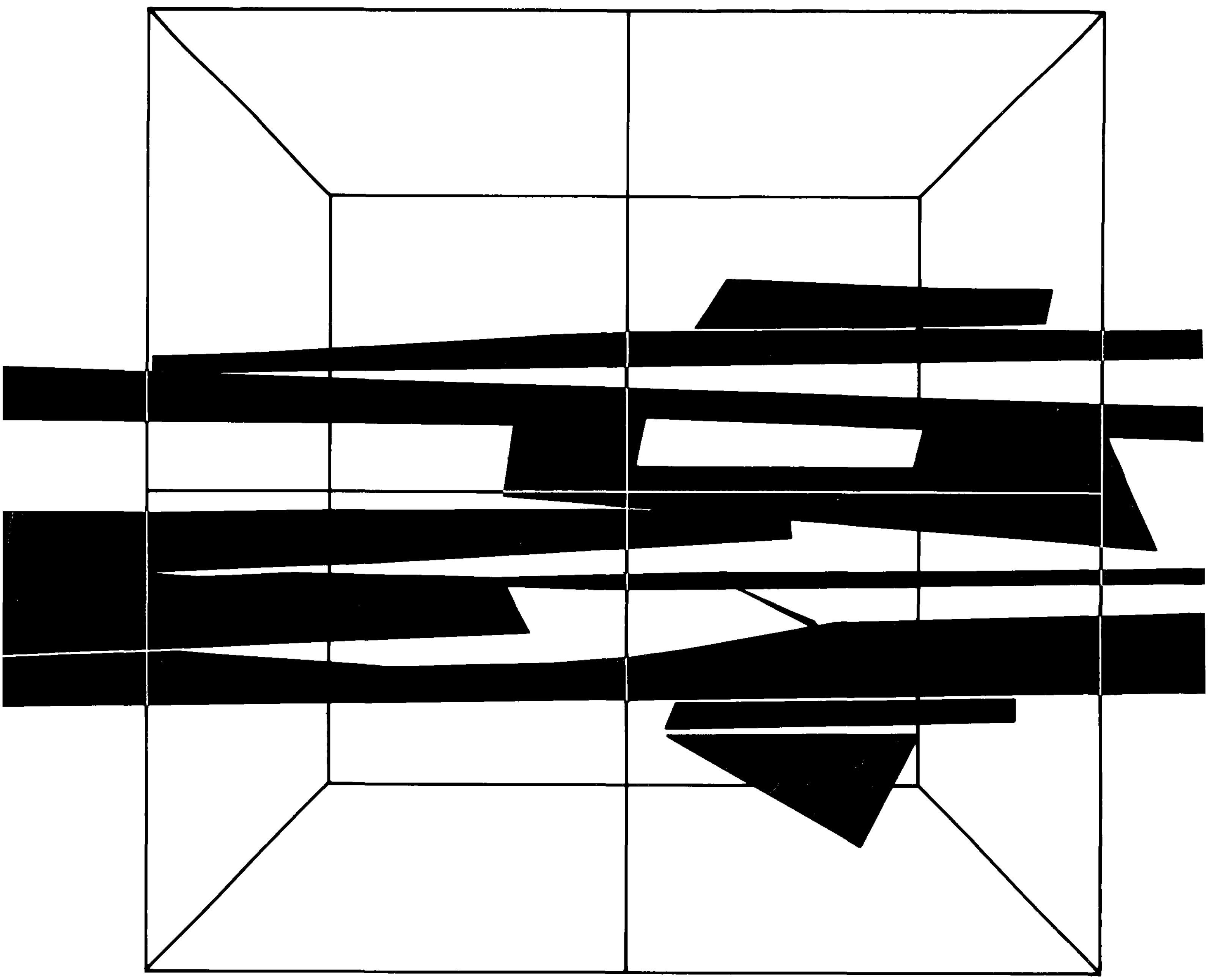
Oceanographic Conditions Suitable for the Sinking of Oil

Report EPS 3/SP/2
May 1986



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OCEANOGRAPHIC CONDITIONS SUITABLE FOR THE SINKING OF OIL

by

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Environment Canada

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ABSTRACT

The density of Canada's surface coastal waters generally varies in the range of 1.022 to 1.027 g/mL, requiring oil to have this density or greater in order to sink in most regions. Freshwater inputs, however, reduce the density to as low as 1.000 g/mL over localized areas. Temperature has a much lesser effect on seawater than salinity (maximum effect of 0.5% versus 3% for salinity) but its seasonal effect is widespread.

Along Canada's Atlantic coast, ice melt at high latitudes and river run-off at lower latitudes are the primary sources of low density water. The most distinctive feature is the decreased density resulting from the influence of the St. Lawrence River on waters in the estuary, around Prince Edward Island and near the Strait of Canso.

In the Arctic Archipelago, ice melt, from either the edge of pack ice, land run-off or glacial melt, is the major factor in reducing density. This creates regions of high variability and often strong horizontal and vertical gradients.

Hudson Bay behaves like a semi-enclosed estuarine system with the many rivers emptying into it and has reduced densities throughout (often in the range 15 to 20 σ_t). In the western Arctic, by far the largest density feature is the Mackenzie River outflow and plume structure which decreases the surface water density throughout most of the Beaufort Sea.

High rainfall and river run-off largely determine the surface density patterns along Canada's Pacific coast. Densities are particularly low in the Strait of Georgia, where densities below 10 σ_t can be observed near the Fraser River plume.

The behaviour of oil once it sinks will be determined by the vertical density structure. Very dense oil (>27 σ_t) would sink to the bottom in most coastal waters. Oil of density 20 to 27 σ_t may become neutrally buoyant at an intermediate depth in the summer on a seasonal pycnocline (created by solar warming of surface waters). More dramatically, freshwater input often creates very strong pycnoclines at depths up to 20 m. Less dense oil (0 to 20 σ_t) would sink here but would become 'trapped' at the pycnocline. Oil, once it has sunk to an intermediate depth of neutral buoyancy, will move with the water body, often in a manner quite contrary to any associated surface slick.

SIGMA-t (σ_t) - a method of presenting the significant digits of water density. Sigma-t (σ_t) is equivalent to (Density - 1.0)x 10^3
Example: A density of 1.0250 g/mL = 25.0 σ_t

RÉSUMÉ

La masse volumique des eaux littorales superficielles au Canada varie généralement entre 1,022 g/ml et 1,027 g/ml, ce qui signifie que le pétrole doit en général avoir une masse volumique égale ou supérieure à ces valeurs pour s'enfoncer dans l'eau. Des apports d'eau douce peuvent toutefois abaisser la masse volumique jusqu'à aussi peu que 1,000 g/ml dans des zones localisées. La température a beaucoup moins d'effet sur l'eau marine que la salinité (effet maximal de 0,5 p. 100 contre 3 p. 100 pour la salinité), mais son effet saisonnier est généralisé.

Le long de la côte atlantique du Canada, la fonte des glaces aux hautes latitudes et l'écoulement des cours d'eau aux basses latitudes sont les principales sources d'eaux de faible densité, notamment dans l'estuaire du Saint-Laurent, autour de l'Île-du-Prince-Édouard et près du détroit de Canso.

Dans l'archipel arctique, l'eau de fonte provenant de la glace de dérive, du ruissellement terrestre ou des glaciers constitue le principal facteur de réduction de la densité, donnant lieu à des conditions très variables et à des gradients horizontaux et verticaux souvent forts dans certaines régions.

La baie d'Hudson se comporte comme un système estuarien semi-fermé; les nombreux cours d'eau qui s'y déversent diminuent les densités partout (souvent de l'ordre de 15 σ_t* à 20 σ_t). Dans l'Arctique occidental, c'est le débit du Mackenzie et la structure de son panache, qui influent le plus sur la masse volumique, réduisant celle des eaux de surface dans la plus grande partie de la mer de Beaufort.

Les fortes chutes de pluie et l'écoulement des cours d'eau déterminent dans une grande mesure comment se répartissent les densités en surface, le long de la côte du Pacifique au Canada. les densités sont particulièrement faibles dans le détroit de Géorgie, où elles peuvent être inférieures à 10 σ_t du panache du Fraser.

Le comportement du pétrole dès qu'il s'enfonce est déterminé par la structure verticale de la densité. Les pétroles à densité élevée (> 27 σ_t) atteignent en général le fond dans les eaux côtières. Le pétrole ayant une densité de 20 σ_t à 27 σ_t peut se maintenir entre deux eaux en été sur une pycnocline saisonnière (due au réchauffement solaire des eaux de surface). Plus radicalement, il arrive souvent qu'un apport d'eau douce donne lieu à de très fortes pycnoclines à des profondeurs atteignant 20 m. Du pétrole moins dense (0 σ_t à 20 σ_t) s'enfoncerait à ces profondeurs, mais pourrait être "piégé" dans la pycnocline. Le pétrole, une fois descendu entre deux eaux, peut se déplacer avec la masse d'eau, souvent tout à fait à l'inverse de toute nappe associée en surface.

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* σ_t (sigma-t): symbole utilisé pour représenter la valeur significative de la densité de l'eau. σ_t équivaut à la masse volumique à laquelle on soustrait 1,0 et qu'on multiplie par 10^3. Exemple: une masse volumique de 1,0250 g/ml égale 25,0 σ_t.

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1 INTRODUCTION

1.1 Factors Affecting the Sinking of Oil

Historically, the behaviour of oil spills has indicated that under certain environmental conditions, oil can sink below the surface. In 1966, a damaged tanker, the Anne Mildred Brovig, released 125 000 barrels of Iranian crude into the North Sea which disappeared before cleanup crews could reach the site. After two tankers collided in San Francisco Bay in 1971, Bunker C fuel oil was rapidly incorporated into near-bottom waters, to be transported independently from the surface slick. Following the wreck of the Amoco Cadiz in 1978, emulsified oil was found to be homogeneous throughout the water column and contamination of bottom sediments had occurred. While monitoring the Hastab 6 well blowout in 1980, off of Saudi Arabia, divers reported seeing layers of oil suspended several metres below the surface.

The purpose of this document is to provide information on where spilled oil might be expected to sink in Canadian territorial waters. Since the specific gravity of crude oils varies from 0.75 to 1.0, and seawater from 1.000 to 1.030, virtually all crude oils, and all refined products except for the heaviest of residual oils, will initially float at sea.

Most weathering processes acting on spilled oil, however, increase its density. Water-in-oil emulsification immediately increases the density of the emulsified lump to a weighted average of the oil and seawater. Evaporation and dissolution preferentially remove the lighter components up to boiling points of about 370°C. Bacterial degradation preferentially removes the paraffins, which are the lightest class of compounds, and so further increases its density. The actual cell weight of the bacteria also increases the density of the oil-bacterial mass. Spooner (1971) reported that bacteria created a brew of approximately neutral buoyancy in laboratory experiments, and after several weeks found the oil largely on the bottom, entangled with bacterial masses. Kinney et al. (1969) observed the same with water-in-oil emulsions in the natural environment. Jordan and Payne (1980) reported an example of Kuwait crude and Iranian heavy crude, both with an initial density of 0.869 g/mL which, upon weathering, created a residue to density 1.023 and 1.027 g/mL respectively.

As long as the density of spilled oil is less than 1.0 g/mL, the oil will tend to float, but if its density exceeds this, the oil may sink depending on oceanographic conditions. This report deals with the conditions which decrease seawater density, thereby encouraging the sinking of oil. The density of seawater is dependent on its temperature and salinity, and varies over a range of 1.00 to 1.03 g/mL. The major processes which may give rise to lower density surface water features are discussed in a general way in the following sections, as a prelude to detailed area-specific discussions covering the Atlantic, Arctic and Pacific coasts in the ensuing chapters.

1.2.1 **Contribution of Salinity.** Large magnitude density changes in seawater (up to 3%) can result over localized areas from decreased salinity due to freshwater influence. The two major sources of fresh water in Canadian coastal regions are river run-off and ice melt:

(a) **River Run-off.** River run-off introduces fresh water to coastal regions creating an estuary. Figure 1 schematically displays the four classifications of estuaries. The salinity distribution is shown but density behaves similarly. The nature of an estuary depends on the volume flow of the river and the depth of the channel. The volume of fresh water supplied will vary seasonally and could result in up or downstream movement of the longitudinal density distribution.

In Figure 1, Type A shows a net movement of water out at all depths with a uniform density with depth. This occurs only in very shallow estuaries where mixing, as a result of friction of the flow along the bottom, can extend to the surface. A spill of low density oil would tend to move out to sea at the surface. Oil dense enough to sink would also move seaward.

Type B shows a net movement out at the surface and in at the bottom. Oil at the surface will be transported out to sea. Since a vertical density gradient now exists, oil or intermediate density may settle on a density surface to be transported upstream.

Type C, or fjord type, has a distinct two-layer system with seaward movement at the surface, slight upstream flow at the boundary, but with a relatively isolated deep layer. Since the boundary between the two layers is very distinct, oil of intermediate density may come to rest there. Very dense oil would sink through to the bottom layer and be subject to limited movement.

Type D, or salt wedge type, is seen in rivers with large volume flows enabling a distinct freshwater layer to remain at the surface. In these estuaries, oil of intermediate density will become concentrated at the tip of the salt wedge no matter where it is split along the estuary. The pollutant will sink out of the surface

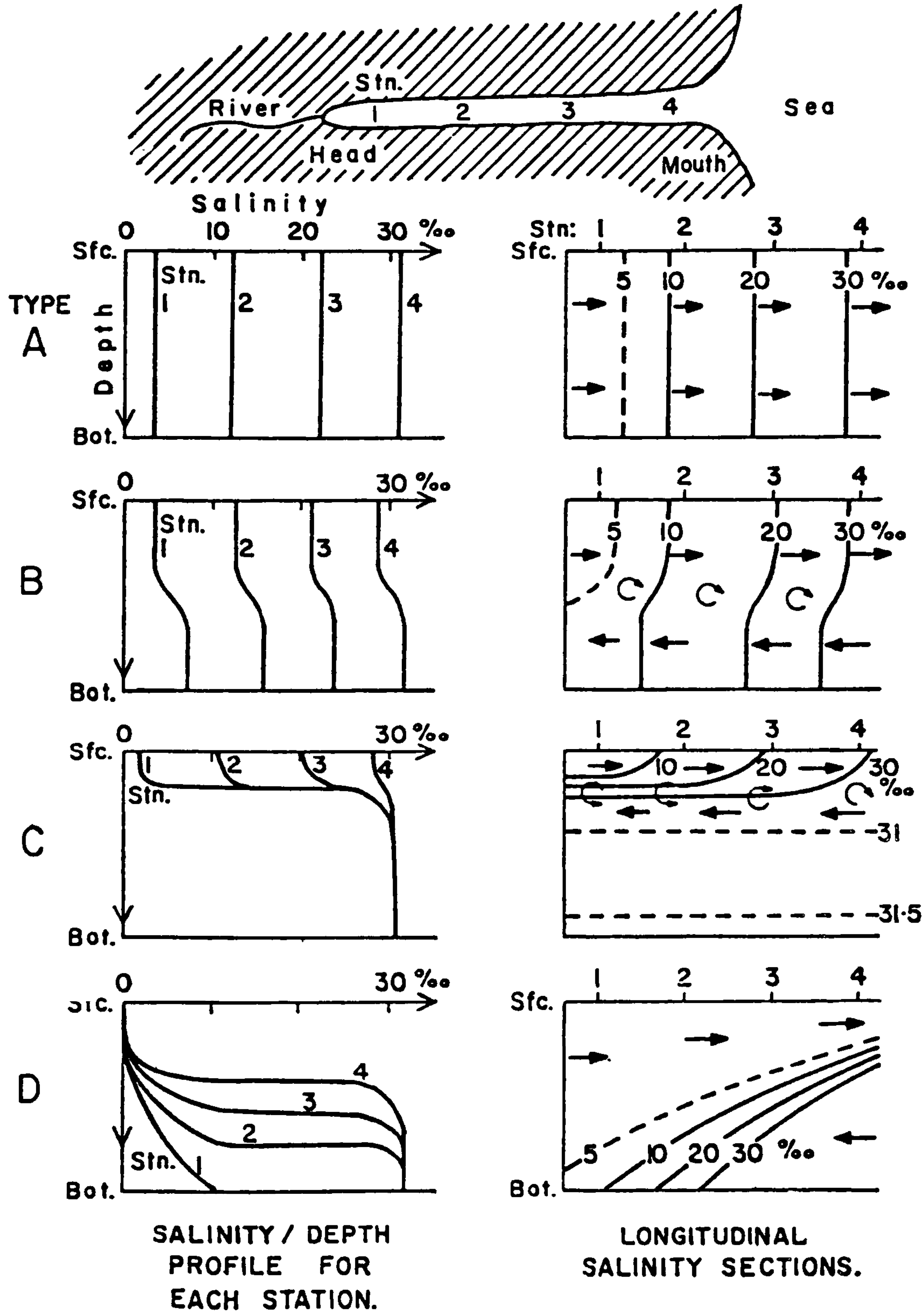


FIGURE 1 TYPICAL SALINITY/DEPTH PROFILES AND LONGITUDINAL SALINITY SECTIONS IN ESTUARIES (Pickard, 1975)

layer and, if lighter than the central wedge, will be carried up the estuary until the density reduction allows it to sink at or near the tip of the salt wedge.

(b) **Ice Melt.** At high latitudes, the seasonal freezing of surface waters and the ice melt in spring and summer cause major changes in surface density patterns. Ice melt creates a shallow freshwater layer below which the density increases rapidly. A seasonal freshwater pulse resulting from the ice melt may travel extensively. On the east coast of Canada its signature has been traced from Hudson Strait along the Labrador Shelf to the Grand Banks of Newfoundland, though at this point its impact on density is minimal compared with temperature.

1.1.2 Contribution of Temperature. Along Canada's Atlantic and Pacific coasts, except for very localized areas near the mouths of rivers, the changes in near-surface temperature are responsible for most of the observed seasonal density fluctuations, as a result of seasonal solar heating patterns. At high latitudes, the intensity of these seasonal changes is reduced.

A typical seasonal pattern of near-surface temperature, which will result in density changes of up to 5 mg/mL or 0.5% is shown in Figure 2. The region of rapid decrease of temperature with depth is known as the thermocline. The seasonal picture results from shifts in the balance between the stratifying influence of solar heating and the mixing influence of winds. In winter, represented by the March profile, there is little solar heating and high wind activity resulting in a well-mixed (uniform) cold (dense) surface layer extending to the bottom or to a permanent thermocline. From spring to summer, solar heating increases, wind activity decreases, and a warm, shallow surface layer develops producing a seasonal thermocline. As this stratification proceeds, it becomes more difficult for winds to mix the water column. During the fall, solar heating is reduced and the surface waters begin to lose heat by radiation to the overlying colder air. The surface water density increases and the surface water sinks, causing convective mixing. At the same time, wind strength and wave influence increase which, along with convection, increase the depth of the thermocline and reduce the average temperature of the surface mixed layer. Radiative heat loss is reduced as the temperature difference between air and sea lessens. This process continues until the depth of the surface mixed layer extends to the limit of wind influence or to the maximum extent of deep convection mixing. This annual process then begins again in the spring.

In general, the effect of temperature on density is less dramatic than salinity but more extensive, causing a seasonal change of about 0.3% (up to 0.5%) in the density of

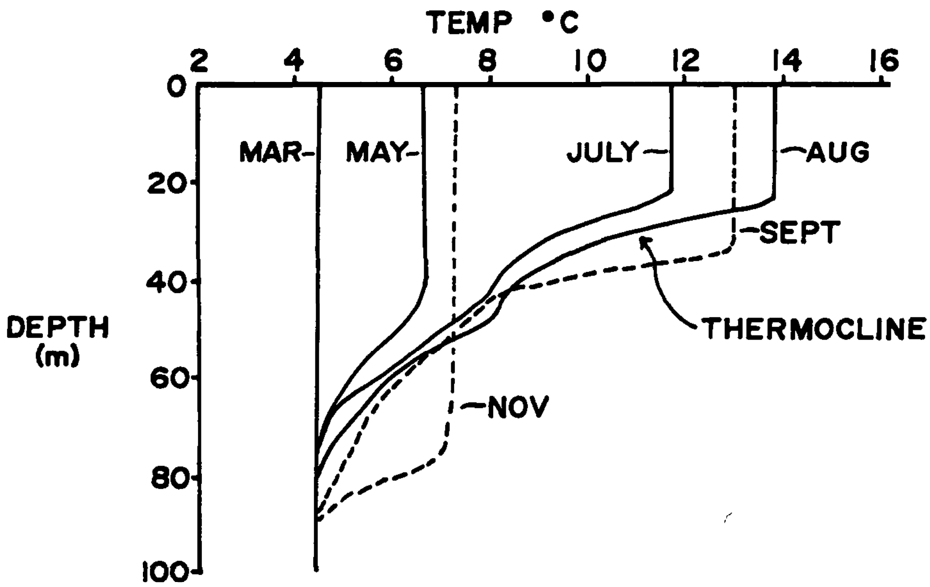


FIGURE 2 TYPICAL SEASONAL PATTERN OF SURFACE WATER TEMPERATURES ON THE ATLANTIC AND PACIFIC COASTS

seawater off the east and west coasts. The temperature effect is smaller on the Arctic coast because the seawater temperature changes are smaller, and because fluctuations at low temperatures have a lesser effect on density.

1.1.3 Disruptive or Mixing Processes. The density features expected from temperature and salinity considerations may be distorted or altered by various mixing processes.

(a) **Upwelling and Downwelling.** In the northern hemisphere, wind driven surface currents have a net depth integrated water transport 90° clockwise from the wind direction. When the wind blows alongshore with the land on the right, therefore, surface waters 'pile up' against the shore. As the surface and nearshore waters are generally less dense, this results in a concentration and deepening (downwelling) of the less dense water nearshore. In summer, the prevailing southerly winds would produce this effect along the western shores of the main north-south oriented coastlines. These therefore represent relatively favorable conditions for the concentration and sinking of oil.

The reverse process is upwelling, which occurs whenever surface waters are forced away from a boundary, or when deep water is forced towards a boundary and has to move upwards. Since density tends to increase with depth, this results in the observation of higher than expected densities at the surface near the boundary.

(b) **Fronts.** Fronts are areas where very rapid changes in the horizontal distributions of water properties occur. In the open ocean their width is typically less than 10 km and on the order of metres in such areas as estuaries. Fronts are often associated with a shift from horizontal density surfaces to almost vertical ones. Fronts may also be associated with boundaries between waters of different sources and upwelling events. In estuaries or shallow seas they can result from having vertically mixed water on one side and stratified water on the other. The circulation near fronts can show convergences and downwelling allowing for concentration of light or buoyant objects.

(c) **Currents and Tides.** Currents and tides can induce vertical mixing (i.e., disrupt stratification) as a result of friction with the bottom or between moving layers. In shallow areas, this bottom friction can result in a uniform water column (e.g., on top of shallow banks and in type A estuaries). In areas of high tidal range, as in the Bay of Fundy, shallow sea fronts may develop between well-mixed and stratified waters with their location often linked with specific bathymetric features. Tides will cause a periodic movement, back and forth, of property contours and increase horizontal mixing. The flow of water of one density over that of another will tend to smooth the density difference at the boundary from a sudden jump to a gradual change.

(d) **Tidelines.** Tidelines are lines of surface water convergence, often at the junction of two opposing currents. Isopycnals (i.e., surfaces of equal density) are generally steeply sloped here, facilitating the vertical motion of water. At the tideline one water mass sinks beneath the other and floating debris is concentrated on the surface. Neutrally buoyant oil in the less dense water mass could sink at the tideline.

(e) **Density Currents.** The most common form of density currents are tidal jets which penetrate inlets on the flood tide. Dense oceanic water brought to the inlet mouth by the flood tide will sink to an equilibrium depth in the inlet. A zone of convergence may develop where the density current separates from the surface. As with tidelines, this convergence concentrates surface debris, including buoyant oil. Oil of neutral buoyancy would be entrained into the sinking jet.

(f) **Internal Waves.** The density surfaces in a pycnocline (i.e., a region of rapid increase of density with depth) may undergo vertical oscillations similar to surface waves. These "internal waves" are smoother and longer than surface waves and are often generated at boundaries. For example, the movement of the tide over a rapid depth change such as a shelf/slope break acts as a paddle moving back and forth and generates internal waves. Internal waves can cause a 10 to 20 metre vertical displacement of the pycnocline. Any object or fluid sitting on or in the pycnocline will undergo a similar motion. This motion is not reflected in any displacement of the sea surface.

Zones of convergence develop over the internal wave troughs. The less dense surface layer deepens here and neutrally buoyant material sinks. These convergence zones would concentrate neutrally-buoyant oil at or just below the surface.

(g) **Langmuir Circulation.** Langmuir circulation cells are believed to be a result of the interaction between wave-induced Stokes drift (due to non-closure of wave orbital velocities) and the wind driven surface current. Alternate bands of convergence and divergence develop with length scales on the order of tens of metres. They are evident as streaks of foam and debris aligned as windrows along the direction of the wind. As with other zones of convergence, they serve to concentrate floating material. Neutrally buoyant oil could sink in a convergence zone, only to reappear in the nearby divergence zone of upwelled water. The net displacement is downwind, but in a corkscrew-like motion. As the range of wind velocities under which these rows develop is limited, and as the presence of oil on the surface may disrupt their formation, this phenomena may not contribute greatly to the observed behaviour of an oil spill.

2 THE ATLANTIC COAST

The Atlantic Coast of Canada is characterized by the variability in its bathymetric features and by the presence of strong currents which can transport water over very long distances. The 200 mile sovereignty limit often lies near the edge of the continental shelf where a sudden increase in depth from an average 200 metres to several thousand occurs. This break is often the meeting site of different water masses, the establishment of fronts and the boundary of strong currents. The large north-south extent of the coastline requires understanding of the latitudinal dependence of seasonal processes, such as solar heating, in determining local hydrographic properties and in altering properties of water moving north or south.

The general current pattern along the Atlantic Coast is summarized in Figure 3. The presence of gyres result from bathymetric constraints and Coriolis effects on the flows. Mixing with adjacent waters, and latitudinal changes in solar heating may alter the source properties of water carried by currents. Local bathymetric features may disrupt the current flow, cause vertical mixing and change the stratification of the water column. Local river run-off may freshen the surface layer sufficiently to be observed in the density signature.

The East Coast of Canada may be separated into five regions for discussion:

1) Baffin Bay, perhaps more Arctic in its grouping, but included here due to continuity of its waters and current pattern with the Labrador Shelf;
2) the Labrador Shelf, with its strong current pattern and polar influence on the hydrography;
3) the Grand Banks and Flemish Cap, whose topography influences the vertical and horizontal density patterns;
4) the Gulf of St. Lawrence, the only area whose circulation and hydrography are greatly affected by fresh river water run-off; and
5) the Scotian Shelf and Bay of Fundy, where tides and intermingling of various waters create many density features such as fronts, regions of upwelling, gyres, etc.

2.1 Baffin Bay

Baffin Bay consists of a deep basin (down to 2400 m) constrained by wide shallow banks extending 400 kilometres from the Greenland Coast and a narrow shelf (less than 200 m deep) along Baffin Island. A sill at 700 m separates the basin from the Labrador Sea to the South, while several channels enter it to the North.

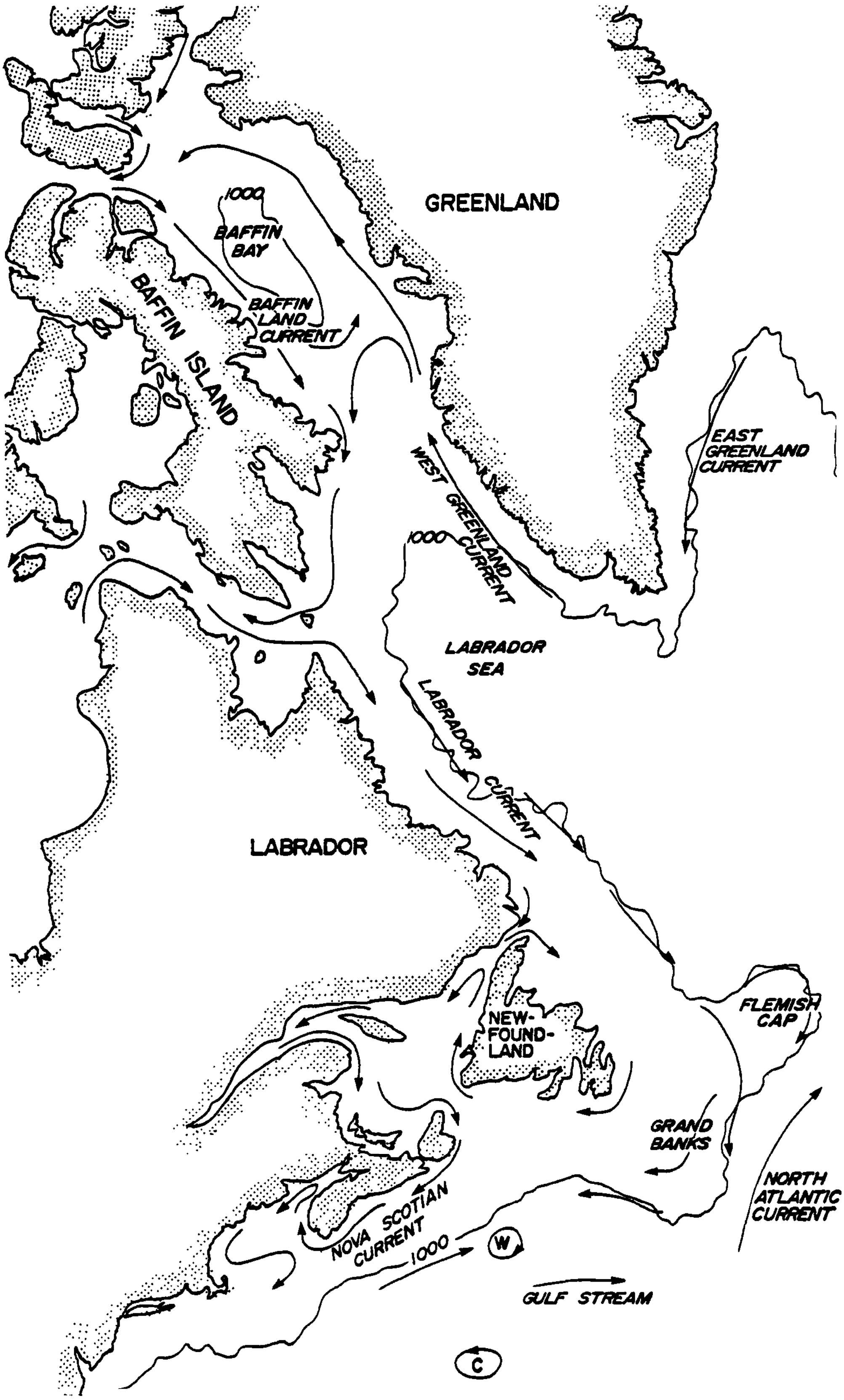


FIGURE 3 GENERAL CURRENT PATTERNS ALONG THE ATLANTIC COAST OF CANADA

South of Lancaster Sound, the general circulation is a large cyclonic (i.e., counterclockwise) gyre in the surface waters with little or no circulation below 1000 m. The surface waters are greatly affected by run-off from Greenland and low salinity tongues can be seen along this coast. In northern Baffin Bay, the West Greenland Current (27.65 to 27.8 σ_t) centred over the slope, is sluggish and drifts towards the West. Its northward extent is variable from year to year. Here it meets Arctic Water (<0°C, 32.5 to 33.7°/oo, 26.2 to 27.1 σ_t) from the North merging to form the Baffin Current. The current intrudes Lancaster Sound then continues south along the Baffin Island coast, concentrated at the shelf break. This current is characterized by cold, lower salinity Arctic water (0 to 2°C, 33.7 to 34.5°/oo, 27.1 to 27.6 σ_t) in the top 300 metres.

At Davis Strait, some of the Baffin Current turns east to close the gyre and to mix with the Atlantic water flowing in. This circulation pattern results in a surface layer 0 to 25 m deep affected by local climatic and ice conditions (-1.0 to 5.0°C, 25 to 33.5°/oo, 20 to 27 σ_t) overlying a cold, upper layer of Arctic water (25 to 300 m deep). The surface 25 m is extremely variable with observed measurements dependent on recent climate and ice history.

The water north of Lancaster Sound is characterized by the almost exclusive presence of Arctic water. In the East, this Arctic water is formed locally (to 150 m in the winter) as a result of freezing which releases salt, thereby increasing surface layer density and creating an unstable situation. In the West, the Arctic water is advected in from Smith, Jones and Lancaster Sounds. In this region and southern Smith Sound, the "North Water" is found. This is a large, open water polynya (i.e., a large, ice-free "lake" surrounded by pack-ice) which persists throughout the winter, possibly as a result of mechanical removal of ice by winds and currents and restraining of ice by ice dams in the North. The warmest surface waters are often seen here in the summer (up to 5°C) from solar heating of the ice-free surface, but densities remain high due to high salinities (~26.2 σ_t). Salinity is the major controlling factor of density in the Arctic at the low water temperatures experienced there.

2.1.1 Vertical Density Gradients. Representative summer vertical density profiles in Baffin Bay are shown in Figure 4. A strong pycnocline in the top 25 m can sometimes be seen. Profile 1 was taken in the "North Water" region where surface temperatures were 5°C, salinities 33.1°/oo with little density reduction. Profile 2, under the influence of recent ice melt, had very cold but fresh surface water (-0.18°C, 25.4°/oo) hence lowered densities. Ice melt acts to reduce surface water temperature while reducing salinity. Profile 3 was an intermediate situation with temperatures at 3°C and salinities

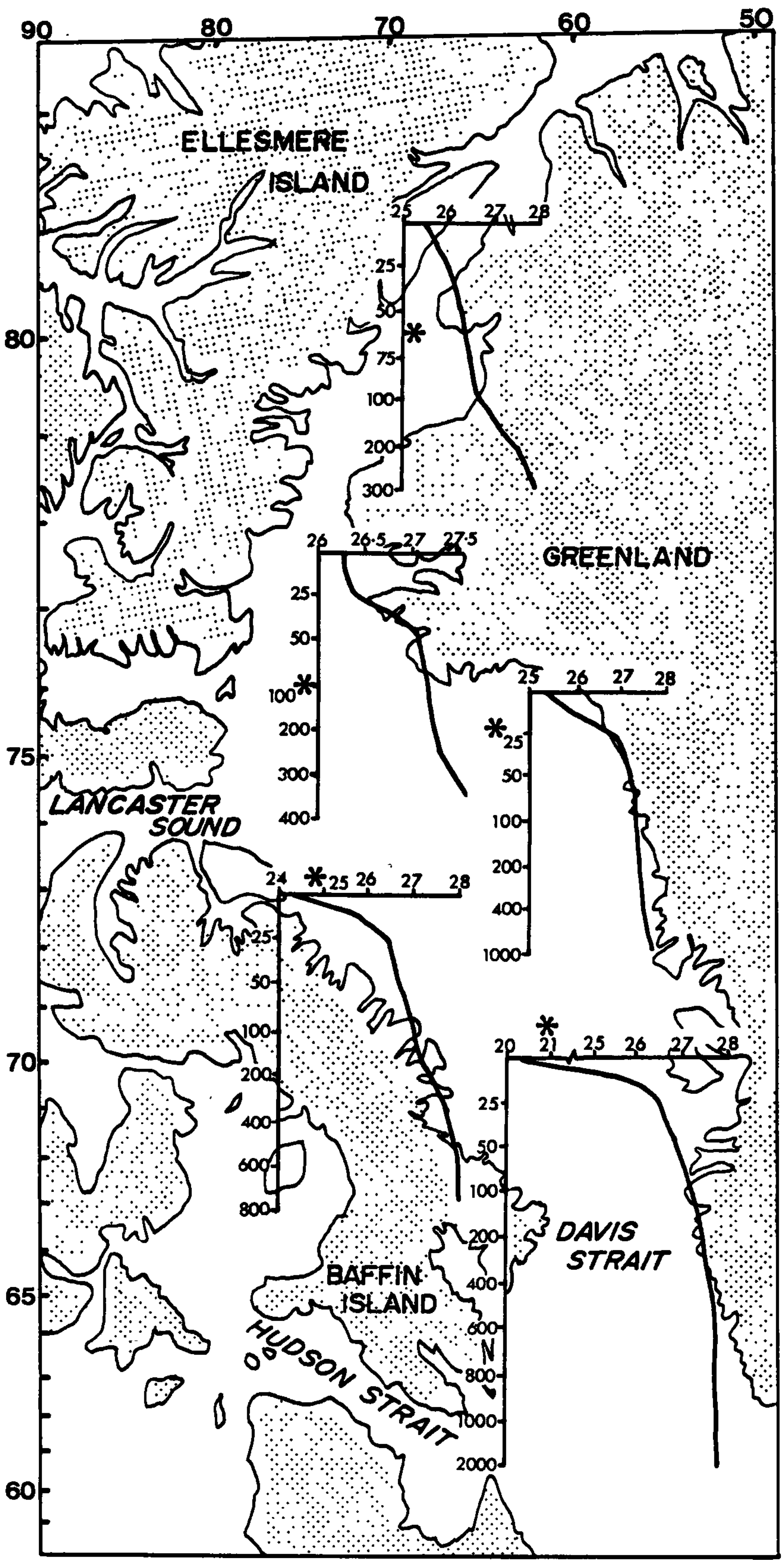


FIGURE 4 REPRESENTATIVE SUMMER VERTICAL DENSITY PROFILES IN BAFFIN BAY

of 30.5‰. These pycnoclines are very variable, localized and dependent on local climatic conditions and recent history. A permanent pycnocline, involving a change of (1 to 1.5 σ_t), exists from 50 to 400 m due to the salinity increase between the cold upper and warm intermediate layers in Baffin Bay. Below 1000 m, uniform conditions exist.

2.1.2 Conditions Favourable for the Sinking of Oil. The contoured open water conditions in Northern Baffin Bay depicts generally high surface water densities of 25 to 26 σ_t, which is also true for waters south to Davis Strait (Figure 5). Only oil with a density greater than 26 σ_t could sink in this region, and unless it is also less than 28 σ_t, would descend to the bottom. Nearshore, lower densities can occur in shallow plumes (less than 10 m deep) extending from a freshwater source (i.e., melting ice edge). The density at the core of such a plume may drop to less than 20 σ_t and oil of lower density (between 20 and 26 σ_t) would sink and become trapped at the bottom of this layer.

2.2 Labrador Shelf

The Baffin Current, flowing through Davis Strait down the eastern coast of Baffin Island, partially enters Hudson Strait where strong tidal mixing with cold, low salinity water exiting Hudson Bay can occur. This water exits Hudson Strait to flow down the Labrador Shelf as part of the Labrador Current and is characterized by temperatures less than 2°C, salinities less than 34.4‰ and densities less than 27.5 σ_t. Past the shelf break, the offshore water is warm and saline (>3°C, >34.5‰, ~27.8 σ_t) being a combination of Labrador Sea and West Greenland Current Water. Figures 6 and 7 illustrate the cross-shelf distribution of summer water properties and sample vertical density profiles respectively. Summer stratification influences the top 100 m; however, its intensity is reduced compared with lower latitudes. Summer maximum temperatures are approximately 7°C near the Strait of Belle Isle, slightly higher than that seen in Baffin Bay. Local river run-off can affect the nearshore waters as illustrated in the most southerly profile (Figure 7) which was influenced by the Churchill River. Other small scale processes should also be occurring along the shelf; however, the data coverage is limited for this region. As can be seen in Figure 6, density increases with depth as a result of summer stratification and horizontally from mixing with more saline waters towards the East. At the shelf break, a dynamic front exists between the swift flowing Labrador Current and Labrador Sea water, corresponding with a temperature and salinity increase, at 50 m, of 4°C and 1‰ with little density change. Like most topographically linked currents, the stream may move back and forth along the slope, meander in its path and possibly become unstable to throw off eddies.

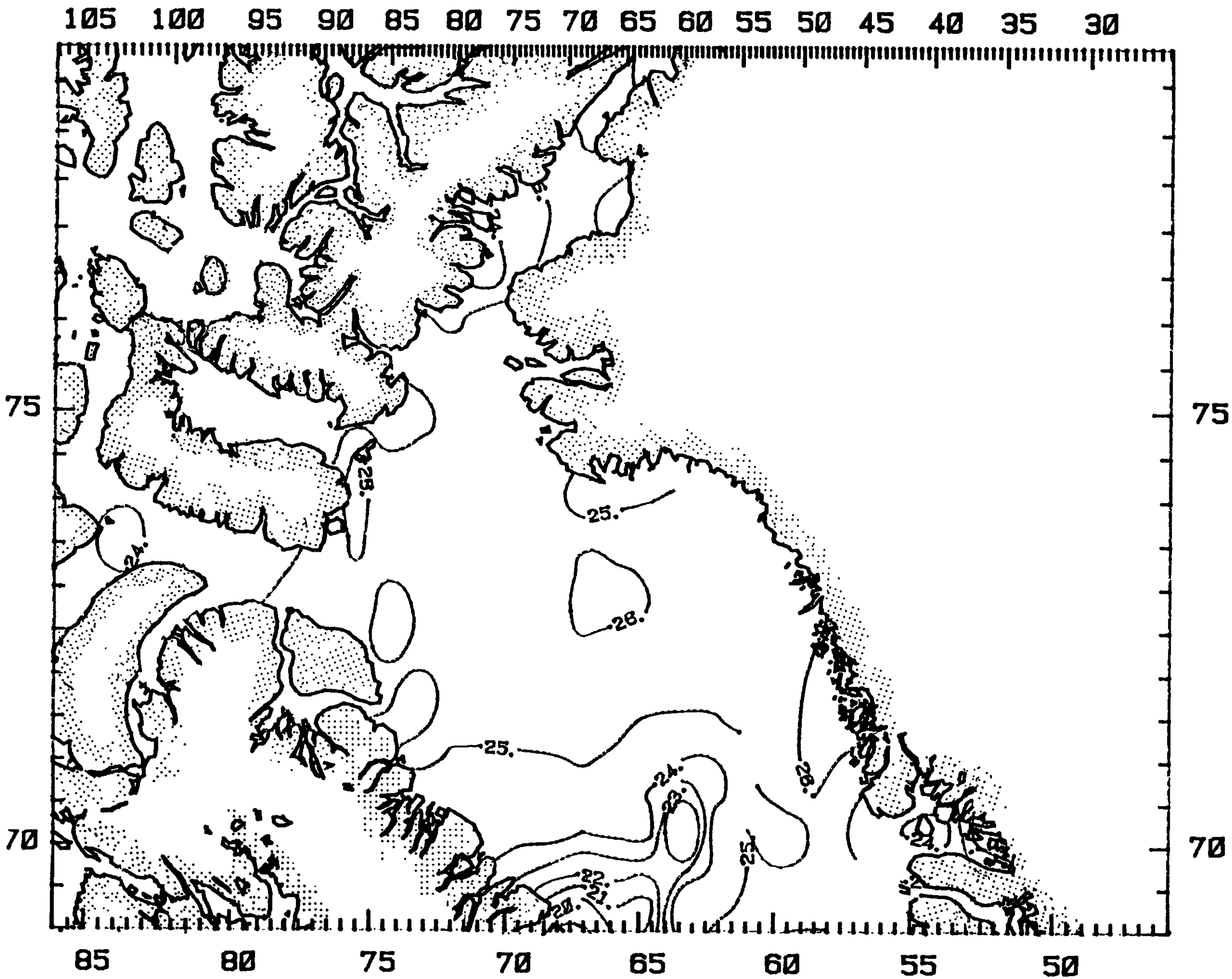
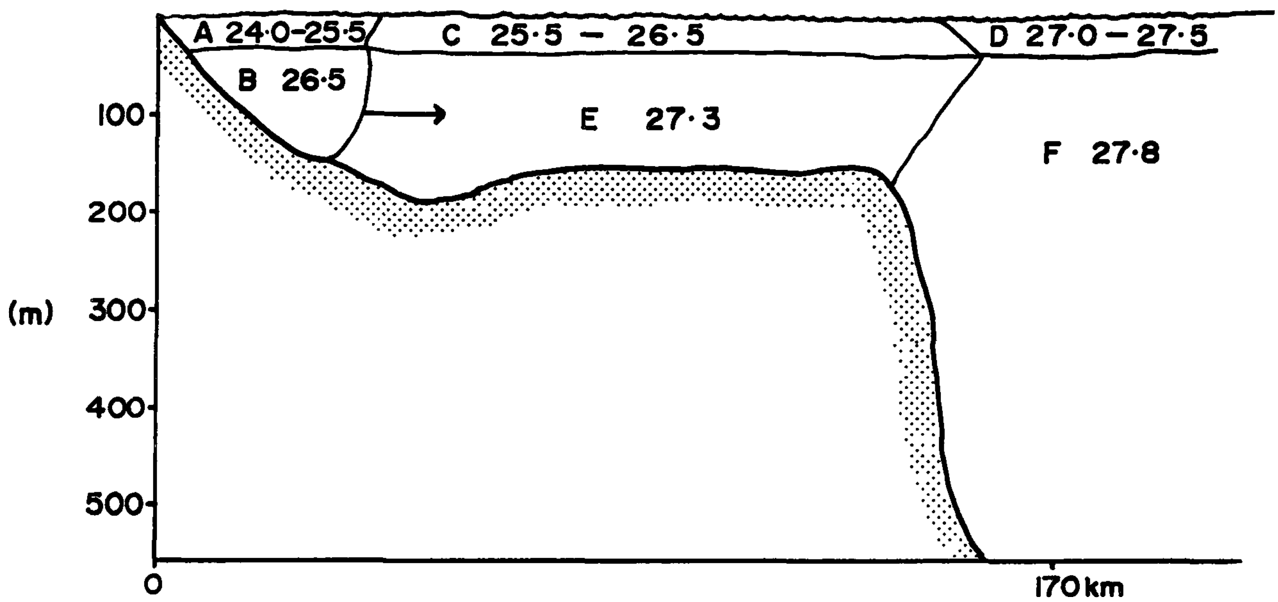


FIGURE 5 CONTOURED SURFACE DENSITIES IN BAFFIN BAY



LABRADOR SHELF - SUMMER

A Surface Labrador coastal water (4.5-6.5° C, < 32.2°/oo)

B Inshore Branch of Labrador Current (-1.0° C, 32.5-33.4°/oo, winter -1.77° C, 33.1°/oo)

C Surface water

D Surface offshore water (3-6° C, 32.5-34°/oo)

E "Labrador Sea Water" (0-2° C, 33.4-34.4°/oo)

F Deep offshore water - Labrador sea water modified by the West Greenland Current (> 3° C, > 34.5°/oo)

FIGURE 6 CROSS-SHELF DENSITY DISTRIBUTION ON THE LABRADOR SHELF

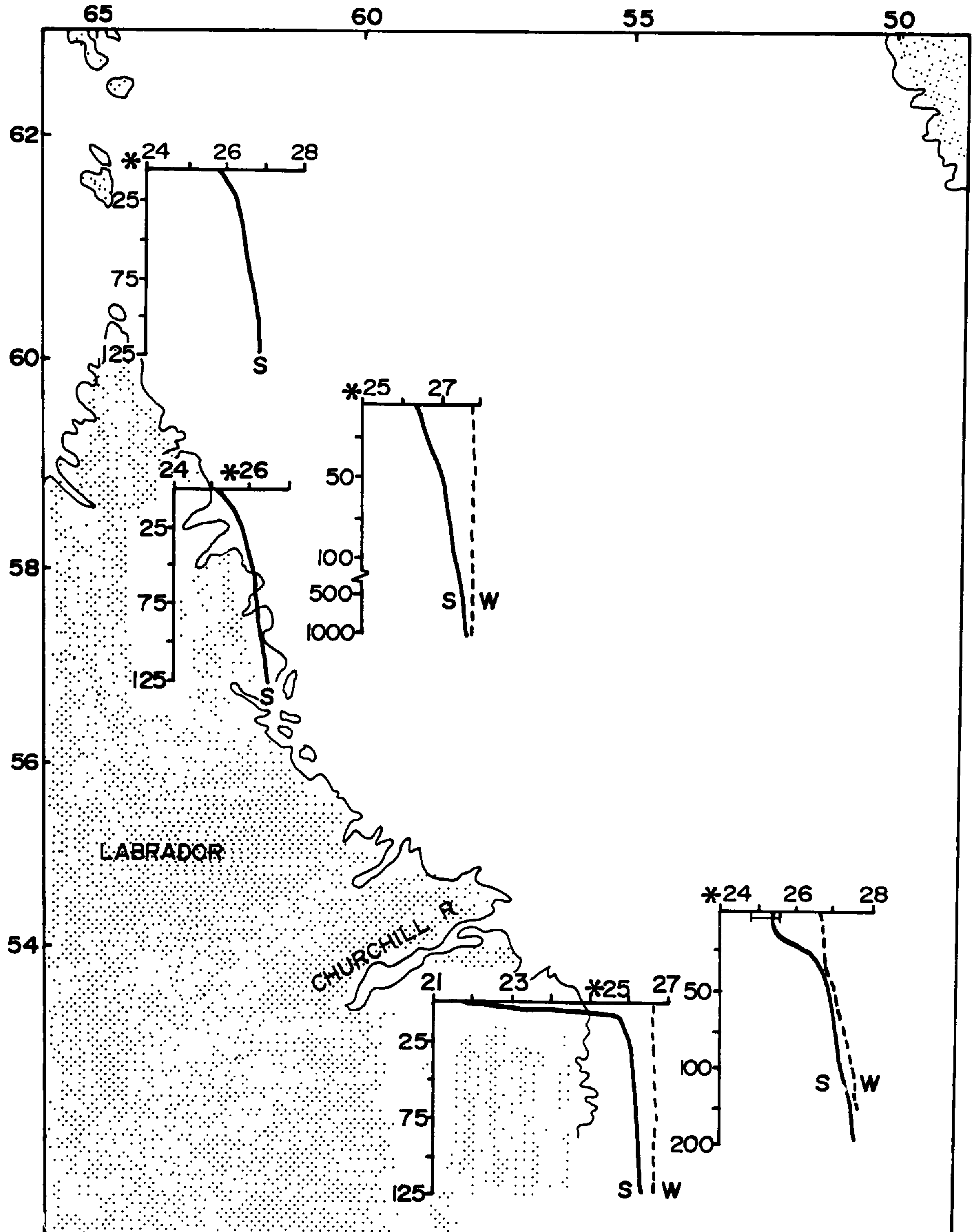


FIGURE 7 SAMPLE VERTICAL DENSITY PROFILES ON THE LABRADOR SHELF (s = summer, w = winter)

In the central Labrador Sea area, the water is relatively homogenous in density between 27.7 and 27.8 σ_t, extending from the surface to 1800 m. Water renewal here is thought to result from deep convective overturning during winter months. How often and exactly where this occurs is still under study but during the phenomena, water can be mixed to depths of 1500 m or more.

2.2.1 Conditions Favourable for the Sinking of Oil. The summer and fall contoured surface density maps in Figures 8 and 9 illustrate the fact that only oil of high density (greather than 25 σ_t) would sink in this region. The only exception is in the localized region near the Churchill River where surface water densities drop down to 20 σ_t. Here a sharp increase in density at a depth of 10 metres could trap oil of density 20 to 25 σ_t. In the winter, surface water values are uniformly greater than 26.5 σ_t and most oil types would float on the surface.

2.3 Grand Banks and Flemish Cap

The important consideration in this region is how topographic steering determines the circulation pattern which in turn affects the hydrographic characteristics on the top and sides of the bank.

The obvious effect of a topographic feature is the creation of an impediment to any flow impinging on the area. If the top of the bank is shallow, a strong current will not move over top but flow around the bank along the slope formed between it and the surrounding depths. A south-flowing current, constrained by Coriolis force on the one hand, will be "steered" by the topography on the other. As a result of this steering, a distinct boundary in water properties can occur at the edge of a bank, between water on top of the bank reflecting local influences; water transported by the current, often over long distances; and open ocean water away from the coast.

A second effect that a bank has on hydrography is a result of the decrease in water depth over the top. This decrease may exclude certain water types found below the maximum depth. It may allow for increased vertical mixing resulting in a uniform water column in the winter. If the bank is very shallow the mixing may persist through the summer creating a different vertical structure on the bank than in the surrounding deep water. The sides of the bank can be the site of internal wave generation and upwelling.

The Labrador Current impinges on the Grand Banks. Here it divides into two branches, a minor coastal stream which stays near shore and turns West around the Avalon peninsula, and a second major branch which flows around the bank. Near the tail of the bank, the Labrador Current may encounter the Gulf Stream moving northeast to create a

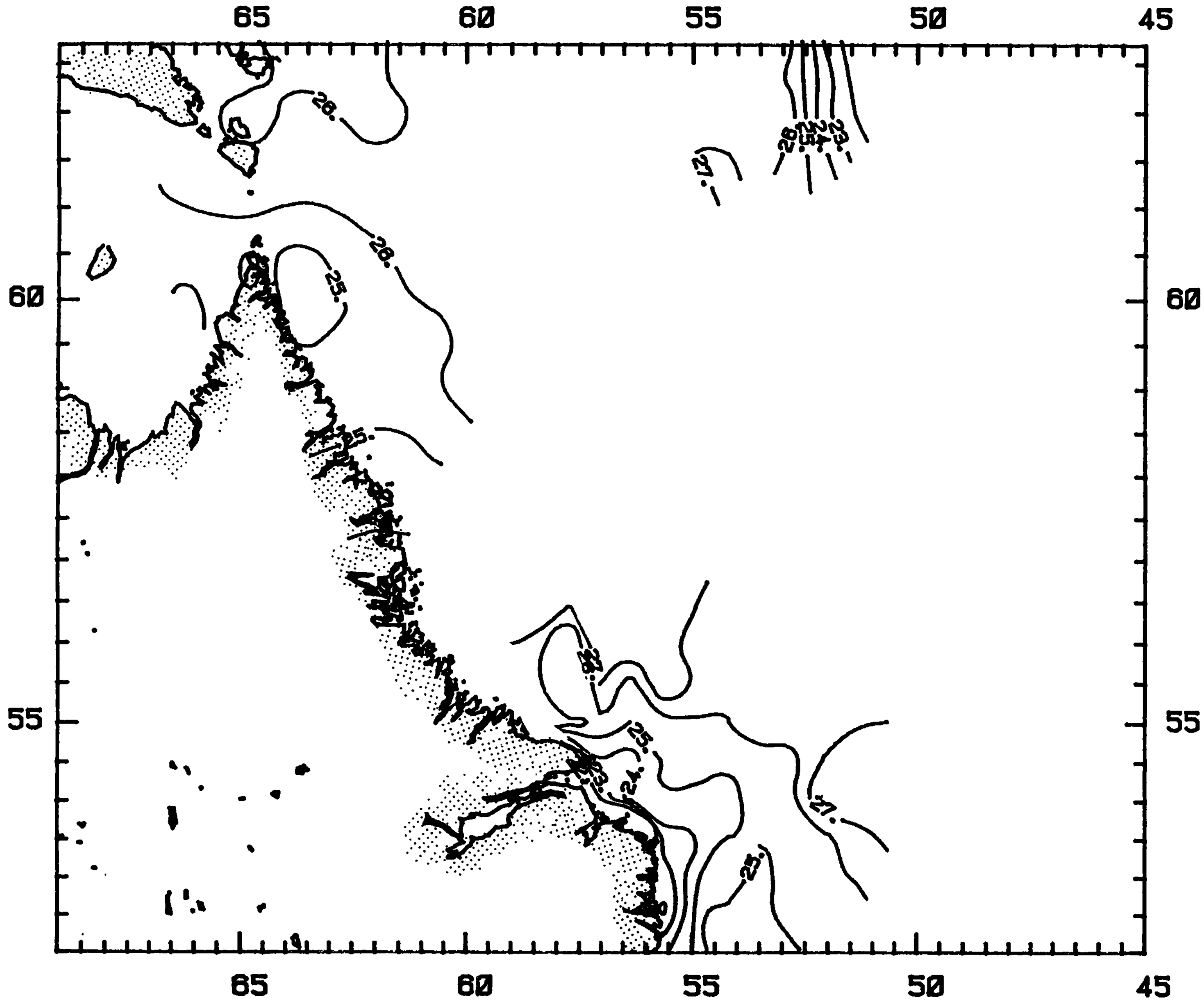


FIGURE 8 CONTOURED SURFACE DENSITIES ON THE LABRADOR SHELF - summer

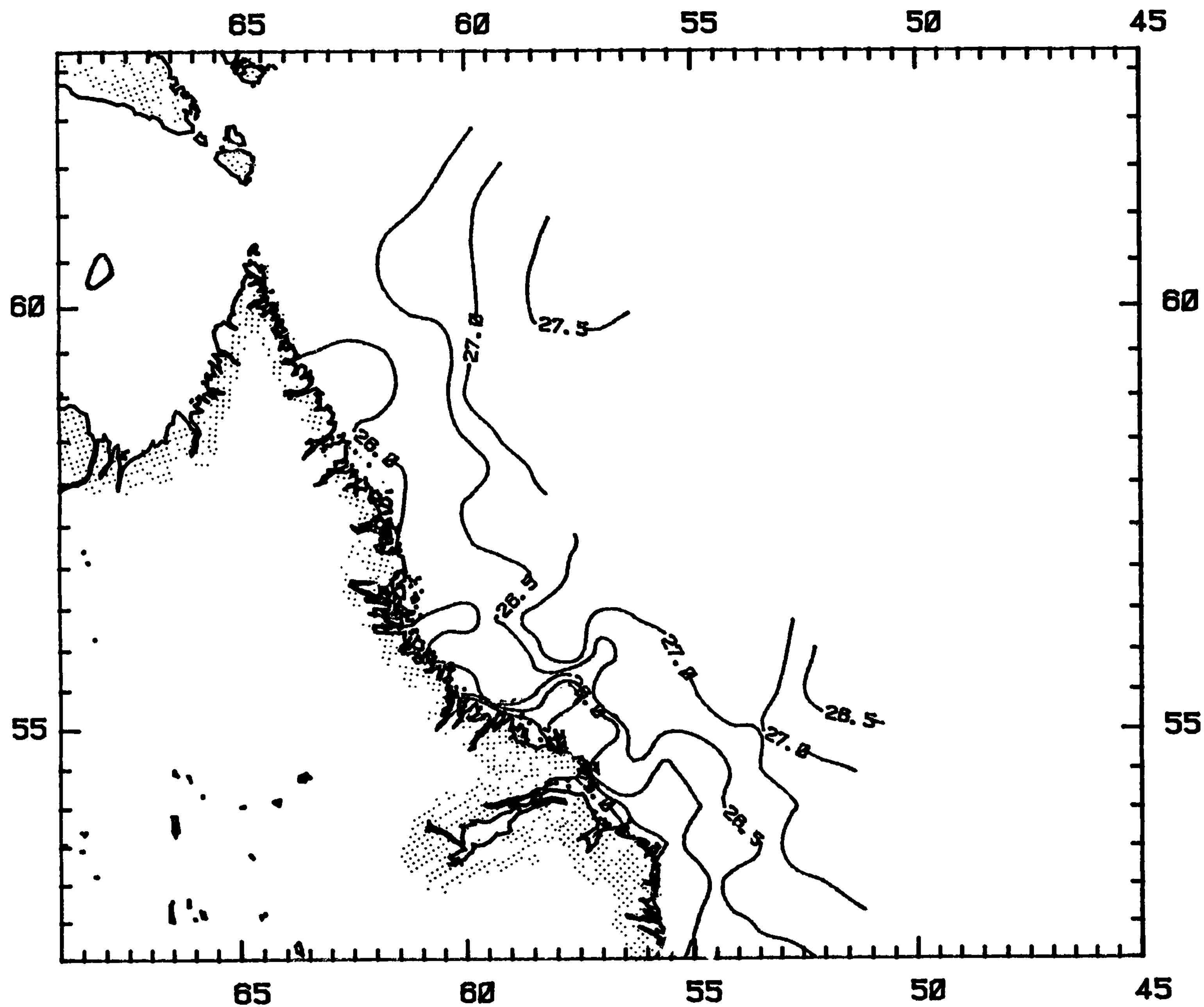


FIGURE 9 COUNTOURED SURFACE DENSITIES ON THE LABRADOR SHELF - autumn

strong temperature front and very variable conditions. On the top of the bank, there is a slower, more diffuse southerly drift. This area is greatly influenced by local winds. In winter, winds can set into motion the whole water column on top of the bank, while in the summer, as a result of stratification, the surface and bottom layers can behave independently with only the surface layer responding and the bottom layer continuing to move southward. Strong inertial motions (i.e., rotation of water as a result of the earth's rotation) with a period of 16 h may be present on top of the bank, as well as a semi-diurnal tide. The strength of the inertial motion is unusual for most coastal waters and results from winds shifting in phase with the earth's rotation and reinforcing the circular water motion.

2.3.1 Vertical Density Gradients. The vertical density profiles at various locations on the bank are illustrated in Figure 10. Figure 11 depicts the average September hydrographic conditions (over all existing data from 1910 to 1980) which occurs along 47°N known as the Flemish Cap section. During September, density change, both vertically and horizontally are at a maximum. The presence of the Labrador Current can be seen in the transect, as a slope in the generally horizontal isopycnals between Stations 7 and 13. A distinct front at the edge of the bank can also be seen in the transect. The hydrographic conditions on the slope of the bank are related to the strength and relative position of the Labrador Current. On top of the bank, the strongest signal is seasonal. Surface temperatures range from less than 0°C in March, uniform to the bottom, to 14°C in August and September. Salinity patterns reinforce the resulting density stratification by freshening at the surface in the summer from $33^{o}/oo$ to $31.75^{o}/oo$. The September transect illustrates the strongest stratification in the year, with a pycnocline between 20 and 75 m. The bank is not sufficiently shallow for vertical mixing in the summer to disrupt stratification; however, in the winter convective overturning and wind mixing can extend to the bottom. There is a general trend of increasing density from west to east across the transect reflecting the change from coastal to more open ocean Atlantic water conditions.

If the transect is moved South along the edge of the bank, a very similar picture exists with the absence of Flemish cap. In Figure 10, extreme conditions may be encountered in the region marked very variable, with Gulf Stream meanders impinging on the bank carrying very warm, saline water (15°C, 34 to $35^{o}/oo$) and creating a strong thermal front with Labrador Current water. The position of this front lies between 42 and 43°N and varies from year to year depending on the northward extent of the Gulf Stream and the conditions existing in the Labrador Current that year.

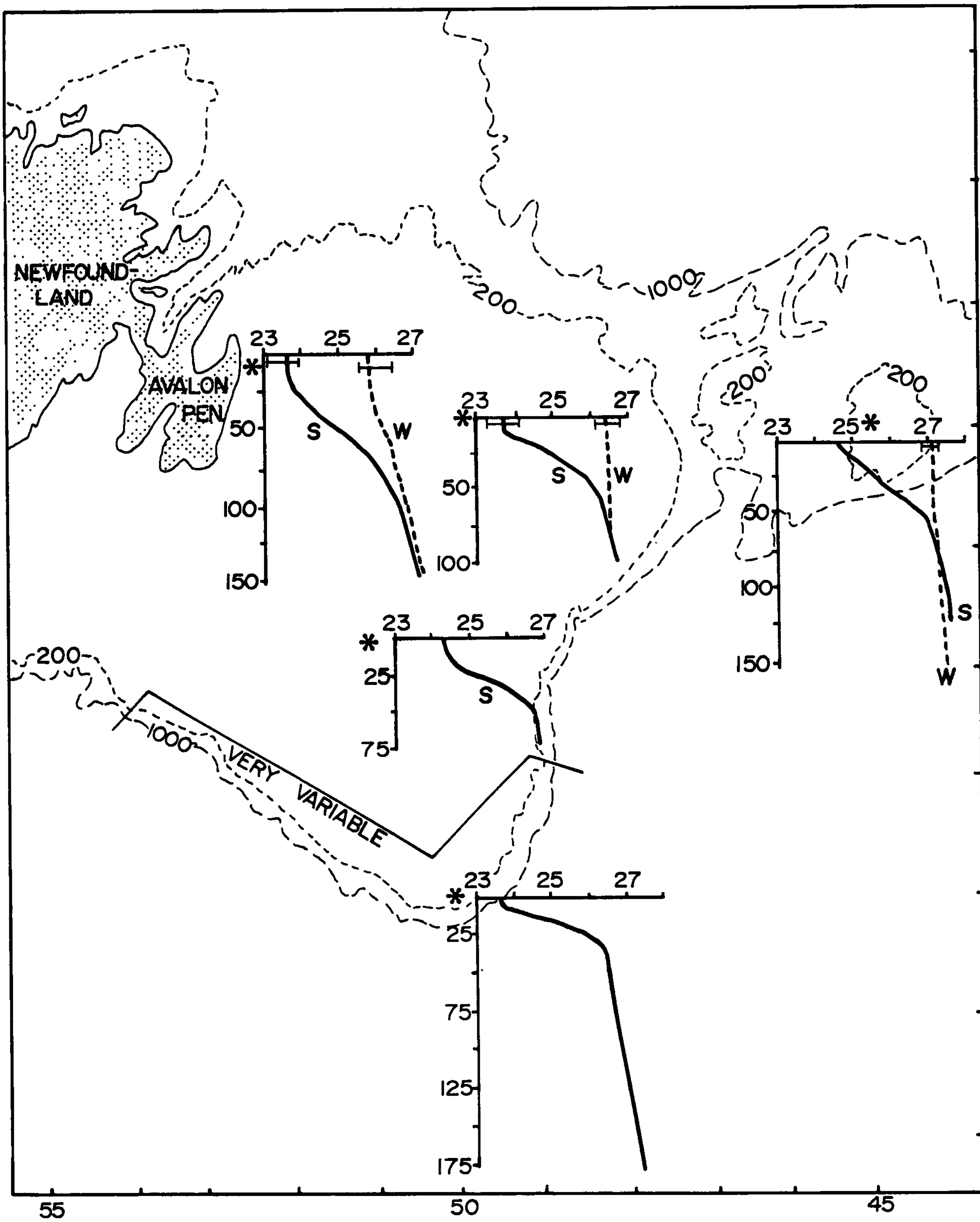


FIGURE 10 REPRESENTATIVE VERTICAL DENSITY PROFILES ON THE GRAND BANKS (s = summer, w = winter)

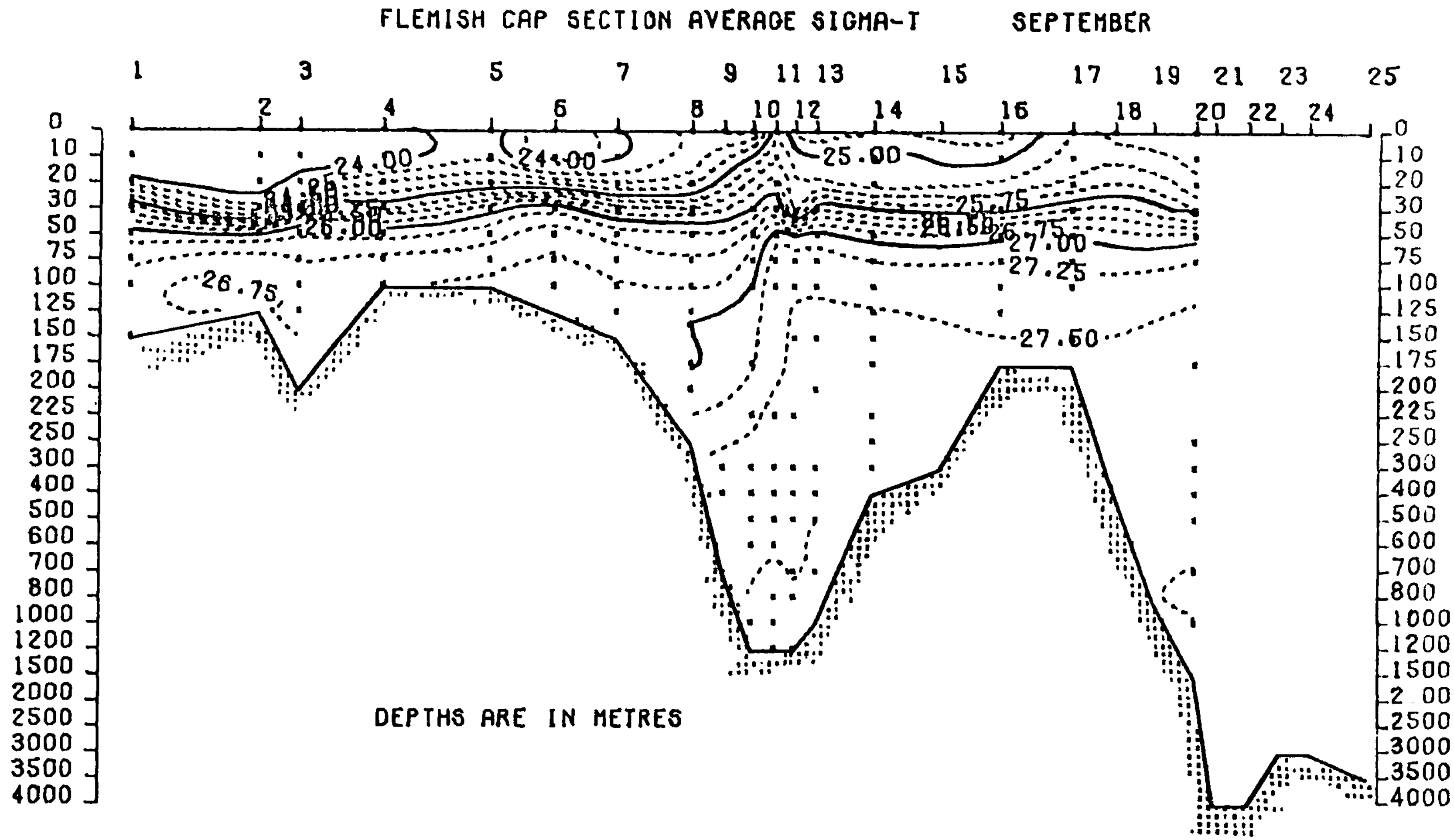


FIGURE 11 SEPTEMBER TRANSECT ACROSS THE GRAND BANKS AND FLEMISH CAP (Keeley, 1981)

2.3.2 Conditions Favourable for the Sinking of Oil. The summer and winter surface densities are shown contoured in Figures 12 and 13. These seasonal contours show that only oil of high density (>24 σ_t in the summer and >26.5 σ_t in the winter) would sink. In the winter, any sinking oil would come to rest on the bottom as there is little density increase with depth. In the summer, oil with a density in the limited range of 24 to 27 σ_t may become trapped by the seasonal pycnocline and reside at an intermediate depth.

2.4 Gulf of St. Lawrence

The Gulf of St. Lawrence is distinguished by its freshwater source, in the St. Lawrence River, and by its system of channels (Laurentian and Esquiman Channel) which disrupts the bathymetry and creates deeps and shallows. The Gulf of St. Lawrence may be further subdivided into five sections showing distinctive hydrographic behaviour. Figure 14 is a location map of these regions and Figure 15 shows representative winter and "summer" density profiles. The "summer" profiles were chosen to show the largest seasonal, vertical density gradients observed. Within the estuary, this occurs in May due to the increased freshwater run-off and not in August as expected from seasonal temperatures.

2.4.1 Upper Estuary. In this region, the major influence of the St. Lawrence River input can be observed. The Laurentian Channel, with depths increasing from 75 m at the head of the estuary (72°W) to 350 m, controls the nature of the estuary. Figure 16 shows a progression of salinity vs depth profiles along the estuary. It can be seen that within the channel, the St. Lawrence estuary resembles the well-stratified type with a distinct two-layer system and only surface salinities experiencing large changes. A temperature decrease acts to reinforce the salinity increase between 5 and 30 m, creating a sharp pycnocline. As the water depth decreases upstream and on the sides of the channel, most of the deep, saline water is prevented access. Increased vertical mixing from frictionally induced turbulence disrupts the two-layer structure and the salinities show a constant increase with depth. This area resembles a slightly stratified estuary with salinites increasing downstream at both the surface and bottom. Tides are important in moving the salinity (and density) contours back and forth. At the head of the channel, the depth decrease is sudden so that the tidal wave moving upstream may be reflected back as an internal tide, observed as internal waves in and below the pycnocline. These internal waves have tidal periods, and amplitudes of 5 to 10 m in the pycnocline and 15 m below (see Figure 17). The head of the channel is also a centre of upwelling as the upstream

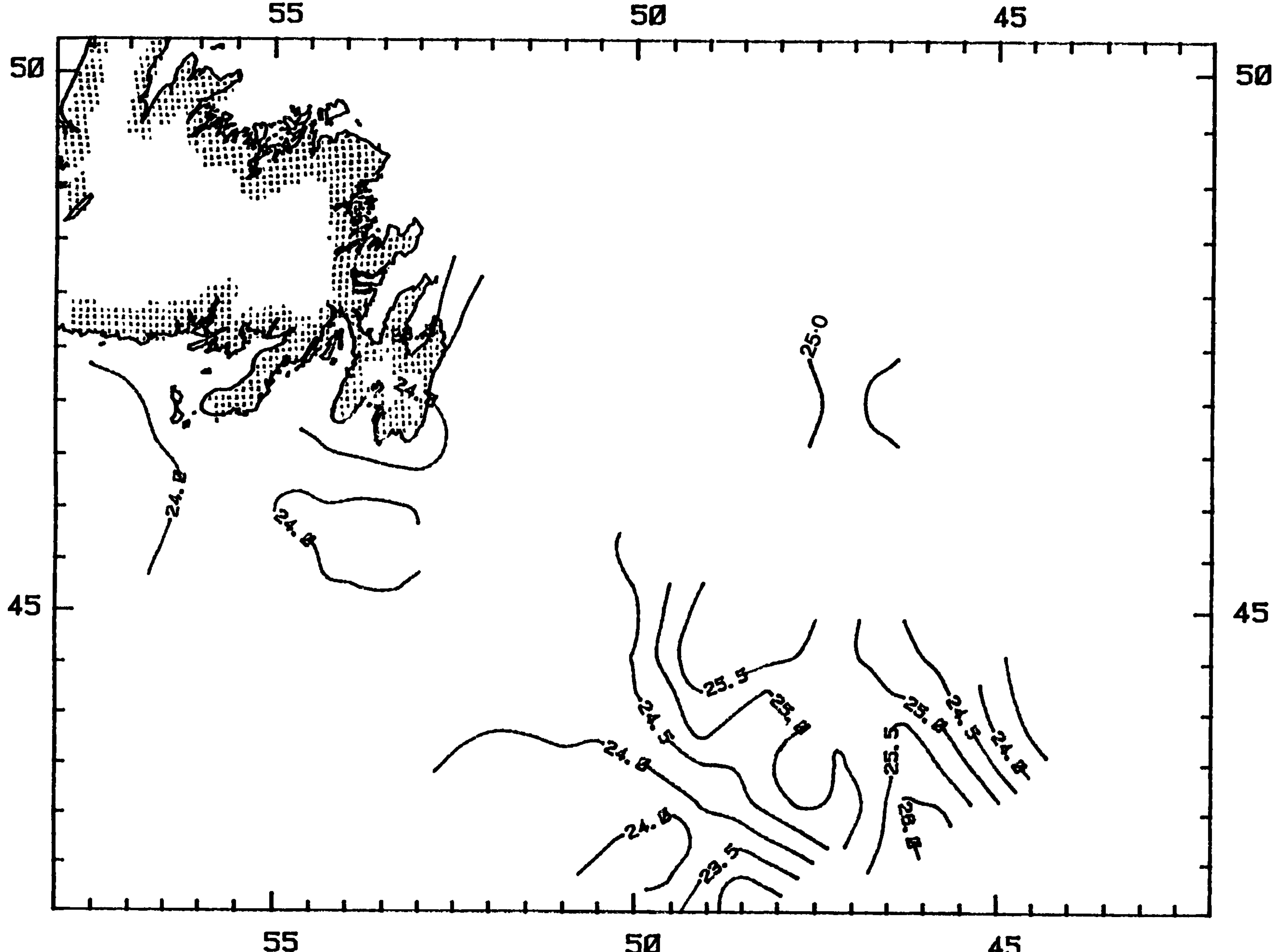


FIGURE 12 CONTOURED SURFACE DENSITIES ON THE GRAND BANKS - summer

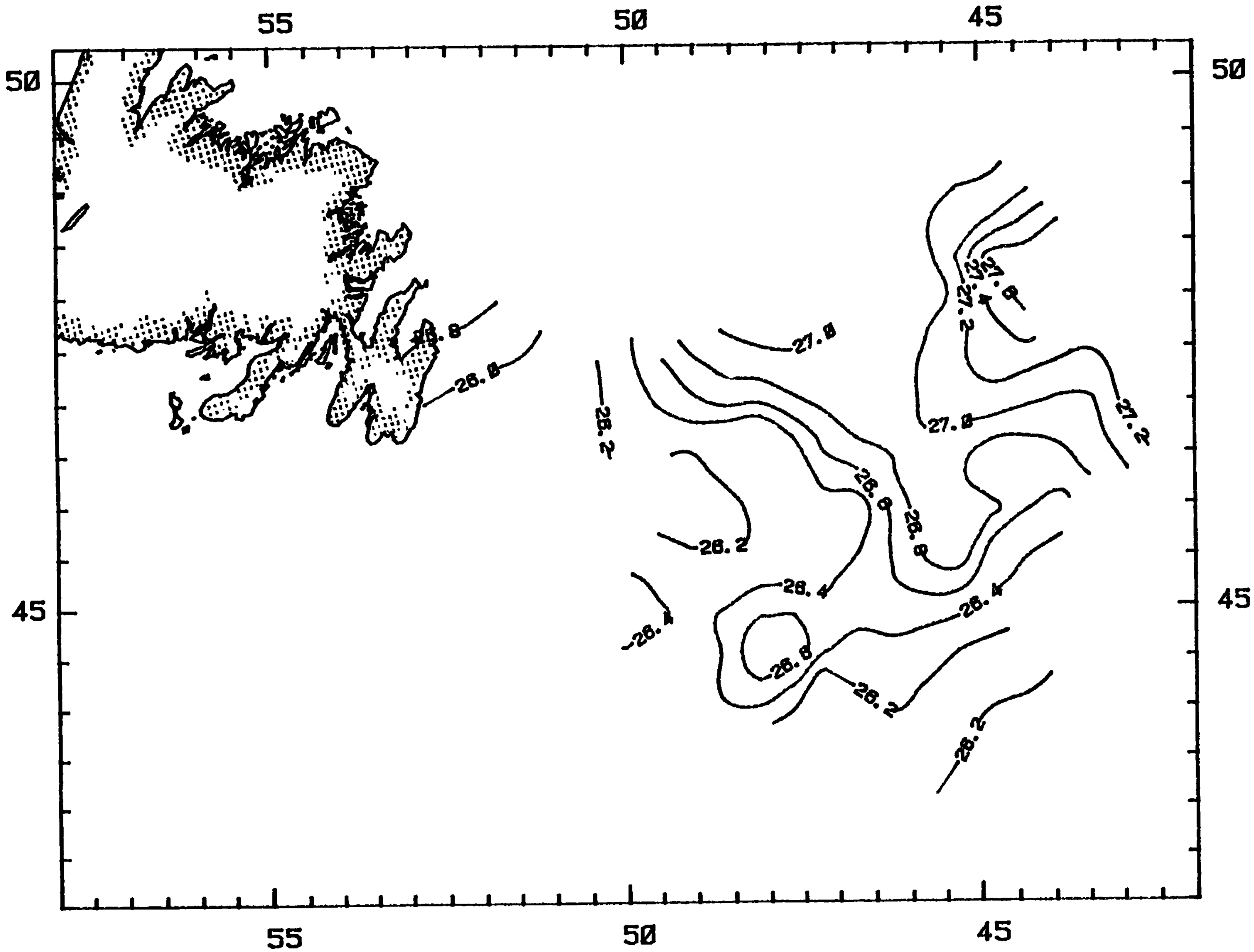


FIGURE 13 CONTOURED SURFACE DENSITIES ON THE GRAND BANKS - winter

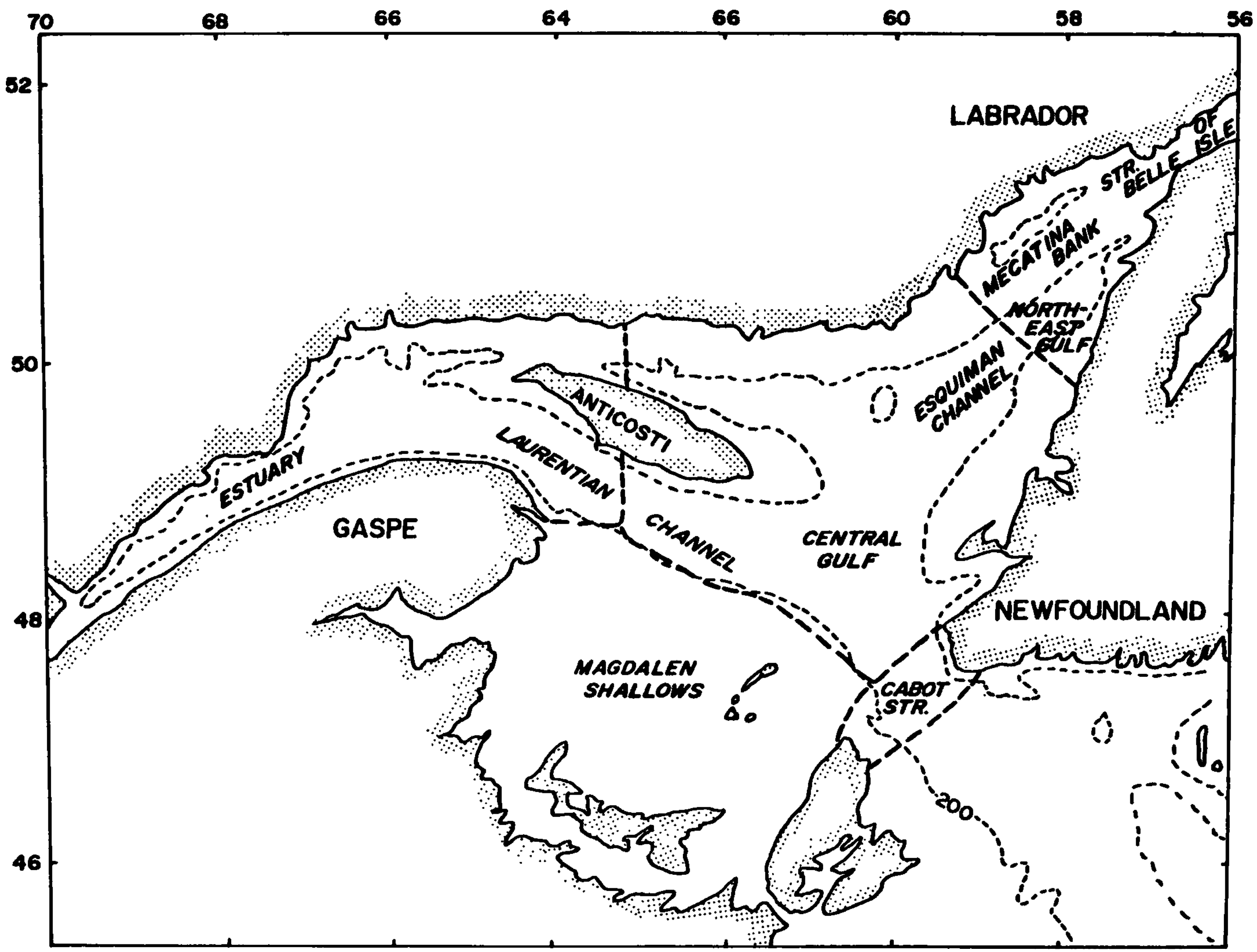


FIGURE 14 LOCATION MAP OF GULF OF ST. LAWRENCE SUBDIVISIONS

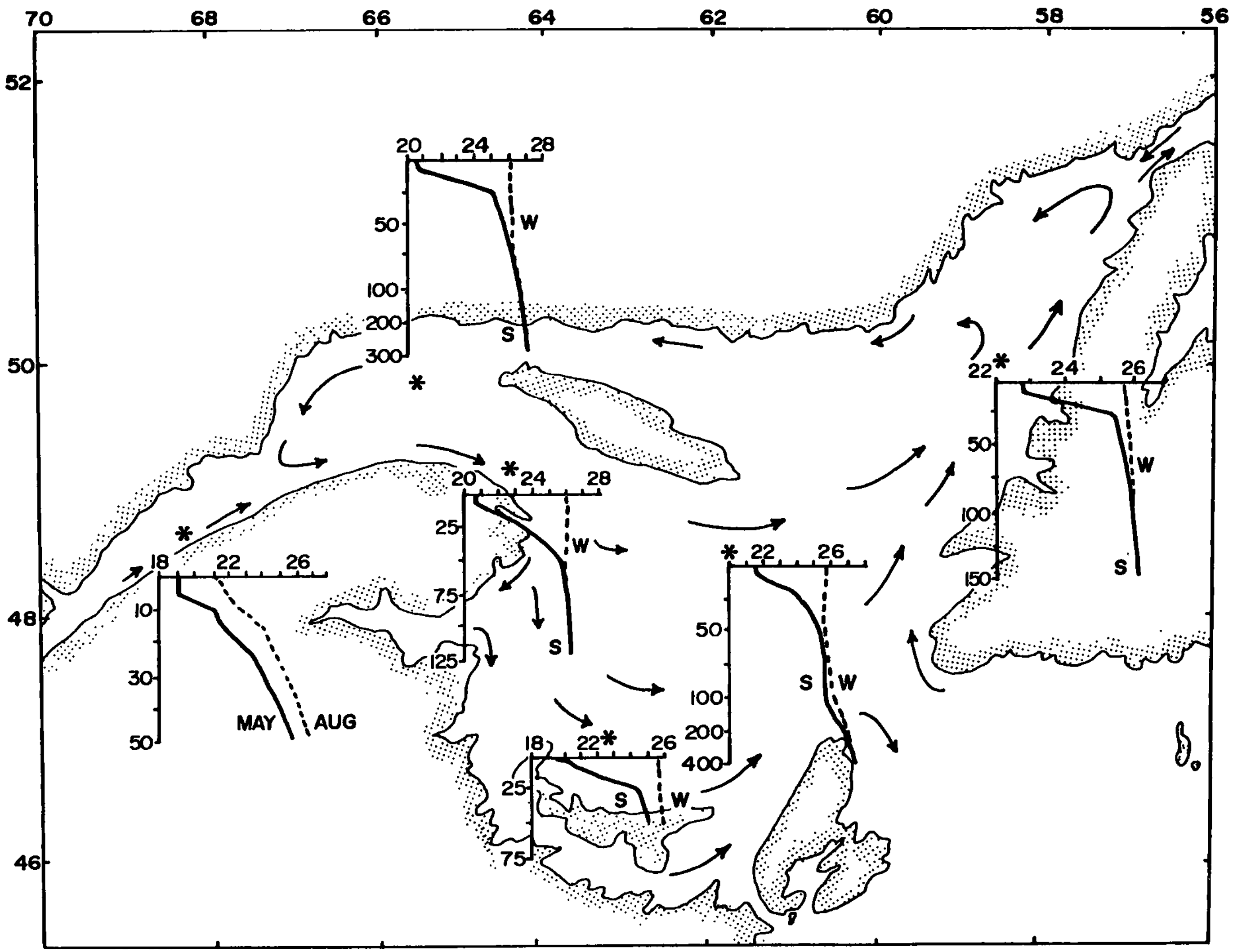


FIGURE 15 REPRESENTATIVE VERTICAL DENSITY PROFILES OF THE GULF OF ST. LAWRENCE

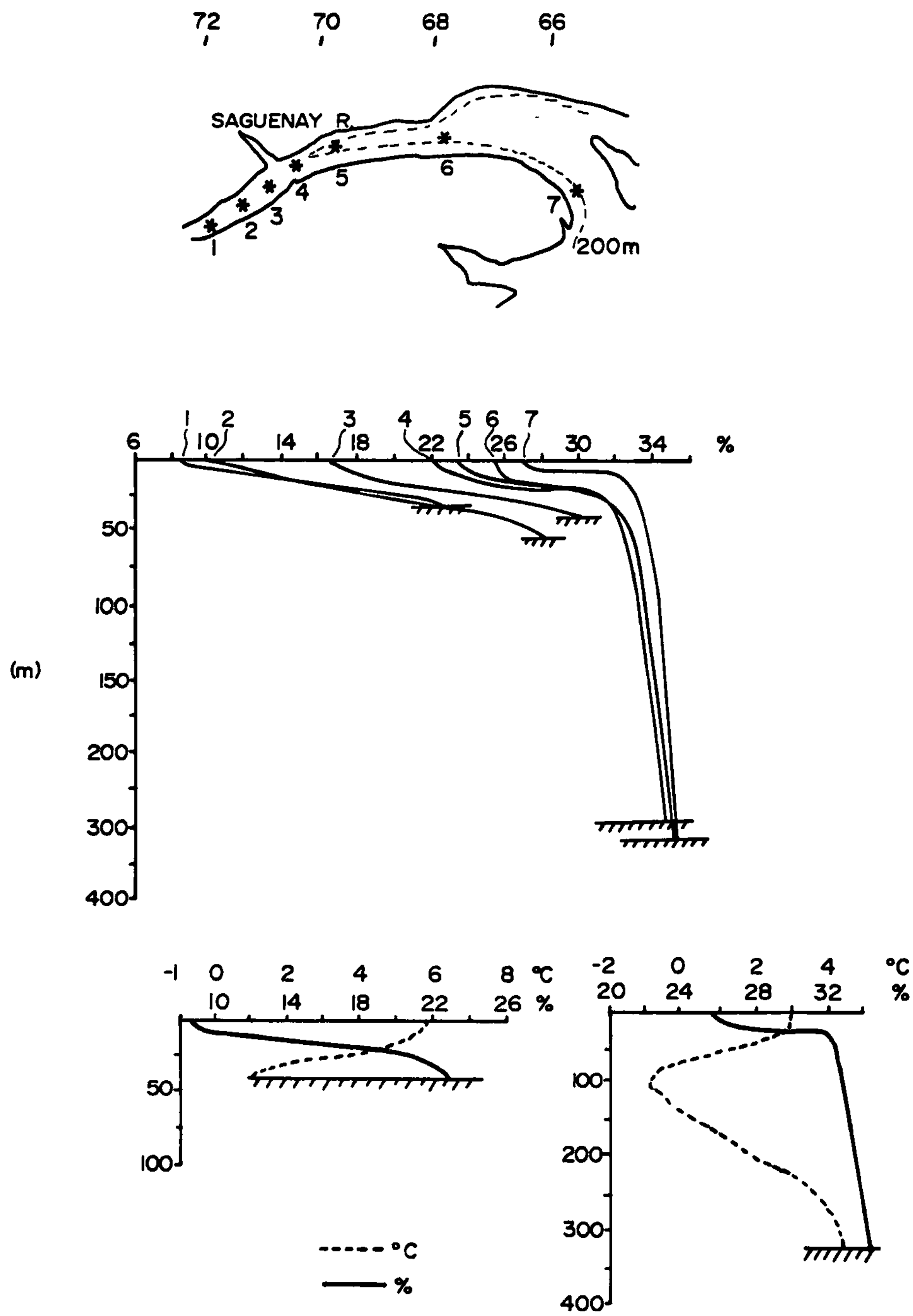


FIGURE 16 SALINITY VERSUS DEPTH PROFILES ALONG THE ST. LAWRENCE ESTUARY

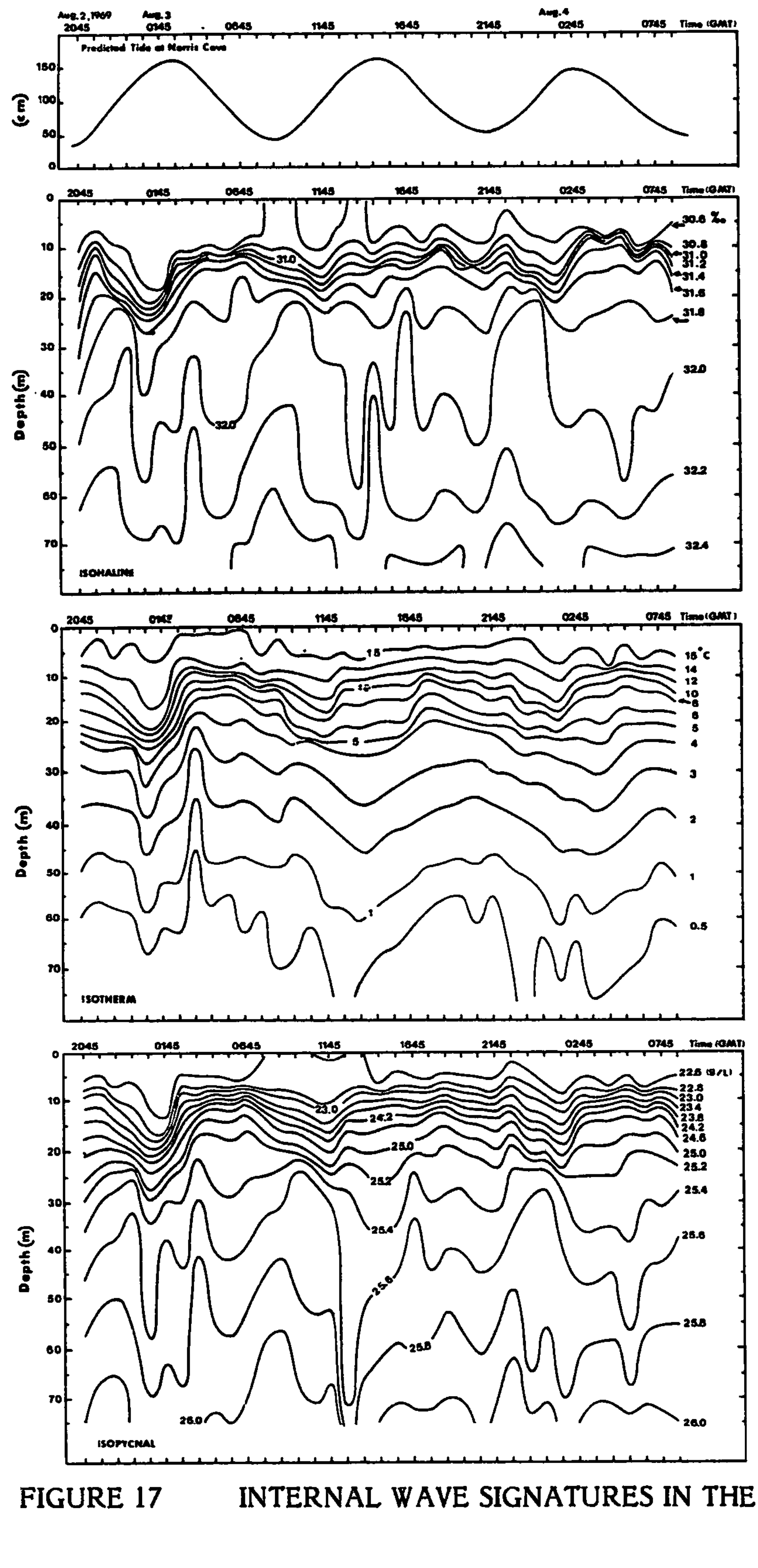


FIGURE 17 INTERNAL WAVE SIGNATURES IN THE GULF OF ST. LAWRENCE

movement of deep water is suddenly impeded. Concentrations of particles and pollutants may be very high here as they are caught between opposing currents.

Seasonal temperature patterns are also important in this region. In the spring, the lower estuary (65° to 68°W) is freed of ice prior to the central gulf. This allows surface layer warming to proceed and can result in temperatures as much as 6°C higher and large horizontal density gradients as salinity reinforces the pattern. In late summer, as a result of upwelling at the head of the estuary and transport downstream of colder water, surface waters tend to be cooler than those in the central gulf and may show higher densities as well.

2.4.2 Baie des Chaleurs, Magdalen Shallows. This is a region of reduced water depths, ranging from 50 m in the central area to 200 m in the East, where it is bounded by the Laurentian Channel. As a result, extreme temperatures are encountered here. Fresh water, entering from Baie des Chaleurs and the estuary via the Gaspe Current, also affects the salinity distribution. The density distribution is therefore very variable seasonally and spatially.

In the winter, the water column is mixed uniformly from top to bottom with an average temperature of -1.5°C. After spring thaw, when surface heating begins, a rapid increase in temperature occurs and the warmest water in the Gulf is encountered (~18°C). As surface waters over the central Gulf never heat up to this point and cooler waters are entering by the Gaspe Current, temperature gradients develop to the North and East. The water over the Shallows is also fresher than that in the central Gulf and the corresponding salinity gradient reinforces the density gradient, with densities increasing from West to East (see Figure 18).

The vertical density profiles (Figure 16), show that the maximum seasonal change in density of surface waters occurs here (from 19 to 26 σ_t). The surface minimum density is reached twice in this area, once at the beginning of July from fresh water entering from the estuary and again in mid-August when surface temperatures are at their maximum. Therefore, in this section of the Gulf, both salinity and temperature are important in determining density structure.

2.4.3 Central Gulf. The Central Gulf region is characterized by the presence of deep channels, by the greater importance of temperature over salinity in determining the minimum surface density and by the reduced seasonal salinity change (around 2°/oo). This latter feature is a result of the circulation pattern restraining most of the fresher water over the Magdalen Shallows.

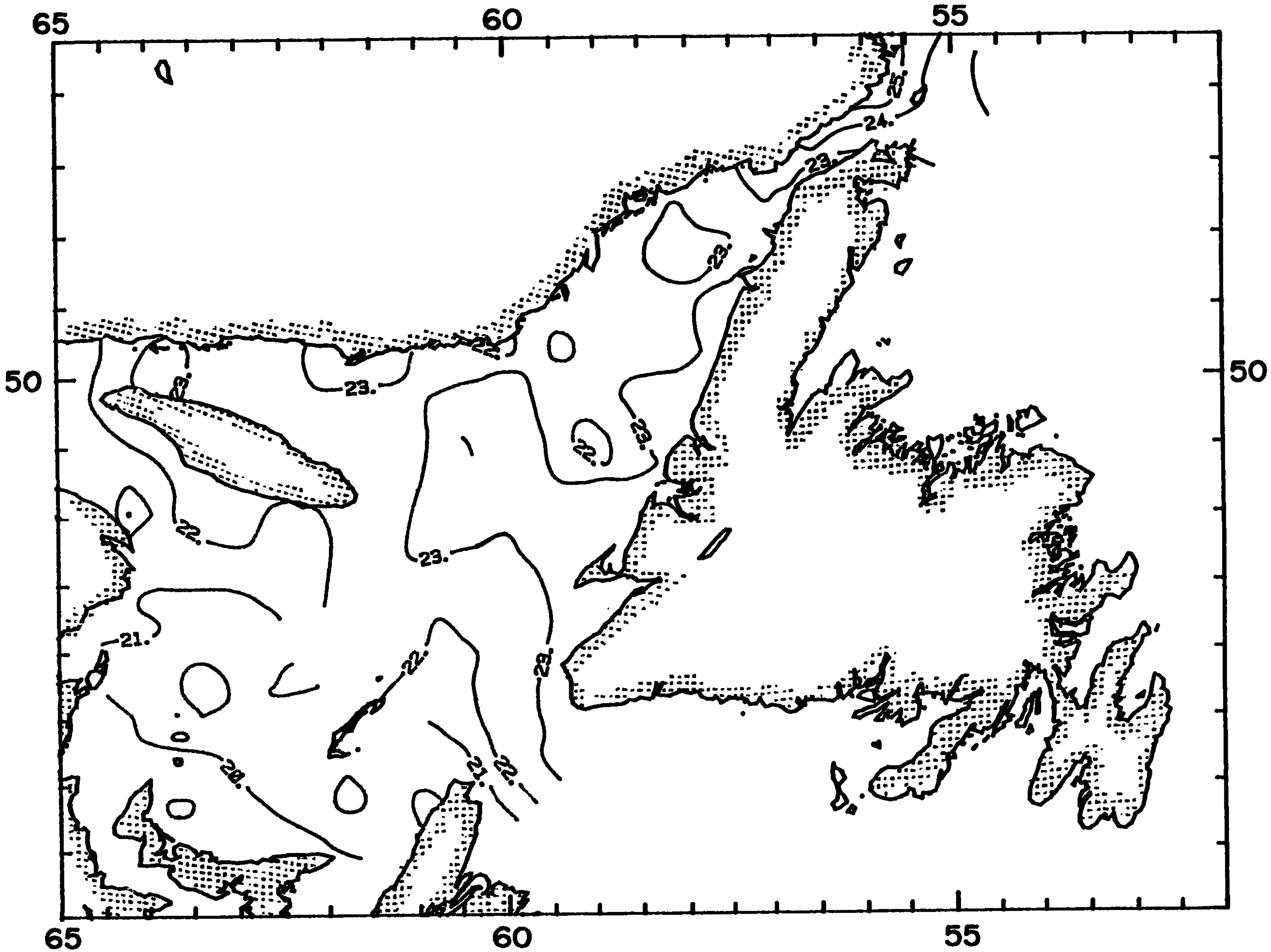


FIGURE 18 CONTOURED SURFACE DENSITIES IN THE GULF OF ST. LAWRENCE - summer

The minimum surface density is associated with a temperature maximum of 14 to 15°C in August, in a surface mixed layer around 10 m deep. In the winter, a two-layer water column exists with the surface layer extending to 100 m, and having a density of 25.8 to 26.5 σ_t. Below this, an increase in temperature and salinity occur with only slight density increase. In the summer, surface heating creates a strong seasonal pycnocline isolating the residual winter cold layer.

2.4.4 **Cabot Strait.** This Strait is one of two links between the Gulf of St. Lawrence and the open ocean. The Laurentian Channel extends through the Strait to the edge of the continental shelf and provides the passageway for the Deep Gulf water to enter. In the summer, warm and fresh water, having passed over the Magdalen Shallows, exits the Gulf of St. Lawrence around Cape Breton, and continues to flow down the Scotian Shelf. Colder and more saline water can enter the Gulf around the Southwest tip of Newfoundland and continue to move up the west coast of Newfoundland. As a result, strong horizontal gradients and fronts, may exist at times across Cabot Strait. The flow through the Strait can be quite variable, however, with surface waters flowing all in or out at any one time.

2.4.5 **Northeast Gulf.** This region is the furthest removed from the influence of St. Lawrence River discharge and has surface salinities averaging 31‰. Away from shore, the seasonal heating pattern is the dominant process affecting density with a resultant minimum of 22 to 23 σ_t in summer. Nearshore, local river run-off can influence surface densities.

Inflow through Cabot Strait can travel up the west coast of Newfoundland along Esquiman Channel. Part of this flow turns back, over Mecatina Bank, to join the westerly flow along the Labrador shore. The rest can exit the Gulf via the Strait of Belle Isle. The Strait of Belle Isle also provides a passageway for surface Labrador coastal water into the Gulf and this may travel along the Labrador shore. This inflow can affect the summer temperature and salinity properties along the north shore as the water is much colder (5 to 6°C compared with 14°C) and fresher (29.5‰ compared with 31‰) than that along the Newfoundland coast. Water of Arctic properties, seen along the Labrador Shelf, generally does not enter the Gulf as the sill depth of the Strait is only 70 m. Little density difference is seen since the temperature and salinity decrease compensate one another. The extent of penetration, the duration and volume flux of the inflow is still under study but thought to be meteorologically forced. Within the strait, shear zones between opposing flows can exist, as well as temperature/salinity fronts. In the winter, much greater inflow may occur, resulting in surface densities of 27 σ_t along the north shore.

Along the north shore, wind driven upwelling may occur during the summer under the prevailing southwest winds. The effect would be very localized and intermittent.

2.4.6 Conditions Favourable for the Sinking of Oil. In summary, within the Gulf of St. Lawrence, the upper estuary shows the largest horizontal surface density changes due to freshwater inflows; densities in the Magdalen Shallows are influenced by both temperature and salinity and in the rest of the Gulf, the changes coincide with the seasonal heating pattern. There is a general increase in surface water densities from west to east across the Gulf.

The highest surface water density observed at any time of the year is 26 σ_t so that oil of greater density will sink everywhere and tend to pass through the water column to rest on the bottom. In the summer, the densities are somewhat reduced (see Figure 18) and oil, with a density between 20 and 25 σ_t, would sink through the surface layer and concentrate on top of the seasonal pycnocline which exists between 25 and 75 metres. It is only within the estuary proper that oil having a density less than 20 σ_t could sink. Figure 19 illustrates the contoured spring surface densities in this region. The horizontal density gradient is strong upstream from the Saguenay River area and the behaviour of an oil spill here would be location dependent. Upstream of Quebec City all oil, with a density greater than fresh water, would sink.

2.5 Scotian Shelf, Bay of Fundy

The Scotian Shelf is a region of meeting of waters whose sources include the Gulf of St. Lawrence via Cabot Strait, the Arctic through the Labrador Current and the tropics via the Gulf Stream.

2.5.1 Vertical Density Gradients. Figures 20 and 21 show the water characteristics across the Scotian Shelf, on a line extending from Halifax towards Bermuda, in summer and winter. Figure 22 illustrates sample vertical density profiles for this region. In the summer, a three-layer system in temperature and a two-layer system in density exist. The surface waters are derived mainly from the Gulf of St. Lawrence by the Nova Scotian Current flowing westward. These are separated from a cold intermediate layer by a strong pycnocline. The cold, intermediate layer (<5°C, 32 to 33.5‰) is derived from the Labrador Current which has flowed around the Grand Banks, across Cabot Strait and which has been considerably modified from the much colder and more saline waters seen

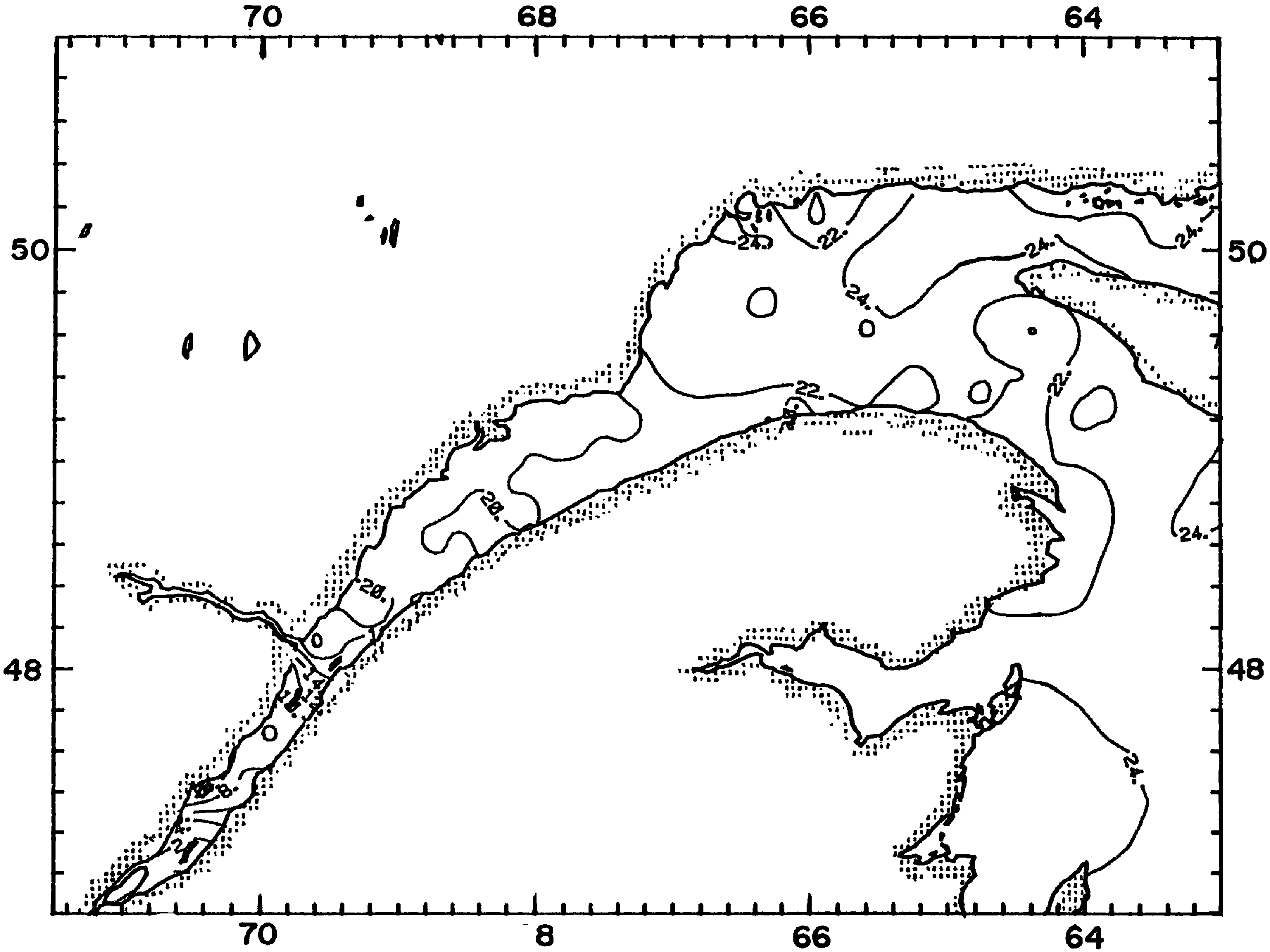


FIGURE 19 COUNTOURED SURFACE DENSITIES IN THE UPPER ESTUARY - spring

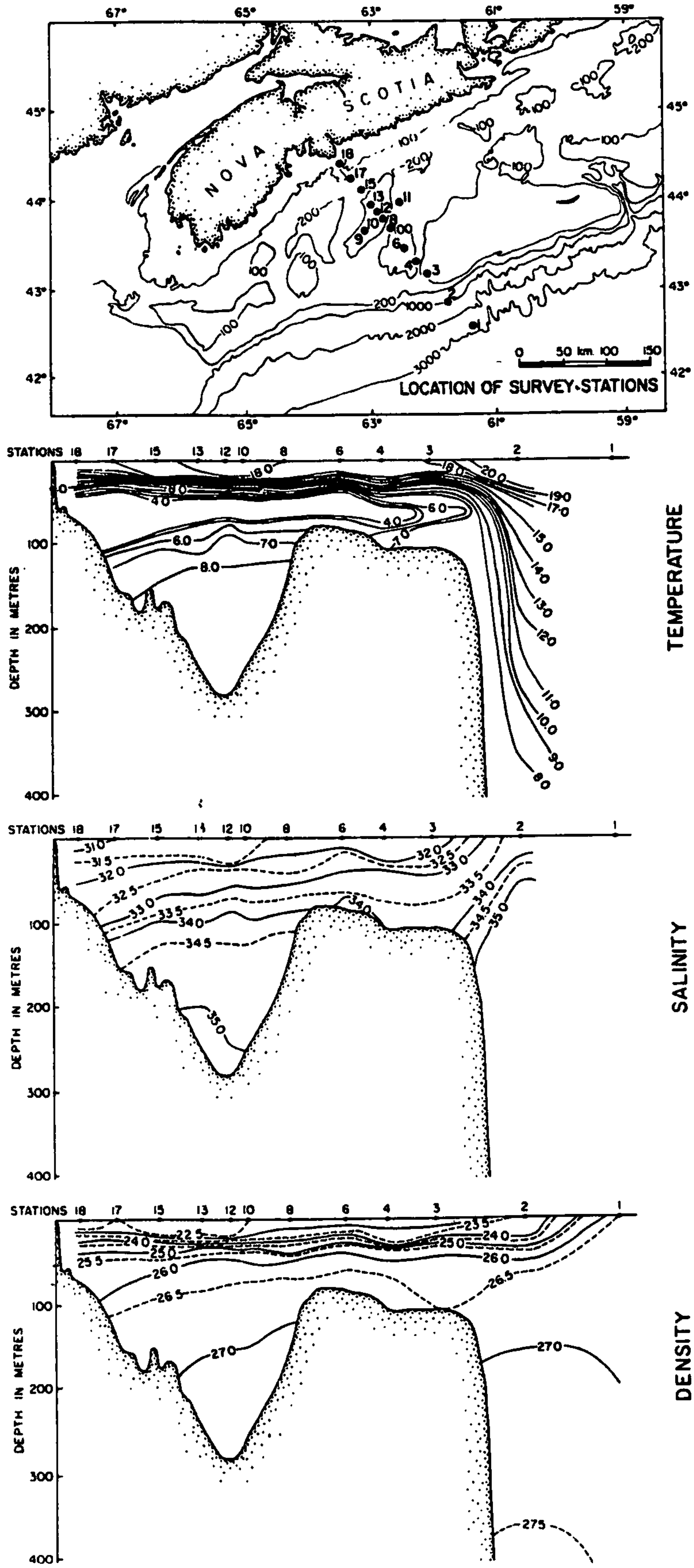


FIGURE 20 CROSS-SHELF SUMMER PROPERTY DISTRIBUTION ON THE SCOTIAN SHELF

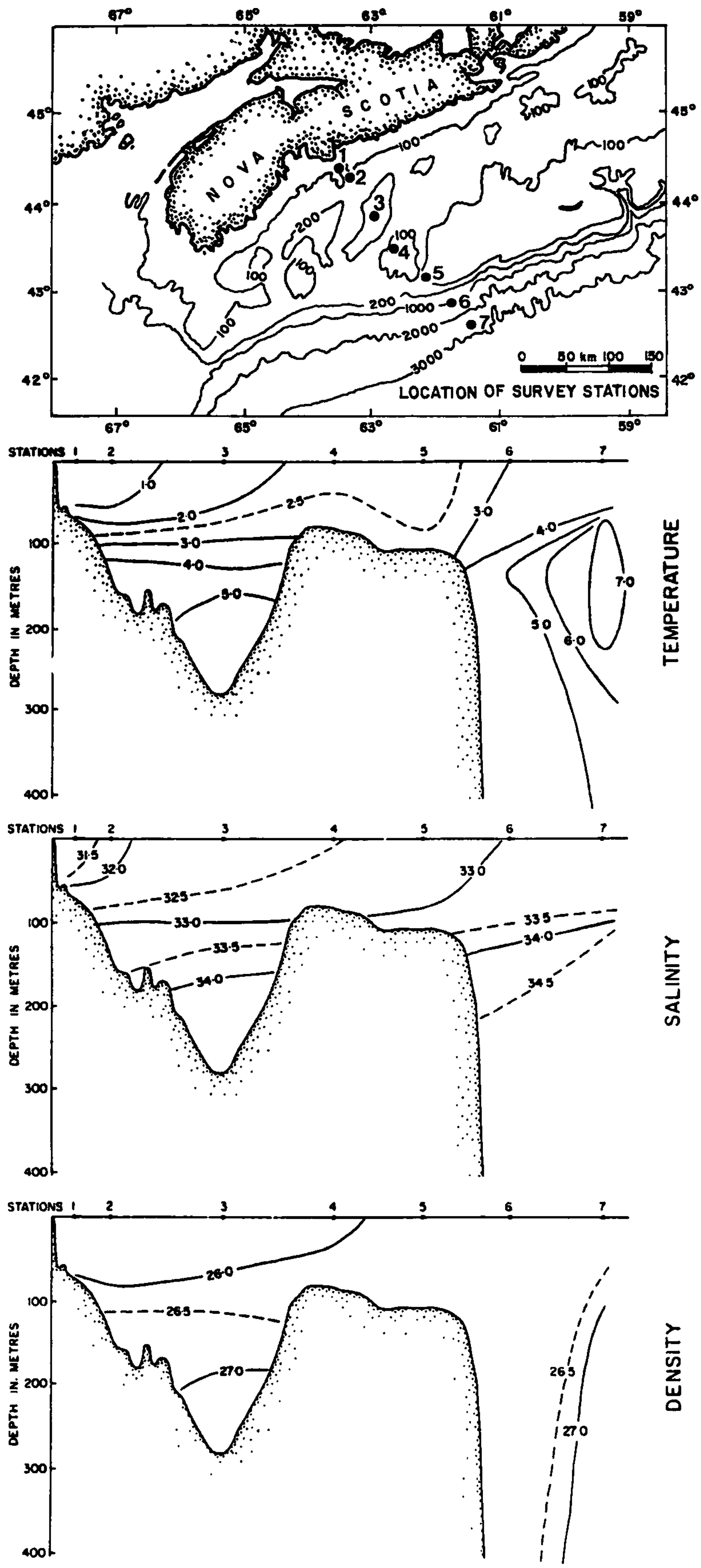


FIGURE 21 CROSS-SHELF WINTER PROPERTY DISTRIBUTION ON THE SCOTIAN SHELF

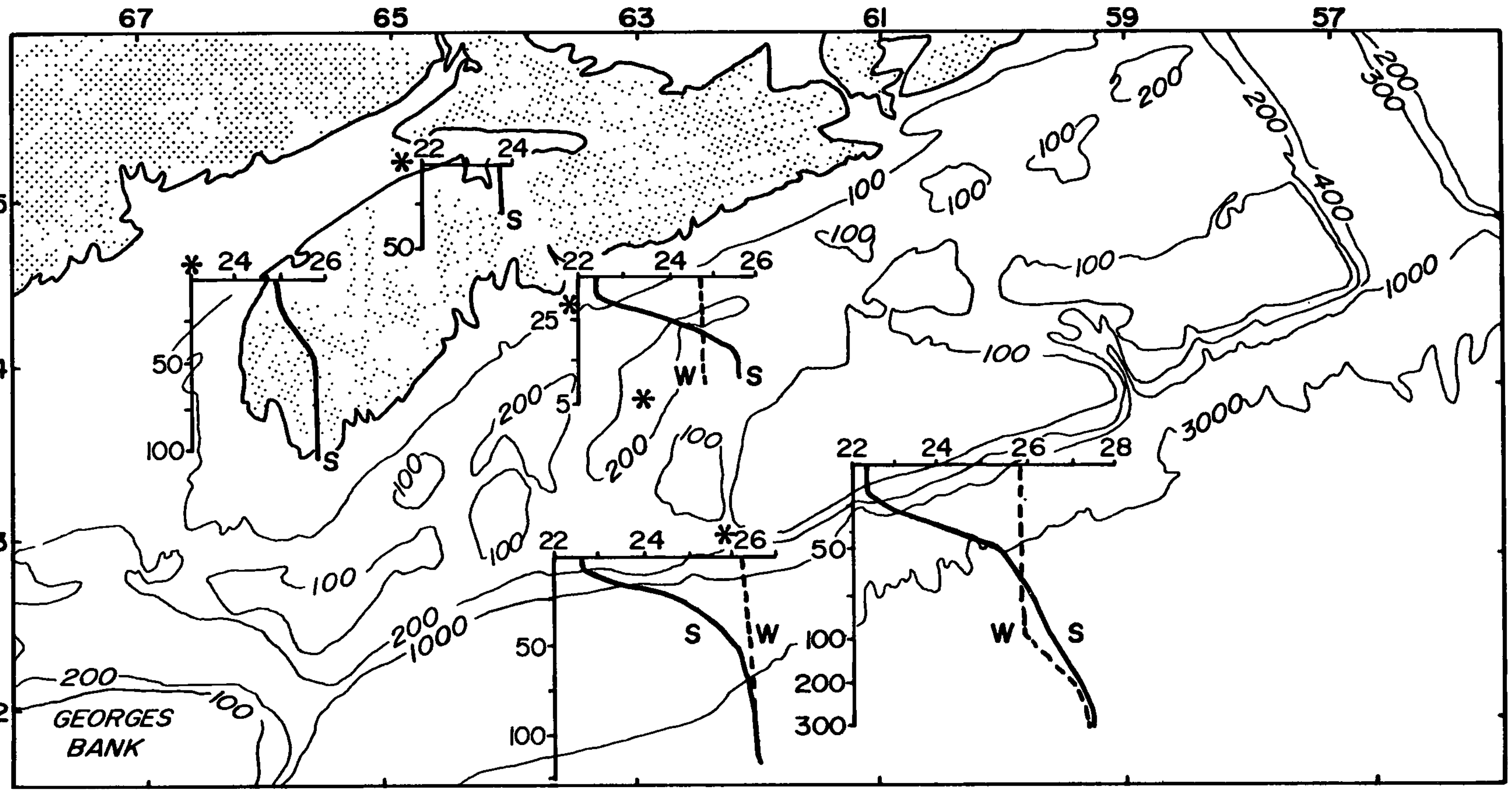


FIGURE 22 REPRESENTATIVE VERTICAL DENSITY PROFILES ON THE SCOTIAN SHELF AND BAY OF FUNDY

previously. It is important to note when considering property transports, that this intermediate layer is a result of advection and not a remnant of winter cooled water which is the case in the Gulf of St. Lawrence and more northerly coastal waters. The bottom layer (>5°C, >33.5‰, 26.5 to 27 σ_t) has similar characteristics as the slope water and reflects its penetration onto the shelf. In the winter, inshore and over the shallow banks, water may be completely mixed to the bottom (Figure 21). Elsewhere only two layers are observed with colder, fresher water overlying warmer, more saline water in the troughs with little density increase with depth. The winter minimum temperatures are higher than those seen on the rest of Canada's Atlantic Coast due to the modifying influence of the warm slope water and lower latitudes.

The slope water, that water lying between the shelf break and the Gulf Stream, is an area of high variability. The surface slope waters result from mixing between the coastal water and the Gulf Stream and show salinity and temperature increases toward the southeast. Below 200 m, a mixture of Labrador and North Atlantic Central Water exists (σ_t >27). The flow in the slope water is toward the East, opposite to that on the shelf. Within the slope water regime, water properties are "patchy" and intermittent events can create large-scale anomalies. One of these is the result of meanders of the Gulf Stream, lengthening and pinching off a ring of current. When this occurs to the left of the Gulf Stream, Sargasso Sea water becomes entrapped and a Warm Core Ring is released into the slope water. These rings have a diameter of about 100 km, may be formed every 2 or 3 months and can have an internal water temperature greater than 20°C with salinities around 36‰ and densities of 25 to 27 σ_t. Rings move southwest against the flow in the slope water often maintaining their integrity. If oil is spilled within them, it could be transported down the length of the slope, as far as Cape Hatteras, or until the ring disintegrates. Patches of lower density shelf water can also be found in the slope region. These may have been pulled off the shelf by the passage of a Gulf Stream ring nearby.

2.5.2 Frontal Regions. Two frontal regions can be observed on the Scotian Shelf and Slope. Between the Gulf Stream and slope waters, a shear zone exists in the currents and a temperature change in the surface waters of 10°C can occur. This region generally lies outside the 200 mile economic limit. A second permanent front exists between the shelf and slope waters often associated with the shelf break. Across its width, temperatures may increase by as much as 6°C and salinity by 2‰. However, little density change occurs and its position is variable, on average over the 100 to 1000 m isobaths. The boundary may be less than 5 km across. As a result of the little density difference across the front, this is a region of intense horizontal mixing such that any buoyant substance (possibly oil) could be spread quickly. The waters interleave with a vertical scale to the layers of 10 to 20 m and a horizontal distance of 2 to 3 km. Mixing occurs by diffusion mechanisms involving differential heat and salt exchange creating instabilities (i.e., "double diffusion"). Downwelling often results due to caballing (i.e., the creation of water of higher density by the mixing of two waters having the same density but different temperature and salinity). This front moves back and forth under the influence of the semi-diurnal tide and local generation of internal tides occurs moving isopycnals vertically 10 to 20 m. The front can be disrupted by the passage of a Gulf Stream ring in the slope waters, which can "pull" water (or oil) off the shelf in its wake. The shelf break is also a zone of intermittent upwelling and downwelling under along shelf winds.

2.5.3 Bay of Fundy - Gulf of Maine. Waters flowing down the Scotian Shelf, enter the Bay of Fundy-Gulf of Maine region, around the tip of Nova Scotia. The water circulates in a counterclockwise manner within this region finally to exit around Georges Bank. The seasonal density picture reflects the pattern of solar heating in the central water. Here a three-layer structure in temperature, similar to that seen in the Gulf of St. Lawrence also exists. Deep waters (>200 m) represent intrusion of slope water through the Northeast Channel (~6°C, 34.5 to 35^o/oo, ~27.2 σ_t). A cool intermediate (2 to 5°C, 32 to 32.5^o/oo, 25.8 σ_t) layer from 50 to 150 m reflects winter cooled water isolated from the surface by summer heating. In the winter it extends to the surface (1 to 2°C, 32^o/oo, 25.8 σ_t) and shows more moderate conditions than in the Gulf of St. Lawrence or further north. Influences of the freshwater run-off into the Bay of Fundy are felt within the upper reaches of the Bay with large changes seen only in the Minas Basin - Cobequid Bay and Chignecto Bay - Shepody Bay arms. These areas resemble a well-mixed estuary (i.e., vertically homogeneous) as a result of strong tidal mixing. The very large tidal excursions move the horizontal distribution over a tidal cycle. Land run-off is felt in April and May as a "spring freshet" creating a tongue of fresher water from St. John River along the New Brunswick shore. The circulation pattern results in a density pattern which shows a decrease across the Bay of Fundy, from the Nova Scotia to New Brunswick shores (of 0.5 to 1 σ_t in some cases).

2.5.4 Mixing Processes. The major factor in disrupting an expected seasonal development of the vertical density structure are the tides. Unlike winds whose influence is seasonal and sporadic (storms), tides are a "continuous" disruptive force. The large tidal currents can mix a water column when the water depths are reduced. This results in the presence of numerous "shallow-sea" fronts between well-stratified and mixed waters. Figure 23 shows the major mixing and frontal areas. They are associated with shallow bathymetry and all, with the exception of those marked coastal which result from local wind-induced upwelling, are caused by bottom friction on the tidal currents. They are persistent features from early May to early October associated with a temperature and density change of up to 5°C and 2 σ_t. These fronts act as boundaries between water masses where oil of similar density may behave quite differently.

Around the tip of Nova Scotia, the inflowing current and the strong tides are capable of generating an upwelling region by means of centrifugal upwelling (Garrett and Loucks, 1976). This results from an imbalance of two forces. The centrifugal force present when a current rounds a corner is balanced by a pressure gradient acting against it. Near the bottom, the current velocity is reduced due to friction, the outward centrifugal force is thus reduced but the inward pressure gradient is not. The bottom waters are forced towards shore and upwell when the boundary is met. The upwelling is independent of the direction of the current and results in local increase in surface water density.

Tides cause not only increased vertical but horizontal mixing of waters so that any oil spilled on the surface would be spread faster than for simple diffusive processes. Increased horizontal mixing can occur from shear dispersion processes and by large eddy formation (metres wide) around uneven bathymetry such as sand bars.

As a result of non-linear interactions between steady flows, oscillating flows (such as tides) and changing bathymetry, a mean current can be produced around certain bathymetric features (i.e., tidal rectification). As a result of the large tides in the Gulf of Maine-Bay of Fundy region, this interaction is a possible cause of a strong current jet around Georges Bank. Any substance (such as oil floating on the surface) will be moved about at a much greater speed than either on top of the bathymetric feature or in the deeper water around it. The top of Georges Bank is vertically well-mixed all year with the central region away from the front, often showing very high temperatures compared to the edge due to its shallowness. This tidal rectification was not seen around the Grand Banks due to the comparatively reduced tidal currents in that area.

In the open areas of the Scotian Shelf and Bay of Fundy, surface water densities rarely fall below 22 σ_t and in the winter they are generally greater than 25 σ_t. Only oil of higher density would sink below the surface. Deep water density, on the shelf is in the order of 27 σ_t which limits the upper range of oil density which would not sink to the bottom, but be trapped at some intermediate level. Figures 24 and 25 illustrate the

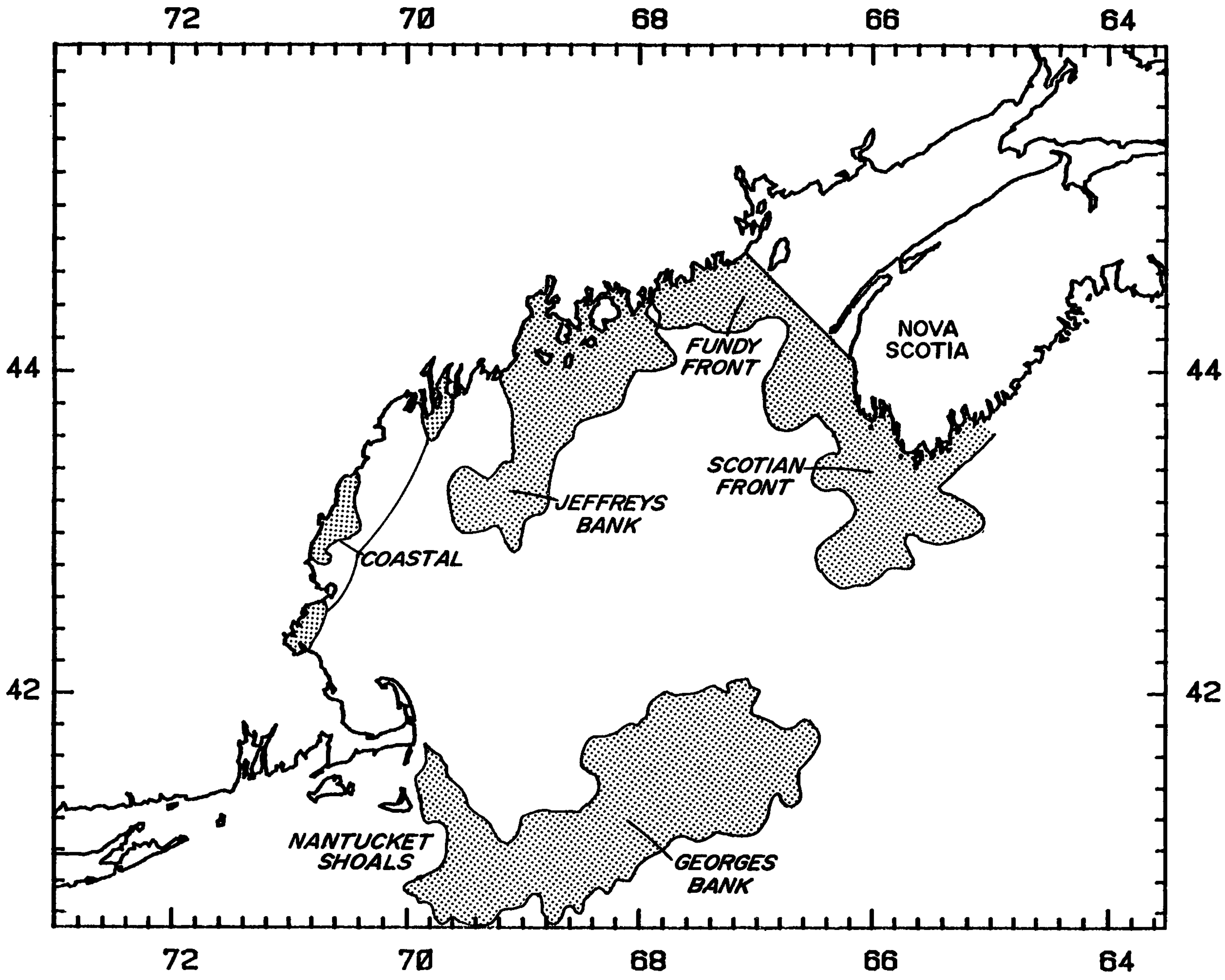


FIGURE 23 MIXING AREAS IN THE GULF OF MAINE AND BAY OF FUNDY

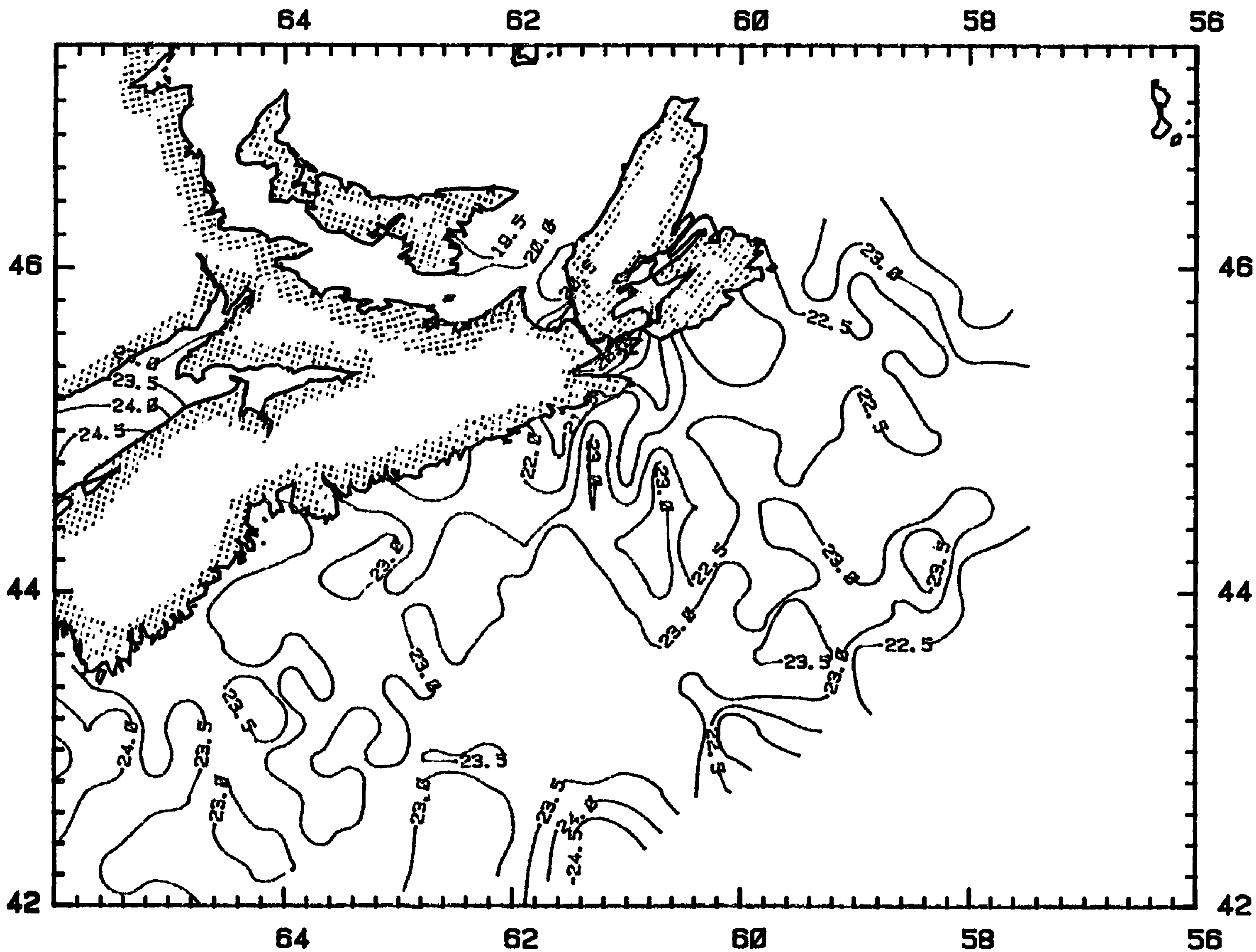


FIGURE 24 CONTOURED SURFACE DENSITIES ON THE SCOTIAN SHELF - summer

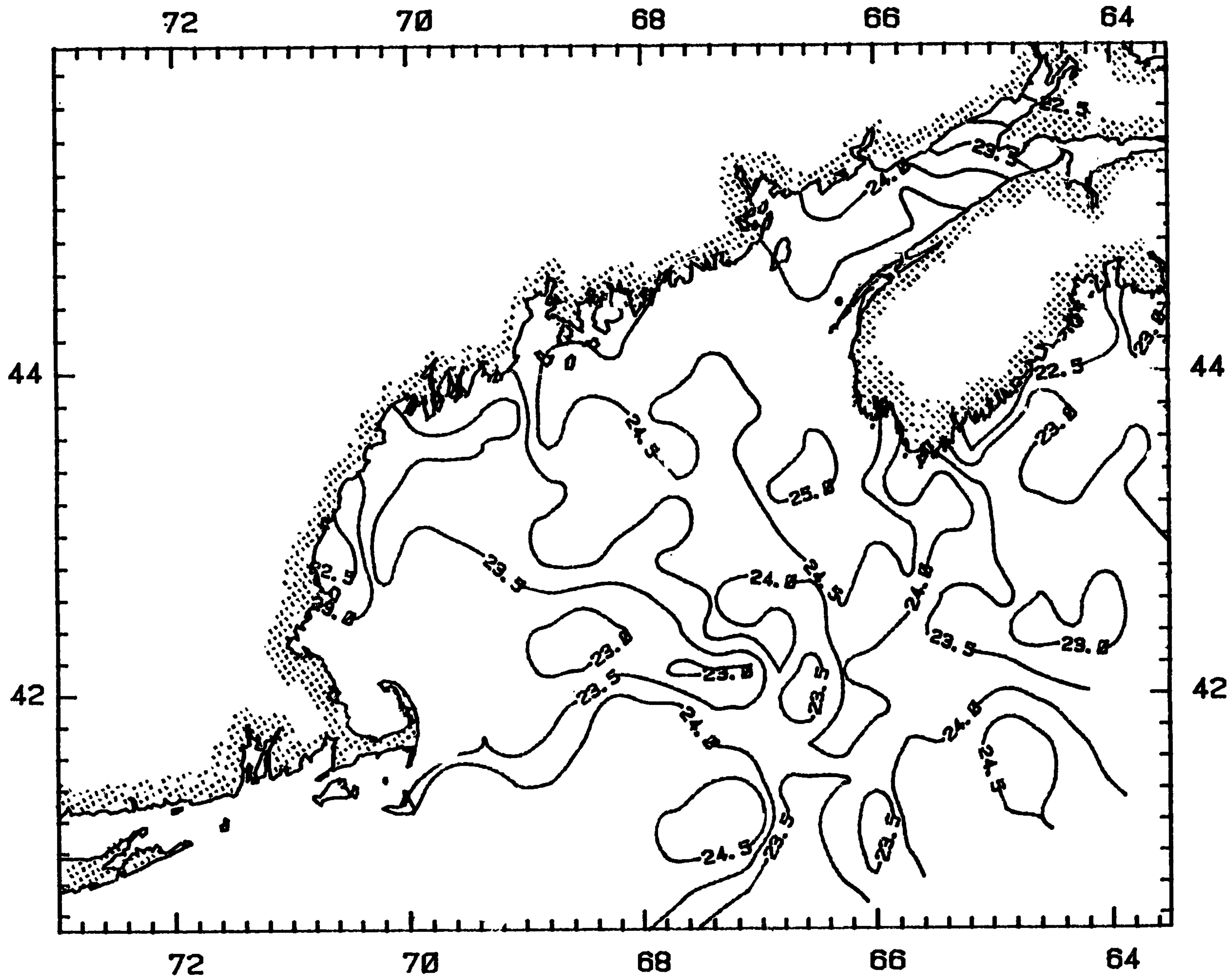


FIGURE 25 CONTOURED SURFACE DENSITIES IN THE BAY OF FUNDY AND GULF OF MAINE - summer

horizontal distribution of surface water values during the summer. Only within the uppermost regions of the Bay of Fundy and in the localized area near the Strait of Canso could lighter oil (10 to 20 σ_t) possibly sink.

3 THE ARCTIC COAST

The Arctic Coast of Canada is examined in 3 regions:

1) Hudson Bay, an unusual estuarine-like area,
2) the Arctic Archipelago, and
3) the Southeastern Beaufort Sea.

3.1 Hudson Bay

The two features affecting the density distribution in Hudson Bay are the circulation pattern, reflecting its semi-enclosed nature and freshwater run-off, and the cycle of ice freeze and thaw, reflecting its latitude.

Within the Bay, there exists a general counter-clockwise circulation. Oceanic waters enter around Southampton Island and are freshened during their passage around the Bay by freshwater run-off. The fresher surface mixture exits Hudson Bay into Hudson Strait where large tidal activity and merging with the Baffin Current creates a mixed, denser water. Tidal activity near the shores of the Bay will also vertically mix the water column.

Hudson Bay freezes completely in winter by January, and melts completely each summer. Ice break-up begins in June and proceeds from east to west in the Bay. By late August it is nearly completely free of ice. In Fox Basin the onset of break-up is much later and it may only become free of ice in late September, early October. As a result of the east to west progression of ice break-up in Hudson Bay, surface waters along the eastern shore become susceptible to solar heating much sooner and increase in temperature and water column stability prior to the west coast. This factor, as well as inputs of fresh water, result in a general decrease in surface water density from west to east and an increase in stratification (Figure 26). During freeze-up the reverse situation tends to occur in the initial stages with the position of the pack-ice boundary advancing from Northwest to Southeast. The winter water column tends to be more uniform with a density of approximately 26 to 27 σ_t throughout.

3.1.2 Conditions Favourable for the Sinking of Oil. Figure 27 illustrates the contoured surface density distribution across Hudson Bay. Oil of density between 15 and 20 σ_t would sink in the southeast as well as in James Bay. This oil could come to rest in the strong seasonal pycnocline at 30 metres. Dense oil (σ_t >26) would sink everywhere and pass through the water column to settle on the bottom.

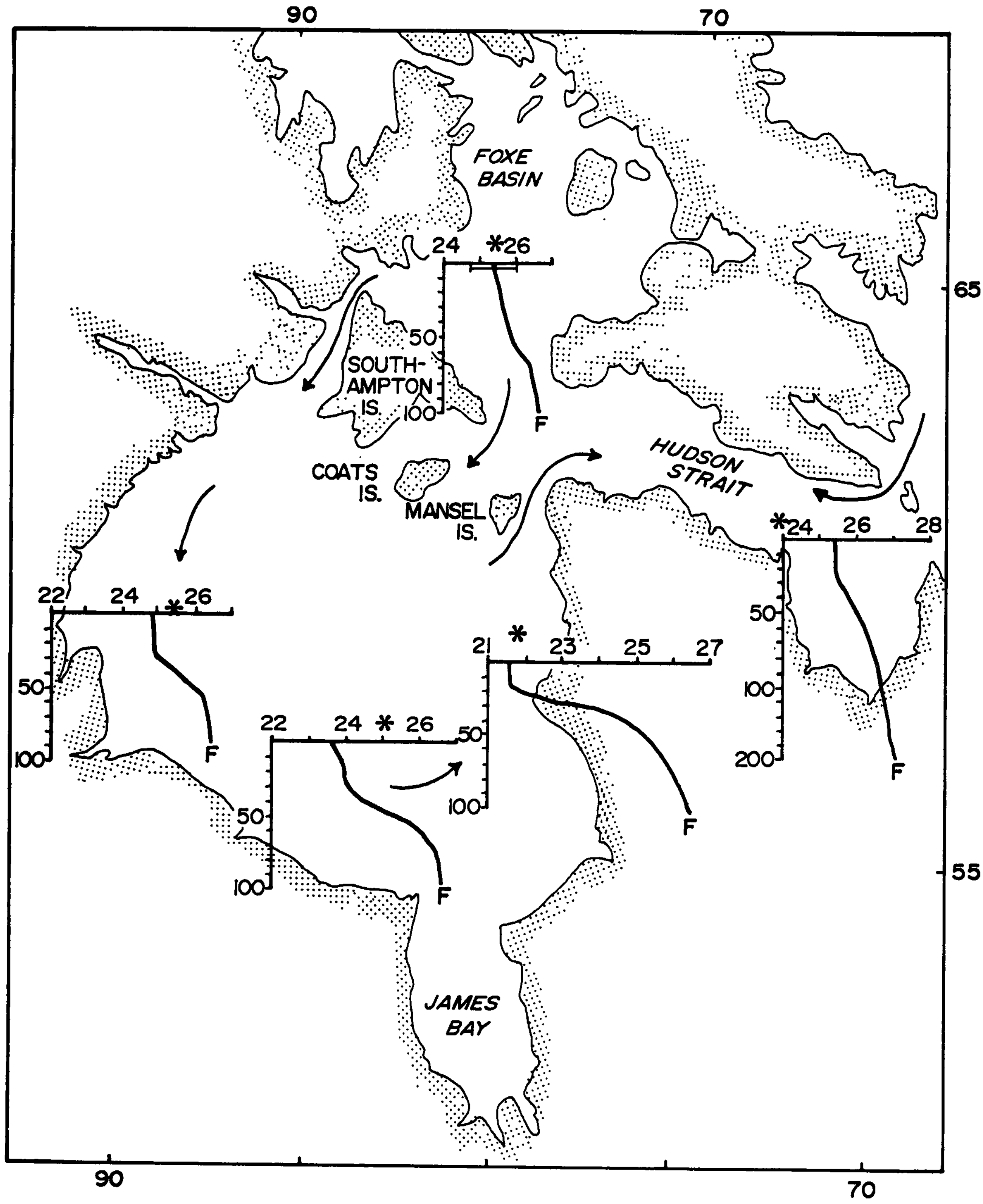


FIGURE 26 REPRESENTATIVE VERTICAL DENSITY PROFILES IN HUDSON BAY

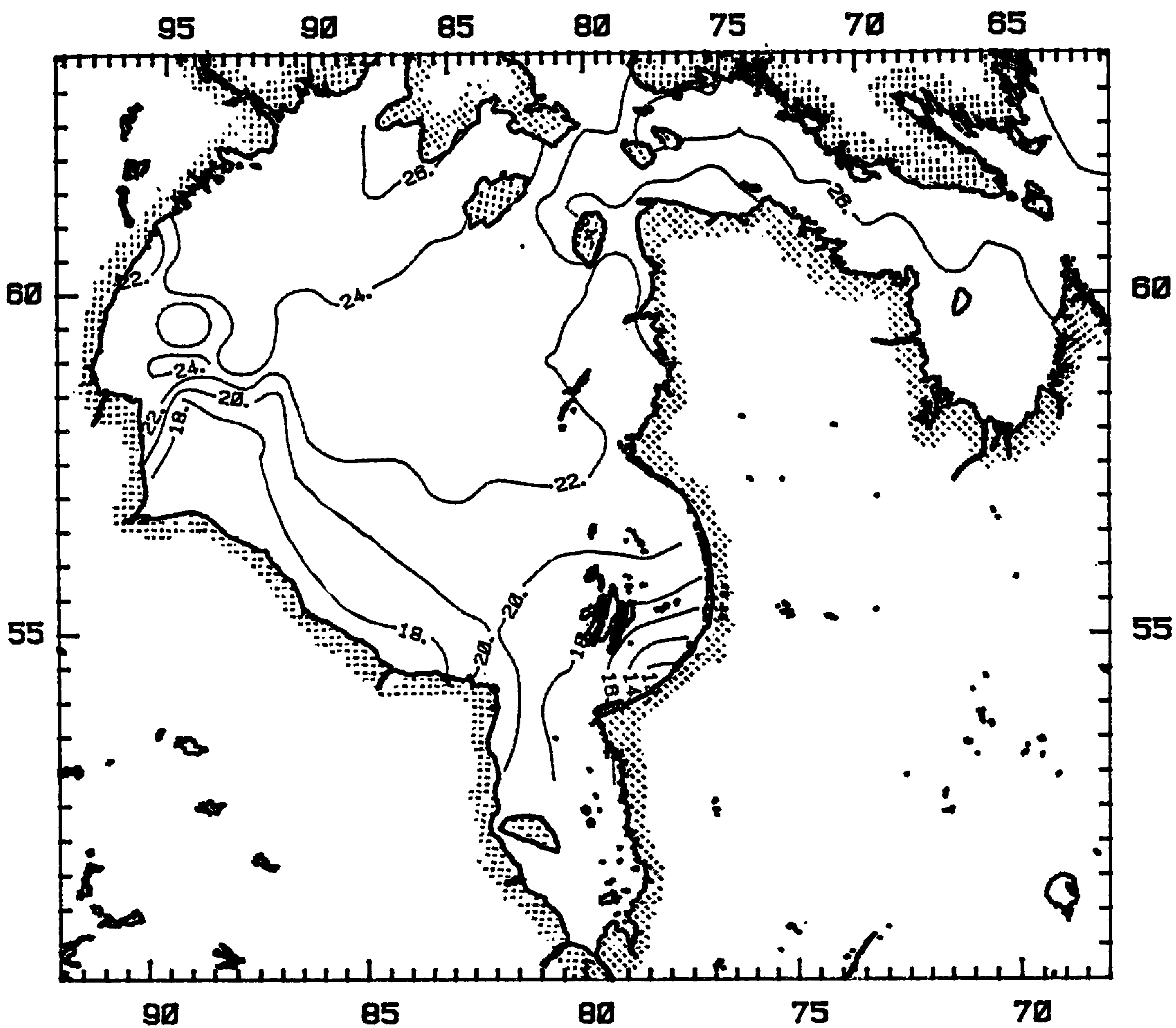


FIGURE 27 CONTOURED SURFACE DENSITY PROFILES IN HUDSON BAY

3.2 The Arctic Archipelago

The general flow of surface waters is to the east and south, from the Arctic Ocean to Baffin Bay through the many channels between the islands (Figure 28). This is attributed to a higher sea level in the Arctic Ocean. Tidal currents are relatively weak, except in narrow passages where they may be substantial. In summer, wind-driven flow often obscures the mean current. May fjords and inlets have an estuarine circulation driven by freshwater input.

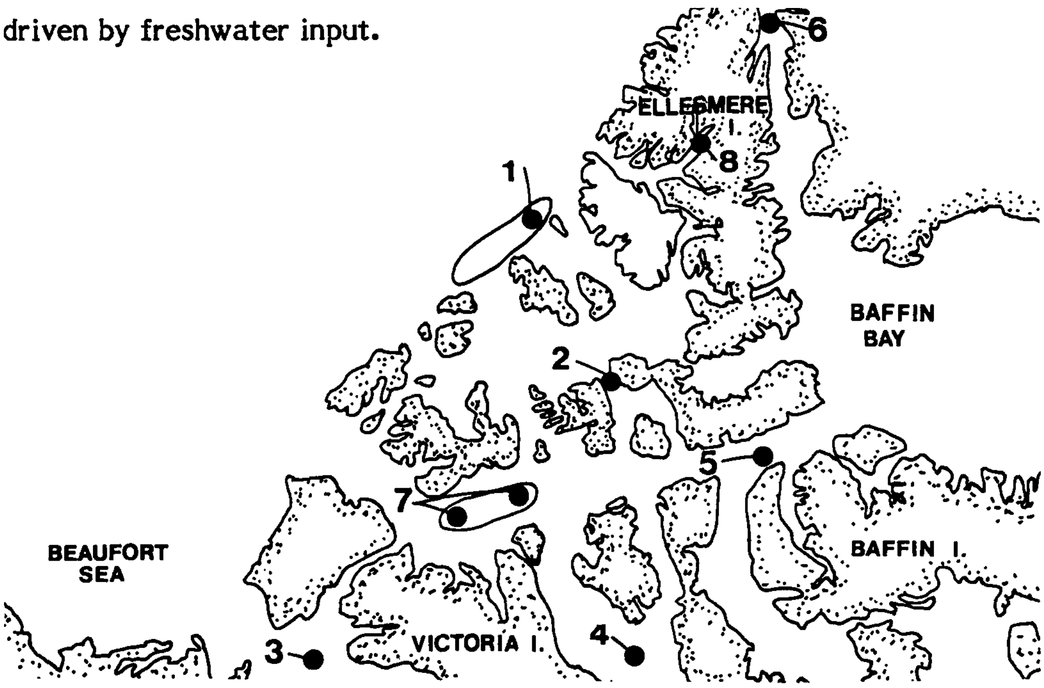


FIGURE 28 LOCATION MAP FOR DENSITY PROFILES IN THE CANADIAN ARCHIPELAGO

Some of the waterways in the Archipelago never clear of ice, particularly to the northwest in the area of Hazen Strait and Prince Gustaf Adolf Sea. During heavy ice years, McClure Strait, Viscount Melville Sound, McClintock Channel, and southern Gulf of Boothia remain ice congested all summer. Northern areas such as d'Iberville fjord become clear of ice only in August, and not every year. However, open water exists in most areas for part of the July through October summer period. In winter the Archipelago is almost entirely ice-covered. There are, however, several areas of recurring polynyas and flow leads with the largest being the Cape Bathurst Polynya of Amundsen Gulf and the North Water in Northern Baffin Bay (Sterling and Cleator, 1981).

In the Archipelago the water density is largely determined by salinity. Therefore, low density surface waters, the most favourable conditions for the sinking of oil, are largely formed by the input or advection of relatively fresh water. The main sources of low density surface water are:

- sea ice melt,
- direct precipitation and associated runoff,
- runoff of meltwater from snow and icefields, and
- relatively fresh water advected from other areas.

Summer melting of sea ice can result in a low density surface layer one to two metres thick. The melting of icebergs produces local, minor and random inputs of fresh water. Runoff from icefields feeds local rivers, and tide water glaciers and icebergs melt continually year-round into inlets.

Mean precipitation is only 10 to 20 cm water equivalent annually (increasing from north to south). Peak rainfall occurs during July-August. There are no major rivers on the scale of the Fraser or Mackenzie. The rivers begin to flow as soon as air temperatures rise above freezing and the snow cover starts to melt. Buildup of flow is fairly rapid with the peak discharge occurring between June and August. Rivers fed by icefield meltwater buildup flow more gradually. The major icefields are on Ellesmere, Axel Heiberg, Devon and Baffin Islands. They appear to be a major freshwater source to the surrounding waters.

Advection of low density water is mainly west to east. The surface waters of the Arctic Ocean are less saline than those further east, and the effect of the Mackenzie River is evident as far east as Amundsen Gulf and possibly further.

3.2.1 Horizontal Density Gradients. The density of the surface waters in summer range from as low as 5 σ_t, up to about 25 σ_t. The low density waters are generally found in sheltered embayments and inlets and near river mouths. Nearshore regions fed directly with icefield runoff also have lowered surface densities. Where wind and/or currents mix the upper layer, surface densities on the order of 25 σ_t can generally be expected.

The surface waters of Nansen and Eureka Sounds and west of Axel Heiberg Island are relatively fresh in summer. This is probably due to increased runoff from the icefields on Ellesmere and Axel Heiberg Islands.

Precipitation, which is greatest to the south, and the relatively large drainage basin of the mainland, result in surface densities of 12 to 16 σ_t during summer in the waters of Queen Maud and Coronation Gulfs.

The density of nearshore waters often exhibits a non-uniformity on the scale of tens to hundreds of metres. An example of such variability is evident in an aerial photo taken near Cape Warrender, Lancaster Sound (Figure 29). The low density water from the icefield runoff shows up lighter than the marine waters because of the high content of ground-up rock "flour". About half a dozen small streams can be seen feeding into this area. The ripple-like features are believed to be concentrations of silty surface water, caused by internal wave motions.

3.2.2 Vertical Density Gradients. Typical density (σ_t) profiles for the locations indicated in Figure 28 have been plotted in Figures 30 and 31. Surface densities in winter under the ice are generally 25 to 26 σ_t, with a pycnocline at 25 to 70 m through which the densities increase to about 28 σ_t.

In summer, the input of fresh water at the surface can produce a 10 to 20 m thick surface layer with relatively low density. In sheltered areas, the surface density may be as low as 5 σ_t. Below 20 m the vertical density structure is similar to the winter profiles.

3.2.3 Conditions Favourable for the Sinking of Oil. Figures 32 and 33 show the contoured surface density distribution in the northern and southern halves of the Canadian Archipelago. In sheltered embayments and near sources of water runoff, densities can drop to below 10 σ_t and oil of density as lows as 5 to 10 σ_t may sink. The strong pycnocline at 25 metres could trap oil of density less than 27 σ_t at this depth. The estuarine circulation established in these areas would result in the oil moving with the layer it finds itself in. Very strong horizontal gradients in surface density can be seen in these figures illustrating the variable and localized conditions in this region.

In winter and more exposed waters, surface densities are on the order of 24 to 26 σ_t and only very dense oil (σ_t >26) would sink. Oil denser than 28 σ_t would pass through the water column to the bottom.

3.3 Southeastern Beaufort Sea

The 200 mile economic boundary extends to about the 3000 m bathymetric contour (Figure 34). However, open water in summer is bounded by the edge of the polar pack which in good years roughly overlies the 2000 m bathymetric contour but in average years follows the shelf edge. The discussion will be limited to summer open-water areas. The movement of oil in and under the polar pack ice is beyond the terms of reference of this study.

The main water mass of interest is the Arctic water layer extending from surface to about 250 m. Below this is water of Atlantic origin. The near-surface properties of the

FIGURE 29 AERIAL PHOTO OF EMBAYMENT EAST OF CAPE WARRENDER, LANCASTER SOUND (30 000 ft, Dept. Energy Mines and Resources). The lighter water is icefield runoff containing rock "flour"

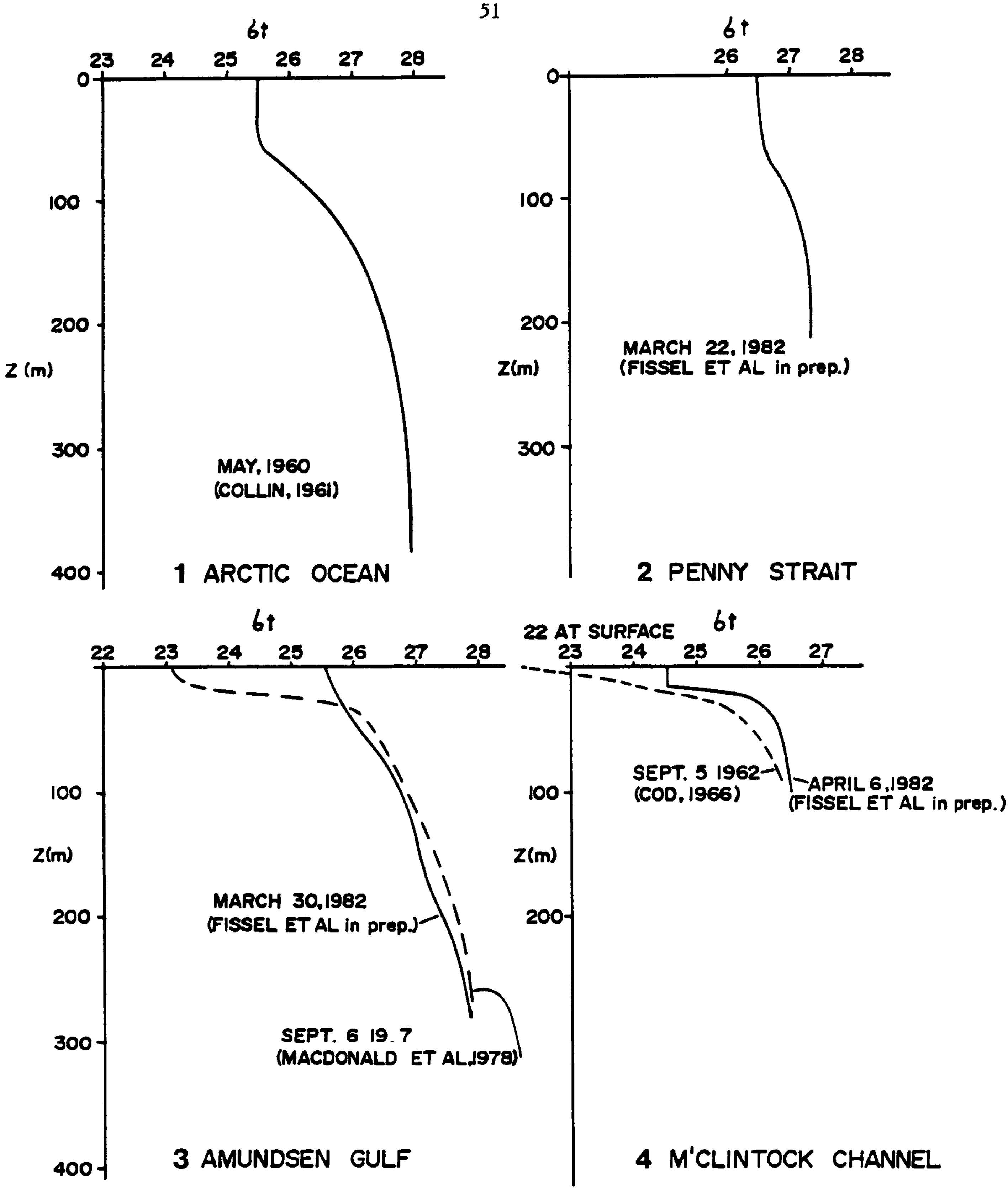


FIGURE 30 DENSITY PROFILES FOR LOCATIONS 1 TO 4 MARKED ON FIGURE 29 (solid - winter, dashed - summer)

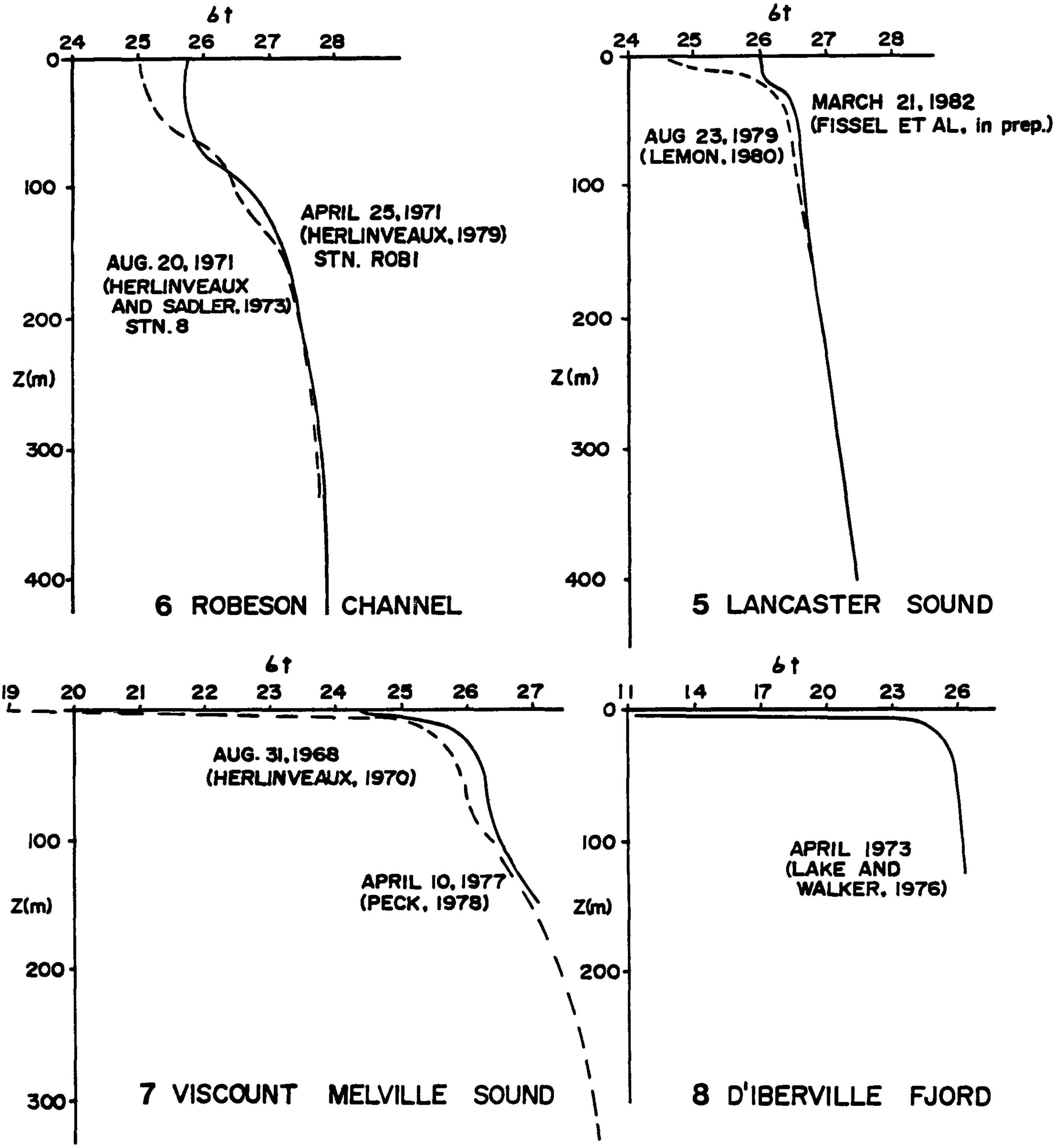


FIGURE 31 DENSITY PROFILES FOR LOCATIONS 5 TO 8 MARKED ON FIGURE 29
(solid - winter, dashed - summer)

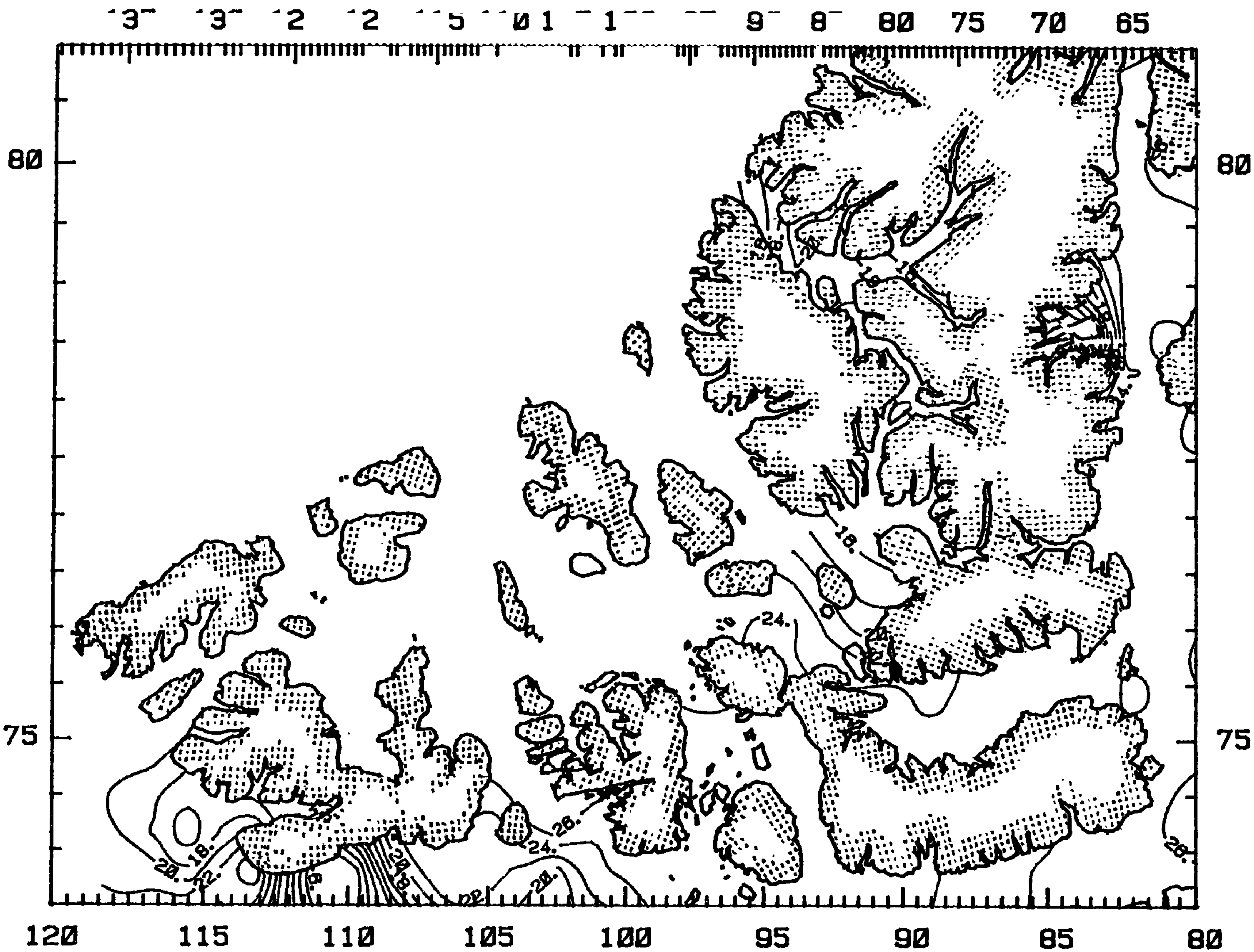


FIGURE 32 CONTOURED SURFACE DENSITIES IN THE CANADIAN ARCHIPELAGO - NORTHERN STRAITS

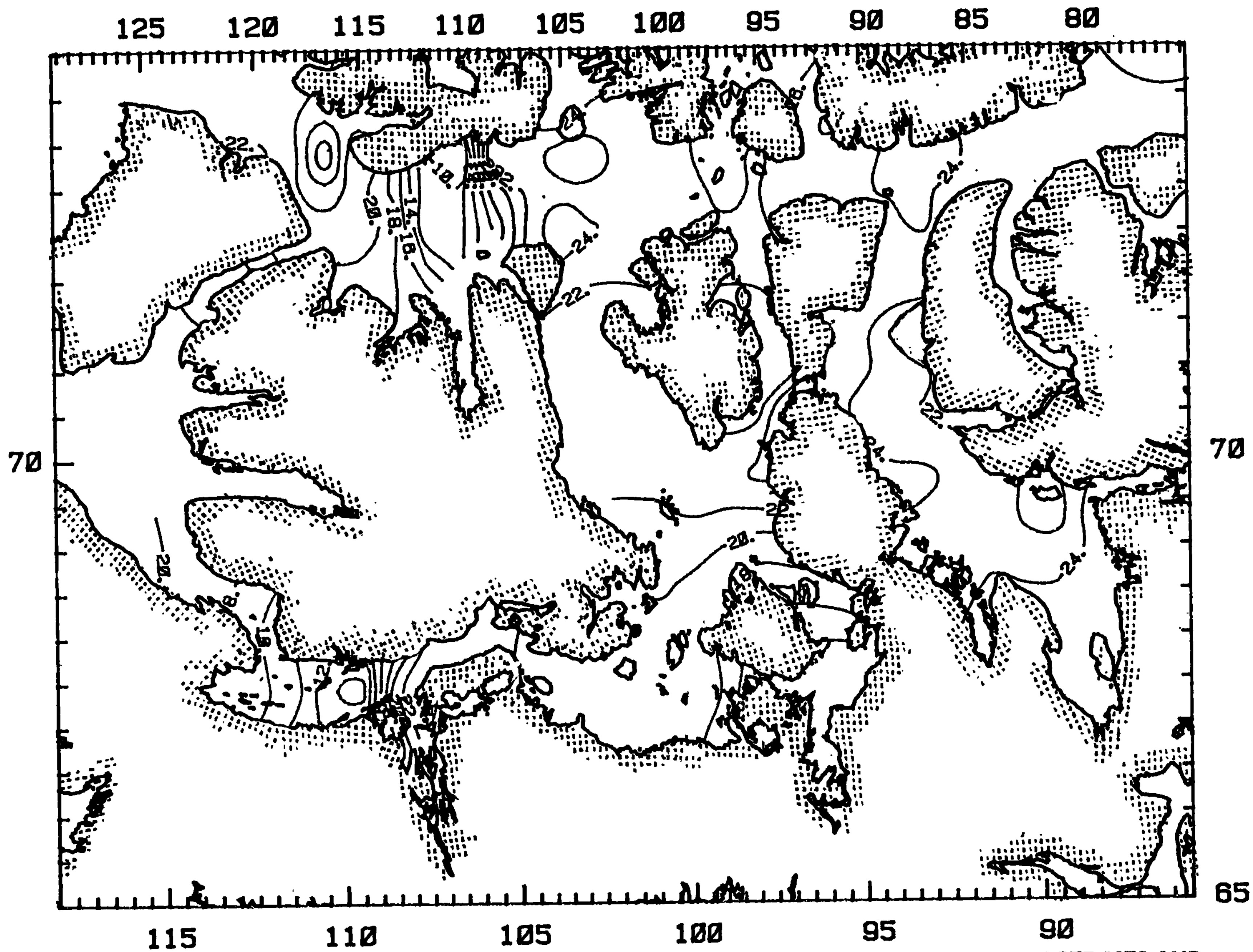


FIGURE 33 CONTOURED SURFACE DENSITIES IN THE CANADIAN ARCHIPELAGO-SOUTHERN STRAITS AND NORTHERN PASSAGE

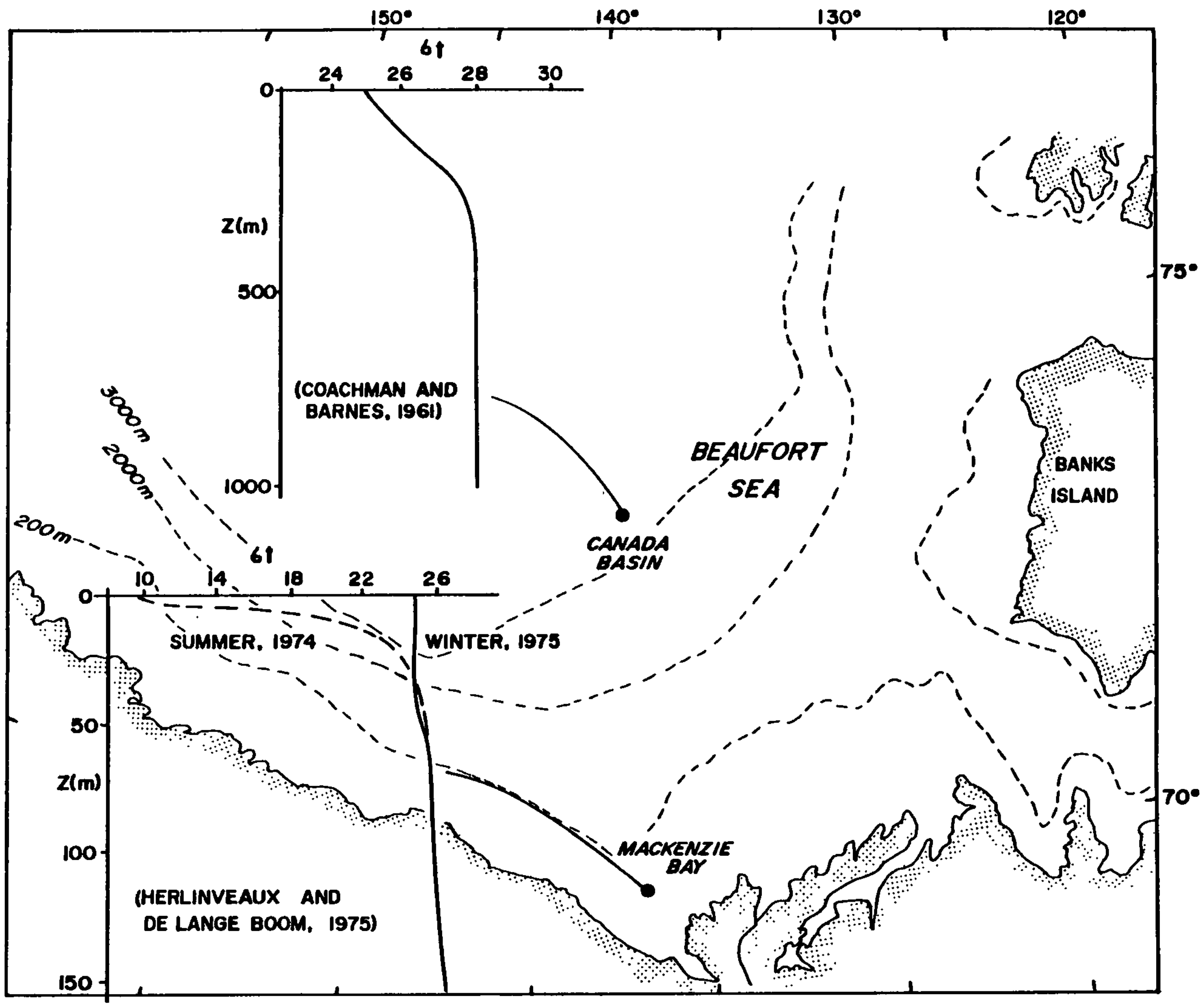


FIGURE 34 SOUTHEASTERN BEAUFORT SEA BATHYMETRY AND TYPICAL DENSITY PROFILES

Arctic water are affected mainly by runoff, solar heating/cooling, and ice formation/melting.

The circulation of offshore waters is dominated by the anti-cyclonic (clockwise) Beaufort Sea gyre. The gyre extends shoreward to about the edge of the shelf (~200 m depth contour). Over the shelf the net summer circulation seems to be to the northeast (the flow along the west side of Mackenzie Bay is to the northwest). However nearshore flows are strongly wind dependent, switching directions with the prevailing northwesterly or easterly winds. The near-bottom flow along the outer shelf during May-September was also found to be northeasterly (Huggett et al., 1975). Nearshore, a shoreward component of bottom current may result to replace water entrained by the surface plume of Mackenzie River outflow water. Tidal flows are weak, generally less than 5 cm/s.

3.3.1 Summary of Known Patterns of Density Gradients. At the low Arctic water temperatures, variability in density is determined largely by changes in salinity. Direct precipitation is low. The Mackenzie River discharge (more than twice that of the Fraser River) is primarily responsible for the variations in density of the surface waters. Its effect is generally felt over most of the shelf. The actual plume is confined to the upper 5 to 20 m and within 30 to 50 km of shore. The plume moves northeast along the coast, deflected by the earth's rotation and may extend as far as Amundsen Gulf.

The actual plume position changes with wind and ice conditions. Northwesterly winds concentrate the plume along the coast, whereas easterly winds move the plume offshore and denser water upwells along the coast. In poor ice years the polar pack crowds the shore and the runoff water is confined to a narrow band along the coast. This happened in 1974 and surface salinities nearshore were less than 5o/oo.

The vertical density structure in the upper 50 m varies seasonally with the Mackenzie River discharge (Figure 34). During summer, runoff and solar heating produce a warm, brackish surface layer roughly 5 to 20 m thick. Surface salinities increase offshore, although the brackish surface layer may extend out to the shelf edge. Measurements have identified low salinity surface water near the ice edge, probably due to the melting of the ice.

In the fall, winds, surface heat loss and salt extrusion during ice formation combine to destroy the summer pycnocline. This results in a well mixed layer down to about 50 m deep. There is a permanent pycnocline at about 250 m at the top of the Atlantic layer. In winter a thin low density layer of water may be found under the ice, from the much-reduced Mackenzie River discharge.

3.3.2 Conditions Favourable for the Sinking of Oil. The maps of surface density show the influence of the Mackenzie River plume (Figures 35 and 36). Two maps for good (1975) and bad (1974) ice years have been included to show the crowding effect of the ice. Peak discharge is in May-June. Discharge rates continue at roughly half the peak throughout the summer. In winter the runoff is much reduced and flows out and alongshore as a thin layer under the ice.

Oil of density as low as 5 σ_t could sink in the plume water, whereas densities nearer 24 σ_t would be required for oil to sink in the waters of non-coastal origin. The summer halocline at 5 to 20 m depth would prevent oil of density less than about 26 σ_t from sinking to bottom. Oil penetrating this pycnocline would enter the lower layer where movement is still in response to the wind, but a landward flow component may be present as a result of the estuarine circulation.

The most favourable locations for oil to sink are generally nearshore in the plume. However, easterly winds move the low density water offshore and cause upwelling of denser water along the coastline. The plume may also tend to encourage sinking of oil due to its suspended sediment load interacting with the spilled oil.

The edge of the plume is characterized by eddy-like features which generally curve cyclonically (counterclockwise) from the plume into the offshore waters. These eddies confuse the general circulation patterns and also create patches of lower density surface water offshore of the main plume. Neutrally buoyant oil could sink upon encountering such a feature or be transported a field with them.

Summer melting of the polar pack produces a band of low salinity water along the ice edge. This low density water suppresses the isopycnals and may provide a route for water and oil to sink beneath the ice (Corse, 1974).

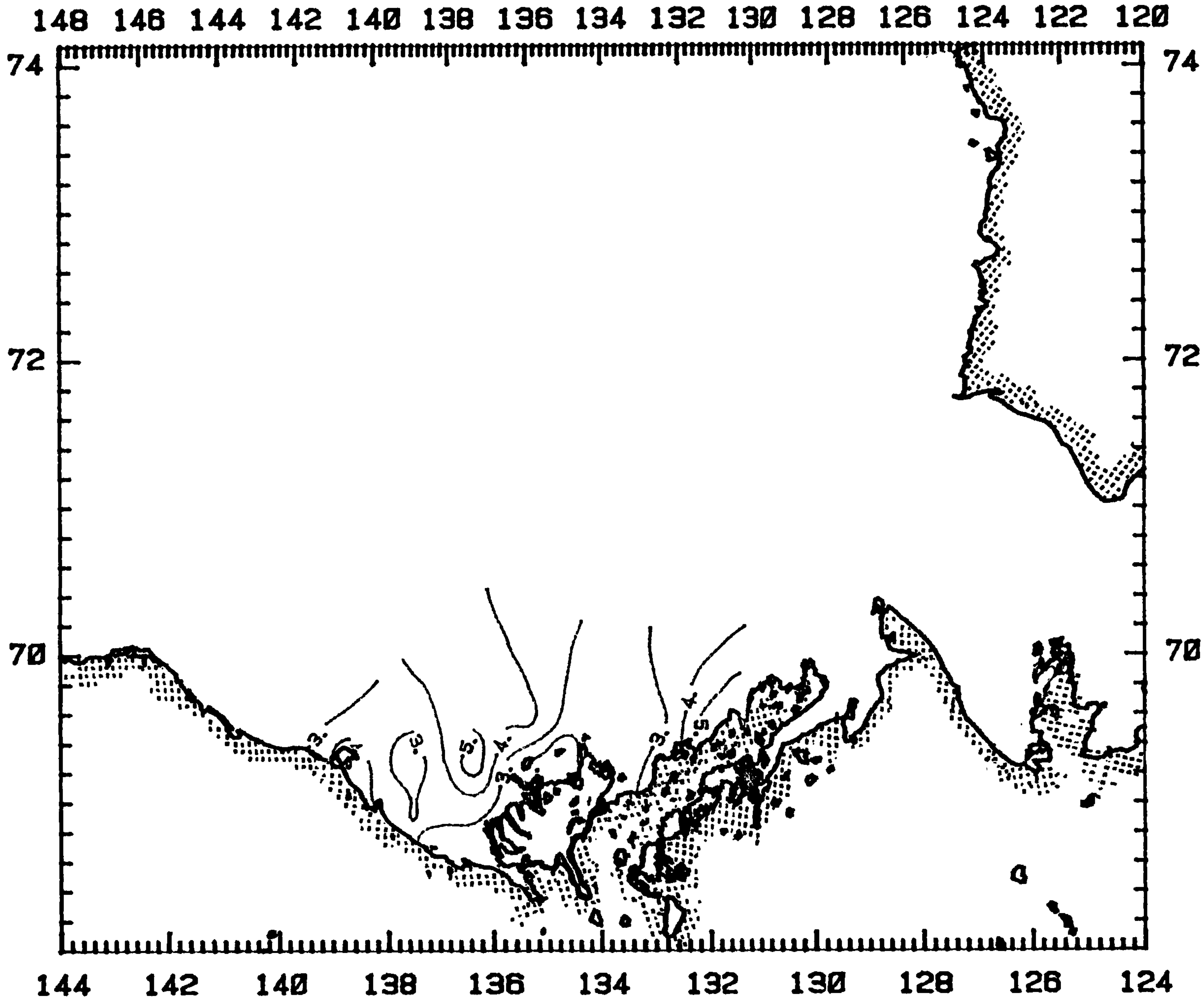


FIGURE 35 COUNTOURED SURFACE DENSITIES IN THE SOUTHEASTERN BEAUFORT SEA - 1974 (poor ice year)

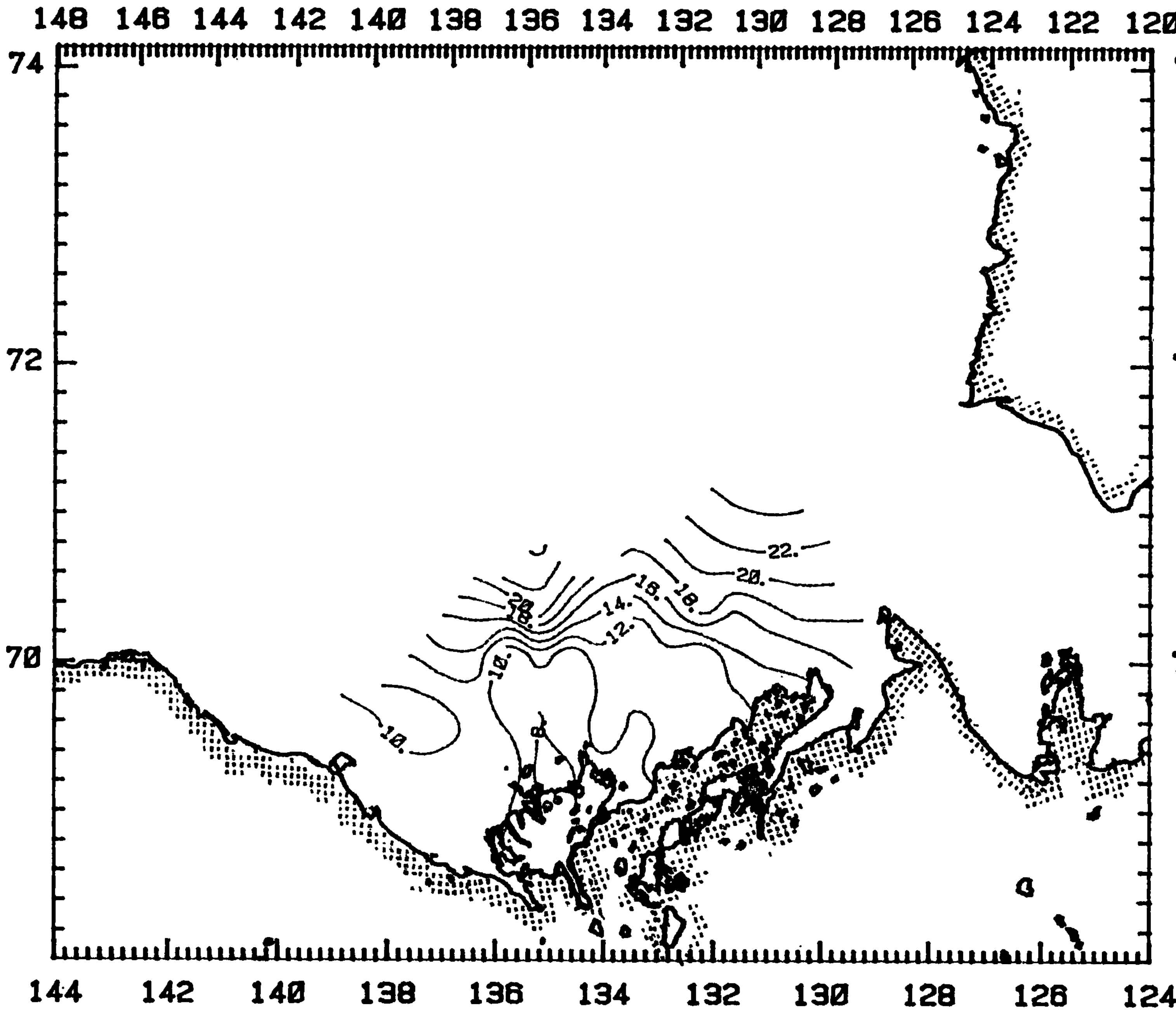


FIGURE 36 CONTOURED SURFACE DENSITIES IN THE SOUTHEASTERN BEAUFORT SEA - 1975 (good ice year)

4 THE PACIFIC COAST

The large-scale pattern of density gradients in the marine waters of British Columbia is primarily a result of the large volumes of freshwater runoff. The average annual runoff varies from 200 to 400 cm/yr compared with 75 to 100 cm/yr for the East Coast and 10 to 15 cm/yr for the Arctic (Anon., 1974). The influence of this low density water runoff extends hundreds of kilometres offshore. The extent varies seasonally with a maximum during the peak May-July discharge period of the main rivers.

The Fraser River is by far the major source of fresh water and is responsible for roughly 75% of the runoff into the Strait of Georgia. The Skeena River is the next most important (with roughly one third the output of the Fraser). Near the river mouths the surface waters may be diluted over large areas. Further offshore mixing and dispersion result in the sea surface salinity being patchy, with brackish water surrounded by more saline waters of non-coastal origin. Numerous creeks, streams and smaller rivers also provide freshwater input. The contribution of low density waters from these sources is largest in December and January when local precipitation is at its maximum. Other freshwater sources include glacial runoff which feeds into many of the coastal fjords. This runoff peaks in mid-summer when solar heating is most effective in melting the ice.

The character of the vertical density structure differs between the nearshore and offshore regions. In the nearshore environment, runoff produces a lower density surface layer. A two layer estuarine circulation often develops. The fresher water flows seaward near surface, while a compensating landward flow of high salinity water occurs at depth. The pycnocline is usually relatively sharp. On the other hand, offshore it is often the variability in temperature which produces the near-surface vertical density structure. Solar heating in summer produces a warm, lower density surface layer, typically 30 m thick. Winter winds and surface heat loss combine to destroy these gradients, leaving a well mixed layer typically 100 m thick, below which is the permanent thermocline.

Apart from these known patterns of density variability on surface waters, there are more transient processes which result in areas of anomalously low density surface water. These processes include: downwelling, geostrophic flow, fronts, Langmuir circulation, internal waves, and mixing or dispersion resulting in non-homogeneity in the surface waters.

Following is a discussion by area of the known patterns of horizontal and vertical density gradients. This will form the basis for discussions on conditions suitable for the sinking of oil. Figure 37 is a location map for these areas for the representative vertical density profiles examined.

4.1 Strait of Juan de Fuca

The Strait of Juan de Fuca provides an east-west connection between the southerly portion of the Strait of Georgia and the Pacific Ocean. Here, surface currents are dominated by the tidal flows which reach speeds of 100 to 180 cm/s. Residual flows due to the estuarine circulation are typically 10 to 20 cm/s seaward at surface, and 10 cm/s landward at depth. During fall and winter, low runoff and southwesterly winds frequently combine to reverse the surface flow, resulting in an easterly residual flow near surface and a compensating seaward flow at depth.

The largest direct source of fresh water is the San Juan River on the northeast side of the Strait. During spring and summer large runoff and northwesterly winds combine to drive a westerly flow at surface, bringing low density Fraser River water into the eastern portions of the Strait.

Monthly maps of horizontal density structure show lower density surface waters to the east (Figure 38). This is primarily due to Fraser River discharge and the effect is strongest during the May through July period of peak runoff. The winter surface density gradients are relatively weak.

The vertical density structure is also relatively weak in winter (Figures 39, No. 5 and Figure 40, bottom). As the volume of runoff increases in spring, an estuarine circulation develops. Low density water flows seaward at surface and a compensating landward flow of high salinity water occurs at depth. The stratification of the water column is further enhanced by offshore upwelling of saline water caused by the summer northwesterly winds (Figure 40, top).

4.1.1 Conditions Favourable for the Sinking of Oil. From Figure 38 it can be seen that oil of density greater than 23 σ_t would sink in the most easterly waters of the Strait. Further west, higher densities would be required in order to sink (>24 σ_t). The large density gradient (pycnocline) between 25 and 75 m (Figure 39, No. 5) would prevent oil of density less than about 26.5 σ_t from penetrating the lower layer in summer. Oil of greater density could reach the lower layer, or bottom, and in summer be transported landward (east) with the deep residual current. In the winter, only oil of density greater than 24 σ_t would tend to sink. If its density was greater than 25 σ_t, it would pass through the water column and be influenced by bottom layer residual flows.

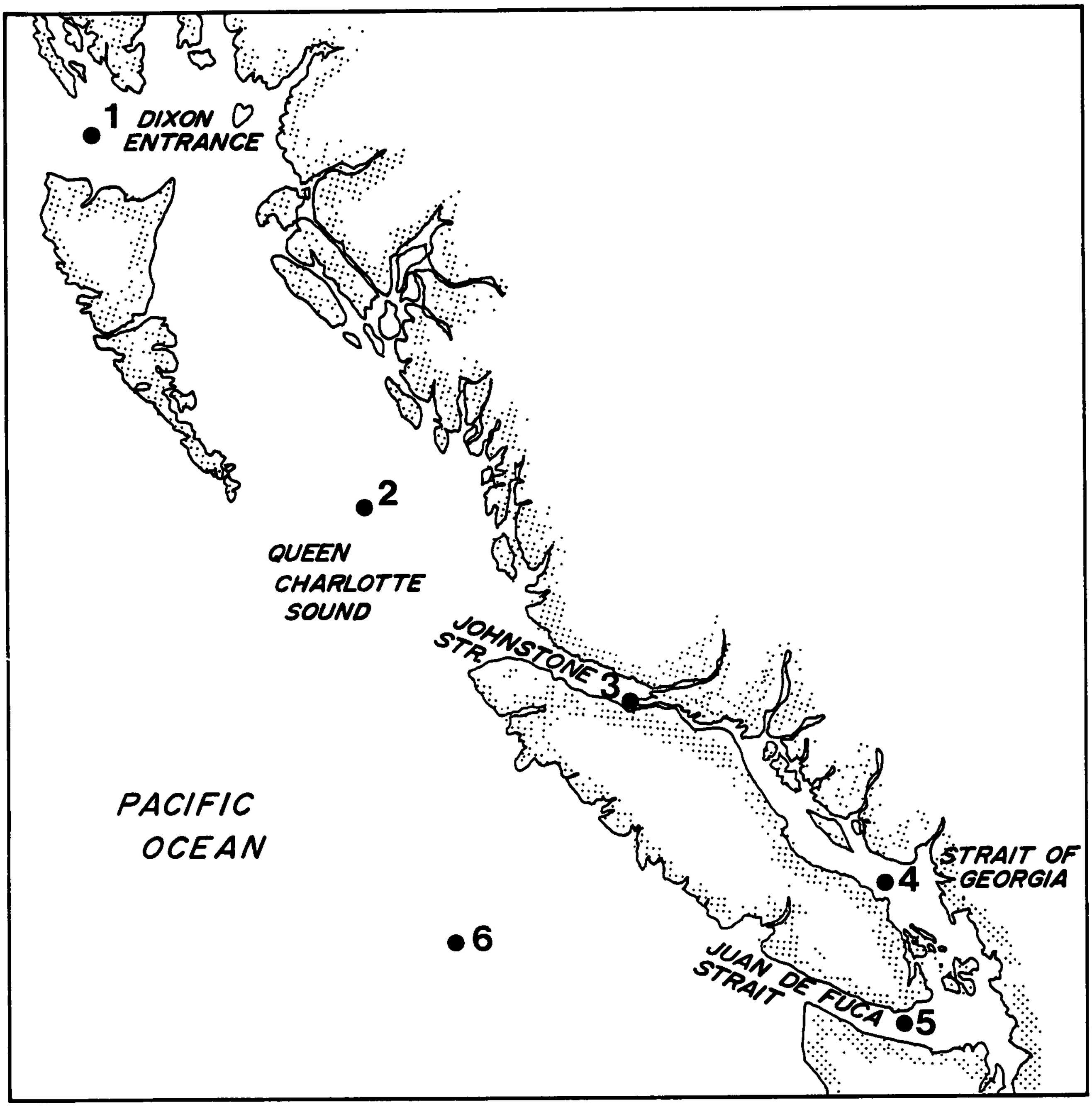


FIGURE 37 LOCATIONS OF REPRESENTATIVE VERTICAL DENSITY PROFILES FOR THE PACIFIC COAST

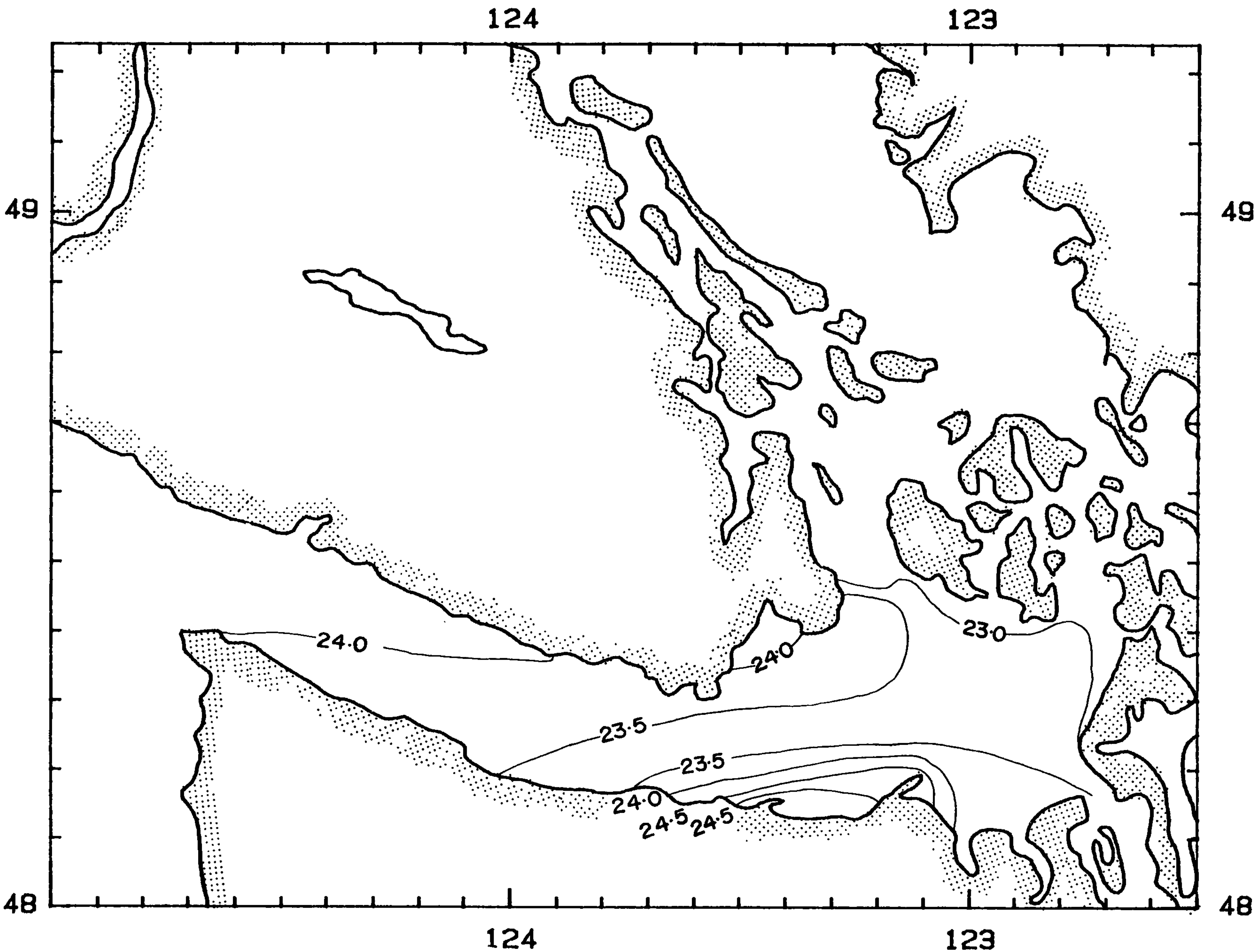


FIGURE 38 CONTOURED SURFACE DENSITIES IN JUAN DE FUCA STRAIT - summer

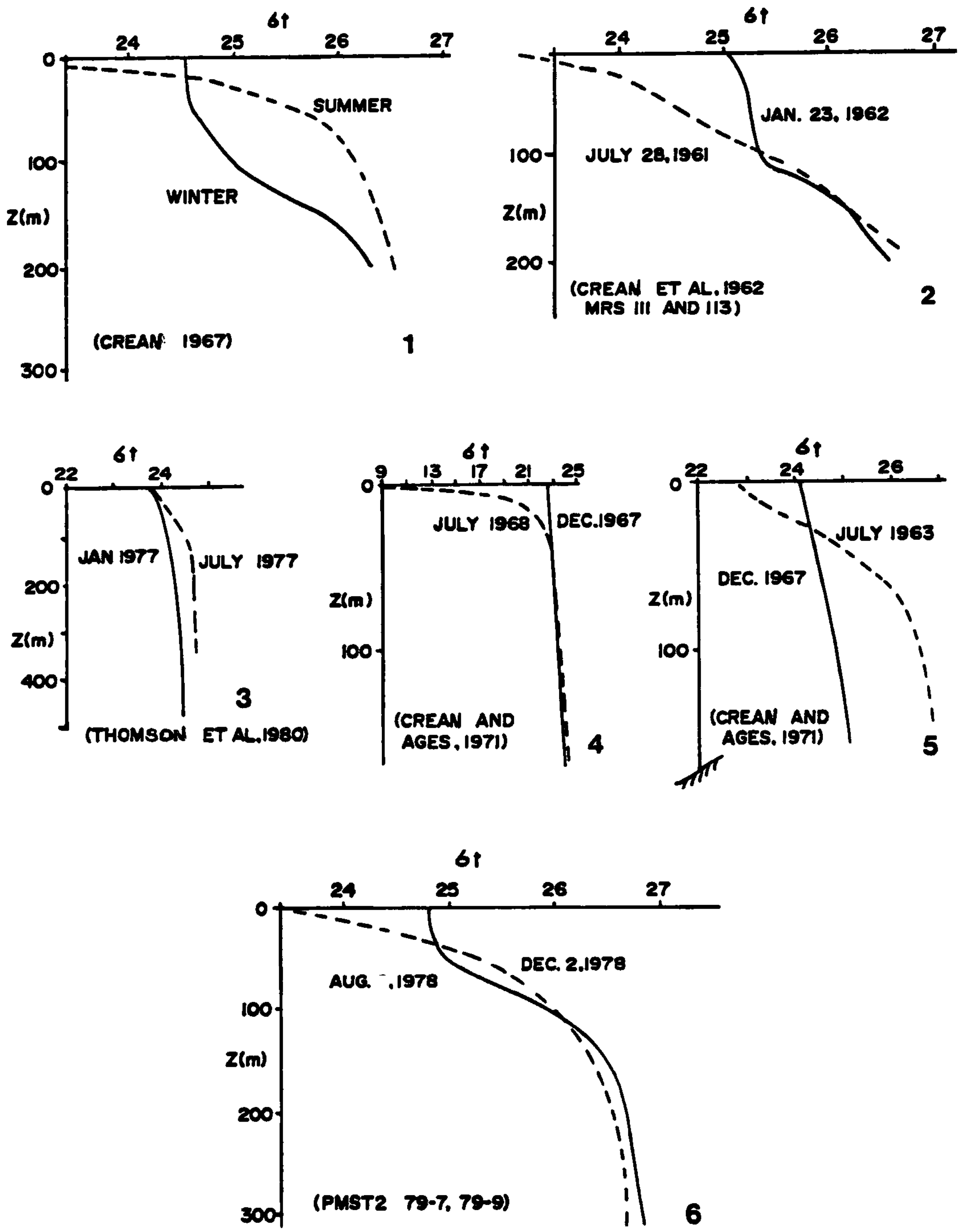


FIGURE 39 REPRESENTATIVE DENSITY PROFILES FOR CANADA'S PACIFIC COAST

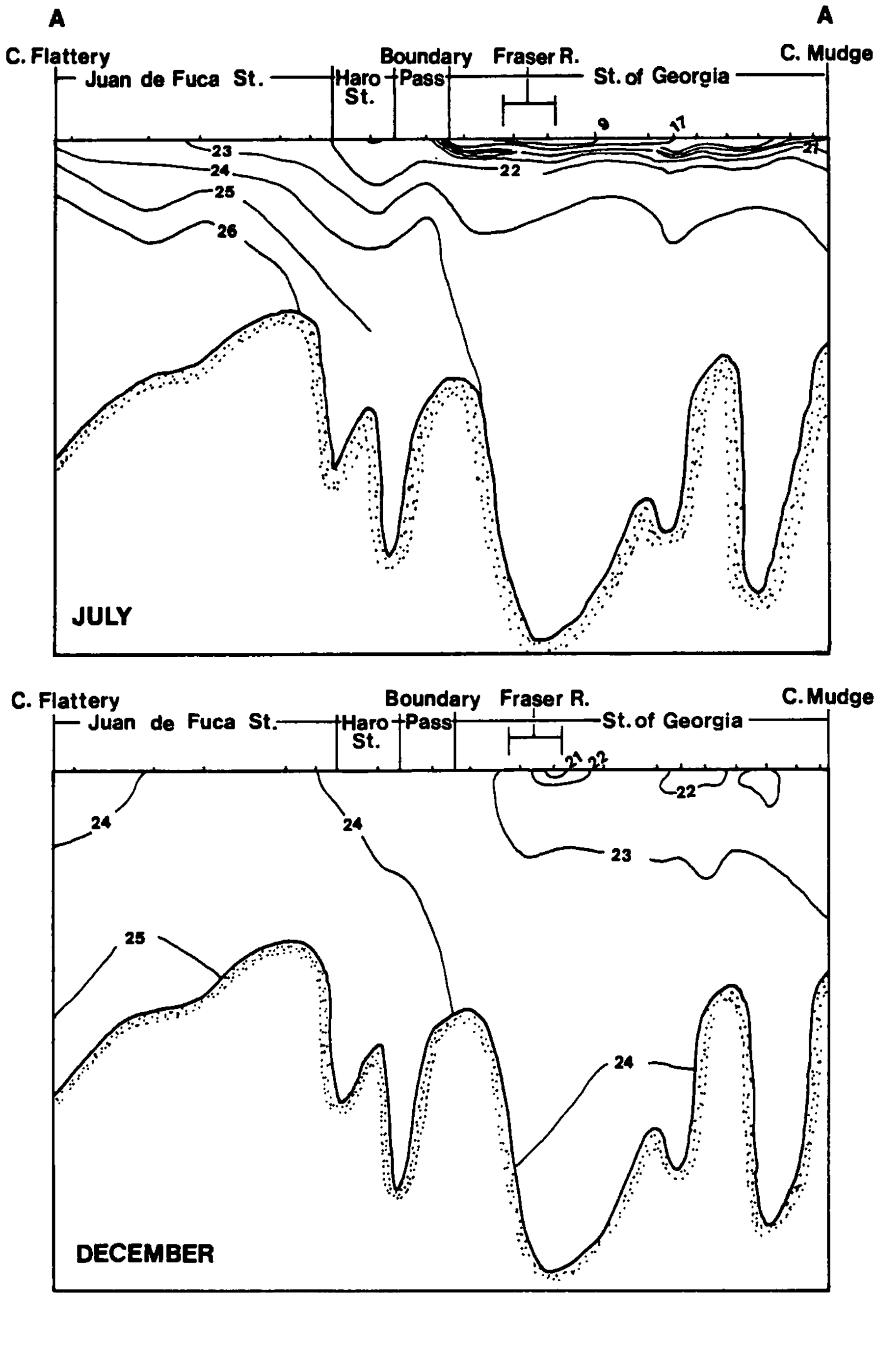


FIGURE 40 VERTICAL CROSS-SECTION OF DENSITY (σ_t) ALONG JUAN DE FUCA STRAIT AND STRAIT OF GEORGIA (Crean and Ages, 1971)

Off the mouth of the San Juan River, surface density may be reduced, particularly during winter when local precipitation is at a maximum. Neutrally buoyant surface oil moving into this area may tend to sink.

4.2 Strait of Georgia

The Strait of Georgia is linked to the Pacific Ocean at both its north and south ends. The connections are by relatively shallow, narrow channels, particularly to the north. The coastline on the west is fairly regular, but the eastern shores are perforated by numerous inlets (fjords). These are glacially scoured valleys which have been flooded by a rise in sea level.

Roughly 75% of the freshwater input to the Strait is from the Fraser River with the Squamish River being the next most important source. The residual circulation is believed to be generally counterclockwise but this is not known for certain. Tidal flow and wind driven currents generally dominate the surface circulation. Internal waves are common when the Fraser River plume overlies denser oceanic water. The sills at the entrances to Boundary Passage and Active Pass serve to generate internal waves which then propagate into southern and central Georgia Strait (Thompson, 1981).

As in the Strait of Juan de Fuca, surface density gradients are relatively weak in winter except directly off the mouth of the Fraser River where salinities are always relatively low (Figure 41). Towards May, solar radiation and the Fraser River discharge combine to produce a warm, low salinity surface layer which extends over much of the southern and central portions of the Strait. This results in a strong summer pycnocline within the upper 25 or 30 m (Figure 39, No. 4). Apart from the main freshwater source of the Fraser River, there are also localized areas of low density surface water associated with smaller rivers emptying into the Strait.

4.2.1 Conditions Favourable for the Sinking of Oil. In most areas of the Strait of Georgia in winter (Figure 41, bottom), surface densities are about 22 σ_t. Oil denser than this would sink and with a density of 24 σ_t or more reach bottom. Near the mouth of the Fraser River, even in winter, there is a brackish surface layer with a density of 20 σ_t or less, depending on the nearness of the river mouth, making these the most favourable areas for the sinking of oil in winter. How deep it sinks will depend on the oil density and the vertical density structure at that particular location.

The summer conditions are much more favourable for the sinking of oil since surface densities of 10 σ_t and less extend over much of the south and central Strait, increasing to 20 σ_t or so at the entrances. The strong pycnocline between the surface and

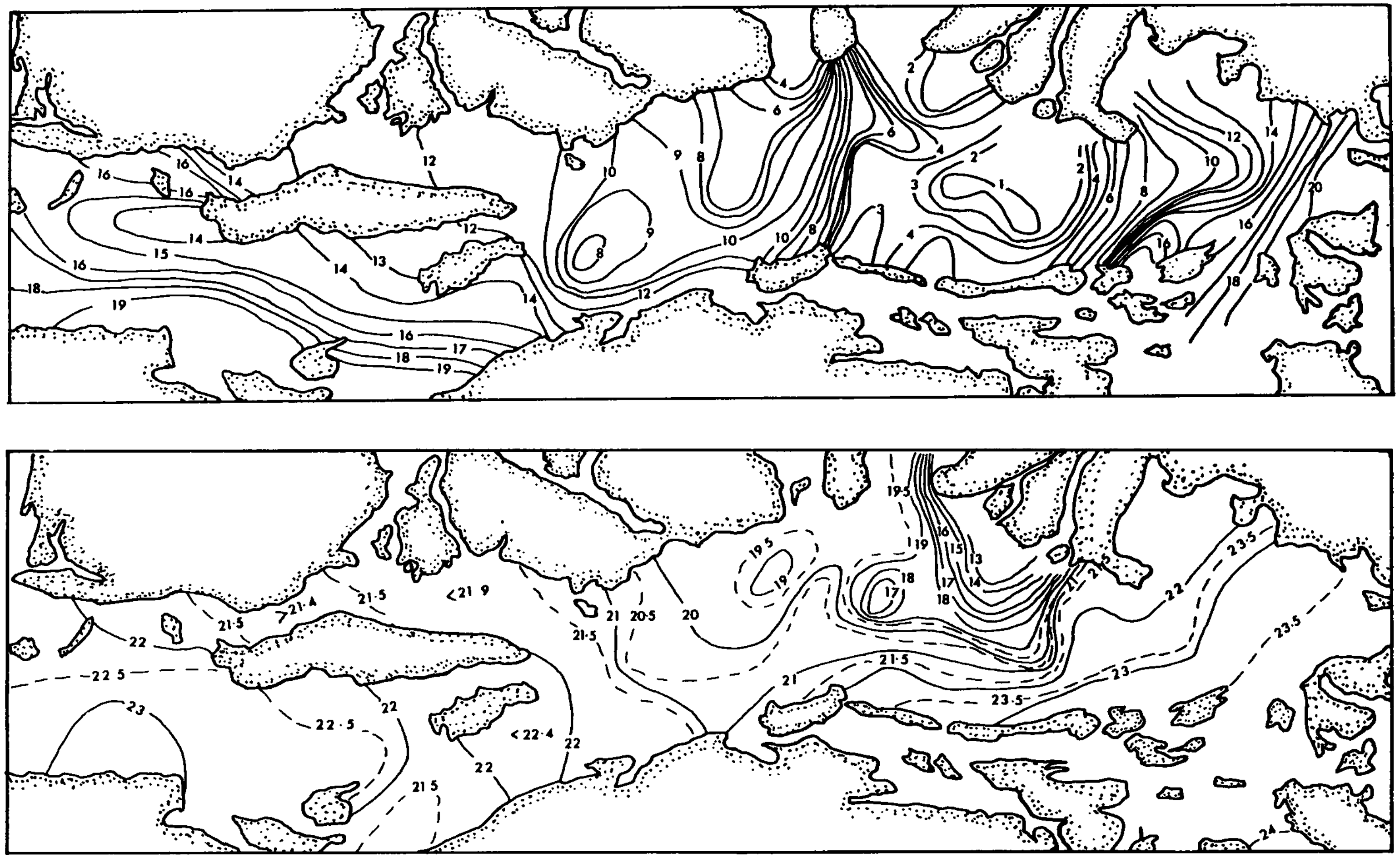


FIGURE 41 CONTOURED SURFACE DENSITIES IN THE STRAIT OF GEORGIA (upper - June; lower - February)

roughly 25 m would prevent oil of less than about 23 σ_t from penetrating the deep layer. Thus for a large range of oil densities (< 10 to 23 σ_t), oil could sink to 10 or 20 m, whereupon it would reach its equilibrium depth. Its movement thereafter would be primarily horizontal, possibly landward opposite to the surface flow direction.

The areas of localized low surface water density are also spots where drifting surface oil could sink. These are generally restricted to the mouths of minor rivers.

The fjords and inlets along the mainland coast generally have an estuarine two-layer circulation. As with the Fraser River system, oil could sink below the relatively low density surface layer and move horizontally with the deep layer residual flow.

4.3 Discovery Passage, Johnstone Strait, and Queen Charlotte Strait

Johnstone Strait and Discovery Passage are narrow channels with strong tidal currents. The vigorous tidal mixing allows for little vertical gradations in density (Figure 39, No. 3). There is however, a relatively weak increase in salinity (and therefore density) both seaward (north) and with depth, due to the estuarine circulation.

Within Queen Charlotte Strait the well mixed waters of Johnstone Strait meet the more stratified offshore waters. Consequently the waters have more density structure, with higher density water seaward and at depth. Surface densities are lowest in winter (from runoff of local precipitation) and highest in fall after the snow melt period. There are no strong pycnoclines in Queen Charlotte Strait in either summer or winter.

4.3.1 Conditions Favourable for the Sinking of Oil. Throughout the year, surface water densities are generally confined within the range 22 to 25 σ_t. Due to the reduced stratification, oil of density 25 σ_t and greater would sink and penetrate to the bottom of the water column. Strong horizontal gradients can exist along the fjords, making these local areas possible regions for the sinking of lighter oil.

4.4 Queen Charlotte Sound, Hecate Strait, and Dixon Entrance

Queen Charlotte Sound and Hecate Strait waterways cover the broad shelf region north of Vancouver Island. The Sound is exposed to the offshore waters, whereas Hecate Strait lies in the lee of the Queen Charlotte Islands. Dixon Entrance forms an east-west passage to the north of the Queen Charlotte Islands (Figure 37).

The major freshwater sources are the Skeena and Nass rivers which discharge large volumes of snow melt in the May-July period. This freshwater is mainly concentrated in the areas of Chatham Sound and eastern Dixon Entrance. Some areas have a salinity minimum in winter due to runoff from local precipitation (Pickard and McLeod, 1953).

The currents are dominated by the tides. These may be modified by wind forcing and runoff induced estuarine circulation.

The vertical density structure (Figure 39, Nos. 1 and 2) reflects the low surface salinities which develop in summer. Some nearshore areas will also have low density surface water in winter due to local precipitation.

The maps of surface density (Figures 42, 43, 44 and 45) show the strong influence of runoff during May-July, particularly in eastern Dixon Entrance. Lower salinity surface waters extend over most of the shelf as well. In winter the surface waters are more saline; however, there remains a gradient with lower density surface waters nearshore and in Dixon Entrance.

4.4.1 Conditions Favourable for the Sinking of Oil. Oil of density greater than about 24 σ_t would tend to sink in most areas in summer. In eastern Dixon Entrance surface waters may drop to 18 σ_t or less making sinking of oil here even more favourable. The summer pycnocline, from surface to about 75 to 100 m depth, would prevent oil of less than 26.5 σ_t from penetrating the deeper waters.

In winter (Figure 45) the surface waters are well mixed to 100 metres, and oil of density near 25 σ_t could penetrate to the pycnocline at about 150 m. A density of 26 σ_t or greater would again be required to reach deeper waters.

Anomalously low density surface water may be found along the mainland coast in winter due to runoff of local precipitation. Neutrally buoyant surface oil being transported alongshore could "sink" upon encountering such waters (i.e., the less dense surface water could override the denser oil).

4.5 Offshore Waters

Offshore waters (out to the 200 mile economic limit) have not been subjected to the same degree of scientific probing as the more nearshore waters. Our level of knowledge is lower and many aspects remain largely unkown.

The variability of salinity and temperature of the offshore waters is determined by different mechanisms than apply nearshore. Although the effects of runoff extend hundreds of kilometres offshore, the low salinity waters are dispersed and diluted. Along the shelf regions upwelling in summer brings high salinity water to the surface. Superimposed on the density variations due to salinity changes, is the seasonal effect of

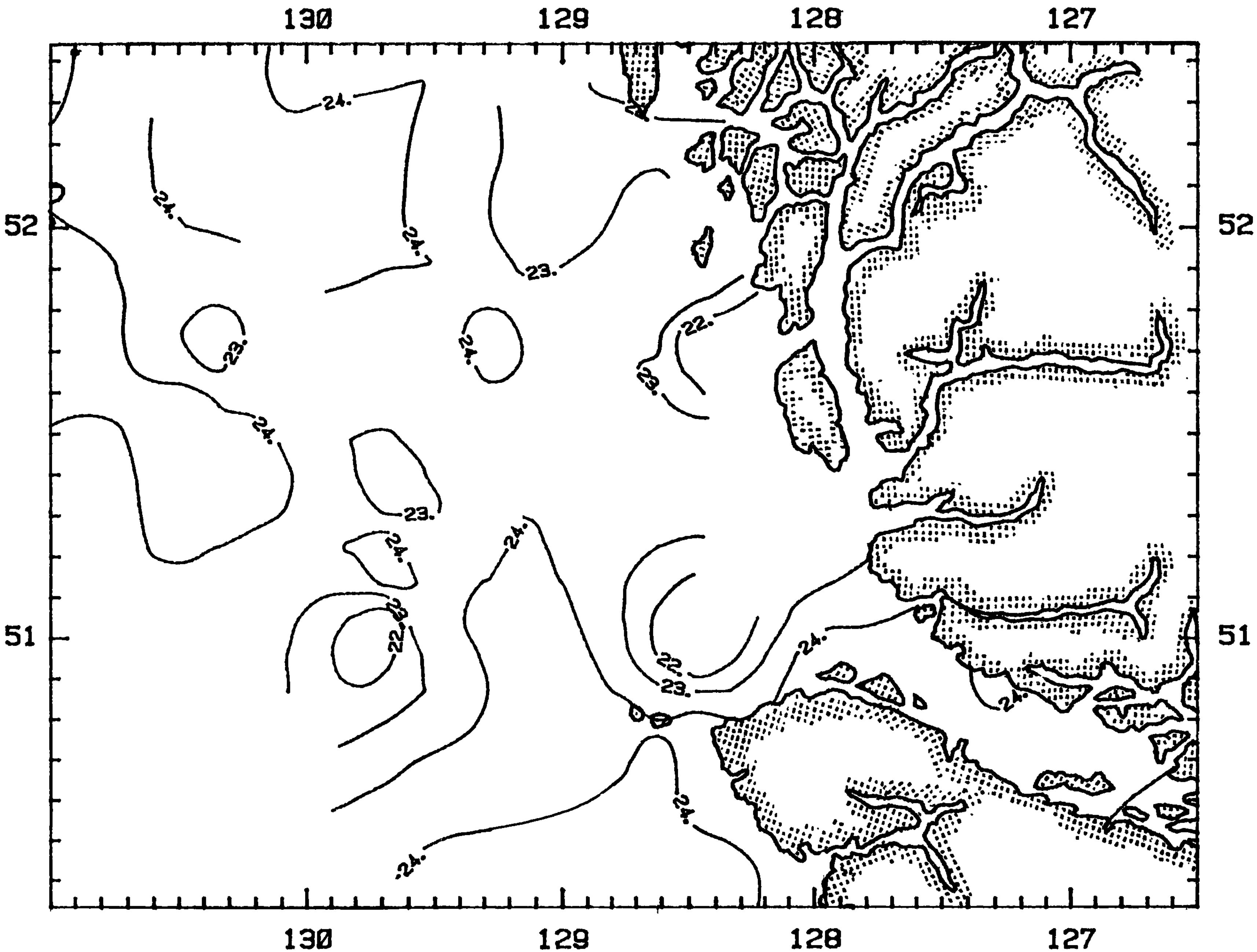


FIGURE 42 CONTOURED SURFACE DENSITIES IN QUEEN CHARLOTTE STRAIT AND QUEEN CHARLOTTE SOUND - May to September

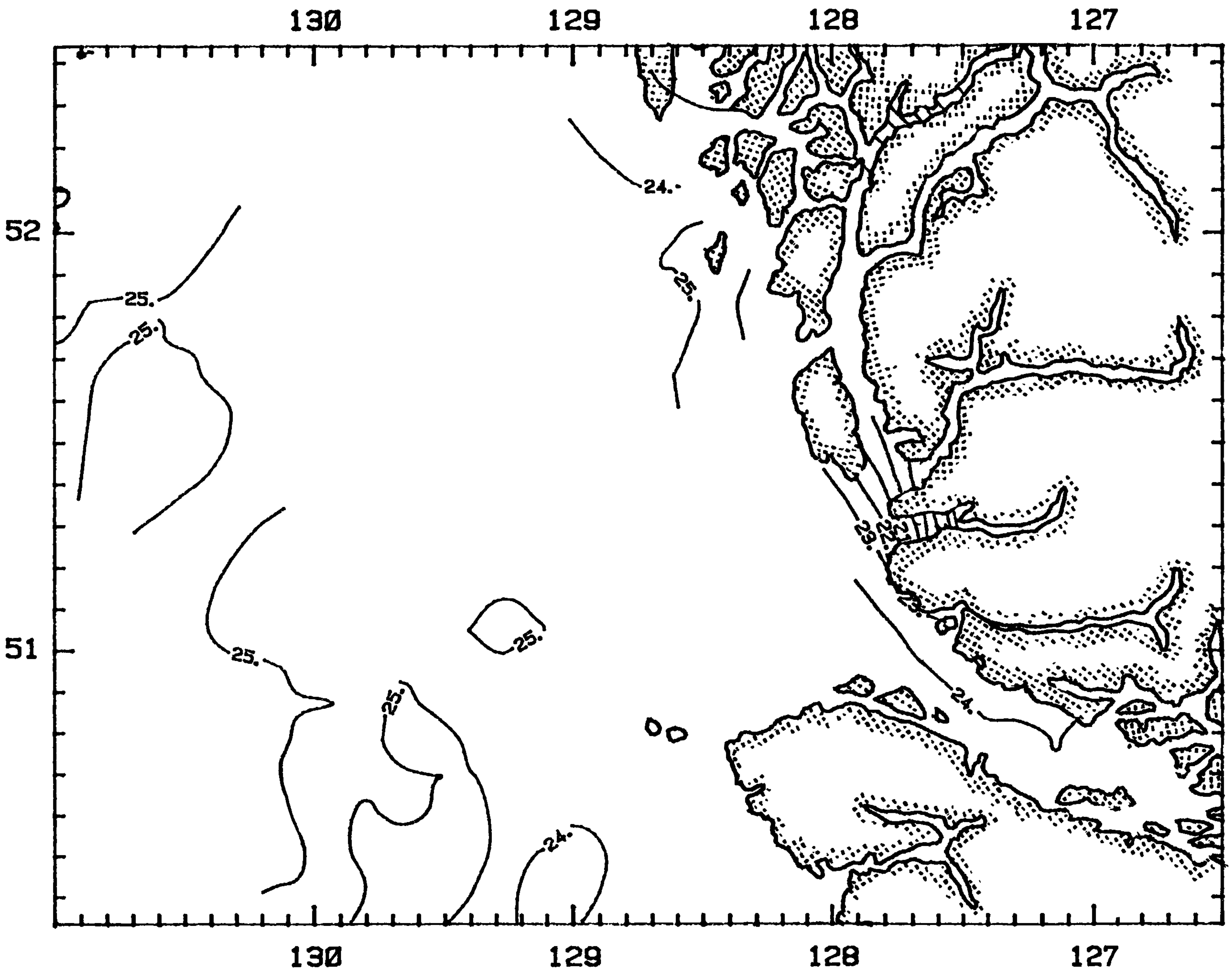


FIGURE 43 CONTOURED SURFACE DENSITIES IN QUEEN CHARLOTTE STRAIT AND QUEEN CHARLOTTE SOUND - October to April

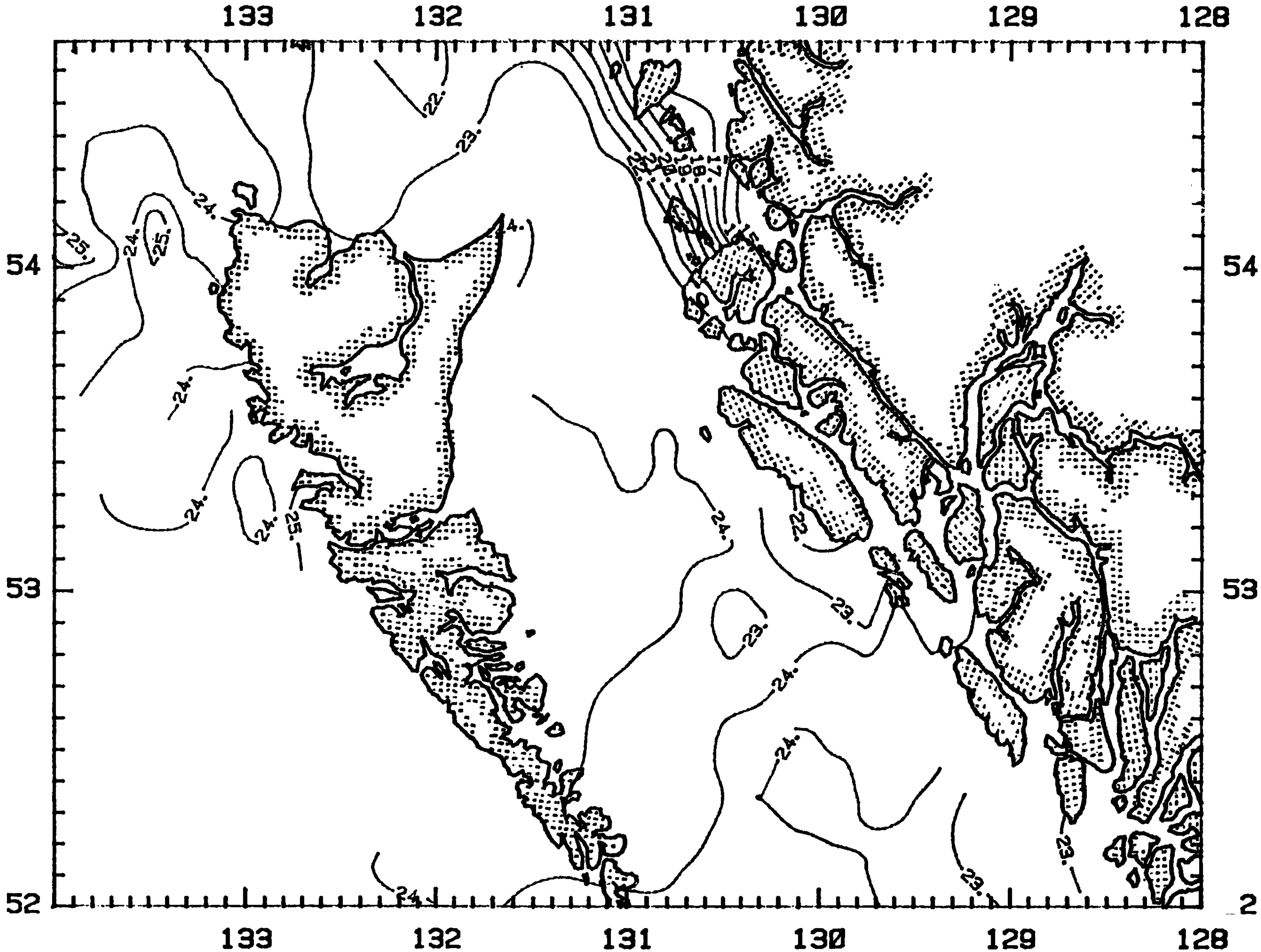


FIGURE 44 CO TOUR D SURFACE D NSITIES IN HECATE STRAIT AND DIXON ENTRANCE - May to September

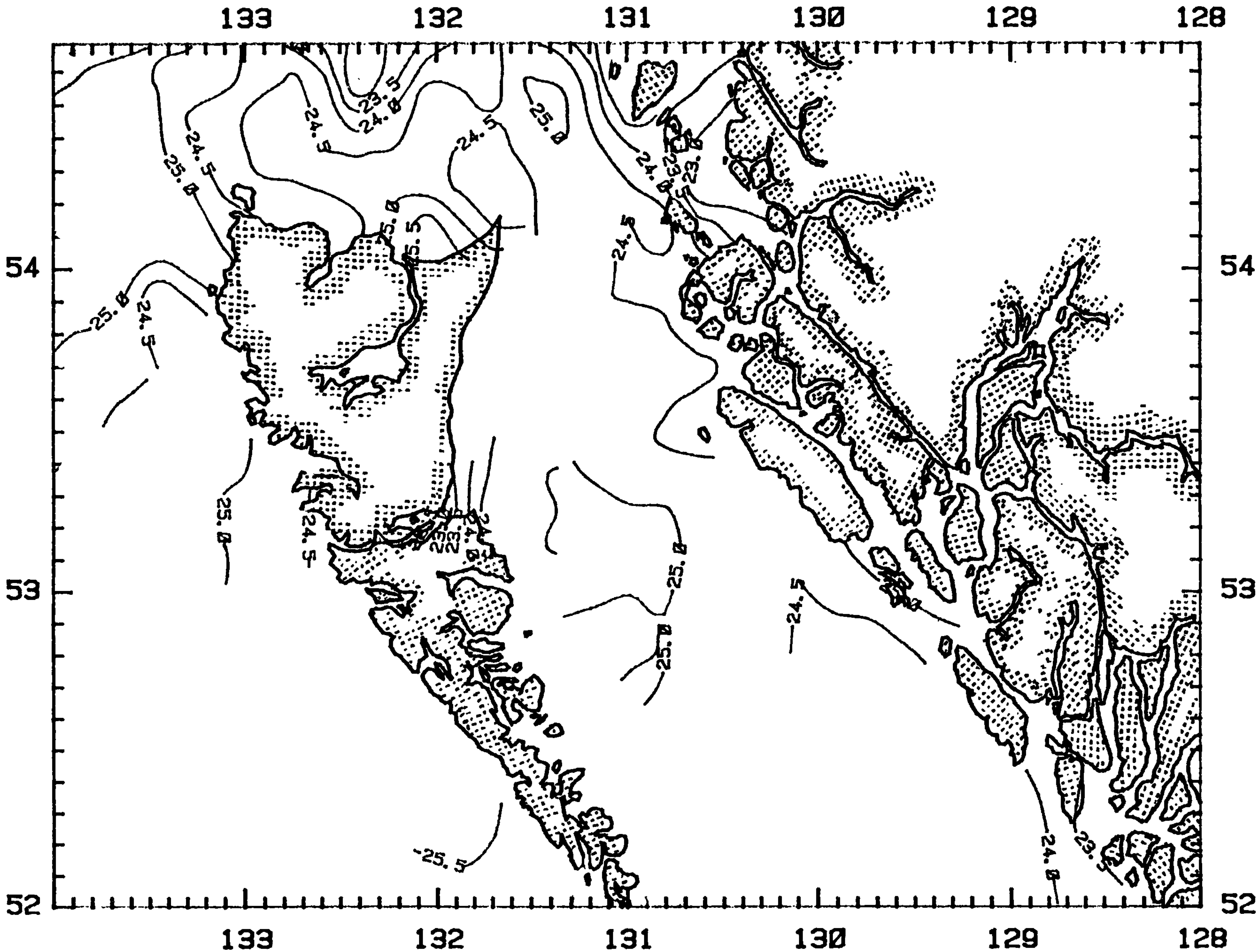


FIGURE 45 CONTOURED S[illegible]RFA[illegible]E DENS[illegible]IE[illegible] H[illegible]RA[illegible] AND D[illegible]XON EN[illegible]C[illegible] - [illegible]ctober to April

solar heating. In summer a warm surface layer forms with a pronounced thermocline, which is later destroyed by winter winds and surface heat loss.

The maps of surface density (Figures 46 and 47) show the general pattern of higher surface density offshore due to the diminishing effect of coastal runoff. Oceanographic station data is relatively coarse, but satellite infrared images reveal that offshore the remnants of coastal runoff are often identifiable as patches of brackish water surrounded by ambient water of non-coastal origin.

Northwesterly winds in summer, and the resulting Ekman drift, drive shelf waters offshore, resulting in upwelling of dense saline water. This effect is most pronounced along the southern and central Vancouver Island coast and south along Oregon where the shelf is relatively wide. Further north, off the Queen Charlotte Islands, the northwest winds are not as prevalent in summer and when they do occur, any upwelling is probably confined nearshore along the narrow shelf.

In winter, high precipitation along the Queen Charlotte and Vancouver Island coasts causes an influx of low salinity waters along the coast. This is in contrast to the May-July peak runoff of rivers such as the Fraser which are fed mainly by snow melt.

4.5.1 Conditions Favourable for the Sinking of Oil. Conditions for the sinking of surface oil are generally most favourable nearshore, particularly in the May-July period of peak runoff; but also during winter in areas nearshore where runoff from local precipitation is discharged. Offshore surface densities generally fall within the 23 to 25 σ_t range and oil would have to be denser than 24 to 25 σ_t in order to sink.

Patches of lower salinity water occur offshore into which oil might sink. Neutrally buoyant oil near the surface could sink in these areas of brackish water. Penetration would be restricted to some relatively shallow depth, by the underlying denser water and the oil could reappear later or be stirred up by mixing of the surface layers. These brackish patches are poorly understood and their extent and locations are extremely variable.

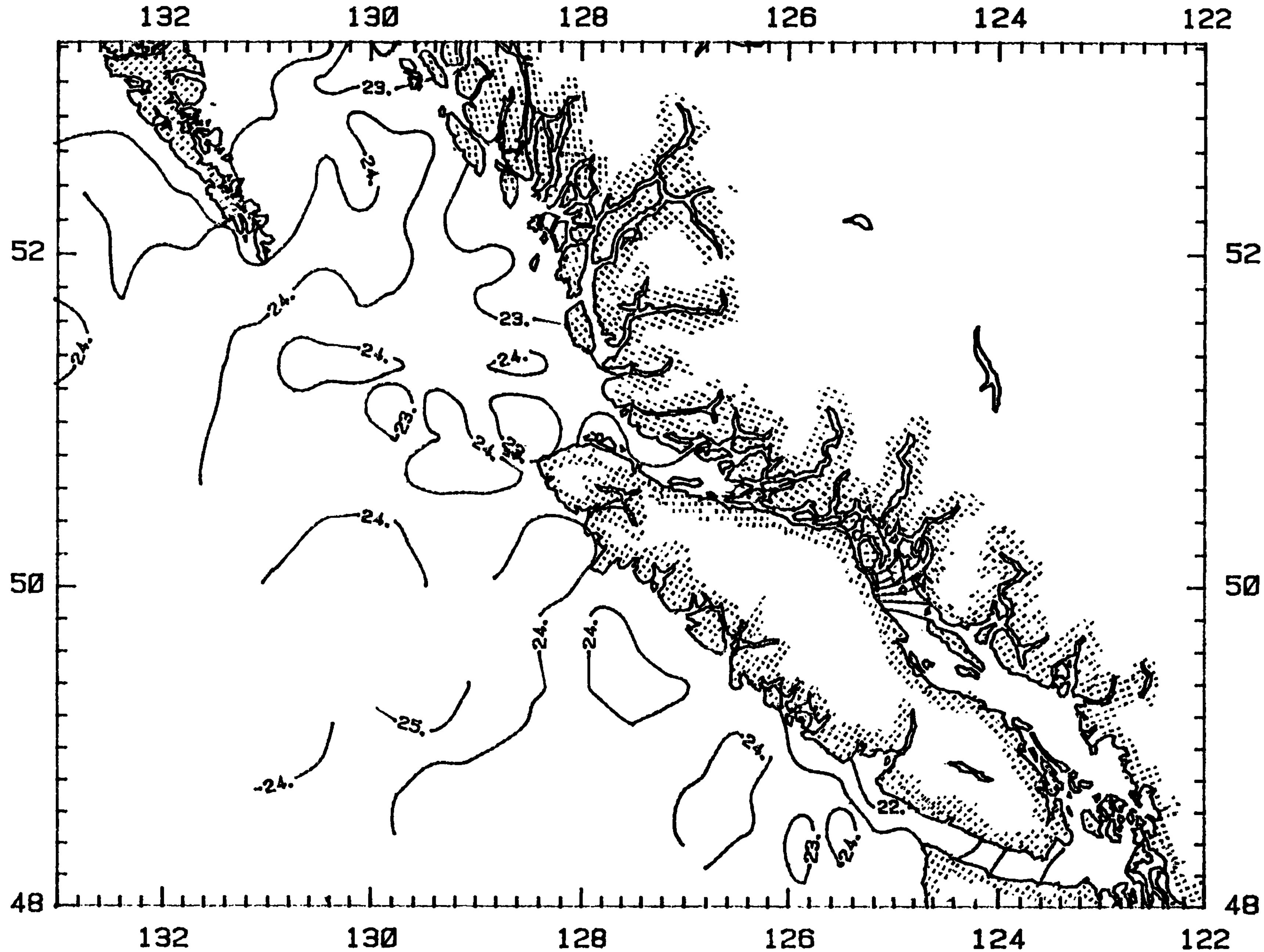


FIGURE 46 CONTOURED SURFACE DENSITIES IN OFFSHORE WATERS - May to September

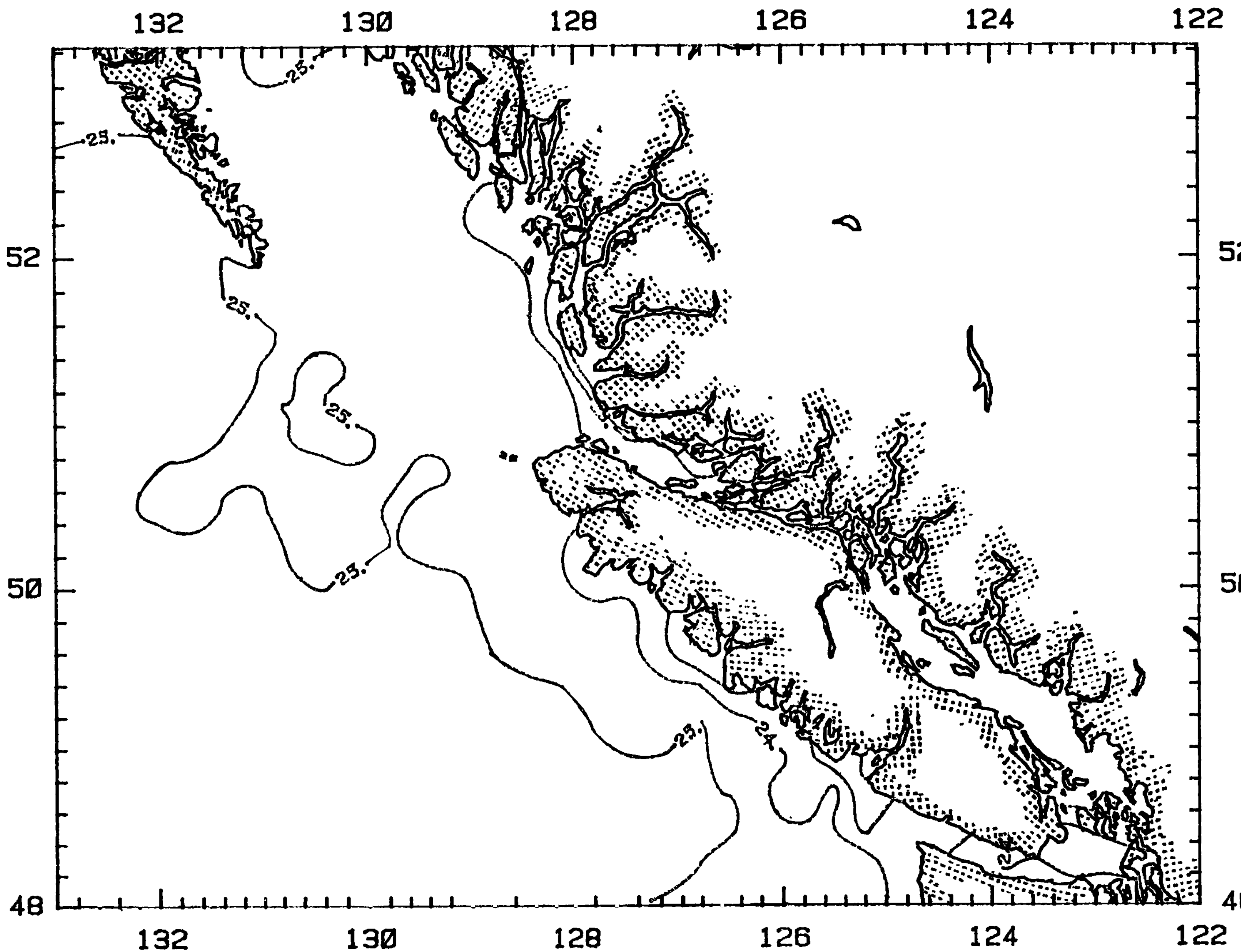


FIGURE 47 CONTOURED SURFACE DENSITIES IN OFFSHORE WATERS - October to April

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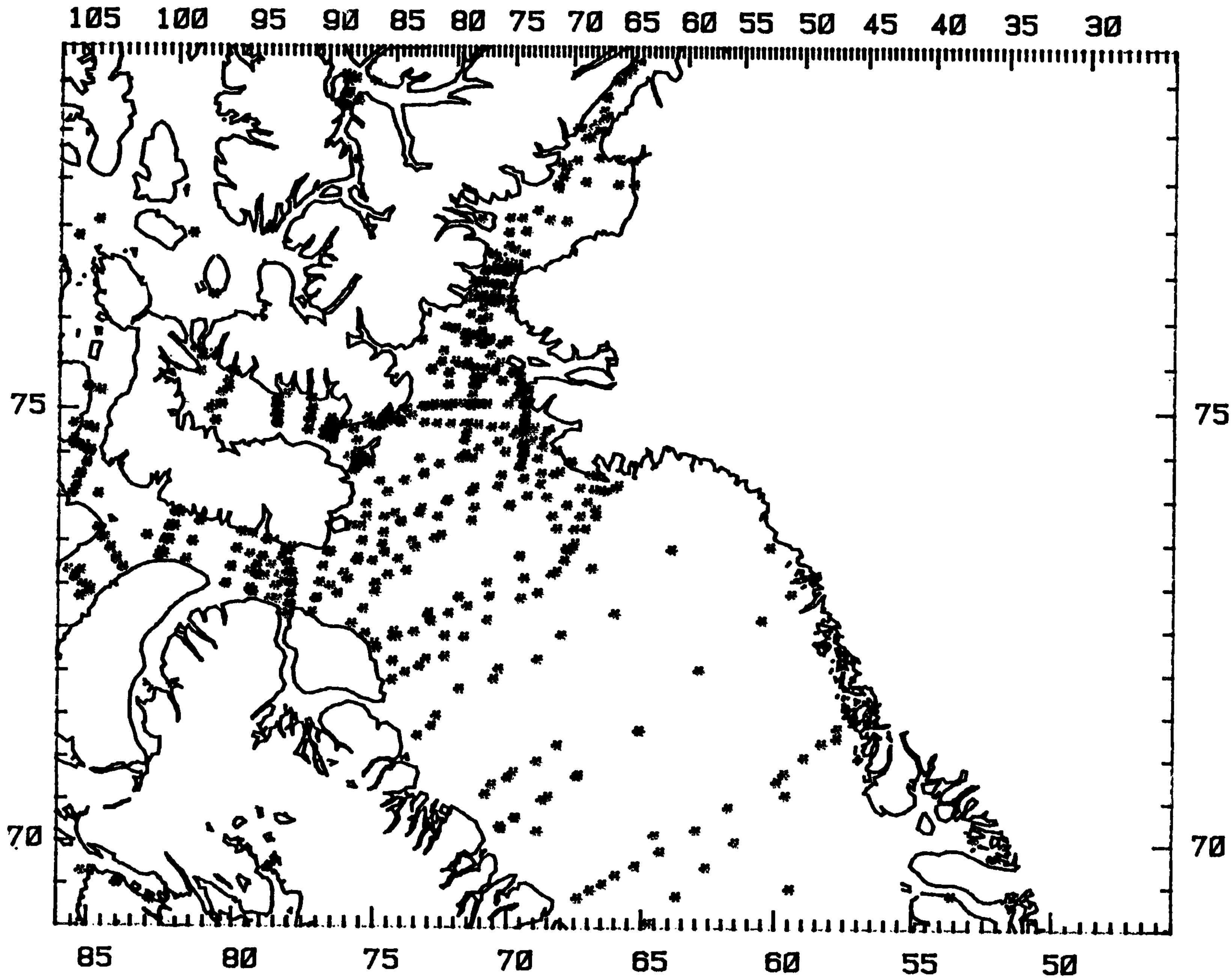
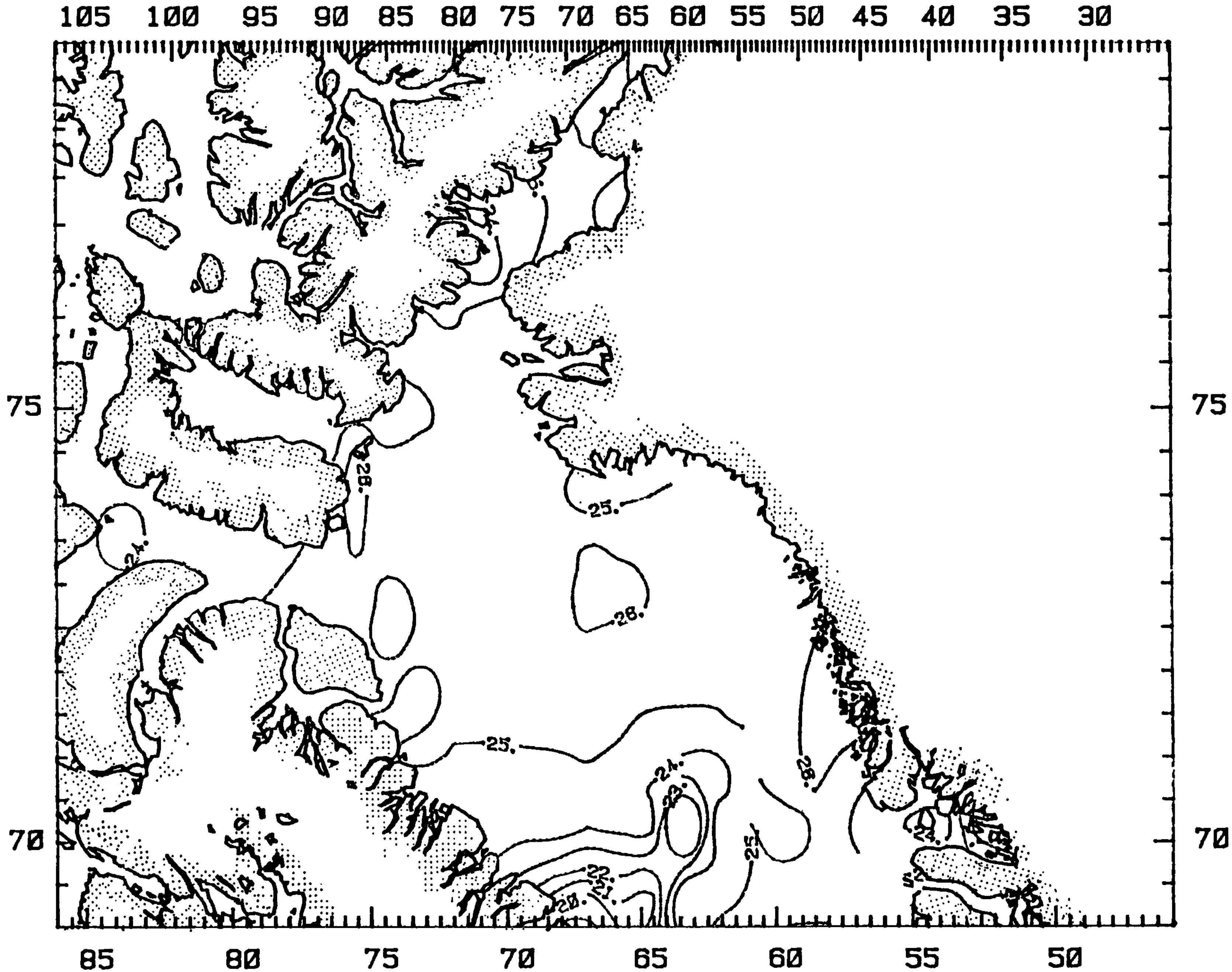
APPENDIX I

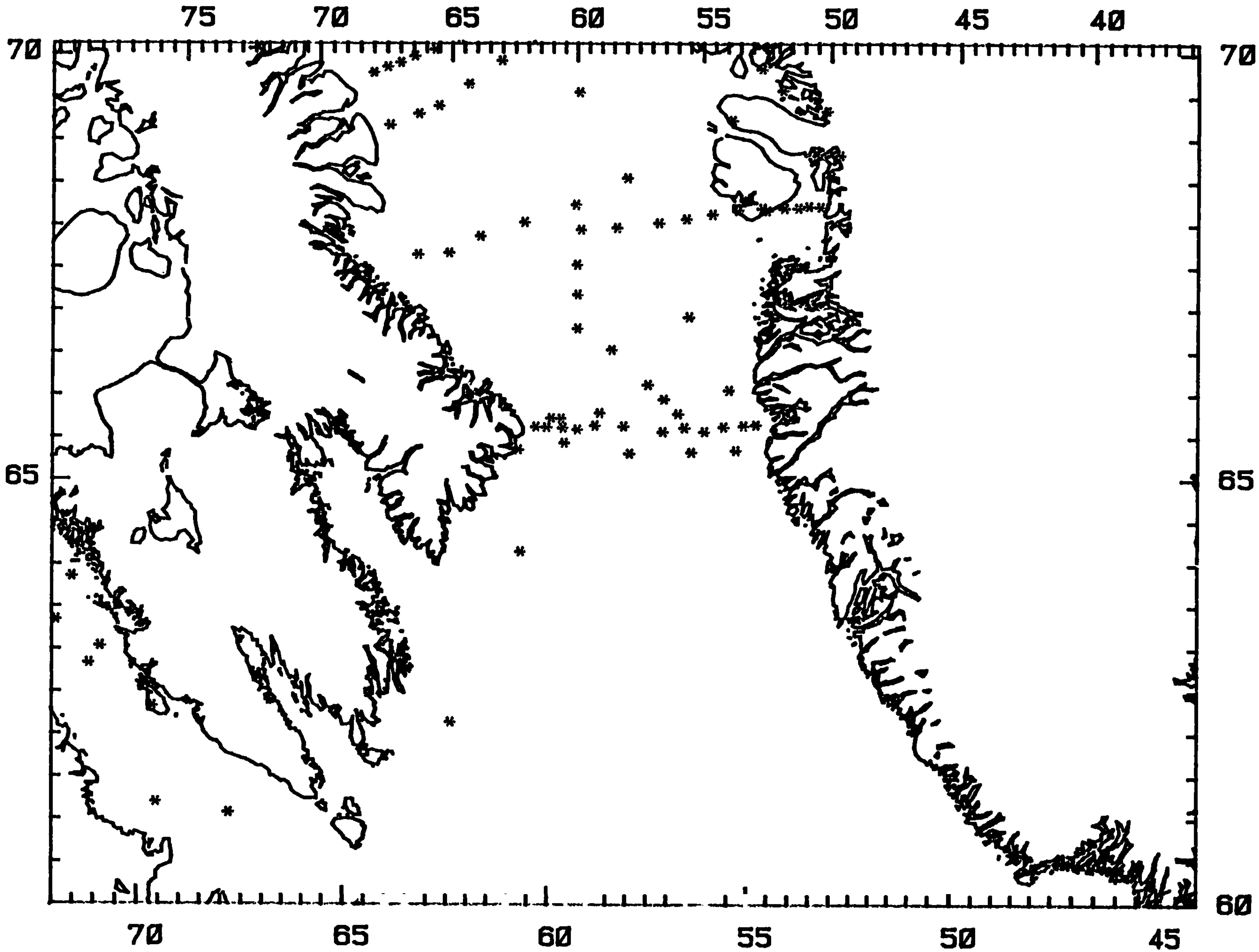
SURFACE WATER DENSITY: ATLANTIC COAST



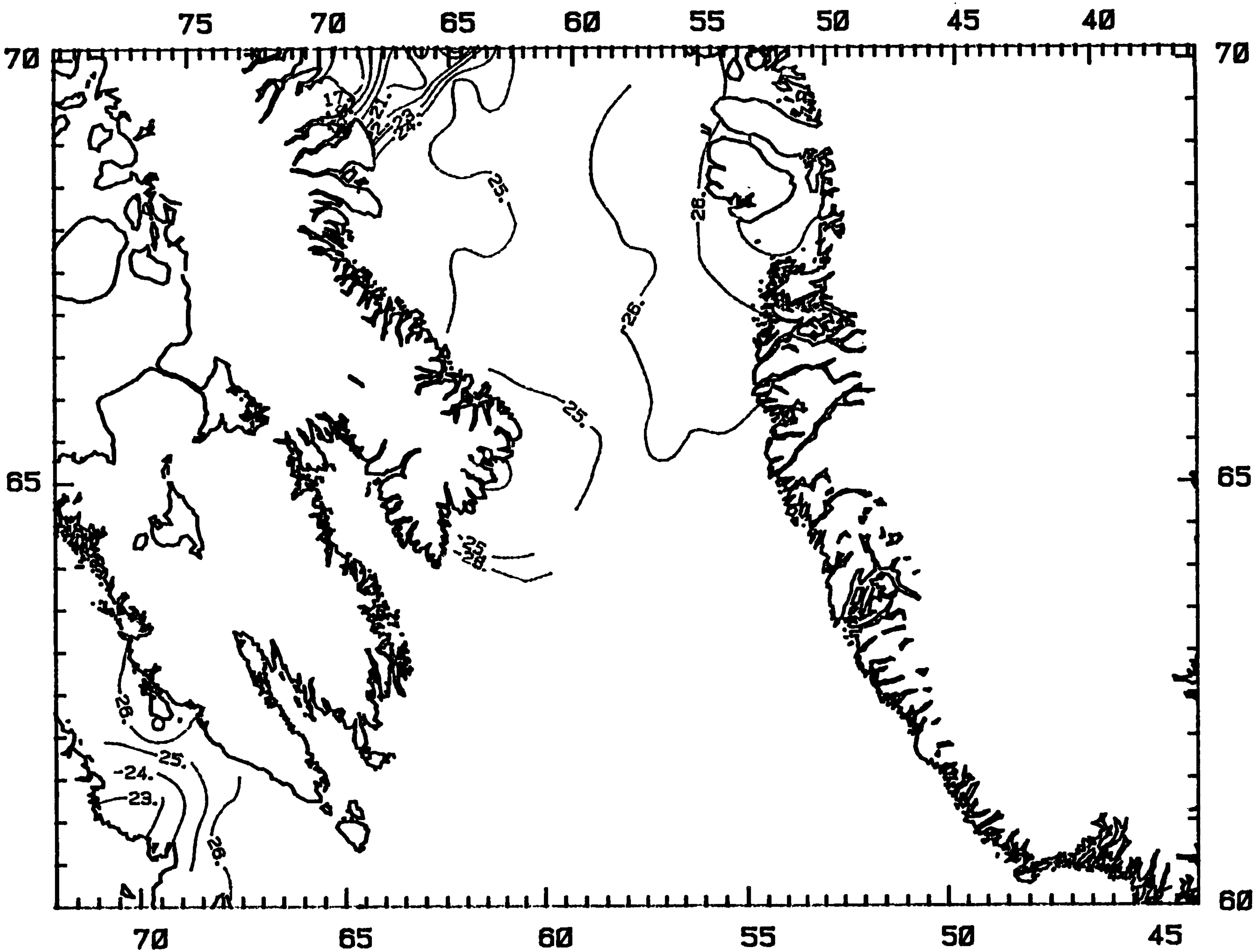
NORTHERN BAFFIN BAY - Sample Locations, Open Water Season



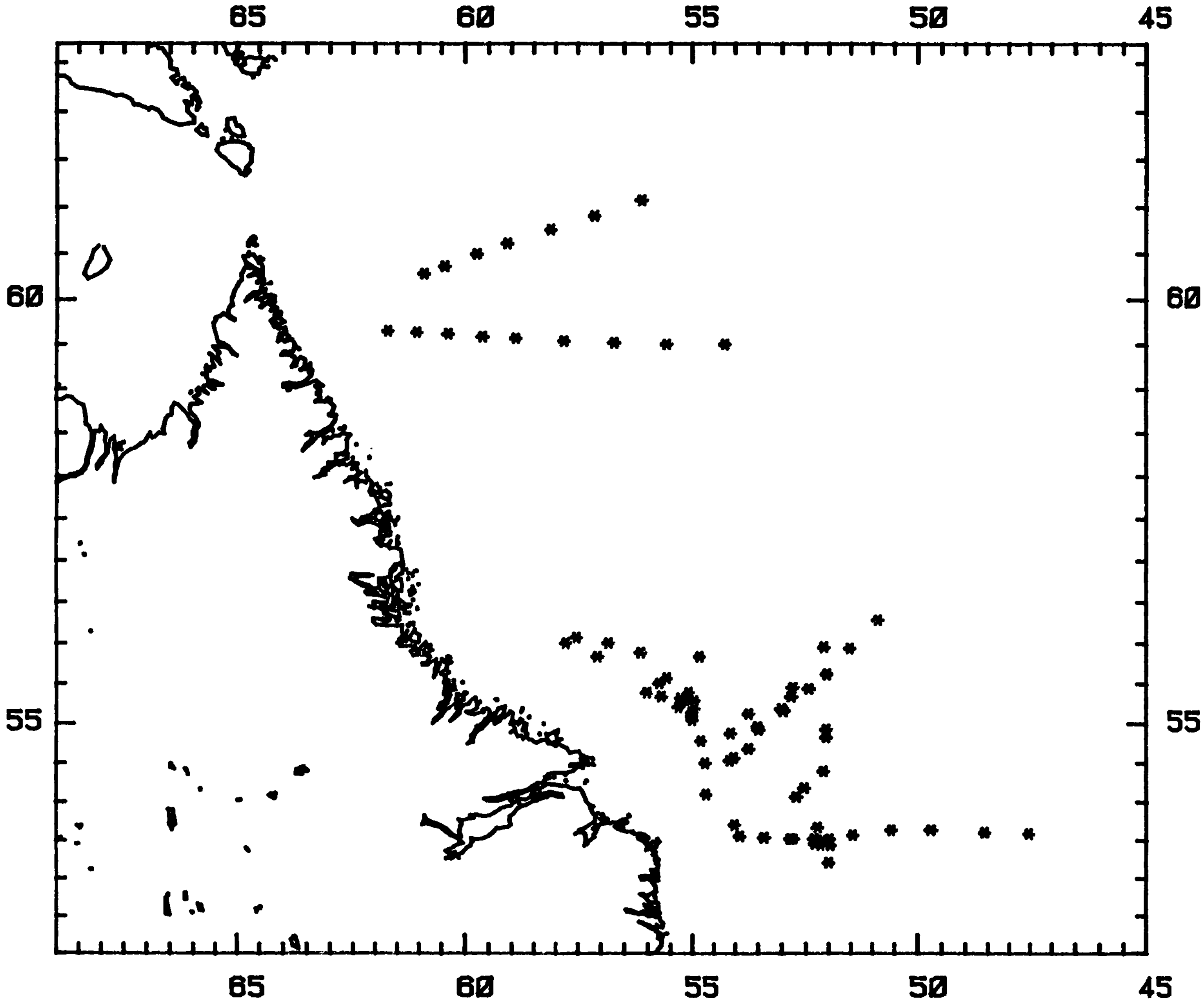
NORTHERN BAFFIN BAY - Contoured Surface Density, Open Water Season



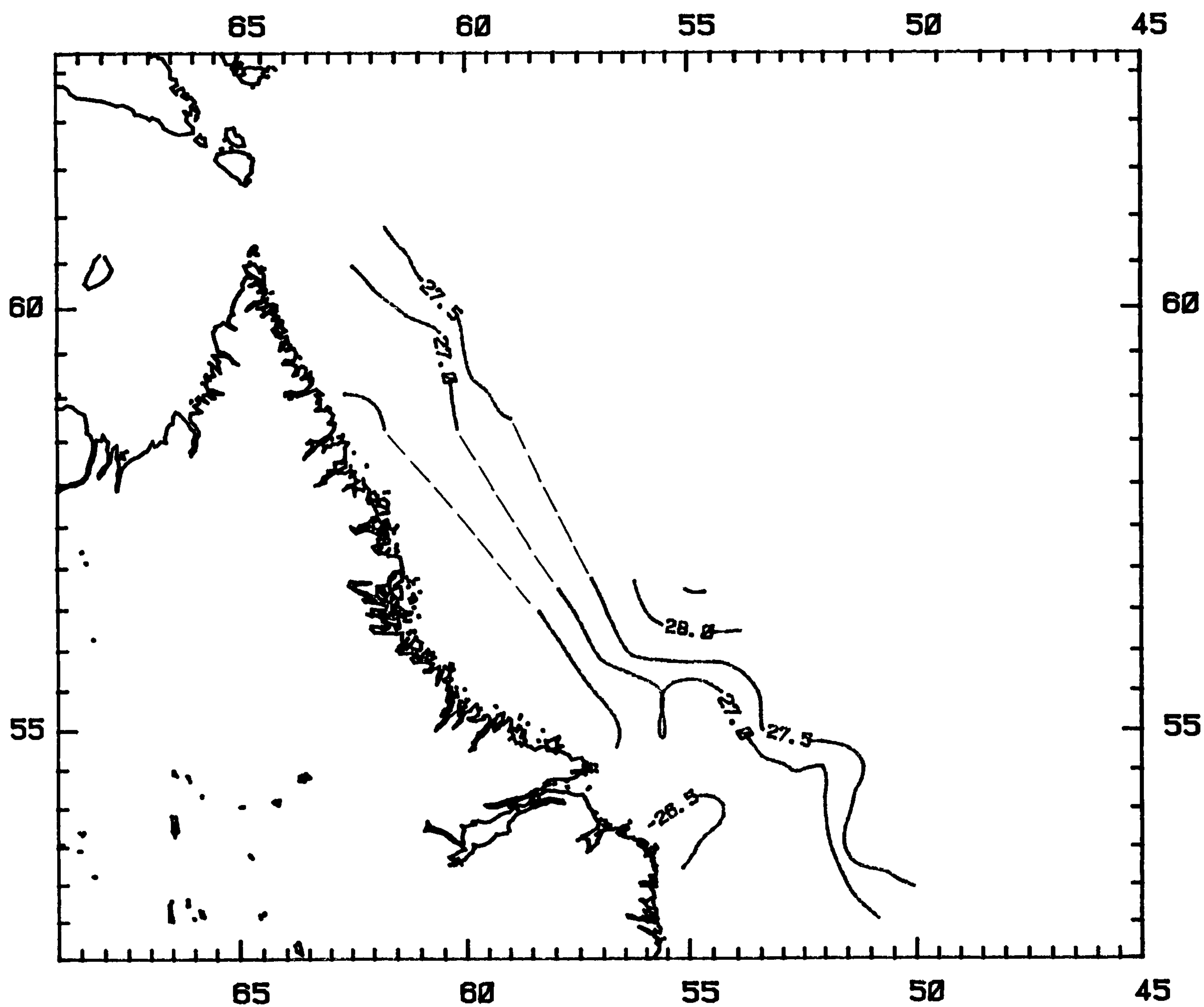
SOUTHERN BAFFIN BAY - Sample Locations, Open Water Season



SOUTHERN BAFFIN BAY - Contoured Surface Density, Open Water Season



LABRADOR SHELF - Sample Locations, January to April



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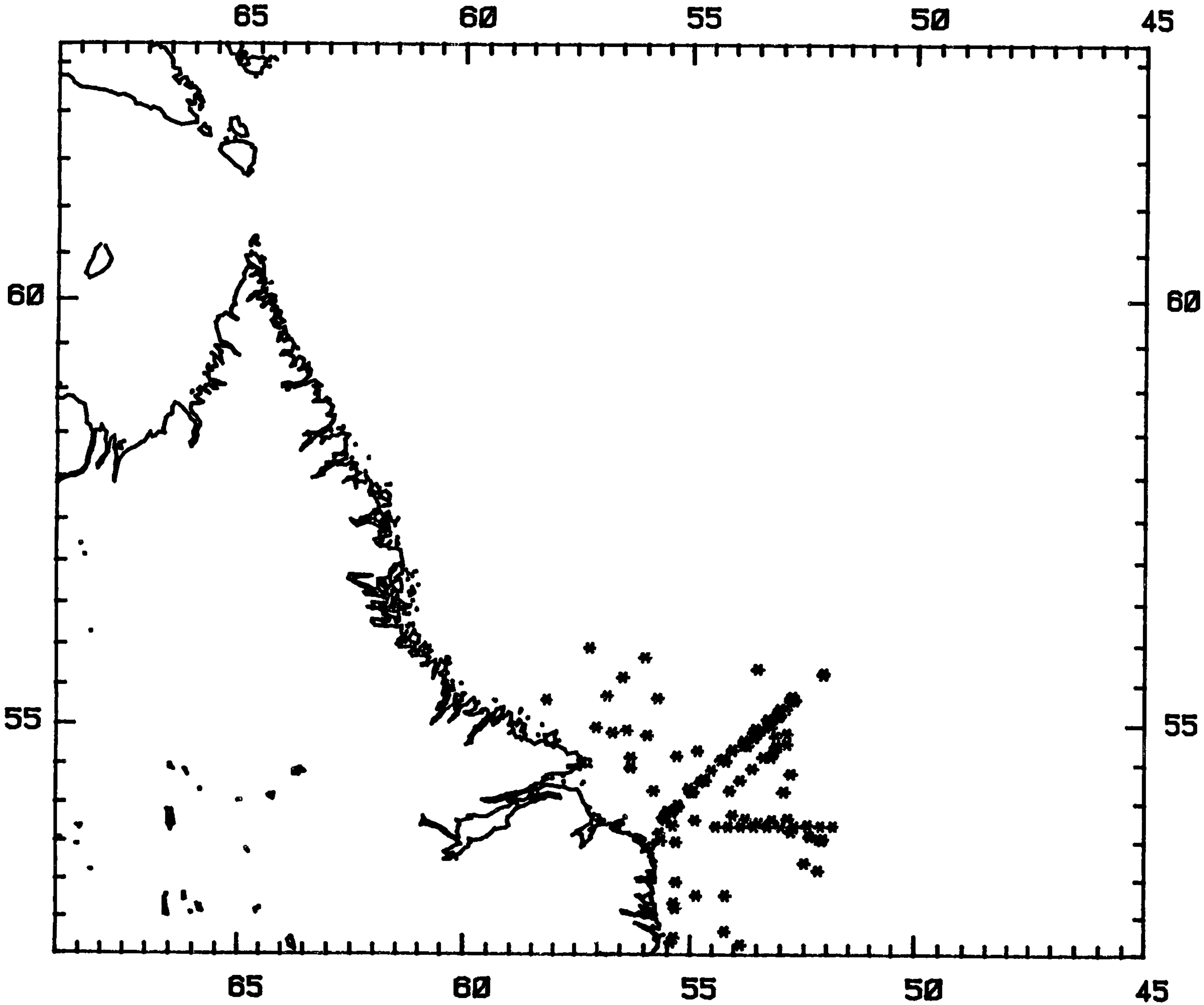

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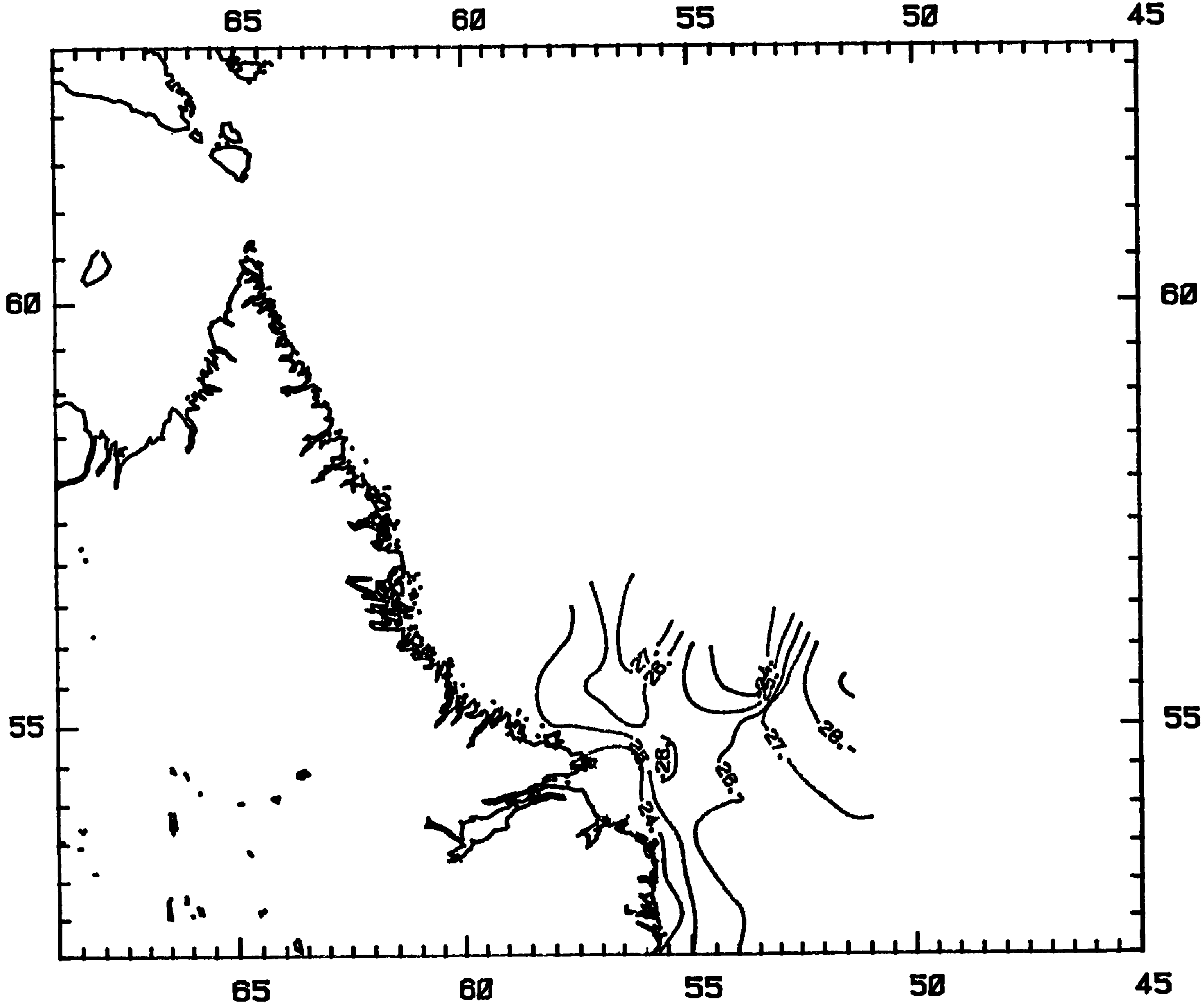

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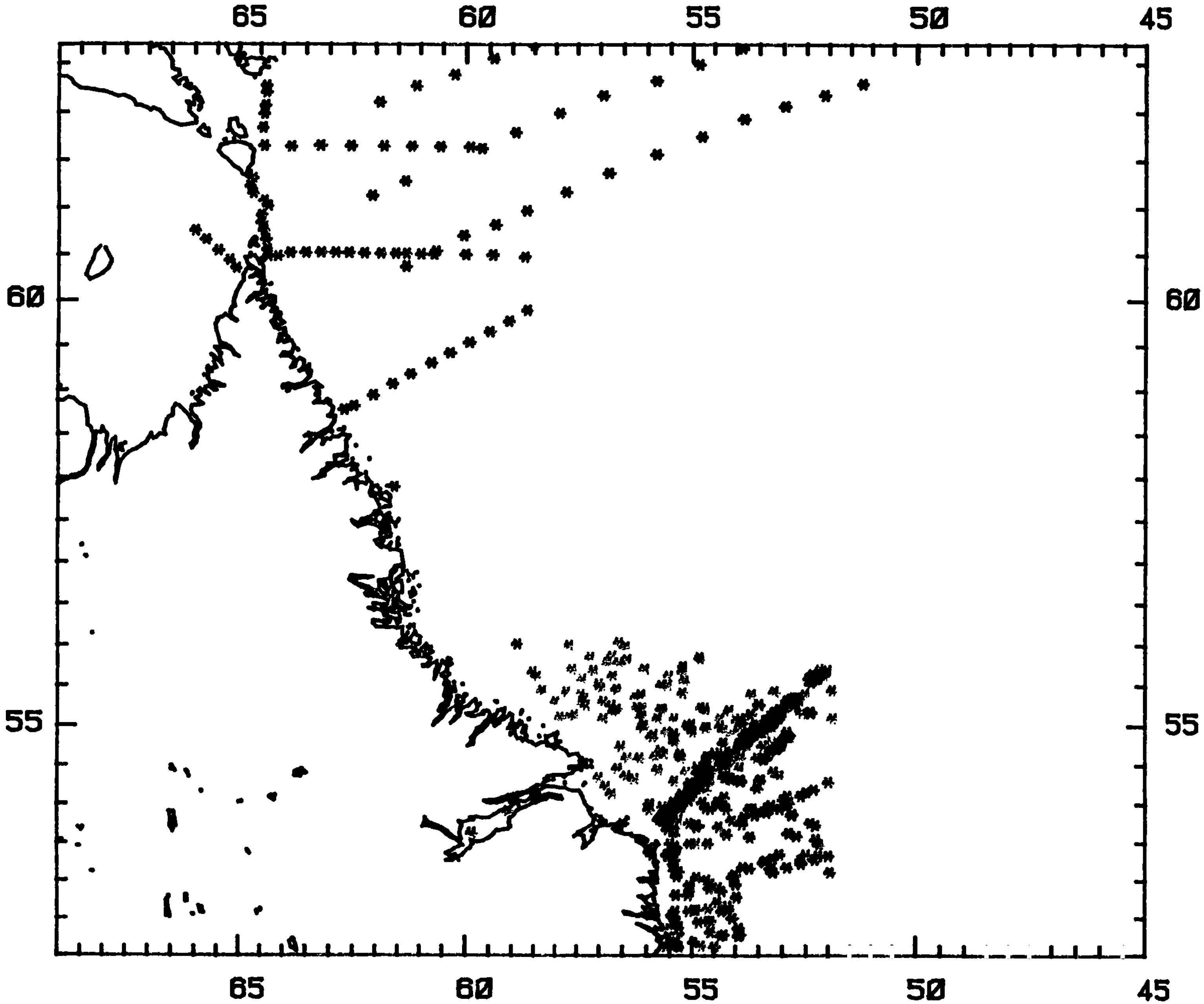

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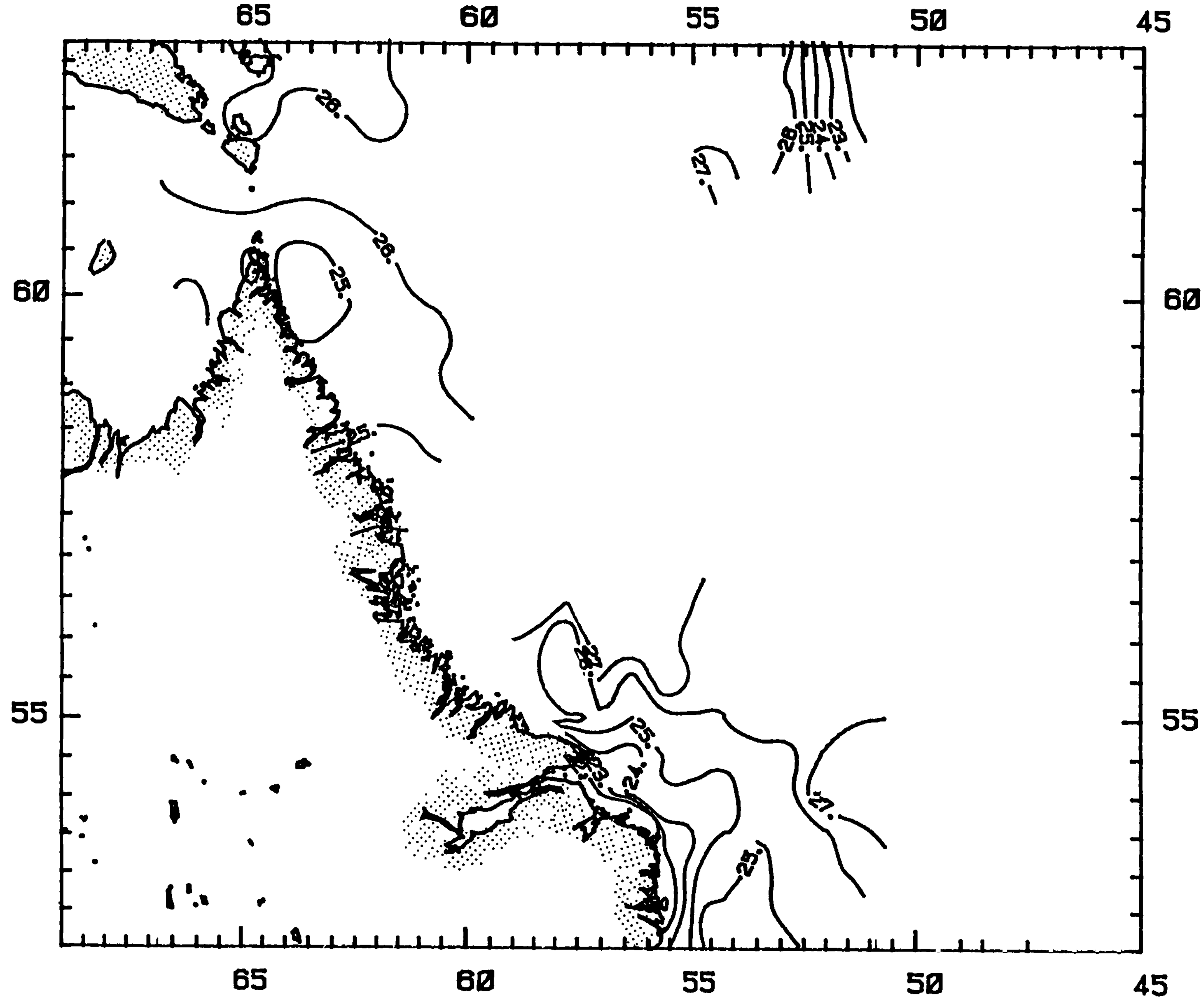

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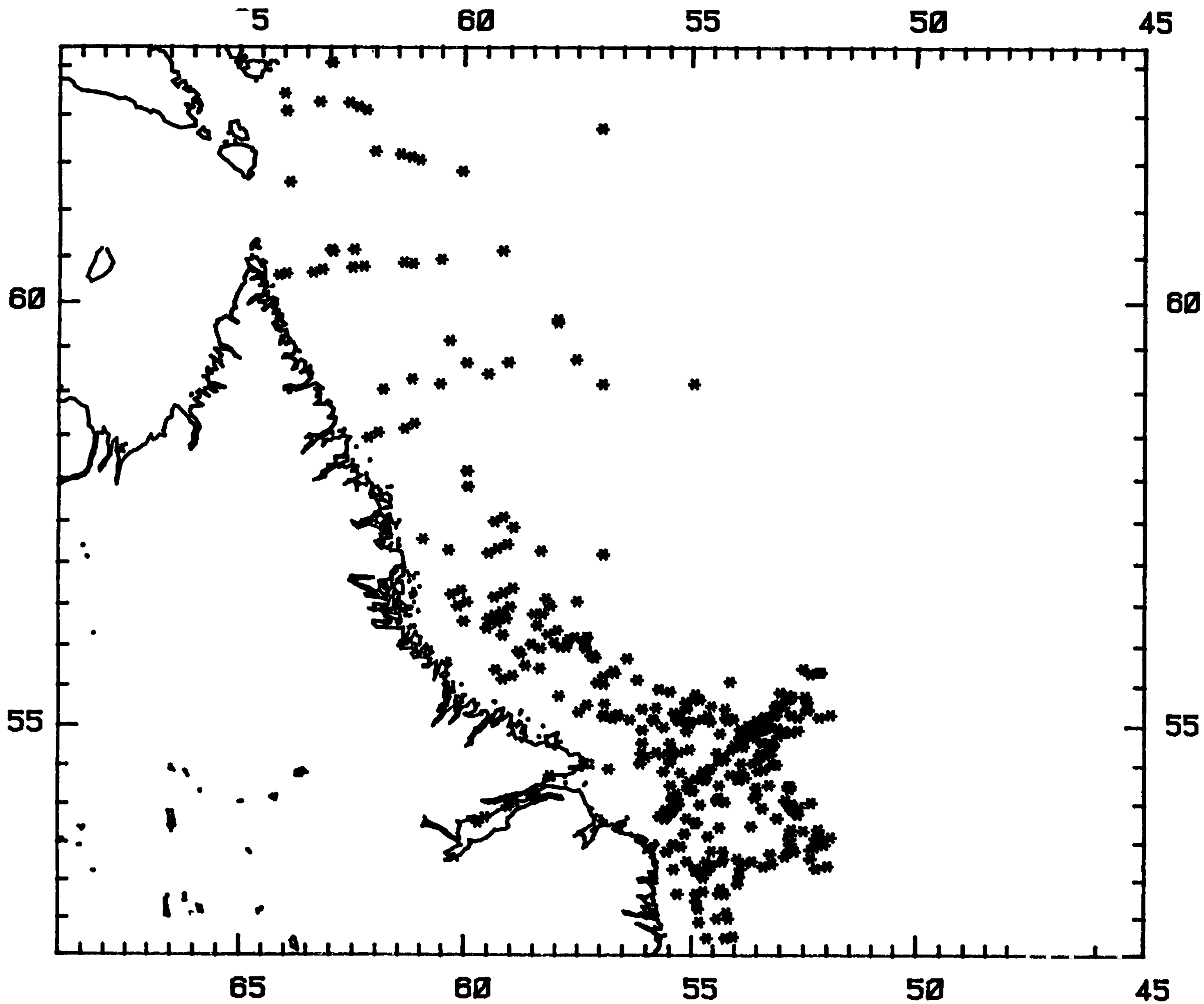

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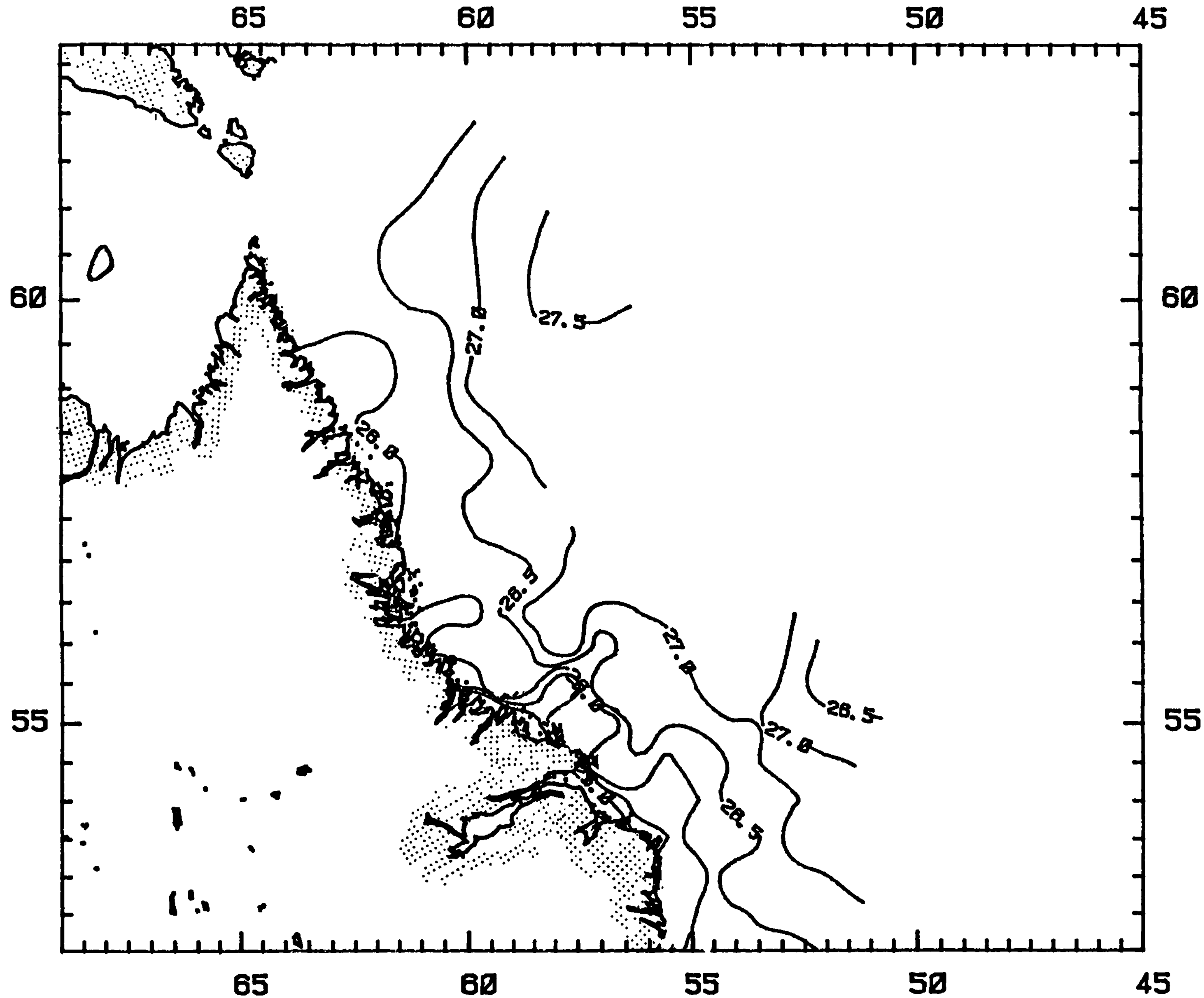

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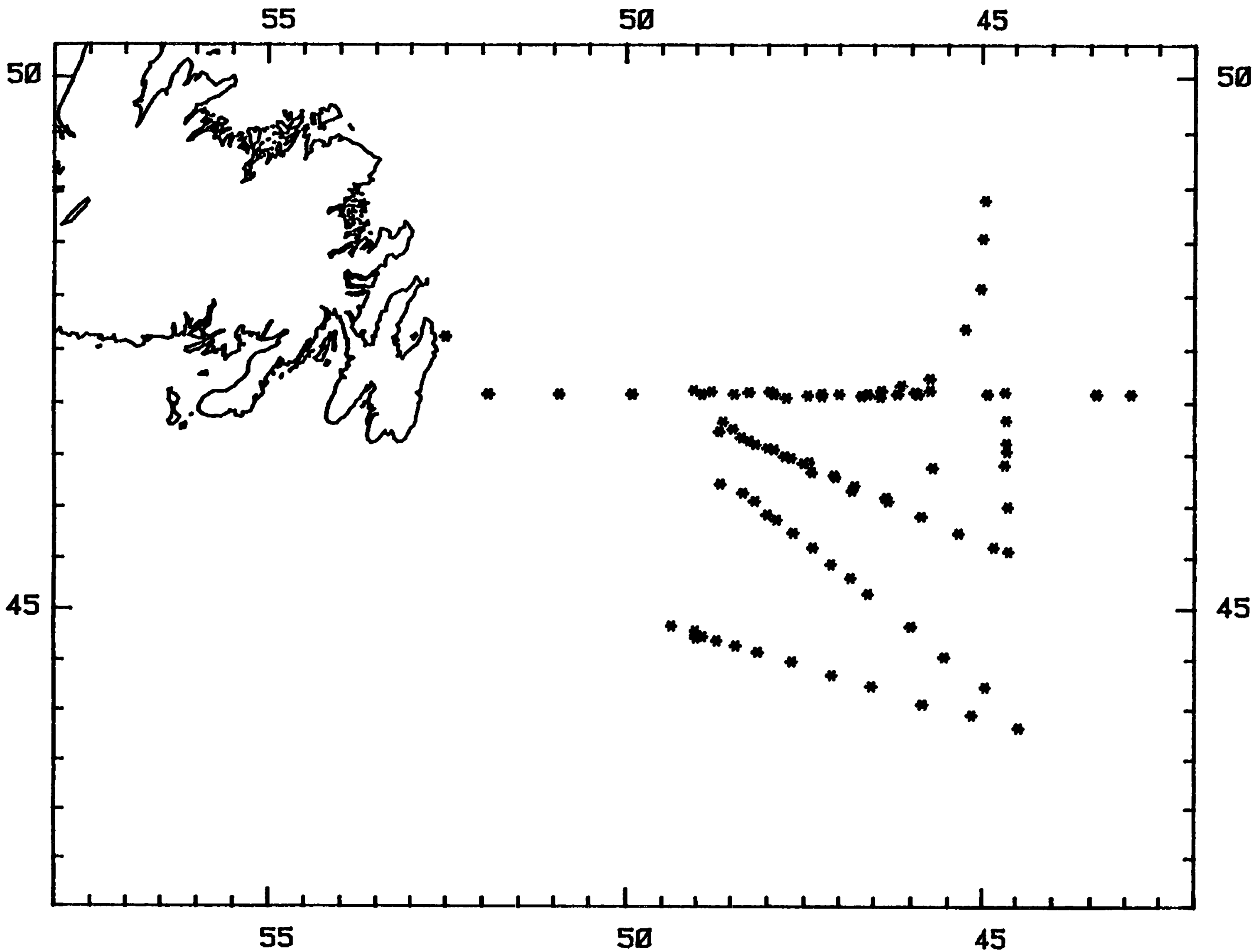
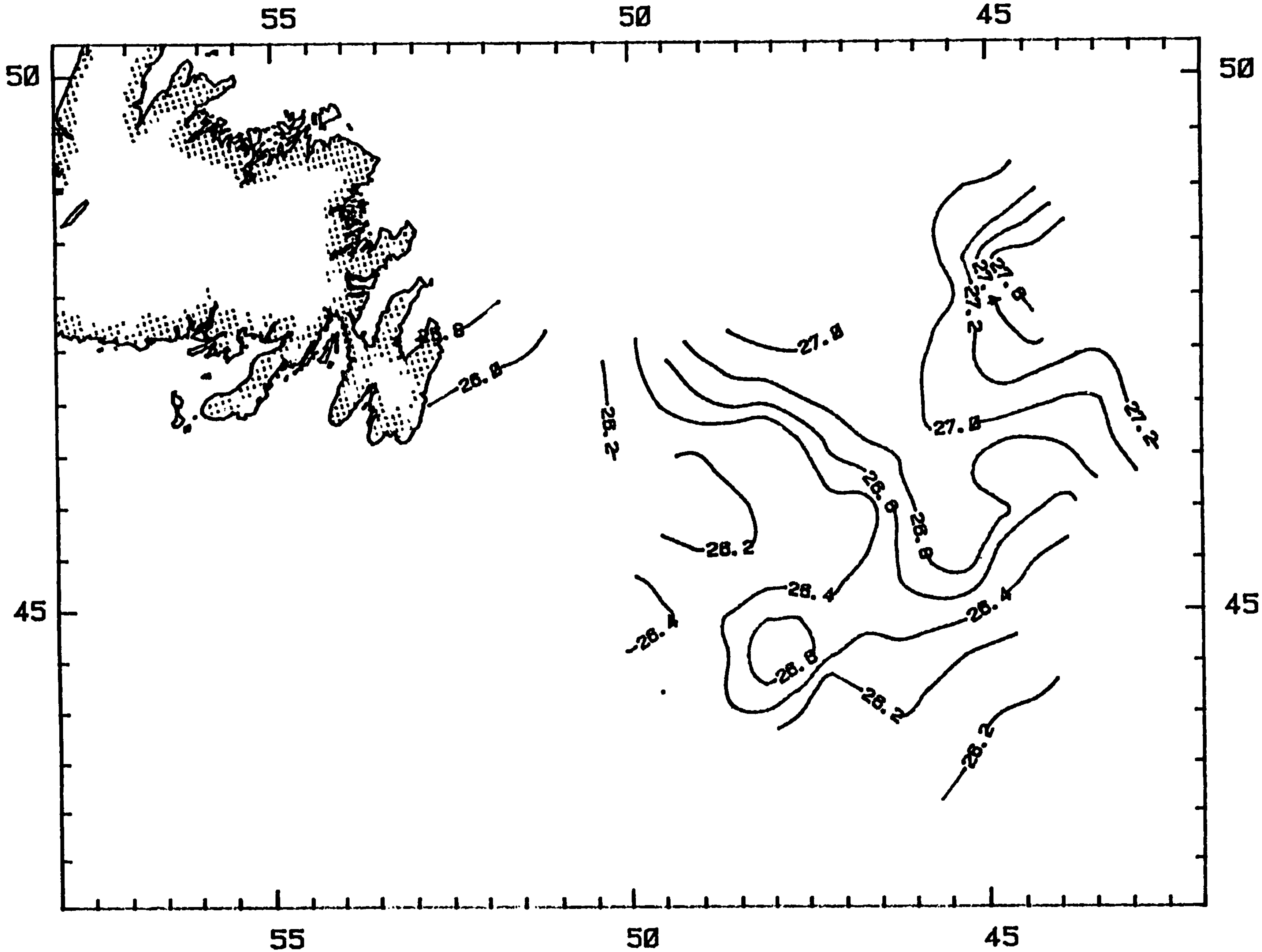


GRAND BANKS - Sample Locations, January to April



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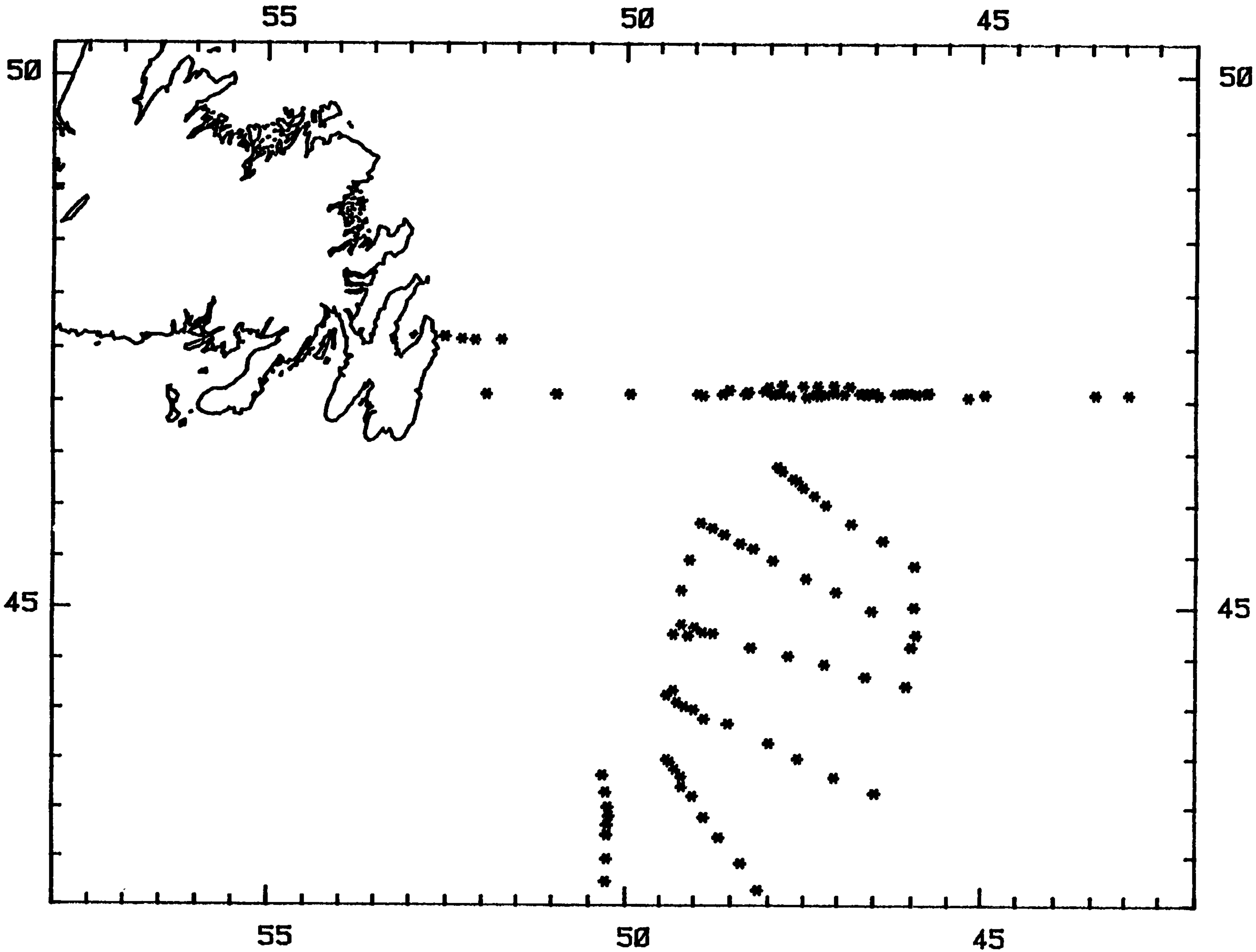
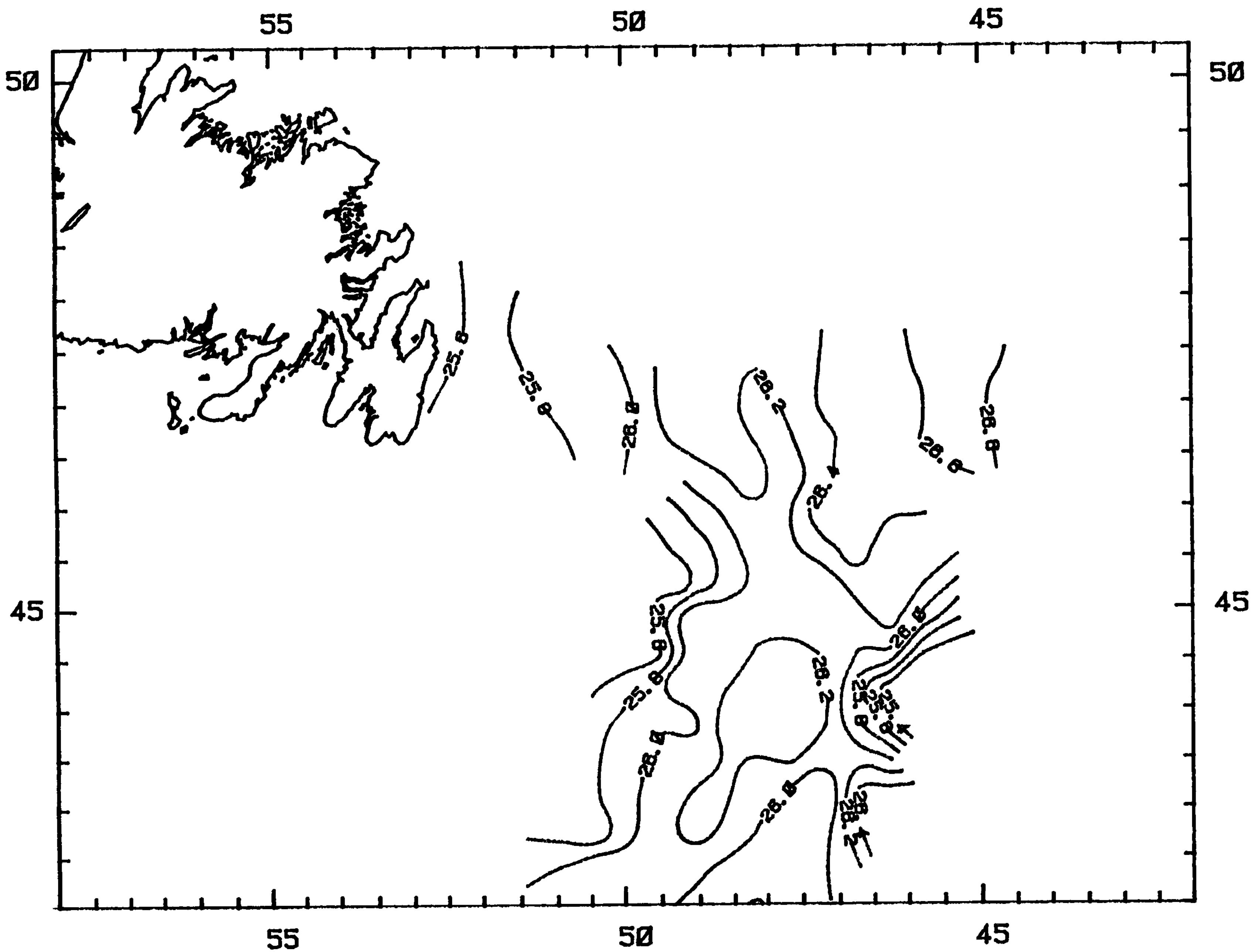


GRAND BANKS - Sample Locations, May to June



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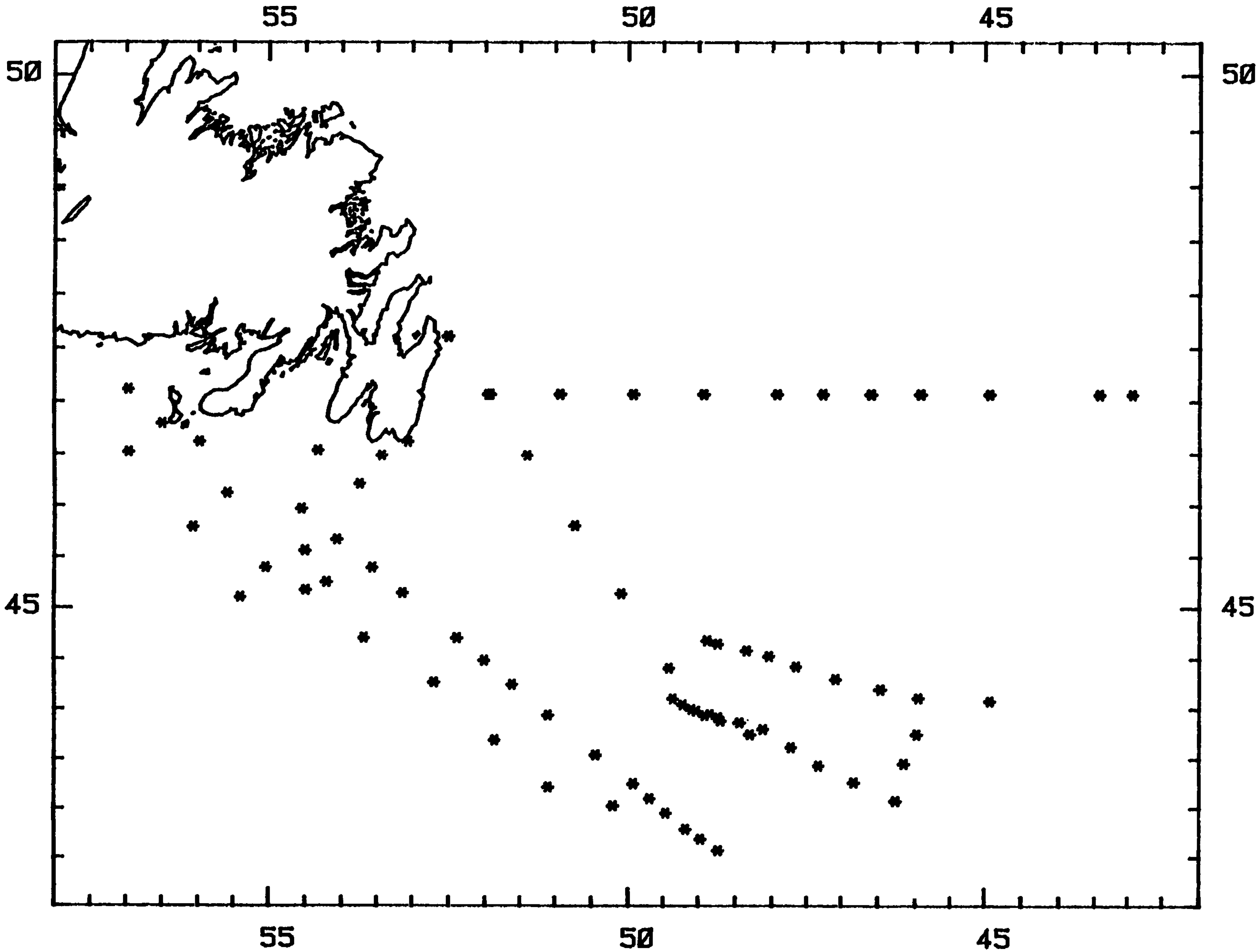

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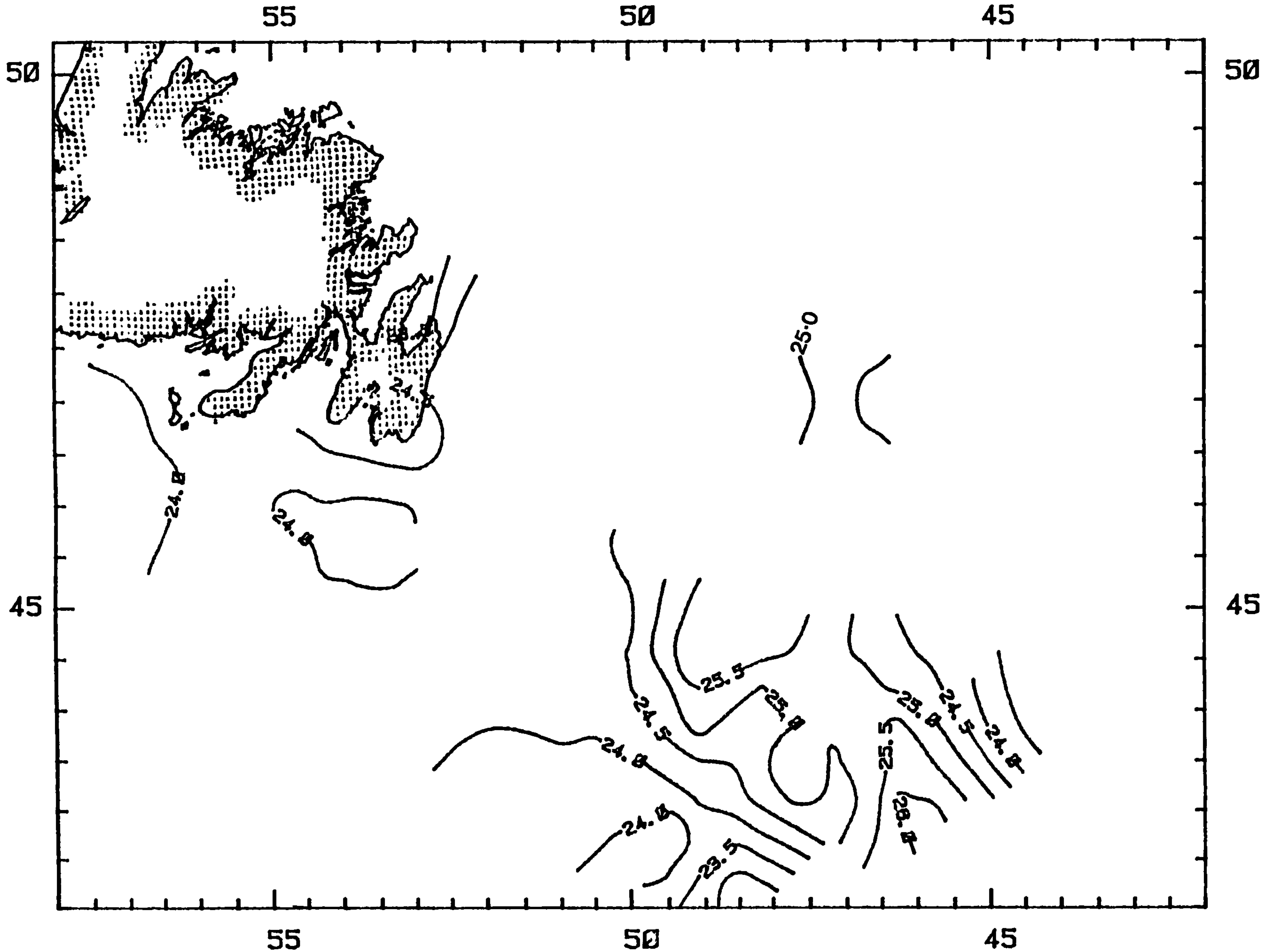

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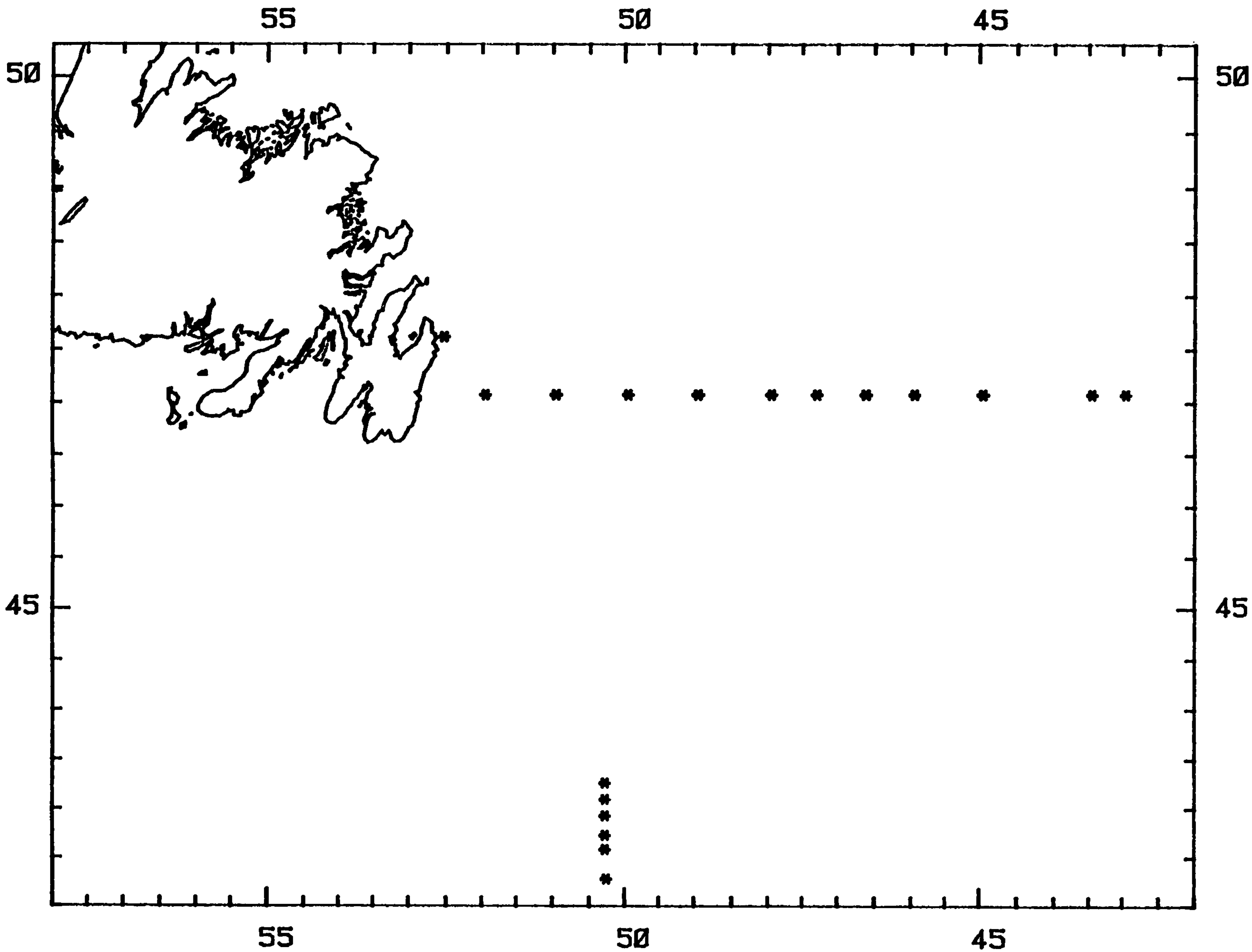

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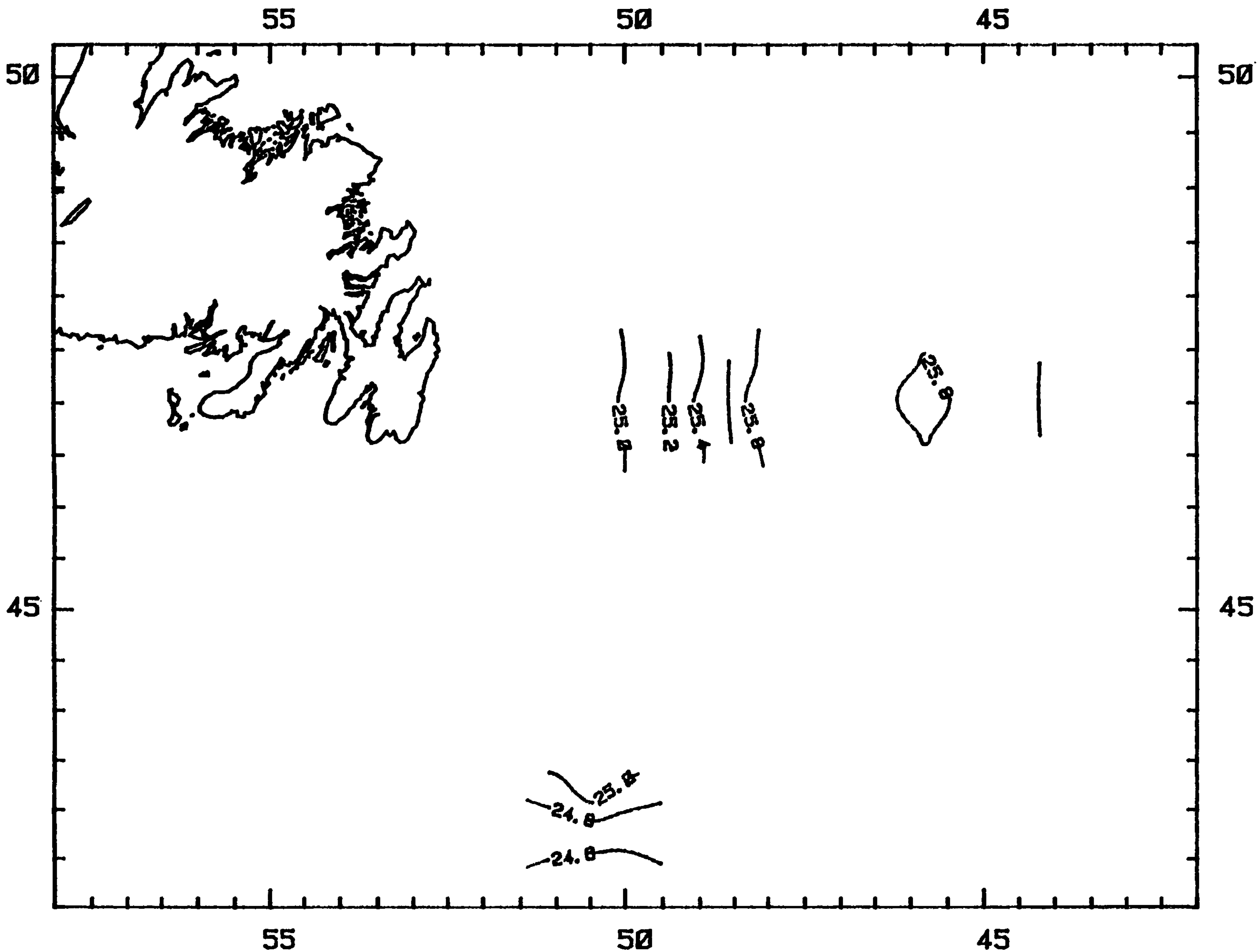

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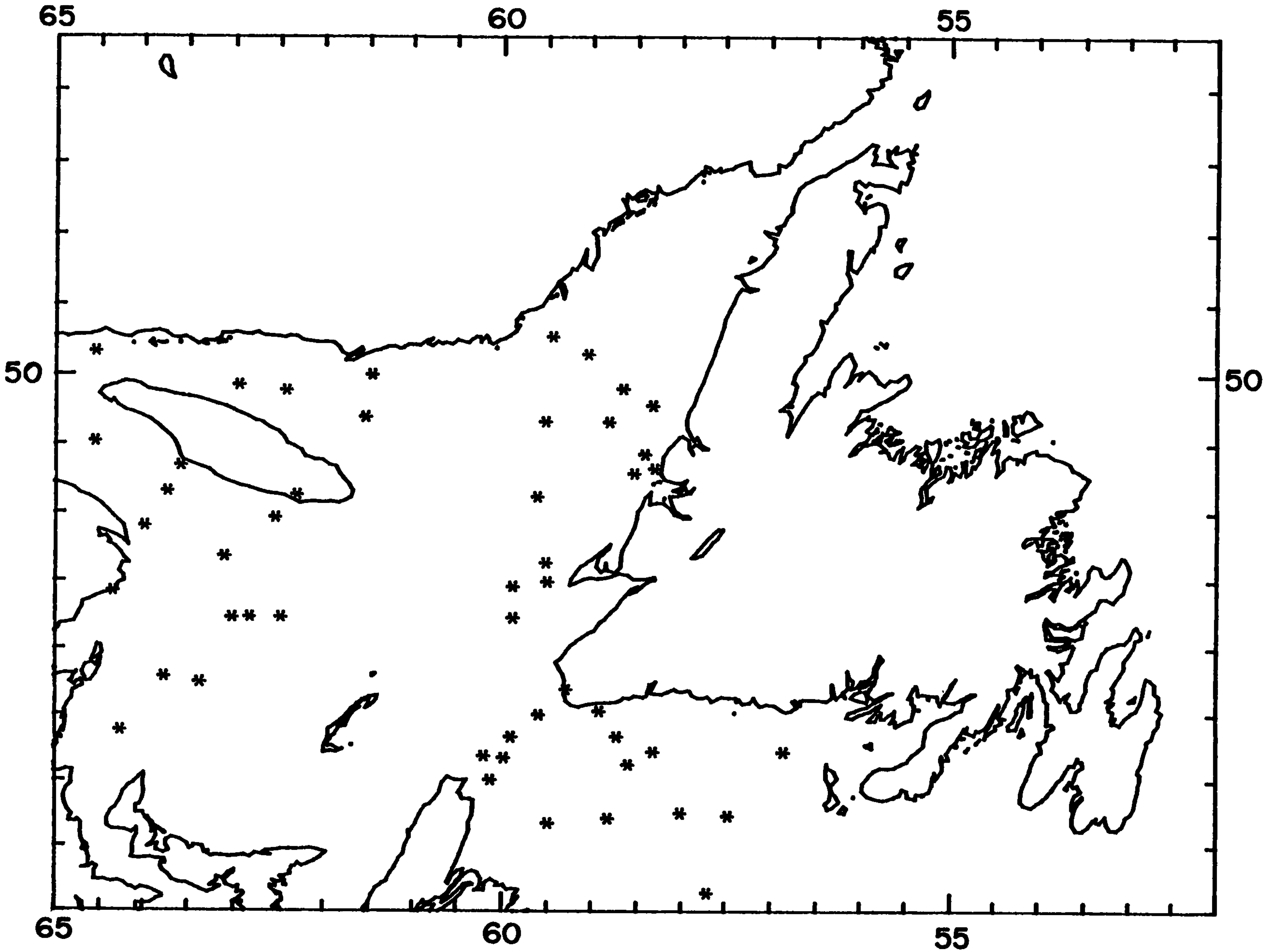
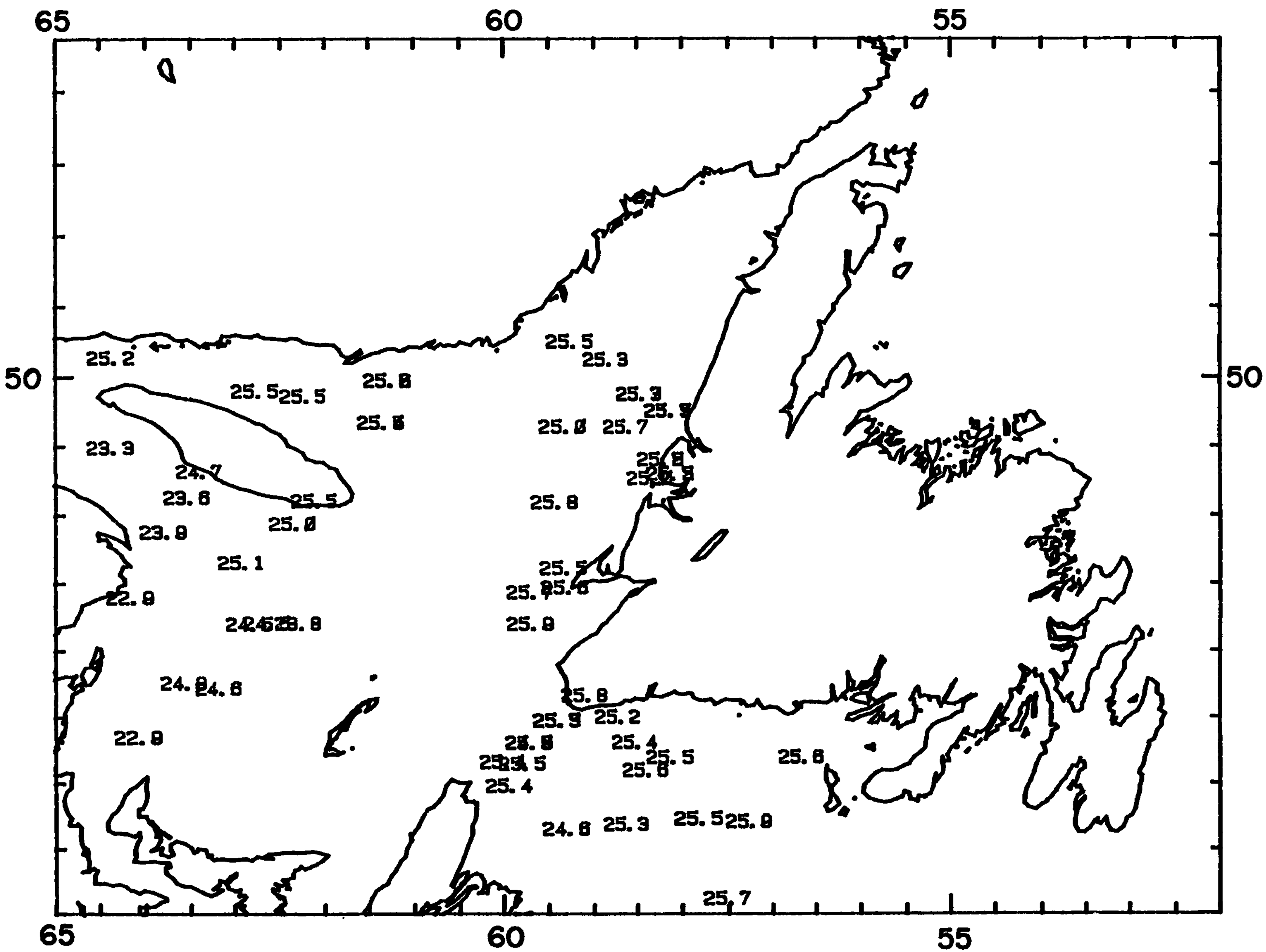
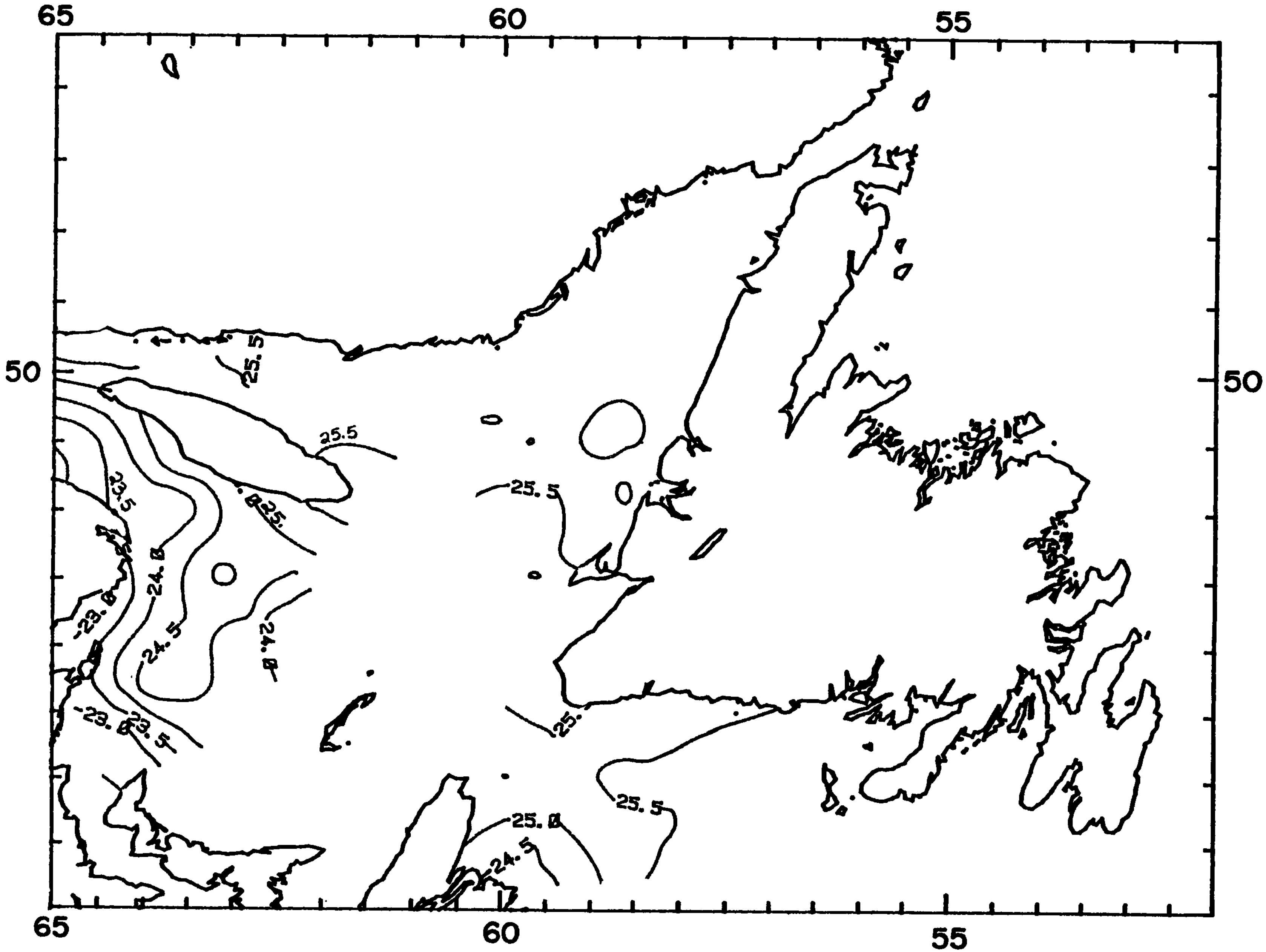


GULF OF ST. LAWRENCE - Sample Locations, January to April



GULF OF ST. LAWRENCE - Sample Values, January to April



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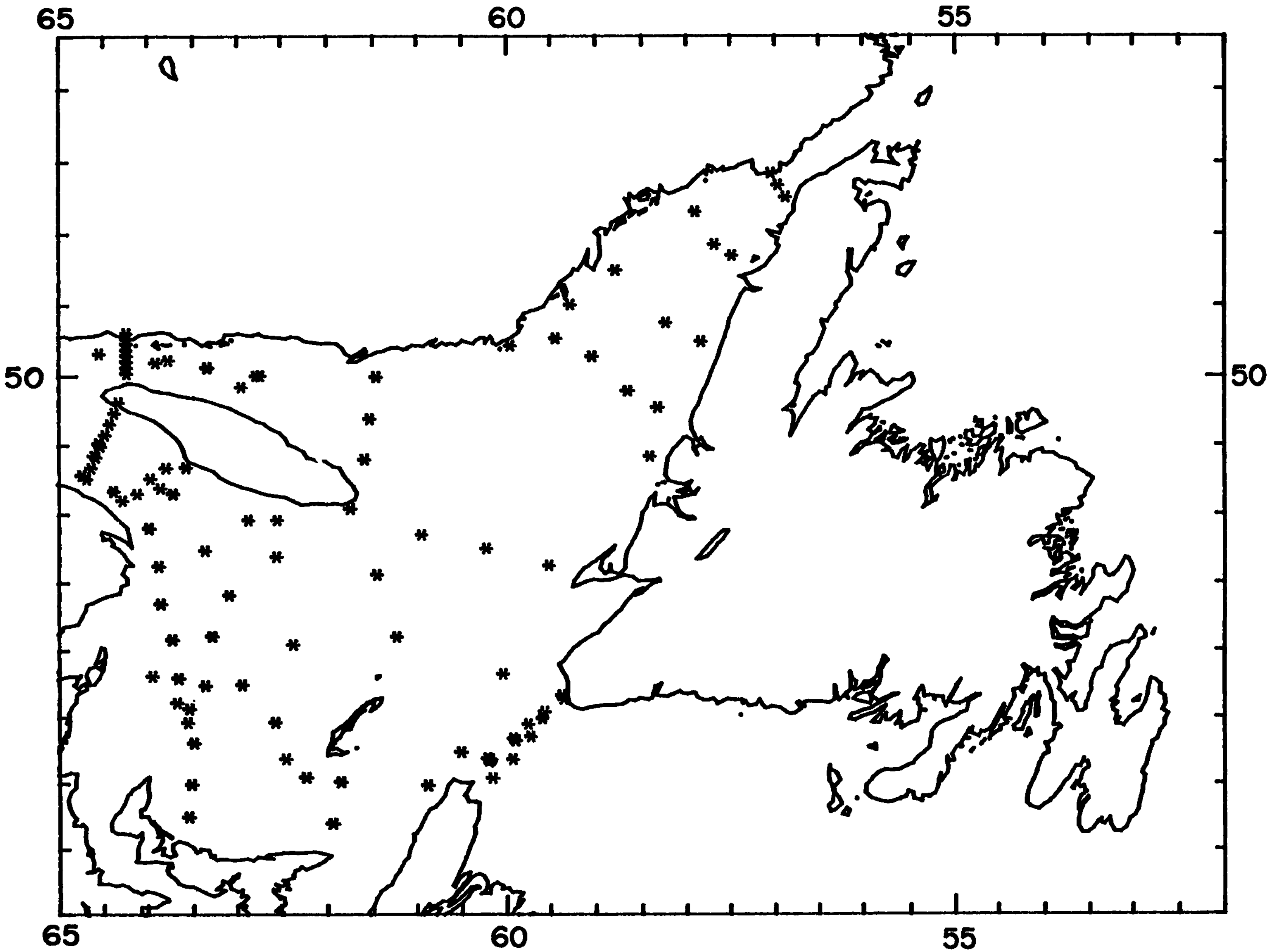
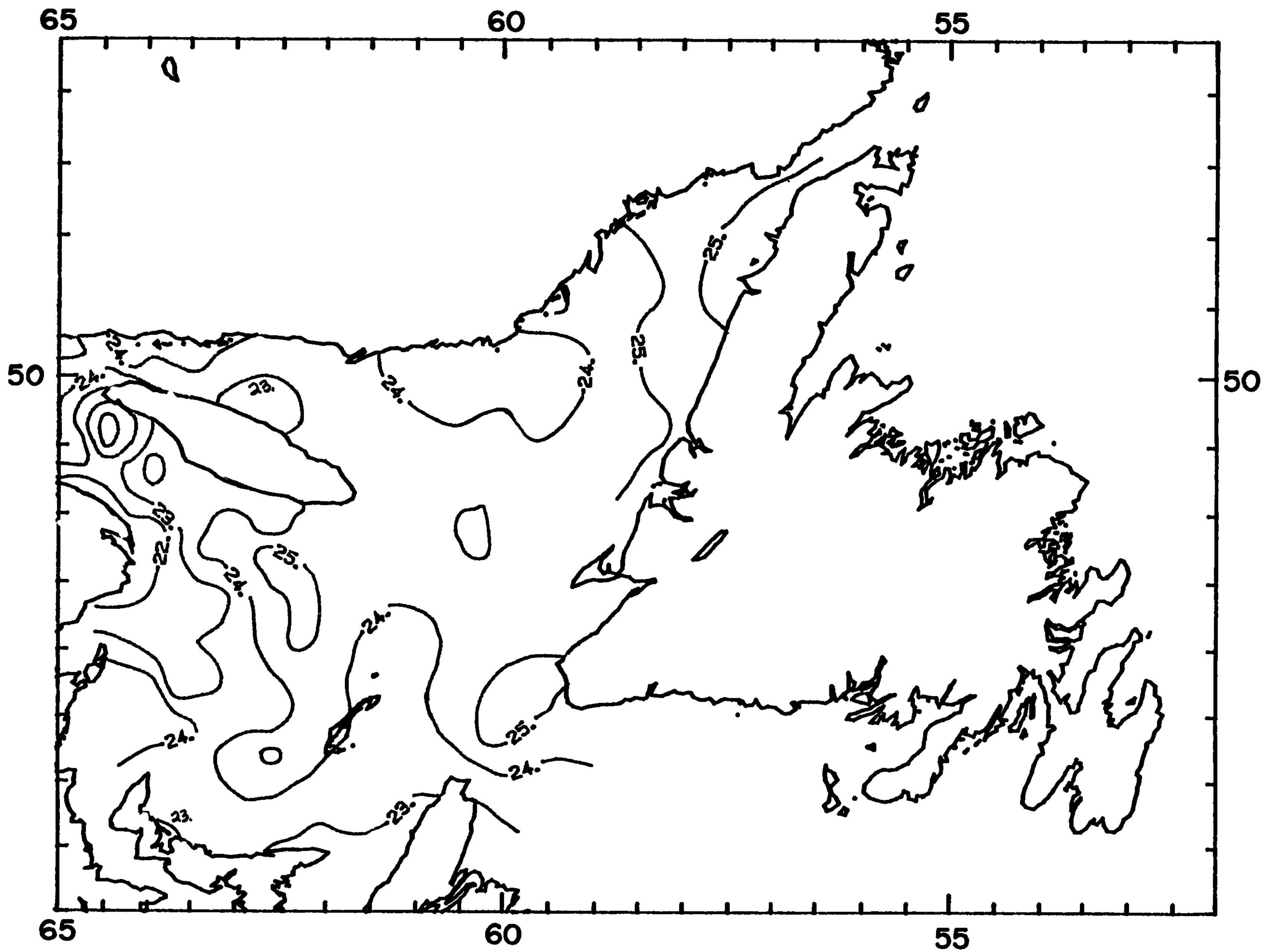


GULF OF ST. LAWRENCE - Sample Locations, May to June



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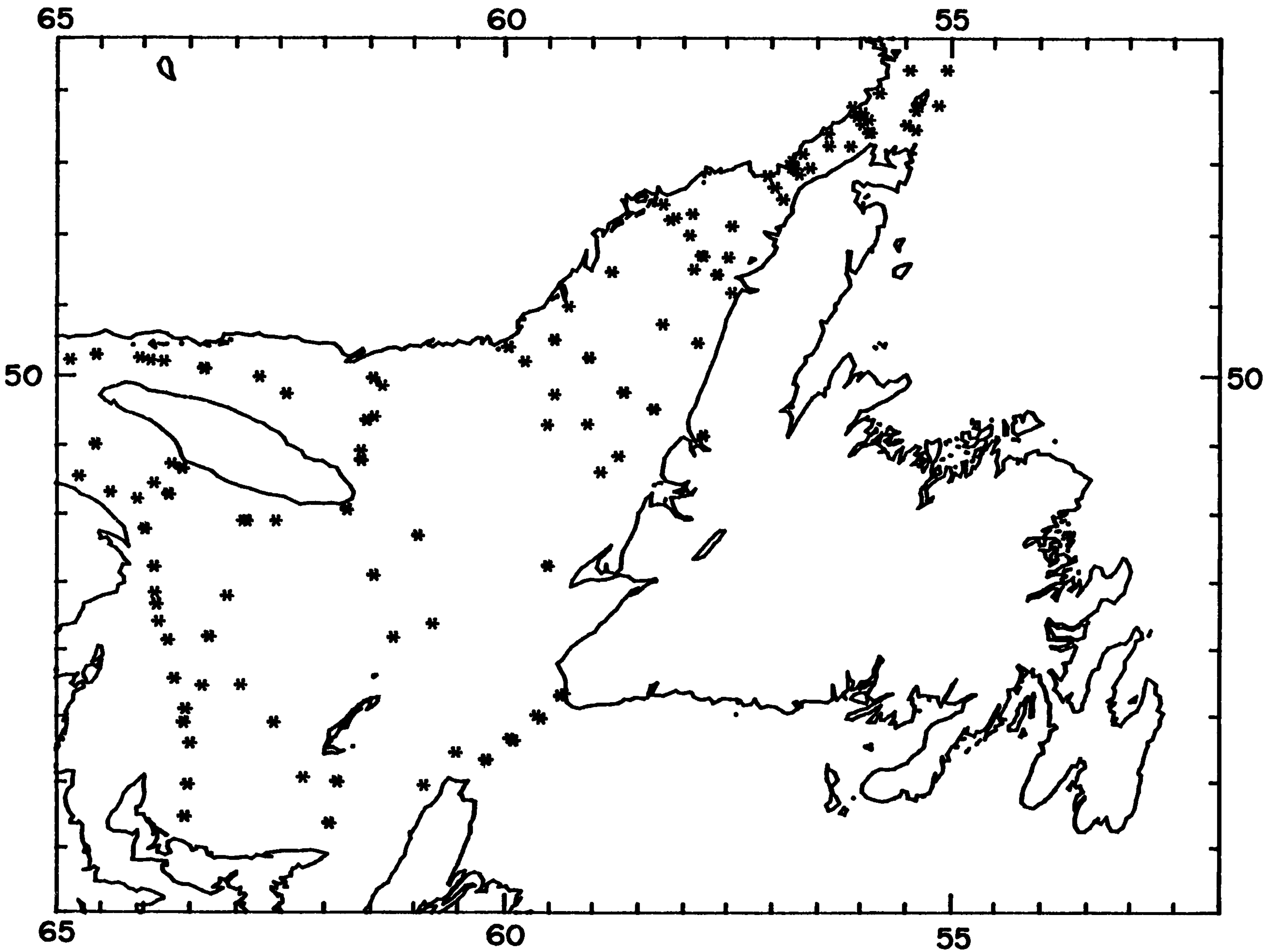

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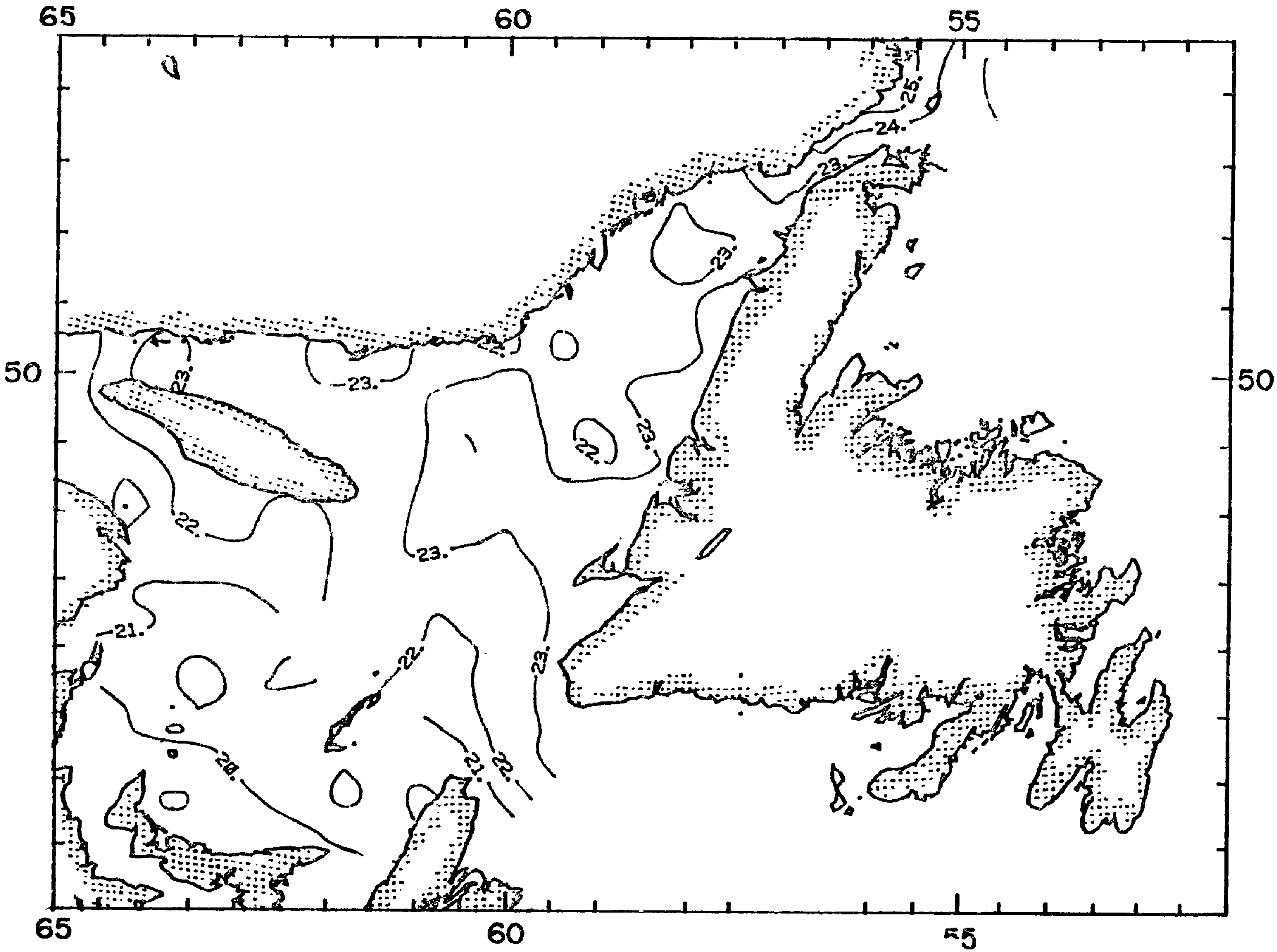

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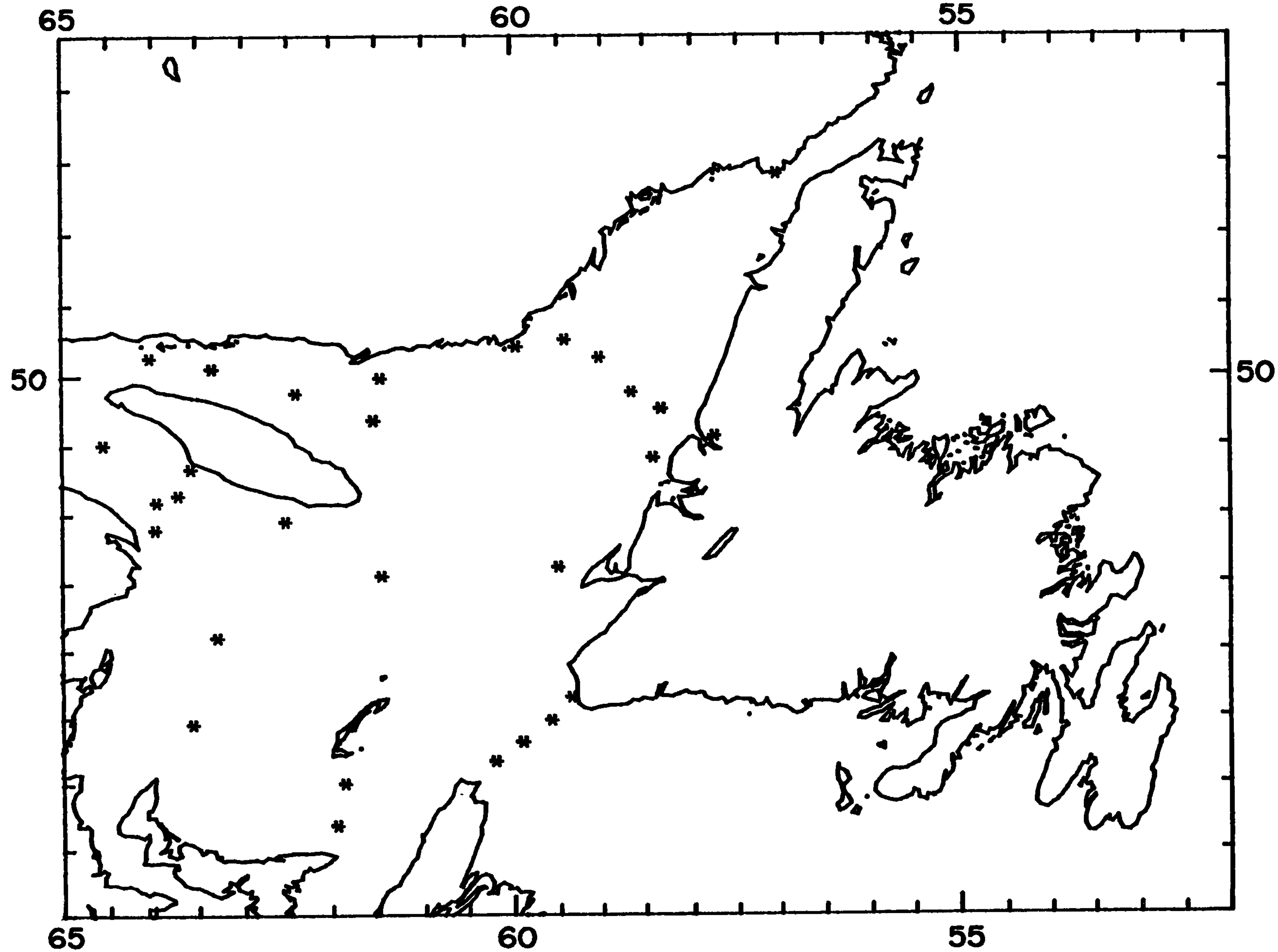

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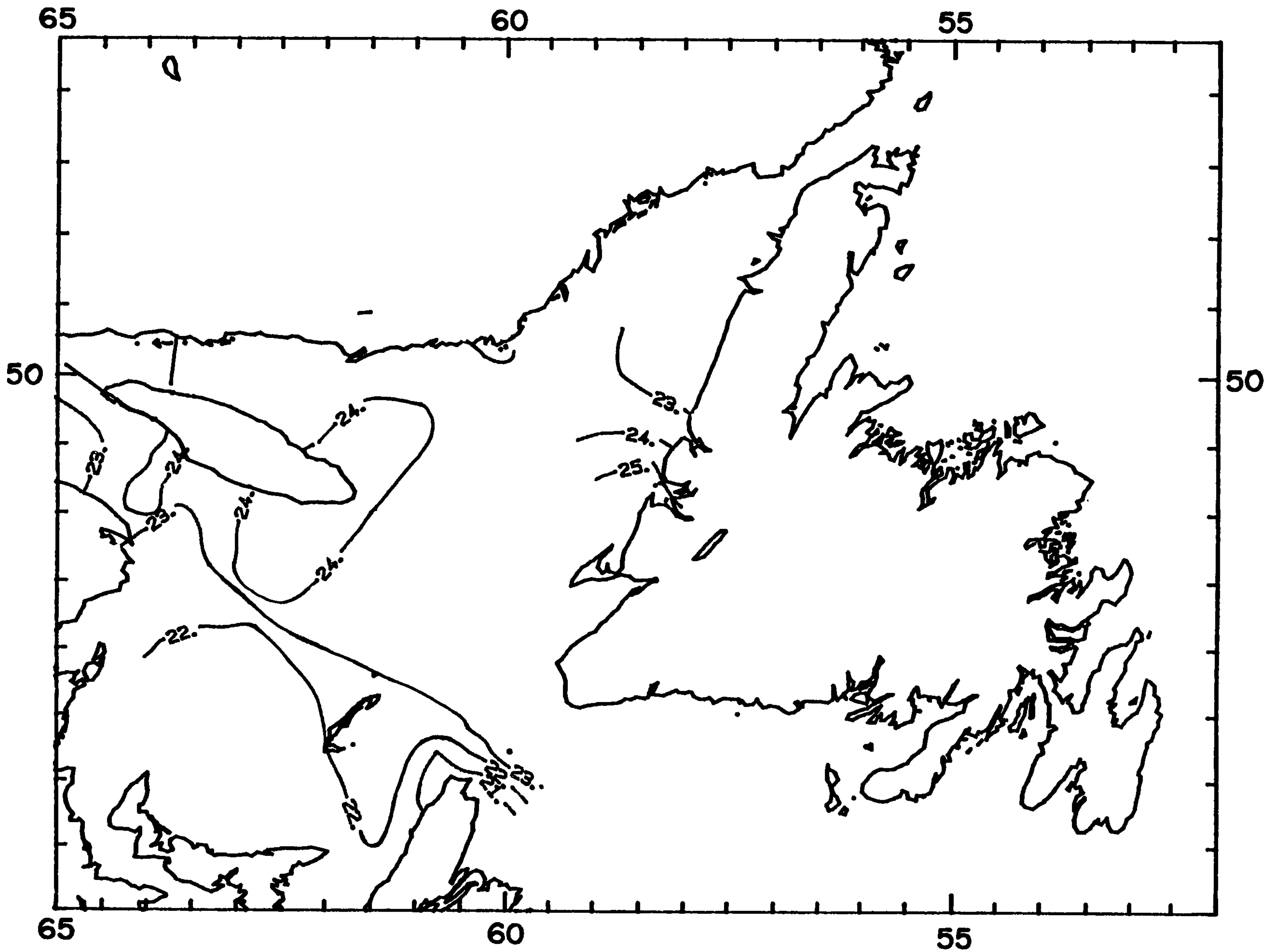
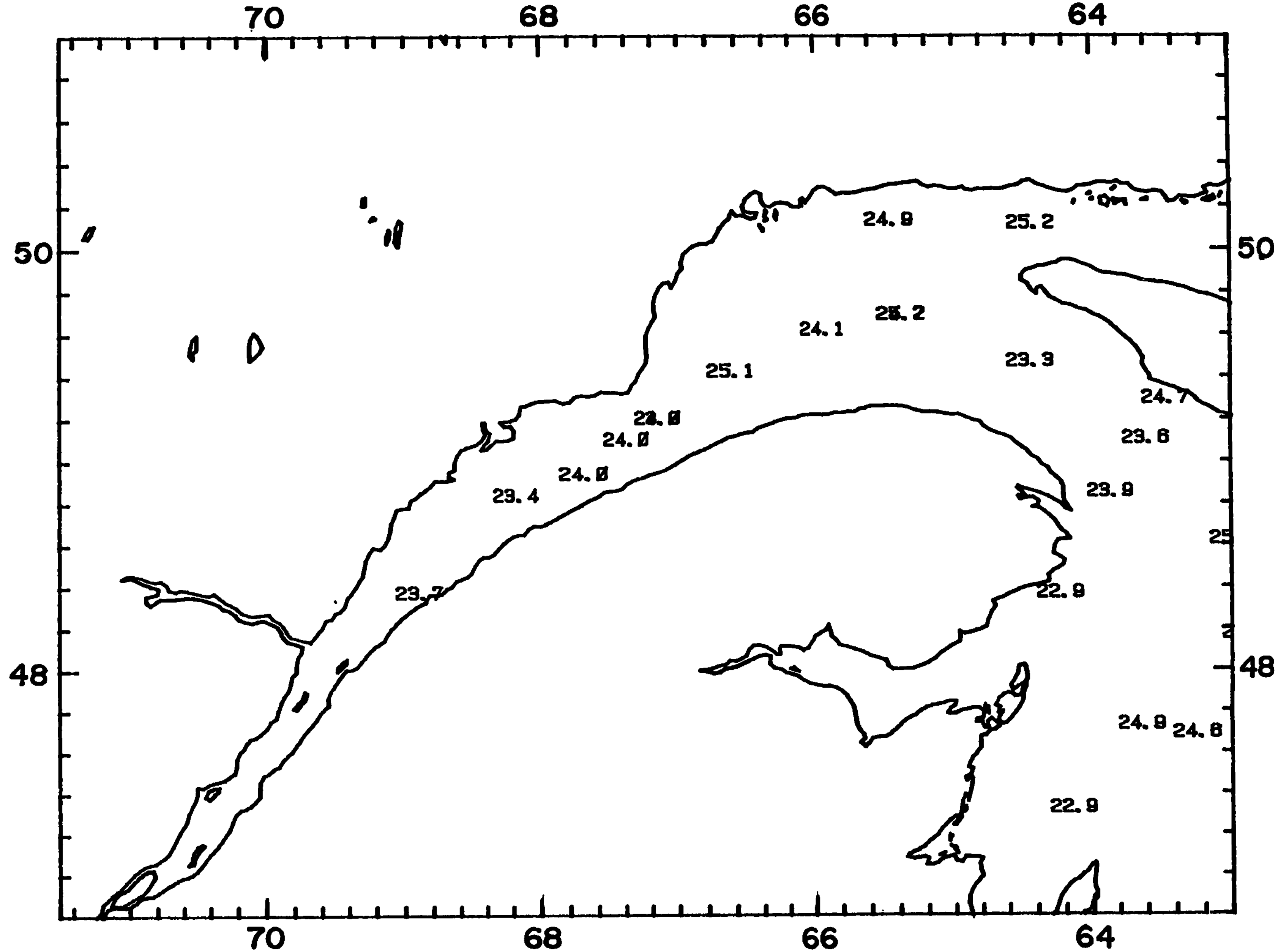
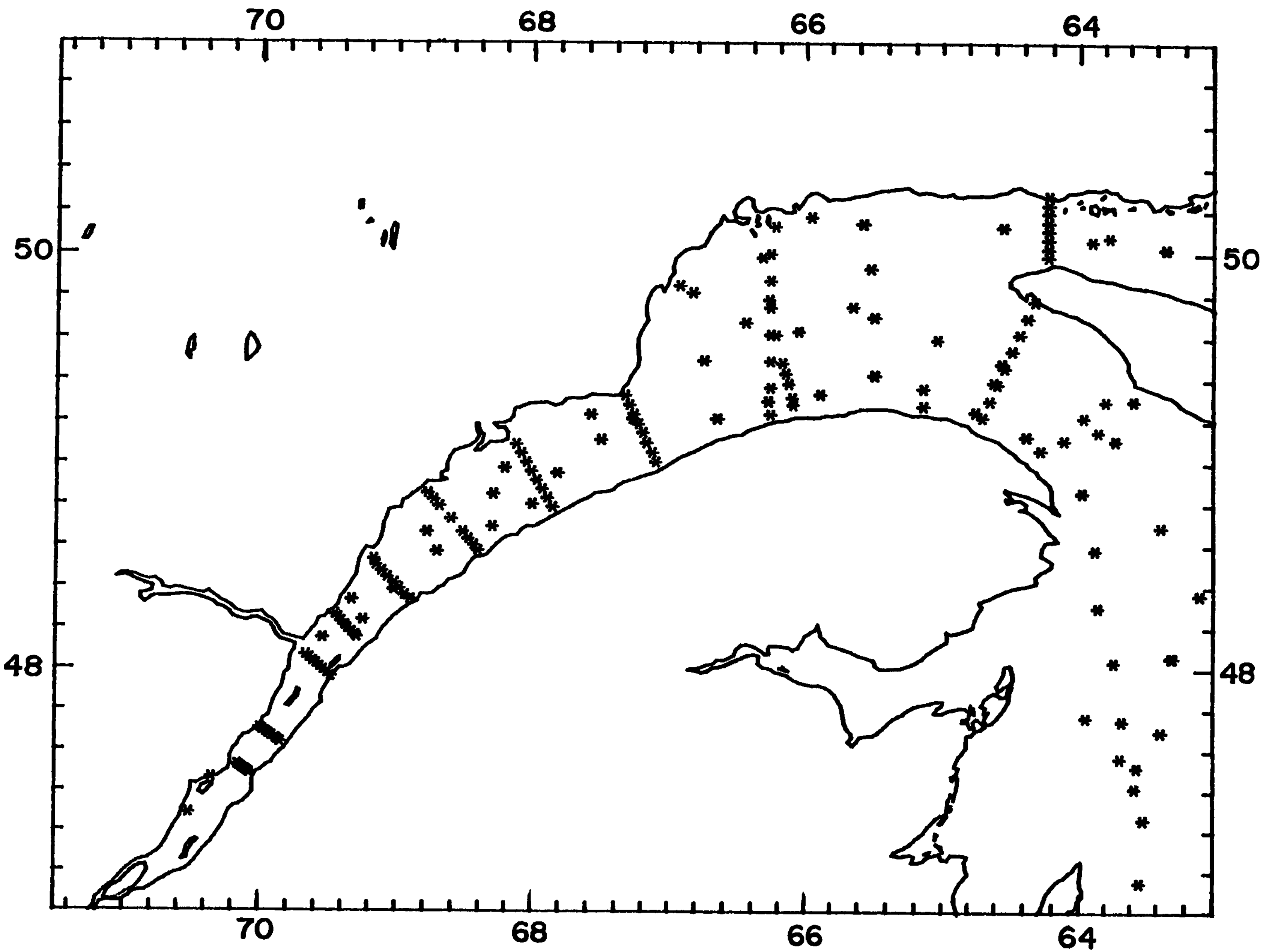


GULF OF ST. LAWRENCE - Contoured Surface Density, Spetember to December



UPPER ST. LAWRENCE - Sample Locations and Values, January to April



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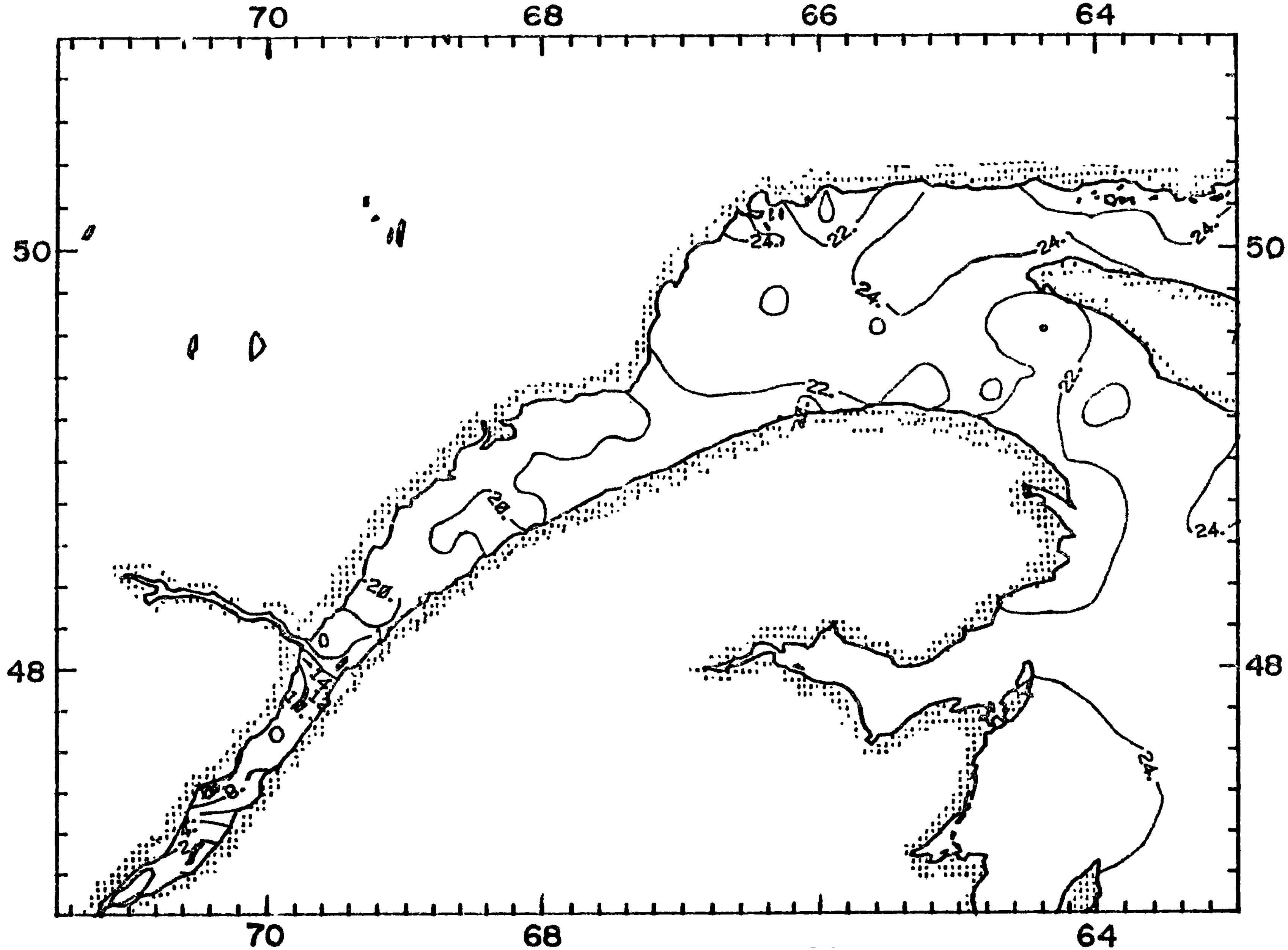

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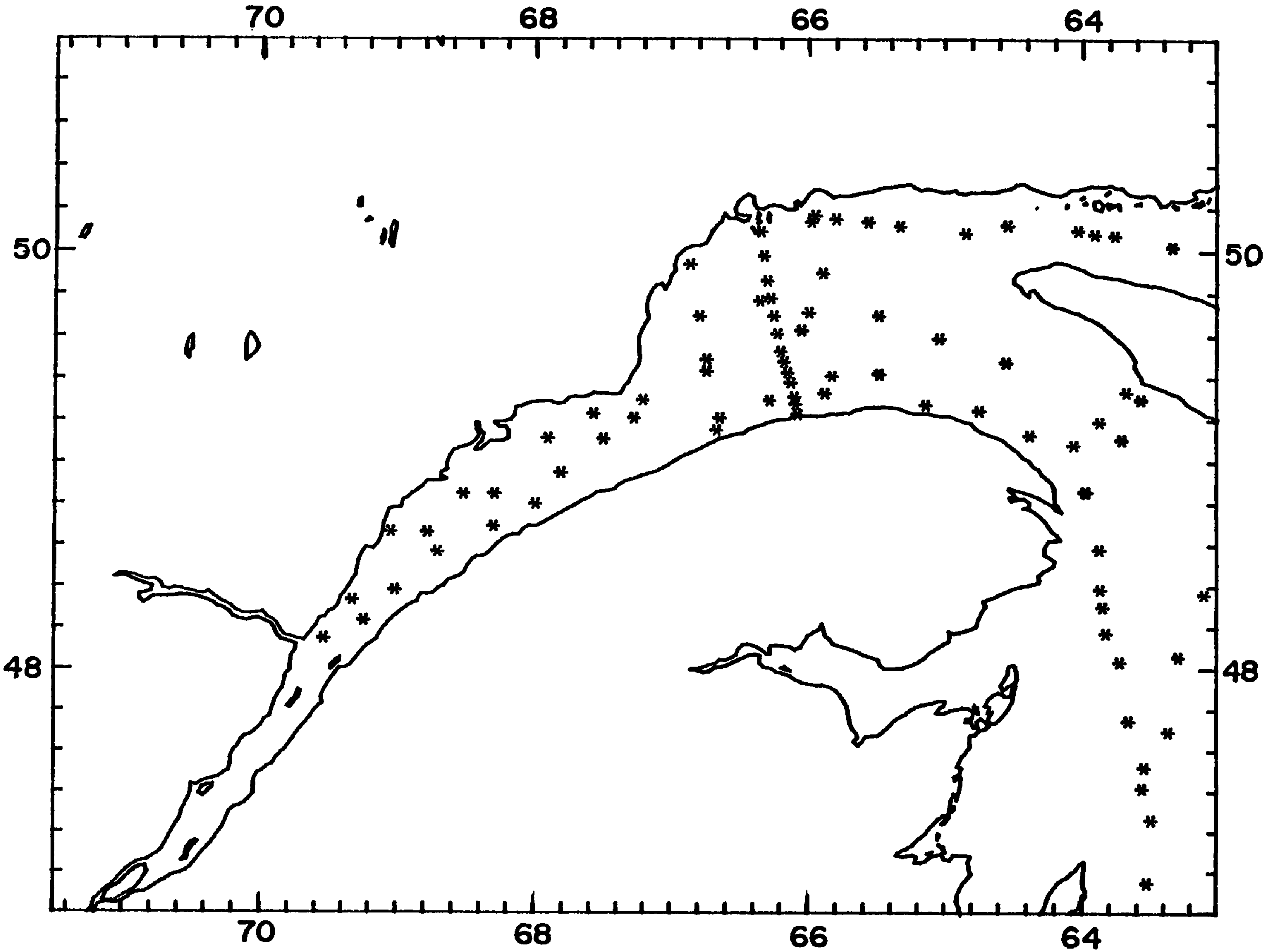

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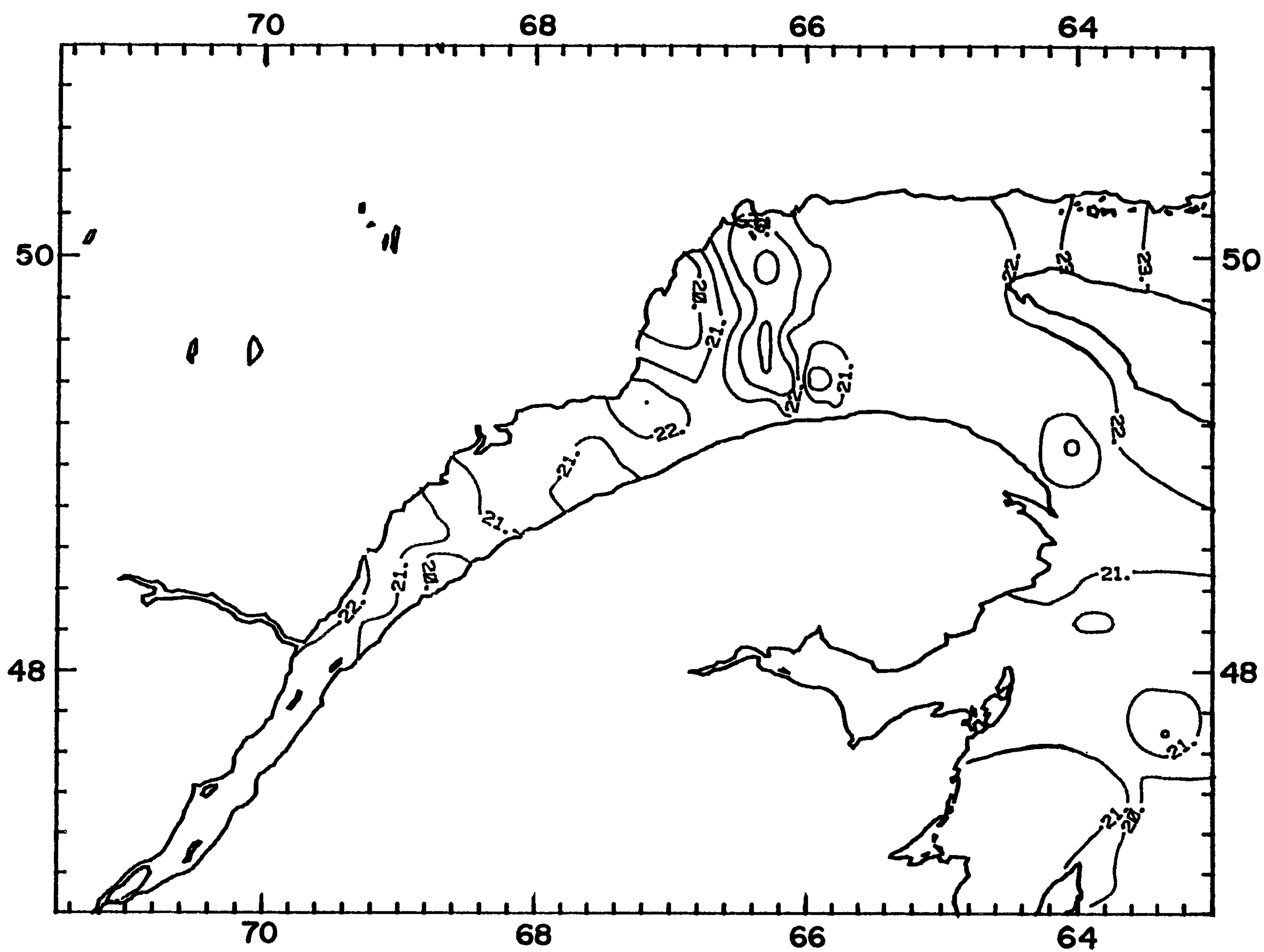

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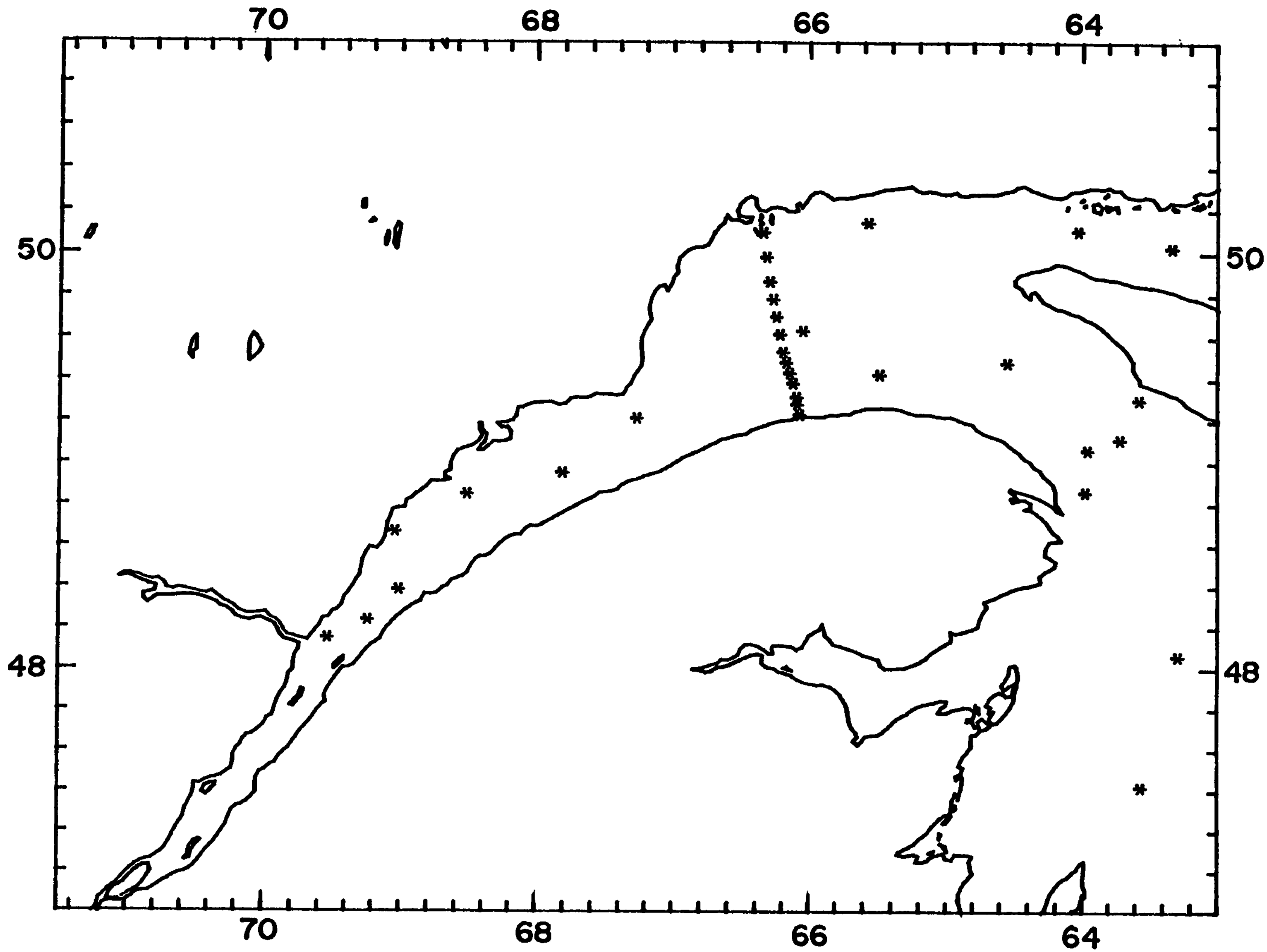

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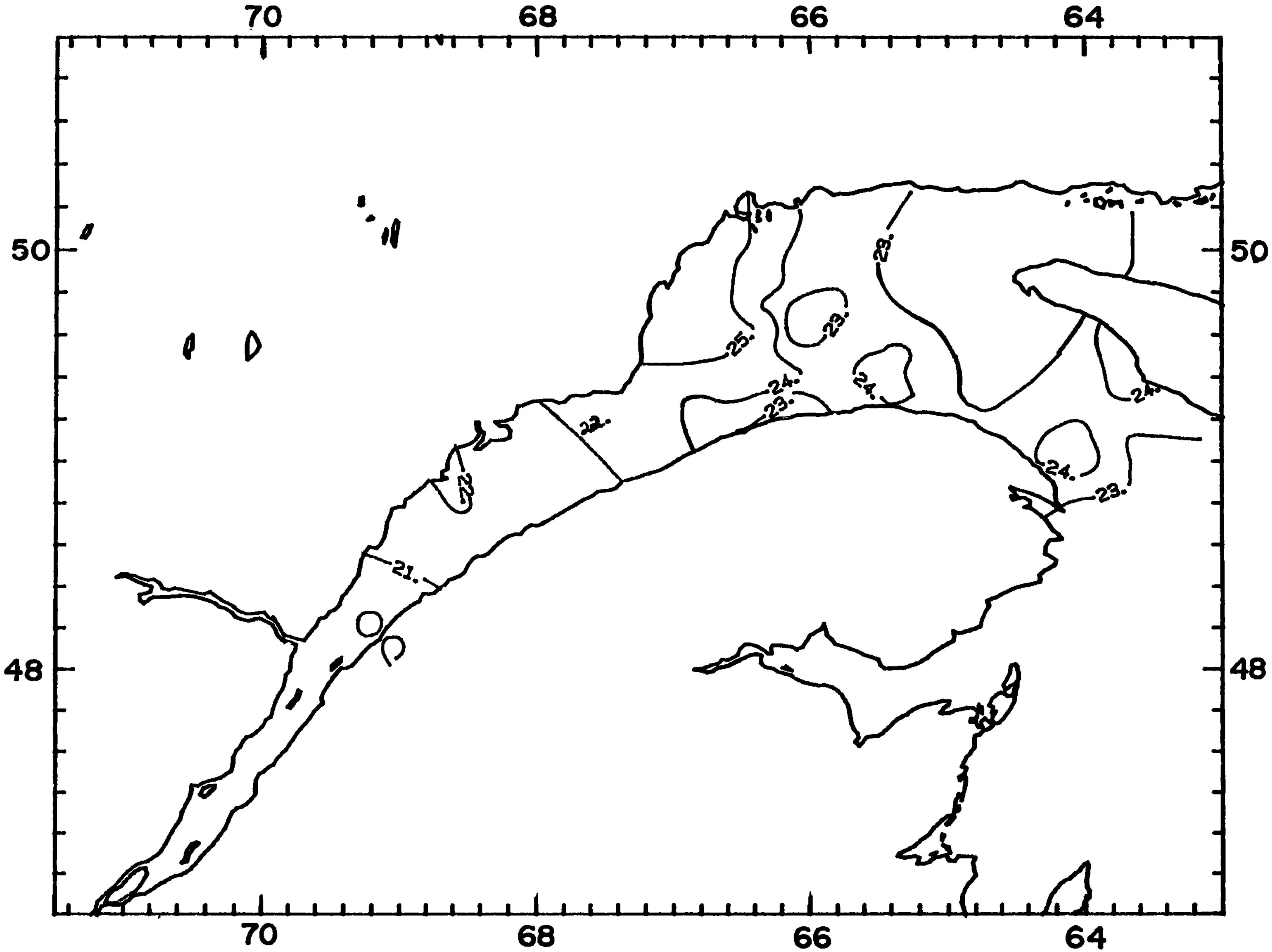

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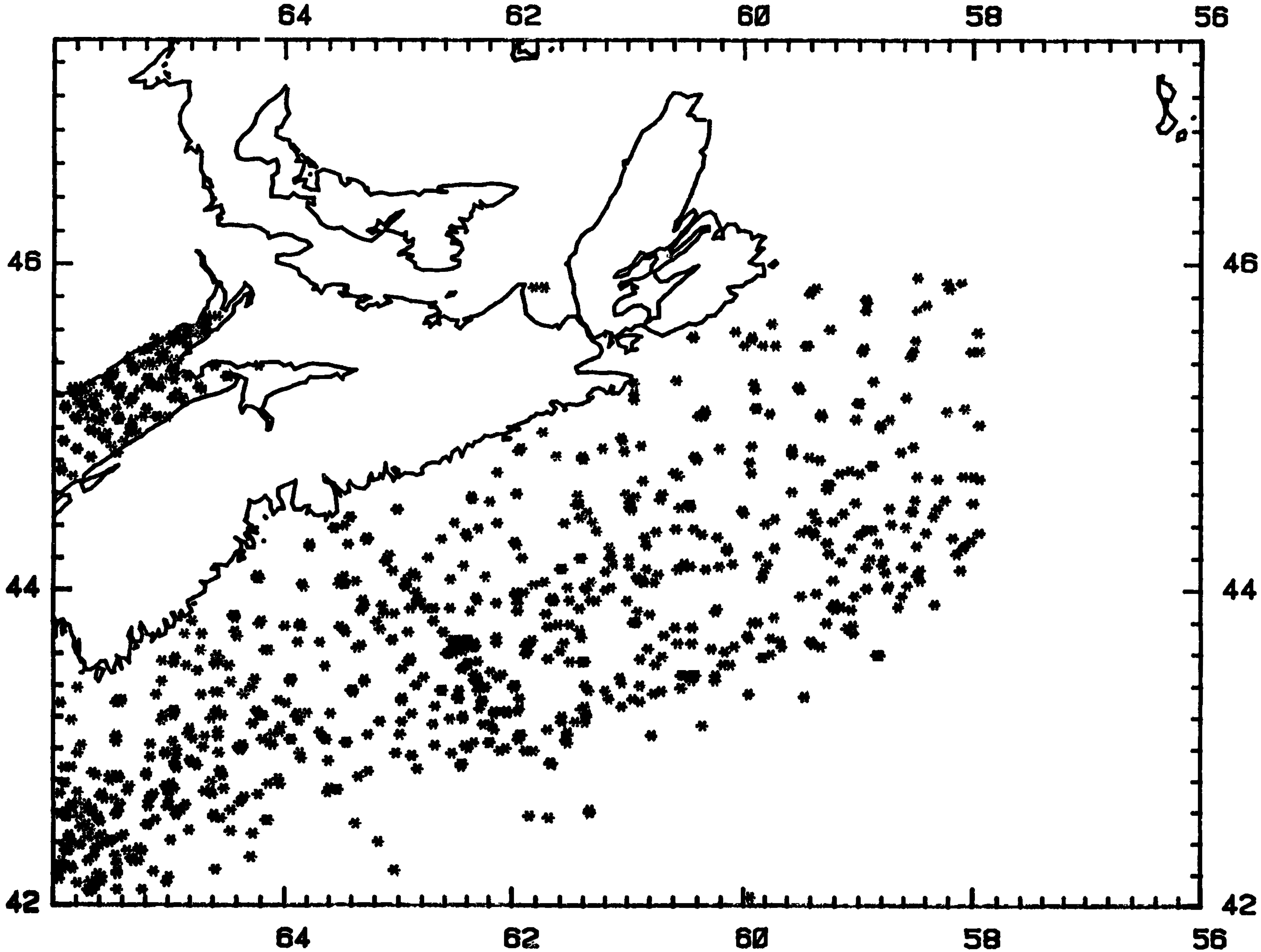
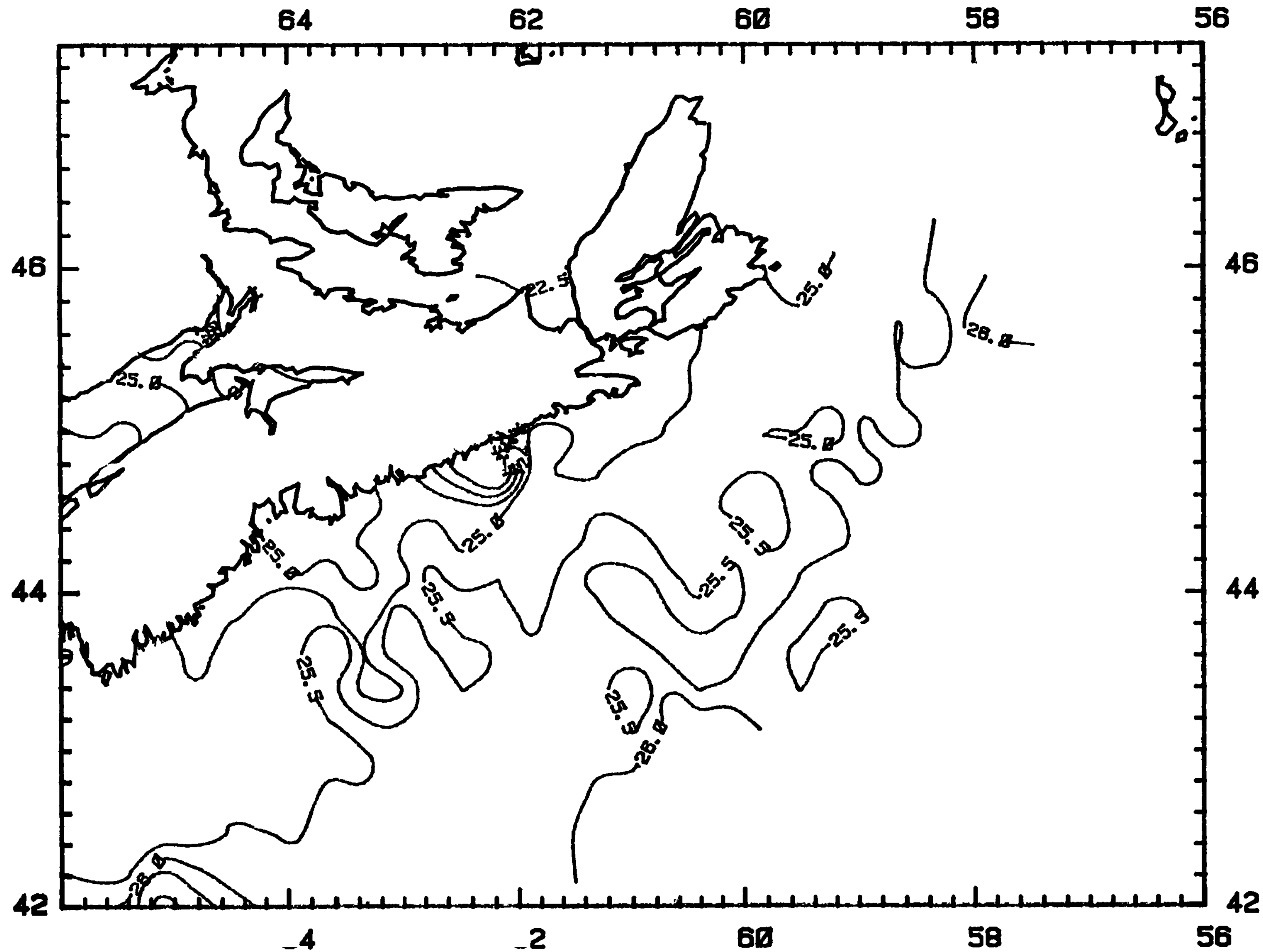


SCOTIAN SHELF - Sample Locations, January to April



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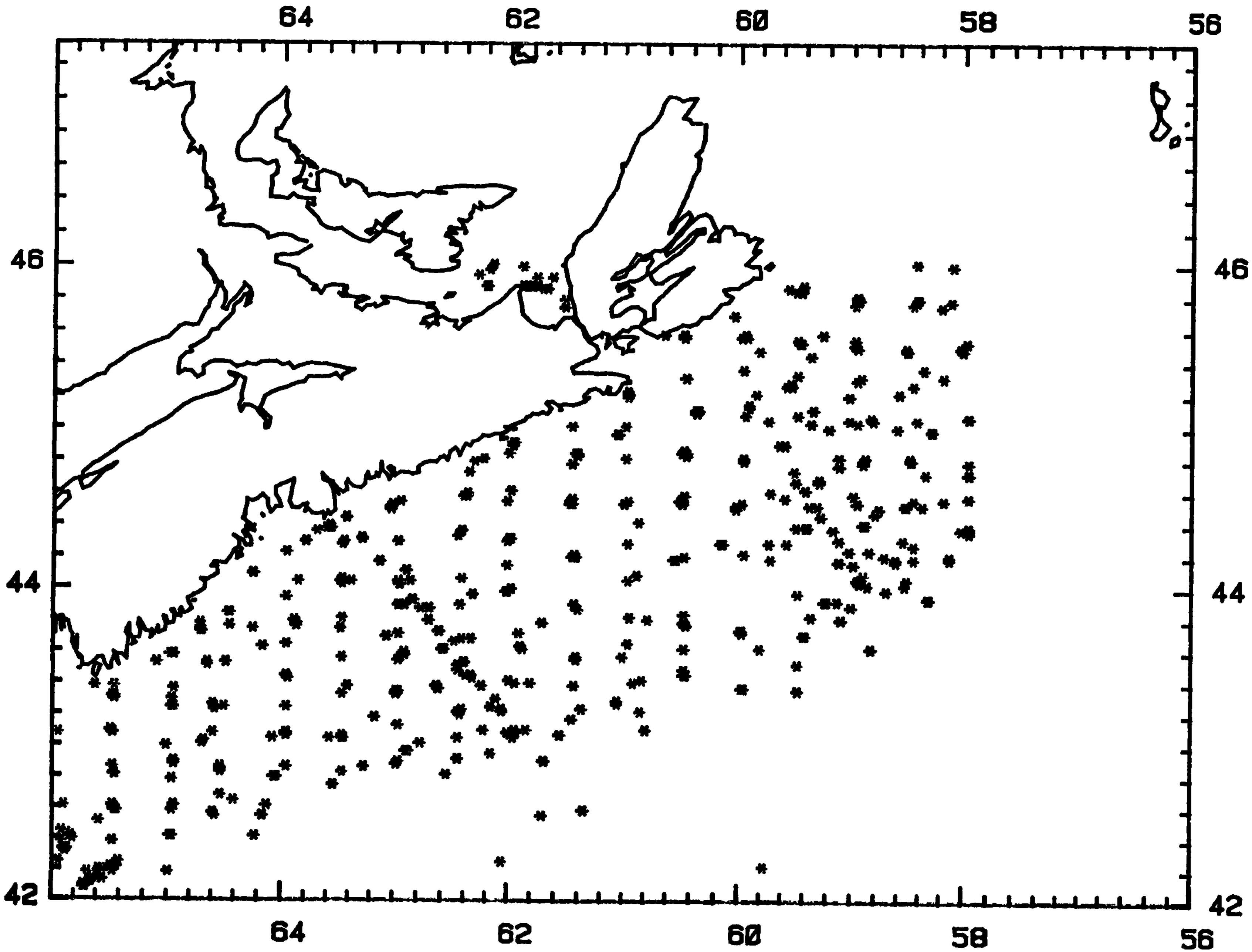

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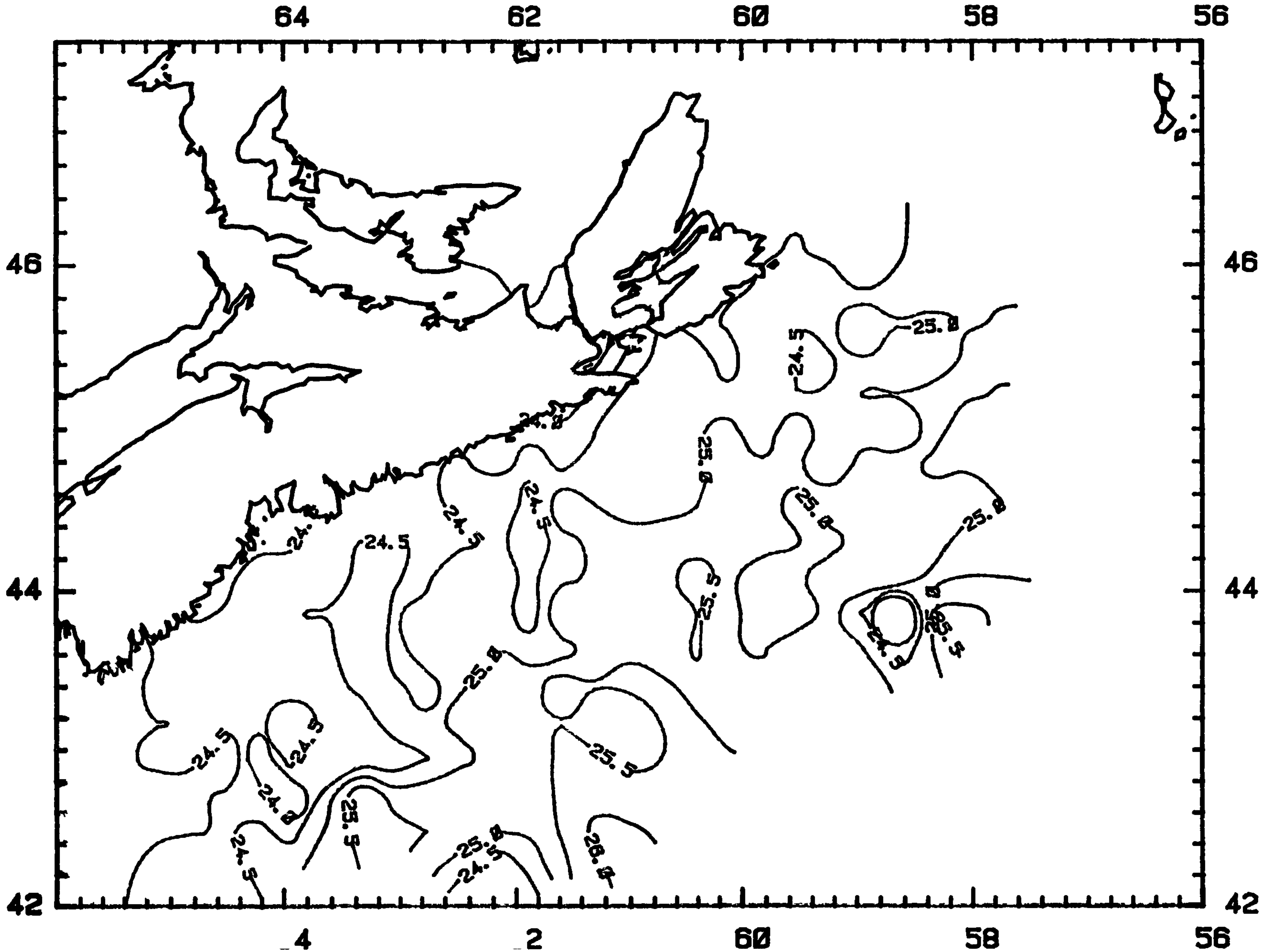

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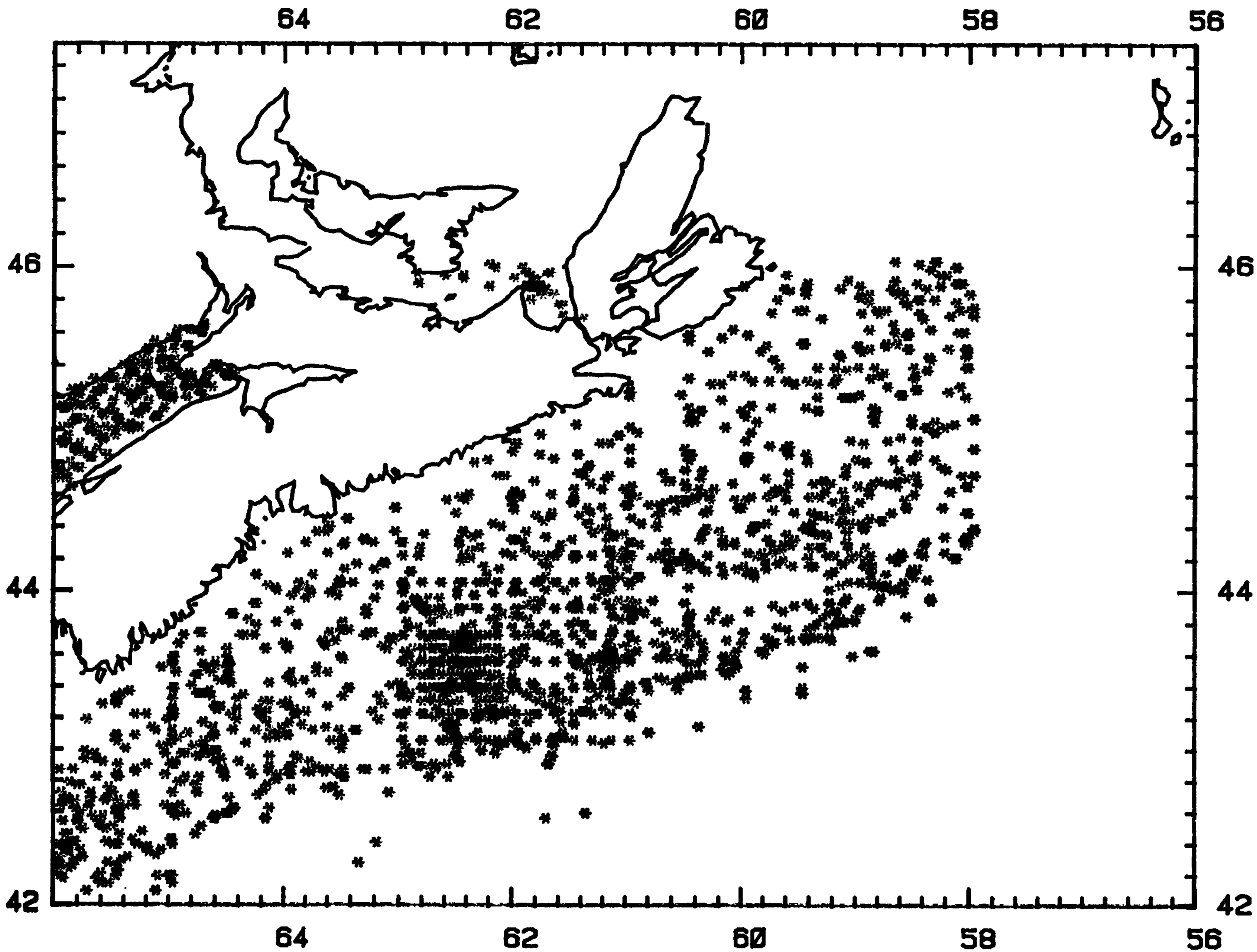

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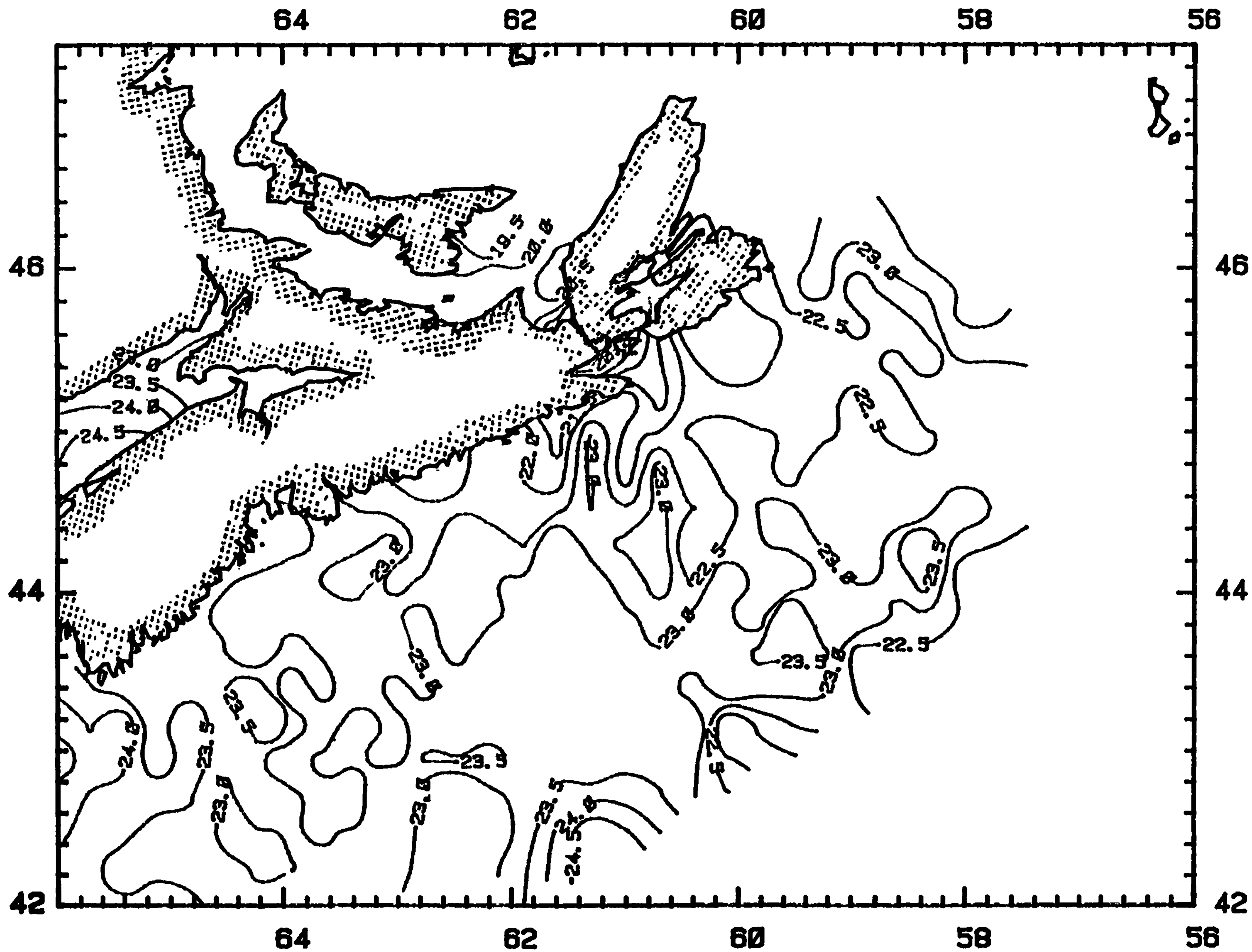

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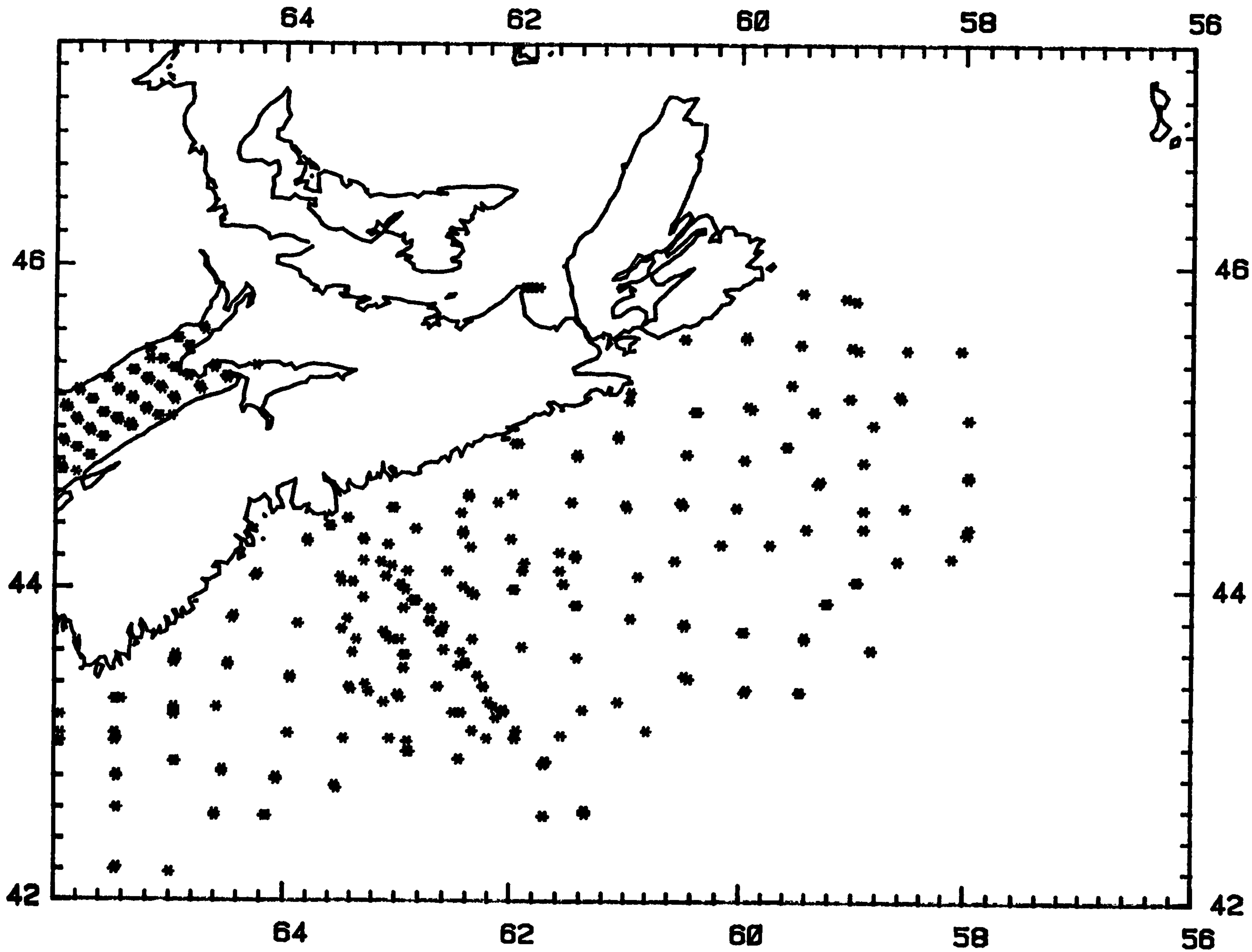

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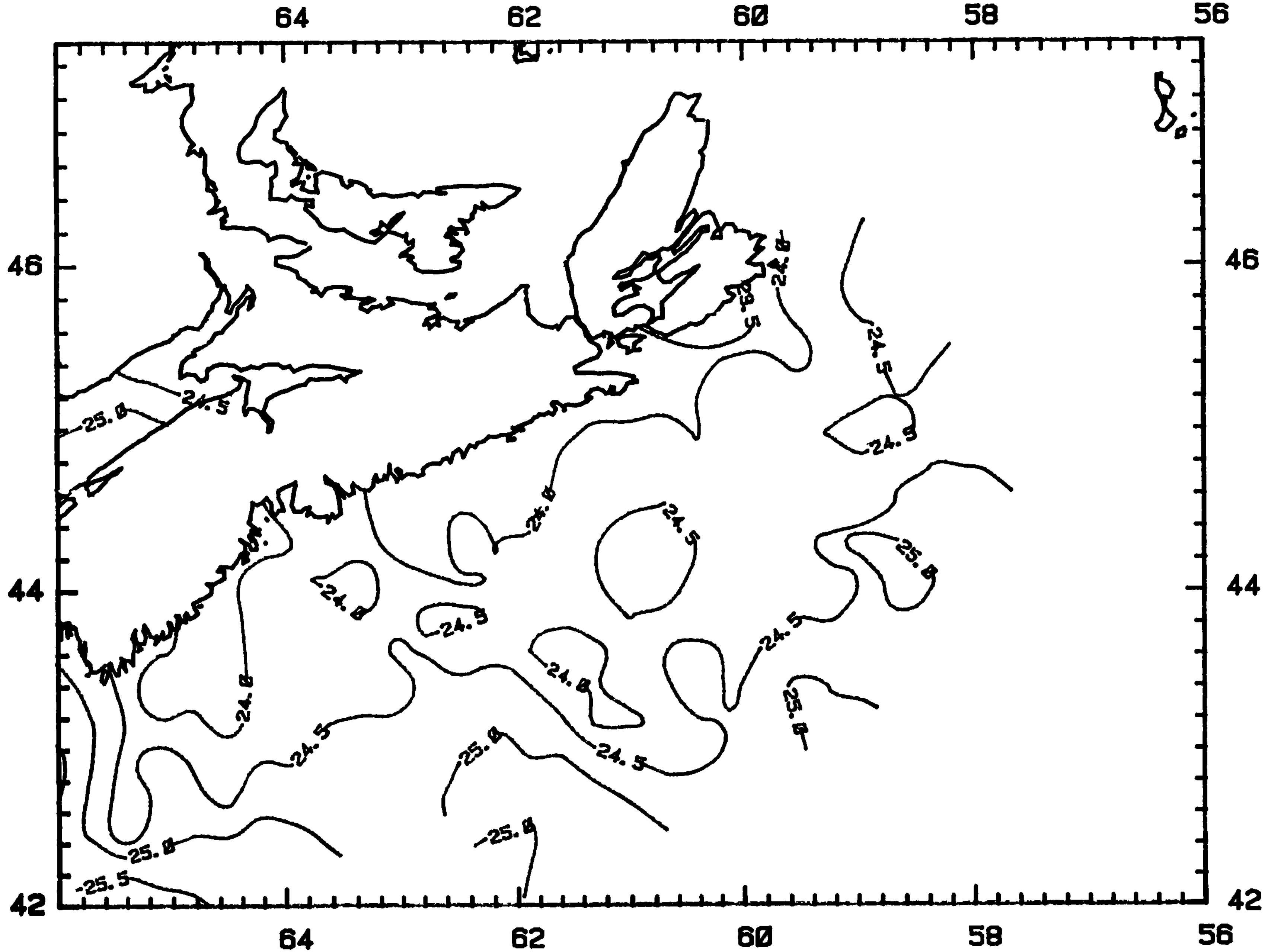

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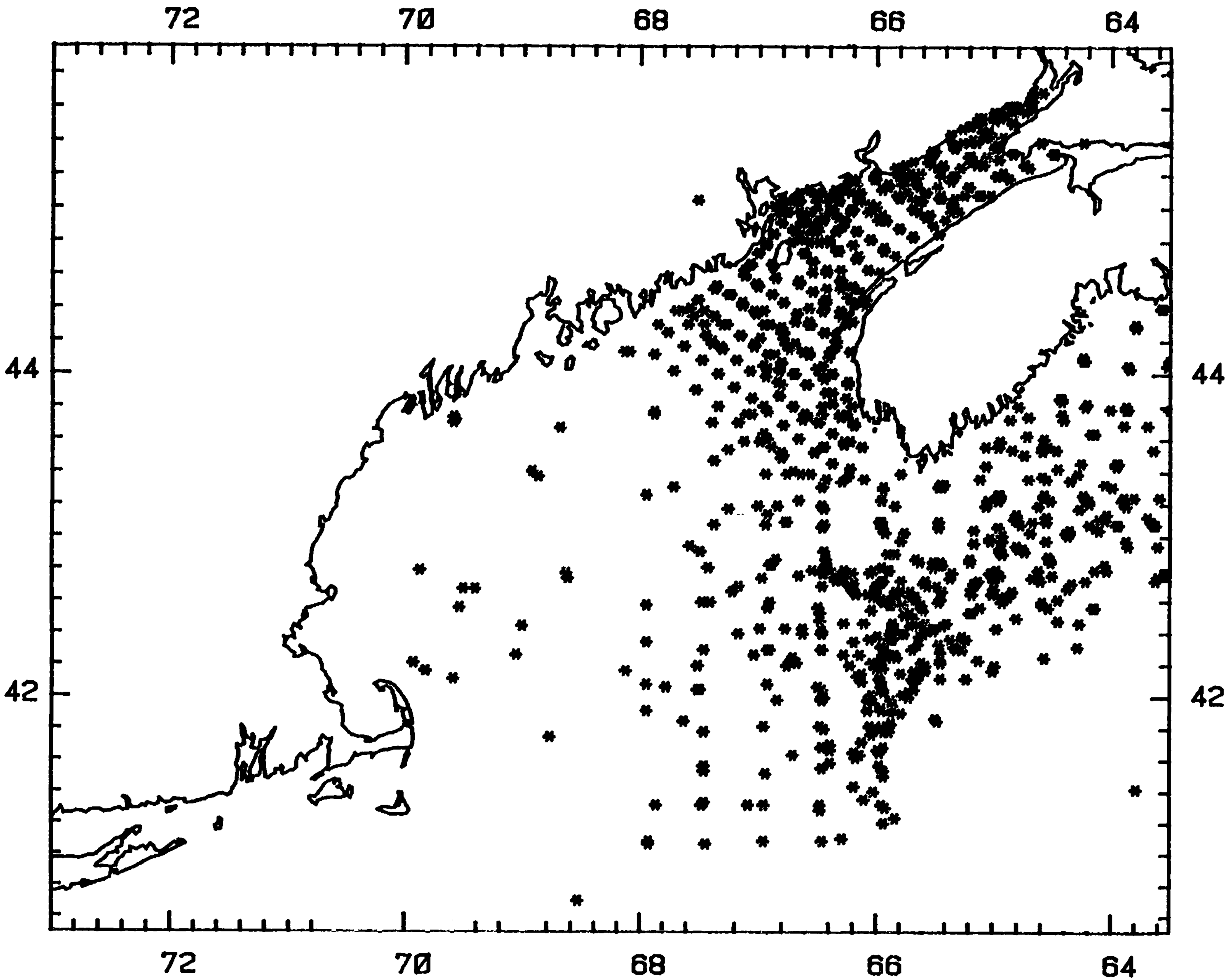
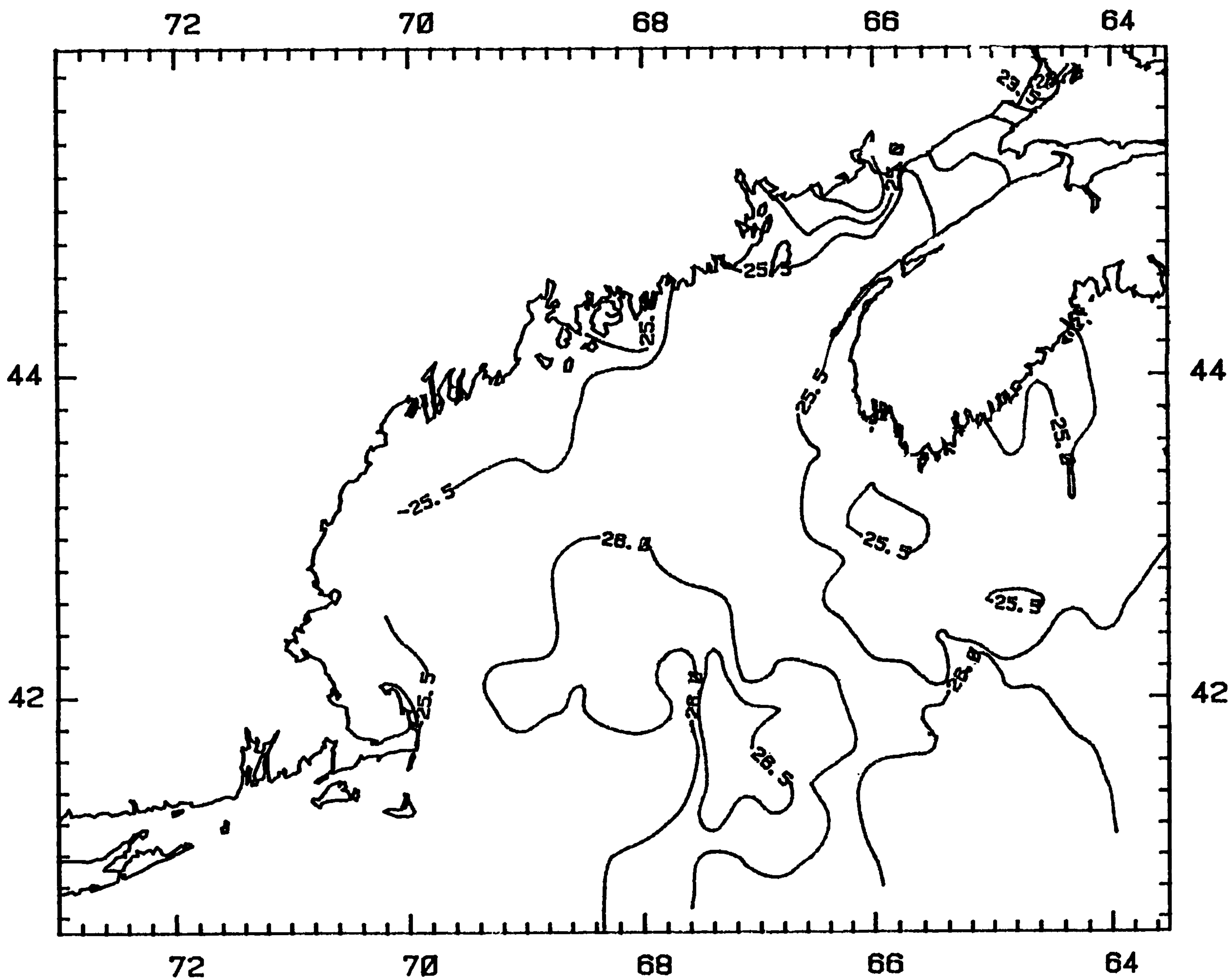
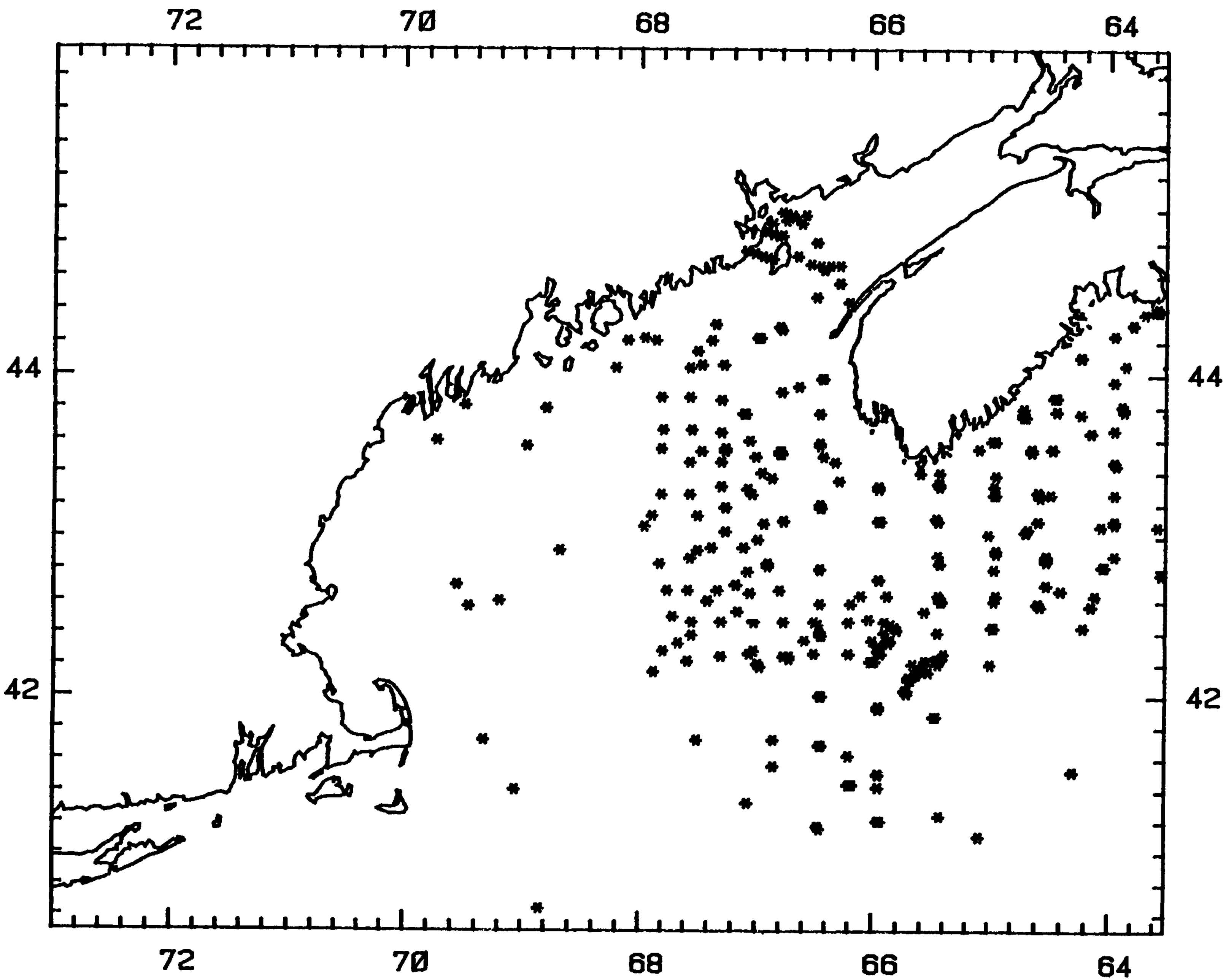


GULF OF MAINE, BAY OF FUNDY - Sample Locations, January to April



GULF OF MAINE, BAY OF FUNDY - Contoured Surface Density, January to April



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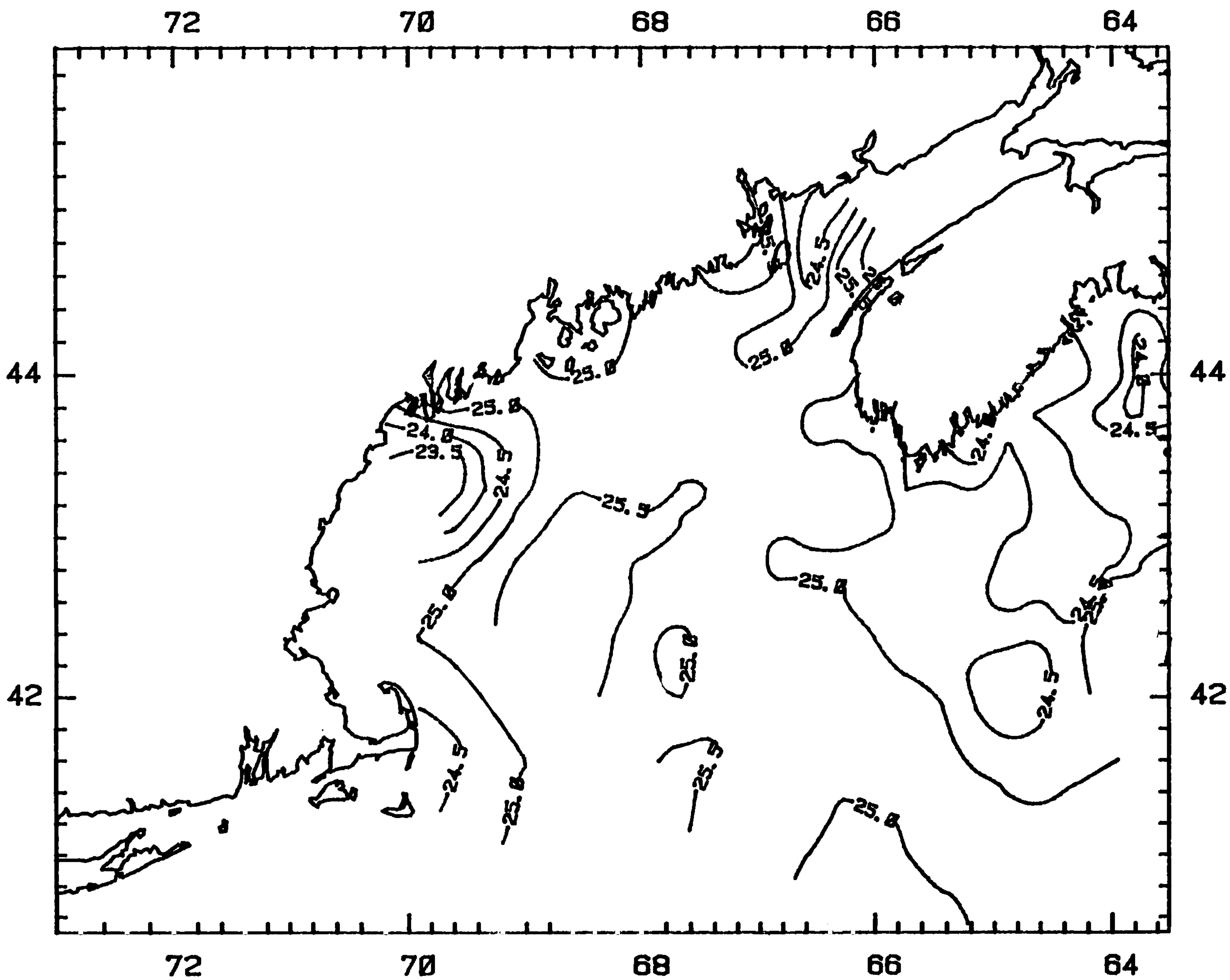
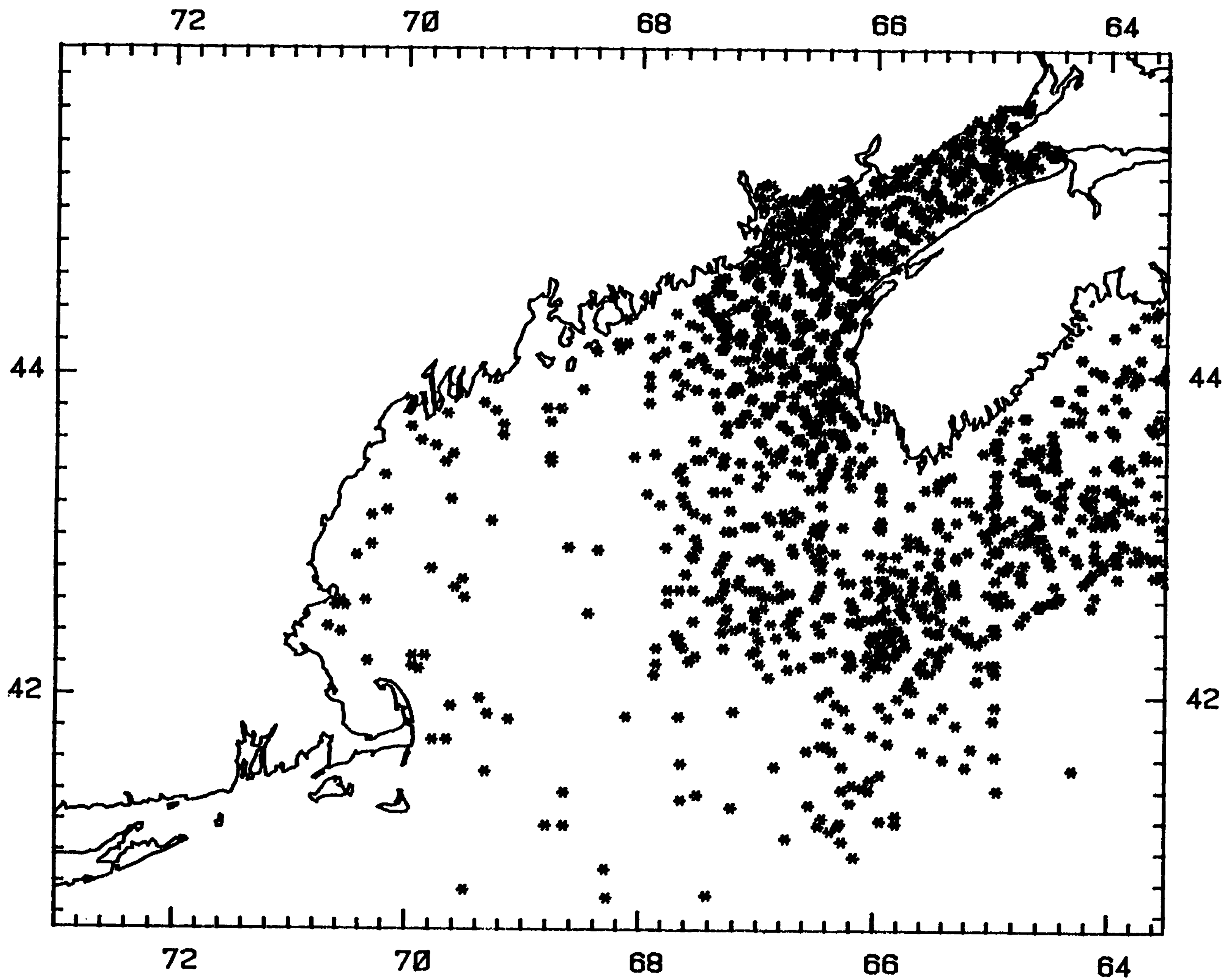


GULF OF MAINE, BAY OF FUNDY - Contoured Surface Density, May to June



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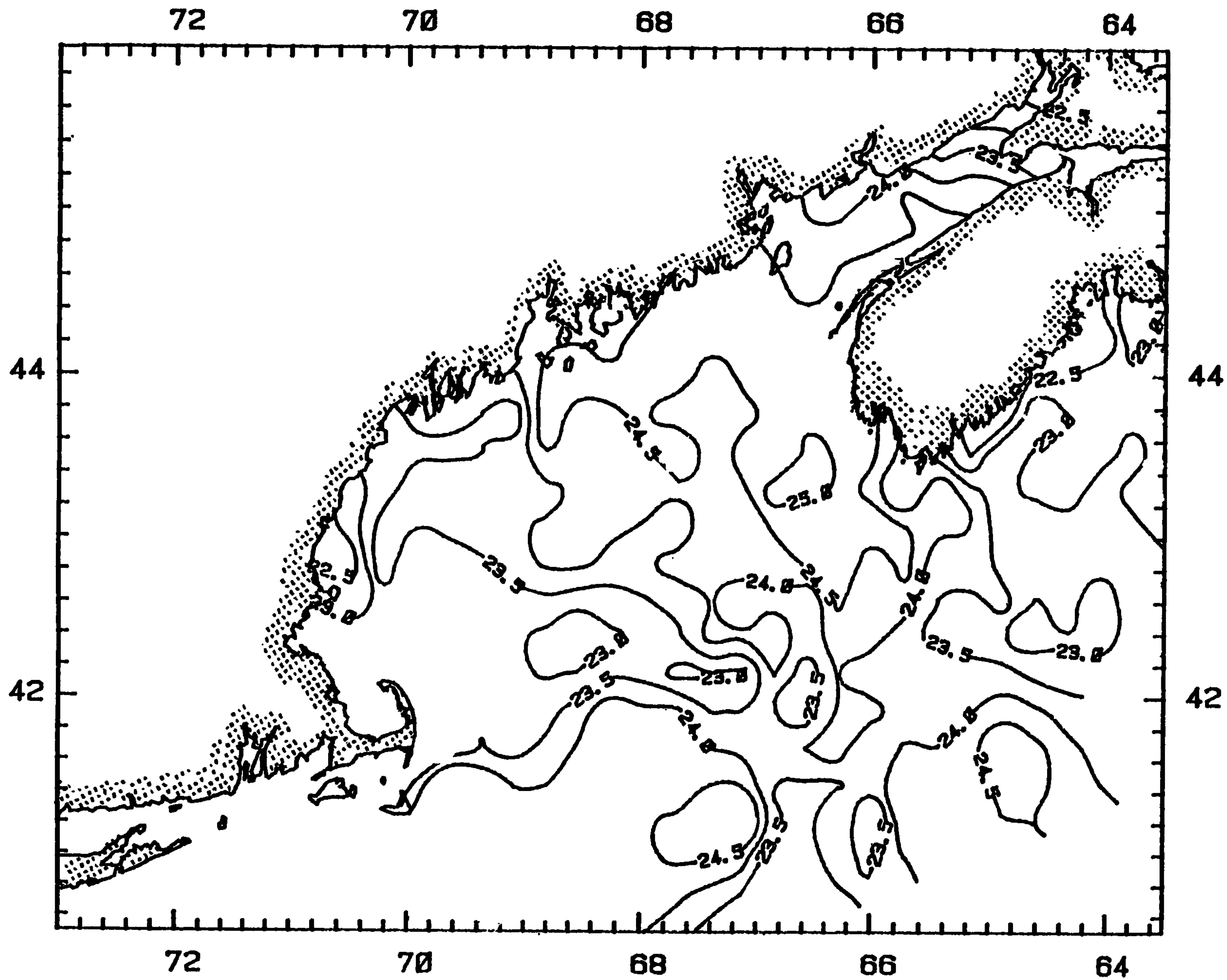

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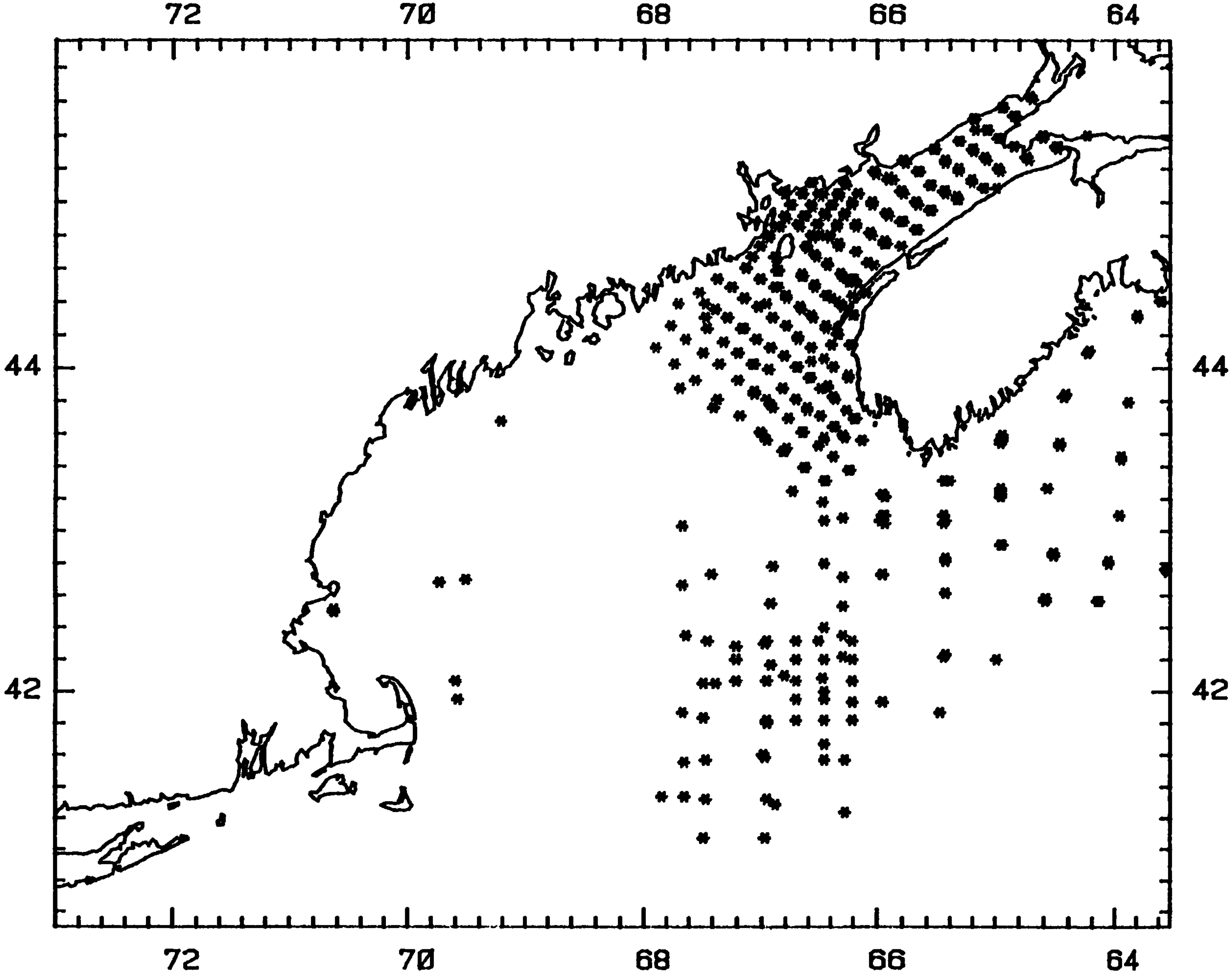

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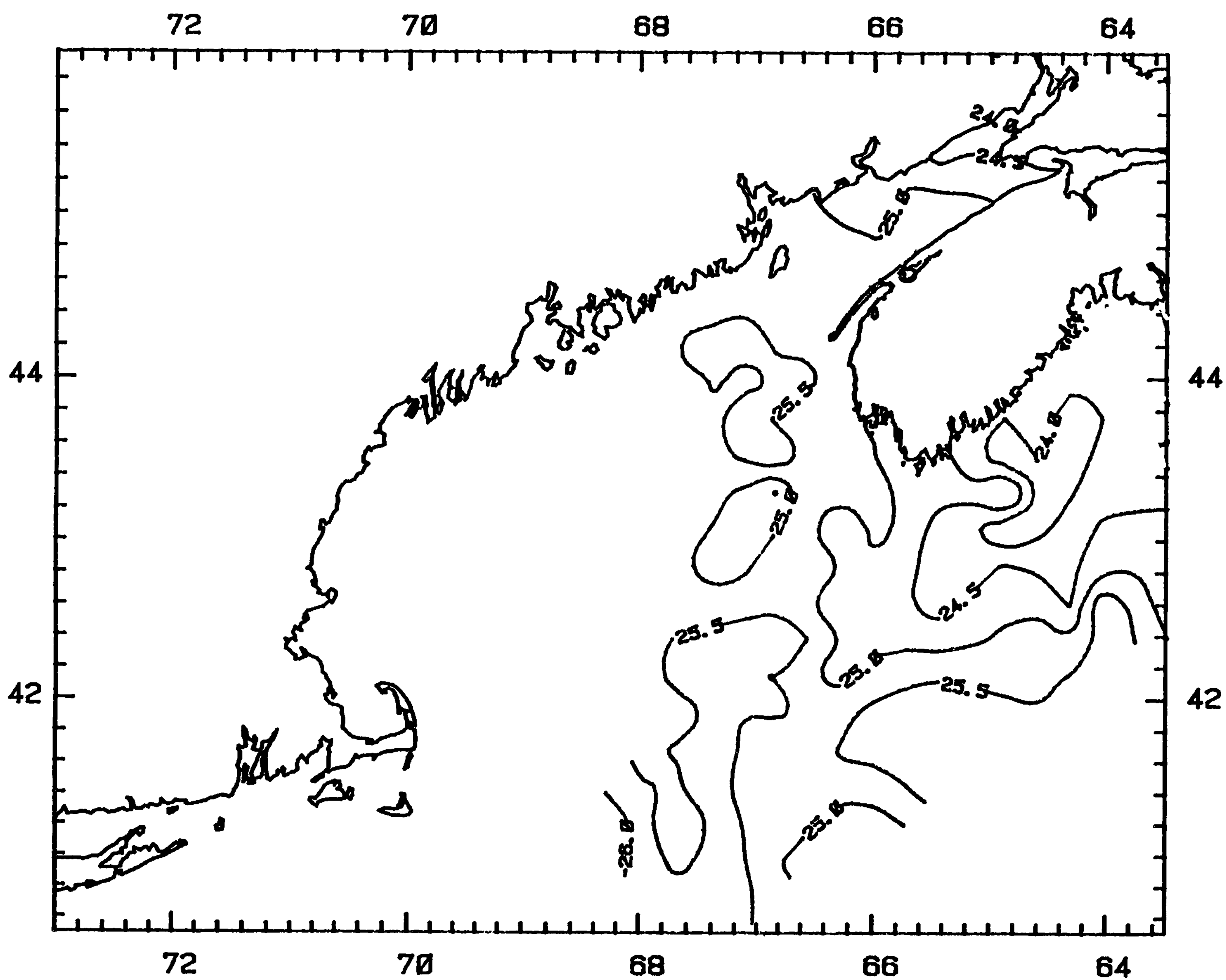
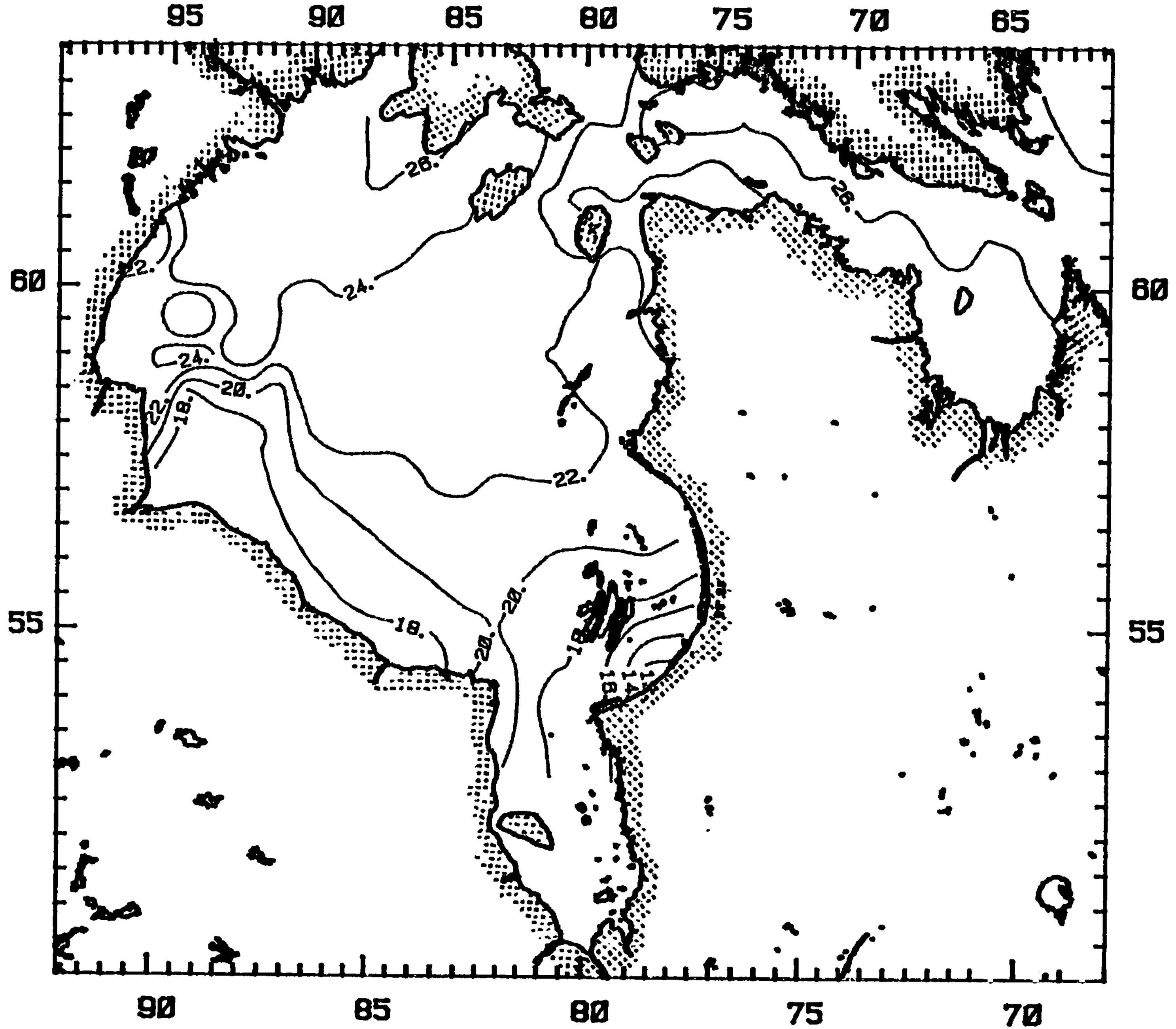


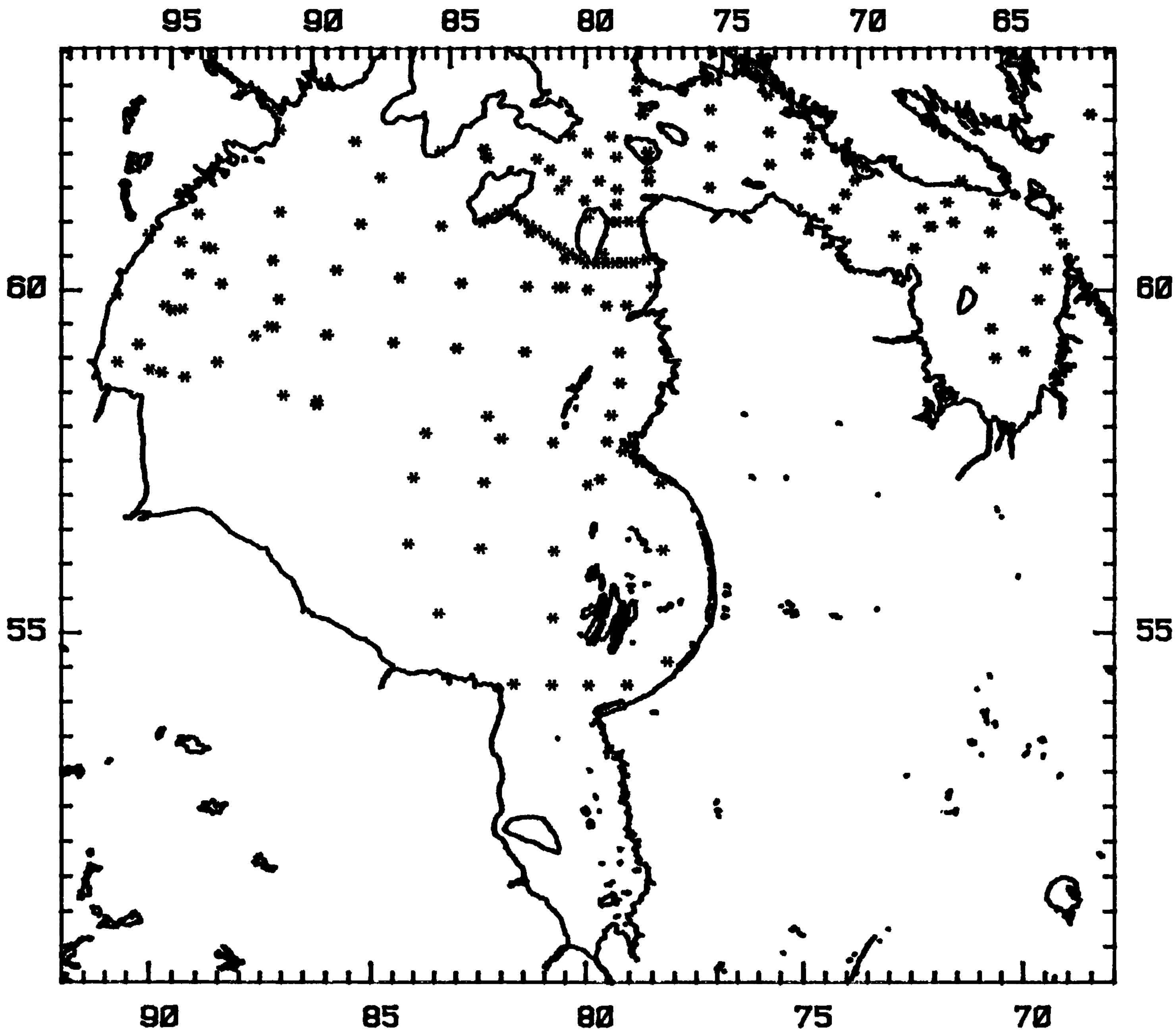
GULF OF MAINE, BAY OF FUNDY - Contoured Surface Density, November to December

APPENDIX II

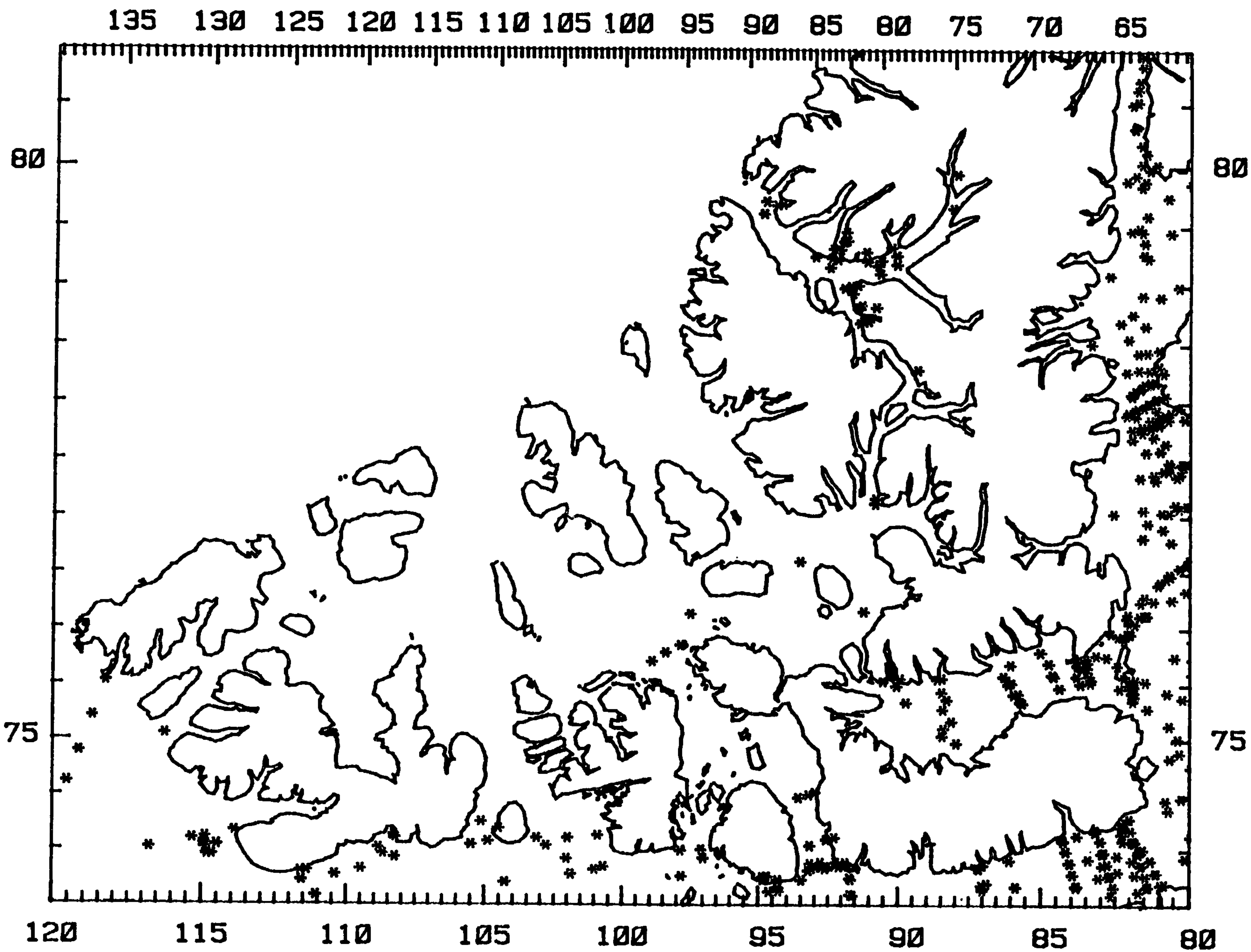
SURFACE WATER DENSITY: ARCTIC COAST



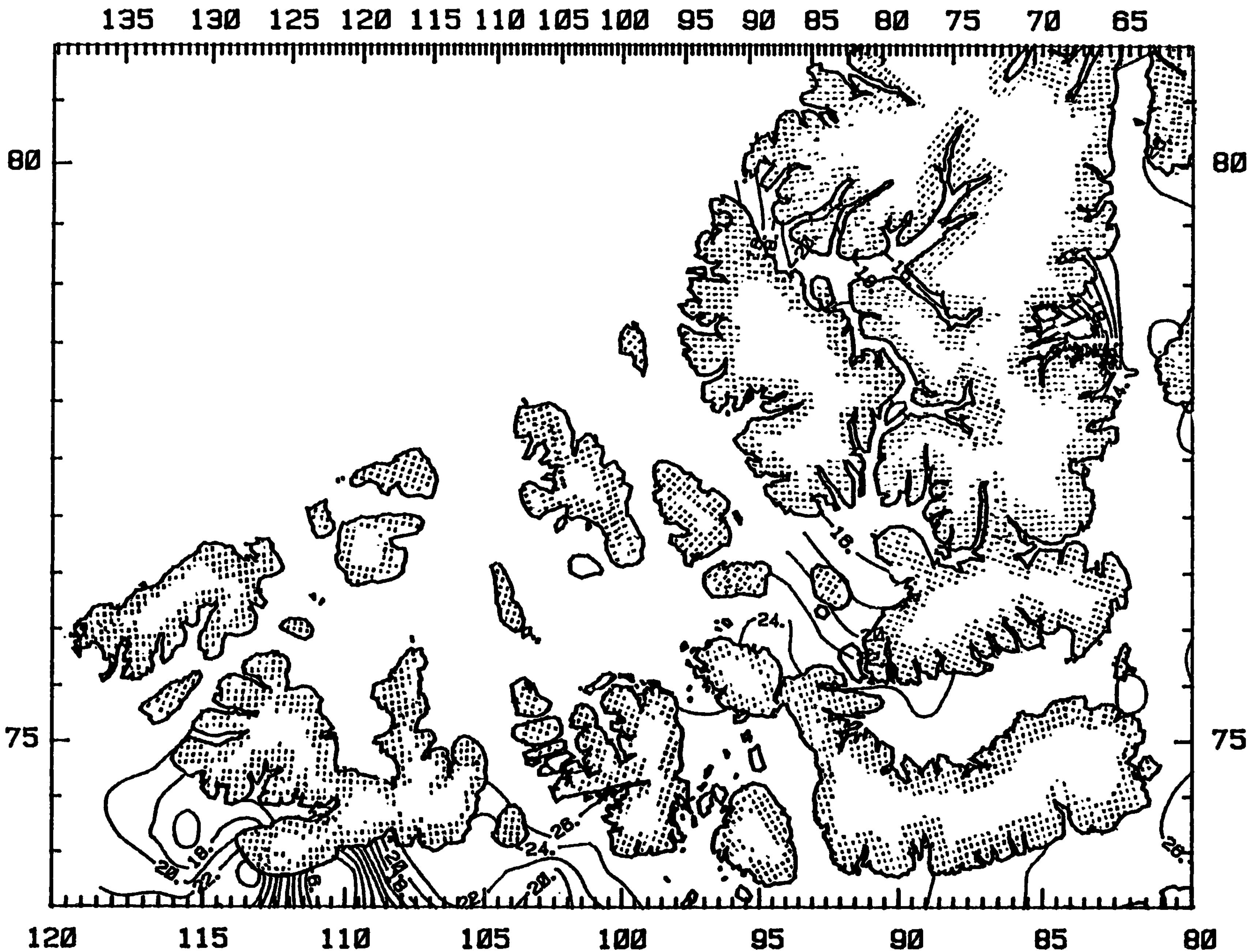
HUDSON BAY - Contoured Surface Density, Open-Water Season



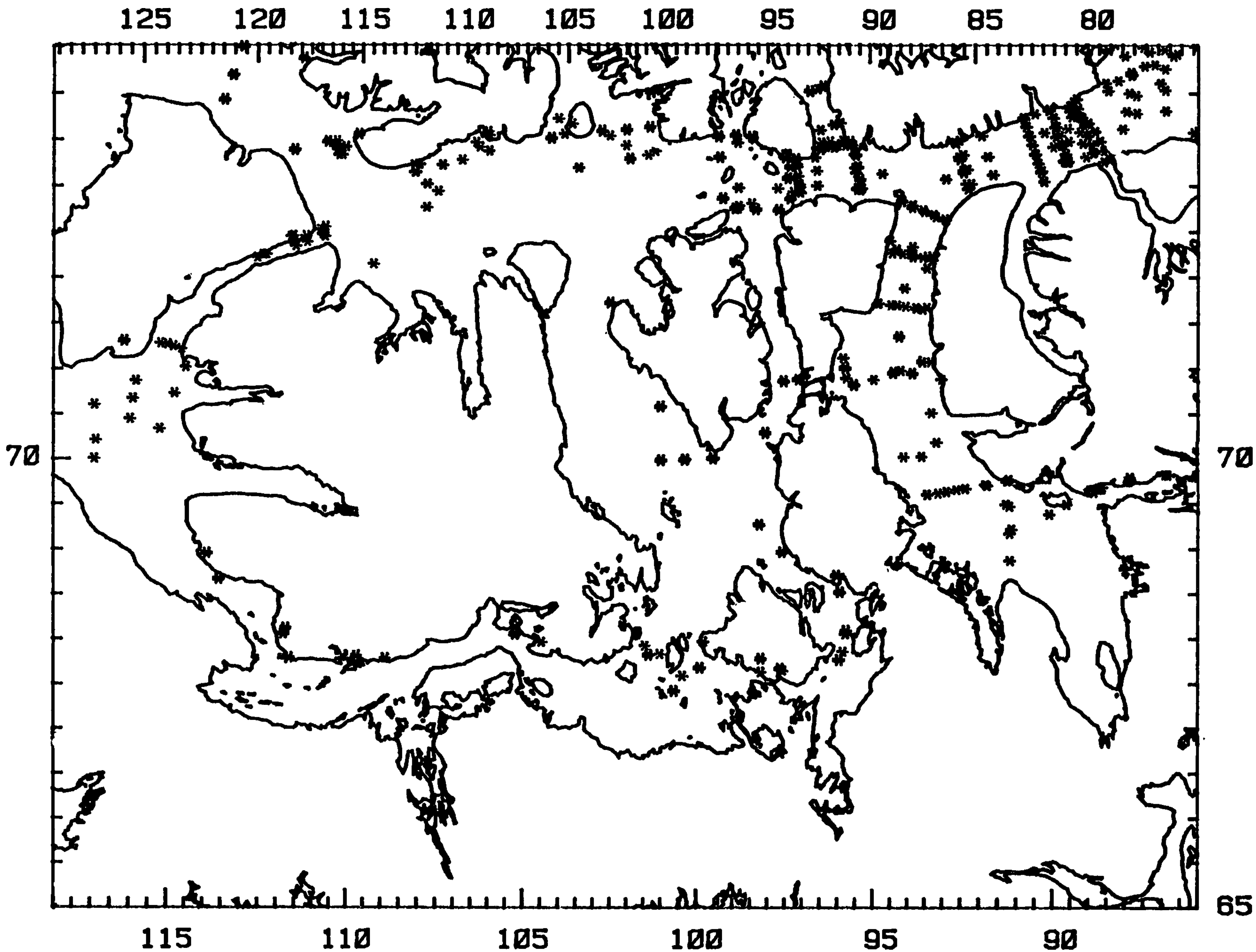
HUDSON BAY - Sample Locations, Open-Water Season



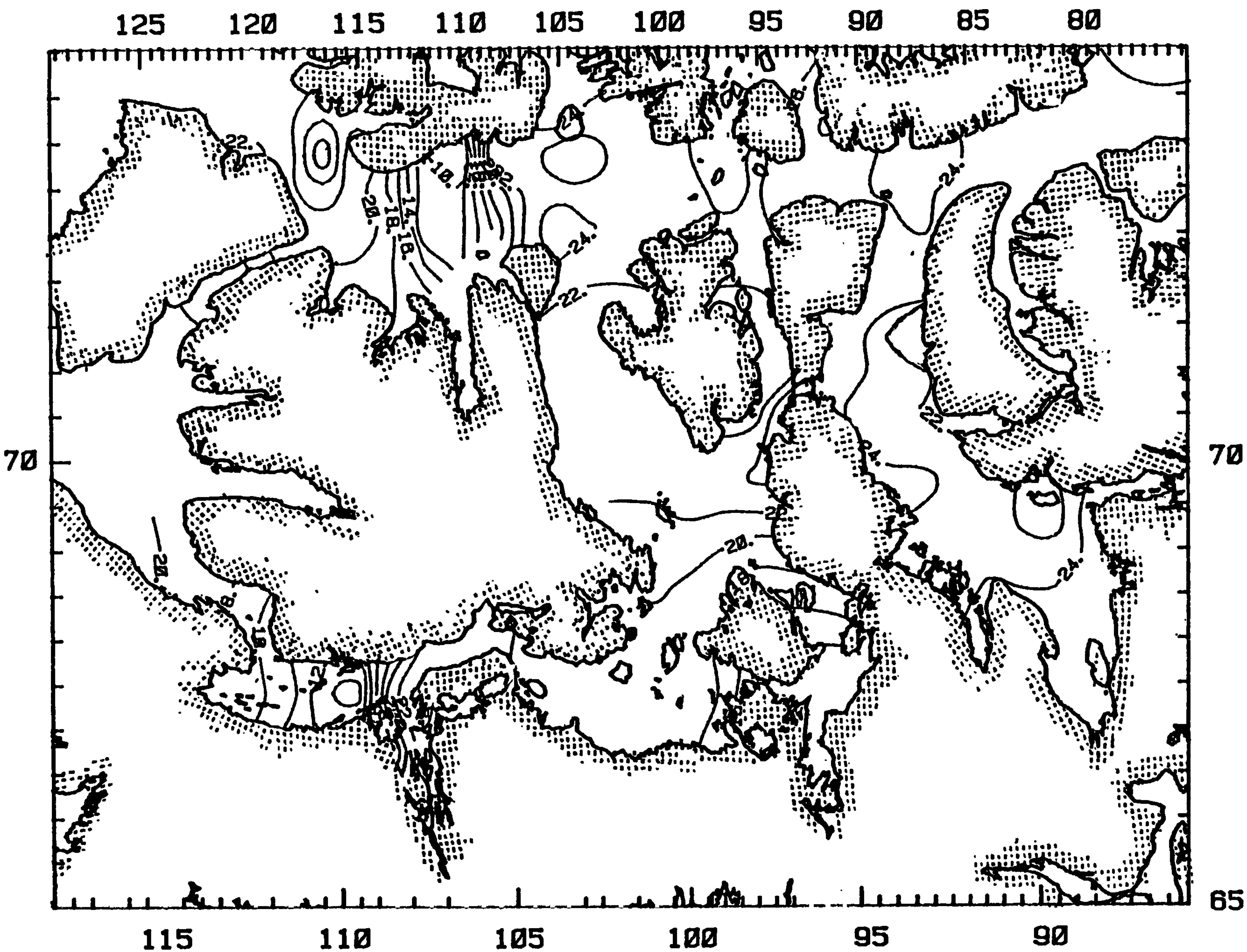
CANADIAN ARCHIPELAGO, NORTHERN STRAITS - Sample Locations, Open-Water Season



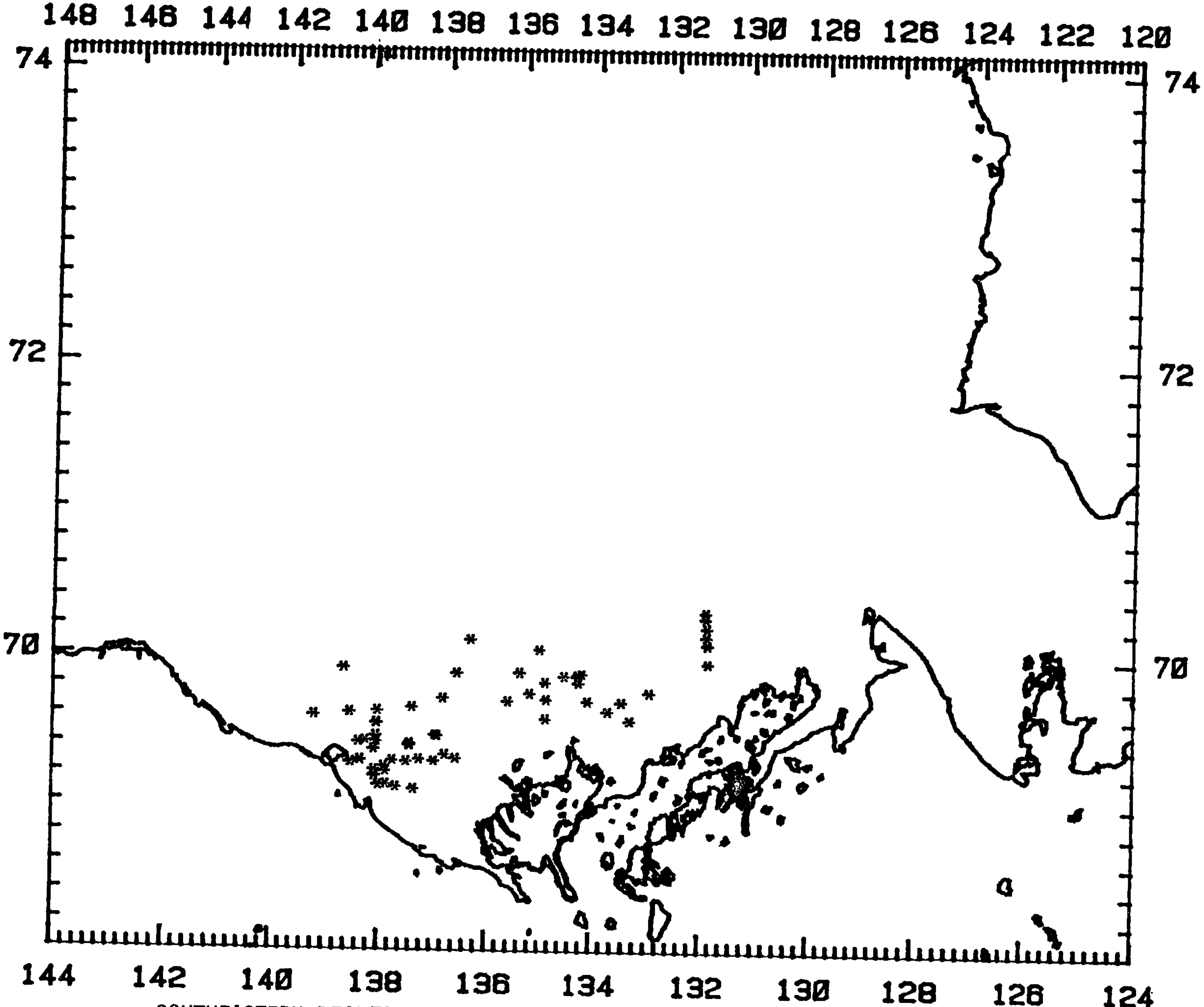
CANADIAN ARCHIPELAGO, NORTHERN STRAITS - Contoured Surface Density, Open-Water Season



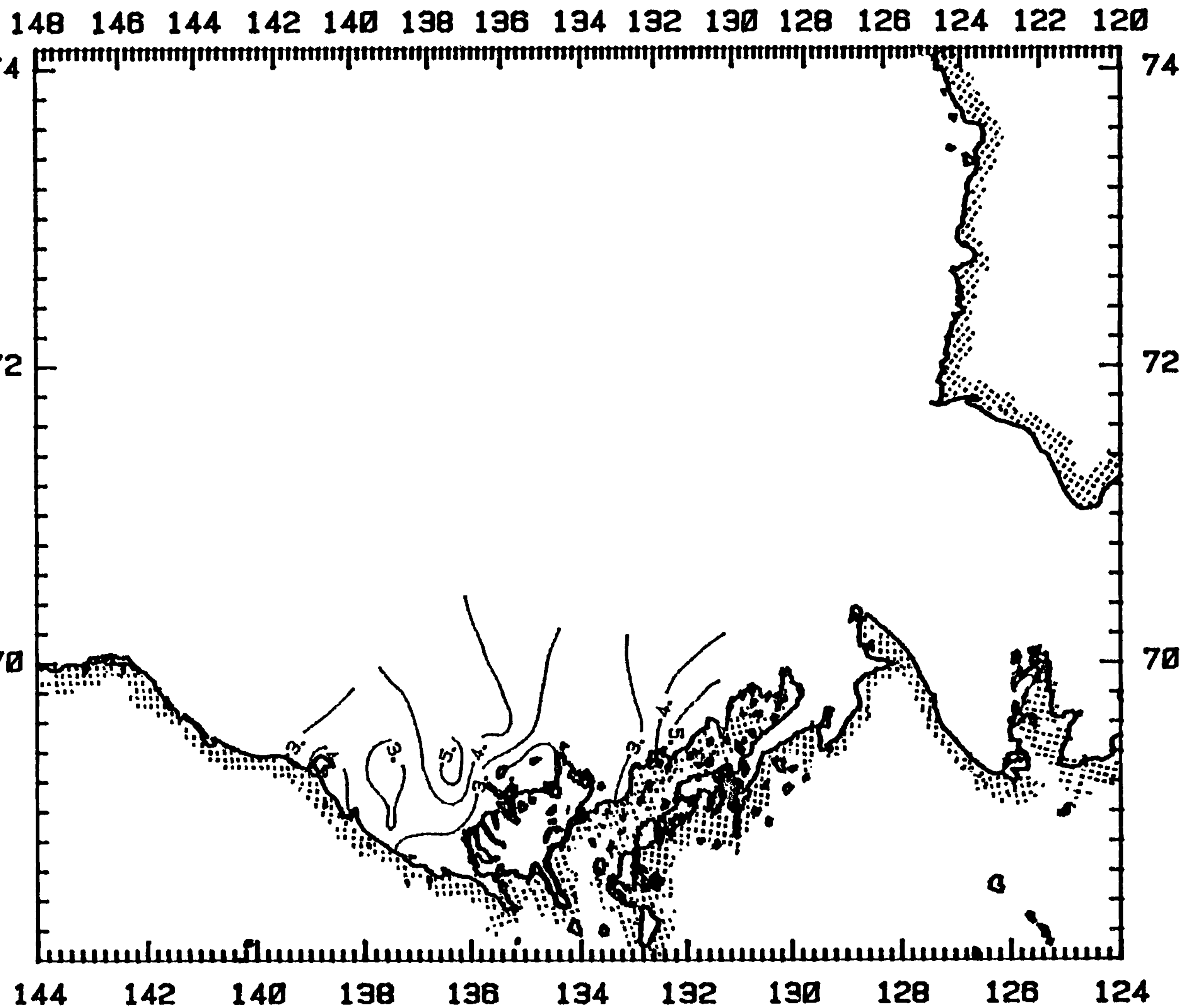
CANADIAN ARCHIPELAGO, SOUTHERN STRAITS AND NORTHWEST PASSAGE - Sample Locations, Open-Water Season



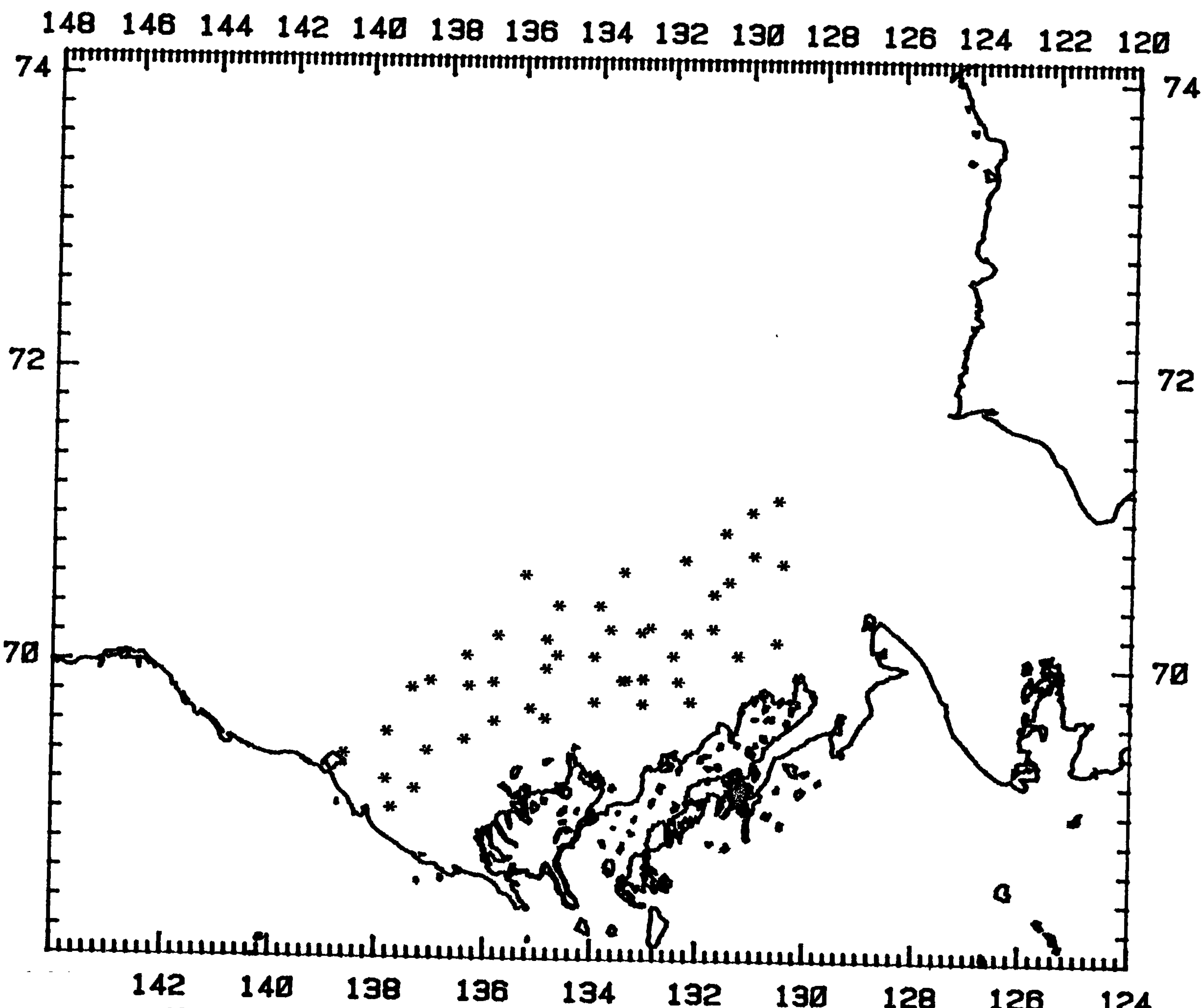
CANADIAN ARCHIPELAGO, SOUTHERN STRAITS AND NORTHWEST PASSAGE -
Sample Locations, Open-Water Season



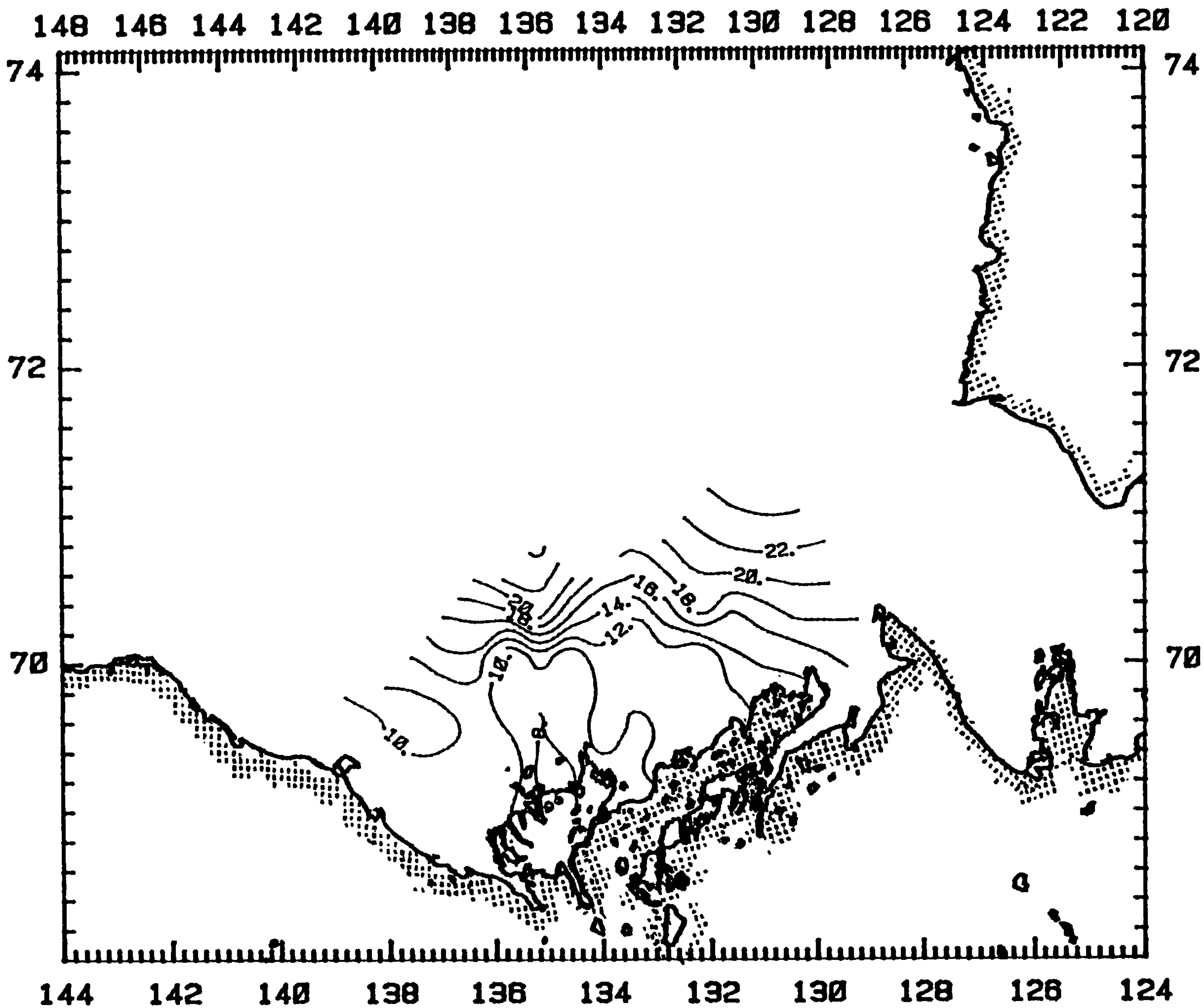
SOUTHEASTERN BEAUFORT SEA - Sample Locations, Open-Water Season 1974



SOUTHEASTERN BEAUFORT SEA - Contoured Surface Density, Open-Water Season, 1974



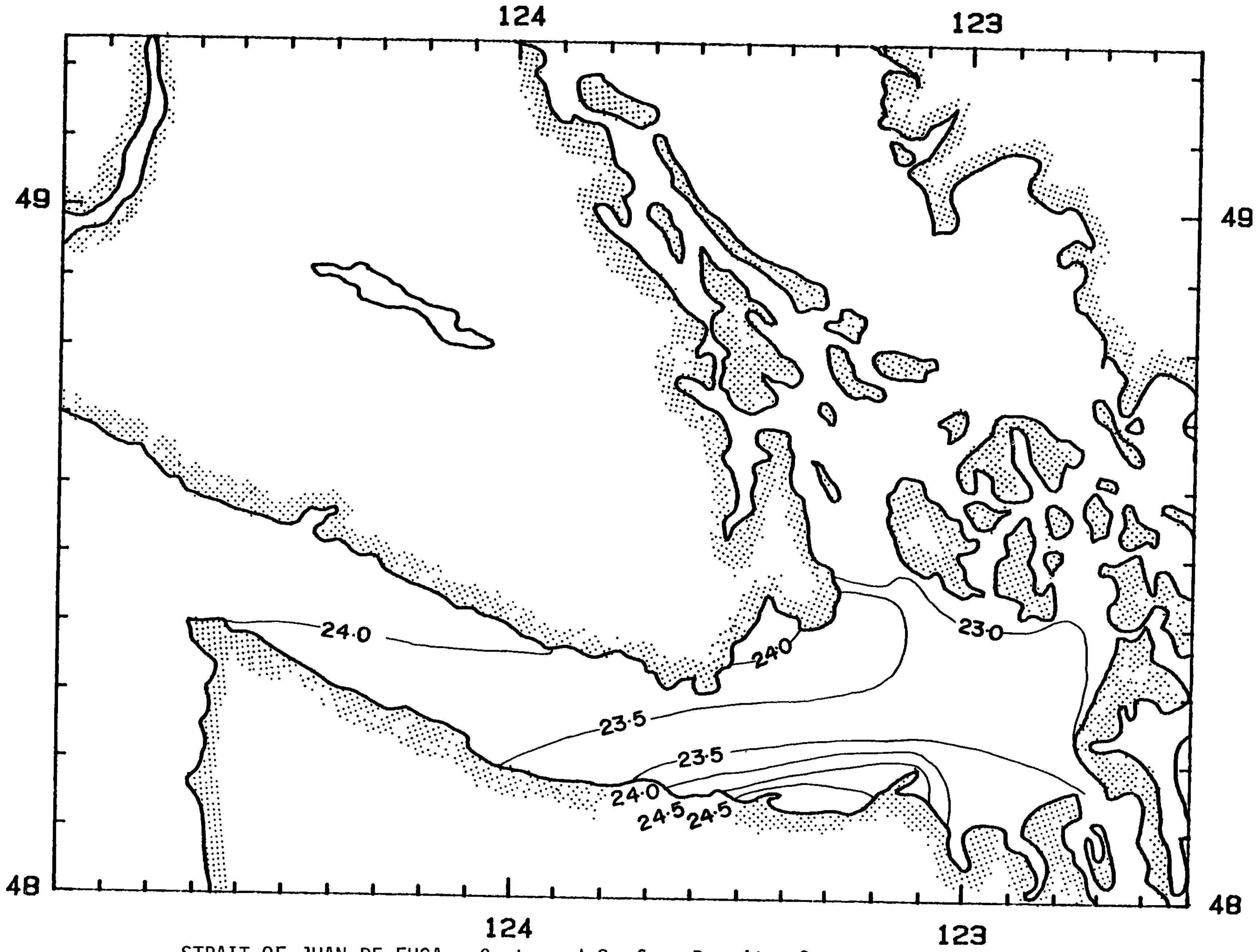
SOUTHEASTERN BEAUFORT SEA - Sample Locations, Open-Water Season 1975



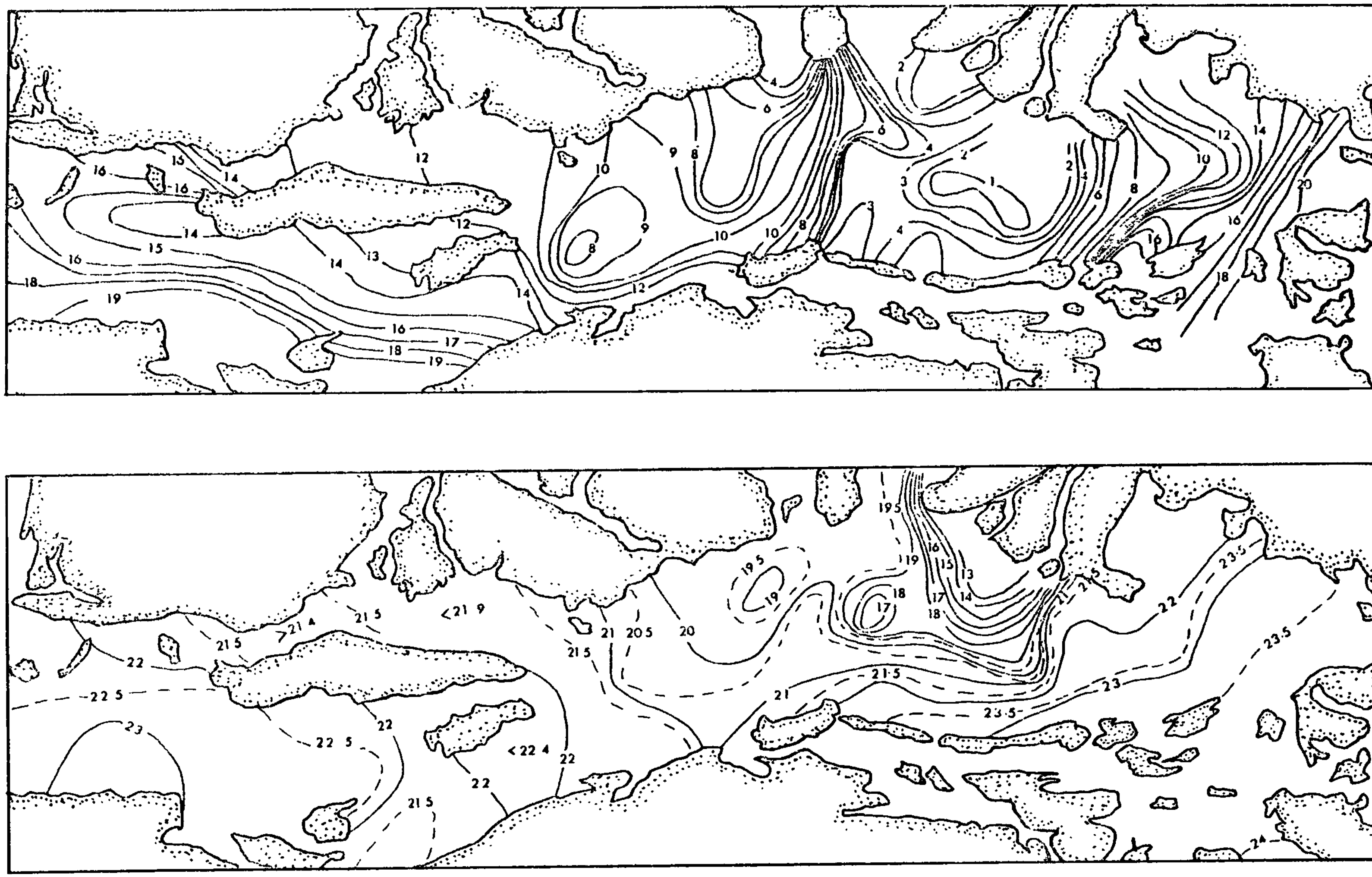
SOUTHEASTERN BEAUFORT SEA - Conto ured Surface Density, Open-Water Season 1975

APPENDIX III

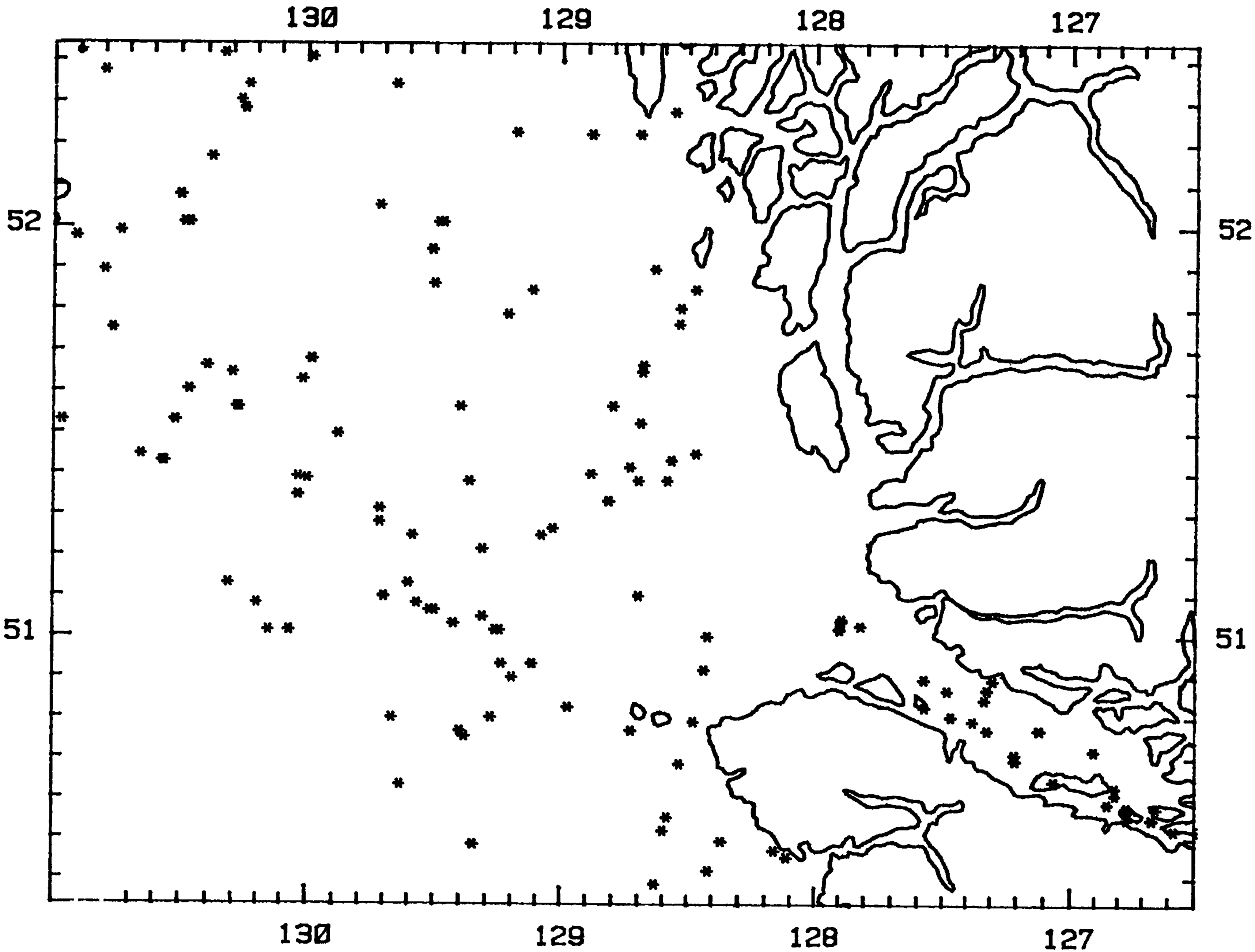
SURFACE WATER DENSITY: PACIFIC COAST



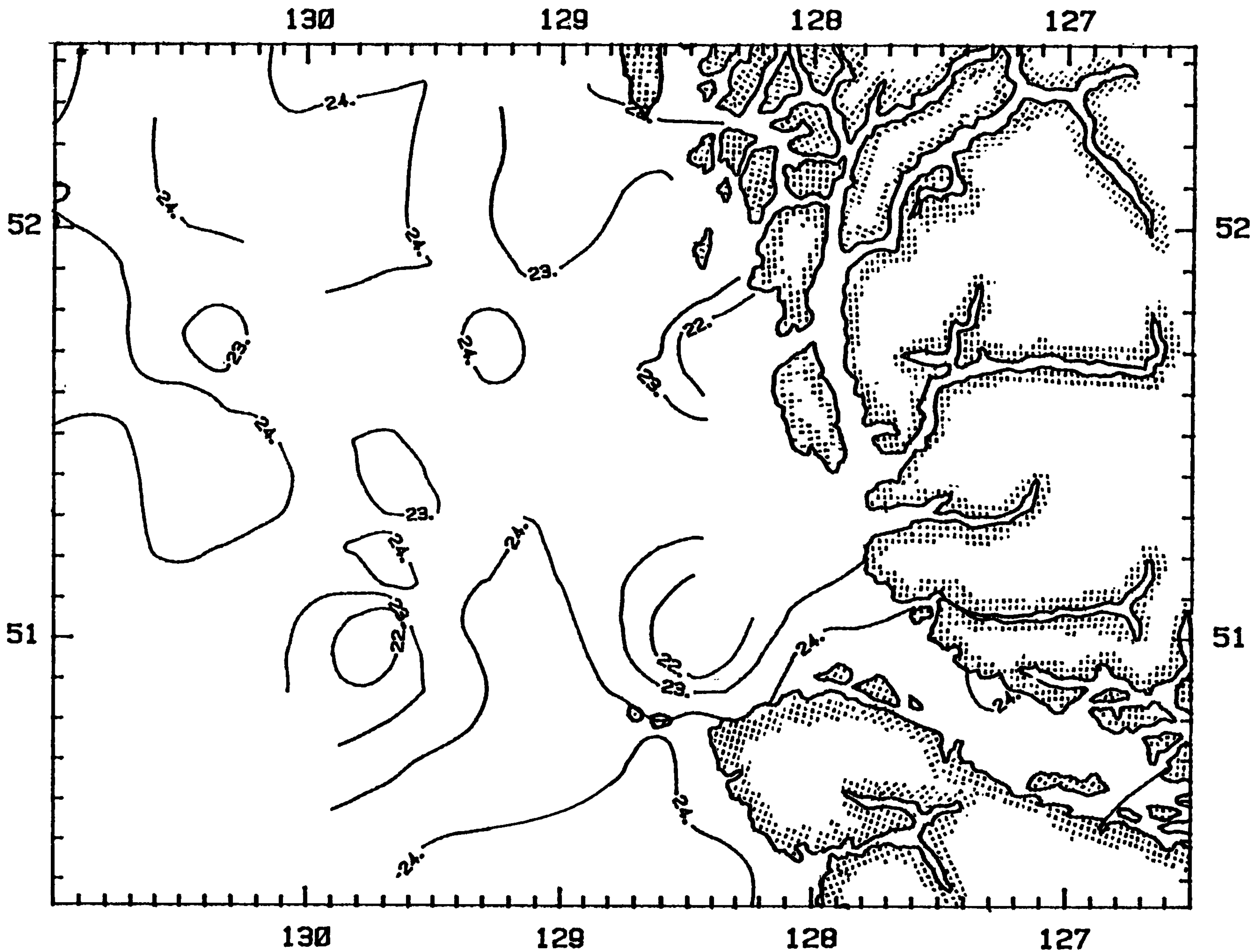
STRAIT OF JUAN DE FUCA - Contoured Surface Density, Summer



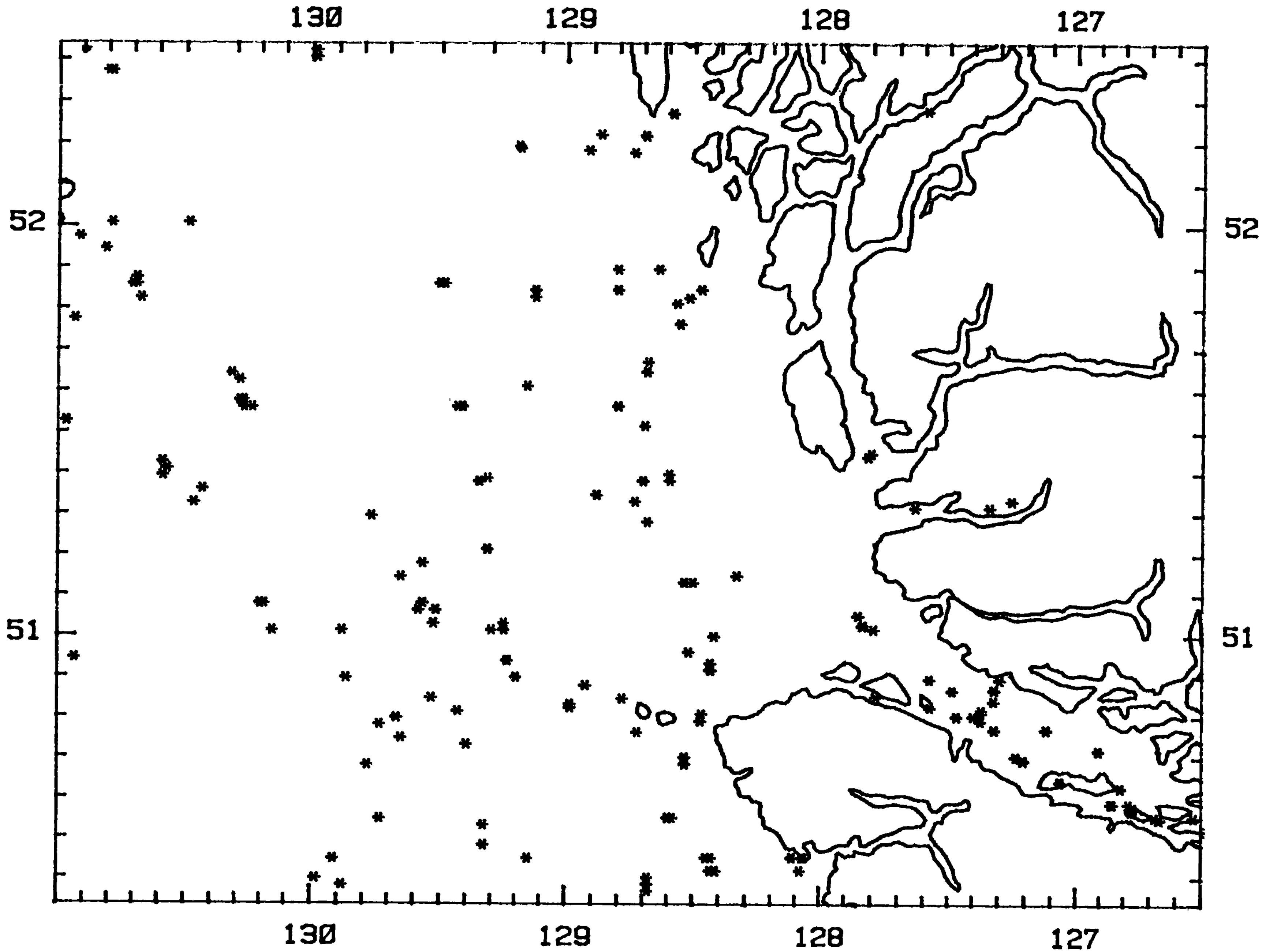
STRAIT OF GEORGIA - Contoured Surface Density, Upper - June; Lower - February



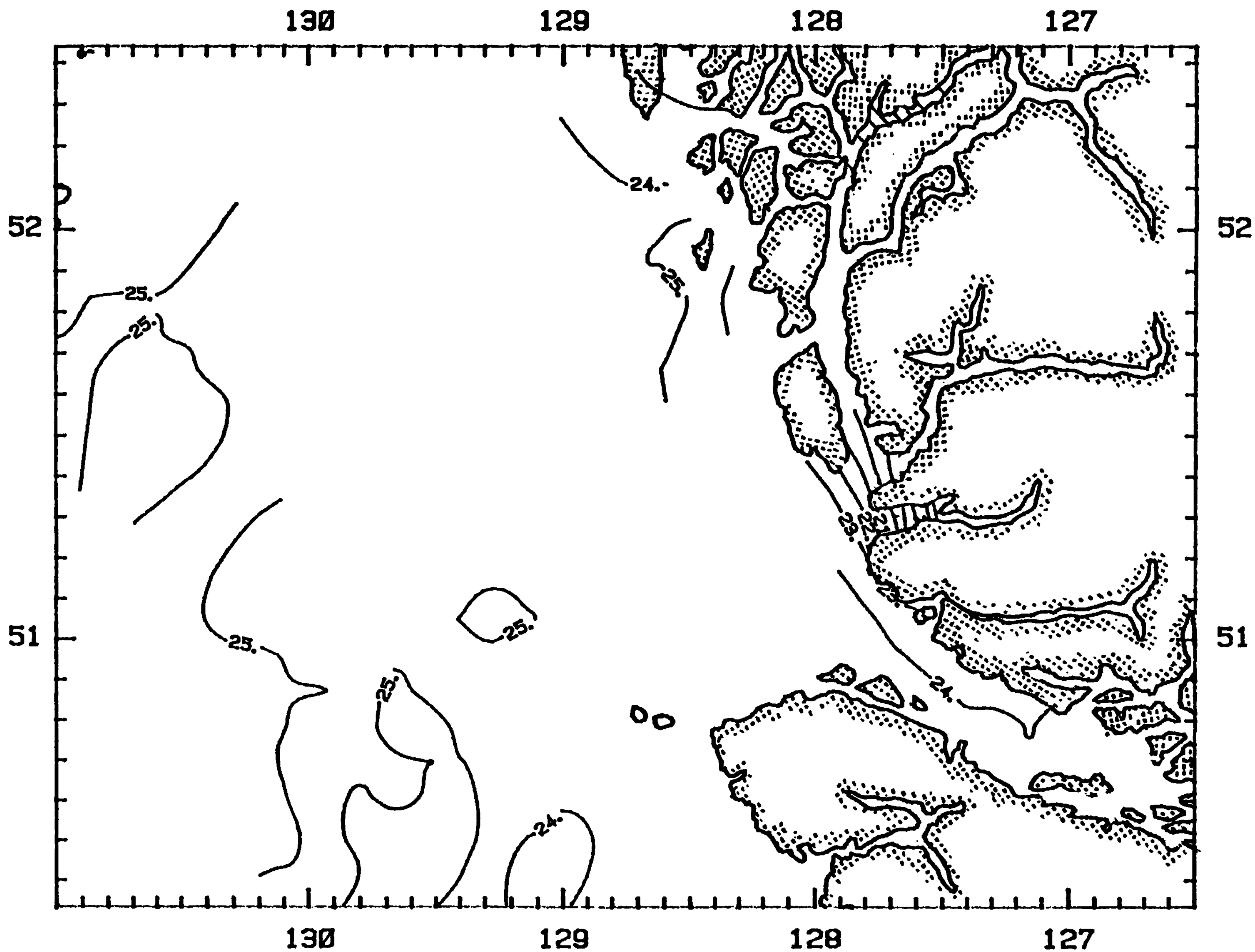
QUEEN CHARLOTTE STRAIT AND SOUND - Sample Locations, May to September



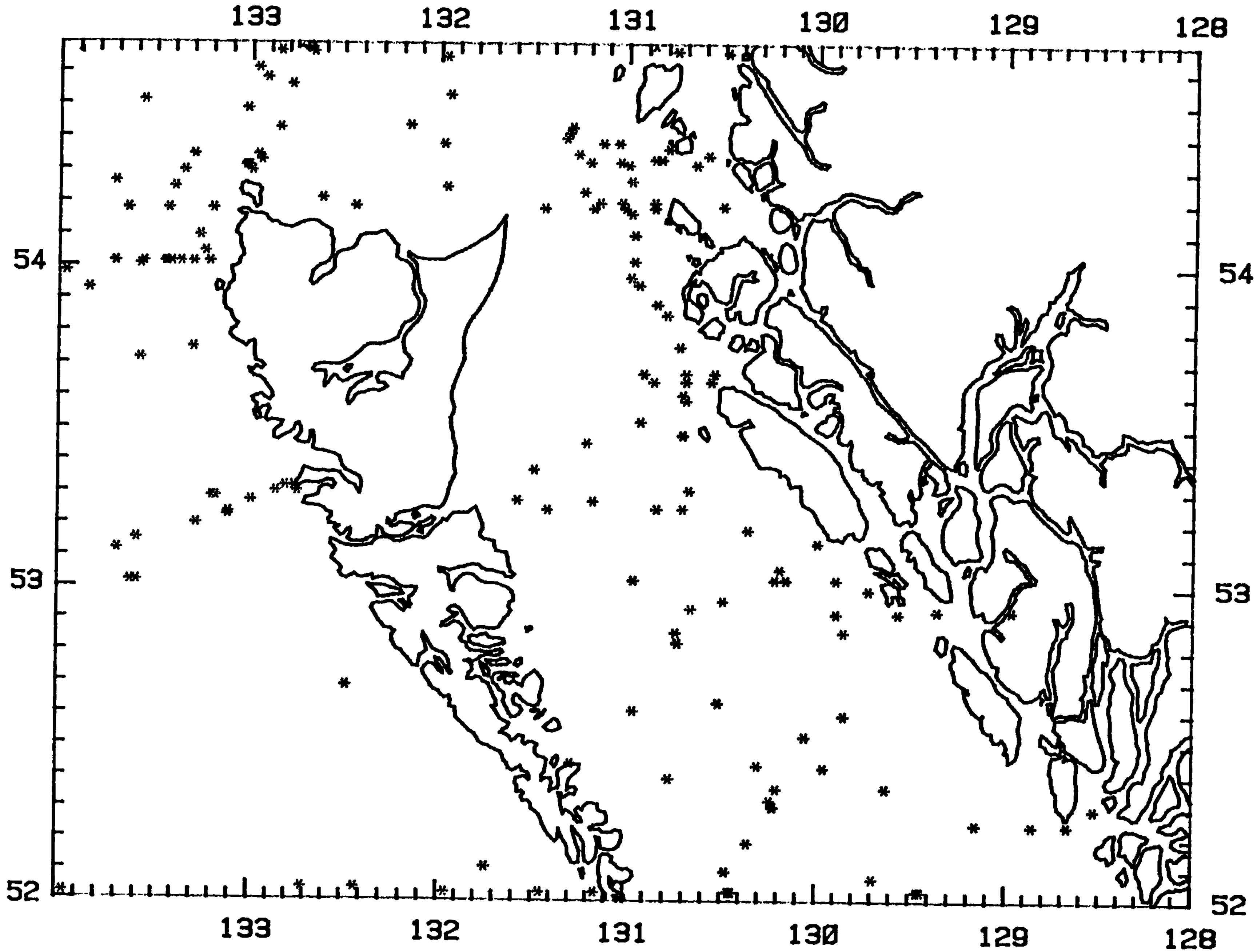
QUEEN CHARLOTTE STRAIT AND SOUND - Contoured Surface Density, May to September



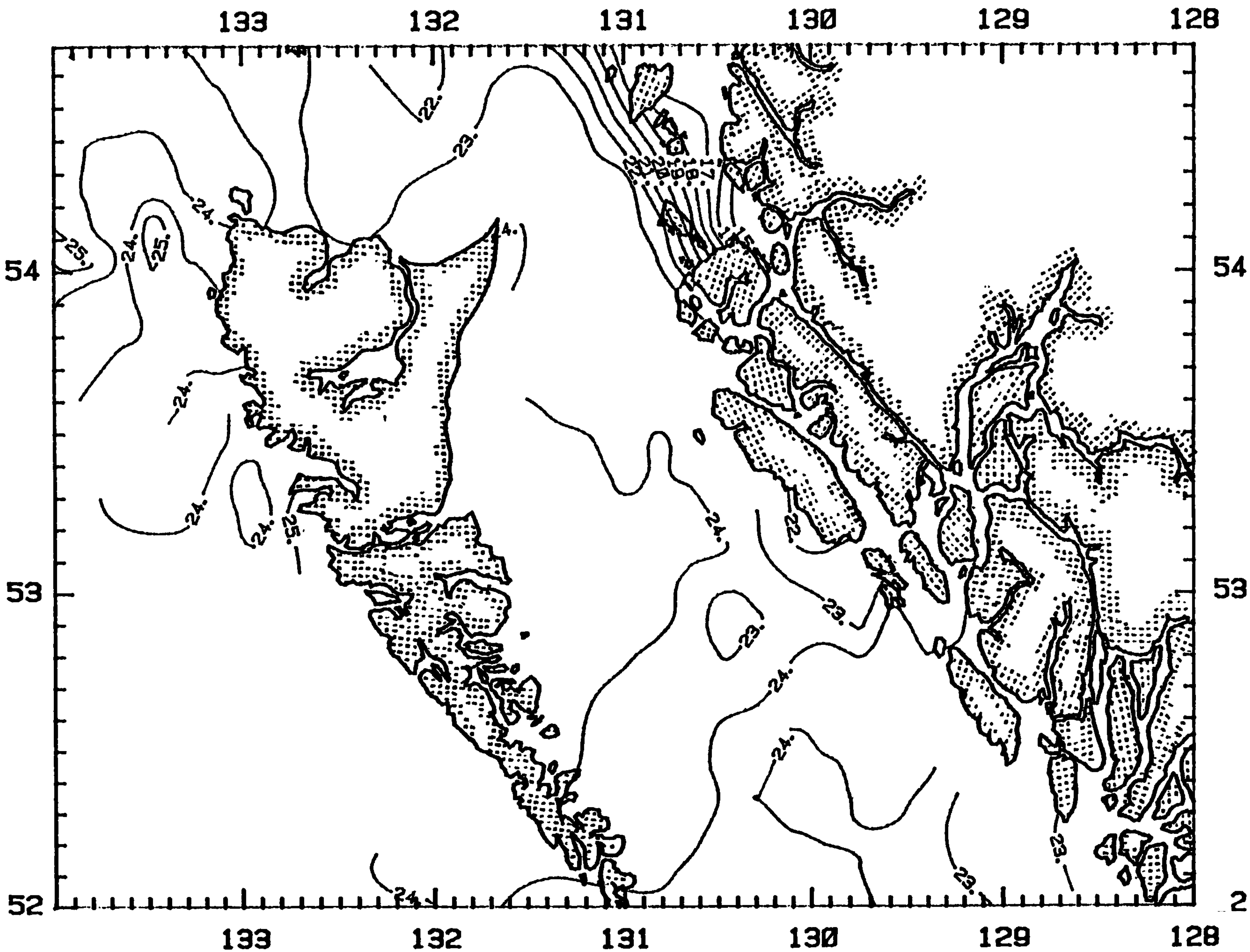
QUEEN CHARLOTTE STRAIT AND SOUND - Sample Locations, October to April



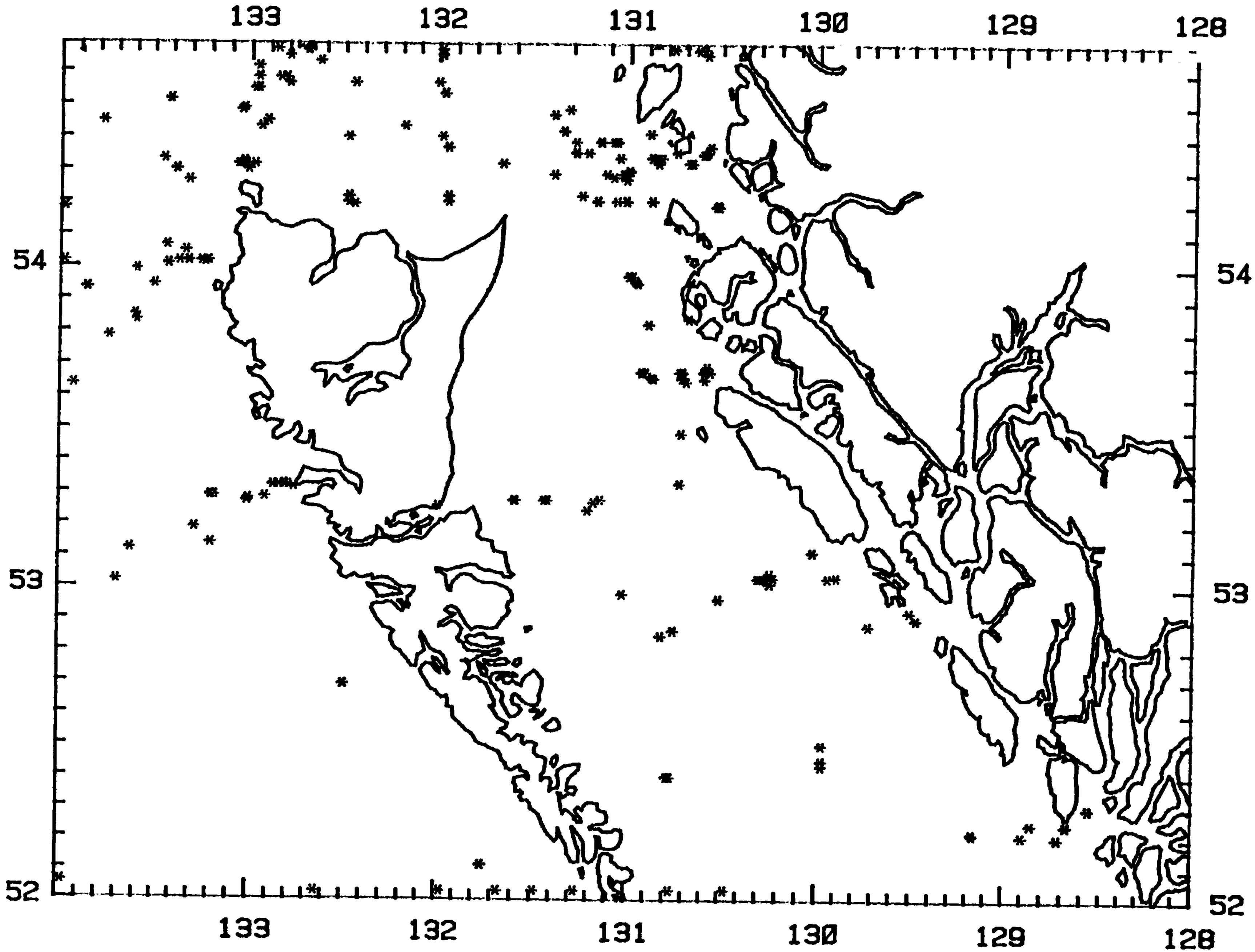
QUEEN CHARLOTTE STRAIT AND SOUND - Contoured Surface Density, October to April



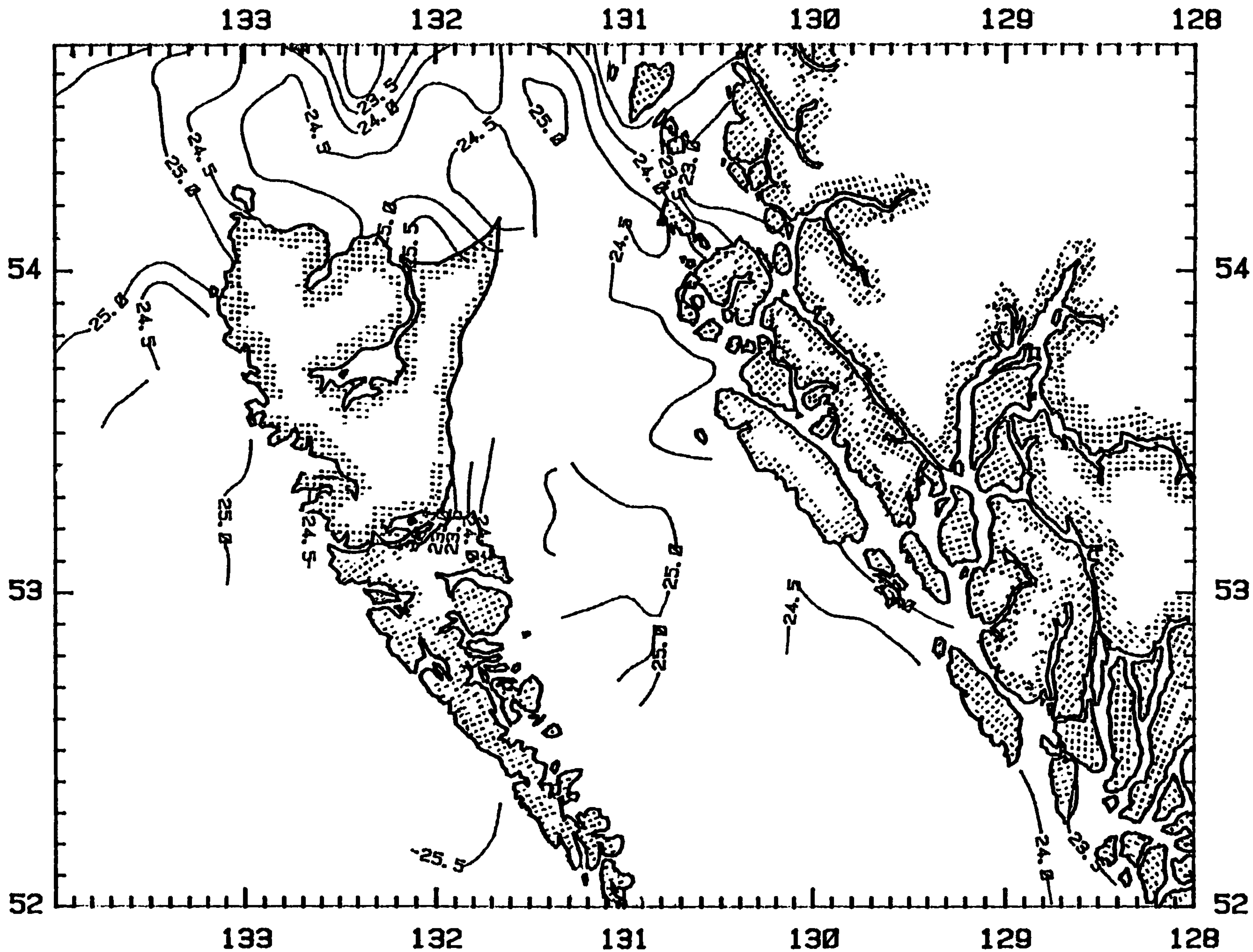
HECATE STRAIT, DIXON ENTRANCE - Sample Locations, May to September



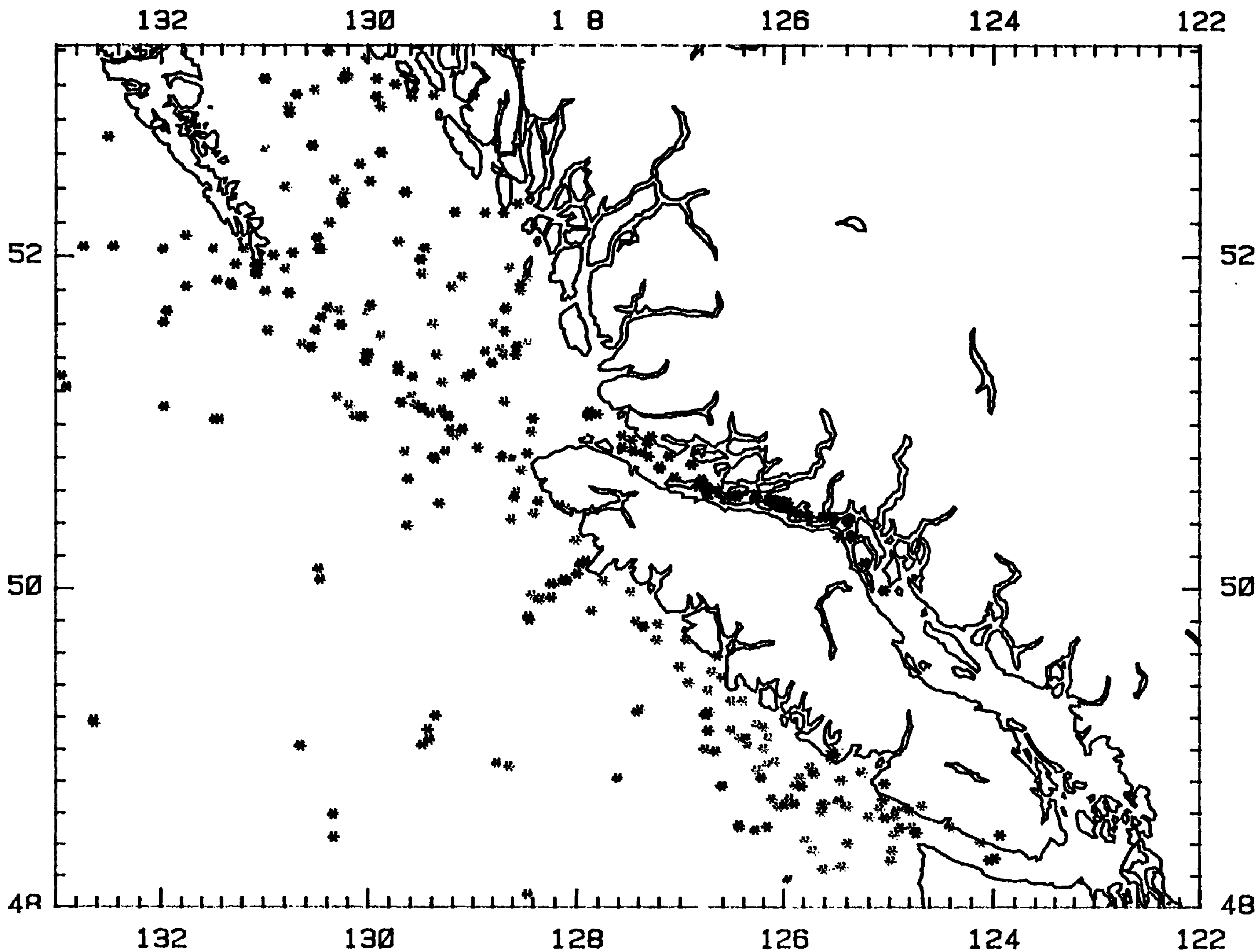
HECATE STRAIT, DIXON ENTRANCE - Contoured Surface Density, May to September



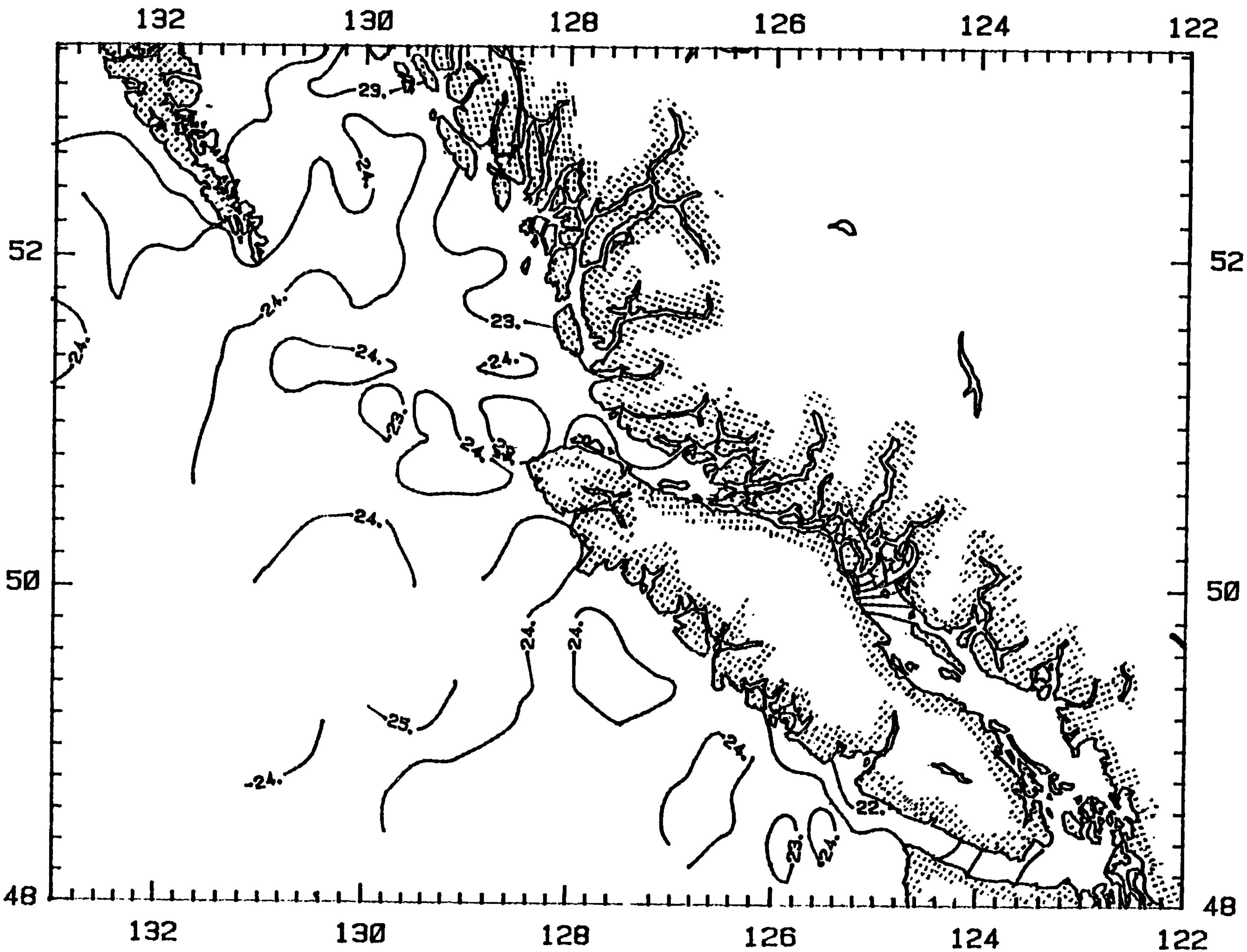
HECATE STRAIT, DIXON ENTRANCE - Sample Locations, October to April



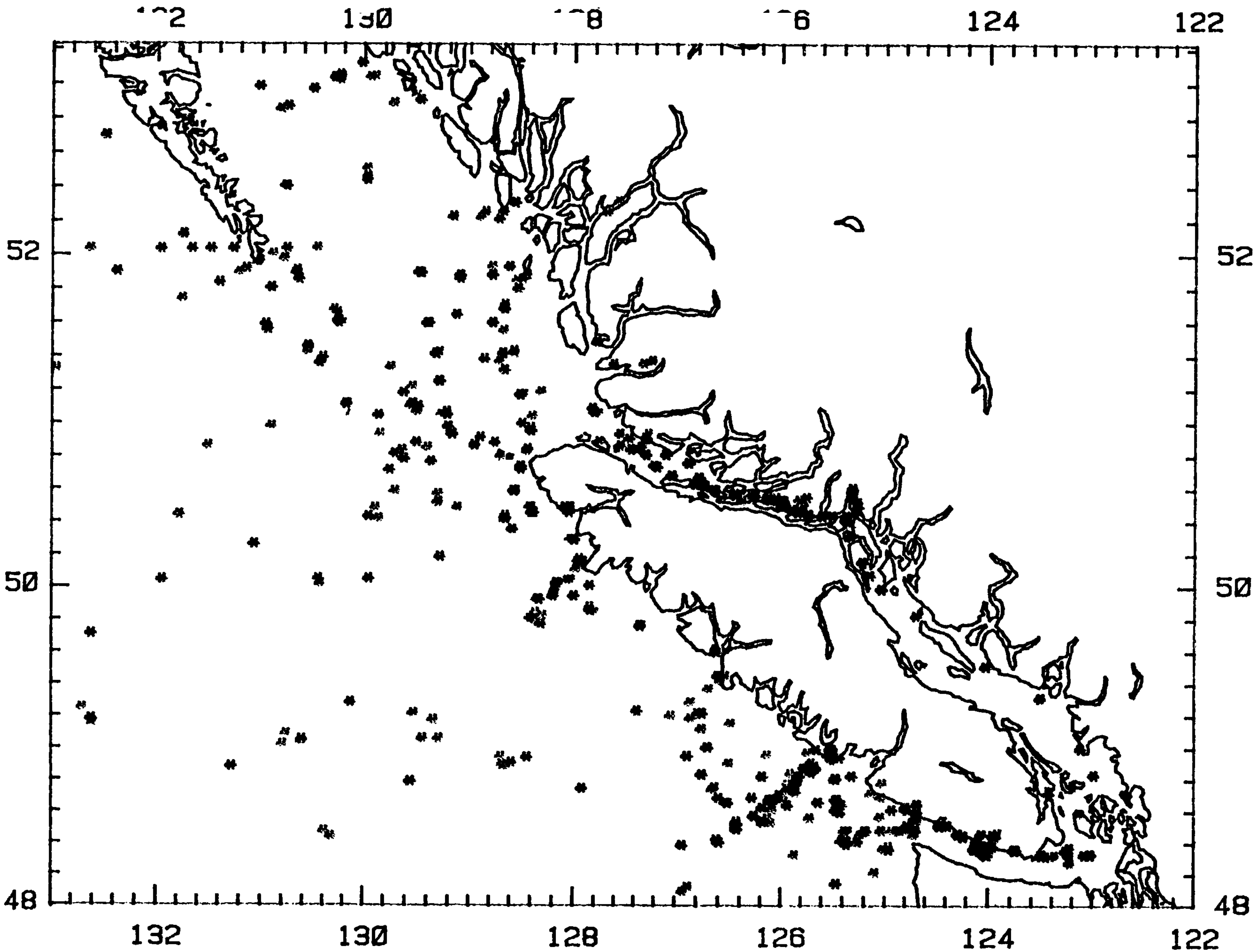
HECATE STRAIT, DIXON ENTRANCE - Contoured Surface Density, October to April



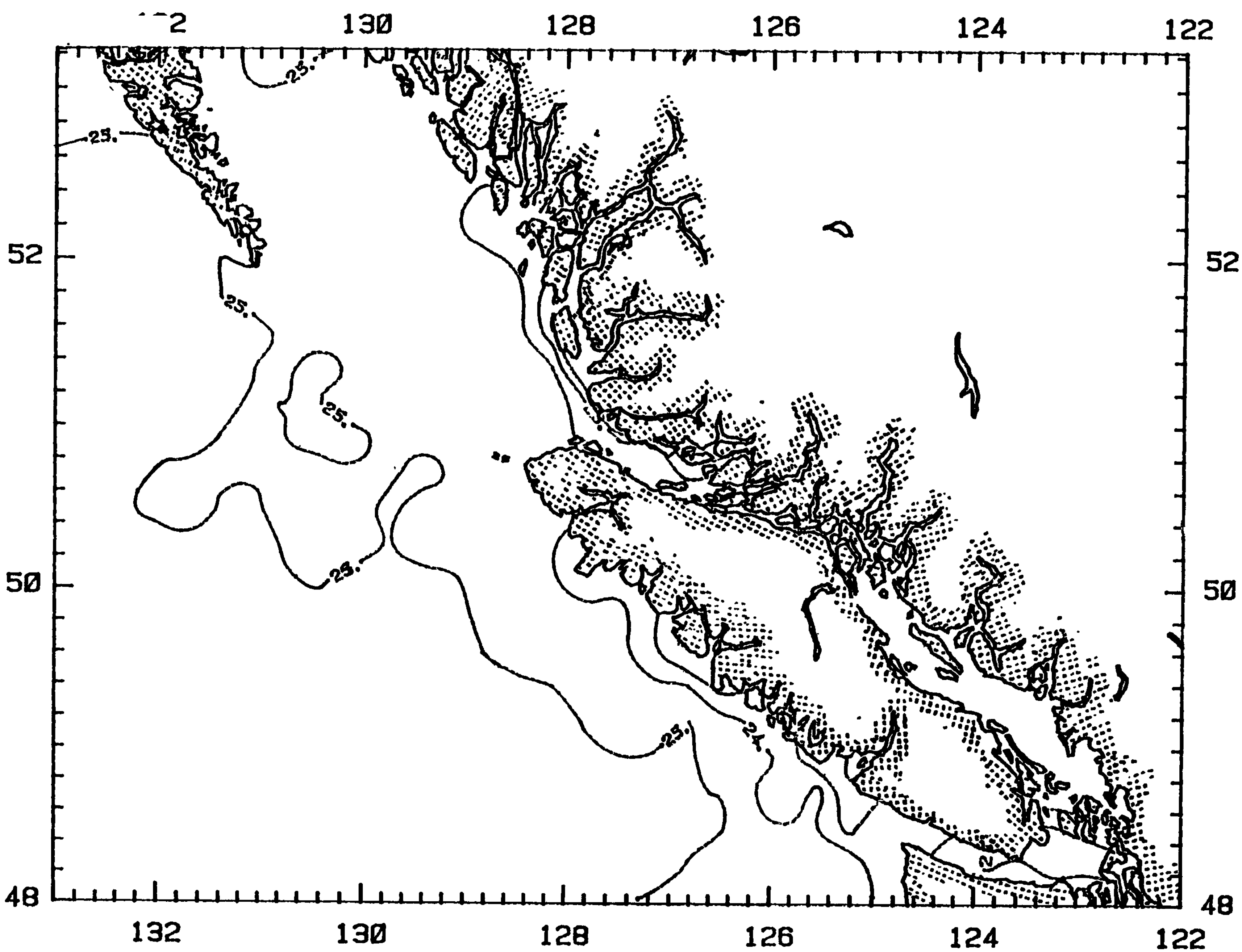
OFFSHORE WATERS - Sample Locations, May to September



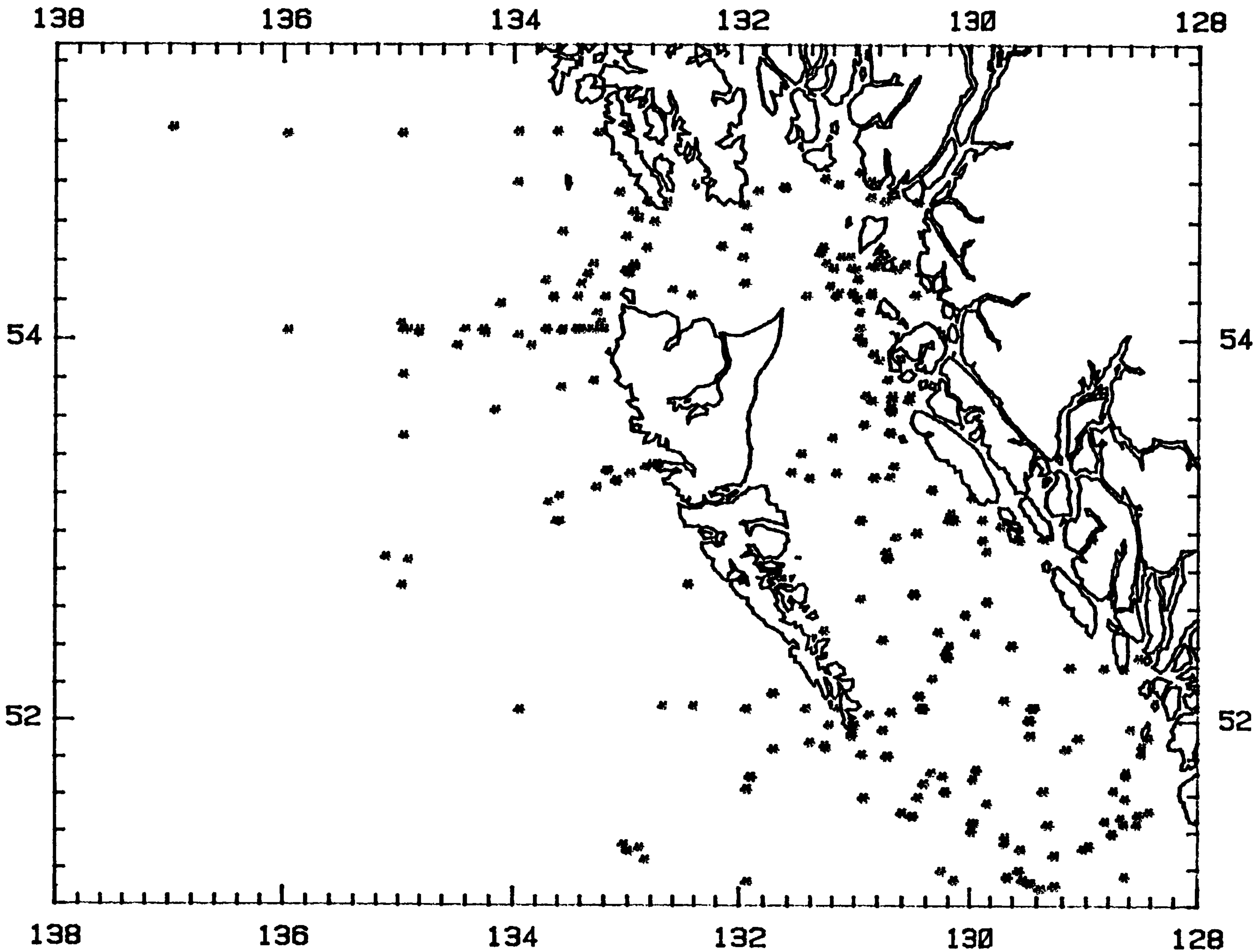
OFFSHORE WATERS - Contoured Surface Density, May to September



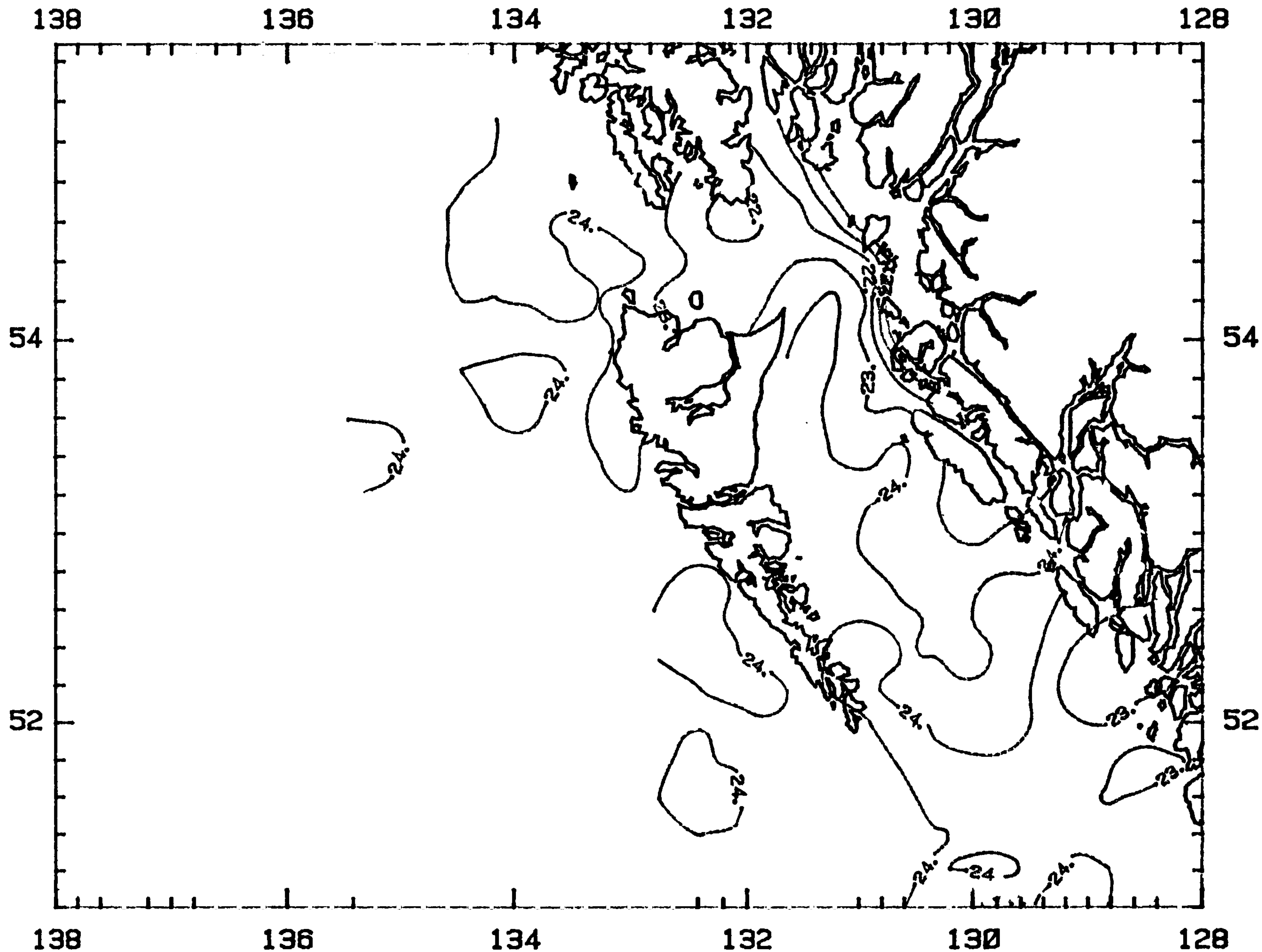
OFFSHORE WATERS - Sample Locations, October to April



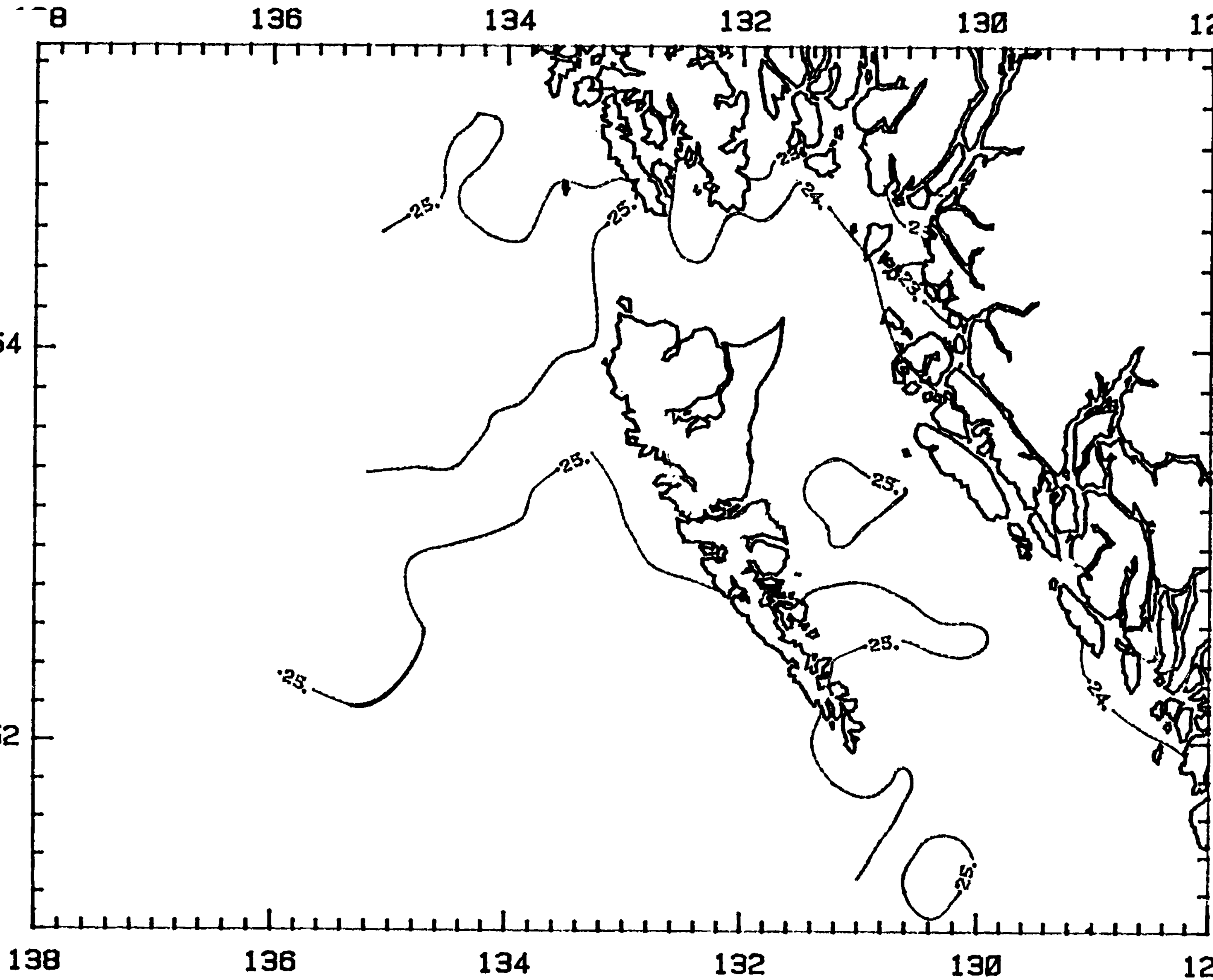
OFFSHORE WATERS - Contoured Surface Density, October to April



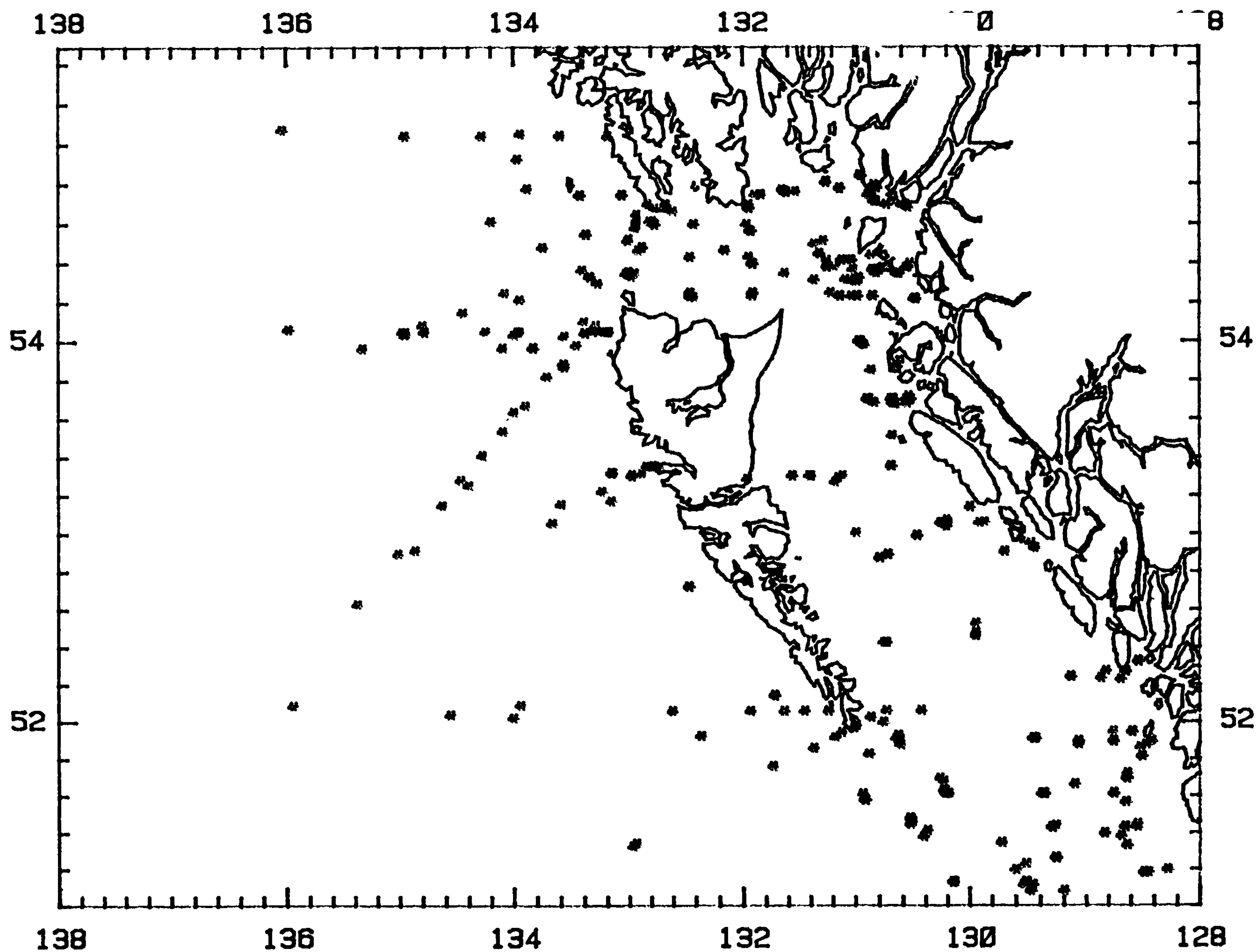
QUEEN CHARLOTTE ISLANDS - Sample Locations, May to September



QUEEN CHARLOTTE ISLANDS - Contoured Surface Density, May to September



QUEEN CHARLOTTE ISLANDS - Contoured Surface Density, October to April



QUEEN CHARLOTTE ISLANDS - Sample Locations, October to April