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ACOUSTIC ABUNDANCE ESTIMATION OF THE STOCK OF NORWEGIAN SPRING SPAWNING HERRING, WINTER 1995-1996

by

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ABSTRACT

Standard echo integration methodology has been applied to the stock of Norwegian spring spawning herring (*Clupea harengus*) wintering in the Ofotfjord-Tysfjord-Vestfjord system during late autumn 1995 and early winter 1996. The primary instruments of acoustic data collection and processing were the SIMRAD EK500/38-kHz echo sounder and the Bergen Echo Integrator. Biological sampling was effected by means of a so-called MultiSampler pelagic trawl in addition to standard pelagic trawls. Compensation was made during postprocessing for the effect of acoustic extinction. The major complication of the survey and challenge of the analysis has been stratification. This is discussed in the context of (1) mixing of immature and mature year classes, each with its own behavioural characteristics apropos of diurnal vertical migration and outwards spawning migration, (2) degree of achieved survey coverage, depending on fjord geometry, navigational hazards, available time, and fish distribution, and (3) ongoing spawning migration. Because of various uncertainties, a series of abundance estimates is presented. These are accompanied by fitted variogram models and geostatistical variance estimates.

INTRODUCTION

The spawning stock of Norwegian spring spawning herring (*Clupea harengus*) has been wintering in the fjords of northern Norway since autumn 1987. The stock has been concentrated, apparently exclusively, in the Ofotfjord-Tysfjord-Vestfjord system (Fig. 1) since autumn 1991, providing excellent conditions for acoustic abundance estimation by the echo integration method (Gunderson 1993). Indeed, comprehensive acoustic abundance surveys have been performed annually since autumn 1992 (Foote 1993a, Røttingen et al. 1994, Foote and Røttingen 1995).

It is no coincidence that this surveying acitivity has followed the solution of technical problems connected with large if not extreme magnitudes of concentration. Specific reference is made to the acoustic registration of dense, extended concentrations without suffering saturation in the echo sounder receiver, achieved with the SIMRAD EK500 echo sounder (Bodholt et al. 1989), and compensation for extinction, requiring both an automatic algorithm (Foote 1990) and numerical values for the characteristic extinction cross section (Foote et al. 1992, Foote 1994).

Notwithstanding the establishment of new instruments and techniques for surveying wintering herring, other problems have become apparent. Chief among these, ignoring for the moment the matter of target strength and its dependence, is that of stratification. In earlier years, this consisted primarily in achieving a sufficient degree of coverage within a period of time that was rather short compared to characteristic times of non-migration movement of the herring within the fjord system. That this was the major concern was due to the dominance of the 1983 year class.

Because of fishing and the recruitment of new year classes, the percentage representation of the 1983 year class has fallen steadily and dramatically over the last two years. The mentioned year class may now represent less than 5 % of the total stock. Thus, in addition to problems of coverage, biological stratification has become a major concern. Year classes from 1990, 1991, and 1992 occur in increasing proportions. Parts of the 1991 and 1992 year classes were not mature, and did not take part in the spawning migration. Thus there were in the survey area herring with different habits of diurnal vertical migration and spawning migration, inter alia. Knowing what is being registered: age and size composition, has become a serious challenge for the survey. This is being addressed by a new development in gear technology, that of the MultiSampler pelagic trawl (Engås et al. 1996).

An additional challenge associated with the survey in January 1996 is that the research vessel was, for operational reasons, not available for survey use before the middle of January. Since the outwards spawning migration begins roughly in early January, this was late indeed to be commencing a stock abundance survey.

The aim of this paper is to describe how the particular acoustic surveys were performed this past winter and how the data were analysed, in order to support the results. Necessarily issues of methodology were involved, and these are described and discussed critically, to point to the need for research in specifics areas, but also to remind ourselves of the complexity of tasks underlying an acoustic abundance survey of a large pelagic fish stock consisting of many year classes.

MIGRATION AND RECRUITMENT BIOLOGY

Adult stock

In August, after termination of the feeding season in the Norwegian Sea, the adult part of the Norwegian spring spawning herring stock migrates to the wintering areas where it concentrates at high densities. Since 1987/88 the wintering areas of the adult Norwegian spring spawning herring have been located in the inner tributary fjords of Vestfjorden in northern Norway, and from autumn 1991, in Ofotfjorden and Tysfjorden (Røttingen 1992). At the end of December- beginning of January, the adult herring start their spawning migration. The herring spawns on the coastal banks of the west and northwest coast of Norway.

The 1983 year class was very strong, followed by weak year classes in the period 1984 - 1988. The 1983 year class recruited to the spawning stock in 1988, and due to the following weak year classes the 1983 year class totally dominated the spawning stock from 1988 until 1993 when the 1989 year class began recruiting to the spawning stock. In this period the fishing mortality was low (F< 0.05, Anon 1996).

Juvenile stock

The main nursery area for the Norwegian spring spawning herring in later years has been the Barents Sea. In this area the herring stay for a period of 2-4 years before they migrate westwards and into the Norwegian coast/Norwegian Sea ecosystem. The first winter after leaving the Barents Sea the juvenile (immature) herring winter along the Norwegian coast. In recent years the Vestfjorden area has been the main wintering area also for the immature part of the population of Norwegian spring spawning herring.

The year classes 1989 and 1990 have been of average strength, but the following year classes, 1991 and 1992, are strong, being comparable in strength to the 1983 year class. These year classes have, after leaving the nursery areas in the Barents Sea, spent their first winter in the Vestfjorden area. The result has been that in 1994-1995, and especially in 1995-1996, there have been large concentrations of immature herring, in addition to the adult component, present in the wintering areas of Vestfjorden. The immature herring do not take part in the spawning migration, which commences in the period from the end of December and beginning of January. These herring leave the wintering area in March-April, at the start of the plankton bloom on the coastal banks.

Stock structure in the wintering areas in 1995-1996

The recruitment development described above has resulted in a complete change in the stock structure in the wintering areas in recent years. Prior to 1993 the stock in the wintering area in Vestfjorden was completely dominated by the 1983 year class, and very little immature herring were recorded due to weak recruiting year classes. In contrast, in 1995-1996 large concentrations of immature herring of the 1991 and 1992 year classes were present and formed complex concentrations with the mature herring. The spawning stock now consists of a series of year classes 1983, 1989, 1990 and the larger individuals of the 1991 year class. Because of this recruitment and an increasing fishery (F in 1995 was approximately 0.17), the proportion of the 1983 year class in the wintering area has decreased to less than 10 %.

ACOUSTIC SURVEYING METHODOLOGY

The acoustic surveying method of choice for use in determining the abundance of a large pelagic stock is that of echo integration (Forbes and Nakken 1972, MacLennan 1990). This has been reviewed several times in recent years (Foote 1993b and 1996, Gunderson 1993).

In essence, echo integration involves the following steps: (1) measuring the volume backscattering coefficient throughout the region of fish occurrence, (2) integrating the coefficient at each station or position of echo sounding to yield a cumulative surface-related measure of fish density, the area backscattering coefficient s_A (Knudsen 1990), (3) allocating this to specific scatterer classes, both in terms of species and size, among other characteristics, (4) converting the derived acoustic measures of fish density to biological measures, for example, number of fish in a certain size class per unit area, (5) integrating derived density measures for each scatterer class over the entire region of occurrence, and (6) compounding the individual abundance estimates for each scatterer class to describe an overall abundance distribution by size for the target species.

The enumeration here is meant to describe the conceptual framework for the acoustic surveys of herring. It should be clear that without close attention to a wealth of logistical and operational matters, including coordination of activities involving vessel crew and research staff, and attention to the state of weather and sea, the entire enterprise can come to naught. Specific measures taken to effect the surveys are now described.

MATERIALS AND METHODS

Acoustic survey and instruments

The first survey was performed with R/V "G.O. Sars" during the period 24 November - 12 December 1995. The second survey was performed with R/V "Johan Hjort" 16-28 January 1996.

The usual complement of acoustic instruments was available on each vessel. The heart of the instrumentation suite was the SIMRAD EK500 scientific echo sounder system (Bodholt et al. 1989) with connected 38-kHz transducer, SIMRAD model ES38B. Attached to this by means of a local area network (LAN) was the Bergen Echo Integrator (BEI) (Foote et al. 1991), a system that is used both as a datalogger and for postprocessing, including entry of interpreted data into a database.

Additional essential instruments connected to the echo sounder or BEI are a differential Global Positioning System (GPS) unit and the ship's log. At present, a Trimble model NT200D GPS with built-in differential receiver is connected directly to the EK500 by serial line.

Survey design

During the months preceeding the cruise, information is accumulated on the whereabouts of herring in the fjord system. This generally comes from two sources: earlier research cruises, if entering the system after the onset of the late summer-early autumn migration, and the fishery.

Nonetheless, both experience and knowledge of herring biology indicate the inescapable need for comprehensive coverage at the outset of the survey. This need must be weighed against the need to put resources where the fish are, that is, to concentrate the coverage in regions of greatest abundance. Since this must be defined first, the surveys are generally performed in stages, especially during the November-December period.

Such a two-stage design is indicated in Fig. 2, which shows the survey designs applied in Ofotfjord in the November-December period. The first survey design is a rather coarse zigzag, which took about 10 hours to execute, exclusive of Skjomen. The second design consists of parallel, evenly spaced transects oriented perpendicular to the east-west axis of the fjord. This second design took about 14 hours to execute, again exclusive of Skjomen.

In the geometrically and navigationally complicated Tysfjord, the applied survey is composed of parallel, zigzag, and ad hoc designs. The survey design for the same 1995 period is shown in Fig. 3.

Vestfjord is often surveyed initially by a large-scale zigzag pattern. This was the case in November 1995. Following this, a detailed design of parallel, evenly spaced transects was followed, as shown in Fig. 4.

Survey designs employed in January 1996 are described in Figs. 5-7. Enumerated strata are described in Tables 1 and 2 for the respective surveys.

Acoustic measurements

The measurements were made with the EK500 echo sounder using a pulse duration of 1 ms and receiver bandwidth of 3.8 kHz. The maximum pulse repetition frequency (PRF) was selected, hence was determined by the number of transducers in use, bottom depth, and signal processing operations. It was roughly 50 pings per minute.

Calibration was performed according to the ICES-recommended procedure (Foote et al. 1987) using each of two standard targets, the 60-mm-diameter copper sphere and the 38.1-mm-diameter sphere composed of tungsten carbide with 6% cobalt binder. Because the calibration exercises were performed after the bulk of the acoustic measurements, required adjustments in scaling factors were made during the analysis.

The particular adjustment factor specified during the calibration exercise are the following: for the November-December 1995 survery, $10^{0.12} = 1.318$, and for the January 1996 survey, 0.878. Thus the measurements made during the first survey had to be adjusted upwards, while those of the second had to be adjusted downwards.

Trawl sampling

Until 1995, a standard pelagic trawl with a vertical opening of approximately 25-30 m has been employed during the surveys to obtain biological samples of herring detected acoustically. By using this trawl technique, it has not been possible to obtain representative samples of the length composition throughout the whole depth extension (40-300 m), since the possibility exists that catches from a deeper layer can be "contaminated" by specimens captured while the trawl passes up and down through shallower depths. Further, when sampling with trawl on the dense concentrations of herring on the wintering grounds, the trawl will be completely filled before it can be lower to the deeper layers of the herring concentrations.

A newly developed sampling device, the MultiSampler (Engås et al. 1996), has been experimentally applied during the herring cruises. The MultiSampler replaces the extension section and codend of the standard pelagic trawl. However, the rigging, trawl speed and other characteristics of the trawl are unchanged. This system for remotely opening and closing three codends (similar codends to the standard pelagic trawl) makes it possible to take three uncontaminated samples during discrete, user-selected periods within a single trawl haul (Fig. 8). During shooting, haulback, and between each sample collection, the MultiSampler is open and fish can pass freely through it and out of the trawl.

Postprocessing of acoustic data

The primary instrument for postprocessing has already been described. This is the Bergen Echo Integrator (BEI). Allocation of acoustic samples to the target species is performed by experienced operators working in concert with biologists. In the specific case of the wintering herring, the appearance of the echogram, indicating the degree of concetration and position in the water column, is decisive for the allocation.

As the allocation is made, the resulting measures of s_A are stored with the chosen degree of resolution. For the concerned fjord surveys, these are 0.1 nautical miles in sailed distance and 10 m in depth.

Following data allocation, a series of quality-control procedures are initiated. These are designed to ensure (1) that all interpreted data are included in the postprocessing, (2) that the values of these of these correspond qualitatively with expectations based on the paper echogram, (3) that operations associated with the transfer of data between databases on board data collection vessel and ashore are effected without corrupting the data, which should never be regarded as a foregone conclusion, and (4) that the registered positions agree reasonbly well with the desired vessel tracks as drawn on the navigator's chart and further defined by a tabulated list of turning points. Errors due to failure of the GPS system are not uncommon, which is understandable because of the high latitude and frequent close proximity of high mountains to the inner-fjord survey regions. Correction of such errors is generally time-consuming, a thankless task for sure, but necessary.

When the data have passed the quality-control tests, they are adjusted according to the calibration and compensated for the effect of extinction. The assumed extinction cross section σ_e is that described in Foote (1994), namely

$$\sigma_e = 2.41\sigma_b,$$

where σ_b is the backscattering cross section. This important factor is also used in the later conversion of the acoustic measures of fish density, the described area backscattering coefficient s_A, to biological measures of fish density according to the formula,

$$\rho_A = s_A / \sigma_b ,$$

where ρ_A is the area density of fish: the number of fish per unit area.

The backscattering cross section is defined by the standard equation for Norwegian spring-spawning herring (Foote 1987),

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

where TS is the target strength in decibels, r_o is the reference distance of 1 m, and ℓ is the characteristic fish length in centimeters. For the finite length distribution of ordinary survey work, the root-mean-square measure is used.

Stratification

Basic ingredients of stratification are the degree of acoustic coverage, hence shape and size of the fjord area and presence of navigational hazards; observed or suspected variations in biological composition of the surveyed fish; and the fish distribution itself. In the absence of accurate remote techniques, physical capture and identification of the observed fish are essential.

As already described, the new MultiSampler pelagic trawl is potentially invaluable, especially for resolving structural differences with respect to depth but also with respect to lateral distance at constant depth, as the herring may not mix very much even on the local scale.

Ultimately, performance of an acoustic survey with a single vessel requires choosing between mutually incompatible but essential activities: sailing to achieve coverage and trawling for the sake of identification, both of which are necessary for proper stratification.

In the survey performed in the winter 1994-1995 (Foote and Røttingen 1995), some strata were defined by depth. This has proved nearly impossible for the current survey because of admitted inadequate trawl sampling. Thus the strata indicated in Figs. 2-7 apply to the entire water column in the respective regions.

Computation of abundance and geostatistical variance

The basic acoustic datum s_A is the result of integrating ping-based measurements over a sailed distance of 0.1 nautical mile. Because of use of the starting position of each interval as the position reference, as well as uncertainty in position, s_A-values compensated for extinction and integrated over the water column are averaged over statistical squares of side length 0.2 nautical mile. These averaged values are themselves averaged over each stratum. Division of the resulting number by the mean backscattering cross section σ_b yields the area density of fish ρ_A. Multiplication of this by the stratum area A yields the number of fish in the stratum, namely

$$N = A\rho_A .$$

When multiplied by the length distribution, this number describes the abundance in the stratum by length.

The variogram γ is also computed for each individual stratum. This is then modelled as the sum of a nugget term $N(h)$, a constant at all distances except at the origin itself where $N(h)$ vanishes, and the spherical function $S(h)$,

$$S(h) = \begin{cases} 1.5h/a - 0.5(h/a)^3 & h \le a \\ 0 & h > a \end{cases},$$

where a is the so-called range (Matheron 1971, Cressie 1991). The model is expressed thus:

$$\gamma\ (h) = A_N N(h) + A_S S(h).$$

Specific model parameters are described in Tables 3 and 4.

The variogram model is averaged with respect to transect position and finite, digitized positions representing the total area or volume of interest. The estimation variance is computed thus:

$$\sigma_E^2 = 2\bar{\gamma}_{tv} - \bar{\gamma}_{tt} - \bar{\gamma}_{vv},$$

where the subscripts describe the source of the positions for computation of the distance lag h used in the several averaging operations.

Given estimates of abundance and estimation variance for the individual strata, the global fjord estimates can be derived by simple addition. The individual strata estimates serve as weighting factors for description of the overall biological structure of the fjord, as through summary histograms of length.

Details on spatial structure

Data on dimensions and variability of wintering concentrations of herring are given in Ostrowski and Foote (1996). These data apply to the major concentrations of herring in Vestfjord during the January 1996 survey. Among other things, presented vertical sections of herring distributions show significantly different degrees of structure across the boundary separating the large mixed concentrations in inner Vestfjord and the migrating fish in outer Vestfjord. This observation is supported by geostatistical analysis.

RESULTS AND DISCUSSION

Variation in biological parameters of herring determined by sampling with the MultiSampler trawl

The MultiSampler trawl was applied to sample the large wintering concentrations of herring (Fig. 9). This sampling instrument revealed a non-homogenous structure with respect to length, age and other biological parameters. Full documentation of all results is not given in the present report as this requires more investigations. However, examples from the MultiSampler catches are given in Figs. 10-12. In Fig. 10 the length and age distributions are presented for each of three different depths (45, 80 and 215 m) within the herring concentration shown in Fig. 9. It can be seen that the average age and length of the herring increases with depth.

Increasing length and age distribution with depth is confirmed in the results from another MultiSampler catch, which is given in Fig. 11. Further analysis of the biological material shows that within single year classes (in this case year classes 1991 and 1992), the larger and more mature individuals are located at greater depths (Fig. 12).

Characteristic fish length for use in the standard TS equation

It should be pointed out that the above results refer to the time of the day when the sampling was carried out. A continuous vertical and horizontal (mainly spawning) migration occurs steadily in the wintering area. The surveying operation takes place continuously throughout the 24-hour period, during which the vertical structure, with respect to age and length distributions, changes continuously.

The MultiSampler concept is so new that sampling strategy is still being developed. During the surveys reported here, no serious attempt was made to stratify the major, mixed concentrations of herring. Only in some areas with minor concentrations of biologically homogenous herring were specific trawl stations applied in computing the characteristic fish length. For instance, this was the case in the outer part of Vestfjord where only migrating adult herring were recorded.

In areas where the major concentrations were mixed, all trawl samples were used with equal weighting and without regard to depth or other stratification in determining fish length. The root-mean-square measure of the resulting composite length distributions for each survey was used in the standard TS equation, yielding the abundance distributions in Fig. 13.

Notwithstanding severe difficulties in stratification, the cumulative distribution functions corresponding to the two length distributions in Fig. 13 are not significantly different. The Smirnov statistic is 0.1315, for which the probability is between 5 and 10%, assuming a sample size of 100. This is near the ordinary limit for being considered significant, but in the context of profound uncertainty in the allocation of trawl samples, is very suggestive of an underlying consistency of analysis.

Abundance estimates

Absolute abundance estimates are summarised by cruise and fjord in Table 5. Clearly, there is a massive outwards movement of the herring in the one and one-half months between the tow cruises. This reflects the onset of the spawning migration.

Absolute abundance estimates are presented for the total surveyed area for each cruise in Table 6. Apropos of the very modest geostatistical estimates of variance, respectively 5.4 and 6.2% of the mean estimates for the two cruises, the difference in mean abundance estimates is indeed striking. This may be tempered, or mitigated, however by considering the exact circumstances of the measurements.

(1) During the cruise in November-December 1995, the neighbouring region of the highest concentrations in Vestfjord was inaccessible to the research vessel due to the presence of gillnets and ongoing fishing operations. The first absolute estimate for Vestfjord given in Table 5 is thus an underestimate.

(2) As already mentioned, the cruise in January 1996 began in the middle of the month, which is much later than was planned or is desirable, since the spawning migration begins in late December or early January. In fact, the migration front was well south of 67^0 by 21 January (Table 2 and Fig. 7). The survey was performed only in a single direction, namely outwards. The coincidence of survey and spawning directions most likely introduced a positive bias into the estimate because of effective, so-called, double-counting of the fish. While no individual fish may have been registered on more than one transect, the area of dispersion of the stock was increasing during the nearly three days it took to perform the survey. Application of the initial high-density estimates to an expanding area would have produced an overestimate. On the other hand, some fish in the front of the spawning migration may have already migrated out of Vestfjord and the survey area by the time of the survey. The intention to perform a second survey in the opposite direction, against the migration flow, was precluded by the exigency of failure of the main electricity generator on board the vessel.

(3) A marked difference in herring behaviour has already been observed across a boundary separating pre-migrating and migrating herring in Vestfjord (Ostrowski and Foote 1996). It is very possible that this is associated with a change in target strength, as due to changing orientation distribution or pattern of vertical migration. At the same time, a certain reduction of the average fat content of the herring can be observed during the wintering stage (Slotte 1996), suggesting the need for more floatation by the swimbladder in January compared with November, and hence a potentially larger target strength (Ona 1990).

It is also observed that the two cruises were conducted with different research vessels. This is not believed to have caused any particular difficulties or differences. Evidence for this is contained in repeated surveys of central Tysfjord by R/V "G O Sars" during the period 28-29 November 1995 (strata t11=t32=t33 in Tables 1 and 3) and earlier repeated surveys by R/V "Johan Hjort". Given twelve-hour difference in start time, first recommended by I. Huse, and the often-claimed extreme sensitivity of fish to both environmental conditions and research-vessel radiated noise (Mitson 1993, 1995), it is scarcely credible that there could be such close agreement in survey results were there strong avoidance reactions.

Other research

In addition to the reported activities, which were aimed directly at estimating stock abundance, a number of other studies were performed. As these are ongoing, they are merely mentioned. (1) The prevalence of *Ichthyophonus hoferi* remains the subject of continued investigation. (2) Determination of herring target strength and its dependences is being studied through measurement of the herring tilt angle distribution by underwater photography. This is also being related to environmental parameters. (3) Surveying measurements at 38 kHz are generally accompanied by measurements at other frequencies, namely 18, 120 and 200 kHz, depending on their availability on the particular research vessel. Whether these can be used for stratification remains to be established. (4) The object orientation approach to software and data integration (Ostrowski 1996) is being employed to accelerate the data-quality-control process. Geostatistical analysis techniques will be incorporated in an attempt to facilitate stratification. (5) The Bergen Echo Integrator continues to be developed, presently with respect to multiple-frequency-echogram presentation and processing, but also with respect to automatic report generation.

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REFERENCES

Anon. 1996. Report of the Northern Pelagic and Blue Whiting Fisheries Working Group. ICES C.M.1996/Assess:14.158 pp.[Mimeo].

Bodholt, H., Nes, H. and Solli, H. 1989. A new echo-sounder system. Proc. IOA, 11(3): 123-130.

Cressie, N. 1991. Satistics for spatial data. Wiley, New York. 900 pp.

Engås, A., Skeide, R. and West, C.W. 1996. The MultiSampler: A system for remotely opening and closing multiple codends on a sampling trawl. Fish. Res. (in press).

Foote, K.G. 1987. Fish target strengths for use in echo integrator surveys. J.acoust.Soc.Am., 82: 981-987.

Foote, K.G. 1990. Correcting acoustic measurements of scatterer density for extinction. J.acoust.Soc.Am., 88: 1543-1546.

Foote, K.G. 1993a. Abundance estimation of herring hibernating in a fjord. ICES C.M. 1993/D:45. 12 pp. [Mimeo].

Foote, K.G. 1993b. Application of acoustics in fisheries, with particular reference to signal processing. In Acoustic signal processing for ocean exploration, pp. 381-390. Ed. by J.M.F. Moura and I.M.G. Lourtie. North-Holland, Dordrecht.

Foote, K.G. 1994. Extinction cross section of herring: new measurements and speculation. ICES C.M. 1994/(B+D+G+H):2. 10 pp. [Mimeo].

Foote, K.G. 1996. Quantitative fisheries research surveys, with special reference to computers. In Computers in fisheries research., Chap. 4, pp. 80-112. Ed. by B.A. Megrey and E. Moksness, Chapman and Hall, London, 254 pp.

Foote, K.G. and Røttingen, I. 1995. Acoustic assessment of Norwegian spring spawning herring in the wintering area, December 1994 and January 1995. ICES C.M. 1995/H:9. 22 pp. [Mimeo].

Foote, K.G., Knudsen, H.P., Vestnes, G., MacLennan, D.N. and Simmonds, E.J. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. ICES Coop.Res.Rep., 144. 69 pp.

Foote, K.G., Knudsen, H.P., Korneliussen, R.J., Nordbø, P.E. and Røang, K. 1991. Postprocessing system for echo sounder data. J.acoust.Soc.Am., 90: 37-47.

Foote, K.G., Ona, E. and Toresen, R. 1992. Determining the extinction cross section of aggregating fish. J.acoust.Soc.Am., 91: 1983-1989.

Forbes, S.T. and Nakken, O. (eds.) 1972. Manual of methods for fisheries resource survey and appraisal. Part 2. The use of acoustic instruments for fish detection and abundance estimation. FAO Man.Fish.Sci., 5: 1-138.

Gunderson, D.R. 1993. Surveys of fisheries resources. Wiley, New York. 248 pp.

Knudsen, H.P. 1990. The Bergen Echo Integrator: An introduction. J.cons.int.Explor.Mer, 47: 167-174.

MacLennan, D.N. 1990. Acoustical measurement of fish abundance. J.acoust.Soc.Am., 87: 1-15.

Matheron, G. 1971. The theory of regionalized variables and its applications. Les Cahiers du Centre de Morphologie Mathématique de Fontainebleau, Fasc. 5, Ecole Nat. Sup. des Mines de Paris. 211 pp.

Mitson, R.B. 1993. Underwater noise radiated by research vessels. ICES mar.Sci.Symp. 196: 147-152.

Mitson, R.B. (ed.) 1995. Underwater noise of research vessels: Review and recommendations. ICES Coop.Res. Rep. (209): 61 pp.

Ona, E. 1990. Physiological factors causing natural variations in acoustic target strength of fish. J.mar.biol.Ass. U.K., 70: 107-127.

Ostrowski, M. 1996. Use of objects in the management of marine data: example of a database amenable to geostatistical analysis. Proc. NODC/IOC Workshop on Chemical and Biological Data Management, Hamburg, 20-23 May 1996. (in press).

Ostrowski, M. and Foote, K.G. 1996. Acoustic portrait of herring in Vestfjord, January 1996, with geostatistical analysis. ICES C.M. 1996/H:31. 12 pp. [Mimeo].

Røttingen, I. 1992. Recent migration routes of Norwegian spring spawning herring. ICES C.M. 1992/H:18. 10 pp. [Mimeo].

Røttingen, I., Foote, K.G., Huse, I. and Ona, E. 1994. Acoustic abundance estimation of wintering Norwegian spring spawning herring, with emphasis on methodological aspects. ICES C.M. 1994/(B+D+G+H):1. 17 pp. [Mimeo].

Slotte, A. 1996. Relations between seasonal migrations and fat content in Norwegian spring spawning herring (*Clupea harengus* L.). ICES C.M. 1996/H:11. 19 pp. [Mimeo].

Table 1. Survey design types for the strata identified in Figs. 2-4, among other places, for the cruise with R/V "G.O. Sars" in November-December 1995. The number of statistical squares of side length 0.2 nautical mile (NM) with acoustic data is denoted by n_s.

	Start time		Stop time		Sailed distance		
Stratum	Date	UTC	Date	UTC	(NM)	n_s	Design type
o 11	1125	0649	1125	1650	89.4	502	Zigzag
o 12	1125	1227	1125	1332	11.6	50	Zigzag
o 13	1130	1733	1130	2129	22.0	110	Zigzag
o 21	1127	0518	1127	1643	105.1	564	Equally spaced parallel transects with endpieces
o 22	1127	1722	1127	1909	9.2	50	Equally spaced parallel transects with endpieces
o 23	1201	2347	1202	1335	23.1	115	Zigzag
o 24	1127	0520	1127	1643	65.4	355	Equally spaced parallel transects with endpieces
o 25	1127	1722	1127	1909	4.9	32	Equally spaced parallel transects with endpieces
t 11	1128	0921	1128	1500	37.9	223	Roughly equally spaced parallel transects without endpieces
t 32	1128	2057	1129	0216	37.7	210	Roughly equally spaced parallel transects without endpieces
t 33	1129	0917	1129	1445	37.1	220	Roughly equally spaced parallel transects without endpieces
t 34	1202	2134	1203	0432	33.2	192	Roughly equally spaced parallel transects without endpieces
t 35	1203	0955	1203	1334	20.2	119	Roughly equally spaced parallel transects without endpieces
t 36	1204	1755	1205	0005	33.1	193	Roughly equally spaced parallel transects without endpieces
t 12	1130	0127	1130	0617	13.1	63	Ad hoc
t 13	1128	1607	1128	1911	17.1	76	Zigzag
t 14	1129	1829	1129	2220	14.4	64	Zigzag
t 15	1129	0610	1129	0627	2.6	14	Ad hoc
t 16	1129	0636	1129	0704	2.8	12	Ad hoc
t 17	1129	0631	1120	0819	9.8	47	Zigzag
t 18	1130	0727	1130	0932	10.6	48	Zigzag
t 19	1130	0759	1130	0855	7.4	36	Zigzag
t 20	1130	1023	1130	1134	6.6	38	Ad hoc
t 21	1130	1038	1130	1107	4.4	20	Zigzag
tj 11	1125	1703	1125	1921	17.9	73	Mid-fjord transects
tj 21	1204	1248	1204	1628	20.6	93	Zigzag
v 21	1126	1436	1127	0513	99.1	516	Parallel equally spaced transects

Table 2. Survey design types for the strata identified in Figs. 5-7 for the cruise with R/V "Johan Hjort" in January 1996. The number of statistical squares of side length 0.2 NM with acoustic data is denoted by n_s.

	Start time		Stop time		Sailed distance		
Stratum	Date	UTC	Date	UTC	(NM)	n_s	Design type
o411	0117	1758	0118	1640	97.7	509	Zigzag
o426	0118	0015	0118	1041	22.0	79	Zigzag
o43	0118	1114	0118	1324	23.3	109	Zigzag
t 41	0116	1517	0116	2155	37.5	213	Roughly parallel equally spaced transects
t 42	0116	2210	0116	2230	2.0	10	Mid-fjord transect
t 43	0116	2230	0117	0355	8.7	50	Ad hoc
t 44	0116	2242	0117	0251	21.6	96	Zigzag
t 45	0117	0511	0117	0713	12.7	51	Zigzag
t 46	0117	0940	0117	0953	2.2	14	Ad hoc
t 47	0117	1000	0117	1012	2.7	10	Ad hoc
t 48	0117	1259	0117	1321	4.6	21	Zigzag
t 49	0117	1248	0117	1331	4.6	26	Ad hoc
v 42	0119	0134	0120	0103	155.0	796	Parallel equally spaced transects
v 44	0119	1720	0120	0844	101.0	510	Parallel equally spaced transects
v 45	0120	0906	0120	1554	34.1	169	Ad hoc
v 46	0120	1155	0121	1012	133.7	755	Parallel equally spaced transects
v 47	0121	1131	0121	1946	69.3	381	Ad hoc

Table 3. Summary of measurement and computational results for the cruise with R/V "G.O. Sars" in November-December 1995, arranged by stratum. The stratum area A is divided by 0.04 NM^2 for comparison with the number of samples n_s after averaging over statistical squares.

Stratum	Area $A(NM^2)$	$A/0.04$	n_s	$\bar{s}_A$	CV	$se/\bar{s}_A$	A_N	a (NM)	$\sigma_E/\bar{s}_A$	l_{rms} (cm)	Δl_{rms} (cm)	$N(10^9)$
o 11	89.52	2238	502	11500	5.9	0.265	0.80	0.70	0.285	31.35	3.29	1.3000
o 12	6.24	156	50	74800	2.0	0.282	0.50	1.50	0.270	25.99	2.05	0.8520
o 13	9.24	231	110	40000	2.3	0.222	0.80	0.50	0.222	31.35	3.29	0.4810
o 21	89.52	2238	564	8590	4.3	0.182	0.60	1.20	0.183	31.35	3.29	0.9640
o 22	6.24	156	50	64300	1.1	0.155	0.00	1.80	0.135	25.99	2.05	0.7320
o 23	9.24	231	115	44200	1.3	0.117	0.00	1.70	0.098	31.35	3.29	0.5320
o 24	89.52	2238	355	9330	4.4	0.233	0.70	1.20	0.231	25.99	2.05	1.0470
o 25	6.24	156	32	73300	1.1	0.195	0.00	1.70	0.163	31.35	2.05	0.8350
t 11	40.24	1006	223	62500	1.4	0.092	0.00	2.40	0.102	30.79	4.22	3.2700
t 32	40.24	1006	210	55700	1.6	0.112	0.00	1.90	0.125	30.79	4.22	2.9100
t 33	40.24	1006	220	62000	1.4	0.096	0.00	1.40	0.107	30.79	4.22	3.2400
t 34	35.08	877	192	98700	1.0	0.072	0.00	4.90	0.089	30.79	4.22	4.5000
t 35	21.84	546	119	222000	1.3	0.116	0.00	3.90	0.140	30.79	4.22	6.3000
t 36	35.08	877	194	59000	1.2	0.085	0.00	5.50	0.119	30.79	4.22	2.6900
t 12	3.68	92	63	76300	1.1	0.142	0.00	0.90	0.093	30.79	4.22	0.3650
t 13	7.20	180	76	37400	2.8	0.327	0.00	0.90	0.377	30.79	4.22	0.3500
t 14	4.12	103	64	72300	1.9	0.239	0.50	1.10	0.205	30.79	4.22	0.3870
t 15	1.60	40	14	13600	1.3	0.339	0.00	0.30	0.334	30.79	4.22	0.0284
t 16	0.56	14	12	19000	1.0	0.299	0.00	0.30	0.289	30.79	4.22	0.0138
t 17	3.36	84	47	49300	1.7	0.253	0.00	0.40	0.227	30.79	4.22	0.2160
t 18	3.80	95	48	146000	1.3	0.193	0.60	0.40	0.195	30.79	4.22	0.7210
t 19	1.52	38	36	211000	1.5	0.248	0.00	0.50	0.175	30.79	4.22	0.4160
t 20	3.96	99	38	5900	3.7	0.594	1.00	1.00	0.594	30.79	4.22	0.0304
t 21	1.96	49	20	44300	2.4	0.532	1.00	1.00	0.532	30.79	4.22	0.1130
tj 11	10.64	266	73	40800	1.5	0.174	0.15	0.80	0.235	27.65	3.06	0.7000
tj 21	9.20	230	93	36400	1.4	0.146	0.50	1.50	0.155	27.65	3.06	0.5400
v 21	102.60	2565	516	36400	2.6	0.114	0.00	1.80	0.092	27.65	3.06	6.0200

Table 4. Summary of measurement and computational results for the survey with R/V "Johan Hjort" in January 1996, arranged by stratum. The stratum area A is divided by 0.04 NM^2 for comparison with the number of samples n_s after averaging over statistical squares.

Stratum	Area $A(NM^2)$	$A/0.04$	n_s	$\bar{s}_A$	CV	$se/\bar{s}_A$	A_N	a (NM)	$\sigma_E/\bar{s}_A$	l_{rms} (cm)	Δl_{rms} (cm)	$N(10^9)$
o 411	89.52	2238	509	2380	8.9	0.394	0.00	1.20	0.566	29.59	3.53	0.4130
o 426	6.16	154	79	26500	1.8	0.204	1.00	1.00	0.204	26.53	2.13	0.2860
o 43	9.24	231	109	12700	4.2	0.406	1.00	1.00	0.406	29.59	3.53	0.1650
t 41	41.20	1030	213	6020	2.8	0.192	1.00	1.00	0.192	29.59	3.53	0.3490
t 42	2.04	51	10	1190	1.1	0.353	0.00	0.50	0.425	29.59	3.53	0.0034
t 43	5.72	143	50	2450	1.7	0.235	0.50	0.75	0.246	29.59	3.53	0.0197
t 44	8.20	205	96	37200	1.3	0.134	0.00	0.50	0.148	29.59	3.53	0.4300
t 45	4.04	101	51	1150	2.6	0.362	0.00	0.40	0.346	29.59	3.53	0.0065
t 46	1.60	40	14	9560	3.7	0.998	1.00	1.00	0.998	29.59	3.53	0.0215
t 47	0.40	10	10	96200	1.5	0.481	0.25	0.40	0.439	29.59	3.53	0.0542
t 48	1.96	49	21	17700	2.7	0.583	0.00	0.40	0.571	29.59	3.53	0.0489
t 49	3.96	99	26	9830	3.5	0.677	1.00	1.00	0.677	29.59	3.53	0.0548
v 42	241.88	6047	796	70200	1.3	0.046	0.00	2.70	0.037	29.59	3.53	23.900
v 44	153.00	3825	510	9140	3.2	0.141	0.50	7.50	0.114	31.64	2.21	1.7200
v 45	166.00	4150	169	13000	5.6	0.432	0.00	0.60	0.639	31.64	2.21	2.6600
v 46	773.52	19338	755	1800	2.7	0.097	0.00	2.70	0.257	31.64	2.21	1.7200
v 47	235.00	5875	381	781	2.3	0.118	0.40	2.80	0.227	31.64	2.21	0.2260

Table 5. Summary of results for the cruises in November-December 1995, denoted '9511' and January 1996, denoted '9601', arranged by fjord and survey. The geostatistical variance is expressed through the normalised quantity $\Delta N / N$. The basis of computation of N is described through the constituent strata, which are otherwise described in Figs. 2-7 and Tables 1 and 2.

Period	Fjord	$N(10^9)$	$\Delta N / N$	Basis of computation of N
9511	Ofotfjord	2.52	0.148	Average of (sum o11-13) and (sum o23-25)
9511	Tjeldsund	0.700	0.235	Single stratum tj11
9511	Tysfjord	5.78	0.073	Sum (average t11, 32, 33) and (sum t12-21)
9511	Vestfjord	6.02	0.092	Single stratum v21
9601	Ofotfjord	0.864	0.289	Sum o41-43
9601	Tysfjord	0.988	0.110	Sum t41-49
9601	Vestfjord	30.2	0.065	Sum v42, 44-47

Table 6. Abundance estimates of the stock of Norwegian spring-spawning herring wintering in the Ofotfjord-Tysfjord-Vestfjord system in November-December 1995 and after the onset of the spawning migration in January 1996.

Period	$N(10^9)$	$\Delta N / N$
9511	15.0	0.054
9601	32.1	0.062

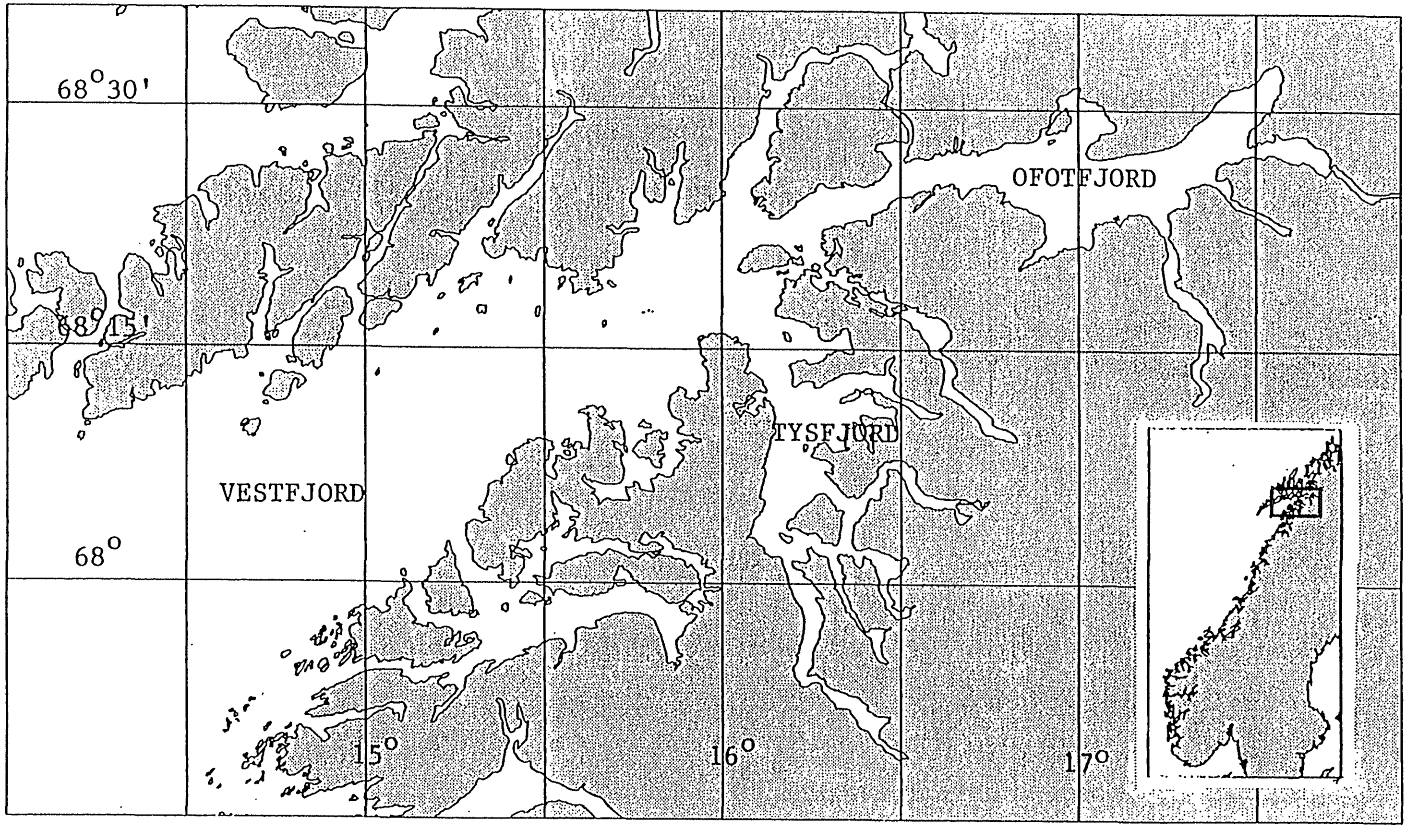

Fig. 1. Location of winter surveys 1995-1996.

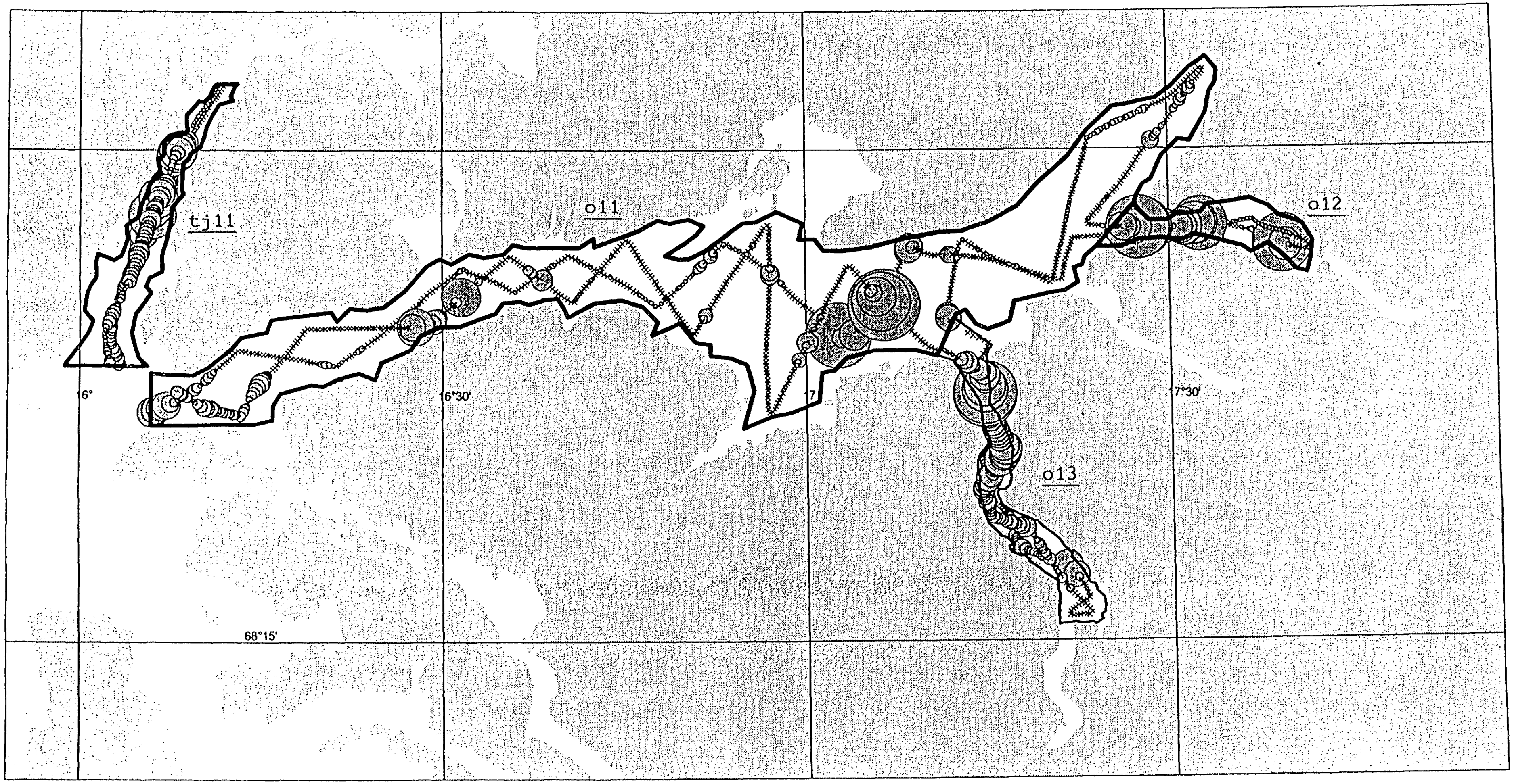

Fig. 2. Part A. Distribution of herring in Ofotfjord in November-December 1995 as observed with two different survey designs. (Part A and B) The distribution in Tjeldsund is also shown in part A. The radius of a circle is proportional to the square root of the extinction-adjusted s_A-value. The maximum s_A-value shown here is 1.378 10^6 m^2/NM^2, where NM denotes nautical mile.

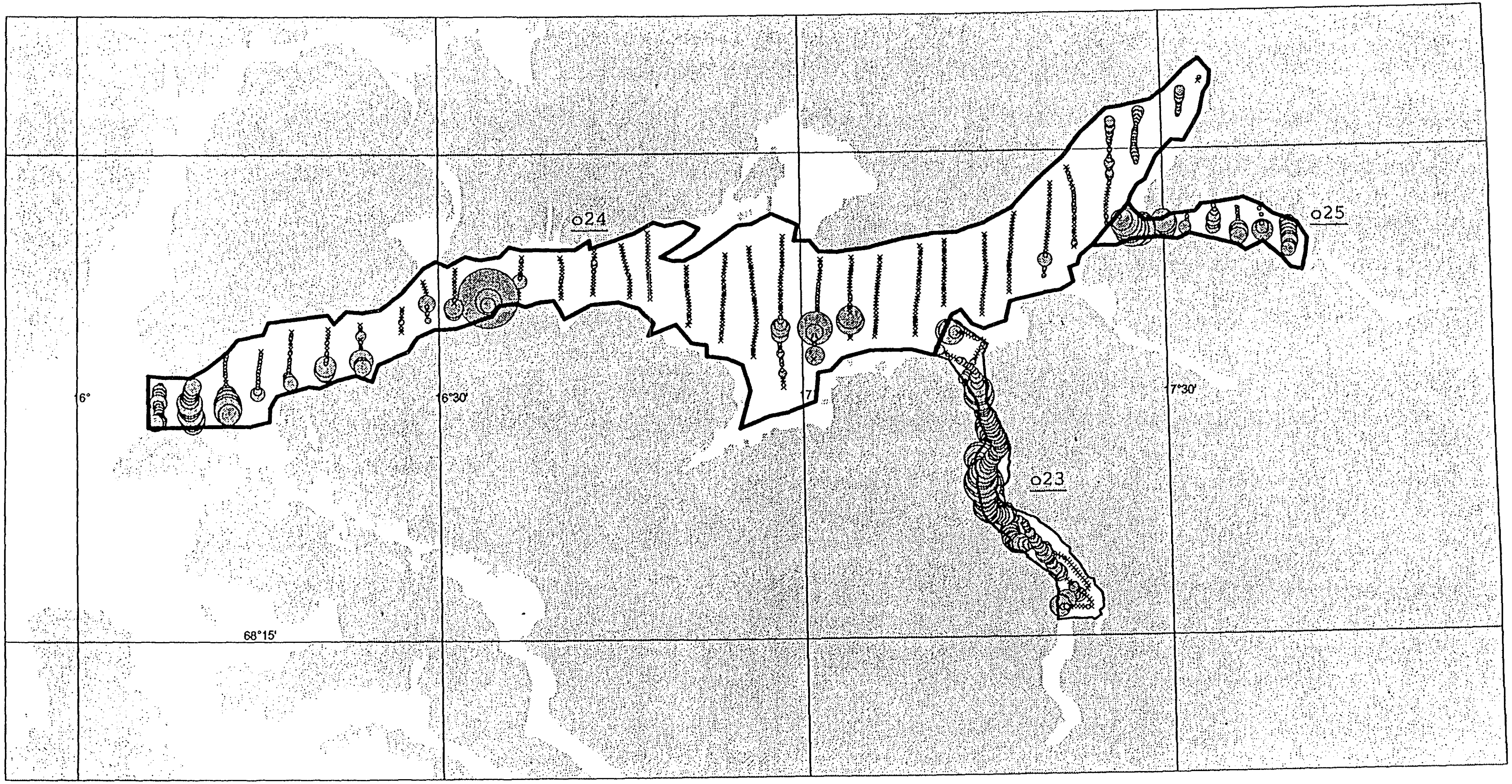

Fig. 2 (Continued) Part B

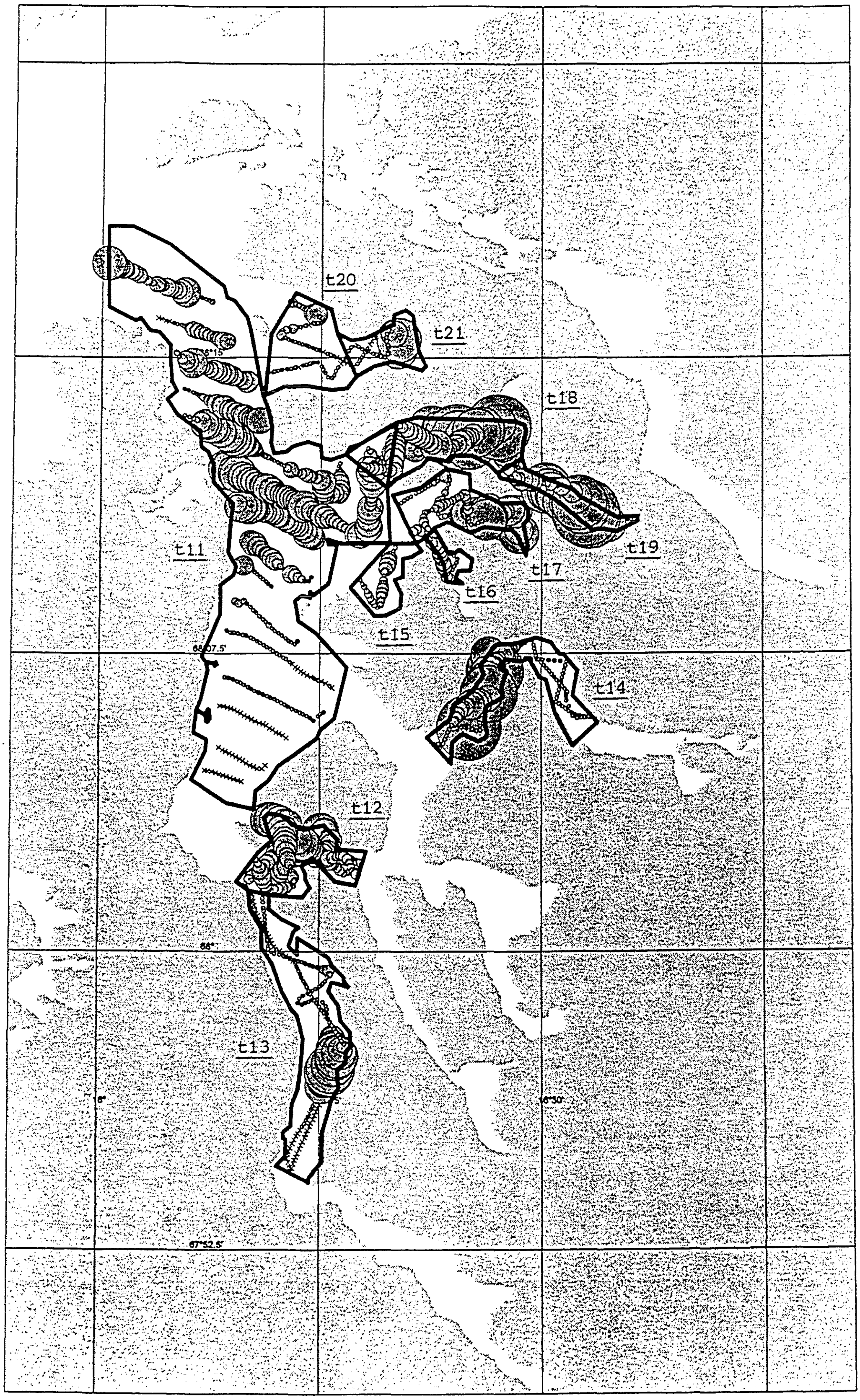

Fig. 3. Distribution of herring in Tysfjord in November 1995. The radius of a circle is proportional to the square root of the extinction-corrected s_A-value. The maximum s_A-value is 1.348 10^6 m^2/NM^2.

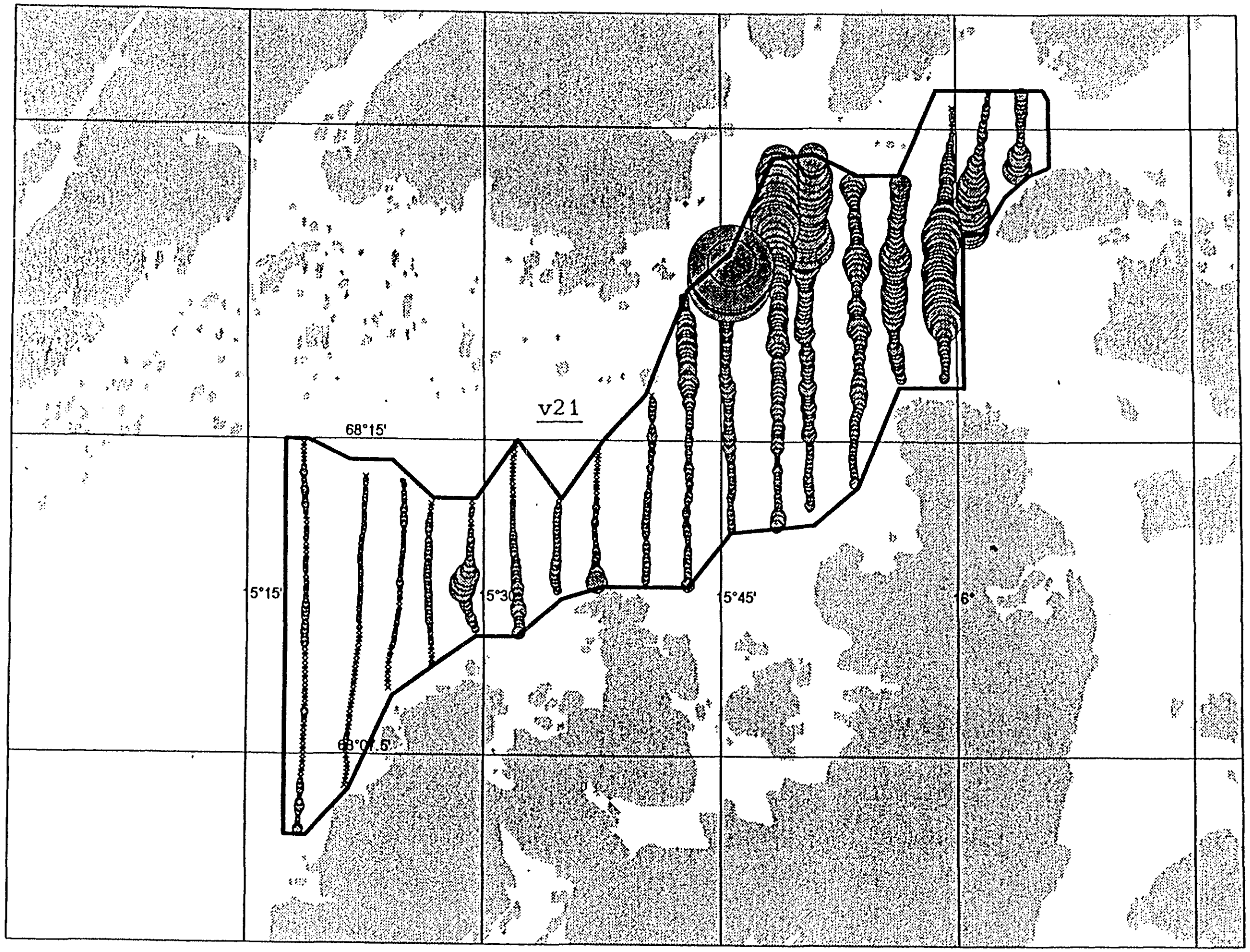

Fig. 4. Distribution of herring in Vestfjord in November 1995. The radius of a circle is proportional to the square root of the extinction-corrected s_A-value. The maximum s_A-value is 1.272 10^6 m^2/NM^2.

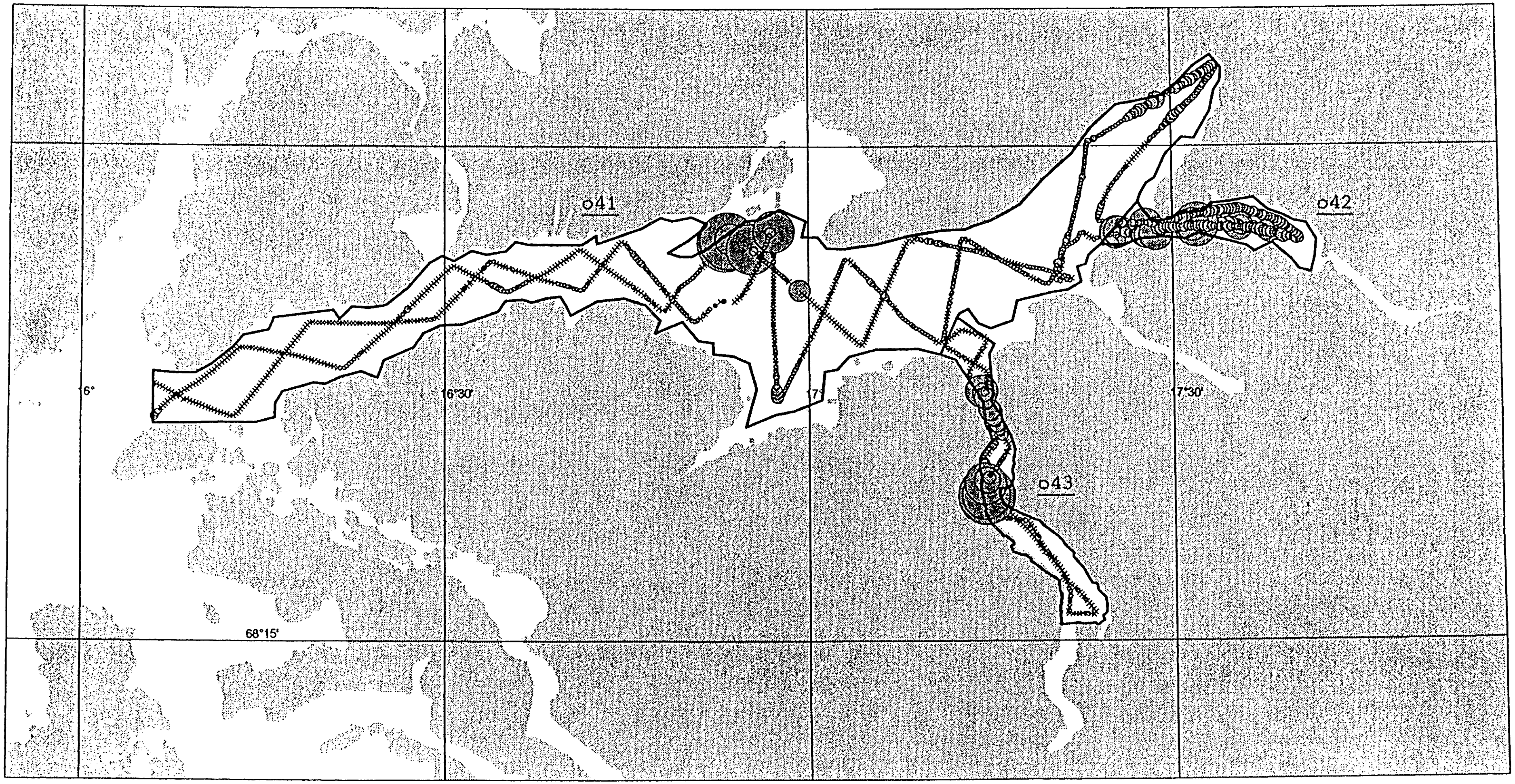

Fig. 5. Distribution of herring in Ofotfjord in January 1996. The radius of a circle is proportional to the square root of the extinction-adjusted s_A-value. The maximum s_A-value shown here is 0.8338 10^6 m^2/NM^2.

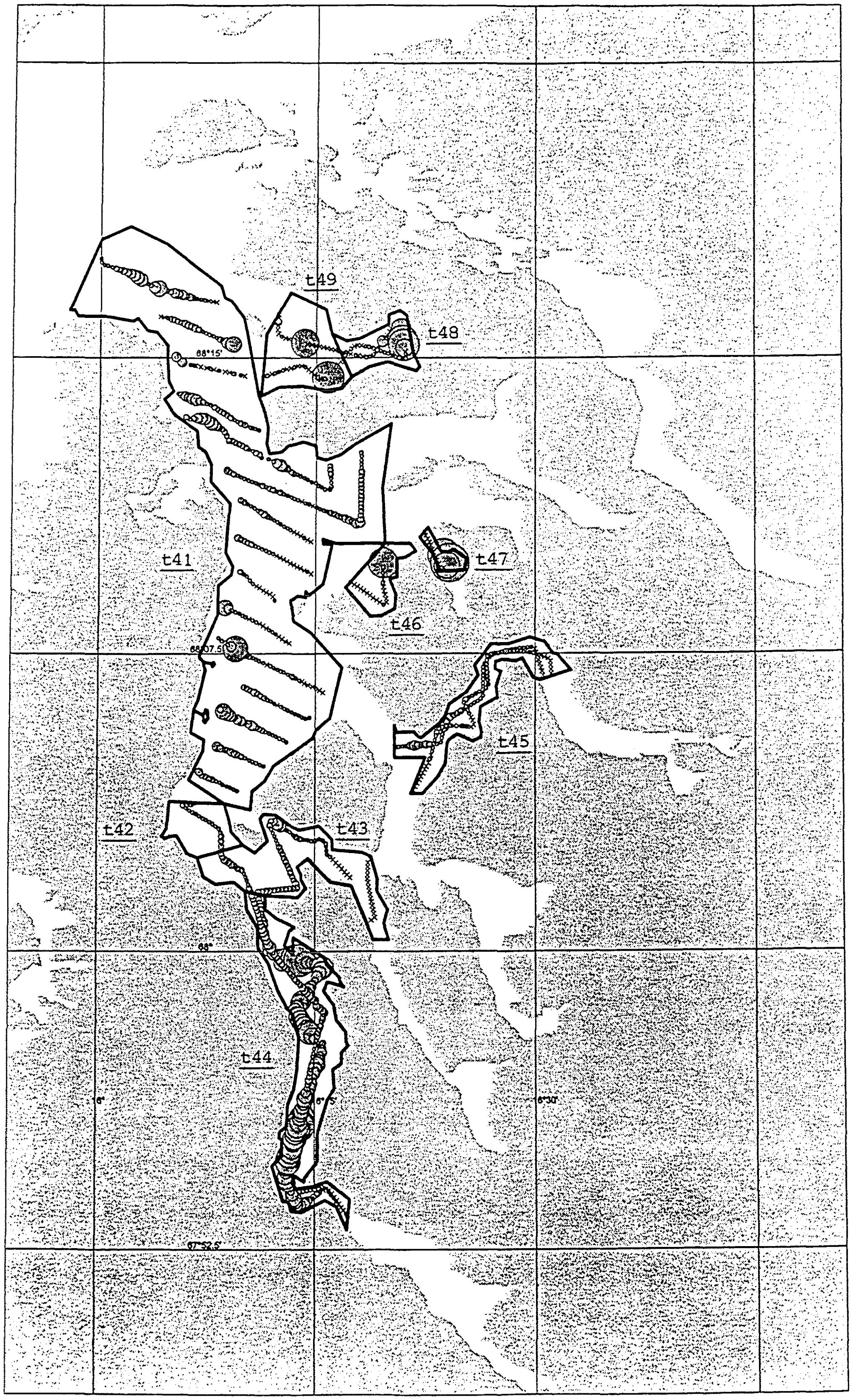

Fig. 6. Distribution of herring in Tysfjord in January 1996. The radius of a circle is proportional to the square root of the extinction-corrected s_A-value. The maximum s_A-value is 0.4201 10^6 m^2/NM^2.

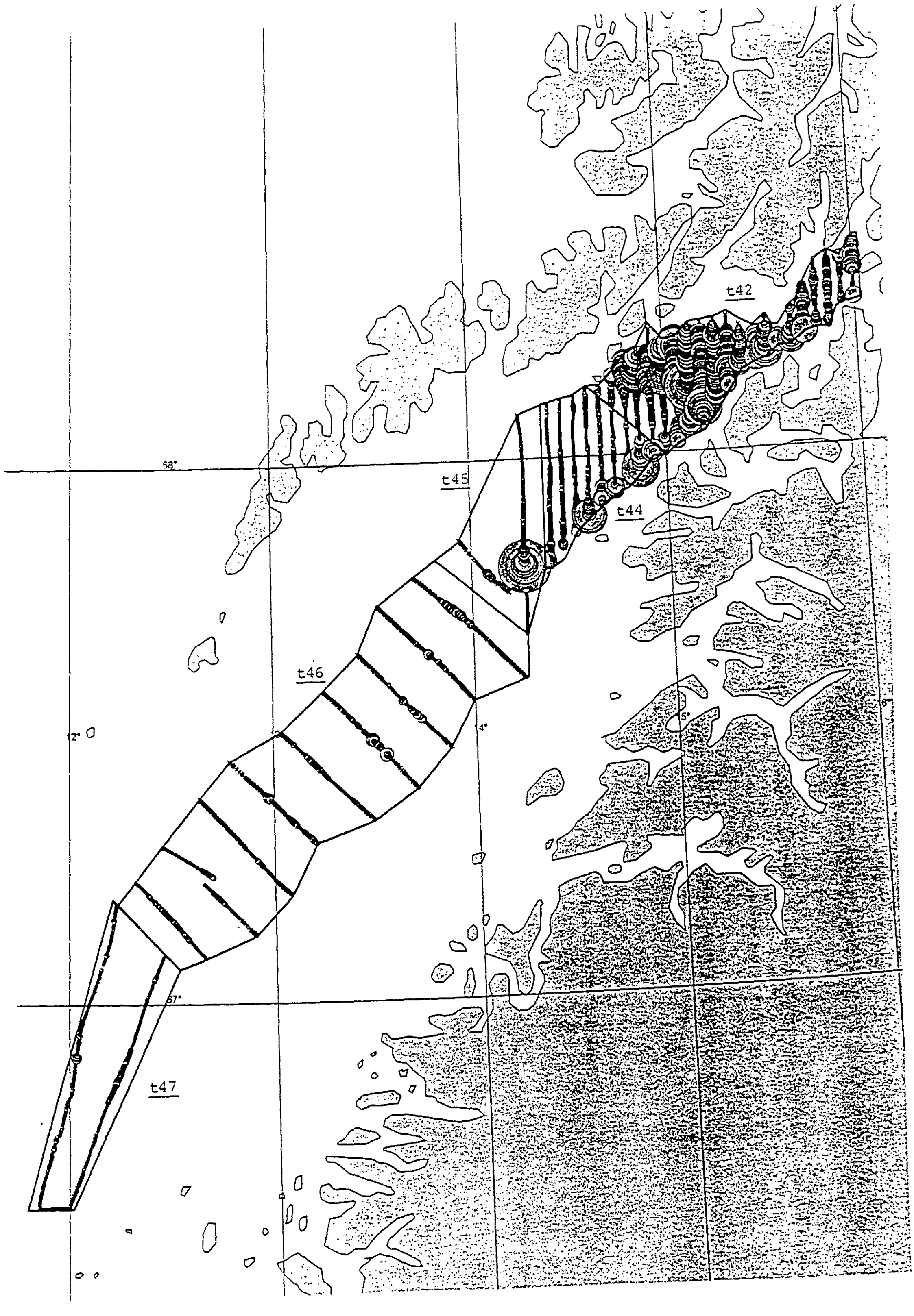

Fig. 7. Distribution of herring in Vestfjord in January 1996. The radius of a circle is proportional to the square root of the extinction-corrected s_A-value. The maximum s_A-value is 1.122 10^6 m^2/NM^2.

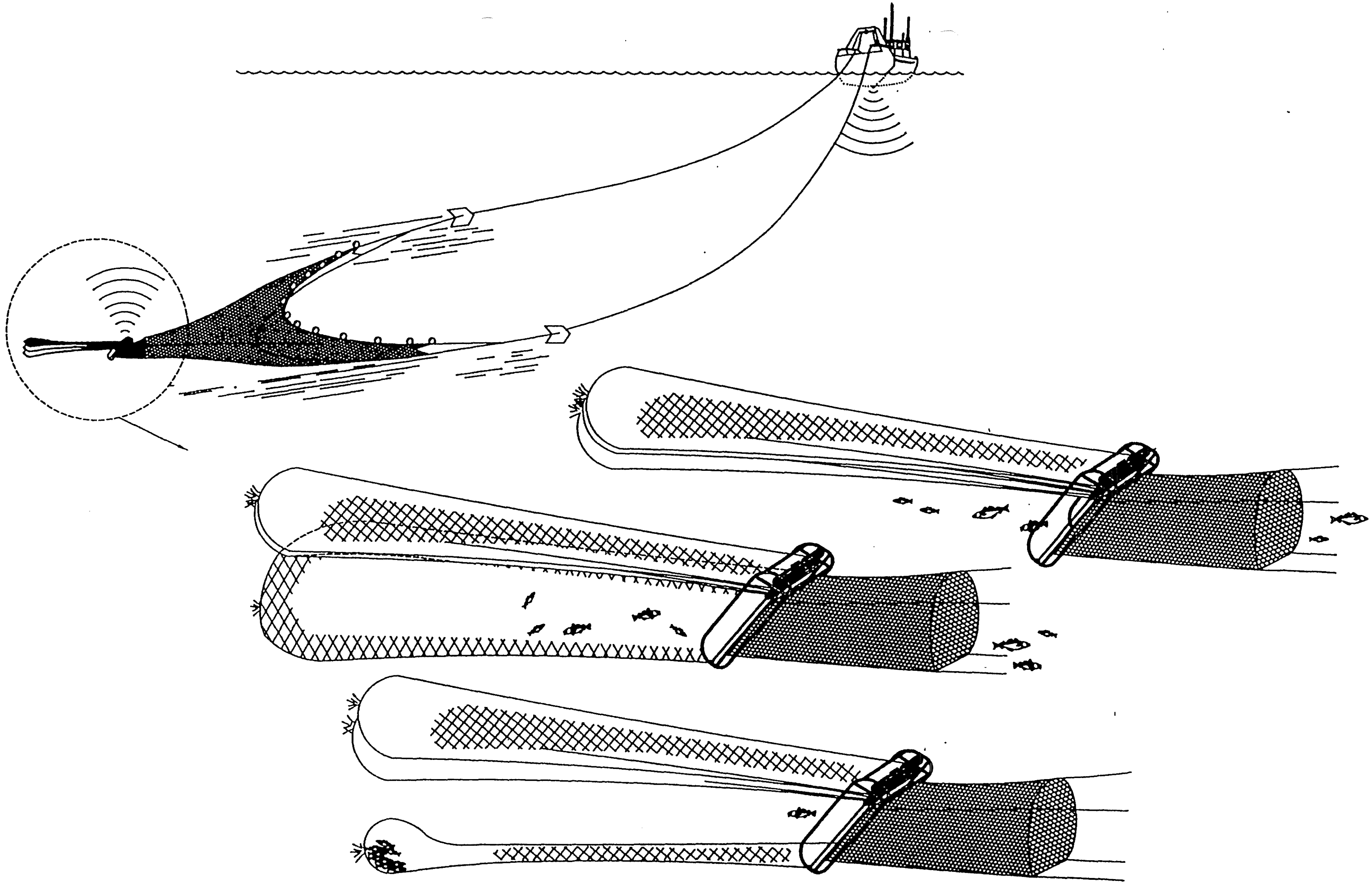

Fig. 8 Schematic presentation of the MultiSampler system (not to scale).

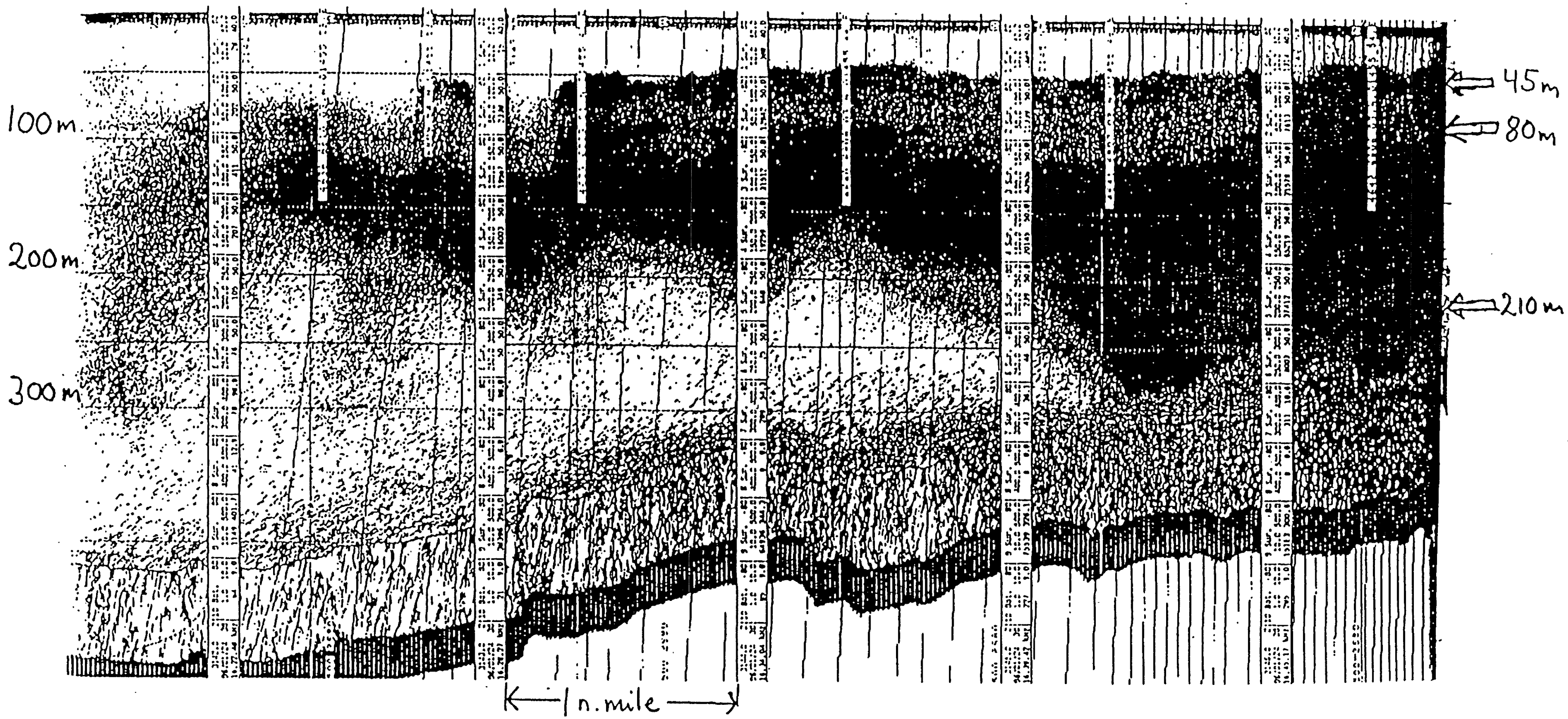

Fig. 9 Echo recordings (EK 500, depth rage 0-500m) of herring on a section along 14°56'E in Vestfjord in January 1996. Arrows indicate where biological samples (see Fig. 10) are taken with the MultiSampler trawl.

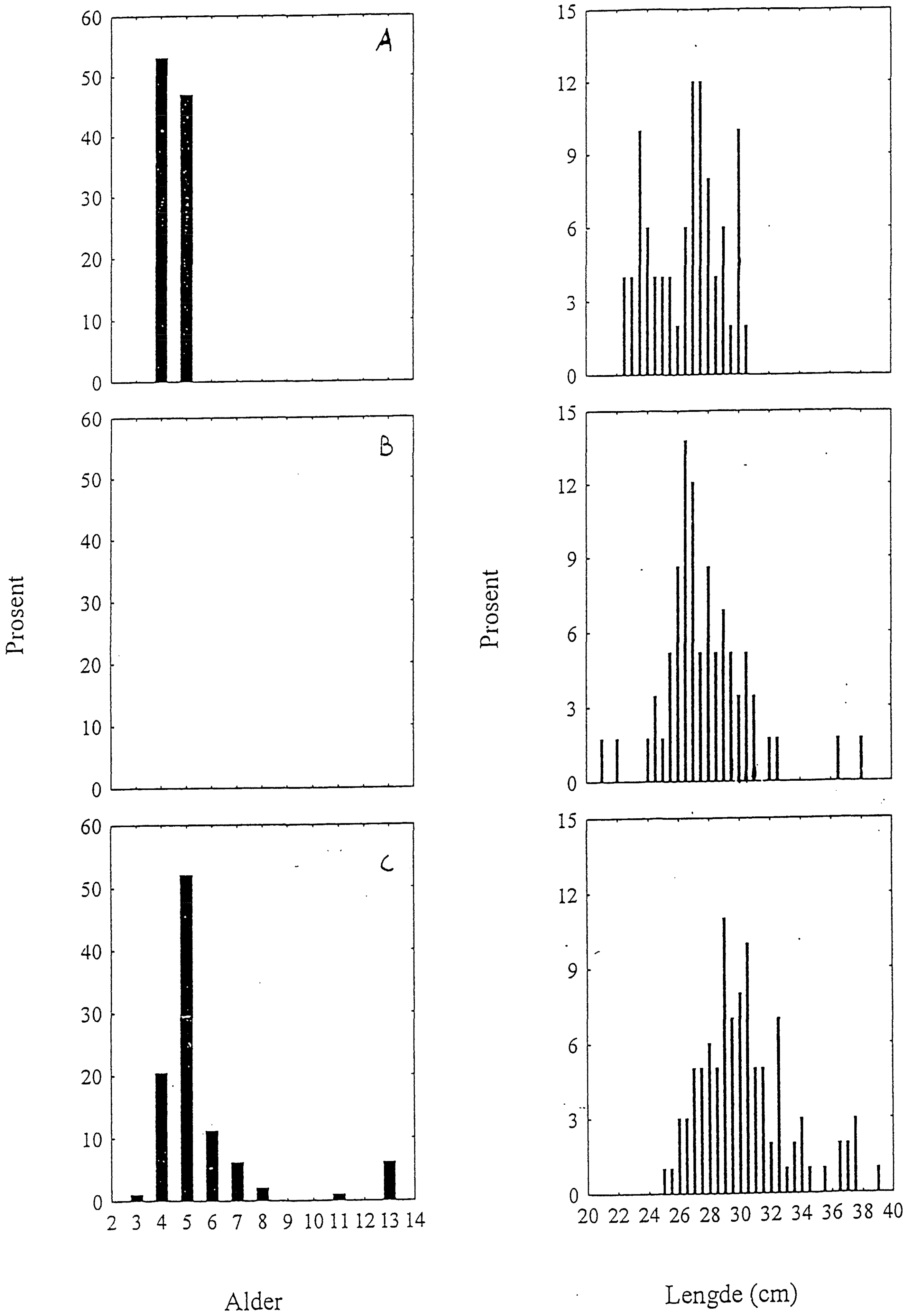

Fig. 10. Age and length distributions of herring sampled by MultiSampler trawl at different depths (A=45m, B=80m and C=210m) of the herring concentration shown in Fig. 9.

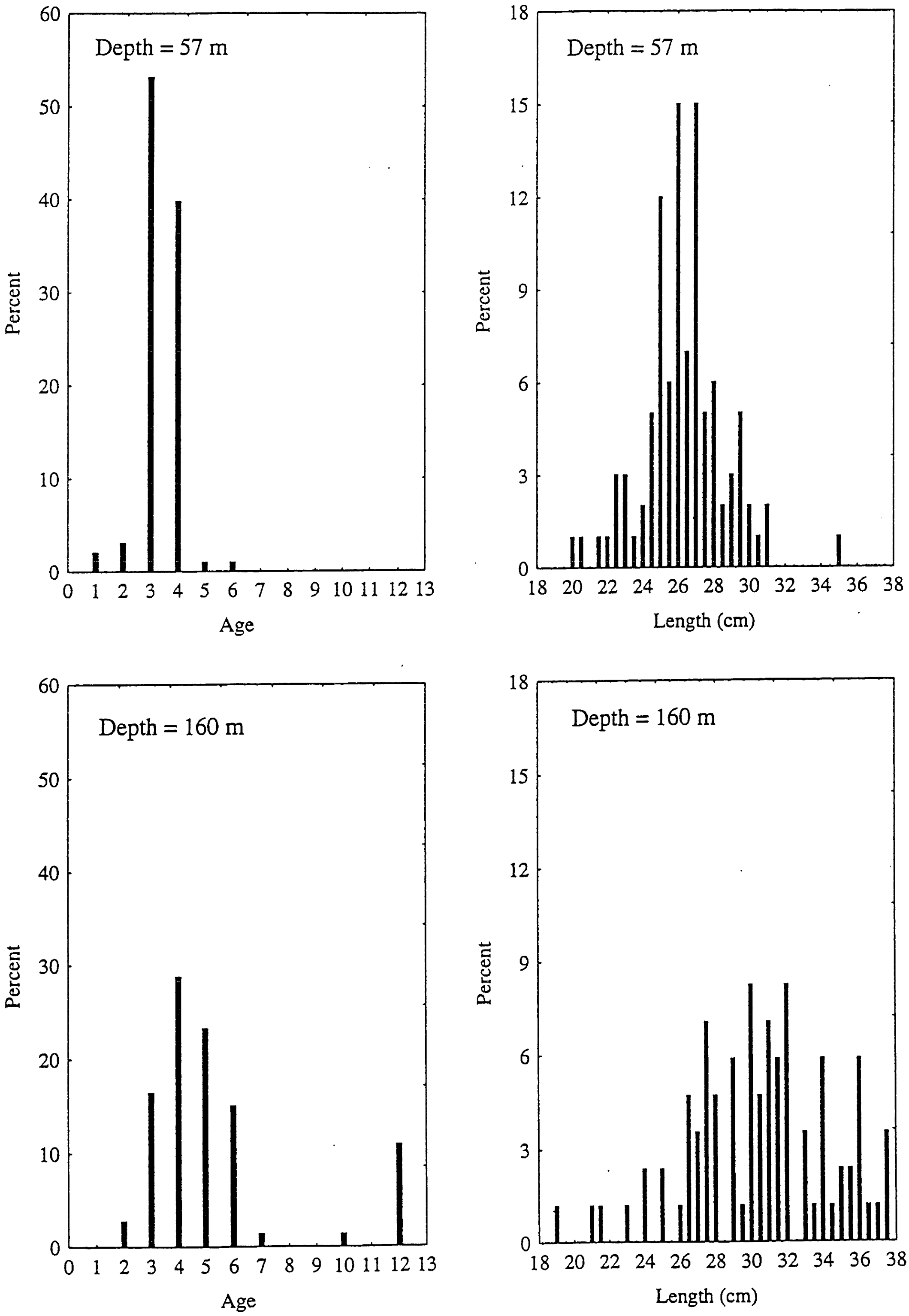

Fig. 11. Age and length distribution of herring sampled by MultiSampler trawl from the same herring concentration at different depths (57 and 160m) in November 1995.

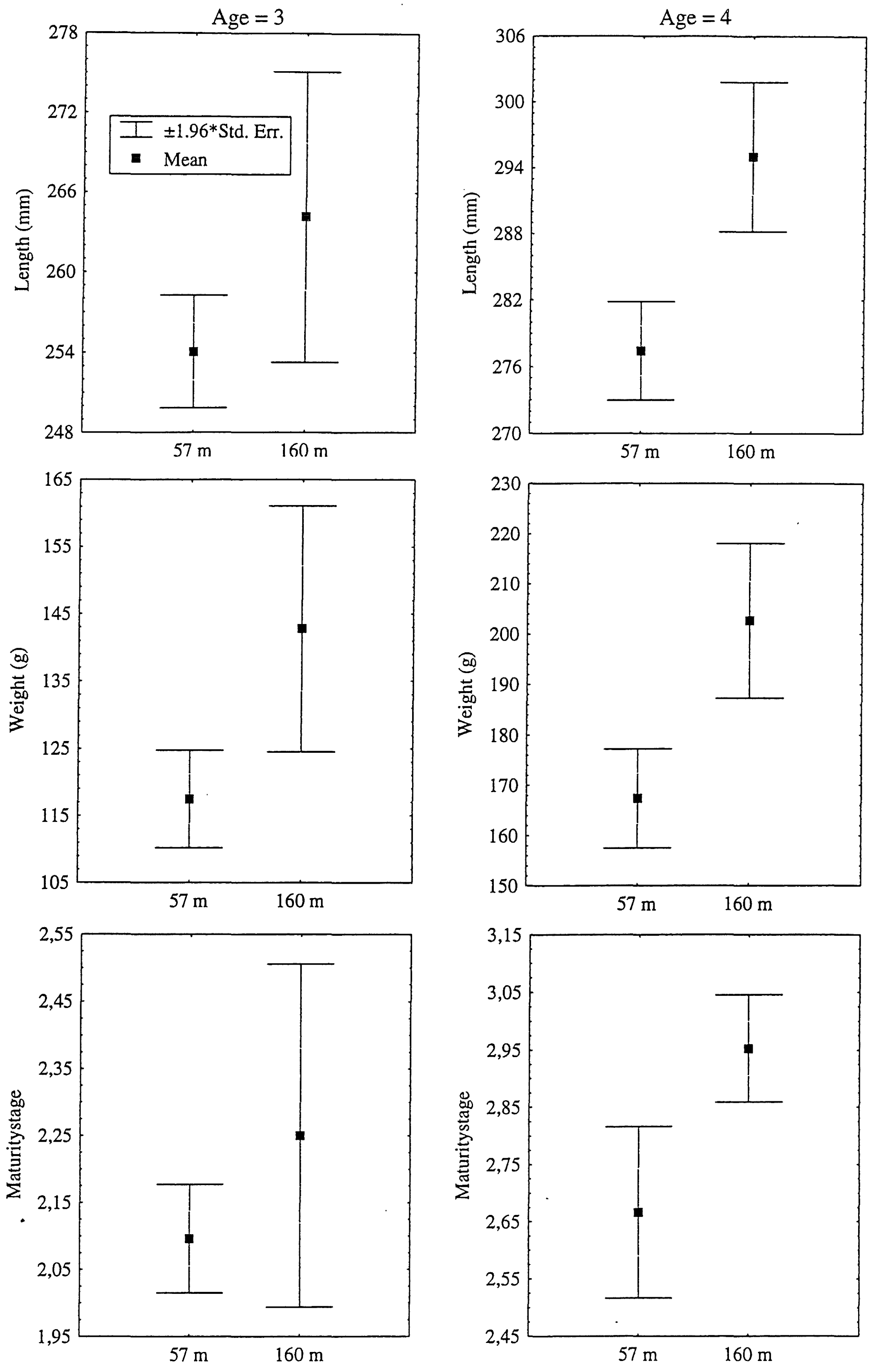

Fig. 12. Herring sample taken by MultiSampler trawl in November 1995. Same station as Fig. 11. The figure shows variation of length, weight and maturity stage within age groups 3 and 4 (year classes 1992 and 1991) from different depths (57 and 160m).

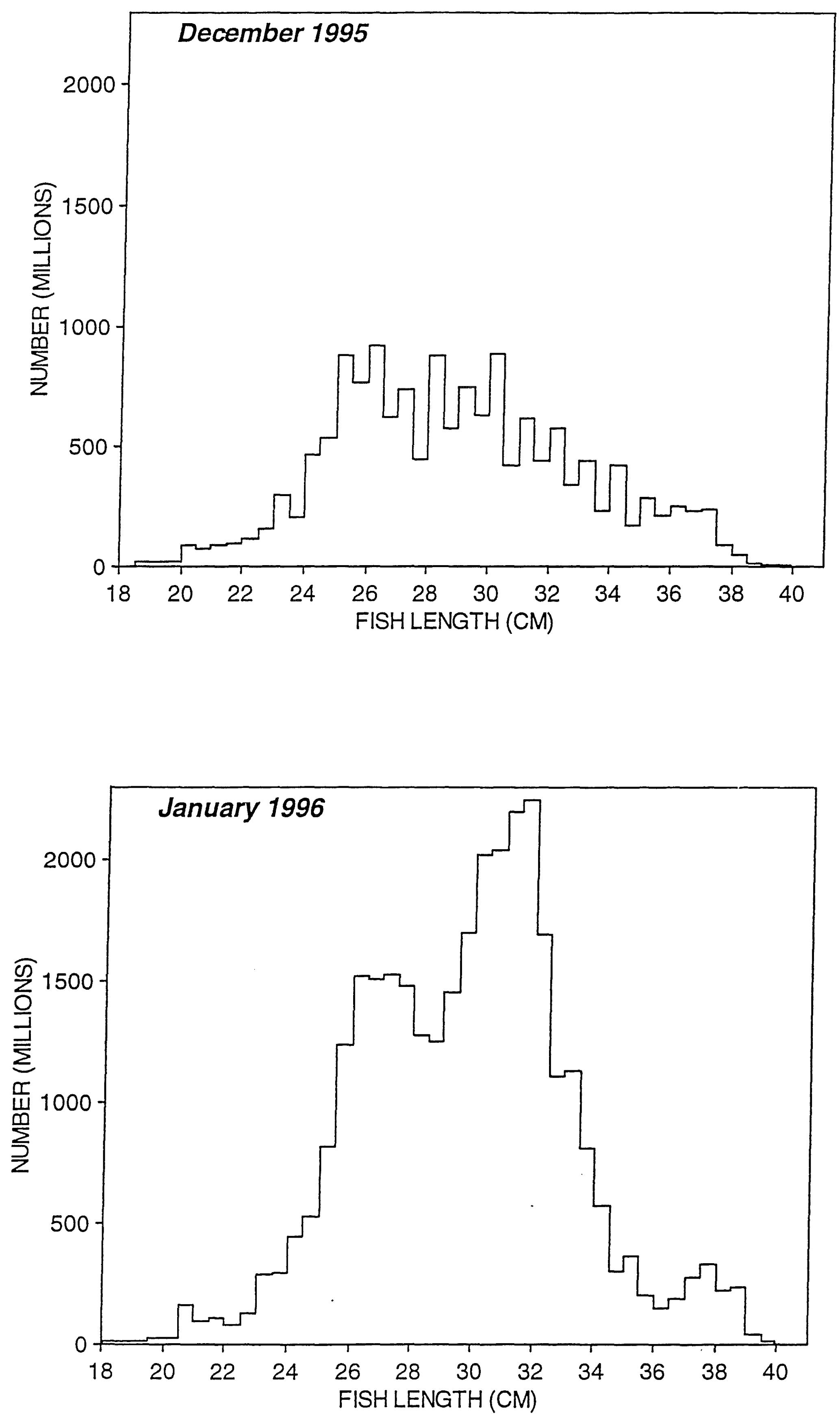

Fig.13. Composite length frequency distribution for the stock of Norwegian spring spawning herring in December 1995 and January 1996.