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Intermediate-Scale Physical Processes and their Influence on the Transport and Food Environment of Fish

CROSS-SHELF PROCESSES NORTH OF SCOTLAND IN RELATION TO THE SOUTHERLY MIGRATION OF WESTERN MACKEREL

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SUMMARY

A combined acoustic and hydrographic survey was conducted west of Shetland in January 1995. Examination of the temperature-salinity structure at the shelf edge north of Scotland reveals a narrow (30 km) core of warm, saline water embedded within a broader distribution of Atlantic water. Current measurements during the winter of 1994/95 demonstrate that the core did not mark the area of maximum transport along the shelf within the Slope Current. Larger scale processes associated with the northwest European shelf edge are important in determining the intermediate scale physical environment encountered by southerly migrating mackerel during the migration to the spawning areas.

The analysis of the acoustic survey data revealed that a large number of the migrating mackerel schools were located in, or close to this warm saline core. Mackerel school structure varied dramatically between the areas affected by this core and other parts of the survey area. In general mackerel formed large distinct schools in mid water. At the shelf edge, schools were found deeper, were more diffuse and tended to form layers, or elongate schools.

Data will be presented showing the changes in school behaviour between the two areas. The relationship between the intermediate scale physical structures and the fish distribution and migration will be discussed.

INTRODUCTION

A persistent current flows along the edge of the continental shelf west of Britain, which may represent a continuous filament of transport, carrying water originating in Atlantic waters, to the south of the Celtic Sea, to the Northern Oceans (Ellett *et al.*, 1979). It is believed the current is predominantly non-wind driven (Huthnance, 1984, 1986) and is dependent on the north-south oceanic meridional temperature gradient. The current is generally marked by a core of warm, saline water at the shelf break, which may reach the surface during the winter, but which is below the seasonal thermocline during the summer (Booth and Ellett, 1983).

The cause of the generally higher temperatures and salinities within the current is the southerly origin of the water masses transported within it. The current may be continually traced, at least from the shelf west of Ireland to the shelf edge north of Scotland (Dooley and Martin, 1969). From a careful analysis of mixing of the different water types that make up the slope current, Hill and Mitchelson-Jacob (in press) suggested that the current was continuous from the Porcupine Bank to the west of Scotland. Water may also be transported into the current from areas south of the Porcupine Bank, although this is still under examination (Turrell *et al.*, 1995).

To the north of Scotland, the slope current is normally confined to the shelf break and is characterised by a narrow core of transport, persistently being observed close to the 500 m contour (Dooley and Crease, 1978). However, the current also has important interactions with the waters on the shelf itself. Water within the current, mixing continually with water further off in the northeast Atlantic, supplies the source water which inundates many parts of the northwest continental shelf. It also to some extent dynamically isolates the shelf waters from processes occurring in the ocean (Huthnance, 1986; Pingree and Le Cann, 1989).

The precise mechanisms whereby water is exchanged across the shelf edge onto the shelf are not yet fully understood. Interactions with topographical features may play a role. During its passage along the shelf edge from the Bay of Biscay to the Norwegian Sea, the slope current encounters several changes in topography. For example, a major topographic feature influencing the current is the Wyville-Thomson Ridge at the entrance to the Faroe-Shetland Channel. Broad oceanic flow towards the northeast over the ridge is diverted towards the slope, possibly enhancing the current there (Huthnance, 1986). Further north the slope current appears to split around the area of the Tampen Bank at the entrance to the northern North Sea. Water above ocean depths of >300 m appears to continue to flow northeast into the Norwegian Sea, while water inshore enters the Norwegian Trench to flow south (Dooley and Martin, 1969). Smaller topographic features, such as changes in the slope of the shelf edge, and submarine canyons may also influence the local strength and direction of the current, and locally increase on-shelf transport.

Another cause of exchange with shelf waters may be due to dynamical variability in the current. Gould *et al.* (1985) noted significant short-period variability within the slope current north of Scotland, over periods of typically four days, associated with wind events. Dooley and Meinke (1981) also noted extreme variability within the current over these timescales, but could not relate them to wind events on all occasions. They ascribed some of the variability to the incursion of oceanic eddies into the shelf edge area.

The short term variability is superimposed upon a seasonal variation in transport within the current. Gould *et al.* (1985), using an intensive year long deployment of current meter moorings across the slope current to the northwest of Shetland, described a seasonal cycle of transport within the current. Maximum flows occurred during the winter months (December-February) while minimum transport took place during the summer (June-August).

Thus it may be hypothesised that periods of weak or reduced transport, caused either by local forcing such as wind stress or the passage of oceanic eddies, or by non-local forcing such as an alteration in the large scale dynamical balance of the shelf edge region, will be associated with greater on shelf transport of warm, saline water. In the results presented below an anomalous distribution of warm water on the shelf indicates that such an increased on shelf transport of water occurred during the winter of 1994/95.

The winter migration of the western mackerel (*Scomber scombrus*) from feeding grounds in the North and Norwegians Seas to spawning areas south and west of Ireland occurs in the months of December to March. The migration path follows the shelf edge for most of its route, with the fish being found generally between the 100 and 250 m contours (Walsh *et al.*, in press). Analyses of commercial catch data have shown that the timing of this migration has changed significantly over the last twenty years. From the late 1970s until the early 1990s the migration occurred steadily later in the year, from late summer in the 1970s to January in the 1990s (Walsh and Martin, 1986). Walsh and Martin speculated that this change may have been due to hydrographic changes in the area following the 1970s salinity anomaly. Walsh *et al.* (in press) showed that the migration pathway coincided with a tongue of warmer more saline water extending along the shelf edge.

It has been suggested that the migration of scombrids may be modulated by "enviroregulation", a process where the fish regulate their immediate environments by behavioural means (Neill, 1984). So if the fish find themselves in some "non-preferred" temperature, they may swim faster or deeper. For example Olla *et al.* (1975) showed that mackerel swam faster at water temperatures below 7°C. These suggestions would support the hypothesis that the migration of the western mackerel is, at least in part, modulated by temperature change. Migration may be triggered by temperature dropping below a threshold, and the route of migration constrained by the, relatively, narrow tongue of warm water described above.

The question that then arises, is what would happen if the fish encounter an area of anomalously high temperatures caused by the type of advection event described above. The present paper describes the results of an acoustic survey carried out in January 1995 to study the migration of the western mackerel. During the survey mackerel were observed acoustically both inside and outside an area characterised by a warm water core on the shelf edge. Evidence will be presented that the behaviour of the fish schools was different in the area of the core, and the implications for the understanding of the role of temperature in modulating the migration discussed.

MATERIALS AND METHODS

Two research vessels were deployed in the area west of Shetland in January 1995 to carry out simultaneous hydrographic and acoustic surveys of the migrating mackerel and their environment.

The Scottish Office research vessel *Scotia* was intended to carry out a series of CTD sections across the shelf edge from 0°E to 4°W. Due to inclement weather only one of these sections was completed. The section ran approximately perpendicularly across the shelf break (approximately 61°N 1°50'W) north-west of Shetland (Fig. 1). Stations were at 10 nmi spacing or 5 nmi at the shelf break (Fig. 2). Observations were obtained using a SeaBird 25 sealogger CTD. Salinity calibrations were performed using *in situ* water samples analysed on a Guildline Portasal salinometer.

The acoustic survey was conducted from the Netherlands (RIVO) research vessel *Tridens*. Four partially overlapping surveys were completed, covering an area from 1°36'E to 4°12'W (Fig. 1). All the surveys followed a zig-zag track design. The first two surveys had a transect spacing of 10 nautical miles (nmi) and covered an area from the shelf break to the 100 m contour. Survey 1 was from 1°36'E to 1°42'W, survey 2 was from 1°42'W to 0°12'E. The second two surveys had a transect spacing of 5 nmi and covered an area within 20 nmi of the shelf break (200 m isobath). Survey 3 was from 2°12'W to 0°00'E, survey 4 was from 0°00'E to 4°12'W. Acoustic data were collected using SIMRAD EK500 38 kHz and 120 kHz split beam echosounders. The transceivers were mounted in a catamaran towed body which was towed from a boom alongside the vessel at a depth of approximately 4 m. The range was maintained at 250 m throughout the survey with a pulse interval of 1.5 msec. Echosounder output was recorded continuously as hard-copy and in digital form. The hard copy of the echogram was printed out in colour using a Hewlett-Packard paintjet interfaced to the echosounder. Digital data was transferred by ethernet to a SUN SPARC IPC computer and recorded transmission by transmission in 0.5 m depth samples on DAT tapes. Echo integration (McLennan and Simmonds, 1991) was carried out over 15 minute intervals (25 nm at 10 knots) by the echosounder and recorded on the printout.

Sea surface temperature and salinity were recorded throughout the survey using a Seabird CT19 in moored mode connected to a pumped sea water supply. The supply came from an inlet approximately 3 m below the sea surface. Salinity calibrations were performed using *in situ* water samples analysed on a Guildline Portasal salinometer. Temperature calibration was by *in situ* thermometer. Simultaneous navigation data were recorded from a GPS navigation system connected to a PC running a plotter (MicroPlot - SIS Systems, Aberdeen). Navigation and Seabird files were merged on the basis of time on return to the laboratory.

For the purposes of this paper only data from the second two surveys will be presented. Mackerel schools were also seen during the first two surveys, but no evidence of the presence of unusual temperature features was seen. This paper will therefore concentrate on the results of the latter two surveys.

RESULTS

The results from the short CTD section across the shelf edge north of Shetland were somewhat unusual (Fig. 2). The warm, saline core normally associated with the shelf break itself was located in shallower waters. Water above the 500 m contour, where typically the maximum transport exists, was cooler and less saline compared to typical conditions. Thus while the slope current was still in evidence at the shelf break (confirmed by current meter observations; Turrell, pers. com.), the water within the current was cooler and fresher. Warm, saline water had been transported onto the shelf.

It is apparent from Figure 2 that the warm water core may have a detectable surface signature. Figures 3a and b show contour plots of sea surface temperatures recorded during acoustic surveys 3 and 4. Figure 3a represents the area between 0 and 2°W. Over the bulk of the area the contours run generally south-east to north-west, representing cooler waters further north. A similar trend was seen in the survey in January 1994 (Walsh *et al.*, 1995). Towards the SW of the area the contours turn to run generally SW to NE. The water is cooler on the in parts of each transect and is warmer towards the shelf break. This tendency was repeated during survey 4 (Fig. 3b), covering the area between 1 and 4°W. A variation of around 0.3-0.4°C can be seen between the in and off ends of the transects.

Figure 4 is an example of the type of mackerel marks seen on the echograms NE of the warm core area, and also on the in parts of surveys 3 and 4. These may be considered as typical of the type of large mackerel mark seen generally throughout the area during this survey and in a similar survey in 1994 (Walsh *et al.*, 1995). The schools form discrete marks, with relatively low echo-energy, and were generally seen in the pelagic zone between 50 and 150 m deep. The echo integrals recorded at 38 and 120 kHz had a ratio of approximately 1:1. The other major pelagic species in the area were herring (*Clupea harengus*) and were readily distinguishable from mackerel. Herring marks were more defined in structure, had a higher echo energy per transmission, and were generally on or near the seabed. The echo integrals recorded at 38 and 120 kHz had a ratio of approximately 2:1. Fishing operations were carried out to confirm these interpretations.

Figure 5 is an example of the type of mackerel mark found in the area of the warm water core. Instead of the discrete, if somewhat shapeless structures of "normal" mackerel schools, these marks formed dispersed layers around 100 m deep in the water column. In the example shown there are also readily identifiable herring schools near the seabed. RV *Tridens* was unable to fish on these marks. However, catches were made by Dutch commercial trawlers on the marks at the same time, and confirmed them to be mackerel. The 38:120 kHz integral ratios for these layer marks was also 1:1 supporting the suggestion that they were mackerel.

DISCUSSION

The appearance on the shelf of the warm, saline core implies that increased on-shelf transport had occurred prior to the survey. The horizontal extent of the anomaly was not directly observed, although the supporting evidence from the SST data recorded during the acoustic survey suggests that a limited incursion occurred. Previously oceanic eddies have been observed in the area, and have been responsible for increased transport onto the shelf. Wind variability prior to the survey may also have caused reduced or even reversed transports within the slope current, which would have also resulted in increased on shelf transport. However, one other mechanism which may have been responsible is a broader scale change in the dynamical balance of the Faroe Shetland Channel area. It is too early to speculate yet as to the exact nature and cause of this change, but there is increasing evidence of greater amounts of reduced salinity water in the surface waters of the Channel during 1994/95.

The observations of change in the mackerel schooling behaviour in the area of the incursion has considerable implications for our understanding of the mechanisms underlying migration in this species. As mentioned in the introduction there has been considerable speculation about the role of temperature (and salinity) in controlling migration. Changes in ocean circulation and associated salinity and temperature changes have been suggested as the cause of the change in timing of the western mackerel migration (Walsh and Martin, 1985). Walsh *et al.* (in press) have suggested that the migration path may be constrained by temperature. Similar suggestions have been made for the Atlantic mackerel in Canadian waters (Ware and Lambert, 1985). Small scale events of warm water advection have also been implicated in on migrations of mackerel in the St Lawrence (Rose and Legget, 1988; Castonguay *et al.*, 1992).

The present study indicates that when southward migrating mackerel encounter an area of unexpectedly high temperatures their behaviour alters. The schools have a different structure in the area of the warm core which is not seen elsewhere in the area and not at all in the previous survey in 1994. Following the hypothesis of "behavioural enviroregulation" proposed by Neill (1984), it is reasonable to suggest that the change in school structure may also indicate a change in migration behaviour. During the acoustic survey of this area in 1994 (Walsh *et al.*, in press) all the mackerel schools encountered were "normal" ie mid-water discrete marks. Calculations showed that these schools were migrating with a speed of around 9-13 nmi per day. We would suggest that the layer schools encountered in the warm core area may have slowed down their rate of migration, or possibly stopped altogether.

This combination of observed differences in schooling behaviour in the area of the anomalous warm core and the hypothesis of "behavioural enviroregulation" (Neill, 1984) leads to the following model to explain what is happening here. Under normal circumstances mackerel begin their migration towards their spawning grounds south-west of Ireland when the water temperature falls below a certain threshold. Recent reports from commercial fishing vessels indicate that the mackerel appear to assemble in the area of Viking Bank (North Sea) in October and remain there until December, at which time the water temperature would have dropped far enough to trigger the start of the migration. Migrating schools appear on the echosounder as "normal" marks. The migration path is constrained by the tongue of warm water which extends up the shelf edge caused by the SEC transporting warmer southern water into northern latitudes. Temperature recordings made in the SEC in 1994 show that the water transported in the current was cooling progressively throughout the period December to February. So the migration would be maintained by the mechanism of "enviroregulation" in response to the cooling water. In 1995 some of the schools encountered an area of markedly warmer waters in the warm water core. The temperature signal may have been reduced or lost, behavioural enviroregulation would no longer be active, and the schools would stop migrating and begin to spread out. Assuming the presence of the warmer water on the shelf to be a transient phenomenon, the water would again start to cool, due to the influence of the cooling SEC, and the fish would resume their migration.

The above hypothesis can only be conjectural. The evidence for a warm water incursion on to the shelf and the change in school structures are conclusive. The interruption of the migration and the role of "behavioural enviroregulation" can only be inferred from these data. The hypothesis is supported, to some extent, by observations from commercial vessels that the layer schools were moving much slower than the "normal" schools.

Previous occurrences of reduced salinity water have been associated with changes in the properties of North Atlantic water itself (Dickson *et al.*, 1988). However more recent evidence has suggested that these periods of reduced salinity may alternatively be due to decreased oceanic inflow into the Faroe Scotland area, and a general change in the circulation processes there. Details of the 1994/95 event are yet to be analysed in detail, but the results presented here support the view that some large scale change may have occurred, resulting in intermediate scale physical variability on the shelf north of Scotland, which in turn resulted in significant biological changes, affecting fish and fishermen alike.

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Figure 1. Survey areas 1 - 4 and Faeroe-Shetland CTD Line

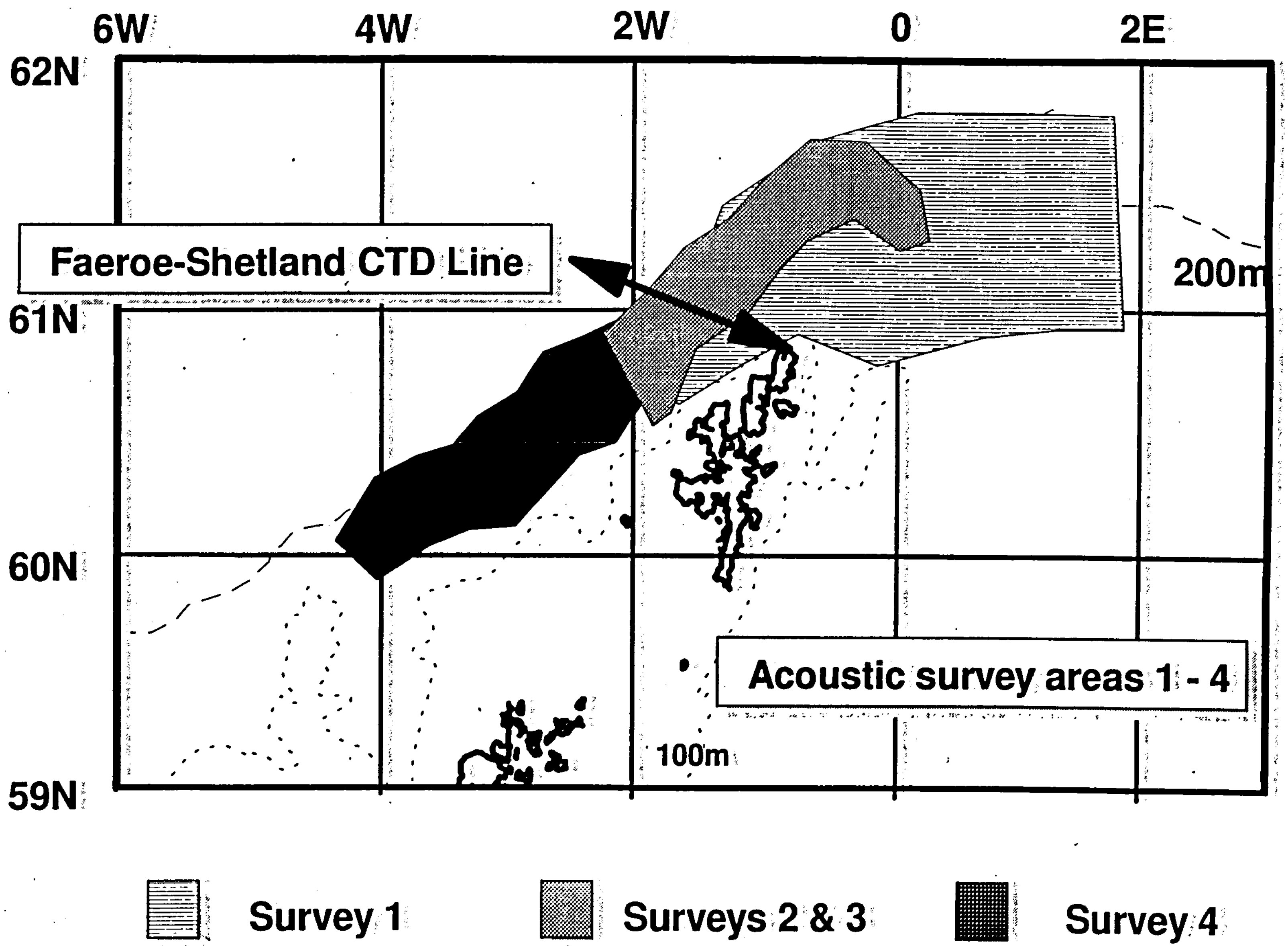
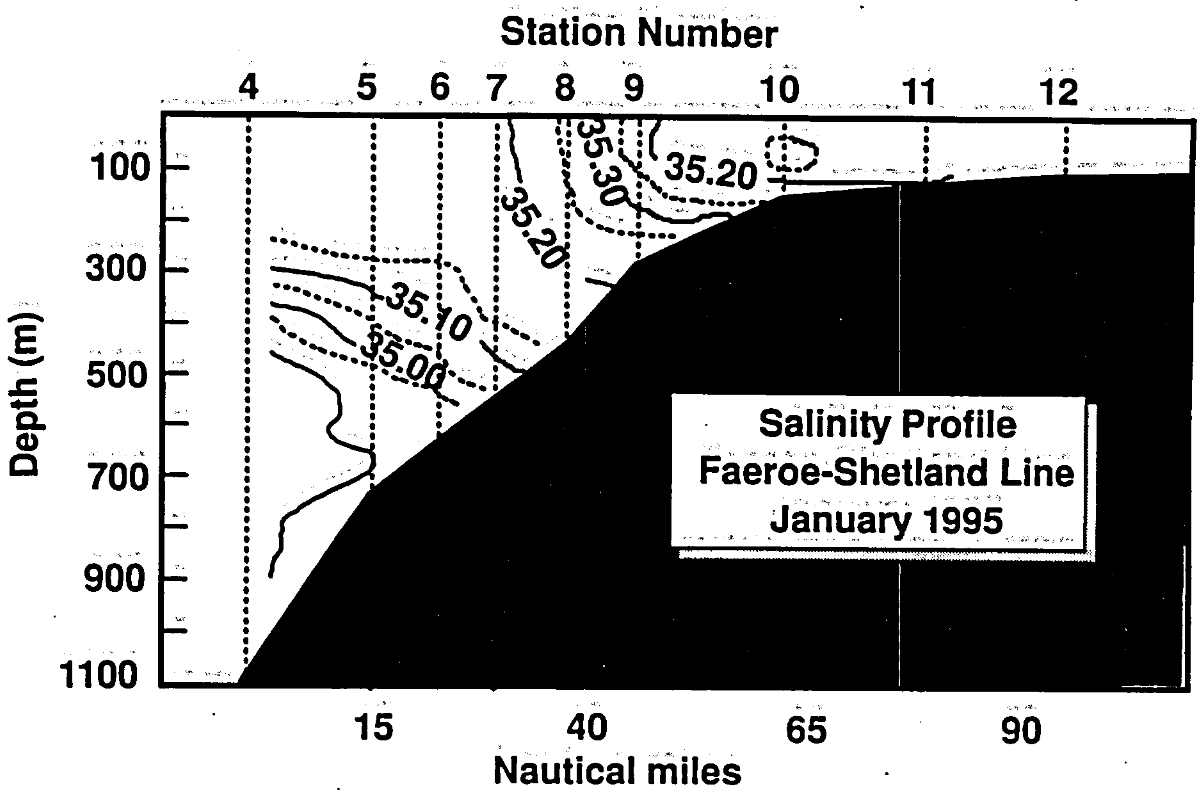


Figure 2. Salinity and temperature profiles on Faeroe-Shetland CTD Line



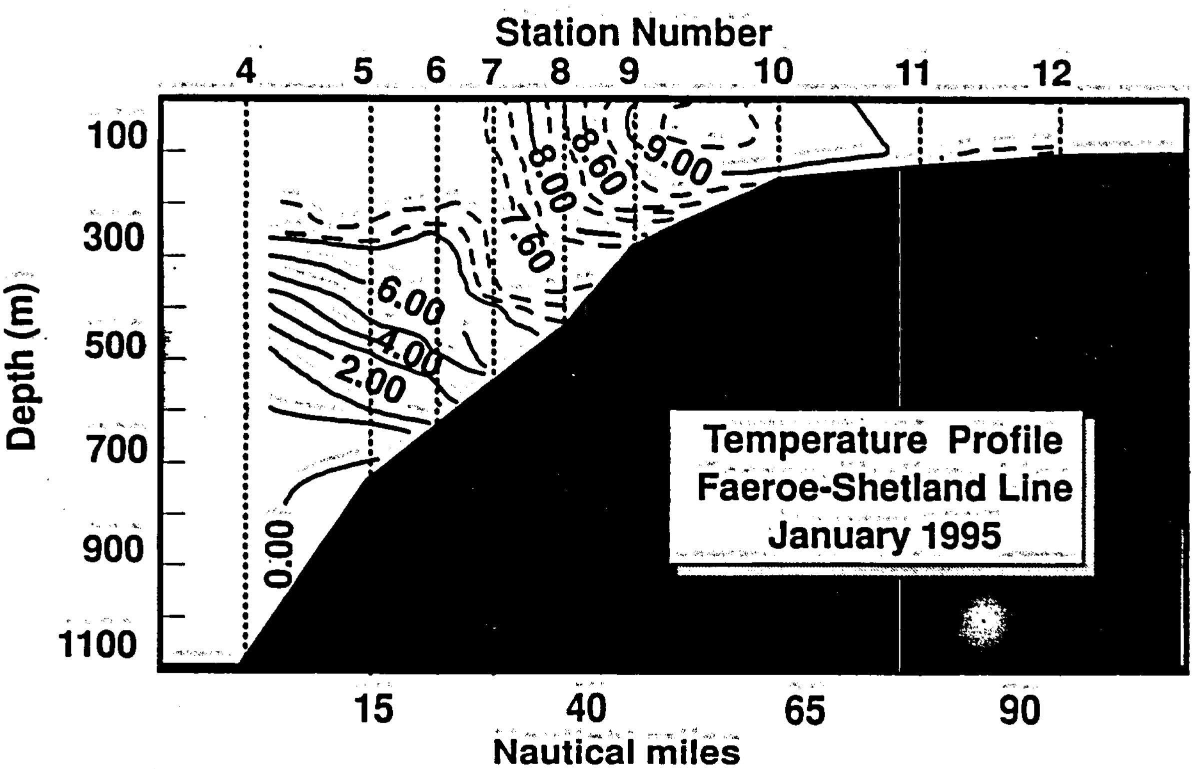


Figure 3a. Isotherm contours for survey 3

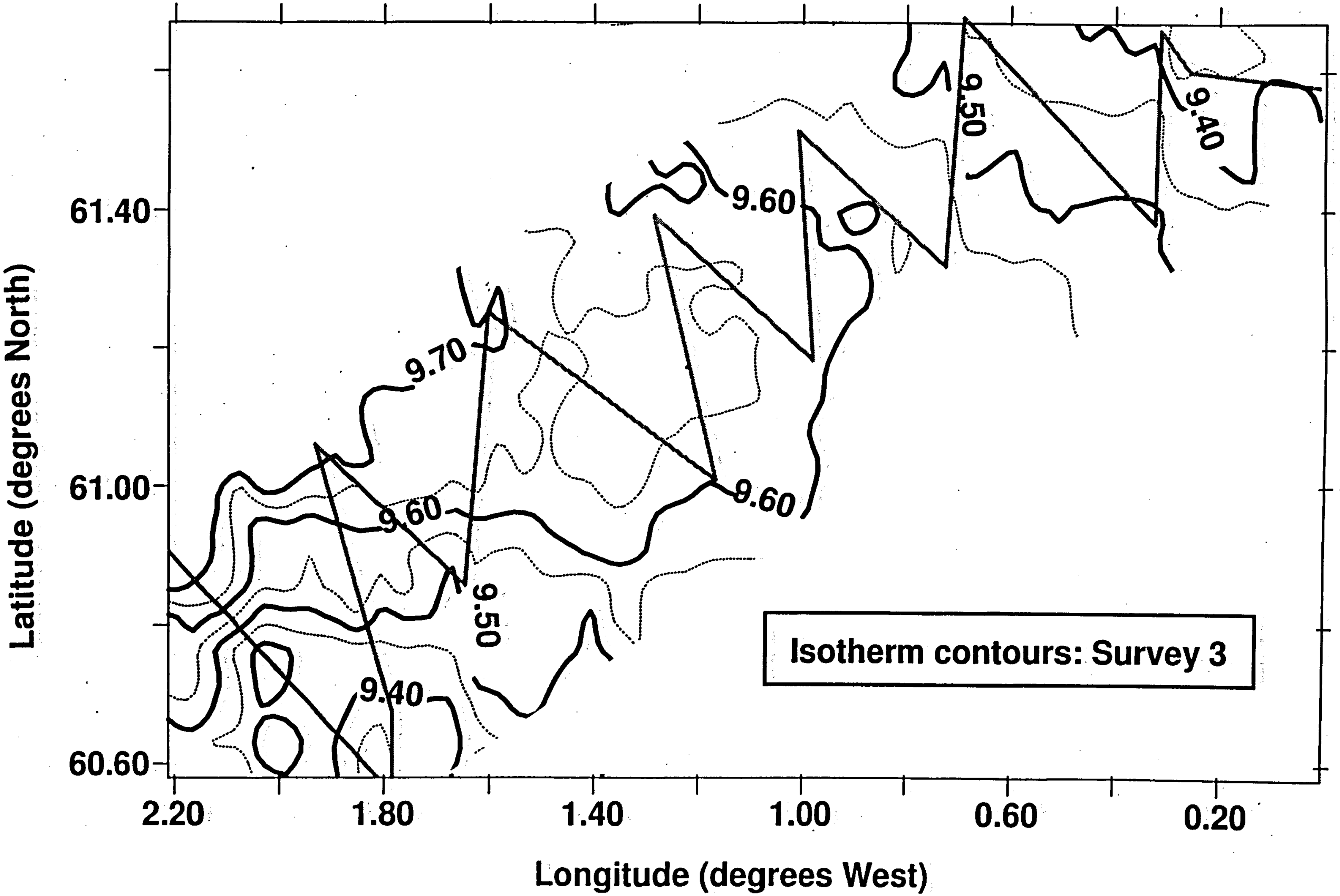
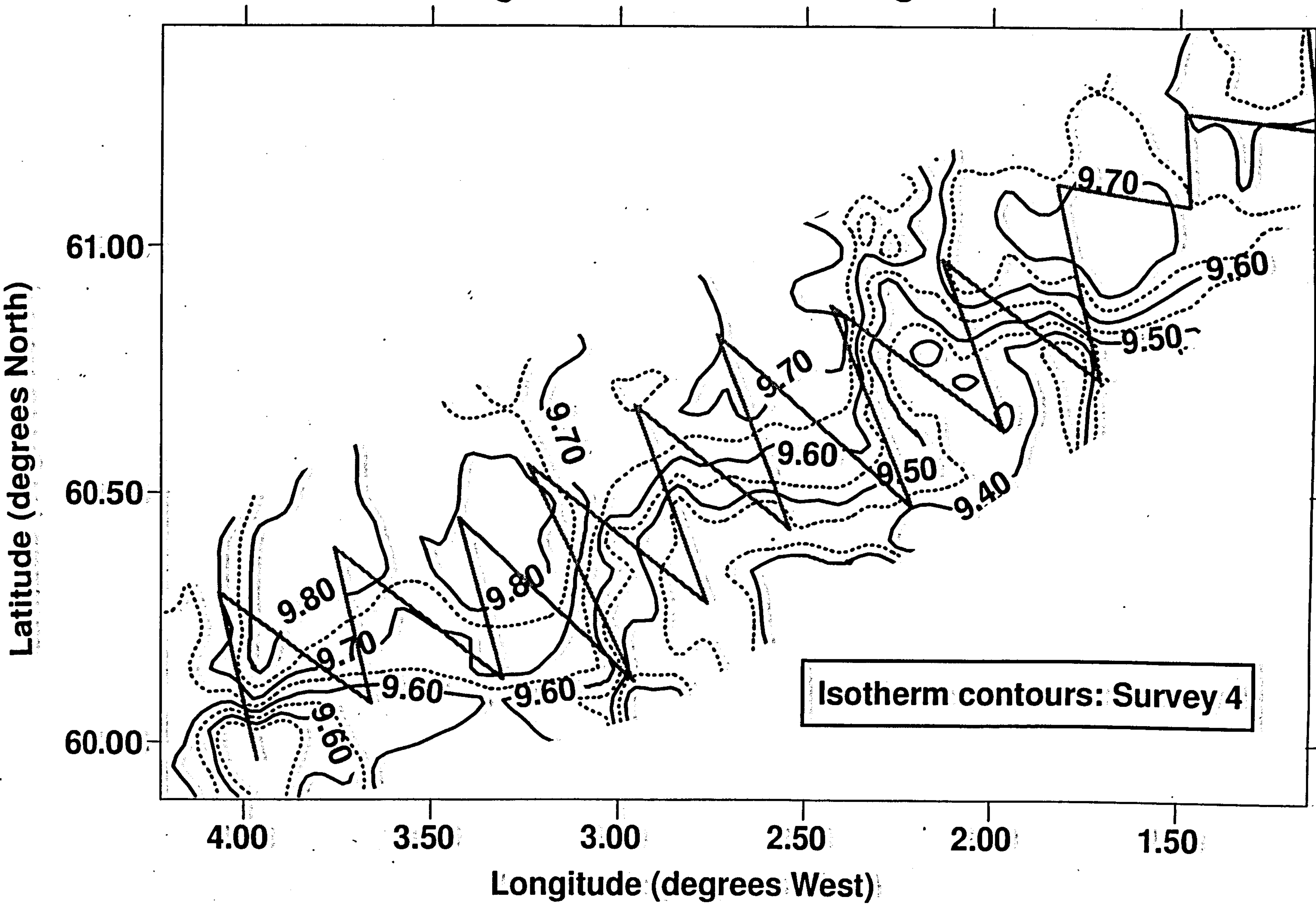


Figure 3b. Isotherm contours for survey 4



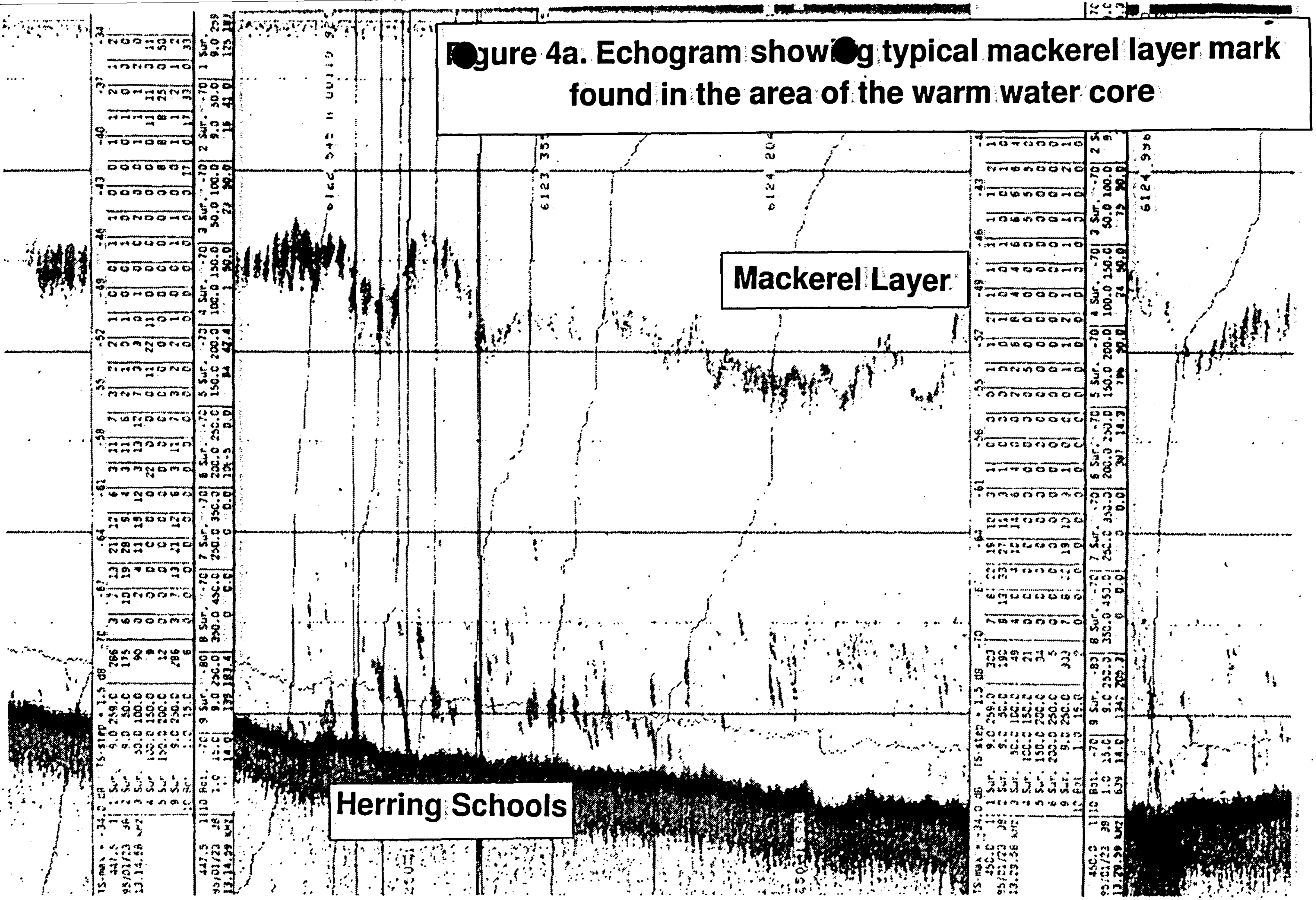


Figure 4a. Echogram showing typical mackerel layer mark found in the area of the warm water core

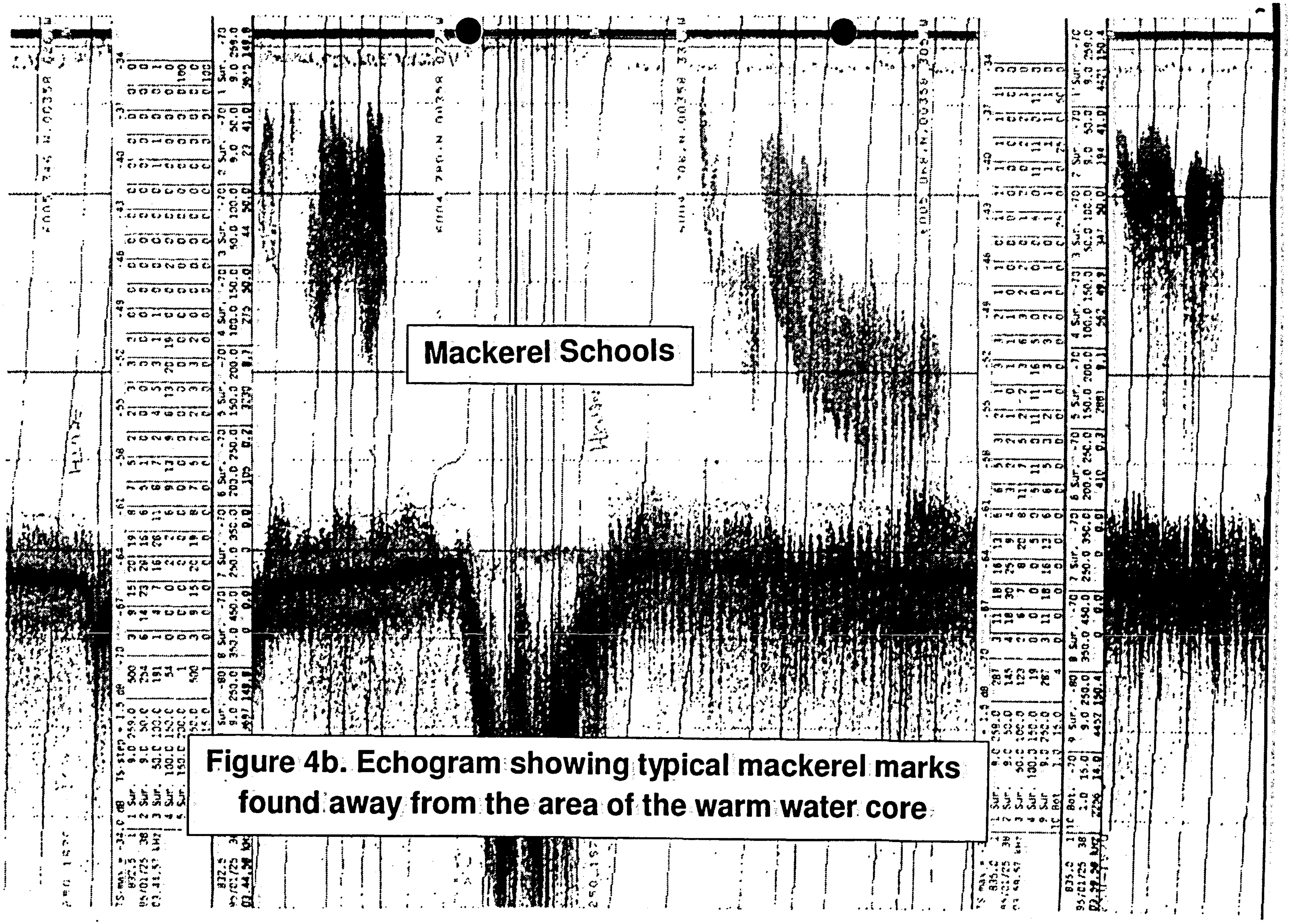


Figure 4b. Echogram showing typical mackerel marks found away from the area of the warm water core