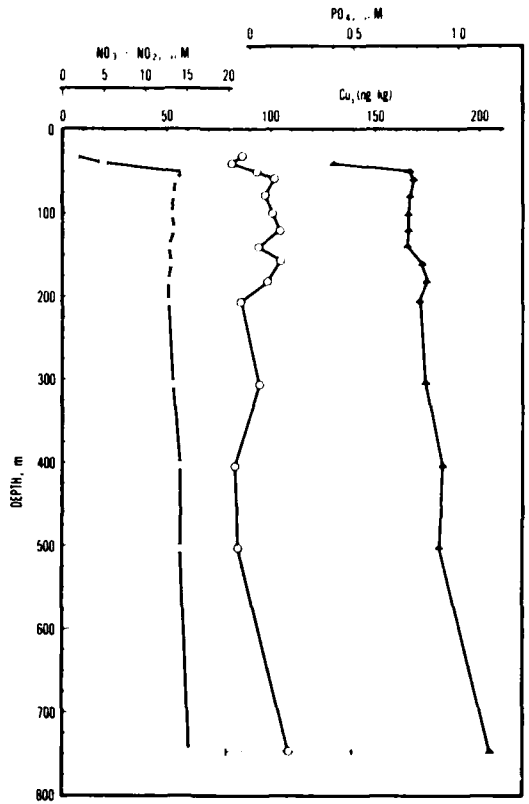

Figure 11. Station 030 vertical profiles showing copper (O), nitrate-plus-nitrite (□), and phosphate (▲).

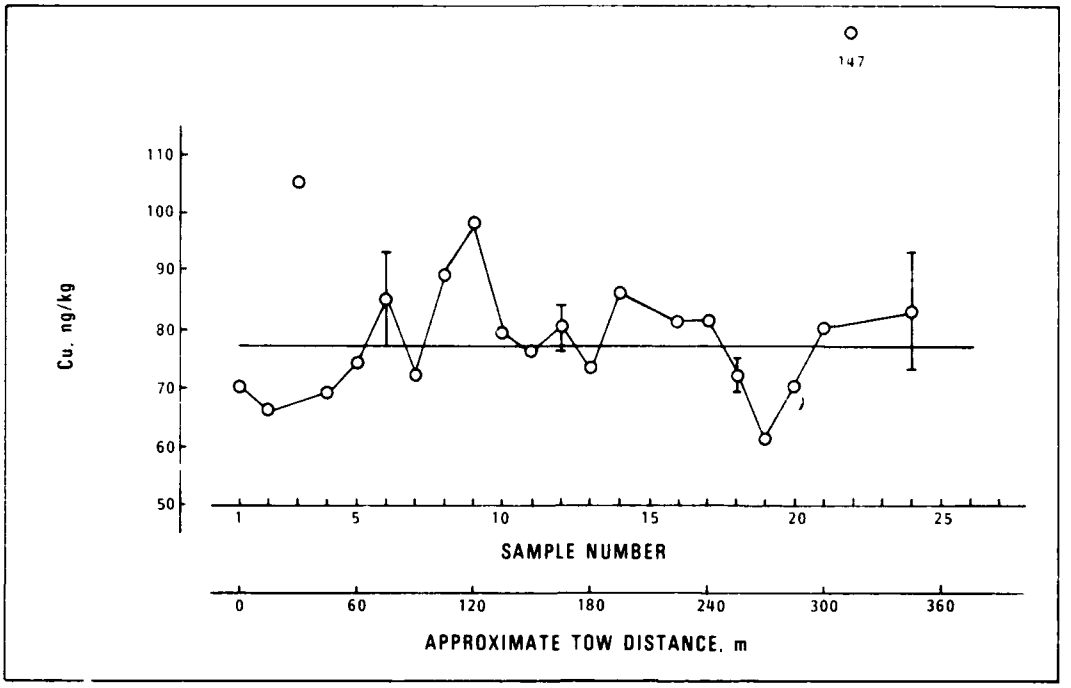

Figure 12. Station 015 horizontal copper profile at 50-m depth. Means of data listed in appendix B are plotted; one sigma error bars are included for data with n>2. Solid line is mean of data set.

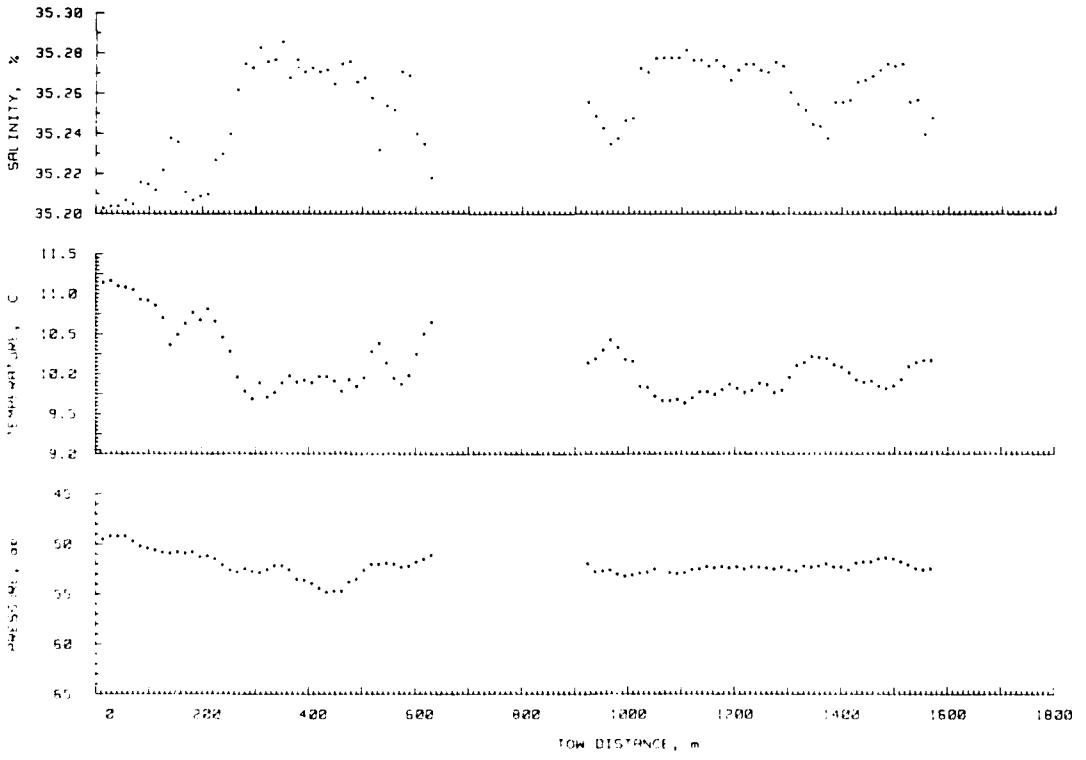

Figure 13. CTD data recorded before and after collection of water samples for horizontal copper profile at station 015.

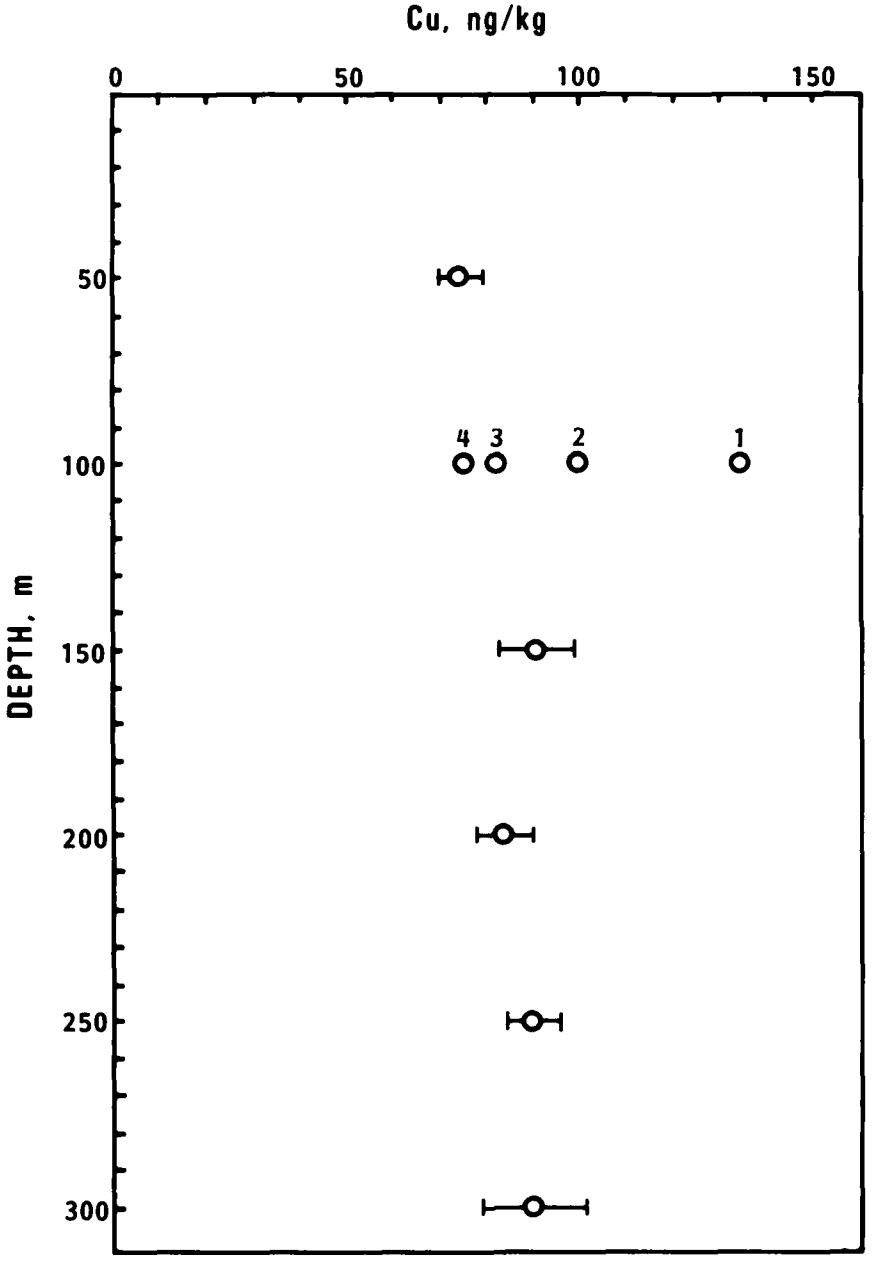

Figure 14. Station 018 sequential vertical copper profiles. For depths 50, 150, 200, 250, and 300 m, the mean concentrations (see table 14) with 1 sigma deviations are plotted. At 100 m, individual points are plotted and identified with their order of collection.

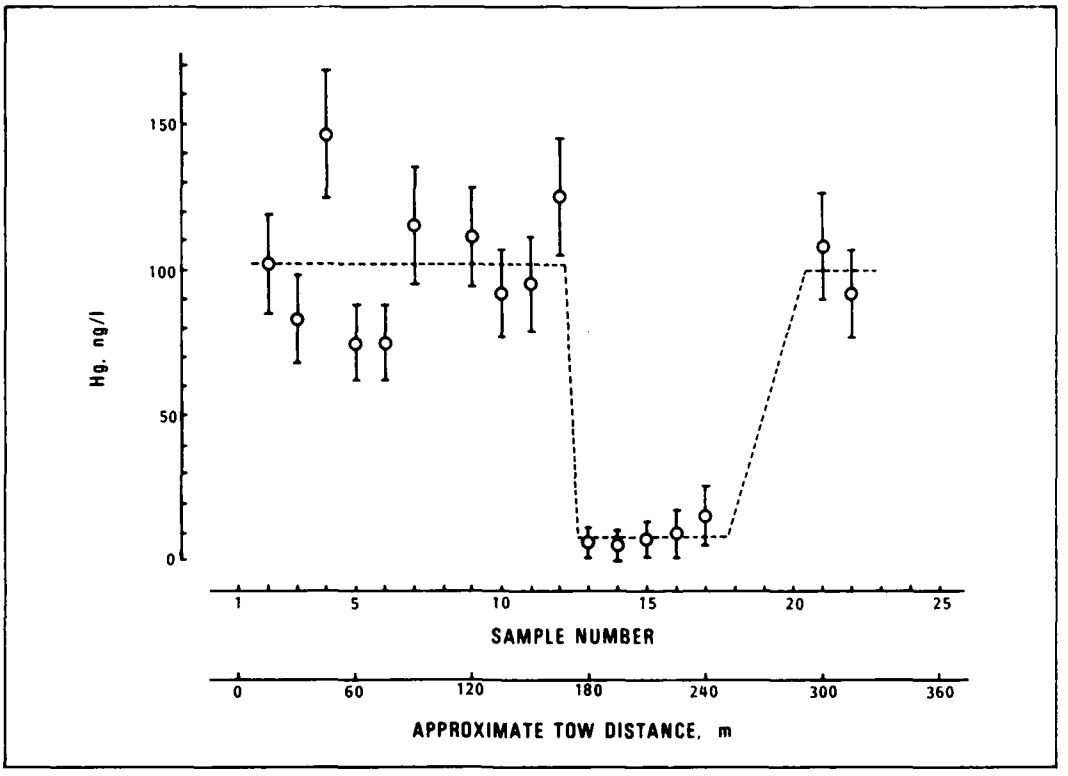

Figure 15. Station 012 horizontal mercury profile at 50-m depth. Dashed line is mean value of each group of points; see appendix C for data.

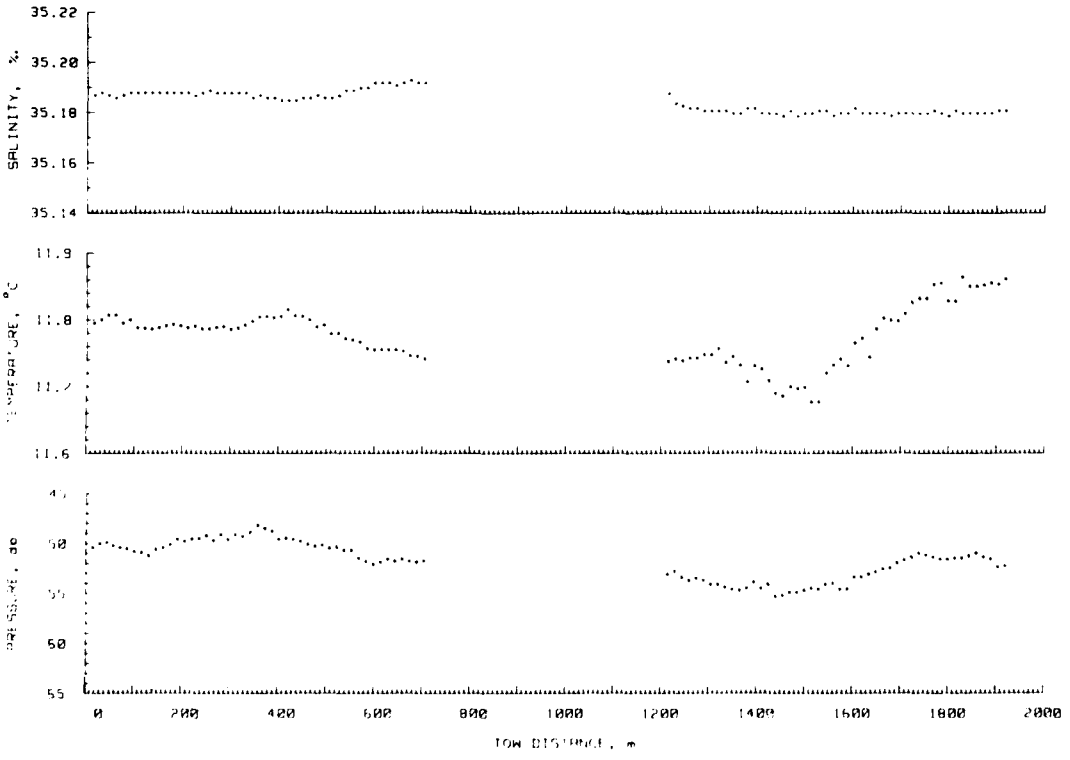

Figure 16. CTD data recorded before and after collection of water samples for horizontal mercury profile at station 012.

the other depths was not very different from the 6% analytical precision specified earlier; for 50, 150, 200, 250, and 300 m, the relative deviation was respectively: 7, 8, 7, 7, and 12 per cent. Insufficient data were available to determine whether the high concentration observed in the first sample at 100 m resulted from contamination.

A horizontal rosette tow was performed at station 012 to collect samples for mercury. The rosette was towed at a depth of approximately 50 m (figure 16), and samples were collected at approximately 15 m intervals (figure 15). In the first 160 m of the tow, the mean mercury concentration was 102 $\pm$ 23 ng Hg/l. Substantially lower mercury concentrations (9.4 $\pm$ 4 ng/l) were observed in the next 60-m interval. Following this low mercury interval, within 60 m, were two samples with high mercury concentrations (108 and 92 ng/l) similar to the first section. The duplicates for samples between the low mercury section and the subsequent high mercury section were in substantial disagreement, suggesting contamination. These sample values are omitted from the above analysis and figure 15, but are listed in appendix D.

The striking feature of this data is the rapid transition from the high to low mercury sections. Within approximately 15 m there was a mercury concentration decrease of 93 ng/l. After 60 m, the mercury concentrations abruptly increase. Temperature data obtained from the CTD before and after the rosette bottles were fired indicate that the rosette was being towed in the mixed layer. However, such sharp concentration gradients seem unlikely within the mixed layer. Vertical CTD profiles place the base of the mixed layer at around 50 to 55 m for this area. The rosette was probably being towed at the base of the mixed layer and perhaps the rapid change in mercury concentration resulted from an excursion of the rosette out of and back into the mixed layer. This could have resulted from either a temporary rosette depth change or from a ripple in the mixed-layer boundary depth.

Data are not available on the vertical distribution of mercury through the mixed layer in this area, but the concentrations observed are consistent with those reported by others. Typical North Atlantic mercury concentrations vary from 3 to 40 ng Hg/l (Mukherji and Kester, 1979; Gardner, 1975; and Leatherland, et al., 1973). High mercury concentrations, 100 ng Hg/l and above, have been associated with areas of natural injection, such as spreading centers or other sites of volcanic and hydrothermal activity (Coderre and Steinthorson, 1977; and Carr, et al., 1974). Gardner and Riley (1974) report mercury concentrations from 16 to 225 ng Hg/l off southern Iceland. Although it is an attractive hypothesis to explain the observed transitions, there are insufficient data to characterize the mixed layer where the tow was made as enriched in mercury from volcanic or hydrothermal areas near Iceland.

The vertical profiles at stations 011 through 030 define a vertical section which traverses the Iceland-Faroe Ridge. Isolines of potential temperature, salinity, and sigma-t drawn for this section (figures 17, 18, and 19) show the Arctic Front above the Iceland-Faroe Ridge at station 921, as well as other features in the area. These figures were drawn using data derived from 1 decibar-interval CTD records obtained at the station locations indicated by tick marks at the bottom of each figure.

The most dominant feature in this region was the Arctic Front, which separated North Atlantic water from a complex mixture of water masses

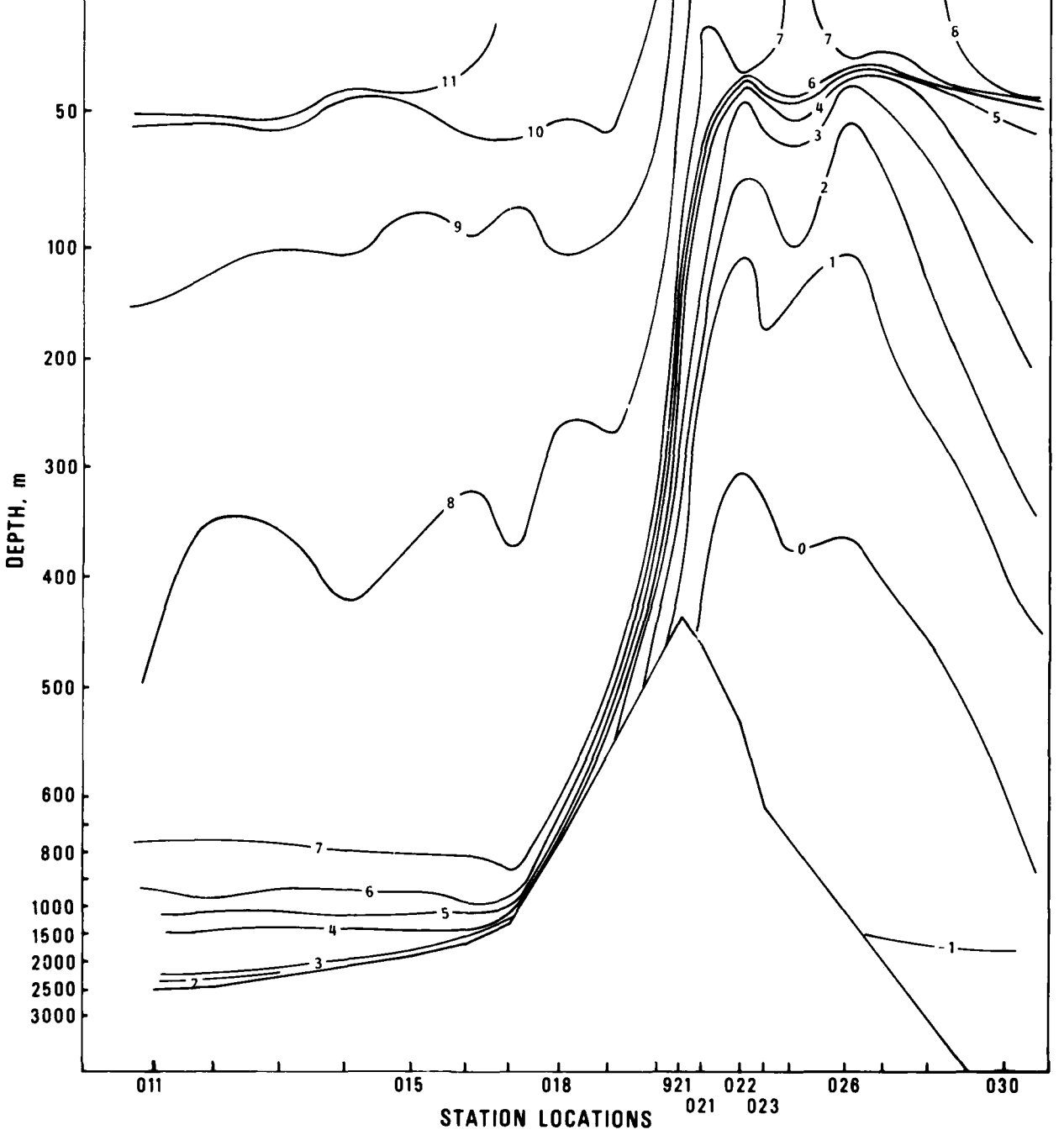

Figure 17. Potential temperature (°C) section across Iceland-Faroe Ridge.

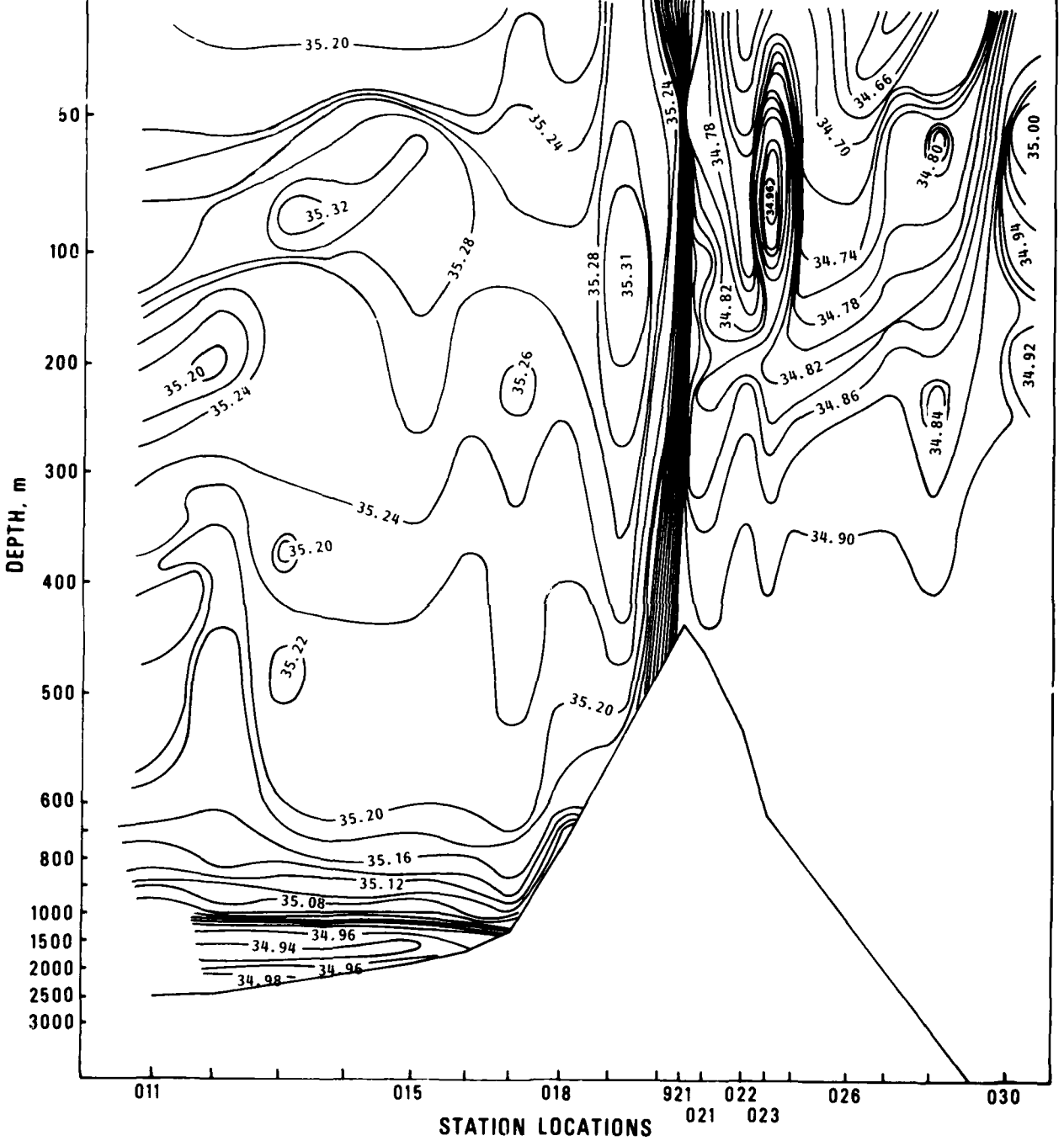

Figure 18. Salinity (°/oo) section across Iceland-Faroe Ridge.

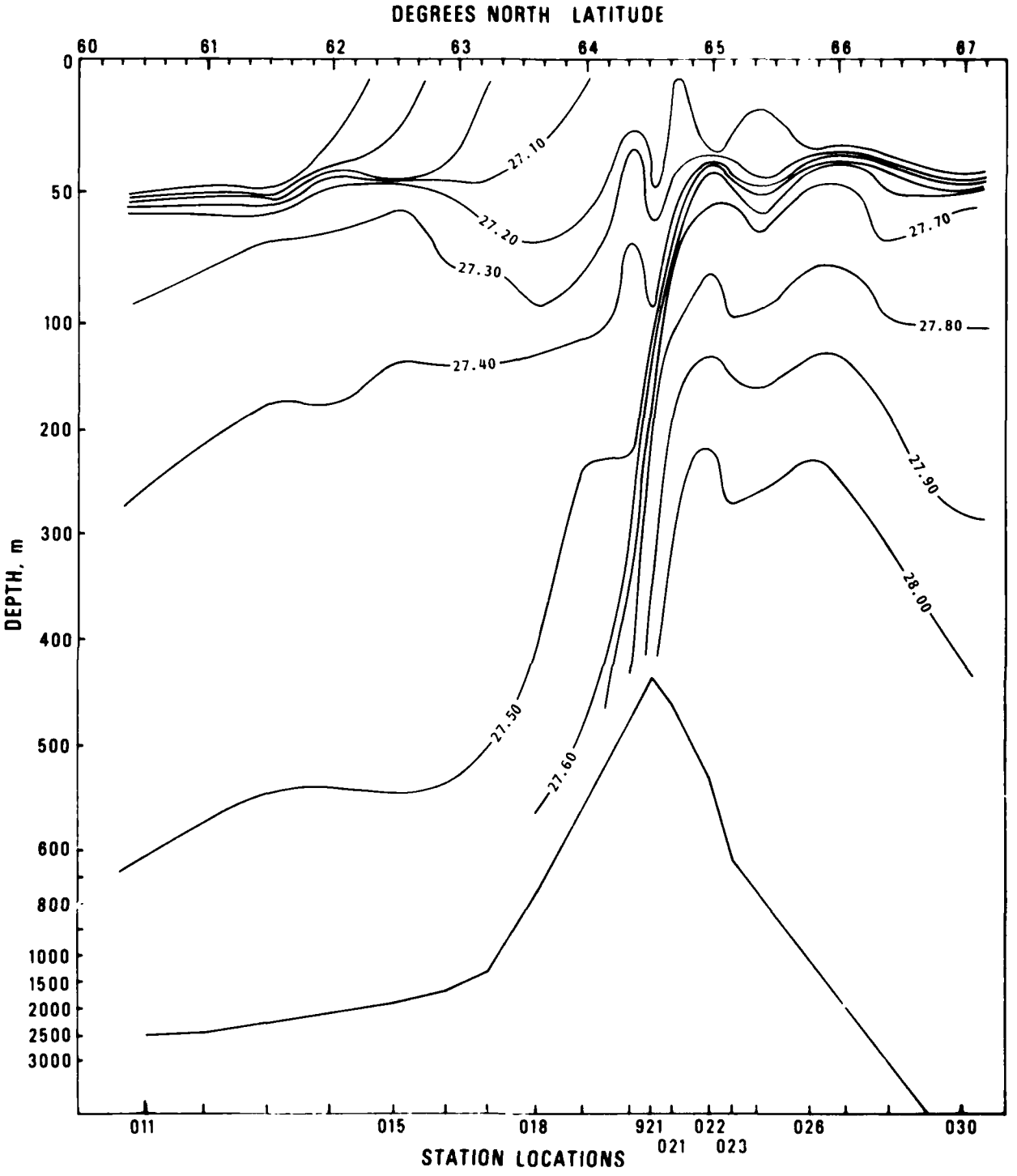

Figure 19. Sigma-t section across Iceland-Faroe Ridge.

around Iceland and in the southern Norwegian Sea (Swift and Aagaard, 1981; and Meincke, 1978). Spatial and temporal variability in the temperature and salinity fields in this area resulted from meandering in the front location, and from eddy formation and migration into adjoining water masses (Hansen and Meincke, 1979). The salinity cross section in figure 18 illustrates some of the complexity and variability of the area. Just north of the front, a strongly defined, eddy-like feature with a high salinity core is apparent. Other less well defined salinity features are also evident in the cross section of the region.

The distribution of copper along this section (figure 20) showed considerable variability. Copper concentrations increased, with respect to North Atlantic water, in water at the frontal zone, station 921, by approximately 39 ng Cu/kg (table 2). Although lobes of water with high copper concentrations extended both north and south from the frontal zone, copper concentrations and gradients in these concentrations were greater in water north of the front than south of it. A lobe of water with high copper concentration (> 100 ng Cu/kg), centered at 150 m, extended northward for 210 km. Observed at stations 021 and 022, this lobe had a thickness of 40 m as it protruded from the front. Further north, at stations 023 and 026, the lobe broadened and encompassed depths from 60 to 400 m. Centered within this lobe was a tongue-like feature with a mean concentration of 130 ng Cu/kg. Directly above the mid-point of the tongue-like feature, at station 023, was a small cell of water, centered at 90 m, which had a mean concentration of 112 ng Cu/kg; the position of this cell coincided with the location of the core of the eddy-like feature shown in the salinity section. Approximately paralleling the outline of the Iceland-Faroe Ridge were parcels of water with concentrations in the 100 to 110 ng Cu/kg range. At station 030, there were small cells of water with concentrations above 100 ng Cu/kg. Except within these lobes and cells, water in the upper 600 m of the Norwegian Sea had copper concentrations in the range of 80 to 90 ng Cu/kg.

Some of the variation in copper concentration can be related to variations observed in the salinity and temperature fields, indicating that water circulation is an important modifier of copper distribution. The water at the core of the eddy-like feature, which had an elevated copper concentration, can be shown to originate at the front. A potential temperature versus salinity (Θ/s) diagram, figure 21, shows the water mass characteristics at each station. Stations 011, 015, and 018, south of the front, had the Θ/s characteristics of North Atlantic water (Swift and Aagaard, 1981). At the front, station 921, salinity varied between 34.85 and 34.94 o/oo and potential temperature varied between 1.6 and 8.2°C. Going north from the front, the Θ/s characteristics for stations 021 and 022 became progressively less similar to the Θ/s character of the front. At the northernmost stations, 026 and 030, there was no evidence of frontal influence. However, the Θ/s character of station 023, where the core of the eddy-like feature ranged from 50 to 100 m, was very similar to the Θ/s character of the front, station 921.

The Θ/s plot of station 023, for the interval between 82 m and 99 m, coincided with the Θ/s plot of station 921 at depths from 202 to 245 m (figure 22). For the same interval, 82 to 99 m, the copper concentrations at station 023 were identical to those found at the front (figures 20 and 22). The correspondence between Θ/s and copper at the front and at the core of the

Table 2. Regional distribuiton of copper‡.

LOCATION	NO. SAMPLES	COPPER ± 1σ ng/kg
North Atlantic (south of Arctic Front)		
0-800 m	35	85 ± 11
> 800 m	5	88 ± 9
Arctic Front (Sta. 921)	10	112 ± 6
Norwegian Sea (north of Arctic Front)		
0-800 m	77	96 ± 9
tongue	4	130 ± 9*
> 800 m	8	100 ± 11

‡ Samples listed in appendix A are included except for those samples which are believed to be contaminated, as indicated.

* Station 23, depth 163 m, 395 ng Cu/kg data point excluded from mean calculation.

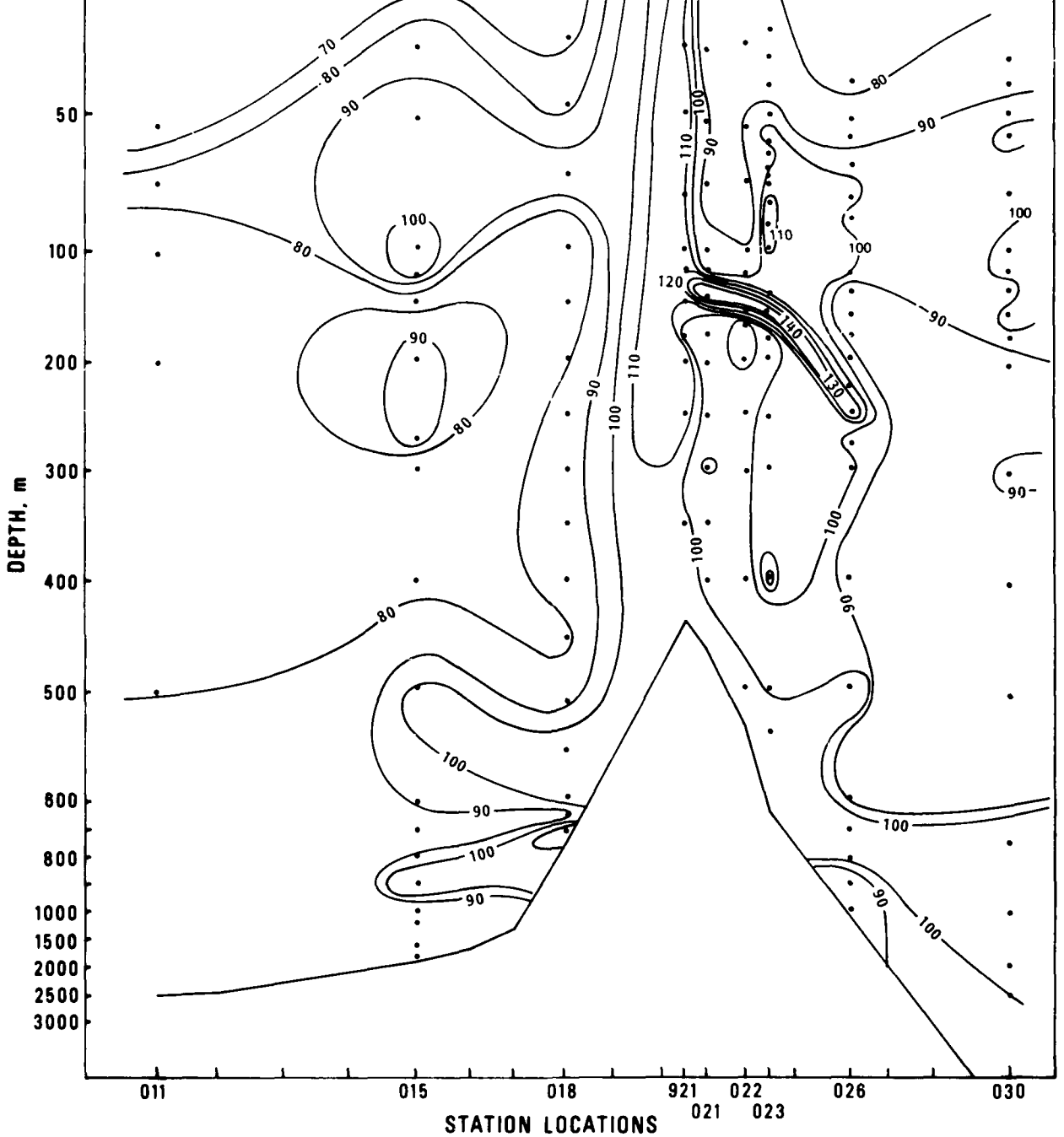

Figure 20. Copper (ng/kg) section across Iceland-Faroe Ridge.

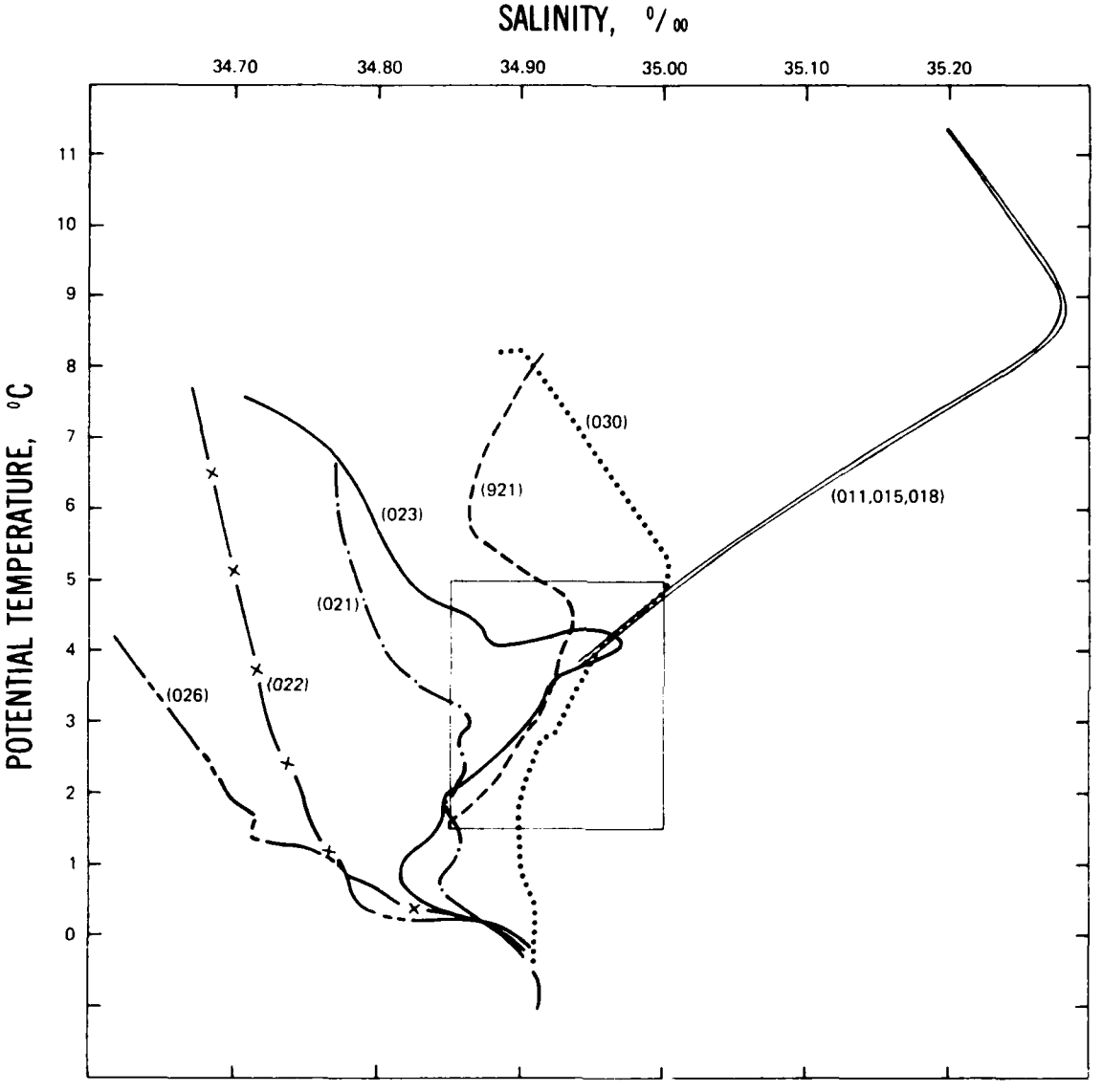

Figure 21. Potential temperature/salinity plot: stations 011 through 030. Lines are best fit through data listed in appendix A. Box outline refers to figure 22.

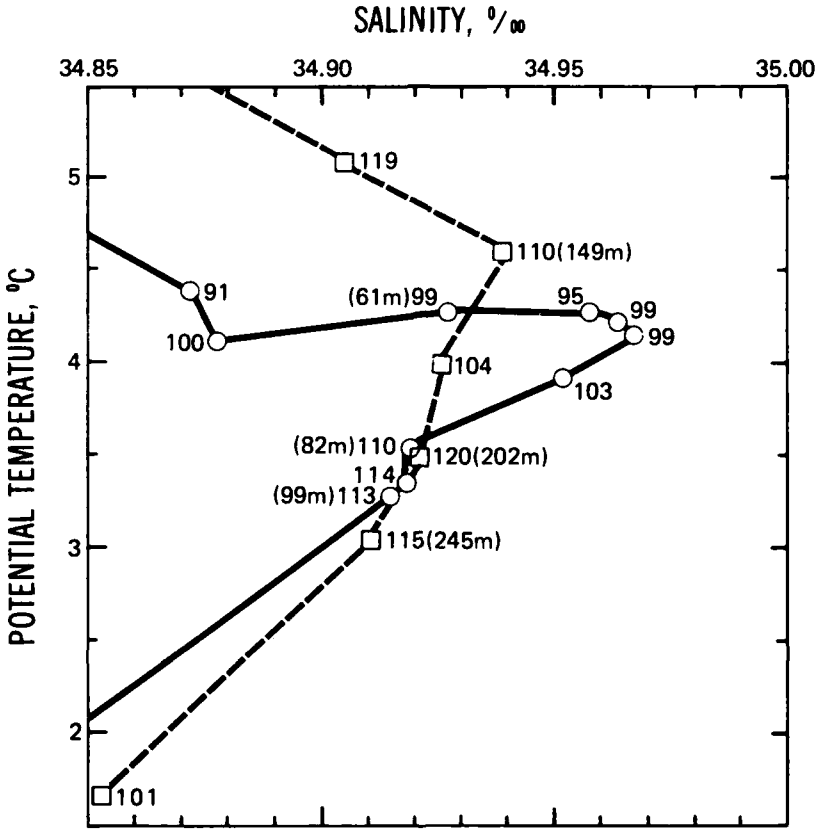

Figure 22. Expanded potential temperature/salinity plot (see figure 21): Arctic Front (dashed line) and eddy-like feature (solid line). Sample locations (depth in parentheses) in the θ/s field are indicated by open circles and squares. The copper concentration (ng/kg) is listed adjacent to each sample.

eddy-like feature suggests that the feature originated within the frontal zone and was then displaced to the north. As it moved north into denser Norwegian Sea water, the core of the feature apparently rose from approximately 225 m at the front to approximately 90 m at station 023. The Θ/s plots, figures 21 and 22, indicate that the top part of the eddy, between 61 m and 82 m, was diluted or replaced with North Atlantic water. Between these depths, the Θ/s plot of station 023 shifts away from the Θ/s character of the front and takes on the character of the coldest, freshest North Atlantic water. Swift and Aagaard (1981) showed that North Atlantic water enters the Iceland Sea from the southwest, circles around the north shelf of Iceland, and flows out to the southeast, into the region where stations 023, 026, and 030 were located. Although data from station 026 do not show the presence of North Atlantic water, a portion of the Θ/s plot for station 030 coincides with the Θ/s plot for the coldest, freshest North Atlantic water. A finger of this North Atlantic water may have intruded into the top of the eddy-like feature at station 023. As previously mentioned, North Atlantic water contained less copper, on the average, than was found at the front or at the core of the eddy-like feature. Therefore, one would expect decreased copper concentrations where this water intruded into the eddy-like feature. This was the case; however, the average concentration of four samples at station 023, between 61 and 99 m, was 99 ng Cu/kg, slightly higher than the mean North Atlantic water concentration of 85 ± 11 ng Cu/kg. Four other samples, from 59, 79, 101, and 120 m at station 030, which had Θ/s characteristics similar to North Atlantic water (figure 22), had relatively high copper concentrations of 102, 98, 101, and 105 ng Cu/kg respectively. This suggests that North Atlantic water may be enriched in copper as it passes over the Icelandic Shelf and provides a source of copper to the southern Norwegian Sea area.

Where covariation in copper and Θ/s is not apparent, processes other than circulation and mixing are implicated for controlling copper distributions. These processes may include absorption or desorption of copper from particles in the water column or at the sediment surface (Boyle et al., 1981; and Boyle et al., 1977). As noted above, locally high copper concentrations occurred at the Arctic Front, a zone defined by steep gradients in physical parameters. These steep gradients alone cannot explain the local enrichment in copper. The concentration gradient, indicated by the copper isolines in figure 20 around the Iceland-Faroe Ridge, suggests that copper was diffusing out of the sediments into the surrounding water. However, since the concentration maximum at the front occurred at mid-depth, the upwelling of copper-enriched bottom water cannot entirely explain the enrichment observed. The highest phosphate concentrations measured also occurred at the front (figure 6). Both phosphate and copper are part of the bio-cycle, and their enrichment may result from the decay of biogenic particles trapped at the front. However, a similar increase in nitrate-plus-nitrite concentration was not observed and this complicates the regeneration interpretation.

None of the other oceanographic data supports the existence of the tongue of water with high copper concentration. Phosphate and nitrate-plus-nitrite concentrations were not enriched in these samples. Nor did the salinity, temperature, or sigma-t fields show any structure which could be associated with this feature. However, it is probably not an artifact since the feature was observed at four successive stations.

CONCLUSIONS

At the base of the thermocline, significant changes in mercury concentration (93 ng Hg/l) occurred over short (10's of m) horizontal distances. The observed changes may be related to perturbations in mixed-layer depth and concentration differences between mixed-layer water and North Atlantic water beneath it. For a similar scale and depth, the mean copper concentration was 77 $\pm$ 9 ng Cu/kg, with no significant trends observed.

Regional differences in copper concentration and gradients in these concentrations occurred in the vicinity of Iceland-Faroe Ridge. South of the Arctic Front, North Atlantic water had a concentration of 85 + 11 ng Cu/kg in the upper 800 m. An enrichment in copper concentration (112 + 6 ng Cu/kg) occurred at the Arctic Front. North of the Arctic Front copper concentrations and concentration gradients were greater than south of the front. Lobes of water with high copper concentration (100 to 110 ng Cu/kg and 120 to 140 ng Cu/kg) extended north into the Norwegian Sea. An eddy-like feature, whose core originated at the front, had copper concentrations similar to those observed at the front. Except for these copper-enriched areas, Norwegian Sea water copper concentrations in the upper 800 m were generally from 80 to 90 ng Cu/kg. While some copper-enriched water was clearly the result of circulation and mixing processes, mechanisms causing enrichments in other areas require other processes, possibly including mid-depth regeneration from biogenic material.

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Appendix A. Station data.

Depth (m)	Θ (°C)	S (°/oo)	O_2 (ml/l)	$NO_3 + NO_2$ (μM)	PO_4 (μM)	Cu (ng/kg)	mean Cu (ng/kg)
Station 011; 60°32'N, 16°34'W.							
55	10.988	35.202	-	3.8	-	64, 66	65
76	9.335	35.252	-	14.3	-	83, 84	84
102	9.206	35.267	-	14.0	-	76, 77	77
203	8.615	35.225	-	14.9	-	74, 77	76
500	7.852	35.211	-	15.2	-	80, 80	80
500**	7.852	35.211	-	15.4	-	218, 223?	221?
Station 015; 62°30'N, 15°02'W.							
26	11.384	35.199	6.127	-	-	84, 89	87
52	9.706	35.260	6.236	-	-	95, 96	96
74	9.034	35.274	9.725	-	-	1307?, 1310?	1309?
99	8.862	35.282	5.974	-	-	106, 108	107
122	8.762	35.286	6.064	-	-	96, 106	101
146	8.693	35.284	6.398	-	-	76, 77	77
171	8.642	35.283	6.588	-	-	401?, 401?	401?
200	8.539	35.277	6.356	-	-	87, 95	91
225	8.504	35.278	6.269	-	-	159?, 160?	160?
270	8.420	35.275	6.188	-	-	93, 93	93
298	8.213	35.243	6.362	-	-	72, 73	73
401	7.951	35.228	6.302	-	-	78, 80	79
497	7.760	35.212	6.246	-	-	96, 101	100
602	7.533	35.204	5.616	-	-	90, 91	91
696	7.387	35.187	6.069	-	-	83	83
792	7.125	35.165	6.221	-	-	88(94, 95)	92
890	6.530	35.119	6.575	-	-	104, 104	104
988	5.699	35.063	6.304	-	-	86, 88	87
1185	4.747	34.997	6.473	-	-	85	85
1385	4.144	34.959	-	-	-	144?, 144?	144?
1581	3.796	34.940	-	-	-	83	83
1777	3.452	34.953	-	-	-	80, 105?(86)	83

Appendix A (cont.).

Depth (m)	Θ (°C)	S (°/oo)	O_2 (ml/l)	NO_3+ NO_2 (µM)	PO_4 (µM)	Cu (ng/kg)	mean Cu (ng/kg)
Station 018; 63°37'N, 13°10'W.							
23	10.444	35.228	6.517	5.4	-	70, 73	72
47	10.441	35.229	6.429	5.6	-	76, 81	79
72	10.210	35.241	6.404	7.9	-	88, 93	91
99	9.577	35.255	6.348	10.1	-	71, 72	72
148	8.778	35.268	6.420	13.3	-	78, 79	79
154	8.454	35.269	6.364	14.5	-	70, 71	71
203	8.306	35.256	6.393	13.9	-	83, 87	85
206	8.193	35.252	6.446	15.0	-	72, 73	73
248	8.084	35.242	6.483	15.0	-	84, 87	86
301	7.938	35.231	6.497	15.3	-	79, 87	83
349	7.858	35.226	6.490	15.0	-	84, 86	85
400	7.761	35.219	6.506	15.0	-	85, 86	86
449	7.677	35.212	6.421	15.2	-	75, 78	77
511	7.516	35.199	6.449	15.4	-	87, 91	89
552	7.246	35.183	6.354	16.0	-	171?, 174?	173?
595	7.057	35.173	6.327	15.9	-	101, 102	102
646	6.373	35.136	6.338	16.4	-	87, 91	89
698	4.812	35.071	6.533	15.7	-	108, 113	111
Station 921; 64°32'N, 11°42'W.							
26	8.144	34.913	-	5.9	0.76	109, 113	111
51	7.235	34.717	-	6.4	0.78	113, 116	115
80	7.056	34.880	-	9.4	0.96	106, 113	110
101	5.742	34.863	-	12.7	1.15	116, 119	118
121	5.082	34.905	-	13.5	1.17	118, 120	119
149	4.615	34.939	-	14.4	1.17	108, 112	110
178	4.001	34.926	-	15.0	1.20	102, 106	104
202	3.502	34.921	-	15.2	1.27	116, 124	120
245	3.050	34.911	-	15.2	1.23	114, 116	115
347	1.679	34.853	-	13.5	1.08	99, 102	101

Appendix A (cont.).

Depth (m)	Θ (°C)	S (°/oo)	O_2 (ml/l)	NO_3+ NO_2 (µM)	PO_4 (µM)	Cu (ng/kg)	mean Cu (ng/kg)
Station 021; 64°43'N, 11°30'W.							
27	6.866	34.768	6.889	4.1	0.37	80, 83	82
53	6.218	34.772	6.858	5.9	0.64	90, 91	91
76	3.792	34.819	6.923	10.7	0.81	82, 84	83
102	3.000	34.865	7.019	13.4	0.90	97, 98	98
119	2.842	34.859	7.093	13.7	0.91	96, 97	97
148	2.418	34.863	7.157	14.0	0.93	142, 143	143
175	1.882	34.848	7.300	13.8	0.93	93, 94	94
204	1.464	34.858	6.994	14.3	0.96	91, 97	94
251	0.714	34.841	7.252	13.6	0.92	95, 99	97
298	0.425	34.858	7.138	14.2	0.96	85, 86	86
346	0.139	34.877	6.911	14.7	0.99	94, 95	95
398	0.015	34.888	6.892	14.3	0.95	93, 97	95
Station 022; 64°59'N, 10°56'W.							
25	7.384	34.674	7.033	1.6	0.18	82, 84	83
55	2.899	34.726	7.507	11.6	0.61	90, 92	91
75	2.112	34.743	7.652	12.5	0.67	88, 88	88
102	1.310	34.757	7.756	12.8	0.68	90, 91	91
123	0.888	34.769	7.649	13.5	0.70	97, 98	98
155	0.626	34.800	7.545	13.7	0.72	129, 130	130
169	0.417	34.814	7.430	14.2	0.75	84, 87	86
198	0.327	34.846	7.228	14.2	0.76	86, 90	88
247	0.221	34.874	7.135	15.0	0.80	95, 96	96
301	0.017	34.892	7.011	15.2	0.82	97, 99	98
398	-0.261	34.905	7.017	15.0	0.83	96, 100	98
492	-	-	7.011	15.1	0.83	108, 109	109

Appendix A (cont.).

Depth (m)	Θ (°C)	S (°/oo)	O_2 (ml/l)	NO_3+ NO_2 (µM)	PO_4 (µM)	Cu (ng/kg)	mean Cu (ng/kg)
Station 023; 65°10'N, 10°25'W.							
20	7.463	34.718	7.034	1.7	-	79, 90	85
29	6.947	34.765	7.039	2.9	-	77, 88	83
41	5.007	34.824	6.976	8.5	-	81, 83	82
51	4.393	34.872	6.895	12.8	-	83, 87	91±4
51*	-	-	-	-	-	84, 88*	
51*	-	-	-	-	-	93, 94*	
51*	-	-	-	-	-	91, 96*	
55	4.120	34.878	6.978	13.5	-	99, 101	100
61	4.283	34.928	6.954	13.7	-	99, 100	99±2
61*	-	-	-	-	-	97, 101*	
65	4.278	34.958	7.002	14.2	-	92, 97	95
71	4.214	34.964	6.733	14.4	-	99, 99	99
73	4.166	34.967	6.843	14.8	-	98, 99	99
76	3.917	34.952	6.941	14.8	-	98, 107	103
82	3.534	34.919	6.994	14.6	-	108, 112	110
90	3.360	34.918	7.036	15.3	-	107, 120	114
99	3.294	34.915	7.096	15.0	-	103, 108	113±10
99*	-	-	-	-	-	115, 127*	
138	1.987	34.844	7.436	14.7	-	106(105, 107)	106
163	1.599	34.844	7.483	14.1	-	389, 400	395
181	1.152	34.823	7.523	14.1	-	99, 99	99
181-P	1.152	34.823	-	-	-	103, 105	104
198	0.868	34.814	7.546	14.0	-	95, 100	98
252	0.371	34.835	7.257	15.5	-	103, 103	103
298	0.219	34.869	7.137	14.4	-	103, 106	105
396	-0.082	34.897	7.117	14.7	-	118, 124	121
493	-0.372	34.908	6.632	15.0	-	95, 96	97±2
493*	-	-	-	-	-	95, 98*	
493*	-	-	-	-	-	95, 99*	
493*	-	-	-	-	-	97, 100*	
531	-0.390	34.909	7.050	15.0	-	113, 119	116

Appendix A (cont.).

Depth (m)	Θ (°C)	S (°/oo)	O_2 (ml/l)	NO_3+ NO_2 (μM)	PO_4 (μM)	Cu (ng/kg)	mean Cu (ng/kg)
Station 026; 65°48', 8°20'W.							
21	7.247	34.655	7.105	1.4	0.19	600?, 628?	614?
39	4.184	34.613	7.657	10.6	0.63	85	79±7
39*	-	-	-	-	-	71, 80*	
53	2.117	34.690	7.726	12.0	0.71	79, 87	88±5
53*	-	-	-	-	-	90, 93*	
53*	-	-	-	-	-	86, 92*	
59	1.938	34.696	7.757	11.4	0.68	74, 79	77±2
59*	-	-	-	-	-	76, 77*	
69	1.681	34.713	7.787	12.3	0.74	91, 94	93
80	1.418	34.721	7.764	12.5	0.86	99, 106	103
88	1.378	34.733	7.759	12.5	0.84	86, 102	94
120	1.064	34.776	7.694	12.3	0.74	97, 102	100
138	0.771	34.784	7.599	12.8	0.77	84, 91	88
159	0.369	34.787	7.531	13.9	0.82	86, 95	91
178	0.291	34.806	7.575	14.4	0.83	84, 89	87
199	0.301	34.835	7.408	14.7	0.89	94, 105	96±6
199*	-	-	-	-	-	91, 92*	
222	0.314	34.856	7.243	15.1	0.89	111, 112	112
247	0.308	34.881	7.142	15.6	0.90	122, 131	127
275	0.259	34.889	7.104	15.5	0.93	87, 88	88
298	0.202	34.894	7.074	15.7	0.92	101, 109	105
395	-0.058	34.902	7.126	15.2	0.94	97(78, 80)	85±10
496	-0.284	34.907	7.097	15.6	0.92	95, 129	112
596	-0.407	34.908	7.191	15.0	0.87	86, 88	87
695	-0.499	34.910	7.167	15.3	0.90	102, 120	111
799	-0.601	34.912	7.159	15.7	0.92	104, 110	107
893	-0.660	34.912	7.140	15.8	0.93	91, 93	92
991	-0.739	34.913	7.155	16.0	0.93	93, 97	87±6
991*	-	-	-	-	-	83, 83*	
991*	-	-	-	-	-	82, 86*	

Appe dix A (cont.).

Depth (m)	Θ (°C)	S (°/oo)	O_2 (ml/l)	NO_3+ NO_2 (μM)	PO_4 (μM)	Cu (ng/kg)	mean Cu (ng/kg)
Station 030; 67°00'N, 5°00'W.							
31	8.203	34.883	6.985	1.6	-	86, 87	87
40	8.228	34.899	6.941	5.0	0.41	81, 83	82
50	5.335	35.012	7.277	14.8	0.77	94, 94	94
59	4.874	35.002	7.092	13.8	0.79	101, 102	102
79	4.180	34.960	7.369	13.6	0.77	96, 99	98
101	3.737	34.948	7.333	13.3	0.77	99, 103	101
120	3.436	34.939	7.552	13.5	0.77	103, 106	105
139	3.318	34.943	7.267	12.9	0.76	83, 98	95
159	3.114	34.933	7.445	13.2	0.83	82,110(101,104)	105
181	2.875	34.921	7.674	12.9	0.85	96, 102	99
206	2.820	34.930	7.746	12.7	0.82	86, 86	86
306	1.824	34.902	7.591	13.4	0.85	74, 75	95
404	0.976	34.901	7.440	14.3	0.93	83, 83	83
503	0.387	34.911	7.491	14.4	0.91	84, 85	85
746	-0.276	34.914	7.220	15.3	1.16	93,115(100,126)	109±15
994	-0.597	34.914	7.195	15.2	1.01	107, 112	110
1969	-1.017	34.911	7.423	15.4	1.79	105, 110	108
2315	-1.047	34.911	-	-	-	98, 102	100
2328	-1.047	34.912	-	-	-	216, 216	216?
2346	-1.047	34.912	-	-	-	112, 114	113
2361	-1.047	34.911	-	-	-	82, 84	83
2384	-1.047	34.911	-	-	-	104, 114	109

Appendix A (cont.).

Depth (m)	Θ (°C)	S (°/oo)	O_2 (ml/l)	NO_3+ NO_2 (µM)	PO_4 (µM)	Cu (ng/kg)	mean Cu (ng/kg)
Station 034; 65°17'N, 5°18'W.							
49	7.075	34.932	6.619	7.5	-	91, 94	93
99	3.849	34.898	7.007	13.5	-	90, 94	92
201	2.706	34.887	7.327	13.0	-	85, 89	87
303	2.162	34.906	7.229	13.9	-	98, 103	101
745	-0.205	34.915	7.004	11.8	-	106	106
991	-0.572	34.914	7.003	12.2	-	129, 132	131
1484	-0.877	34.913	-	-	-	102, 109	106
1970	-0.998	34.912	-	-	-	106, 115	111
2954	-1.047	34.913	-	-	-	107, 107	107
3843	-1.047	34.913	-	-	-	107, 107	107

* Multiple 1ℓ samples taken from the same Go-Flo bottle.
** Second rosette bottle at same depth.
? Suspect contamination.
-P Go-Flo bottle mounted above plastic-coasted stainless steel ninger.
( ) Reextraction of same sample on different day.

Appendix B. Station 015; 62 30'N, 14 57'W. Rosette tow for copper. Samples were collected at 50 m at an approximate horizontal spacing of 15 m. See figure 14 for accompanying CTD data obtained before and after sample collection.

Sampling Order	Cμ (ng/kg)		Cμ (ng/kg)
1	69, 71		70
2	65, 66		66
3	103, 107		105+
4	64, 74		69
5	64, 83		74
6	86, 86	(71, 85) (88, 98) (81, 82)	85 ± 8
7	71, 72		72
8	88, 89		89
9	98, 98		98
10	78, 79		79
11	76, 76		76
12	80, 81	(79, 80) (74, 80) (81, 87)	80 ± 4
13	71, 75		73
14	84, 87		86
15	---		---
16	78, 83		81
17	80, 81		81
18	68, 70	(88?, 159?) (74, 75) (70, 76)	72 ± 3
19	60, 62		61
20	65, 74		70
21	75, 85		80
22	144, 149		147+
23	---		---
24	69, 69	(80, 82) (86, 92) (91, 93)	83 ± 10
Mean			77 ± 9

( ) Multiple 1 ℓ samples taken from the same Go-Flo bottle.
? Suspect contamination; value excluded from mean calculations.

Appendix C. Station 018; 63°36'N, 13°13'W. Multiple drop rosette cast. Four cycles between 50 and 300 m were made to obtain four successive profiles. All samples were collected within 13 minutes.

Profile	Depth (m)	Θ (°C)	S (o/oo)	Cμ (ng/kg)	mean Cμ* (ng/kg)
1st	52	10.243	35.253	67, 71 (72,77) (71,74) (73,75)	73 ± 3
	98	9.172	35.275	130, 140	135
	150	8.561	35.280	79, 88 (84,93)	86 ± 6
	199	8.374	35.271	86, 86	86
	248	8.242	35.262	82, 90 (91,105)	92 ± 10
	300	8.071	35.251	103, 106	105
2nd	50	10.250	35.250	64, 66 (71,73) (68,69) (70,81)	70 ± 5
	100	9.134	35.274	100, 100	100
	152	8.540	35.277	87, 92	90
	199	8.374	35.271	93, 93	93
	249	8.242	35.262	84, 84 (93,98)	90 ± 7
3rd	52	10.243	35.253	68, 70 (79,81) (80,82) (76,80)	77 ± 5
	97	9.178	35.276	82, 84	83
	152	8.540	35.277	93, 94 (108,108)	101 ± 8
	200	8.371	35.271	79, 79	79
	248	8.242	35.262	86, 89 (101,102)	95 ± 8
	299	8.075	35.252	87, 88	88
4th	49	10.255	35.250	87, 90 (76,78) 81,89) (79,79)	82 ± 5
	98	9.172	35.275	75, 77	76
	149	8.573	35.279	78, 79 (93,97)	87 ± 10
	199	8.374	35.271	80,80	80
	246	8.243	35.261	78, 82 (83,84)	82 ± 3
	300	8.071	35.251	78, 79	79

( ) Multiple 1 ℓ samples taken from the same Go-Flo bottle.

* One sigma deviations listed for samples with n>2.

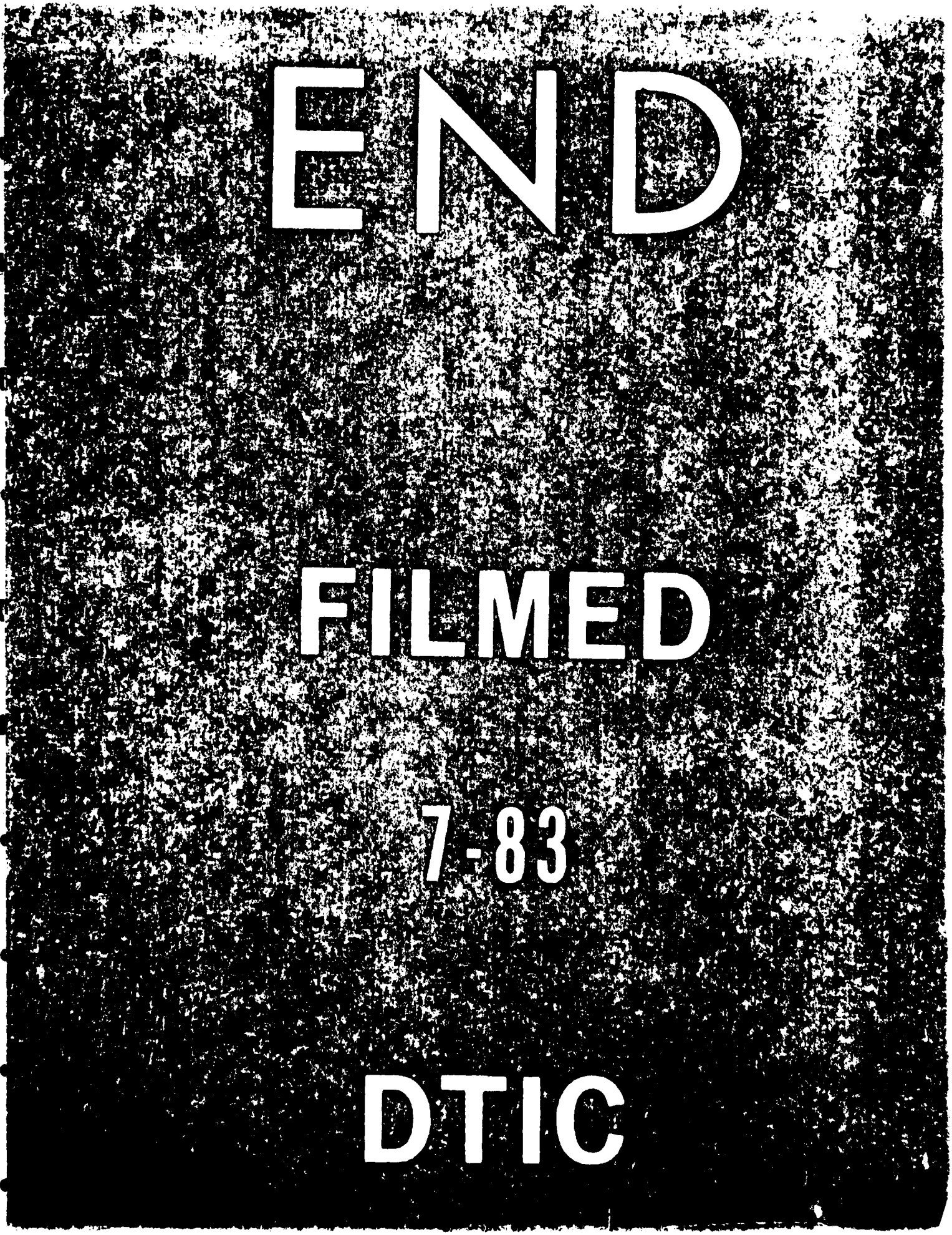
Appendix D. Station 012; 61°00'N, 16°07'W. Rosette tow for mercury. Samples were collected at 50 m. See figure 16 for accompanying CTD data obtained before and after sample collection.

Sampling Order	Hg (ng/l)	mean‡ (ng/l)
1	145 ± 22; 250	@
2	111 ± 17; 92 ± 15	102 ± 17
3	74 ± 12; 92 ± 15	83 ± 15
4	153 ± 22; 138 ± 20	146 ± 22
5	75 ± 13; -----	75 ± 13
6	75 ± 13; 75 ± 13	75 ± 13
7	98 ± 16; 132 ± 20	115 ± 20
8	400*; 680*	@
9	111 ± 17; -----	111 ± 17
10	92 ± 15; -----	92 ± 15
11	98 ± 16; 92 ± 15	95 ± 16
12	132 ± 20; 117 ± 17	125 ± 20
13	7 ± 5; 7 ± 5	7 ± 5
14	4 ± 5; 7 ± 5	6 ± 5
15	4 ± 4; 11 ± 6	8 ± 6
16	16 ± 8; 4 ± 4	10 ± 8
17	7 ± 5; 25 ± 10	16 ± 10
18	86 ± 14; 250*	@
19	145 ± 22; 425*	@
20	69 ± 12; 153 ± 23	@
21	124 ± 18; 92 ± 15	108 ± 18
22	92 ± 15; 92 ± 15	92 ± 15

* Suspect contamination.
@ Difference between duplicates is greater than reported deviation.
‡ Mean of duplicate samples listed; deviation reported is the greater deviation listed for each sample. Where only one sample concentration is available, it and its deviation is also listed in this column.

Distribution List

UNSECDEF (R&E)	1
ASN, R, E&S	1
CNO (Op-02, -21, -95, -95T, -952)	10
COMNAVOCEANCOM	2
CNR (Code 103T, 480)	2
NISC	1
NORDA	2
NRL	3
NUSC	2
NAVPGSCOL	2
NFOIO	1
DARPA	1
DIRSSP (SP-202, -2025)	4
DTIC	12
APL/JHU (STE)	6


END
FILMED
7-83
DTIC