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ACOUSTIC ABUNDANCE ESTIMATION OF WINTERING NORWEGIAN SPRING SPAWNING HERRING, WITH EMPHASIS ON METHODOLOGICAL ASPECTS

By
Ingolf Røttingen, Kenneth G. Foote, Ingvar Huse, and Egil Ona
Institute of Marine Research
P.O.Box 1870, N-5024 Bergen, Norway

ABSTRACT

The spawning component and part of the juvenile stock of Norwegian spring spawning herring have been wintering in a fjord system in northern Norway in recent years. Conditions for measuring the stock size have been excellent. Here, results are presented from the December 1993 and January 1994 cruises with R/V "Johan Hjort", supplemented by measurements with R/V "Michael Sars" in December 1993. Following a review of the biology, principal elements of the survey are described, namely design, acoustic measurements, and biological sampling. A variety of auxiliary studies, some ongoing, are breifly reviewed. The subjects of these are (1) acoustic extinction, (2) fish orientation *in situ*, (3) fish target strength *in situ*, (4) geographic differences in size distribution and associated dynamics, (5) herring fat content, (6) hydrography with respect to herring distribution, (7) inter-ship calibration of echo integrators, and (8) multi-frequency echo integration. Methods of analysis: criteria for echogram interpretation, stratification, global averaging, and geostatistical estimation of variance, are described. Results of the acoustic survey are expressed through absolute numbers for abundance, composite size distribution, and estimates of confidence associated with the degree of coverage based on geostatistics. The results are placed in the context of other methods of assessment and prognoses. Error sources in the acoustic abundance estimate are enumerated and critiqued. Outstanding problems, if obvious, are mentioned.

Evaluation acoustique de l'abondance du stock hivernal de hareng norvégien, frayant au printempts, en institant sur les aspects méthodologiques

Résume

La composante adulte ainsi qu'une partie des juvéniles du stock hareng, frayant au printemps, hivernent dans un fjord du nord de la Norvège depuis quelques années. Les conditions pour évaluer l'abondance du stock étaient excellentes. Dans cette note, sont présentés les résultats de campagnes effectuées en décembre 93 et janvier 94 par le R.V. Johan Hjort, completées par des mesures effectuées par le R.V. Michael Sars en décembre 93.

Après un revue de la biologie, les principaux éléments de la campagne sont décrits: plan de campagne, mesures acoustiques et échantillonnage biologique. Des études complémentaires variées sont décrites brièvement. Elles concernent les point suivants: (1) extinction acoustique, (2) orientation in-situ des poissons, (3) index de réflexion in-situ, (4) différences géographiques dans la distribution des tailles, (5) taux de matière grasse du hareng, (6) hydrologie en relation avec la distribution, (7) intercalibration des écho-intégrateurs des navires et (8) écho-intégration multifréquence. Les différentes méthodes d'analyse sont décrites: critères d'interprétation des échogrammes, stratification, moyennage global et estimation de la variance géostatistique. Les résultats de la campagne acoustique sont exprimés en nombre absolu pour l'abondance, la distribution en taille et l'intervalle de confiance en relation avec le degré de couverture basé sur la géostatistique. Les résultats sont examinés dans le contexte d'autres méthodes d'évalution et de prévision. Les sources d'erreur dans l'estimation acoustique d'abondance sont enumérées et critiquées. Si nécessaire, les problèmes majeurs ont été mentionnés.

INTRODUCTION

In recent years, the stock of Norwegian spring spawning herring has been acoustically surveyed while wintering in the Ofotfjord-Tysfjord system in northern Norway (Fig. 1). Abundance estimation of the stock according to the acoustic survey performed in December 1992 has been documented (Foote 1993). Adjunct studies on the frequency dependence of target strength have also been documented, both from the mentioned cruise and from a briefer cruise to the same area in December 1991 (Foote et al. 1992a, 1993).

Principal conclusions drawn from these and other survey cruises to the same area are that the conditions for performing an acoustic abundance survey of herring are excellent, and that auxiliary studies are essential for improving knowledge of fish biology, behaviour, and acoustic scattering properties. That is, development of methodology is viewed as an integral part of the apparently more routine work of surveying.

The Institute of Marine Research has accepted these conclusions in authorizing acoustic survey and research cruises in December 1993 and January 1994. The major work of these cruises is summarized here. In particular, estimates of stock abundance are given, and auxiliary studies are outlined. Each of these studies may require a separate paper for elaboration, and some have already been prepared and are duly cited below.

This paper is divided into the following sections: migration biology, materials and principal methods, auxiliary studies, methods of analysis, results, and discussion. Attention is called particularly to the final part of the discussion, in which outstanding problems are reviewed. Progress on these is important for improving estimates of herring stock abundance and, through improvements in methodology, those of other pelagic fish stocks too.

MIGRATION BIOLOGY

The Norwegian spring spawning herring stock spawns in February-March on the coastal banks of the west and northwest coast of Norway. After spawning, the herring migrate to the Norwegian Sea, where they feed in summer in scattered concentrations over large areas in the open ocean (Røttingen 1992). The herring are mostly distributed in the upper layer of the water masses, where they feed mainly on copepods.

In August, after the end of the feeding season, the herring migrate to the wintering areas where they concentrate at high densities. Since 1987/88 the wintering areas of the Norwegian spring spawning herring have been located in the inner tributary fjords of Vestfjorden in northern Norway, i.e., Ofotfjorden and Tysfjorden (Fig. 1). At the end of December-beginning of January, the herring start their spawning migration.

The wintering period seems to be the most suitable period for acoustic abundance estimation using echo integrator techniques. This is because the stock at that time is confined to a limited geographical region which is protected from the ocean (and bad weather). Further, admixture with other species is almost negligible.

However, the situtation in the wintering area should not be regarded as static and homogenous. Dynamic changes occur, such as migrations, both diurnal and horizontal (with likely changes in associated tilt angle distributions), gonad maturation, and decreasing fat content. These factors are of significance in acoustic abundance estimation.

Wintering areas

Ofotfjorden is situated at the inner part of the Vestfjord area (Fig. 1). It is 65 km long and has an east-west axis. The maximum width is 10 km. It has a sill of about 320 m towards Vestfjorden at Barøy. Just inside the sill there is a 27-km long and narrow basin with a depth of about 550 m, which is remarkably flat in places.

Tysfjorden runs north-south and has a sill of about 200 m in the outlet against Vestfjorden. The fjord basin has depths down to 900 m, but both bottom and general topography are more complicated than in Ofotfjorden. The fjord has many tributaries, some of these have relatively shallow waters, others have depths down to 450 m.

The hydrographic situation of these fjords, with special emphasis on the oxygen situation, is discussed in Dommasnes et al. (1994). Generally speaking, the herring winter in water masses with a temperature of 5-7°C and a salinity of 34-35 ppt.

a) Immigration to the wintering areas

In August the adult herring migrate eastwards from the feeding areas in the Norwegian Sea and appear in increasing concentrations west of Vesterålen. Here, the adult herring ecounter immature herring which utilize these areas for feeding in summer.

By September the herring enter Vestfjorden, and the front of the migration gradually moves eastwards. This is followed by a corresponding geographical development in the fishery. Older herring dominate in the catches at the front of this migration (Fig. 2a).

In the beginning of October, the herring enter Ofotfjorden and Tysfjorden, the older herring arriving first. Figure 2b gives the length and age distribution of the herring in the outlet of Tysfjorden at the beginning of October and in December 1993, indicating that by December the older herring in the outer part of the fjord have been replaced by younger, immature fish.

By the end of October, the herring have reached the inner tributraries, and in the beginning of November the younger herring have joined the older herring in the wintering area. In some areas the young herring mix with the older, in other areas the young and the older occur separately. This is illustrated in Fig. 2c, which shows length distributions of herring from different fjord tributaries to Tysfjorden in December 1993 and January 1994.

In a period of one month from the middle of November, there seem to be only limited horizontal migrations. These migrations are, however, resumed at the end of December when the herring start the spawning migration.

b) Emigration from the wintering areas

The first individuals probably start emigrating from the wintering area in the latter part of December, perhaps earlier, marking the start of the spawning migration.
The older individuals are the first to commence the emigration.

As with immigration, the older individuals dominate the migration front out of the wintering areas. This is in agreement with earlier investigations, showing that the older individuals have a more rapid maturation rate than first-time spawners and younger individuals of the spawning stock (Lambert 1987, Ware and Tanasichuk 1989).

The general situation in the wintering areas in January is thus an emigration of the older fish. This emigration takes place in deeper water masses than does the immigration. This is probably related to the currents of the water masses in the fjord. The outward migrating herring undertake diurnal migrations only to a limited degree. In January the immature herring remain in the inner part of the wintering area.

The progress of emigration is illustrated by the change in length distribution of herring sampled from the inner part of the wintering area (off Narvik) on 1 December 1993, 10 and 16 January (Fig. 3a), and by the length distrubution of herring from the inner, middle and outer part of the wintering area in the period 11 - 16 January 1994 (Fig. 3b). The figures show that by the middle of January the older herring have left the inner part of the wintering areas and are located in the outer part, taking part in the spawning migration.

In February most of the maturing herring have left the wintering area, and only the immature are left. These will migrate out of the fjord in a feeding migration as the zooplankton spring bloom commences in the coastal areas.

The general migration dynamics of the wintering situations is illustrated highly schematically in Fig. 4. Figure 4a gives the situation in October while the herring is immigrating to the wintering areas. The older herring enter the wintering areas first (Fig. 2b). A diurnal migration is observed during the immigration.

Figure 4b shows the situation in December. Both older and immature herring are located in the inner parts of the wintering area. In some areas they mix, in some areas they occur separately (Fig. 2c). Diurnal migration is observed.

Figure 4c shows the emigration situation. The older herring emigrate first, thus the older herring are located in the outer part of the wintering area (Fig. 3a). The older herring are located in deeper water masses than during the immigration. Only limited diurnal migration is observed.

MATERIALS AND METHODS

Vessel operations

Two research vessels were involved in the December 1993 measurements in Ofotfjorden and Tysfjorden: R/V "Michael Sars" operated during the period 29 November-15 December, and R/V "Johan Hjort" during the period 4-15 December. Both vessels performed large-scale acoustic surveys of the fjord system, based on the same survey design, at the beginning of their respective cruises. R/V "Michael Sars" then performed a series of special acoustic and environmental measurements in addition to an acoustic calibration and inter-ship calibrations with R/V "Johan Hjort". This second vessel performed a series of acoustic surveys, repeated in certain areas, in addition to an acoustic calibration and inter-ship calibrations.

Only R/V "Johan Hjort" performed measurements in the fjord system during the second cruise, 6-17 January 1994. These consisted of a large-scale survey of both fjords, additional, finer-scale surveys of regions of dense concentration, and an acoustic calibration exercise, in addition to special acoustic and photographic measurements.

Salinity-temperature-depth (STD) profiles were measured by both vessels, which also performed trawling. Own-vessel catches were supplemented by samples from commercial fishing boats participating in the on-going herring fishery.

Survey design

Various survey grids were employed in repeated coverages of Ofotfjorden and Tysfjorden. The basic first-time survey was conducted along the tracks indicated in Fig. 5. The zigzag pattern for Ofotfjorden was first used in December 1992 (Foote 1993), but is based on an earlier design by the first author (IR). The patterns for both fjords attempt to ensure a comprehensive broad-scale coverage of the herring distribution in a reasonable time. Constraints on this were that the survey and any auxiliary measurements be completed within about ten days, and that individual fjords or fjord areas be surveyed in time periods that are short compared to large-scale movements of the herring in the fjord. At a vessel speed of eight knots, Ofotfjorden including Rombaken and Skjomen can be covered in about 15 hours and Tysfjorden in about 24 hours.

On the basis of findings from the first survey, supplemented with knowledge from trawling and the local fishery, further, denser survey designs were developed. For the particular cruises in December 1993 and January 1994, these consist in designs of parallel, equally spaced transects in the regions of largest concentration, namely Ofotfjorden, but also in the central part of Tysfjorden. The basic design of parallel transects used in Ofotfjorden in January 1994 extended from 16°19.5'E to 17°16.1'E, with intra-transect distance of 0.5 nautical miles (NM).

Parts of the first, broad-scale design, and variants of zigzag and parallel designs, were employed in other interesting areas. These included for example, Skjomen to ensure both daytime and night-time coverages, and such navigationally difficult areas as Hulløysundet and Kjøpsviksundet. In designing a finer-scale system of transects for Hylløysund, for instance, the lowering of a power line from 35 m to 26 m over high water since the December 1992 survey, affected the placement of transects, hence design.

Principal acoustic measurements

These were made with the SIMRAD EK500 echo sounder system (Bodholt et al. 1989) and Bergen Echo Integrator (BEI) (Foote et al. 1991). Large-scale measurements were made with both vessels, but only those made with R/V "Johan Hjort" are analyzed here. The primary frequency was 38 kHz, with pulse duration 1 ms and receiver bandwidth 3.8 kHz. The pulse repetition frequency was nominally about 1/s, but this was dependent on the bottom depth, which was often in excess of 500 m, and use of multiple frequencies. In general, two EK500 systems were operated concurrently, each with two transducers. Thus measurements were performed at 18, 120, and 200 kHz, in addition to 38 kHz.

The cruising speed during surveying was about eight knots. Hull-mounted transducers were used during surveying. The towed 38-kHz transducer was used during some special short-range measurements. Both 38-kHz transducers and the 120-kHz transducer are split-beam devices.

Data from the EK500 system were automatically logged on BEI together with such indentifying data as vessel log and Global Positioning System (GPS) coordinates. Survey data consisted of digitized time series of the volume backscattering strength, with 1-m resolution in depth over the 500-m range and 2-m resolution over the 1000-m range. Each such time series was supplemented by a near-bottom time series of values covering the region from 10 m over the detected bottom to 5 m under the same, with 0.1-m depth resolution.

All postprocessing was performed on BEI. Survey data were generally interpreted within 24 hours of collection, and often within four hours. The process of interpretation is described in the section on analysis methods.

The acoustic instruments were calibrated during each cruise according to the standard-target method recommended by ICES (Foote et al. 1987). The calibration targets were the 125-mm-diameter copper sphere at 18 kHz, 60-mm-diameter copper sphere at 38 kHz, and 38-mm-diameter sphere of tungsten carbide with 6% cobalt binder at 120 and 200 kHz. The instruments had performed stably, with insignificant change in performance over the previous year, consistent with the basic level of uncertainty in calibration state. As on earlier occasions, for example, that described by Foote et al. (1993), calibration of the transducer at 18 kHz was difficult, with estimated uncertainty of ±1 dB. The uncertainties at 38, 120, and 200 kHz, are, respectively, ±0.2, ±0.5, and ±0.5 dB.

Biological sampling

The biological samples of the herring originate from research vessel catches (trawl) and from catches from the commercial fishery (purse seine). Figures 6a and b show the sampling locations in October-December 1993 and January 1994, respectively. Altogether 44 samples, each consisting of 100 herring, were taken. Of these, 18 samples were taken by research vessel and 26 from the commercial fishery.

AUXILIARY STUDIES

Acoustic extinction

Concentrations of herring were often sufficiently dense and extended to cause significant acoustic extinction and make compensation necessary. Conditions were also suitable for measuring the extinction cross section according to a method employed earlier (Foote et al. 1992b). Given the different composition of the herring stock relative to its 1983-year-class-dominated state when the extinction cross section was measured in 1988, 1990, and 1991, the measurement was performed anew. Results of this are described in detail elsewhere (Foote 1994).

In brief, pairwise echo integration of the herring layer and flat bottom in outer Ofotfjorden demonstrated the diminution of bottom echo due to the intervening fish layer. Statistical analysis suggests that the ratio of extinction and backscattering cross sections is 2.41±0.33. In absolute terms, the extinction cross section is 22.7 cm^2 for herring length distribution with mean 33.9, root-mean-square 34.0, and standard deviation 3.2 cm.

While the extinction cross section undoubtedly depends on depth, fish size, degree of maturation, and behaviour, e.g., orientation distribution, knowledge of this is at least as limited as that associated with the backscattering cross section. Thus, in the computation reported below, the mean ratio of extinction and backscattering cross section, σ_e / σ_b, is assumed to be 2.41. The absolute value of σ_e is related to fish size through the defining equation for σ_b,

$$TS = 10 \log \frac{\sigma_b}{4\pi r_o^2} = 20 \log l - 71.9,$$

where *TS* denotes target strength, r_o is the reference distance of 1 m, and l denotes the rms fish length in centimeters. The *TS-l* relation is the standard one used for Norwegian spring spawning herring (Foote 1987).

Fish orientation *in situ*

Herring tilt angles were measured using underwater equipment with strobe illumination. Pictures were taken either with manual or automatic release. Angles were measured from copied positives using a specially developed Autocad programme and a digitizing tablet. Only herring visually evaluated to swim parallel to the picture plane and in the central 1/3 of the picture vertically were measured. A typical day situation is presented in Fig.7a. Most herring are swimming horizontally. Fig. 7b shows a night situation. Here the majority of the herring are swimming with a pronounced upward tilt. Both sets of observations are from below 200 m depth. Consequently the swimbladder is compressed to less than 1/20 of its surface volume. A possible explanation for the difference in tilt angle may be that at night the fish swim more slowly than at daytime and do not school. With the low bouyancy resulting from the compressed swimbladder, the herring therefore have to swim at an upward angle in order to maintain depth. The observed tilt angles will obviously have a strong impact on *TS*. Further investigation is therefore needed to find whether the tilt angle distribution is the same in the survey situation as it is during such studies as when the ship is drifting. There seems to be no systematic difference between tilt angle measurements made in December and January. The tilt angle measurements are further addressed in Huse et al. (1994).

Fish target strength *in situ*

Herring target strength was studied by *in situ* techniques from R/V "Michael Sars". A cabled rig containing a SIMRAD EK500 split-beam transducer, SIMRAD FS3300 scanning sonar, and Photosea stereo camera, was lowered into the herring layers to resolve individual fish for target strength measurements and to measure volume density by counting methods. The three systems were calibrated several times during the survey. The results from these experiments are reported elsewhere.

Preliminary analysis of the data sampled within the herring layers indicates that the *in situ* target strength of herring is significantly higher than what is deduced from the target strength-length relation as presently applied in biomass calculations ($TS = 20 \log L - 71.9$). These high target strengths measured *in situ* using a split-beam system are comparable to the target strength values obtained from combined individual countings and echo integration.

The findings of a large difference between the applied target strength-length relation for biomass calculations and *in situ* target strength data are also discussed in other reports (Kautsky et al. 1990, Reynisson 1993).

Geographic differences in size distribution and associated dynamics

The basic dynamics of the migrations to and from the wintering areas is described in a previous section (Migration pattern of Norwegian spring spawning herring). As a result of these migrations, the length and age distributions of herring in the different parts of the wintering area vary throughout the wintering period (Figs. 2 and 3). This must be taken into account when converting the average backscattering cross section to herring abundance, because the conversion factor (*TS*) is length dependent.

Thus the total herring distribution area is divided into strata (five strata for the December 1993 survey, six for the corresponding survey in January 1994). These are shown in Figs. 6a and b, and data on mean length of the herring in the different strata are given in Table 1.

a) December 1993 survey

The herring in the main basin in Tysfjorden (stratum A, Fig. 6a) were mainly herring of the 1983 year class. A typical length and age distribution of this type of herring is shown in Fig. 2b. In the tributary fjords Stefjorden and Indre Tysfjorden (stratum B), however, there were consentrations of younger and partly immature herring (Fig. 2c). In other tributaries (Hellemofjorden) there were the same large herring as in the main basin (Fig. 2c).

With the exception of the tributary Skjomen (stratum E) with immature herring, there were in December a mixture of the 1983 year class and younger year classes in the entire Ofotfjord (mainly the year classes 1988, 1989 and 1990) (Figs. 3a and b).

b) January 1994 survey

With the exception of Ofotfjorden (stratum D), the stratification from December 1993 was applied for the abundance estimation of the January 1994 acoustic data with minor adjustments.

In January, the large, mature herring were migrating out of Ofotfjorden, so the larger herring were distributed in the western part of the fjord and younger in the eastern (Figs. 3a and b). Consequently, Ofotfjorden was divided into two strata, east and west of 17°E (strata I and J, Fig. 6b, Table 1).

Herring fat content

The fat content of the herring in the survey area was determined from purse seine catches delivered at a meal production plant in Bodø. The method used for determining the fat content is Na_2SO_4 grinding with ethyl ether extraction. The mean fat content of herring during the November/December survey was 16%, decreasing to 15 % in the January survey. Figure 8 shows the variation in fat content in the wintering period 1993/94.

Hydrography with respect to herring distribution

Environmental variables such as temperature, salinity, and dissolved oxygen were measured using a Seabird 911+ CTD probe with oxygen sensor. The recorded oxygen measurements were compared against discrete water samples at from 10 to 15 depths using the Winkler method at most of the 35 stations (Fig. 9). A correction of the continously recorded oxygen was made by a linear regression between measured oxygen by the CTD and measurements using the Winkler method at the same depths,

$$(O_2 = O_{2(CTD)} \times 0.830 - 0.198, \quad n = 126, \quad r^2 = 0.94).$$

The general topography and hydrography of the fjord system are described by Dommasnes et al. (1994). Similar conditions were also observed in November/December 1993. The fjord water occupied by the wintering herring maintains an almost constant temperature of 7.0°C and a salinity between 34.0 and 34.9 ppt at the depths between 70 and 230 m (Fig. 10). A typical two-layer minimum in dissolved oxygen, one at 70 - 100 m depth and one at about 200 m depth, is directly related to the vertical distribution of herring biomass in the fjord. The main biomass is found in the deeper layer (Fig. 11), while parts, or occasionally the whole layer, ascend from 200 m to about 50 m depth during night-time. The herring tended to avoid water with dissolved oxygen less than about 1.5 ml/l, and was not observed to stay in water with oxygen below 1.0 ml/l. The observed variable diurnal migration pattern may also indicate that the migration is an oxygen-influenced migration.

Inter-ship calibration of echo integrators

During the first cruise, the two research vessels performed two inter-ship calibration exercises in which the reference target was the mid-water scattering layer of herring. The first exercise was performed three times along a 16-NM east-west transect in the eastern half of Ofotfjorden, spanning a depth range from about 200 to 500 m. The vessels followed each other with 1-NM separation, exchanging the lead after each transect. The range of acoustic fish densities, expressed in units of the area backscattering coefficient when measured over 0.1-NM intervals, spanned four orders of magnitude, from 40 to 600,000 m^2/NM^2. The exercise miscarried, however, from loss of instrument settings on one of the vessels, revealing at the same time a weakness in the acoustic system, which does not periodically log all instrument settings in a file for possible reference use, as in a case like the present one.

A second inter-ship calibration exercise was performed in Tysfjorden over an 8-NM transect from the western side of Haukøyfjord east to Stefjord with continuation towards its end, covering a depth range from about 700 to 160 m. Again, one ship followed the other with distance of 1 NM between vessels. The lead was exchanged after the first of the two transects.

Data collection by the two vessels were analysed in the customary manner, with 0.1-NM resolution. These values were further averaged over 0.2-NM intervals to help alleviate inevitable differences in corresponding positions of the vessels. A linear regression analysis was performed of corresponding values of area backscattering coefficient s_A, namely s_A for R/V "Michael Sars" on that for R/V "Johan Hjort". If the respective variables are denoted y and x, then the coefficients a and b in the equation $y = ax + b$ were determined by ordinary linear regression analysis. The result for s_A applicable to the entire water column is that a is not significantly different from unity, nor is b significantly different from zero. The same results apply to the data from each transect treated separately and from the combined transects.

For measurements made at 38 kHz and for the combined transects, the values of the coefficients with first standard deviations are the following: $a = 0.931 \pm 0.049$ and $b = 1084 \pm 1906$. The mean values are $\bar{x} = 29459$ and $\bar{y} = 30471$, each with units of s_A.The number of 0.2-NM intervals is 92.

Multi-frequency echo integration

As mentioned, measurements with R/V "Johan Hjort" were made simultaneously at each of four frequencies, 18, 38, 120, and 200 kHz. The corresponding pulse durations were 2, 1, 0.3, and 0.2 ms. The nominal receiver bandwidths were 10% of the respective transmit frequency.

Data from each tranceiver were broadcast over the local-area network (LAN), where they were received by BEI and automatically logged for further processing. Data at 18, 120, and 200 kHz were interpreted together with the 38-kHz data. This involved development, testing, and adoption of an extension to BEI during the first cruise, an entirely successful operation due to R.J. Korneliussen.

A comparison of data from the first survey of the cruise in January 1994 is performed in Table 2. The reported values are derived directly from the measurements, without attempt at compensation for extinction, as the frequency dependence has yet to be determined. The measurements are to be viewed in the light of the uncertainties in calibration, described above in the section on principal acoustic measurements.

METHODS OF ANALYSIS

Echogram interpretation

In this process, specific acoustic registrations are classified on the basis of their appearance on the echogram, which is generally displayed on the electronic screen of the workstation running BEI, aided by such auxiliary data as catch composition and STD profile, *inter alia*. Classification consists of assigning registrations to the target species, herring, or to non-target species. Values of s_A are automatically computed for operator-delimited or -selected regions of the echogram, split by scatterer class according to the interpretation, and stored in a database.

Stratification

Clearly, according to Figs. 1 and 5, the survey region is geometrically complicated. Consequently, the region has been divided into more limited geographical regions, mainly on the basis of degree of acoustic coverage, for the purpose of computing average backscattering cross sections and experimental variograms. For Ofotfjorden, these consist of (1) central Ofotfjord including Herjangsfjord but excluding Bogen, Rombaken, and

Skjomen, (2) Rombaken, and (3) Skjomen. The occurrence of fish in Bogen was minimal, justifying its neglect. Tysfjorden is divided into the following seven regions:
(4) Hellemofjord, (5) eastern Hulløysund and Mannfjord, (6) inner Tysfjord, (7) Kjøpsviksund, (8) eastern Haukøyfjord including Stefjord, (9) western Haukøyfjord, and (10) northern Tysfjord. The boundaries of these regions are somewhat arbitrary, but are apparently justified by the encountered distributions of herring.

Biologically, and for purposes of assignment of the average backscattering cross section to s_A-values, the fjords are divided into the regions described in the section on geographic differences in size distribution and associated dynamics.

The geographical subdivisions are affected only in one way: for the January 1994 survey cruise, the data of central Ofotfjorden must be separated into two parts, as the data lie west or east of the meridian at 17°E. The respective areas are 51.2 and 40.6 NM^2.

Tjeldsund was acoustically surveyed in December 1993, but with finding of a rather small quantity of younger herring in the context of the biomass present in the Ofotfjord-Tysfjord system. Data from Tjeldsund are not analyzed here.

Global averaging

Because of uncertainty in the precise positions of data collection, notwithstanding use of GPS, and because of integration over 0.1-NM intervals of sailed distance, values of s_A are averaged over individual blocks, or statistical squares, of side length 0.2 NM. These are part of a grid of blocks covering the entire survey region.

The arithmetic mean of blocks containing measured s_A-values is computed. This is converted to a measure of biological density according to the fundamental equation of echo integration, namely

$$s_A = \rho_A \bar{\sigma} ,$$

where ρ_A is the sought area density of target scatterers.

The cumulative abundance figure is derived by multiplying ρ_A by the total surface area of the region. The result is the estimated total number N of scatterers. The length distribution characteristics of the region is derived by multiplying the length probability density function by N.

Geostatistics

Application of geostatistics in the analysis of fish abundance survey data is becoming well known (Laurec and Perodou 1987, Conan et al. 1988, Petitgas and Poulard 1989, Guillard et al. 1990, Petitgas 1993). For the present data, experimental variograms have been computed for the various strata, and models have been fitted to these. In some cases, the data show an absence of structure, at least at the basic scale size of analysis, namely 0.2 NM. In other cases, structure is seen at all scales, with linearly increasing variogram. In between, there are important cases of bounded variograms, which can be fitted by summing nugget and spherical-function terms.

Use of these models allows the estimation variance to be computed. This has been effected in the very manner that the acoustic survey data from December 1992 were analyzed (Foote 1993).

RESULTS

These are presented through a short series of tables. In Table 3, total abundance for the Ofotfjord-Tysfjord system is given in summary form. Estimates are based on the initial large-scale zigzag survey designs followed during both cruises. Estimates without and with compensation for extinction are shown. Corresponding composite length distributions, formed by combining the individual length distributions weighted by the respective stock abundance estimate, are presented in Table 4.

Abundance estimates for central Ofotfjord, as surveyed with the initial large-scale zigzag pattern and subsequent fine-scale system of parallel, equally spaced transects, are compared in Table 5. In analyzing the data from the several designs, end-links connecting the parallel transects are both included and excluded. The estimation variance and standard error of the mean are also presented in Table 5.

DISCUSSION

Error sources

Clearly, the results show a strong internal consistency. This does not prove their validity, but argues importantly for the availability of the fish to acoustic surveying (Gunderson 1993), a prerequisite for their abundance assessment.

Major questions to be asked about the kind of survey reported here concern the spatial distribution of the stock, degree of acoustic coverage, appropriateness of values of backscattering and extinction cross sections, and possible presence of avoidance reactions or other behavioural effects due to the passage of the research vessel. One observation of the reported cruises confirms earlier observations of herring in the same fjord system, namely that the spatial distribution occasionally changes dramatically over a rather short period of time, say 12-24 hours, ignoring regular changes associated with diurnal, vertical migration and daytime schooling behaviour. Rather large horizontal movements appear to be unpredictable. Often, however, there appears to be little horizontal movement over a period of days. Surveys that can be conducted in a period of 12-24 hours seem capable of yielding reasonable measures of abundance, at least under prevailing conditions.

The degree of acoustic coverage relative to the stock distribution and area to be surveyed is assessed by the estimation variance. In the case of herring as measured in central Ofotfjord in January 1994, comparison of values of the estimation variance with corresponding values for the standard error of the mean shows no regular pattern. The first quantity includes information on spatial structure, through the variogram, while the second disregards this. It has been earlier argued that the estimation variance is the more useful measure (Anon. 1993).

Whether the stock abundance estimates are to be interpreted as absolute or relative depends entirely on the backscattering cross section or target strength. Here, the standard target strength-fish length relationship for Norwegian spring spawning herring has been applied. The results from previous acoustic surveys in the wintering area (Foote 1993) have, together with other estimates of the spawning stock (from tagging), been utilized by the ICES Working Group on Atlanto-Scandic Herring and Capelin (Anon. 1994) in a tuning process to estimate the stock size as a starting point for a stock prognosis. This prognosis has been the basis for management of this commercially important stock. However, fundamental work on the target strength-length relation, of which some topics are outlined in the present paper (*in situ* target strength measurements, tilt angle distribution in relation to depth, impact of changing fat content on the target strength), remains to be done. The situation is similar with respect to the extinction cross section. Determination of this quantity is intrinsically statistical, but it probably shares dependence with the same variables that influence the backscattering cross section.

Avoidance reactions have not been proven to be absent. If present, however, these have not prevented results obtained at different times from showing a consistency made more remarkable by the apparent specificity of reactions to time, place, and intangible *in situ* conditions. While results from the large-scale survey with R/V "Michael Sars" have not been presented here, for want of time, a preliminary analysis of data not compensated for extinction indicates agreement to within about 10% of the corresponding result shown for R/V "Johan Hjort" in Table 3. Such an agreement argues strongly for the absence of significant avoidance reactions.

Outstanding problems

That there are outstanding problems is evident from the number and extent of auxiliary studies performed concurrently with the surveying measurements. Thus, measuring the acoustic properties of herring *in situ*, especially to delineate such possible dependences as those of depth, depth history, physiological state including fat content (Ona 1990), and orientation remains a subject of the greatest importance to stock abundance estimation. The problem of the reported discrepancy between *in situ* TS measurements using split-beam techniques and TS-length relations used in the acoustic biomass estimation of important herring stocks (Norwegian spring spawning herring, Icelandic summer spawning herring, and North Sea herring) must be solved.

Geographical separation or structuring of the stock even within a limited fjord system is replete with biological implications. Describing this structure, not to mention understanding it, is necessary for proper stratification in analyzing large-scale survey data, as attempted in this work. Understanding the connection of spatial distribution of herring with hydrography, especially dissolved oxygen content, is similarly important.

Multiple-frequency echo integration is a potentially valuable tool for learning about fish behaviour and scattering properties. Speculation on this is found, for example, in Foote et al. (1993). The tool remains to be developed, however. Certainly to realize this potential, gross uncertainties due to inferior transducer performance must be eliminated. The solution is clear: replacement of the current 18- and 120-kHz transducers mounted on board R/V "Johan Hjort" with new transducer models that operate at the same frequencies.

ACKNOWLEDGEMENT

Fellow participants on the cruises are thanked for their steadfast help. The following are particularly thanked: K.A. Hansen and A. Romslo for interpreting gigabytes of data, R.J. Korneliussen for work on BEI, A. Nødtvedt for analyzing biological samples during the January 1994 cruise, and Ø. Østensen for preparing distribution maps and testing a new plotter during the December 1993 cruise. Two guest scientists, T. Kinacigil and M. Tiarsin, are thanked for participation in laboratory work, especially including swimbladder morphometry. The officers and crews of the vessels are saluted for their cooperation and patience, especially during navigationally intensive and wearying parts of the surveys.

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Table 1. Biological state of Ofotfjorden and Tysfjorden in which the mean backscattering cross section σ_b is differentiated. The root-mean-square length ℓ and target strength are derived from the equation $TS=20 \log \ell - 71.9$, where ℓ is expressed in centimeters.

Cruise period	Fjord region	ℓ(cm)	TS(dB)	σ_b (cm^2)	Stratum
December 1993	Tysfjord	35.23	-41.0	10.1	A
December 1993	Stefjord, Inner Tysfjord	31.63	-41.9	8.1	B
December 1993	Tjeldsund	27.80	-43.0	6.3	C
December 1993	Ofoten	34.16	-41.2	9.5	D
December 1993	Skjomen	25.20	-43.9	5.2	E
January 1994	Tysfjord	35.15	-41.0	10.0	F
January 1994	Inner Tysfjord	28.50	-42.8	6.6	G
January 1994	Stefjord	28.80	-42.7	6.7	H
January 1994	Ofotfjorden W of 17^{o}E	34.03	-41.3	9.4	I
January 1994	Ofotfjorden E of 17^{o}E	30.89	-42.1	7.7	J
January 1994	Skjomen	25.20	-43.9	5.2	K

Table 2. Mean values of s_A uncompensated for extinction as measured simultaneously at each of four frequencies during the January 1994 cruise, selected from four geographical and biological strata. The quantity ℓ denotes the root-mean-square fish length, and n_s the number of statistical squares of side length 0.2 NM in which there are measured values of s_A. The asterisks call attention to the absence of data at 120 kHz from a 5-NM interval of integration, which reduced n_s to 235 and 34 at the respective locations. The coefficient of variation cv is expressed in parentheses below the mean value of s_A.

Stratum	Area (NM^2)	ℓ(cm)	n_s	$s_A(1000m^2/NM^2)$ & (cv) vs. f(kHz) 18	38	120	200
Central Ofotfjorden W of 17°E	51.2	34.0	310	89.6 (1.4)	76.1 (1.4)	49.4 (1.5)	89.5 (1.4)
Central Ofotfjorden E of 17°E	40.6	30.9	237*	73.1 (2.0)	63.2 (2.1)	51.6 (2.3)	56.7 (2.1)
Rombaken	5.2	30.9	58*	0.19 (4.3)	0.19 (3.3)	0.15 (2.6)	0.18 (2.0)
Skjomen	9.5	25.2	110	14.3 (5.9)	13.3 (6.2)	10.1 (4.1)	9.0 (3.7)

Table 3. Abundance figures for herring in the Ofotfjord-Tysfjord system, derived from the large-scale zigzag surveys, expressed as total numbers of fish. Computations are performed both without and with compensation for acoustic extinction.

Cruise period	Without compensation	With compensation
December 1993	$9.5\ 10^{9}$	$13.2\ 10^{9}$
January 1994	$10.2\ 10^{9}$	$14.6\ 10^{9}$

Table 4. Probability density functions of length for herring over the entire Ofotfjord-Tysfjord system, obtained by weighting length distributions for individual biological strata by the estimated abundance in each stratum, expressed as percentage. The weighting functions are computed both without and with compensation for extinction.

Length (cm)	December 1993		January 1994	
	Without	With	Without	With
19.25	0.31	0.25	0.05	0.07
19.75	0.05	0.04	0.05	0.06
20.25	0.00	0.00	0.05	0.06
20.75	0.50	0.41	0.31	0.36
21.25	0.20	0.17	0.06	0.06
21.75	1.01	0.86	0.19	0.24
22.25	1.01	0.87	0.50	0.58
22.75	2.38	2.00	0.96	1.17
23.25	1.01	0.86	0.99	1.09
23.75	1.47	1.19	0.90	1.02
24.25	0.66	0.54	0.37	0.40
24.75	0.20	0.17	0.27	0.29
25.25	0.66	0.57	0.43	0.45
25.75	1.61	1.33	1.14	1.26
26.25	2.71	2.31	2.02	2.11
26.75	2.57	2.16	3.08	3.24
27.25	2.71	2.41	4.12	4.25
27.75	1.09	1.02	3.19	3.30
28.25	1.77	1.70	3.84	4.02
28.75	0.80	0.71	2.23	2.36
29.25	0.69	0.69	2.76	2.92
29.75	1.34	1.30	2.84	3.01
30.25	1.08	1.07	3.69	3.85
30.75	1.51	1.53	3.81	4.03
31.25	4.30	4.41	4.73	4.83
31.75	2.47	2.50	4.32	4.43
32.25	4.81	4.86	6.10	6.07
32.75	4.56	4.74	4.88	4.82
33.25	5.64	5.80	3.99	3.88
33.75	2.43	2.50	3.09	2.95
34.25	3.41	3.55	2.65	2.53
34.75	4.57	4.80	2.55	2.37
35.25	9.88	10.44	2.87	2.73
35.75	8.23	8.81	5.24	4.97
36.25	9.83	10.39	6.67	6.28
36.75	6.81	7.13	6.31	5.85
37.25	4.40	4.55	4.47	4.17
37.75	1.05	1.09	2.48	2.30
38.25	0.29	0.29	0.93	0.83
38.75	0.00	0.00	0.72	0.65
39.25	0.00	0.00	0.10	0.09
39.75	0.00	0.00	0.03	0.03

Table 5. Comparison of abundance estimates of herring surveyed in central Ofotfjorden by the large-scale zigzag design on 7 January 1994 and by a system of parallel, equally spaced transects with 0.5-NM separation on 9-10 January 1994. Numbers N are given both without and with compensation for extinction. The estimation variance σ_E and standard error of the mean, se, are expressed as percentages of the mean.

		Without compensation			With compensation		
Stratum	Survey design	N	σ_E	se	N	σ_E	se
W of 17°E	Zigzag	$4.14\ 10^9$	10.2	8.1	$5.54\ 10^9$	14.4	12.9
W of 17°E	Parallel w/end	$5.30\ 10^9$	6.8	5.8	$7.31\ 10^9$	9.6	7.9
W of 17°E	Parallel w/o ends	$5.50\ 10^9$	7.4	6.2	$7.59\ 10^9$	11.8	8.9
E of 17°E	Zigzag	$3.32\ 10^9$	22.7	13.8	$5.62\ 10^9$	29.4	20.0
E of 17°E	Parallel w/ends	$1.35\ 10^9$	10.1	12.1	$1.71\ 10^9$	10.8	14.7
E of 17°E	Parallel w/o ends	$1.42\ 10^9$	13.3	13.3	$1.83\ 10^9$	15.2	16.0

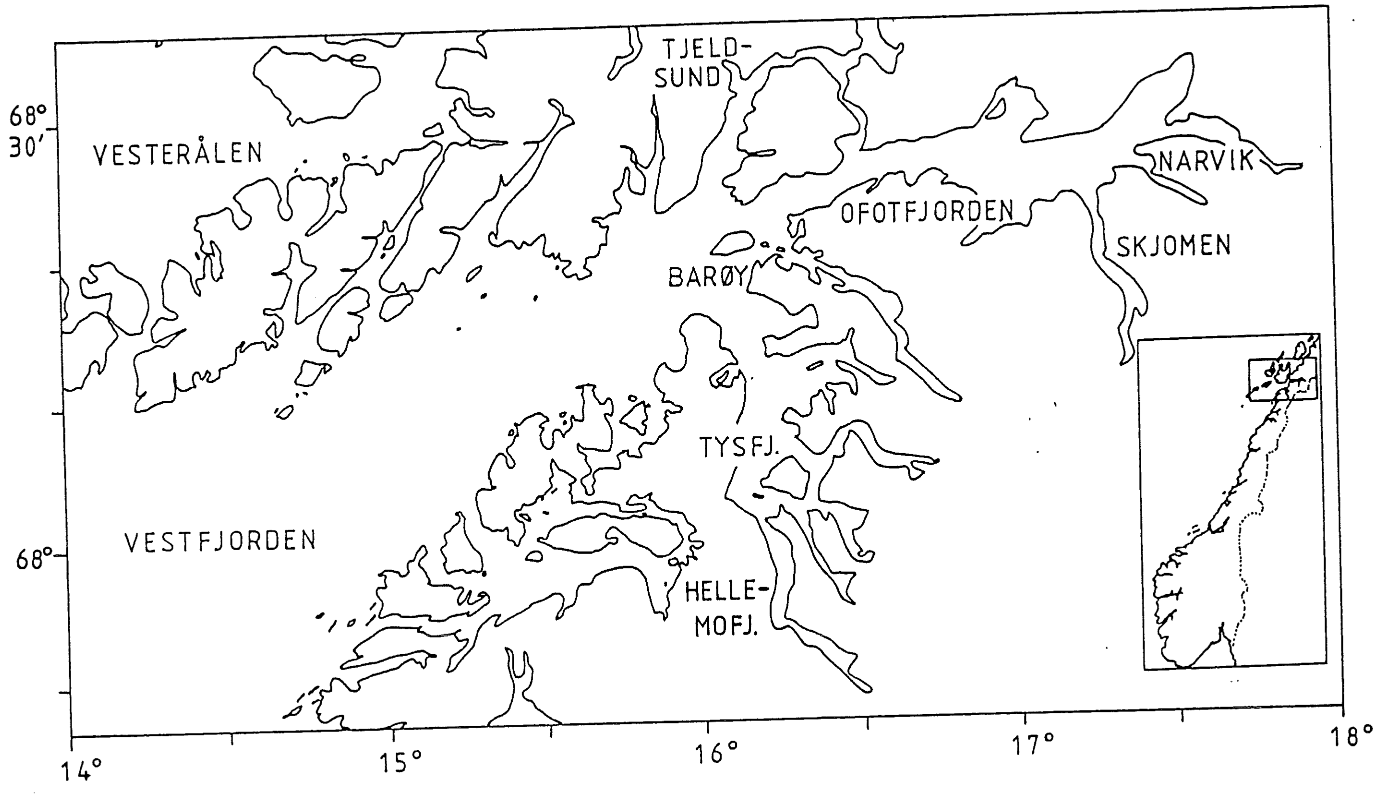


Fig. 1 Ofotfjorden, Tysfjorden and adjoining areas.

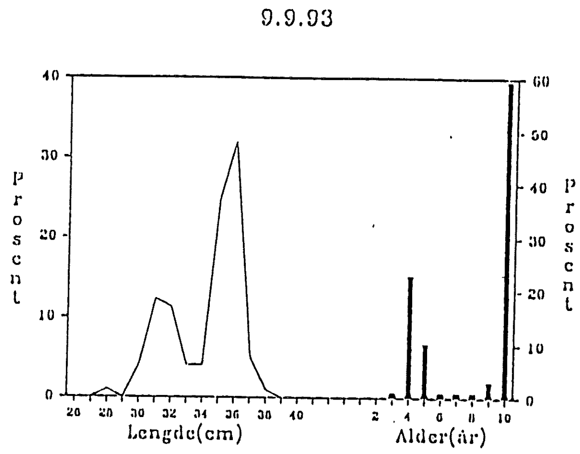


Fig. 2a Length and age distribution of herring at the front of the immigration to the wintering areas. Vestfjorden (approximately 14° E), 9.9 - 1993.

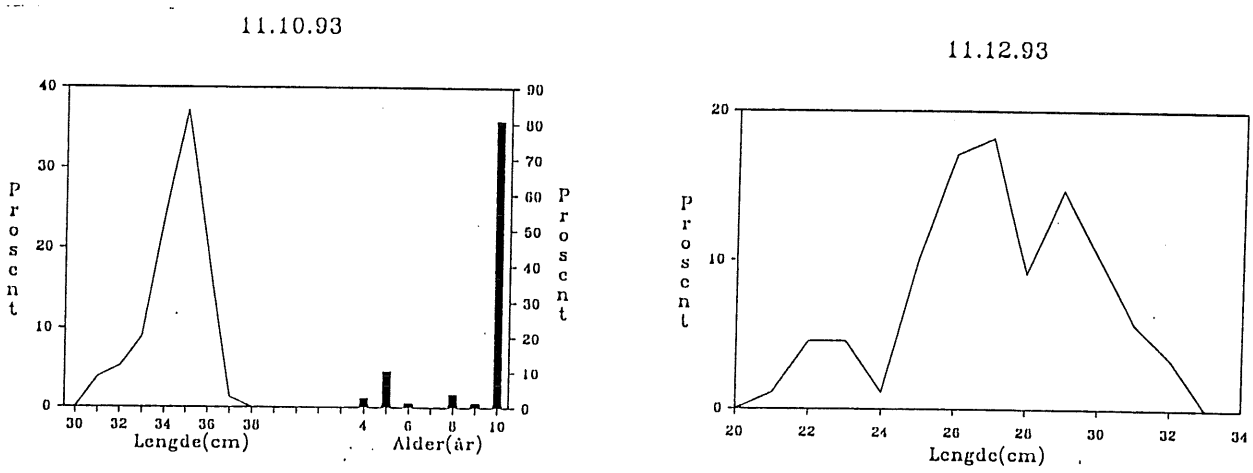


Fig. 2b Length distributions of herring at the outlet of Tysfjorden, 1.10 and 11.12 - 1993.

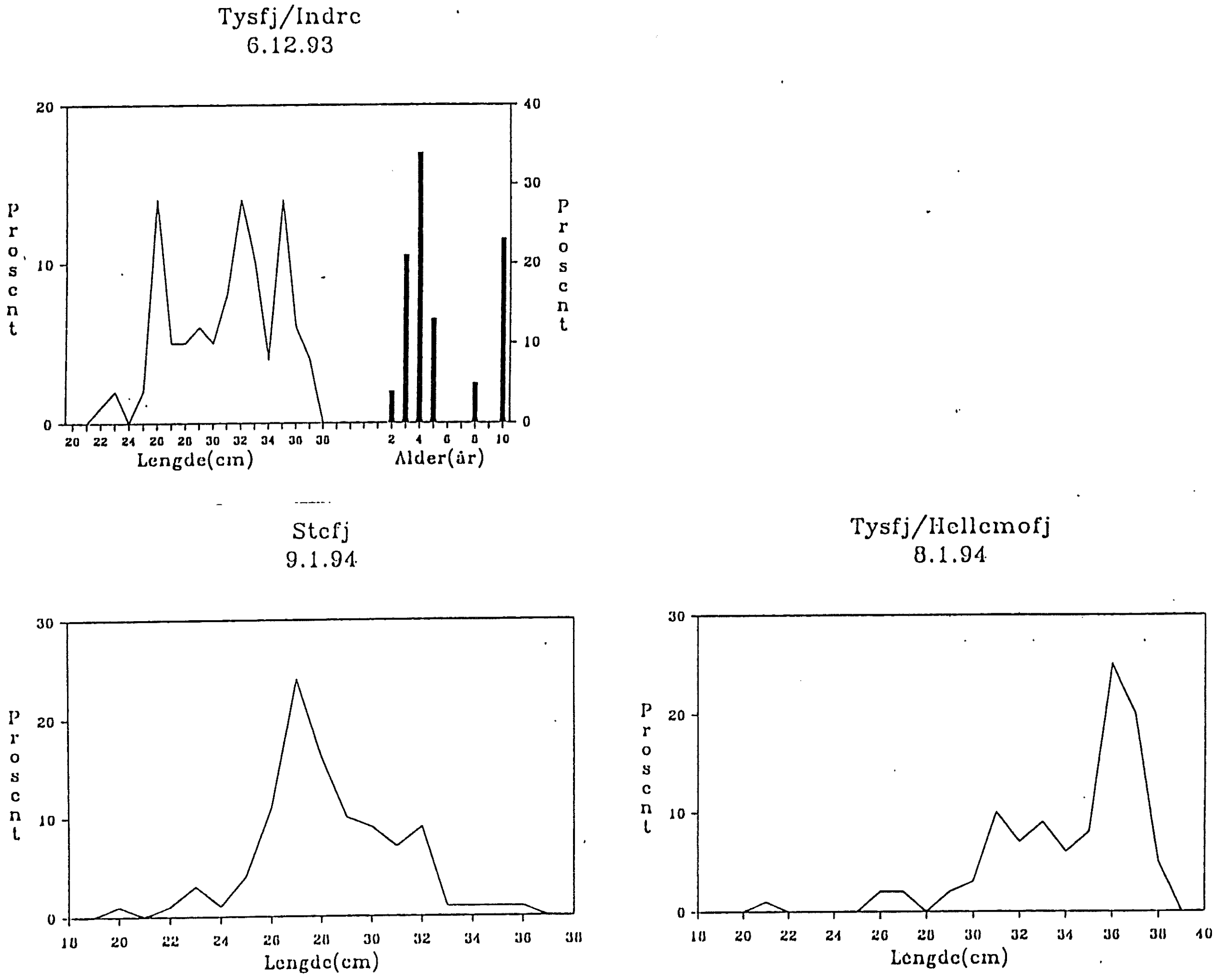
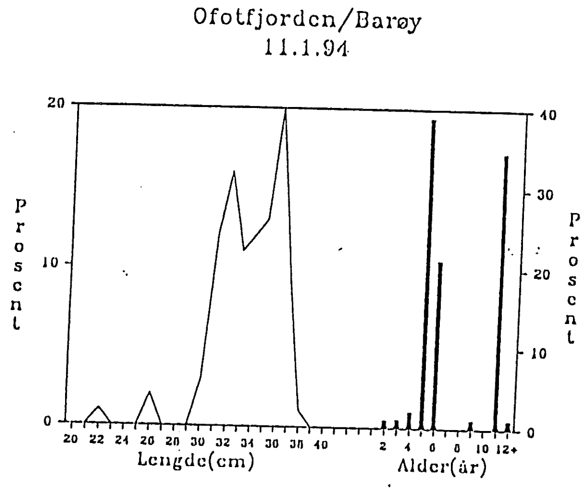
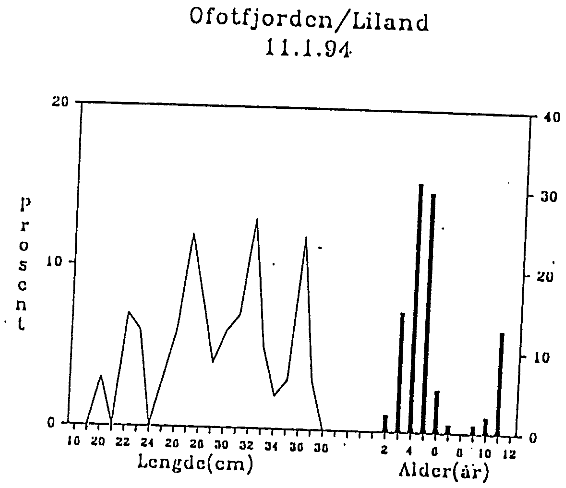


Fig. 2c Length distributions of herring in different tributaries of Tysfjorden in December 1993 and January 1994.





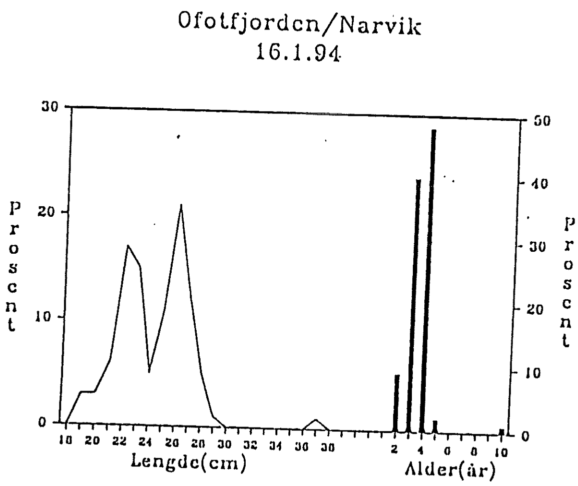


Fig. 3a Length distributions of herring from the outer (upper left), middle (upper right) and inner part of Ofotfjorden in the period 11 - 16 January 1994.

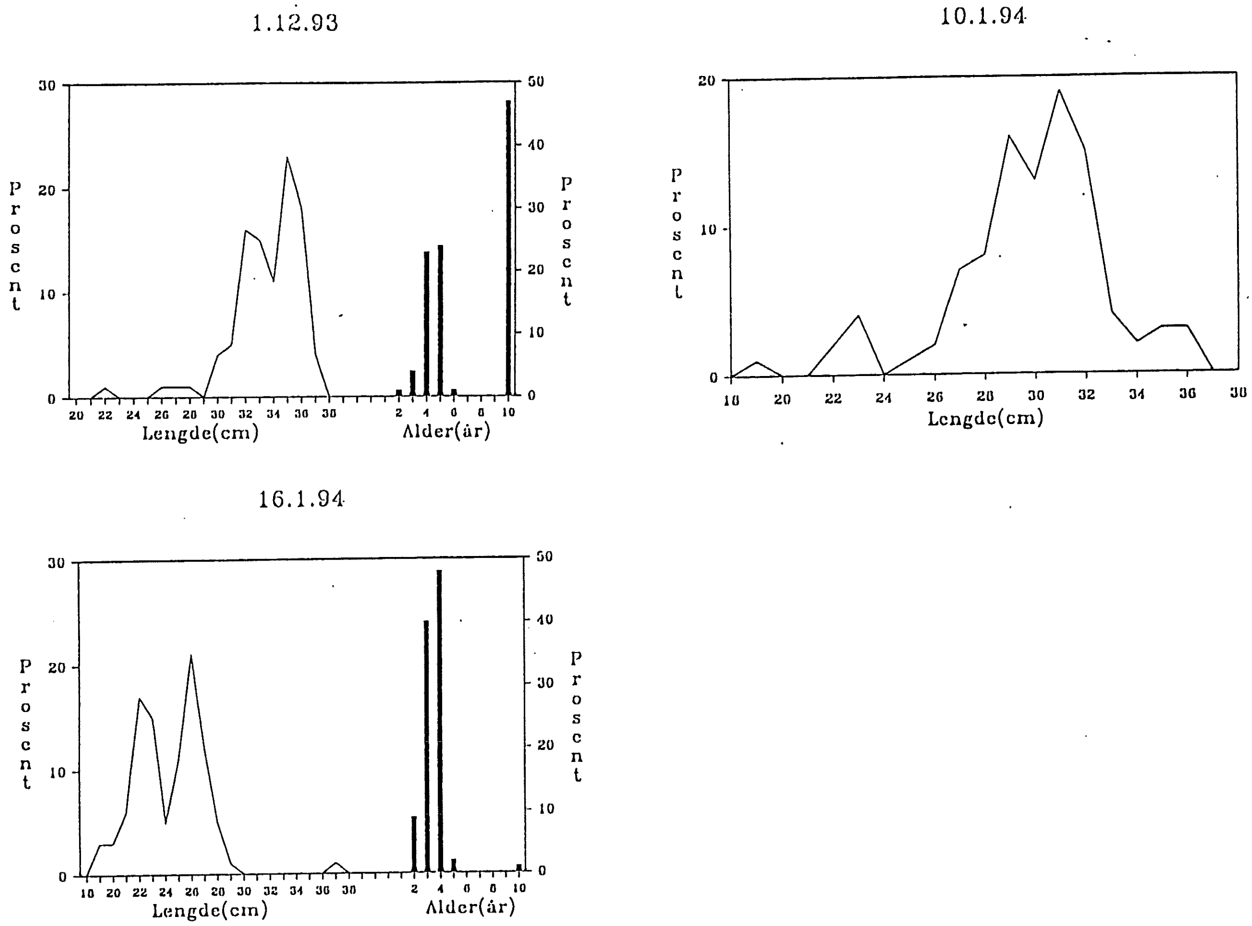


Fig. 3b Changes in length distribution of herring from the inner part of the wintering area (at Narvik) from 1 December 1993, 10 and 16 January 1994.

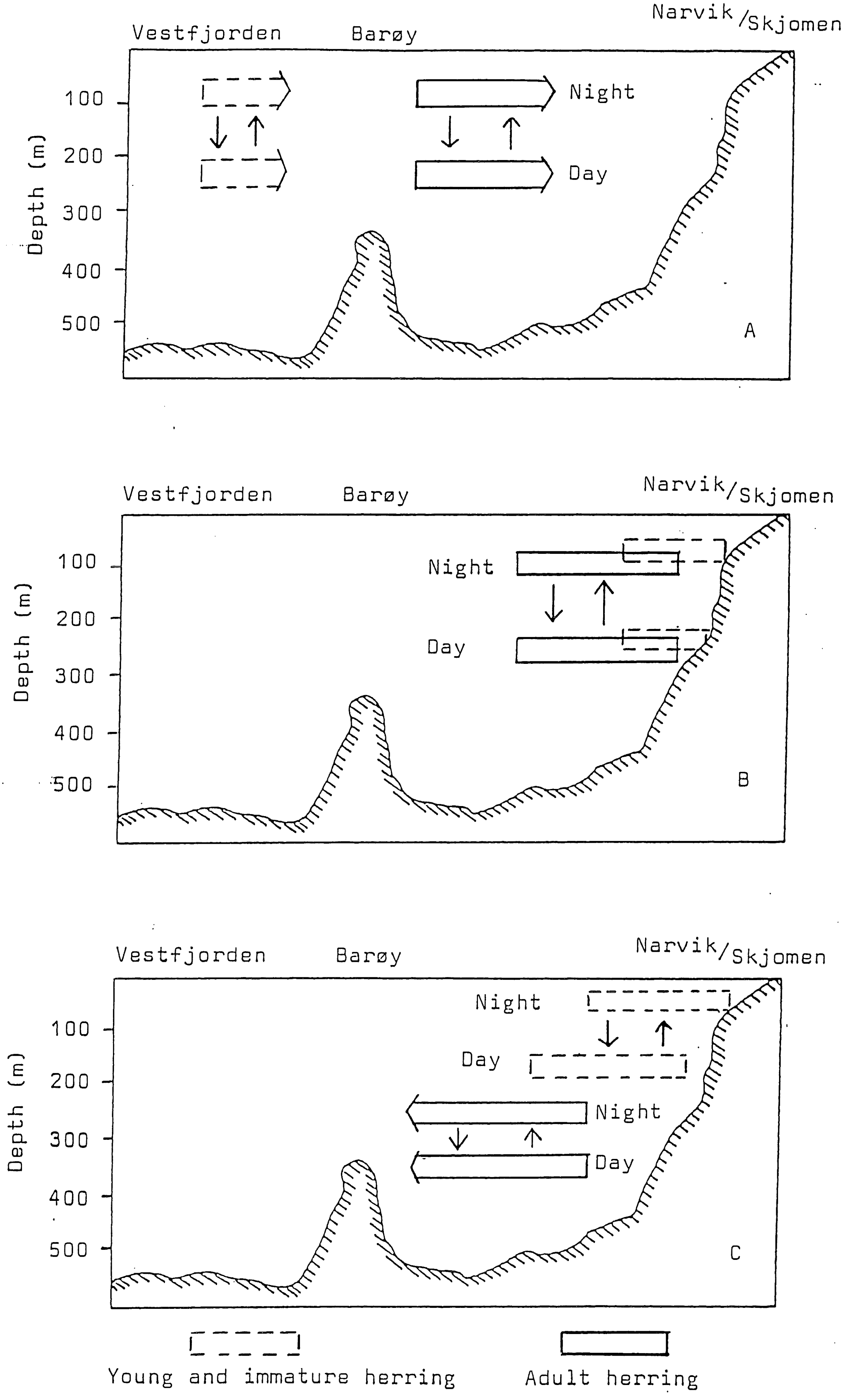


Fig. 4 Schematic presentation of immigration and emigration in relation to the wintering area. See text for explanation.

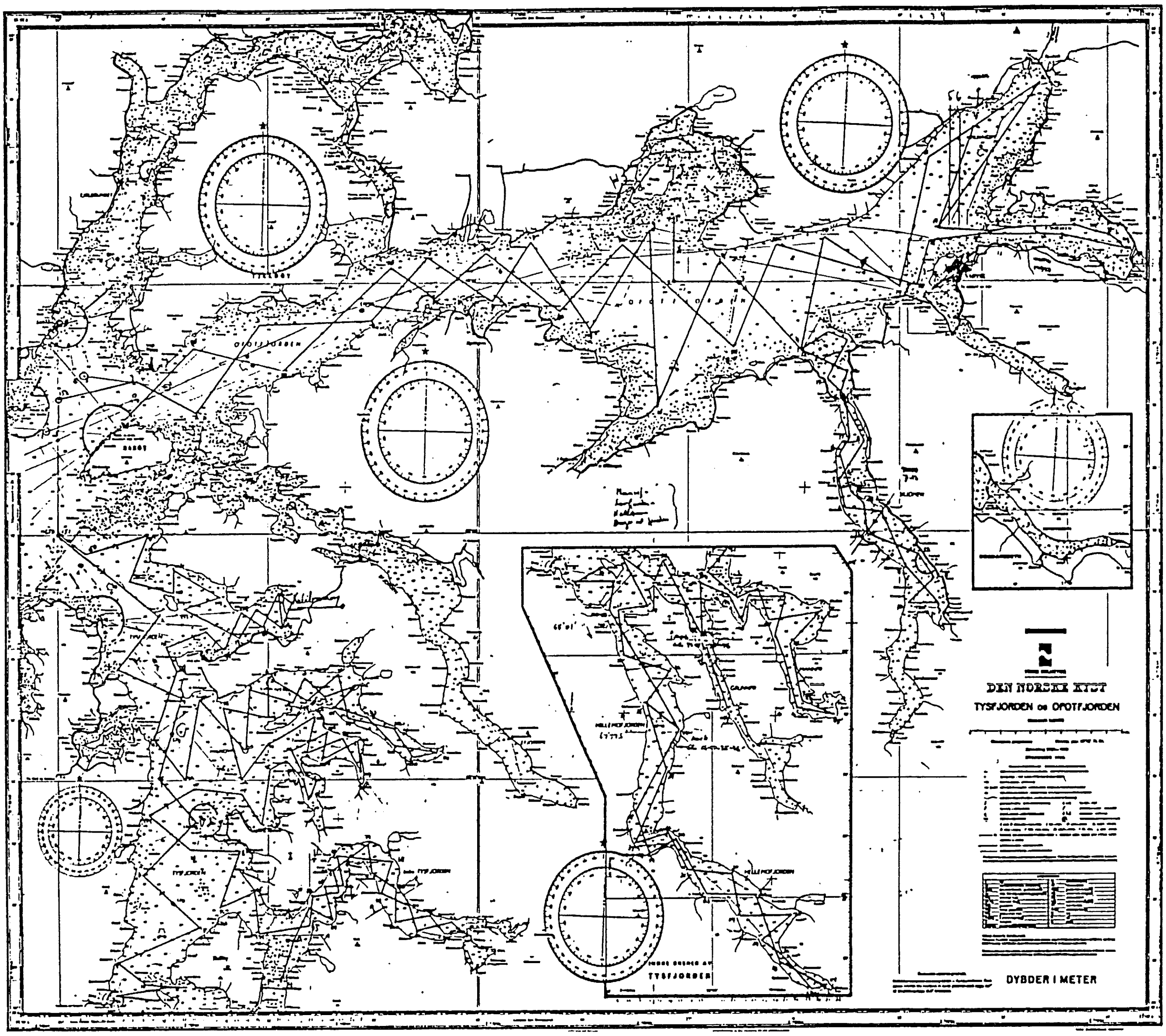


Fig. 5   Survey tracks in Ofotfjorden and Tysfjorden

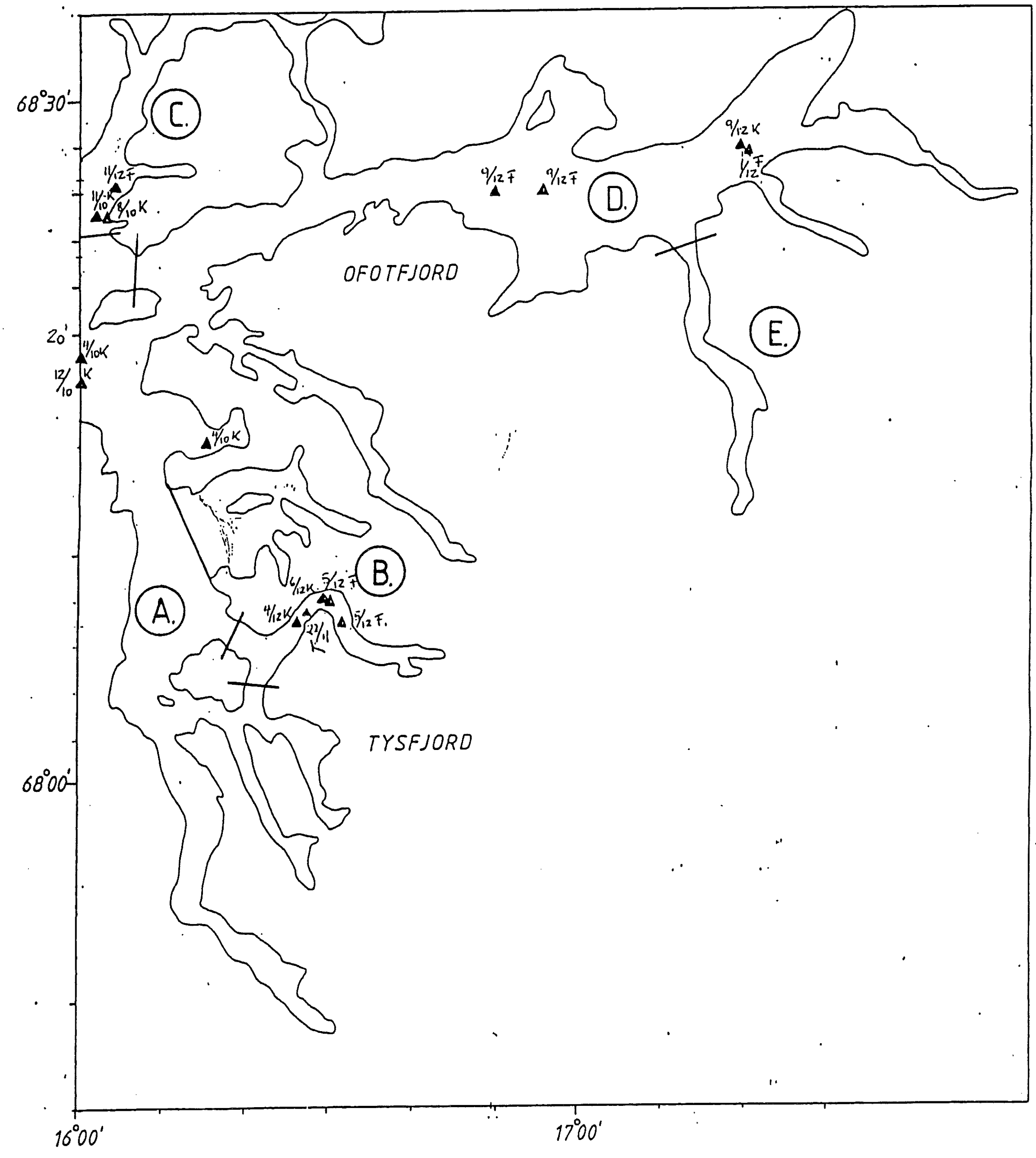


Fig. 6a Location of biological samples of Norwegian spring spawning herring in the wintering areas, October-December 1993. F= Reseach vessel (trawl), K= Commercial catch (purse seine). Encircled letters denote different strata (Table 1)

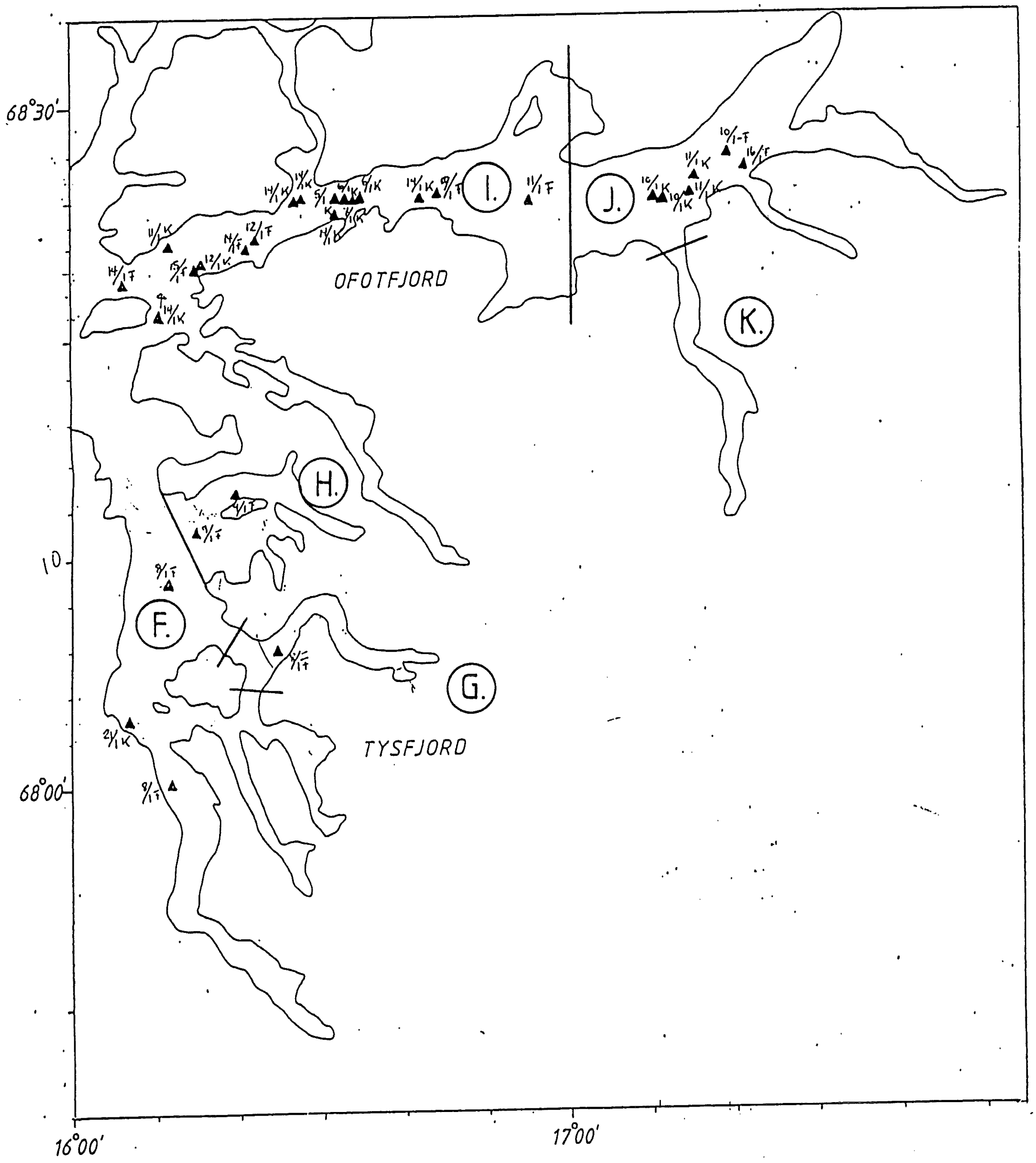


Fig. 6b Location of biological samples of Norwegian spring spawning herring in the wintering areas, January 1994. F=Research vessel (trawl), K=Commercial catch (purse seine). Encirled letters denote different strata (Table 1).

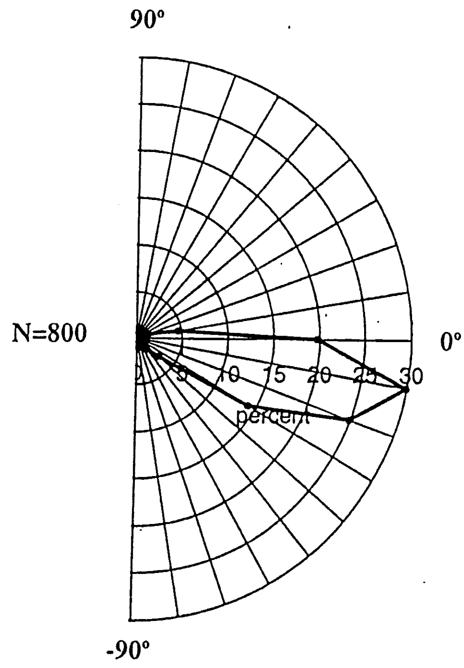


Fig. 7a Tilt angle distribution of herring in the wintering area. Daytime situation.

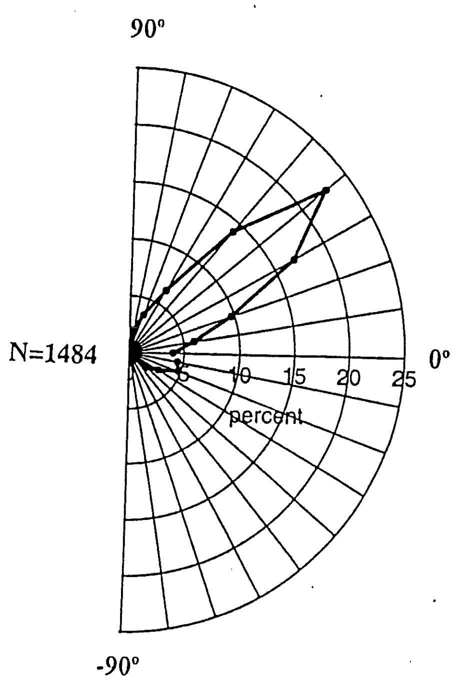


Fig. 7b Tilt angle distribution of herring in the wintering area. Night-time situation.

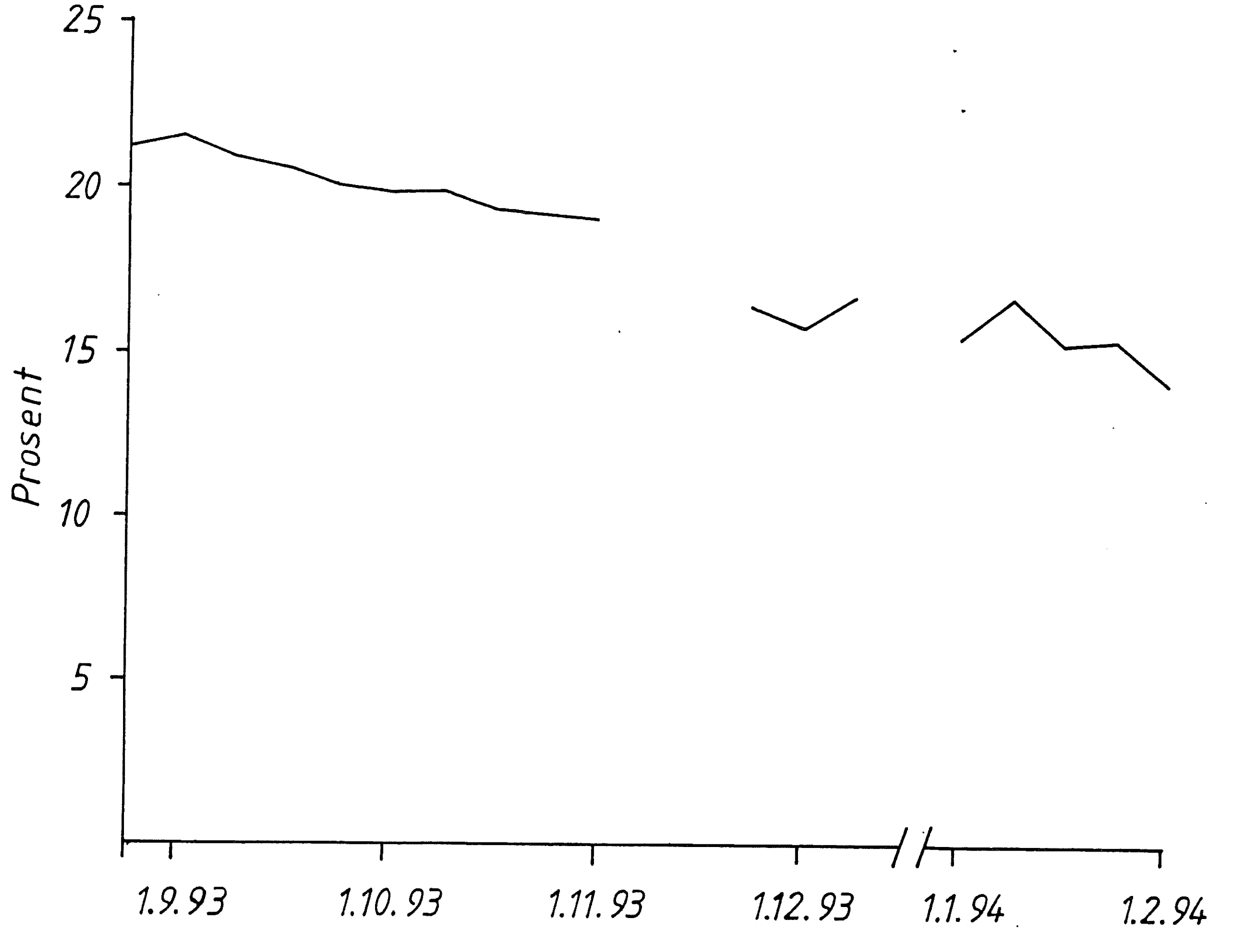


Fig. 8 Variation in fat content of herring in the wintering area in the period 1.9-1993 to 1.2-1994.

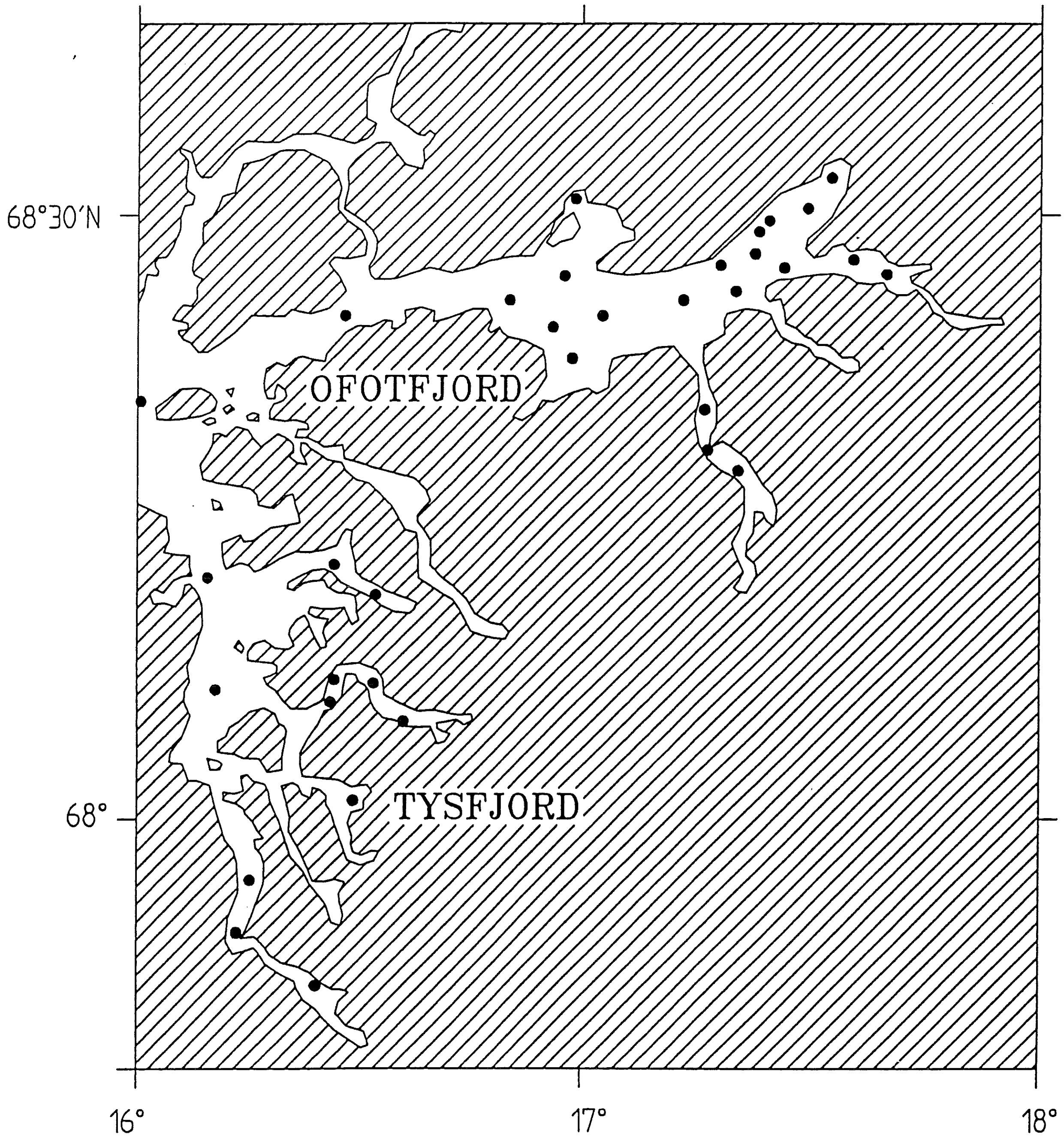


Fig. 9 Hydrographical stations worked from R/V "Michael Sars" during the November/December 1993 survey.

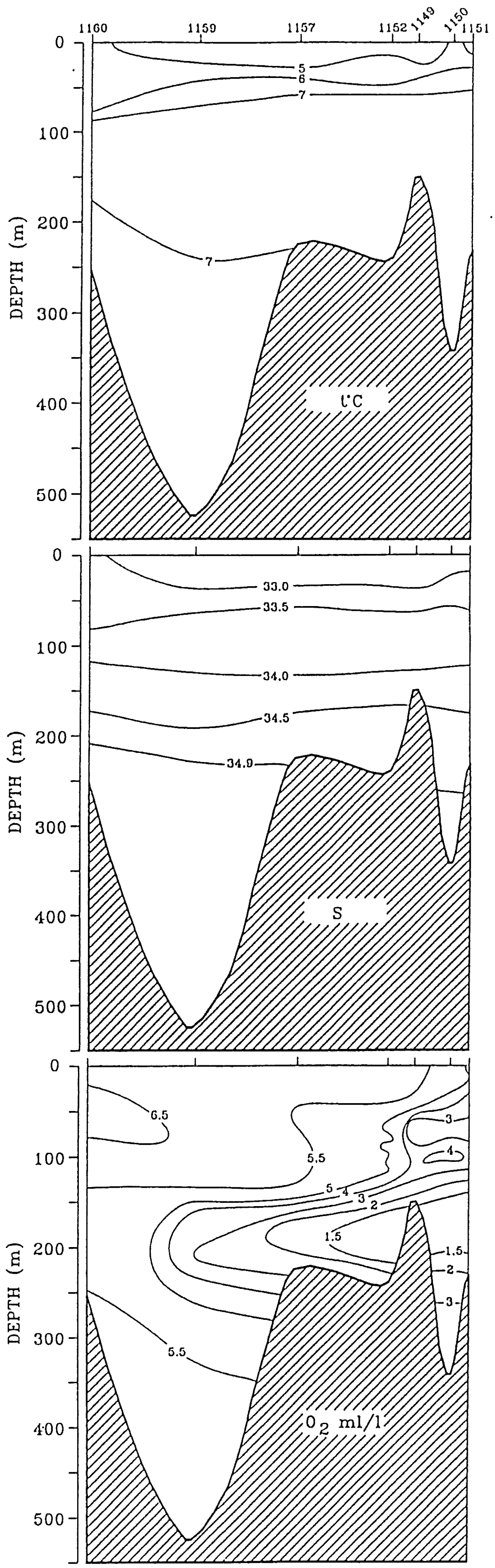


Fig. 10 Section along the entire Ofotfjorden showing temperature, salinity and oxygen conditions.

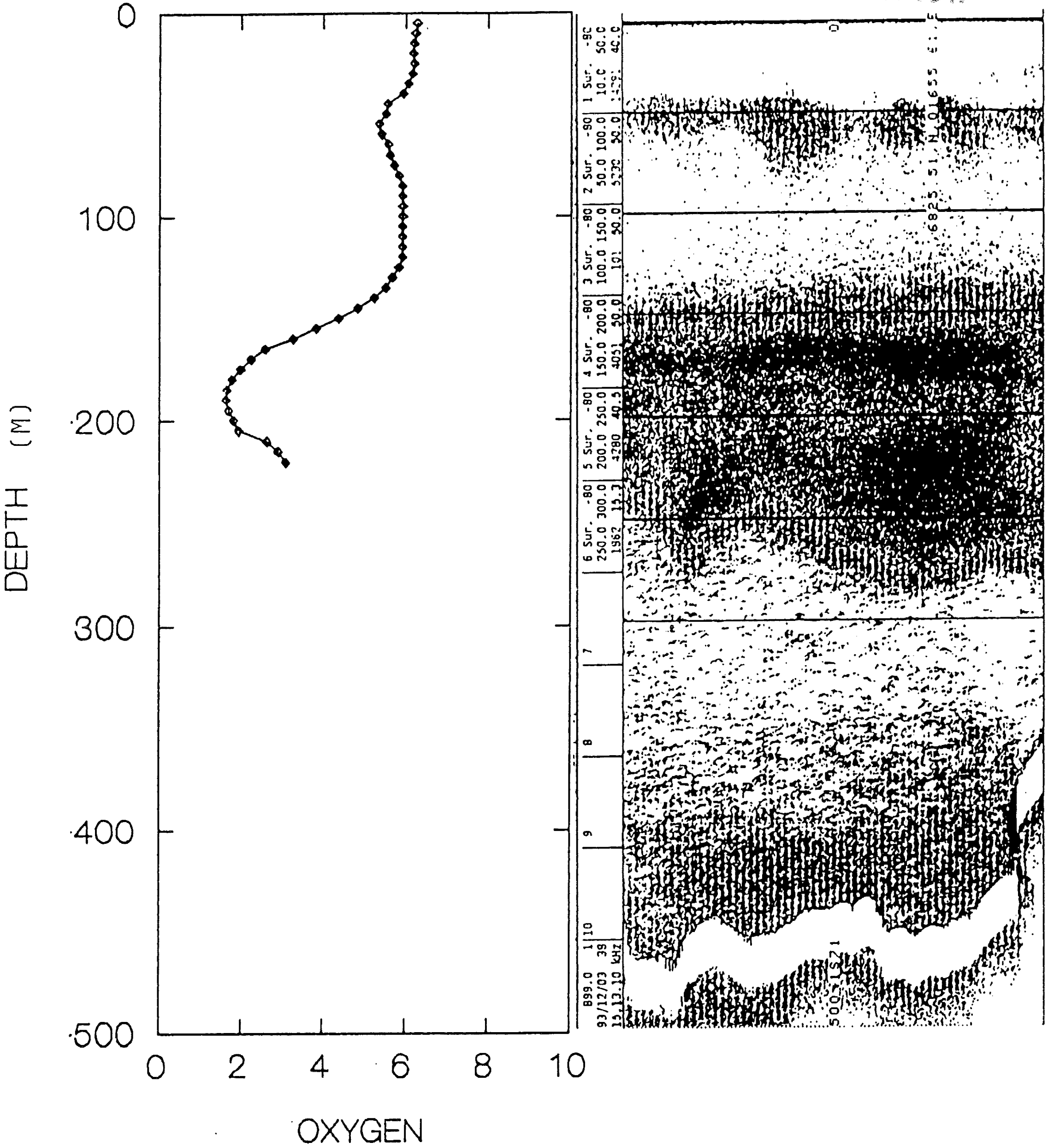


Fig. 11 Echo recordings of two herring layers, with corresponding oxygen profile.