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Review of hydroacoustic methodology and Pacific hake biomass estimates for the Strait of Georgia, 1981 to 1998

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ABSTRACT

The purpose of this paper is 1) to make available to assessment scientists a review of the methods used in six acoustic surveys that were completed between 1981 to 1998 to estimate Pacific hake (*Merluccius productus*) abundance in the Strait of Georgia and 2) to provide a time series of hake biomass standardised to a single target strength value. This includes a description of the evolution of the acoustic system, data collection, analysis, presentation techniques and sources of uncertainty unique to each survey. A method for calculating biomass based on a target strength length relation is presented and biomass estimates from all surveys are given. Calibration, target strength and survey data are statistically examined to obtain a representative confidence interval that can be used as a guide for all surveys. Additional sources of uncertainty should be recognised when interpreting Pacific hake abundance from this time series. These include: 1) the 1993 survey is an overestimate due to inclusion of plankton back-scattering; 2) based on examination of sex ratio and survey timing, all surveys are conservative estimates of biomass; and 3) comparable results from all surveys are obtained by providing biomass estimates based on a single mean TS and on our new length-based TS model. We include recommendations for improving future surveys.

RÉSUMÉ

Le présent document a pour objet de 1) communiquer aux scientifiques effectuant des évaluations un examen des méthodes qui ont été utilisées pour la réalisation de six relevés acoustiques, entre 1981 et 1998, dans le but d'estimer l'abondance du merlu du Pacifique (*Merluccius productus*) dans le détroit de Géorgie et 2) de présenter une série temporelle de biomasses du hareng normalisée en fonction d'une même valeur d'indice de réflexion de cible. On y trouve une description de l'évolution du système acoustique, de la collecte de données, de l'analyse, des techniques de présentation et des sources d'incertitude uniques à chaque relevé. Une méthode de calcul de la biomasse fondée sur la relation indice de cible et longueur ainsi que des estimations de biomasse pour tous les relevés sont présentées. L'étalonnage, l'indice de cible et les données des relevés font l'objet d'un examen statistique qui permet d'obtenir un intervalle de confiance représentatif pouvant servir de guide pour tous les relevés. Il faut tenir compte d'autres sources d'incertitude au moment de l'interprétation de l'abondance du merlu du Pacifique fondée sur cette série temporelle. Ce sont : 1) le relevé de 1993 a été surestimé par de la réflexion sur du plancton, 2) l'examen du sex-ratio et du moment de réalisation montre que tous les relevés ont donné lieu à des estimations conservatrices de la biomasse et 3) des résultats comparables pour tous les relevés sont obtenus à partir d'estimations de biomasse fondées sur un même indice de réflexion moyen et de notre nouveau modèle d'indice de réflexion fondé sur la longueur. Nous formulons des recommandations pour l'amélioration des relevés.

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1.0 INTRODUCTION

Hydroacoustic surveys of Pacific hake biomass have formed the basis for assessments of the offshore stock since the early 1980's. Specifically, time-series of absolute abundance from the surveys have been used to fit catch-at-age models used to model populations and determine appropriate yield options. A similar modelling approach is being developed for the Strait of Georgia stock using hydroacoustic surveys that have been conducted intermittently since 1981. While methods and results have been published for individual surveys, changes to hydroacoustic systems and analytical procedures make interpretation of the time series in an assessment framework difficult.

The purpose of this paper is twofold. The first is to make available to assessment scientists a review of the methods used in six acoustic surveys that were completed between 1981 to 1998 to assess Pacific hake (*Merluccius productus*) in the Strait of Georgia. This includes a description of the evolution of the acoustic system, data collection, analysis, presentation techniques and sources of uncertainty unique to each survey.

The second is to provide a better time series of hake biomass estimates. To achieve this goal we present biomass estimates based on a single mean TS and on our new TS length based model. A mean TS will give a good relative biomass when fish size and TS remain constant, while the new model will provide our best estimates that are compensated for the substantial decrease in adult hake length and the increase in juvenile hake that has been observed over the years. Findings from a review of published and measured TS are included to substantiate our procedures and results.

2.0 REVIEW OF METHODS

In this section we review the biomass estimation process with emphasis on areas where changes have occurred that could influence the time series. Acoustic procedures and their physical foundations have been well documented by Clay and Medwin (1977), Mitson (1983) and MacLennan and Simmonds (1991). It is therefore our goal to minimise the use of technical jargon and provide detail only as required.

2.1 Survey design

The Strait of Georgia is a semi-enclosed marine basin averaging about 222 km (120 nm) long by 28 km (15 nm) wide with a mean depth of about 155 m and a maximum depth of 420 m (Thomson 1981) (Figure 1). Pacific hake aggregate to spawn in the deep basins of the Strait of Georgia from late February to May (McFarlane and Beamish, 1985). In late May, post-spawning hake aggregate in shallower depths and begin dispersing to the west side of the Strait along Vancouver Island and into the northern Strait (McFarlane and Beamish, 1985). They are available to the mid-water trawl fleet during this period and the majority of the catch is taken during peak spawning in late March/April and during

May (Figure 3). Very little is known about the summer feeding distribution and pre-spawning migration patterns. They are not sufficiently aggregated to be available to the industry during June-November.

The basic survey design used regularly spaced parallel transects that cross perpendicular to the long axis of the Strait (Figure 1). Nominal spacing was 3 nm and transect were terminated at the 30 m isobath or 0.5 nm from shore. The overall survey area and transect layout have remained constant over the years.

However, coverage of sub areas, such as Malaspina Strait, Jervis Inlet and Sabine Channel, were variable among years owing to navigational and/or time constraints.

Fishing was conducted to confirm species composition of observed echo sign and to determine length, sex, maturity, and age of hake occupying the assessed layers.

2.2 Research vessels

The 1981 survey operations were conducted from the F.R.V. G.B. REED, a 54 m, 1000 h.p. Scottish design side trawler. The vessel was equipped with a BioSonics single frequency, single beam echo integration system and towed transducer assembly described below. The G.B. REED was decommissioned in 1988 and replaced with the CCGS W.E. RICKER which was used for all subsequent acoustic surveys. Fishing operations were conducted in 1981 using the M/V ARCTIC HARVESTER, a 44.5 m commercial stern trawler.

The W.E. RICKER is a 58 m, 2500 h.p. research stern trawler. The vessel was first equipped with the BioSonics acoustic system which was used for the 1988 and 1993 surveys. In 1995, the vessel was refit with a dual frequency, split-beam Simrad EK500 acoustic system.

2.3 Fishing and catch sampling methods

Fishing gear has changed considerably over the years. During the 1981 survey a Canadian Diamond 7 midwater trawl was used. A Canadian Diamond 5 midwater trawl with 6m vertical mouth opening was employed for the 1988 and 1993 surveys while a Model 250 Polish rope trawl midwater net with a 14 m vertical mouth opening was used from 1996 to 1998. All nets used a 3 cm herring codend. The selectivity of the three nets has not been compared and it is likely that it differs. The continuous use of a small-mesh codend throughout the series at the very least, provides confidence regarding the presence or absence of modes of juvenile hake. Since acoustic surveys do not rely on catch rate data from test fishing and by-catch is minimal the only potential impact is on the relative amounts of juvenile hake. Indeed, it is likely that all three nets underestimate the true proportion of juvenile fish.

Catch sampling has remained essentially unchanged over the survey period. Trawl catches were spilled from the codend into a below deck hopper and sorted by species into tubs off a conveyor belt. All tubs of fish were weighed on a deck balance to the nearest kilogram. For large catches, representative subsamples of hake were selected by retaining at least three tubs of fish from the start, middle, and end

of the hopper load. Half of the tubs retained were randomly selected for routine biological sampling. With small catches the entire catch was sampled. Measurements of fork length to the nearest cm, sex, and maturity were recorded for all hake sampled (Weir et al. 1978). Otoliths were collected and stored in a 1/1 glycerine/freshwater solution with 0.3% thymol for subsequent age determination.

2.4 Acoustic systems

Measurements of the acoustic backscatter cross section provide the basic information for biomass estimation. An echosounder measures this quantity by transmitting a known sound pulse and recording the received echo energy. We will use S_v and S_V to denote the volume backscatter cross section in physical and dB units, respectively. The corresponding area backscatter cross section is obtained by integrating S_v over the portion of the water column of interest. It is denoted by S_a and S_A in physical and dB units, respectively.

Significant changes have occurred in hardware and at all levels of data collection and analysis in the time frame of the Strait of Georgia hake surveys. Foremost among these has been the evolution of the acoustic system itself. Described below are the two major hardware configurations we have used.

2.4.1 BioSonics system

The BioSonics system that was used from 1981 to 1993 was based on a BioSonics 101 precision echosounder, towed body and Simrad ceramic transducer. The original configuration also included a Simrad chartrecorder, an Ecosonics digital echo integrator and a 1/4" analog magnetic tape for data backup (Kieser 1983). The Ecosonics integrator was based on a DEC PDP 11/10 computer with CAPS 11 operating system. Bottom tracking was provided by the Ecosonics and echo integration proceeded from 5 to 500 m. Twenty consecutive intervals that increased with depth from 5 to 50 m were recorded every minute to digital cassette. Position information was from radar fixes and was only available for transect ends. Data analysis relied entirely on in-house software. A BioSonics 120 echo integrator, BioSonics chartrecorder and a PC were added for the 1988 survey (Shaw et al. 1990). Substantial software upgrades had been implemented by that time.

Although the BioSonics system included a proven scientific sounder, its comparatively low signal to noise ratio limited our ability to discriminate smaller targets and targets at depths greater than 250 m. Its limited dynamic range could cause receiver saturation that would result in reduced echo integration measurements. This was more likely to affect herring rather than hake distributions. From 1988 on, echograms were generated on a BioSonics thermal chartrecorder. Good black and white images were obtained, however, these showed much less density information than their more recent colour counterparts. Furthermore, thermal recordings tend to fade with time. Much of the original echo intensity and image sharpness may have been lost in recordings from earlier surveys making visual comparison with recently recorded echograms difficult.

2.4.2 Simrad system

After 1995, we began operating a Simrad dual-frequency, split-beam acoustic system (Kieser et al. 1998). This system has a better signal to noise ratio, and approximately double the dynamic range (measured in dB) of the BioSonics system we used. These improvements provide better fish detection at depth and avoid signal saturation for dense aggregations. To date, only data collected on the 38 kHz receiver are used for biomass estimation, however, information gathered by the 120 kHz receiver are used to help classify targets within 200 m range. These data are particularly useful in discriminating plankton from fish. The system produces colour echograms with a calibrated logarithmic colour scale ranging from grey through blues, greens, reds, and dark brown at the maximum echo intensity (Figure 4). This colour scale provides better definition of low and high echo intensities improving echo interpretation and selection by giving more information on fish school densities and bottom hardness.

The Simrad system included a Simrad EK500 38/120 kHz split beam echosounder (Simrad 1993a; Bodholt and Solli 1992; Bodholt 1990), two colour printers for echogram recording, a Simrad BI500 data logging and analysis system (Simrad 1993b). Position for every ping was recorded from a differential GPS receiver.

The 38 and 120 kHz transducers were mounted on a single retractable ram located near midship at keel depth (~4.3 m). All survey work was conducted with the ram fully extended. The resulting transducer depth of 5.5 m was sufficient to significantly reduce vessel noise, hull-induced turbulence and aeration (J. Traynor, AFSC-RACE, NMFS, Seattle, Wash., pers. comm.). These facilities were complimented by a range of PC based, commercial and in-house software that included navigation and charting software (SeaPlot, Advanced Marine Technology Corp. 1993), a geographic information system (CompuGrid, Langford 1996) for mapping and spatial and statistical analysis software (S-Plus, Mathsoft Inc. 1995).

The EK500 echosounder was connected via local area network (LAN) to a UNIX workstation that provided the platform for the BI500 software. The BI500 was used to log acoustic and navigation data, annotate echograms, and store EK500 parameter files. Echo integration and TS data telegrams from the EK500 were recorded; echo amplitude and angle information (sample data telegrams) were not recorded to conserve disk space.

The BI500 Scrutinise program was used for visual echogram interpretation and to select the appropriate echoes for further analysis. The Report and EchoTrace programs were used to extract echo integration and TS data to ASCII files for final processing on a PC.

Vessel tracklines were monitored with the SeaPlot software, and a log file was maintained to record EK500 log numbers for key events such as transect and set locations.

2.5 Echo editing and signal classification

Procedures for echo editing and signal classification have also improved significantly. Analysis of the BioSonics data began by identifying and grouping target aggregations on the black and white echograms by ping number (time) and depth bins (range). Ping and depth information from each group were then manually transferred to a control file that was used to extract the appropriate echo intensity information from the echo integration data file. The resolution of the editing process was limited by the 1 minute ping sequences and 5 to 50 m depth intervals that were used during initial data collection.

Echo editing procedures have been greatly enhanced with the installation of BI500 scientific post-processing system in concert with the EK500 acoustic system. This commercial software provides an interactive tool for off-line echo interpretation, selection, and integration of the acoustic data within operator defined echogram regions. The program displays 5 nm colour echogram sections on a computer screen and provides considerable flexibility in adjusting echo colour intensity for improved viewing and classification of acoustic sign, and for delineating and grouping echogram regions. The software writes the selected echo intensities (Sa) to a relational database and ASCII summary tables are easily extracted. Digitally stored echograms can be quickly recalled for examination and more effective data exploration and re-examination is possible with shorter data processing times.

Evolution of our acoustic data collection and processing systems has brought more stable systems performance, improved data quality and enhanced signal classification.

2.5.1 1998 echo editing procedure

The BI500 Scrutinise program was used to review the electronic echogram and to categorise echo sign from five major species groups: hake, pollock, herring, rockfish, and plankton. The assignment of echogram structures to species or mixed species groups was based on echogram appearance and on information from representative trawl catches. Transect location, bathymetry and acoustic bottom and sub-bottom images provided additional information.

The acoustic sign was classified into dense, localised aggregations or schools and into generally less dense, extended layers.

School formations are principally herring or rockfish. Herring schools are often observed above 100 m depth and are readily identified by their high density, needle-like or oval shapes (Figure 4). Rockfish (*Sebastes sp.*) are present at most depths but their characteristic column-like formations are most often seen in association with steep slopes, rugged bottom and/or pinnacles. Dogfish are also caught in varying amounts by the trawl gear at most depths, however, unless densely schooled, their low target strength contributes relatively little to the echogram and to the measured echo intensity.

Extended layers in the Strait of Georgia can generally be grouped into three categories: 1) surface 2) midwater, and 3) deep.

1. Surface Layer

A shallow layer of targets often exists from near surface to about 150 m, however, depending upon the time of year of our survey, the density and extent of the layer can vary considerably (Figure 4). Samples collected with various gear types show that the aggregation is highly mixed and may include euphausiids, myctophids, larval fishes, and some juvenile hake (14 - 20 cm). Given this layer is largely composed of zooplankton, environmental conditions affecting primary production near the surface (<50 m) can have a significant impact on its extent, density and composition. The near surface and surface layers in Figure 5c provide an example of this variability.

We classify the surface layer as 'miscellaneous mixed' since the variety of species caught and the varying selectivity of the sampling gear with respect to each species prevents more accurate apportioning of the acoustic sign. The occurrence of juvenile hake in only some of the shallow trawl sets suggests a heterogeneous distribution throughout the Strait.

2. Midwater Layer

A fairly concentrated scattering layer, often with many single targets visible, is typically observed below the surface layer from about 150 to 250 m (Figure 4). Catch data from trawls in this midwater layer show that targets are primarily hake, ranging in length from about 14 to 35 cm. Pollock occasionally form a component of the layer, but are usually only found in specific areas of the Strait. The depth boundaries of this layer can also vary significantly. Pacific hake catches from this layer contain pre-spawning females and spawning males.

3. Deep Layer

A layer similar in appearance to the midwater layer is often identifiable at depths below 250 m. The degree to which this layer can be separated on the echogram from the shallower midwater band varies. In deeper basins of the Strait, a more thinly distributed, but homogenous layer is readily evident (Figure 4). Trawl catches indicate this layer is comprised of actively spawning male and female hake. At the basin edges, the midwater and deep layers appear to merge (Figure 5b). In such cases, delineation is based on adjacent zones with obvious separation and on trawl catch information.

A comparative examination of echograms from 1996, 1997 and 1998 is based on typical colour echograms collected along Transect 12 and 38 in the central and northern basins (Figures 5 and 6). The figures illustrate the features of colour echograms mentioned earlier and highlight some of the observed changes in echo distribution and density in successive years. No comparison with BioSonics echogram recordings is offered owing to the deterioration of the thermal print black and white images mentioned earlier.

All echograms in Figures 5 and 6 show the shallow, midwater and deep layers but with very different densities and at varying depths. The SV colour threshold for the 1996 echogram was -65 dB while -70

dB was used in subsequent years, the corresponding slight colour shift will render especially light layers less visible in the 1996 echogram.

The 1996 echogram (Figure 5a) presents a very light shallow layer of targets at about 125 m. The 1997 record indicates a similar layer but with more density and colour (Figure 5b). This difference is largely due to the difference in SV colour threshold. The 1998 echogram, however, is markedly different with the same layer appearing much more dense and shallower at about 100 m (Figure 5c). Trawl data from each year confirm the composition of the shallow layer as 'miscellaneous mixed' with euphausiids, larval and juvenile fishes, including some hake.

A similar density increase is observed in the near surface backscatter layer (<50 m) that is seen in the upper range bin. The increase in the shallow and near surface layers may be related to the timing of the surveys as primary/secondary productivity will quickly lead to an increased number of scatterers early in the year. The 1998 assessment was done in late March a full month later than previous surveys (Table 1).

Below the surface layer is a midwater layer that often extends to bottom. The blue to green colours indicate substantially higher densities that include single fish aggregations and dense schools (eg. Figure 5b 150 to 250 m). Density and distribution of this zone also varies extensively from year to year (Figure 6).

Trawl catches indicate that the midwater layer is dominated by hake of varying size, sex, and maturity. In some areas pollock may contribute substantially. This is not evident from the echogram. In 1997, for example, trawl data showed that pollock represented upwards of 75% of the catch on one section of Transect 15 to a depth of about 200 m. Nearby trawl catches indicated less than 25% pollock for the same depth layer, and showed that pollock were not present in any amount below 200 m.

Usually we are able to visually separate the midwater and deep layers. In the 1998 echogram (Figure 5c), for example, targets along Transect 12 were clearly aggregated in a layer ranging from 125 to 200 m. Single fish targets of similar intensity appear deeper than 200 m but are distributed much more diffusely suggesting that separate classification of this zone is appropriate. This is supported by trawl data from the midwater and deep layers that yield hake of different size with larger fish residing at greater depths.

2.6 GIS based mapping and biomass estimation

A raster based GIS (Langford 1996) has been used for mapping and biomass estimation of the Strait of Georgia surveys since 1993 (Table 1). Basic procedures have changed little with successive surveys and are described below based on our most recent 1998 survey. Biomass and distribution analyses were based on the scrutinised Sa values derived from the echo editing procedure described earlier. The GIS was used to generate transect maps from the average Sa measurement positions (Figure 1), and fish distribution maps by plotting vertical lines that are proportional to the Sa values (Figure 7a). The

200 m isobath is shown to indicate the location of the deep basins.

The first step in the GIS based analysis was to create a geo-referenced matrix that encompasses the survey area. Each element presents a 60 by 60 m² area and all elements were initialised with a background code. The measured Sa values were then entered at their appropriate locations to create a sparse Sa matrix.

Biomass estimation requires interpolation of the Sa matrix; proximal analysis was chosen for its simplicity and robustness (Kieser and Langford 1991; Langford 1996; Cooke et al. 1992; Kieser et al. 1995). Proximal creates an interpolated Sa matrix by replacing all unknown elements with the value of the nearest Sa.

A mask (Figure 7b) was created to define the area for biomass estimation. It was designed to cover the area between transects and to extend about half the transect spacing on all sides. The area was then limited to water deeper than 50 m. The sparse Sa matrix was buffered and clipped (Langford 1996) to implement the mask M. Biomass B was estimated as:

$$B = k \cdot A_0 \sum_{ij} Sa_{ij} \quad (1)$$

where ij is within Mask M and $k = (4 \cdot p \cdot 1852^2 \cdot 10^{TSw/10})^{-1}$.

A_0 is the area for each matrix element (3600 m²) and TSw is the target strength per unit weight (see below). Sa_{ij} are the elements of the interpolated Sa matrix and the summation is over all elements that are within the mask M.

The biomass estimation process described here is appropriate when a single species of uniform size is present. This is a reasonable assumption for the adult hake layers in the Strait when the fraction of juvenile fish is small. A biomass estimation model that accounts for different species and fish lengths will be described in a later section.

Biomass estimation for the 1981 and 1988 surveys used an equivalent area expansion process that relied on multiplying each surface density measurement with an appropriate small area and summing these products. The small area for a given surface density measurement location was obtained by multiplying half the distance between adjacent measurement locations by half the spacing between the neighbouring transects.

Early surveys only recorded the position of the transect end points. The position of the fish surface density measurement locations therefore was obtained by interpolating between endpoints. Care was taken to maintain constant vessel speed on each transect. Table 1 includes a record of the position fixing and area expansion procedures that were used during the review period.

2.7 Target strength and biomass estimation

Target strength is a key parameter for biomass estimation. Over time we have used several TS values for the Strait of Georgia surveys (Table 1). From 1981 to 1988, we used a mean TSw of -32 dB/kg.

In 1993 we adopted TSw=-35 dB/kg to generate consistent results with researchers from the US NMFS who were using this value for their offshore hake biomass estimation.

Biomass estimation in simple situations may be based on a mean TS that is expressed either per fish (TSn) or per unit fish weight (TSw). Either estimator is appropriate when a single species with a narrow, uni-modal length distribution is present. In our earlier surveys, we used TSw as this approach is less dependent on fish length and does not require a separate fish length weight relation.

Given a TS length relation TSn or TSw can be calculated from mean fish length and mean fish weight when the length histogram is narrow. Conversely, the broad and multi-modal fish length frequencies, which we have observed more recently for Strait of Georgia hake (Figure 2), require TS be computed from length histograms that are representative for the surveyed aggregation.

We have completed four TS literature reviews (Taylor and Kieser 1982; Kieser 1983; Kieser 1992; Stanley et al. 1998) and an analysis of *in situ* TS measures from the Strait of Georgia (Kieser et al. 1996) to obtain an appropriate TS length relation:

$$\text{TSn}(l) = 20 \cdot \log(l) - 68.0 \quad (2)$$

Details are given in Appendix 1, reproduced from Kieser et al. (1998). Calculation of TSw from Equation 2 requires a length (cm) weight (g) relation:

$$w = 0.00650 \cdot l^{2.9969} \quad (3)$$

The coefficients are from McFarlane and Beamish (1985) and are typical for the Strait of Georgia (G.A. McFarlane, Pacific Biological Station, pers. comm.).

Table 2 gives TS estimates that are based on Equation 2 and 3 and on a number of representative fish length and weight distributions. The results for TSn and TSw (Table 2) are based on the length distributions shown in Figure 8, while mean length (Length) was used to compute TSn1 and TSw1. Mean squared length (Length²) was used for calculating TSn2 and TSw2. Table 2 show that TSn2 equals TSn. Thus mean squared length can always be used to compute TSn. It also shows that TSw2 is a better approximation of TSw than TSw1, however good agreement is obtained for the narrow length distribution from Set 16 (Figure 8).

Target strength is a function of fish length and species. With more complex, multi-species situations and more variable length distributions, as we now see in the Strait of Georgia, application of a single TSw value cannot account for the contribution of different groupings to the biomass estimate. We have a TS-length based biomass estimation model that is appropriate for these situations. It is described in Appendix 2.

Briefly, our biomass estimation model uses Equation 2 to estimate TS for the aggregations that have been identified by scrutinising the echo data. Representative sets provide species and fish length information. Fish number density for all aggregations is estimated and the length weight relationship (Equation 3) is used to estimate biomass. Our present limit for assigning sets to aggregations is at the transect level, consequently species and length information from one or several sets are assigned to Sa values from one or several transects. Grouping Sa values by transect has been an effective way to associate set information and Sa values, however our spatial resolution also reflects the limited amount of information that is available for this task.

2.8 Acoustic system calibration

Acoustic instruments used to estimate the abundance of organisms in the sea do so by measuring the echo energy from scatterers in the water column. An absolute measurement of acoustic backscatter energy requires a calibrated acoustic system (Robinson 1984; MacLennan and Simmonds 1991). Calibrations can be carried out by comparing the acoustic system against a standard hydrophone or by measuring a standard target.

The BioSonics acoustic system was calibrated against a standard hydrophone at the Applied Physics Laboratory, University of Washington, Seattle (Kieser 1983; Saunders et al. 1992). The echosounder, echointegrator, transducer cable and transducer had to be removed from the vessel and transported to the calibration site. Calibrations were completed before each cruise or at least once a year. The BioSonics system showed variation in the order of .5 dB which agrees with accepted standards for hydrophone calibrations reported by Foote et al. (1987a, 1987b) and MacLennan and Simmonds (1991).

A standard target calibration is used for the Simrad acoustic system. Procedures outlined by Foote et al. (1987a, 1987b) and in the EK500 operations manual (Simrad 1993a) are followed. A target with known acoustic properties is suspended under the vessel in the acoustic beam. Advantages of a standard target calibration are that the acoustic system remains on the vessel, that measurements are made under conditions that are nearly identical to those used during the survey and that the calibration can be repeated as needed. However, very calm sea conditions and the absence of interfering fish targets are a prerequisite for a good calibration. Tidal movement and interference from fish targets were noted for the last two calibrations (Table 3, Column A = N); calibration values collected on these occasions were therefore not used. Long term system stability is given by the coefficient of variation of the calibration time series (Table 3, last row). We assess the critical short term stability that applies for the duration of each survey from the variations observed during our calibration exercises. This variation generally is less than 0.2 dB which compares well with the optimal accepted sphere calibration accuracy of 0.1 dB (Foote et al. 1987a; Foote et al. 1987b; MacLennan and Simmonds 1991).

2.9 BioSonics/Simrad intercalibration

An intercalibration between the BioSonics and Simrad systems was conducted in 1995 as part of a joint Canadian and US Pacific hake survey off Vancouver Island. Objectives of this work were to compare the Canadian BioSonics and Simrad systems on the W.E. RICKER with the US Simrad system on the MILLER FREEMAN (Wilson and Guttormsen 1997).

Simultaneous measurements with the Canadian BioSonics and Simrad systems were made from the W.E. RICKER. Pacific hake concentrations were measured along several transects and a comparison of both systems was obtained by plotting BioSonics Sa against EK500 Sa values from all transects (Figure 9). The BioSonics Sa values were consistently higher than those measured by the Simrad. A straight line least square fit through the origin gives the slope of BioSonics over Simrad Sa as 1.43, the slope for the logarithmic data is 1.06. The correct slope is expected to be between these values. An attempt was made to apply the intercalibration model described by Kieser et al. (1987) to clarify the difference, however we were unable to complete the analysis in the time available.

Part of the difference between the BioSonics and Simrad Sa values may lie in the relatively small Sa range that was covered and in the large scatter of the data points. The latter was expected due to the contagious nature of the fish distributions. Also, the difference needs to be seen in relation to the BioSonics and Simrad calibration accuracy, noted earlier as 0.5 and 0.2 dB or 1.12 and 1.05 times, respectively. The calibration results imply that the BioSonics based estimates may be too high or that the Simrad values could be low. The concurrent intercalibration with the Simrad system on the MILLER FREEMAN indicated that the two Simrad systems compared well (Wilson and Guttormsen 1997). This suggests that the BioSonics based estimates are likely too high.

Further intercalibration work was planned to resolve the difference, however loss of the BioSonics towed body and transducer made this impossible. Given the one time nature of the results and their uncertainty we do not recommend that corrections are applied to earlier Strait of Georgia estimates.

3.0 PACIFIC HAKE BIOMASS ESTIMATES

3.1 Pacific hake distribution

Pacific hake distribution from the 1993, 1996, 1997 and 1998 surveys are shown in Figure 13a through d. Hake densities are indicated by vertical lines that are proportional to the combined Sa from the midwater and deep layers. An Sa value of 2000 corresponds to 6 nm, a linear scale is used and larger values are truncated. The 200 m depth contour is outlined to delineate the deep basins. The hake distribution varies between years but a preference for the central deep basins is apparent. Comparable figures from the 1981 and 1988 surveys are unavailable as the original distribution plots were hand drawn contour maps. Data for the 1981 survey are no longer available in machine readable form. Those for 1988 are available but a new analysis has not been completed.

3.2 Biomass estimates

Biomass estimates are reported for all surveys. Estimates in Table 4 are based on a constant TSw of -32 dB/kg, those in Table 5a were obtained from our new biomass estimation model and use the TS length and length weight relations that are given in Equation 2 and 3 respectively. As pointed out earlier a constant TS will give a good relative biomass when fish size and TS remain constant, while the new model will provide our best estimates that account for the substantial decrease in adult hake length and the increase in juvenile hake that has been observed over the years. Note that the TS length based estimates in Table 5a are lower from 1993 through 1998, owing to fish size reduction, than those based on a constant TS of -32 dB/kg. Table 5b gives a summary of the mean TS, length and weight that characterise the biomass estimates shown in Table 5a.

3.3 Biomass uncertainty

Acoustic biomass estimation includes several components that contribute to the uncertainty in the final estimate. Our discussion includes the three most important sources: 1) acoustic system calibration, 2) target strength, and 3) uncertainty due to the sampling process of the fish distribution. System calibration and target strength uncertainties generally impose a bias while transect based sampling produces bias and variance. Additional sources of variation such as the identification of hake targets, vessel and ambient noise, etc. are contributory but considered relatively minor.

3.3.1 Acoustic system calibration

The standard error for system calibration has been discussed earlier and is restated here for reference purposes as 0.2 dB or 6%. The corresponding coefficient of variation (cv) is 3%.

3.3.2 Target strength

An estimate of the uncertainty in TS can be obtained by examining the TS measurements that are shown in Appendix 1 Figure A1-3. A linear least square fit to all points gives a TS length relation with $c = -67.87$. The corresponding TS and cv for a 35 cm fish are -36.99 ± 0.45 dB. The estimate for c shifts to -68.43 dB when only the four most reliable points published by Williamson and Traynor (1984) and Traynor (1995) are used. This brief exploration provides some support our target strength length relation (Equation 2) and suggest a cv of 0.45 dB or 11%.

It is obvious that TS bias is likely to be larger than calibration bias, however it is also important to realise their different nature. Calibration bias would be expected to vary with each calibration and from cruise to cruise, however TS bias will be constant as long as factors such as fish behaviour and maturity that effect the TS length relation remain unchanged. Thus TS bias could be essentially constant over a long period of time resulting in stable relative biomass estimates.

3.3.3 Sampling methods

Pacific hake have a strong tendency to aggregate in schools and in areas that are characterised by deep basins. The resulting contagious fish distributions and our transect based, sequential sampling procedures make it difficult to obtain accurate estimates for the survey sampling error. However, variance estimates based on the measured Sa values and on transect biomass provide a convenient upper limit (McLennan and Simmonds 1991, Stanley et al. 1999). Using the 1998 Strait of Georgia Survey as an example we find cv's of 4% and 14% based on all Sa values and on transect biomass, respectively. For the 1997 survey we obtain 4% and 11%, respectively. These estimates are expected to be high as they assume random sampling and normally distributed data.

Geostatistical procedures (Petitgas and Lafont 1997) account for the spatial structure and the correlation between data points. First results for the 1998 Strait of Georgia survey indicate a cv of less than 3.5% for the biomass from the combined deep basins. Similar results are obtained when only data from the central deep basin near Halibut bank are used. Of course even geostatistical procedures only can reflect the variance that is present in the data themselves. Other sources of variation will only be available through repeat surveys. In light of these uncertainties we choose the conservative 11% figure from the previous paragraph for the following summary.

Assuming that the system calibration (3%), TS (11%) and survey sampling (11%) errors are uncorrelated they can be combined as the sum of squares to yield an overall cv of 16% (Bevington, P.R. 1969). Given a normal distribution the 95% confidence interval would be between $\pm 31\%$ limits (Bevington, P.R. 1969). Note that these figures are potentially misleading as we combine different types of errors; as Sa measurements are non random, correlated and skewed. These estimates are offered to guide the reader in his interpretation of the results.

4.0 DISCUSSION

Overall we are satisfied that the methods applied throughout the time series are sound, however several flags of concern should be raised, notably poor comparability with swept-volume trawl surveys, uncertainty with the 1993 survey, and the impact of survey timing.

4.1 Comparison with swept-volume surveys

Swept-volume trawl surveys were conducted in 1981 and 1988 (Thompson and McFarlane 1982; Shaw et al. 1990). The hydroacoustic estimates were 37% and 42% lower, but within the 95% confidence limits of the swept-volume estimates. These results suggest that the acoustic method is conservative, however we feel that swept-volume trawl surveys can provide complementary information but cannot be used to verify acoustic estimates for two reasons. Primarily swept-volume trawl surveys

suffer from an untraceable bias from the unknown effective mouth opening of the trawl. Secondly catching fish is a hunting process that is highlighted by fish actively avoiding the net and the fisher guiding the net to catch the fish. Under these circumstances catch rate is unlikely to be closely related to fish density.

4.2 1993 survey estimates

The biomass of hake found during the 1993 survey appears anomalously high relative to the other surveys (Table 4). Examination of the echograms indicates echosign of sufficient intensity and area to support a substantial biomass, however, hake biomass may be overestimated for several reasons.

Given the better quality colour echograms of the more recent surveys and the improvements to the overall data collection and analysis procedure described earlier, we now have information available to us which allows for a more critical examination of the black and white echograms from earlier survey. Our review of the 1993 results suggests that the echogram scrutinising, including identification of hake layers and assignment of species proportions, may be incorrect. Operational constraints at the time of the 1993 survey prevented concurrent sounding and fishing. The hydroacoustic survey was run from March 8-17 while fishing was carried out March 18-25. Presuming the aggregations were stable we would have been able to determine species composition and confirm echosign. However, the distribution of hake was considerably different between the two time periods. A heavy scattering layer centred at 140 m (Figure 10) may have included plankton and/or pollock which is not evident on the black and white echograms. Although it may be possible to discern the presence of plankton in the layer by digitising the archived data and producing a colour echogram, the absence of fishing sets precludes examination for the presence of other species, in particular pollock. It is not possible to apportion the acoustic sign to species without concurrent sampling of the layer. Evidence from the 1997 survey (Cooke et al. 1998) showed pollock represented a significant portion of the catch in a given area but was not identifiable on the echogram.

4.3 Survey timing

One major concern is whether the entire Strait of Georgia hake population is available in the two weeks taken to conduct surveys in most years. This is a key question if the survey is to be of use as an index of either relative or absolute abundance. There was early, although inconclusive, evidence that hake biomass builds in the Strait of Georgia over the spawning period. Kieser (1983) conducted hydroacoustic surveys during January, February, and April of 1981 and found that the biomass of hake increased by 47% between January and February, and by 58% between February and April. Interpretation of the April survey data was confounded however, by a deep plankton layer and Kieser (1983) indicated that biomass during that survey was likely over estimated. Hydroacoustic surveys since 1981 have been conducted during late February and early March in an attempt to estimate abundance as close to the peak in spawning biomass as possible while avoiding interference from the increased plankton abundance later in the spring.

There is some evidence from the time series that this compromise in survey timing (Table 1) has resulted in conservative estimates of hake biomass (Table 4). In Figure 11, the hake gonad maturity conditions described by Weir et. al. (1978) have been collated in pre-spawning, spawning and post-spawning categories by survey month and year. The darkened plots represent maturity samples taken during or as close as possible to the spawning survey in that year. In April 1981, when the peak in biomass likely occurred, female maturities were dominated by post-spawning hake. If the peak in biomass occurs during this period then all of the surveys have taken place in advance of the peak (Figure 11).

Additionally, the sex ratio of mature fish during all of the surveys is biased to males (Figure 12). Since there is no evidence for sex-specific mortality rates it is possible that some of the females are not present in the Strait. The percentage of females has ranged from 18 to 39% and has averaged 31.5% by number over the six surveys presented (Figure 12). This suggests that the number of hake could be underestimated on average by a factor of 1.4. The process likely entails males entering the Strait earlier and staying longer (McFarlane et al. 1983). Females enter the Strait, spawn and remain in the Strait to feed thus the sex ratio likely equalises over time. For example, the sex ratio in the April 1981 survey was 42% females, whereas the February, 1981 survey shows only 37% females. Also, there was no sign of post-spawning, shallow feeding aggregations that were noted in April 1981.

Overall, these results suggest the hypothesis that biomass of hake accumulate to a peak in late spring. Ideally a number of short surveys should be conducted within a year to identify time of peak spawning and capture maximum hake biomass. Surveys operated later in the spring will be impacted by the increase in plankton production noted earlier. Given the improved signal characteristics of the Simrad acoustic system and with carefully directed sampling of the various layers, identification of hake in the water column should be possible.

5.0 SUMMARY AND RECOMMENDATIONS

We have generated time series of Pacific hake biomass estimates based on $TS_{w}=-32.0$ dB/kg and using TS-length and length-weight relationships. Several sources of uncertainty should be recognised when interpreting the Pacific hake abundance from these time series:

1. An analysis of calibration results, TS and survey sampling has generated a coefficient of variation of 16%. Although conventional and accepted procedures have been used this figure remains subject to the limitations of the statistical analysis and assumptions that have been made. This figure is believed to be conservative with respect to the data at hand, however it is subject to survey timing and the availability of hake in the survey area discussed earlier.
2. Recent surveys show a very light distribution of Pacific hake at depth greater than 150 m. Signal attenuation at these depth is sufficient to potentially underestimate the portion that appears as single fish on the echogram. A small biomass correction is expected, however detailed calculations will be required to provide a quantitative answer.

3. The 1993 survey is an overestimate due to inclusion of plankton back-scatter. It could be re-analysed to eliminate the plankton layer.
4. Based on examination of sex ratio and survey timing, all surveys are expected to be conservative estimates of biomass. This concern will be the subject of future stock-assessment research.
5. An intercalibration between the BioSonics and Simrad systems suggests that the earlier estimates from the BioSonics system may be too high, however our one time point estimate for the difference is insufficient to justify a correction.
6. Pacific hake length distributions have changed significantly during the review period. Under these circumstances it is important to base biomass estimation on appropriate TS-length and length-weight relationships. These calculations generate a lower biomass than previously reported.

The results of our review lead to a number of recommendations regarding the survey:

1. Conduct multiple surveys within one year to capture peak biomass.
2. Examine feasibility of April or summer surveys when biomass availability is high or close to maximum.
3. Examine adjacent inlets and other unsurveyed areas to confirm that the majority of adult hake are in the survey area.
4. Convert historic acoustic data to a standard format for further analysis.
5. Conduct *in situ* target strength work to further test length-based target strength models.
6. Expand investigation of recognised geostatistical procedures to generate a better estimate of the survey sampling error.
7. Investigate the potential for underestimating the deep layer due to threshold bias. This is particularly relevant for recent surveys that show an increasing component of deep scattered fish.
8. Incorporate alternative sampling methods such as underwater cameras to examine the selectivity of trawl gear with respect to fish size and species composition.

6.0 ACKNOWLEDGEMENTS

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Table 1. Summary of the 1981 to 1998 Pacific hake surveys includes cruise start and end dates, vessel names (G.B. REED and W.E. RICKER), acoustic system used, vessel positioning technology, and fishing gear type (D7 = Diamond 7; D5 = Diamond 5; RT = Rope Trawl). Acoustic analysis procedures and TS applied are described in the text.

Date	Vessel	Vessel Position	Acoustic System	Interpolation	Target Strength	Layers	Depth Surveyed	Gear Type	Fishing	References
Jan 12 - 23, 1981	GBR	Radar	BioSonics	Width	-32	2	50-250m	D7	Y	Kieser 1983
Feb 09 - 20, 1981	GBR	Radar	BioSonics	Width	-32	2	50-250m	D5	Y	Kieser 1983
Apr 13 - 24, 1981	GBR	Radar	BioSonics	Width	-32	2	50-250m	D5	Y	Kieser 1983
Mar 18 - 28, 1988	GBR	Loran	BioSonics	Width	-32	2	50-250m	D5	N	Shaw et al 1990
Mar 08 - 25, 1993	WER	Loran	BioSonics	GIS	-35	2	50-bottom	D5	Y	Saunders et al 1998
Feb 20 - Mar 05, 1996	WER	GPS	Simrad	GIS	-35	2	50-bottom	RT	Y	Kieser et al 1998
Feb 17 - 28, 1997	WER	GPS	Simrad	GIS	TSLen	3	50-bottom	RT	Y	Cooke et al 1998
Feb 16 - 26, 1998	WER	DGPS	Simrad	GIS	TSLen	3	50-bottom	RT	Y	--

Table 2. Comparison of target strength estimation procedures. The mean length (Length), mean length squared (Length²), mean weight (Weight), TS_n and TS_w are based on length histograms from the 1997 Strait of Georgia survey (Figure 8a). Target strength based on mean length is given by TS_{n1} & TS_{w1} and that based on mean length squared is given by TS_{n2} & TS_{w2}. Note that TS_n is equal to TS_{n2} and that TS_{w2} is a better estimate of TS_w than TS_{w1}. All TS estimates use the TS-length relation from Equation 2.

Set	Length cm	Length ² cm ²	Weight G	TS _n dB	TS _w dB	TS _{n1} dB	TS _{w1} dB	TS _{n2} dB	TS _{w2} dB
4	14.6	270.9	44.9	-43.67	-30.2	-44.71	-27.74	-43.67	-28.26
9	23.2	638.2	128.1	-39.95	-31.03	-40.69	-29.74	-39.95	-30.11
16	35.0	1236.5	282.7	-37.08	-31.59	-37.12	-31.52	-37.08	-31.54
19	29.0	891.4	183.2	-38.5	-31.13	-38.75	-30.71	-38.5	-30.83

Table 3. A calibration time series for echo integration (TR_{SV}) and target strength measurements (TR_{TS}) for the WE RICKER EK500 38 and 120 kHz systems. Date, calibration location, water temperature and target depth are shown in addition to the calibration values. The TR_{SV} and TR_{TS} columns give the calibration results for SV and TS measurements, respectively. Column A will be Y when the new calibration value has been applied and N otherwise. The coefficient of variation (cv) is given in dB.

			38 kHz					120 kHz				
Date	Location	Temp	Range	TR_{SV}	A	TR_{TS}	A	Range	TR_{SV}	A	TR_{TS}	A
		°C	m	dB	dB	m	dB	m	dB		dB	
950301	1	na	na	26.5	Y	27.3	Y	na	25.5	Y	25.5	Y
950822	2	8.0	na	26.4	Y	26.5	Y	na	25.7	Y	25.7	Y
960221	3	na	17.6	27.1	Y	27.0	Y	20.0	25.5	Y	25.2	Y
960810	4	8.0	25.4	26.6	Y	27.2	Y	23.0	25.7	Y	25.8	Y
970224	3	8.1	25.8	27.1	Y	27.2	Y	23.2	25.3	Y	25.4	Y
970811	3	10.0	25.3	27.1	Y	27.1	Y	23.2	25.7	Y	25.8	Y
980119	3	7.8	27.9	27.1	Y	27.0	Y	25.7	25.2	Y	25.8	Y
980323	5	9.6	24.1	27.2	N	27.1	N	22.0	25.4	N	25.4	N
980818	6	13.6	19.3	27.0	N	27.1	N	16.8	25.0	N	25.2	N
			CV:	0.29		0.22			0.24		0.25	

Locations: 1. Simrad, 2. Kendrik Inlet, 3. Departure Bay, 4. Mayne Bay, 5. Hotham Sound, 6. Balcom Bay.

Table 4. Biomass summary for 1981 to 1998 Strait of Georgia Pacific hake surveys. Biomass includes all hake age groups, TSw=-32.0 dB/kg.

Date	1981	1981	1981	1981	1988	1993	1996	1997	1998	
Vessel	Jan 12-23	Feb 09-20	April 13-24	April 13-24	March 18-28	March 08-25	Feb 20-05	Feb 17-28	Feb 16-26	
Sounder	GBR	GBR	GBR	GBR	WER	WER	WER	WER	WER	
Comment	BioSonics	BioSonics	BioSonics Measured	BioSonics Adjusted	BioSonics	BioSonics Fishing March 18-25	EK500	EK500	EK500	
Area	Biomass, t									
Shallow	South	1793	2960	31341	3980	10606	10369	6242	1497	19
	North	3944	3706	8936	1540	na	19341	4517	2292	0
	NA	1788	1853	2011	0	na	na	na	na	0
	Malaspina	6096	3038	9326	0	na	878	1658	470	0
	Sabine	172	1153	1512	0	na	391	0	86	0
	Total	13793	12710	53126	5520	10606	30979	12417	4345	19
Deep	South	19795	36210	46499	46499	53625	56839	39775	30259	30583
	North	10147	14746	4839	4839	na	24219	21954	14796	5164
	NA	896	715	671	671	na	na	na	na	0
	Malaspina	3878	8270	6700	6700	na	6539	2385	3587	3238
	Sabine	832	2483	3031	3031	na	3659	0	402	2012
	Total	35548	62424	61740	61740	53625	91255	64114	49044	40998
Shallow and Deep	South	21588	39170	77840	50479	64231	67208	46017	31756	30602
	North	14091	18452	13775	6379	na	43559.5	26471	17088	5164
	NA	2684	2568	2682	671	na	na	na	na	0
	Malaspina	9974	11308	16026	6700	na	7416.5	4043	4057	3238
	Sabine	1004	3636	4543	3031	na	4050	0	488	2012
	Total	49341	75134	114866	67260	64231	122234	76531	53389	41016

Table 5a. Biomass summary for 1981 to 1998 Strait of Georgia Pacific hake surveys based on detailed calculations.

Date	1981 Jan 12-23	1981 Feb 09-20	1981 April 13-24	1981 April 13-24	1988 March 18-28	1993 March 08-25	1996 Feb 20-05	1997 Feb 17-28	1998 Feb 16-26	
Vessel	GBR	GBR	GBR	GBR	WER	WER	WER	WER	WER	
Sounder	BioSonics	BioSonics	BioSonics	BioSonics	BioSonics	BioSonics	EK500	EK500	EK500	
Comment			Measured	Adjusted		Fishing March 18-25				
Area	Biomass, t									
Shallow	South	2060	3401	36010	4573	10759	5176	2294	1102	7
	North	4532	4258	10268	1769	na	9655	1660	1687	0
	NA	2054	2129	2311	0	na	na	na	na	0
	Malaspina	7004	3491	10715	0	na	438	609	346	0
	Sabine	198	1325	1737	0	na	195	0	63	0
	Total	15848	14604	61041	6343	10759	15465	4564	3198	7
Deep	South	20904	38239	49104	49104	55415	55773	34556	26731	25120
	North	10715	15572	5110	5110	na	23765	19073	13071	4242
	NA	946	755	709	709	na	na	na	na	0
	Malaspina	4095	8733	7075	7075	na	6416	2072	3169	2660
	Sabine	879	2622	3201	3201	na	3590	0	355	1653
	Total	37539	65921	65199	65199	55415	89543	55702	43326	33674
Shallow and Deep	South	22964	41640	85114	53677	66174	60949	36851	27833	25127
	North	15247	19830	15378	6880	na	33420	20734	14758	4242
	NA	3000	2884	3019	709	na	na	na	na	0
	Malaspina	11099	12224	17791	7075	na	6855	2682	3515	2660
	Sabine	1076	3947	4938	3201	na	3786	0	418	1653
	Total	53387	80525	126240	71542	66174	105008	60266	46524	33681

Table 5b. Mean TS, length and weight from 1981 to 1998 Strait of Georgia Pacific Biomass calculations.

Date		1981	1981	1981	1981	1988	1993	1996	1997	1998
Vessel		Jan 12-23	Feb 09-20	April 13-24	April 13-24	March 18-28	March 08-25	Feb 20-05	Feb 17-28	Feb 16-26
Sounder		GBR	GBR	GBR	GBR	WER	WER	WER	WER	WER
Comment		BioSonics	BioSonics	BioSonics	BioSonics	BioSonics	BioSonics	EK500	EK500	EK500
				Measured	Adjusted		Fishing March 18-25			
TS Shallow	TSn, dB/#	-35.8	-35.8	-35.8	-35.8	-36.1	-44.3	-45	-42.2	-45.3
	TSw, dB/kg	-32.6	-32.6	-32.6	-32.6	-32.1	-29	-27.6	-30.7	-27.9
	Length, cm	38.5	38.5	38.5	38.5	39.1	14.6	14.1	17.3	13.3
	Weight, g	479.5	479.5	479.5	479.5	392	29.3	18.5	70.7	18.2
TS Deep	TSn, dB/#	-36	-36	-36	-36	-36	-36.8	-38.3	-37.8	-40.1
	TSw, dB/kg	-32.2	-32.2	-32.2	-32.2	-32.1	-31.9	-31.4	-31.5	-31.1
	Length, cm	39	39	39	39	39.8	35.7	29.3	31.4	22.3
	Weight, g	417.4	417.4	417.4	417.4	414.7	327.5	205.6	231.5	128

Appendix 1: Estimation of TSw from the TS Length Relation

Target strength measurements at 38 kHz were analysed from seven data sets that coincided with trawling operations. An echogram of single fish targets (echo traces) was generated by plotting target depth versus ping number (Figure A1-1). The set position is indicated to allow comparison of target distribution and fish capture position. TS and fish length histograms (Figure A1-2) were generated and mean TS and mean length for Pacific hake for each set were plotted (Figure A1-3; values 1 to 7).

Our *in situ* TS measurements (Figure A1-3; values 1 to 7) are in good agreement with the TS length relation (Foote 1987)

$$TS_n = 20 \cdot \log(l) + c \quad (1)$$

where TS_n is target strength per fish (dB/#), l is fish length (cm), and c is a constant. Our measurements (Kieser et al. 1996) are described by a TS length relation with $c = -66$ dB (Figure A1-3, upper dashed line). Williamson and Traynor (1984) and Traynor (1996) report TS measurements (Figure A1-3; values 8 and 9, respectively) which suggest a TS length relation with $c = -68$ dB (Dorn 1996; Figure A1-3, solid line). The difference between the TS-length relationships may reflect a bias in our TS results due to the greater target depth.

The lower dotted line in Figure A1-3 shows the length dependent TS curve that corresponds to the constant TS per unit weight of $TS_{w0} = -35$ dB/kg used in our previous hake surveys (Kieser 1992; Taylor and Kieser 1982). This curve was plotted using the length weight relationship

$$w = a \cdot l^b \quad (2)$$

and the relation between TS_n and TS_{w0}

$$TS_n = TS_{w0} - 10 \cdot \log\left(\frac{w}{1000}\right) \quad (3)$$

where weight, w , is in grams, and coefficients a and b are 0.0065 and 2.9969, respectively. The values for a and b are based on length weight measurements from sets made on Pacific hake in the Strait of Georgia during February 20 to March 3, 1981 (McFarlane and Beamish 1985). Length weight samples from February/March 1996 generated essentially identical coefficients (Kieser et al. 1998). It is evident that the dotted line has a different slope and is significantly lower than the dashed and solid lines in Figure A1-3.

For biomass estimation it is convenient to convert TS per fish, TS_n dB/#, to TS per unit weight, TS_w dB/kg. Equations 3 yield:

$$\text{TSw}(l) = (20 - 10 \cdot b) \cdot \log(l) + (c - 10 \cdot \log(w/1000)) \quad (4)$$

Given the preliminary nature of our length based TS analysis, we have followed Dorn (1996) with $c = -68$ dB in order to provide length dependent biomass estimates. Equation 4, with parameters a, b, and c above (Figure A1-4, solid line) yields TSw of -27.6 and -31.5 dB/kg for fish of 14 and 35 cm length, respectively. Comparing these values to the constant or length independent TSw of -35 dB/kg (Figure A1-4, lower, dotted line) indicates an offset and a divergence that increases with decreasing fish length.

The conversions between fish weight, length, and TS are nonlinear, thus Equation 4 can only be used to obtain mean TS from mean length if all fish are of similar length.

Appendix 2: Biomass Estimation by Species and Fish Length Groups

Biomass estimation by fish length group

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1 Relation between SA, Fish Number and Fish Weight

The EK500 measures S_A , the mean backscattering area per square nautical mile. The mean backscattering area per square meter is:

$$(1) \quad s_a = S_A (4\pi 1852^2)^{-1}.$$

The total backscatter from the survey area A is given by the number of fish in each length group, N_i , and the average backscatter cross section per fish, tsn_i :

$$(2) \quad A s_a = \sum_{i=1}^m N_i tsn_i = N tsn,$$

where $N = \sum_{i=1}^m N_i$ is the total number in the survey area A and $tsn = \frac{1}{N} \sum_{i=1}^m N_i tsn_i$ gives the average backscatter cross section for all fish.

Note: $tsn_i = \sigma_{bs_i} = \frac{\sigma_s}{4\pi} = 10^{J_{Sn}/10}$.

Alternately the total backscatter can be expressed by the weight of fish in each length group, W_i , and the corresponding average backscatter cross section per unit weight, tsw_i :

$$(3) \quad A s_a = \sum_{i=1}^m N_i w_i \frac{tsn_i}{w_i} = \sum_{i=1}^m W_i tsw_i = W tsw,$$

where $W = \sum_{i=1}^m N_i w_i$ is the total weight of fish in the survey area and $tsw = \frac{1}{W} \sum_{i=1}^m N_i tsw_i$ gives the average backscatter cross section per unit weight for all fish.

2 Average backscatter cross section for Fish Number and Fish Weight Estimation

Given independent information of the fish length distribution we can estimate tsn and tsw :

$$(4) \quad tsn = \frac{\sum_{i=1}^m n_i tsn_i}{\sum_{i=1}^m n_i},$$

$$(5) \quad tsw = \frac{\sum_{i=1}^m n_i w_i tsw_i}{\sum_{i=1}^m n_i w_i} = \frac{\sum_{i=1}^m n_i tsn_i}{\sum_{i=1}^m n_i w_i},$$

where n_i , the number of fish in each length group, may be obtained from representative catches in the survey area and tsn_i and tsw_i can be estimated from the TS length relation that is given below.

It follows that the total number of fish in the survey area, the number of fish in each size group and the weight of fish in each size group are given by:

$$(6) \quad \begin{aligned} N &= \frac{As_a}{tsn}, \\ N_i &= N \frac{n_i}{\sum n_i}, \\ W_i &= N_i w_i / 1000. \end{aligned}$$

Where W_i and w_i are in kg and gr, respectively.
A corresponding relation applies for fish weight.

$$(7) \quad \begin{aligned} W &= \frac{As_a}{tsw}, \\ W_i &= N \frac{n_i w_i}{\sum n_i w_i}. \end{aligned}$$

3 Length Weight Relationship

A length weight relationship,

$$(8) \quad w = al^b,$$

is used to relate fish weight w (grams) and length l (cm). Typical coefficients for Pacific hake are $a = .0065$ and $b = 2.997$. The coefficients are determined from set data when sufficient information is available.

4 Target Strength Length Relation

Numerous target strength measurements and scattering theory support the following TS length relation (Foote 1987):

$$(9) \quad TSn(l) = 20 \log l + c$$

where $TS_n = 10^{tsn(l)/10}$ is target strength per fish (dB/No), l is fish length (cm), and c is a constant.

In situ TS measurements by Williamson and Traynor (1984), Traynor (1996) and those done recently from the W.E. RICKER suggest $c = -68$ for Pacific hake (Dorn 1996).

The backscatter cross section per fish therefore is:

$$(10) \quad tsn(l) = 10^{TS_n(l)/10} = l^2 10^{c/10}$$

The backscatter cross section per unit weight is obtained from the definition of tsw used in Equ 3 and Eqs 6 and 8:

$$(11) \quad tsw(l) = \frac{tsn(l)}{w/1000} = l^{2-b} \frac{1000}{a} 10^{c/10}$$

The $w/1000$ is used as w in Equ 6 is in gr while $tsw(l)$ is per kg.

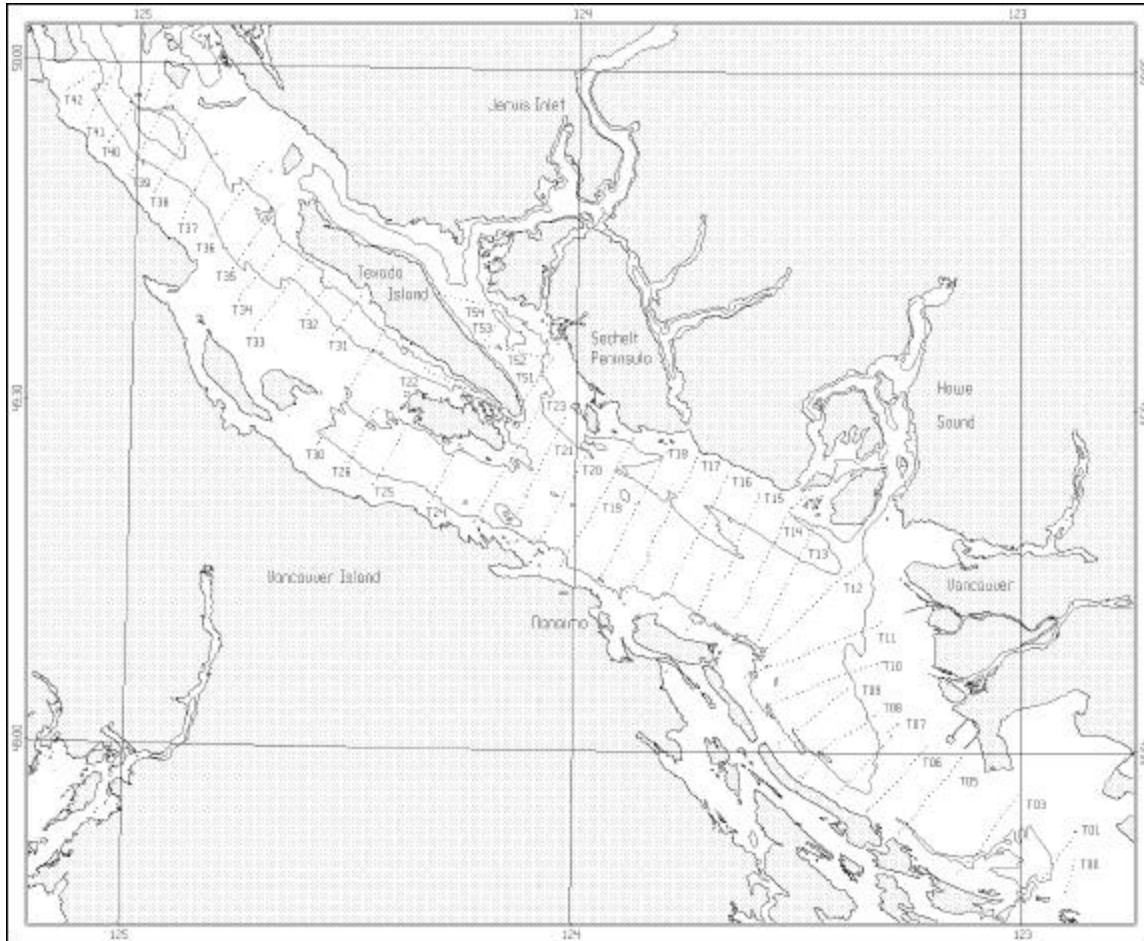


Figure 1. The survey area is sampled by regular spaced parallel transects that cross perpendicular to the long axis of the Strait of Georgia. Nominal spacing is 3 nm and transects terminate at the 30 m isobath or 0.5 nm from shore.

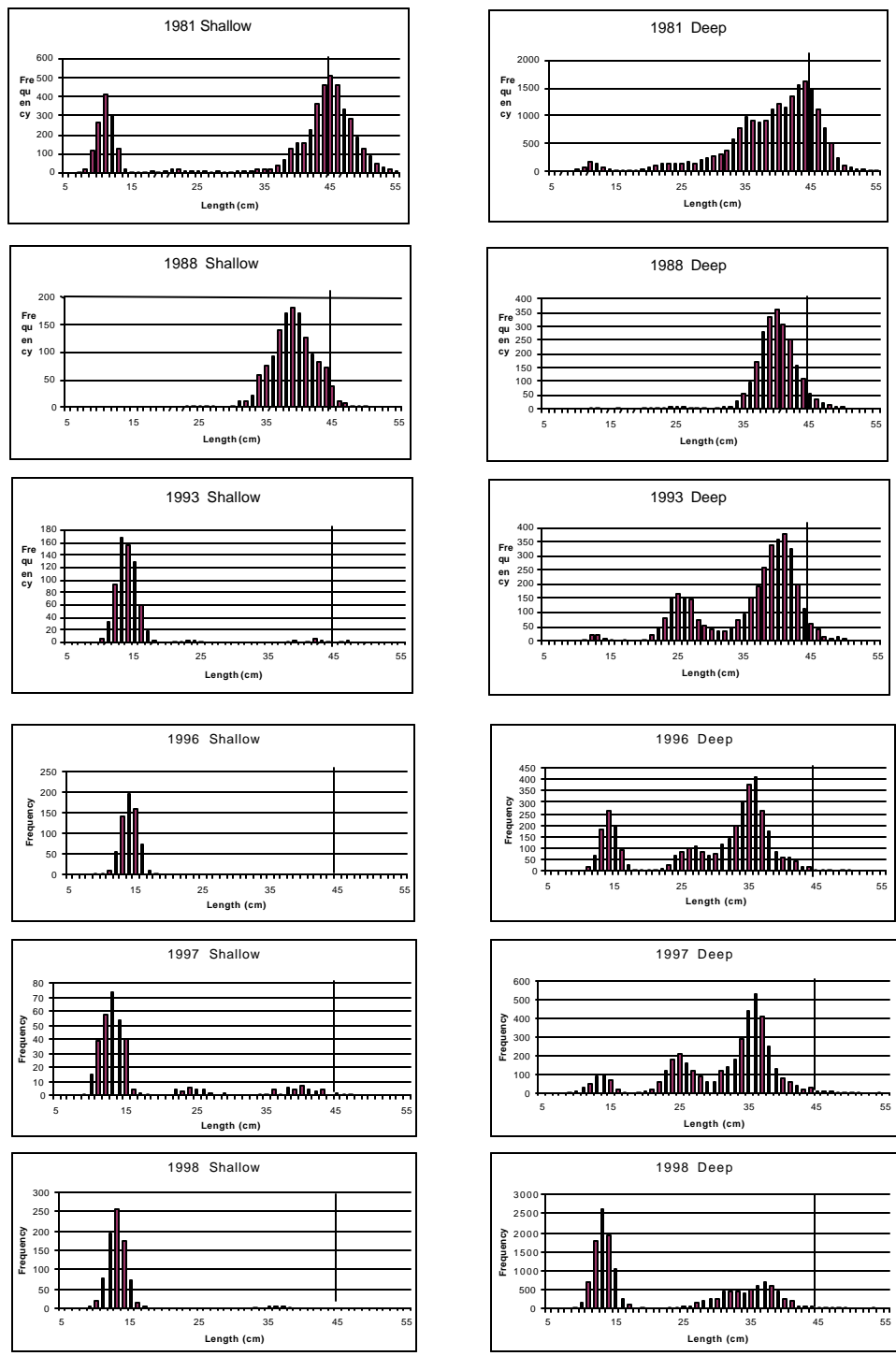


Figure 2. Pacific hake length histograms for the shallow (<150 m) and deep layers (>150 m) for 1981 to 1998. Information is from pooled sets for each year and is believed to be representative for the entire Strait of Georgia. Note fish length reference mark at 45 cm.

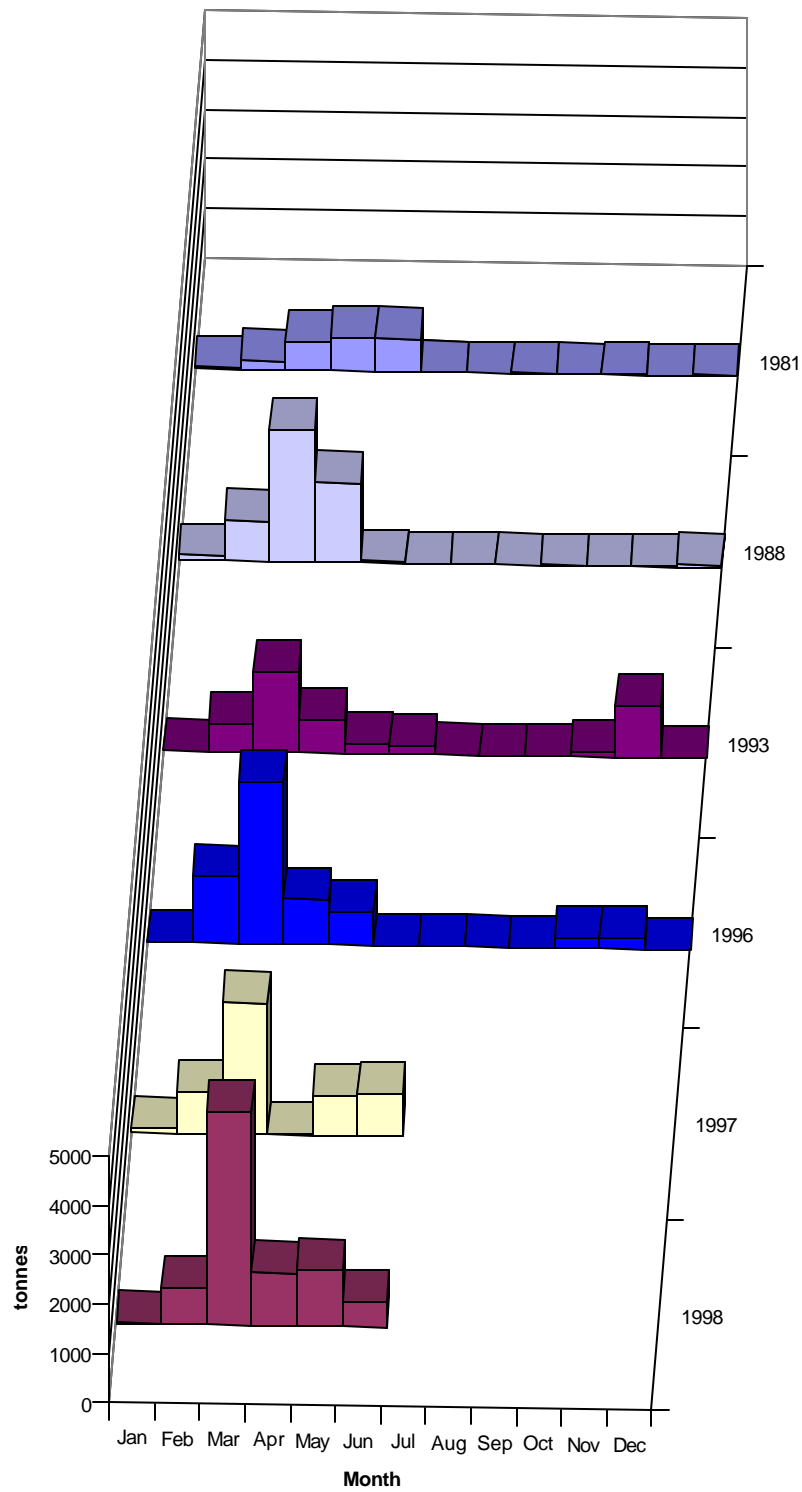


Figure 3. Monthly commercial catch of Pacific hake (t) in the Strait of Georgia for all survey years.

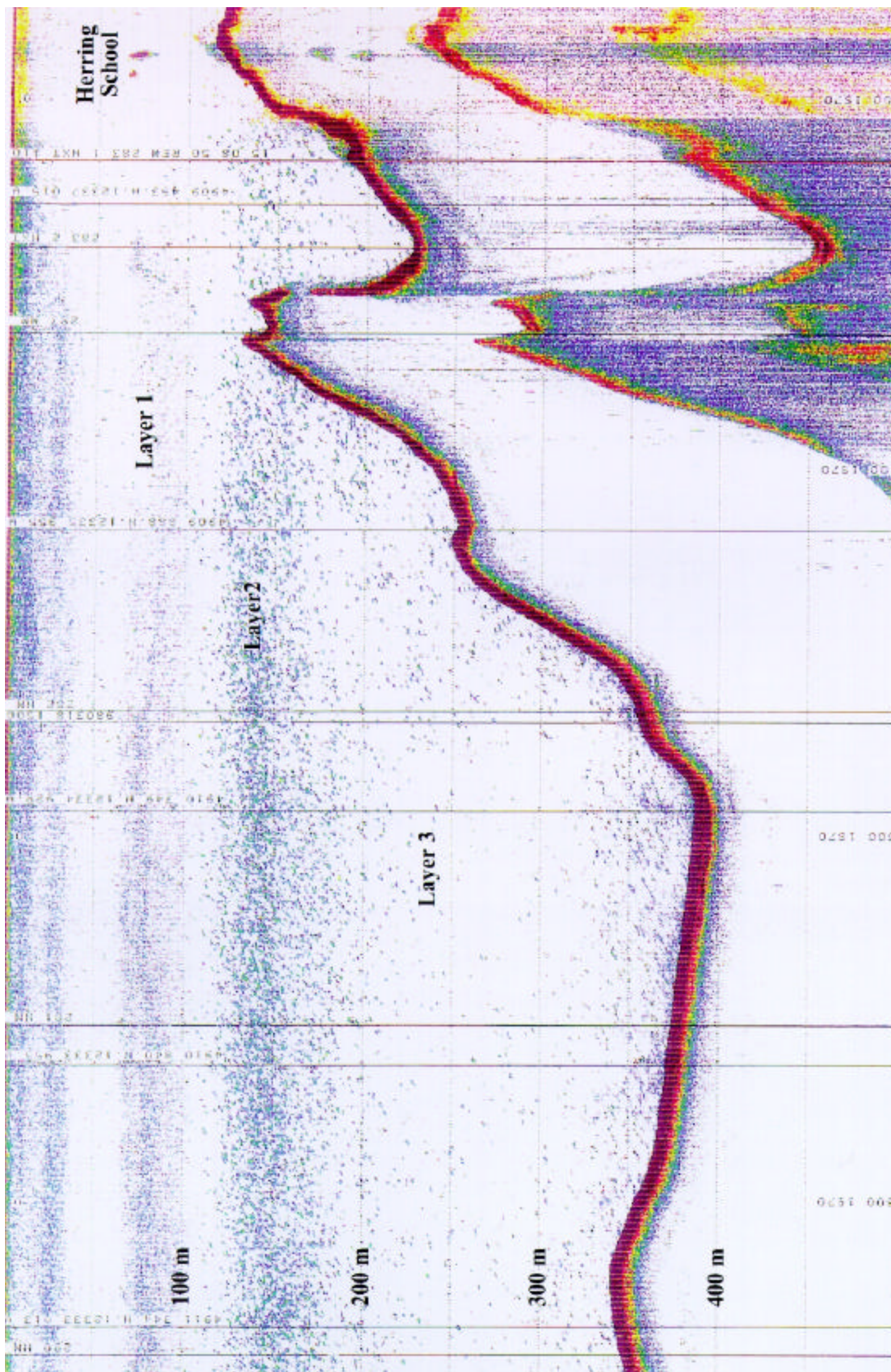


Figure 4. Echogram from the central Strait of Georgia, Transect 12, March 8, 1998. Dense aggregations and the three layers are described in the text.

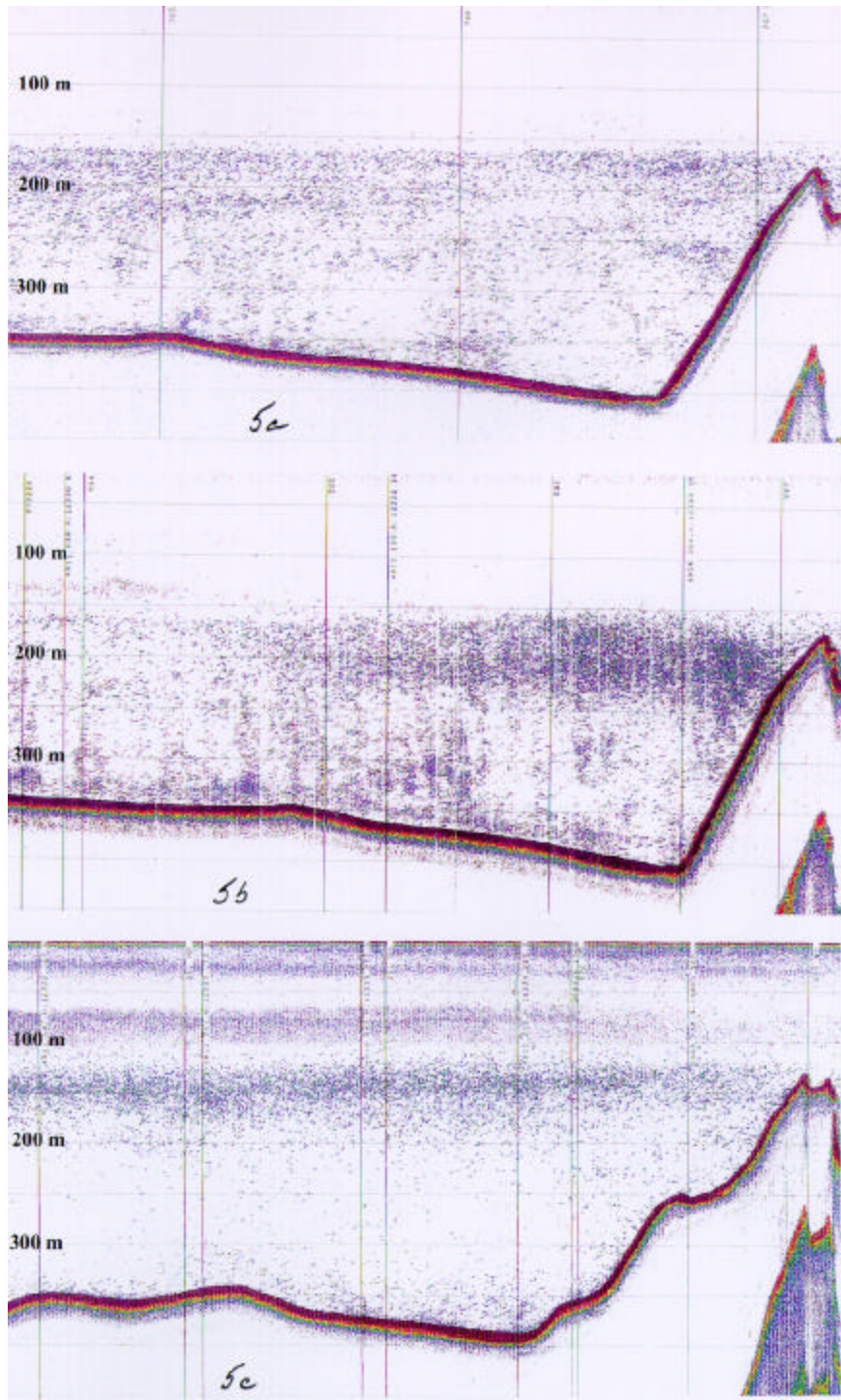


Figure 5. Echograms collected along Transect 12 in the central Strait of Georgia in 1996 (5a), 1997 (5b), and 1998 (5c) highlight annual differences in fish density and distribution. Differences in the bottom profile reflect slightly different transect locations.

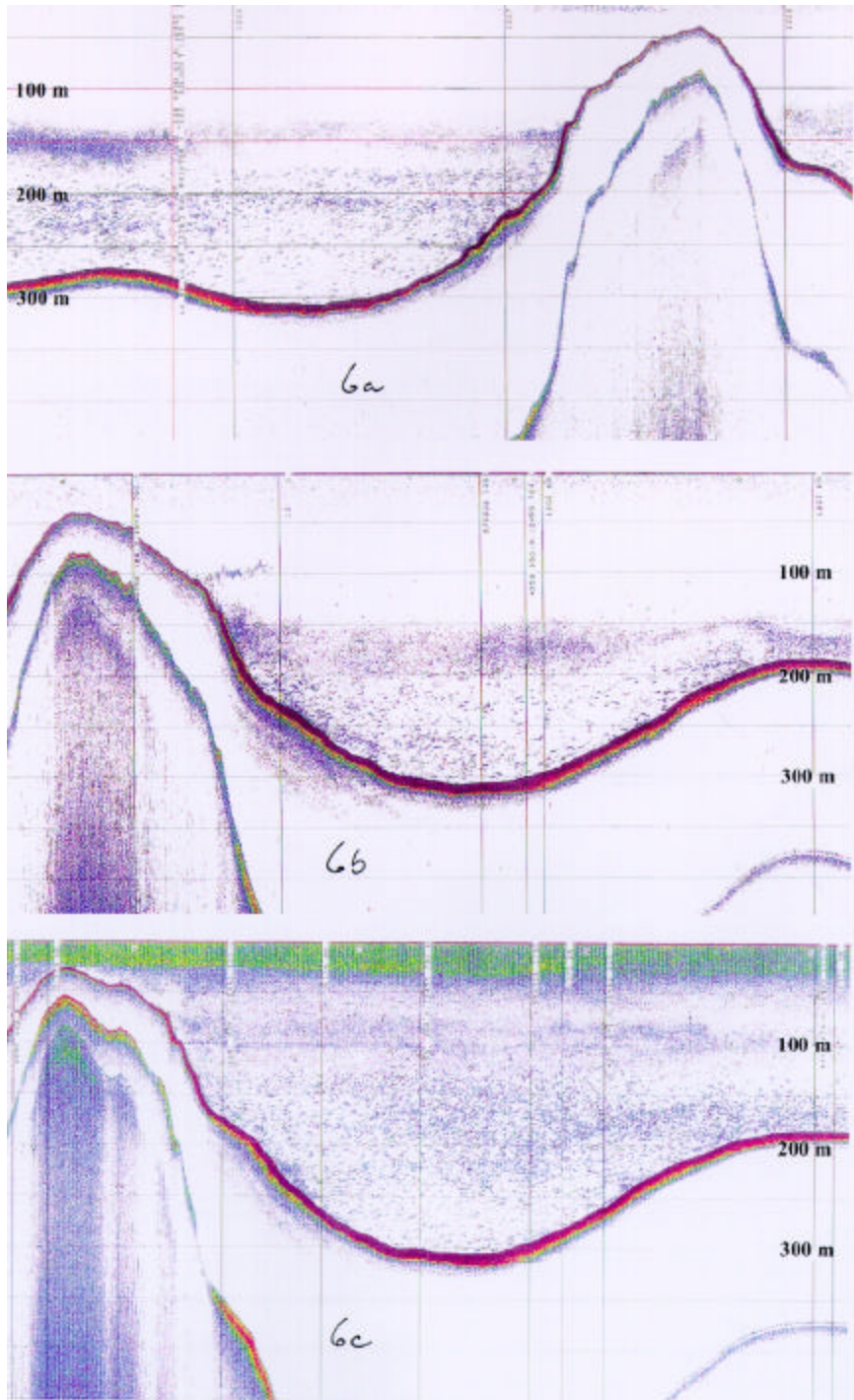


Figure 6. Echograms collected along Transect 38 in the northern Strait of Georgia in 1996 (6a), 1997 (6b), and 1998 (6c) highlight annual differences in fish density and distribution. Note direction of travel in 1996 is opposite to 1997 and 1998.

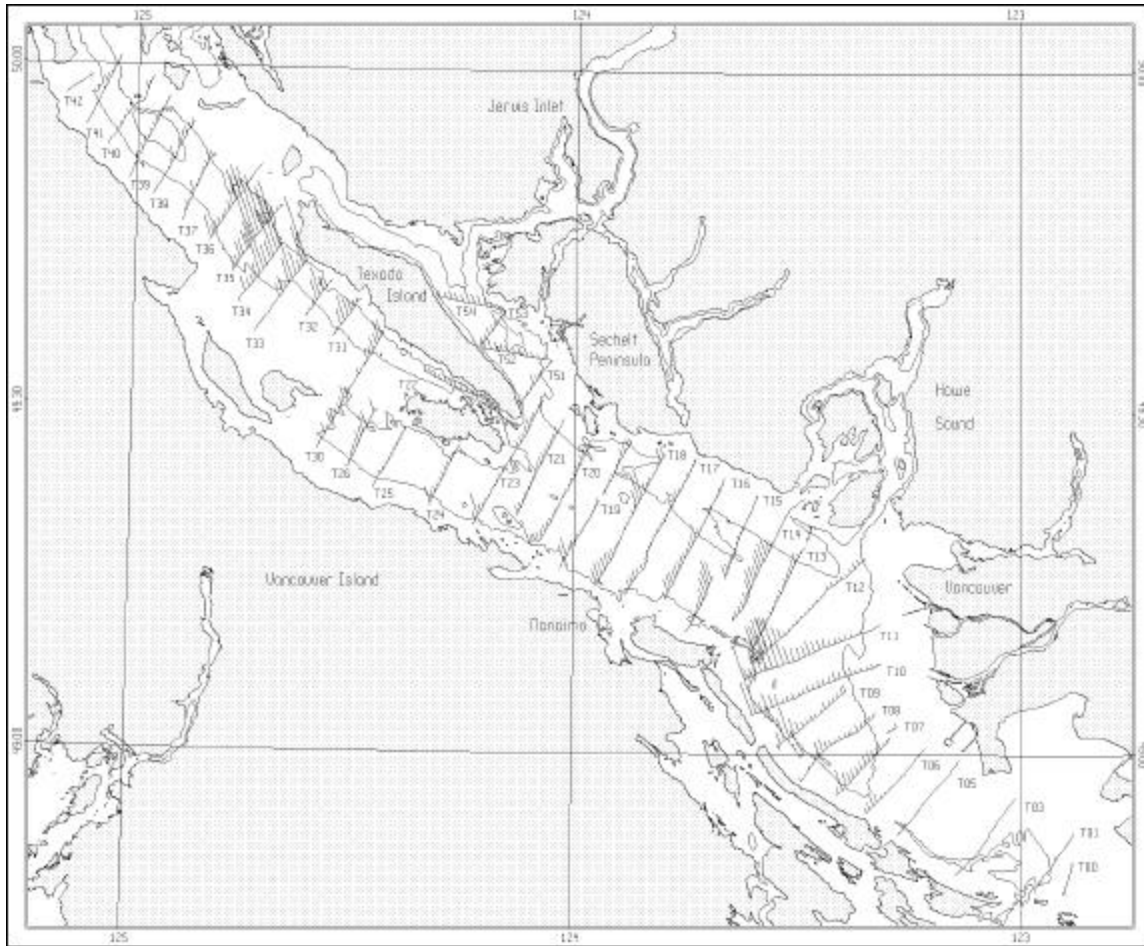


Figure 7a. Typical biomass distribution map from the Strait of Georgia. The 1998 midwater (~150-250m) adult Pacific hake distribution is indicated by the uprights that arise from the transects.

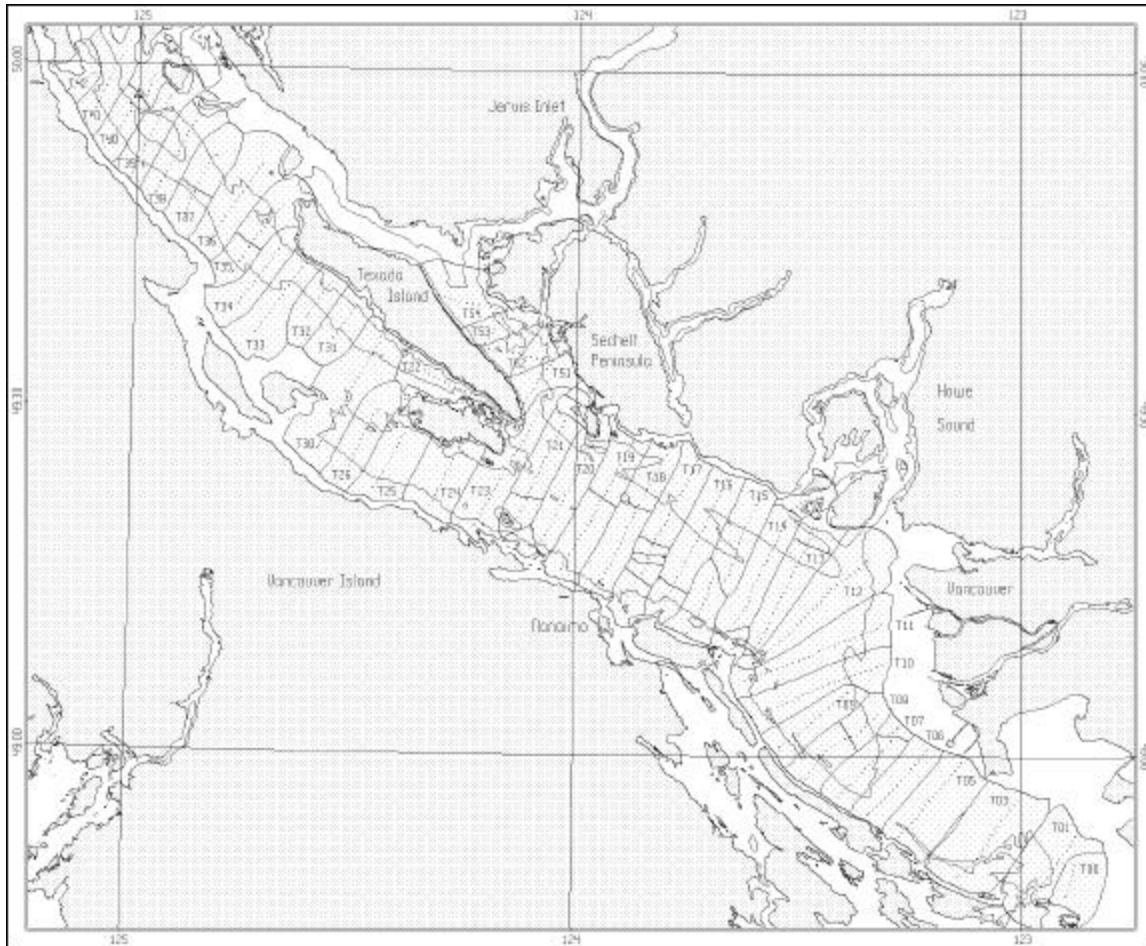


Figure 7b. Typical 'mask' for the Strait of Georgia. The mask is used to delineate the survey area. Areas shallower than 50 m are excluded.

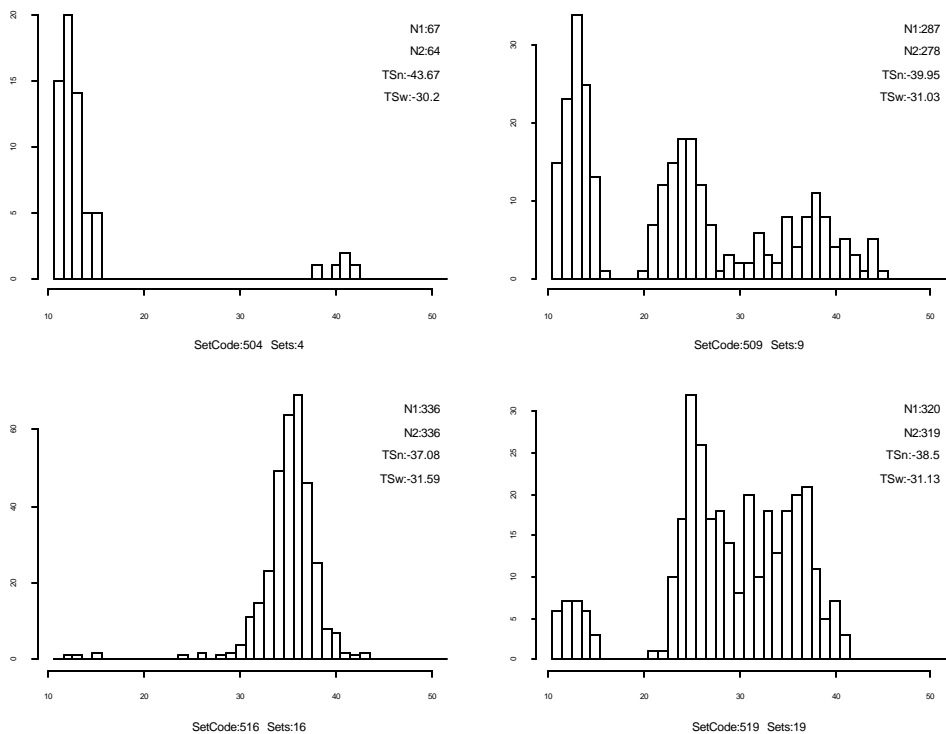


Figure 8a. Typical length histograms from the 1997 Strait of Georgia survey.

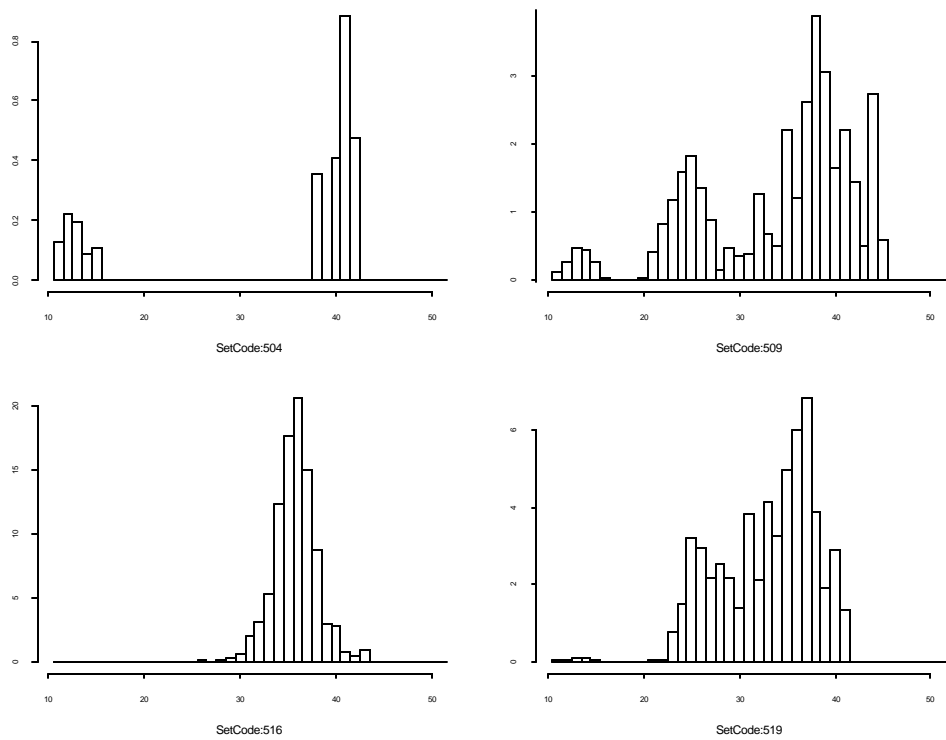


Figure 8b. Typical weight histograms from the 1997 Strait of Georgia survey.

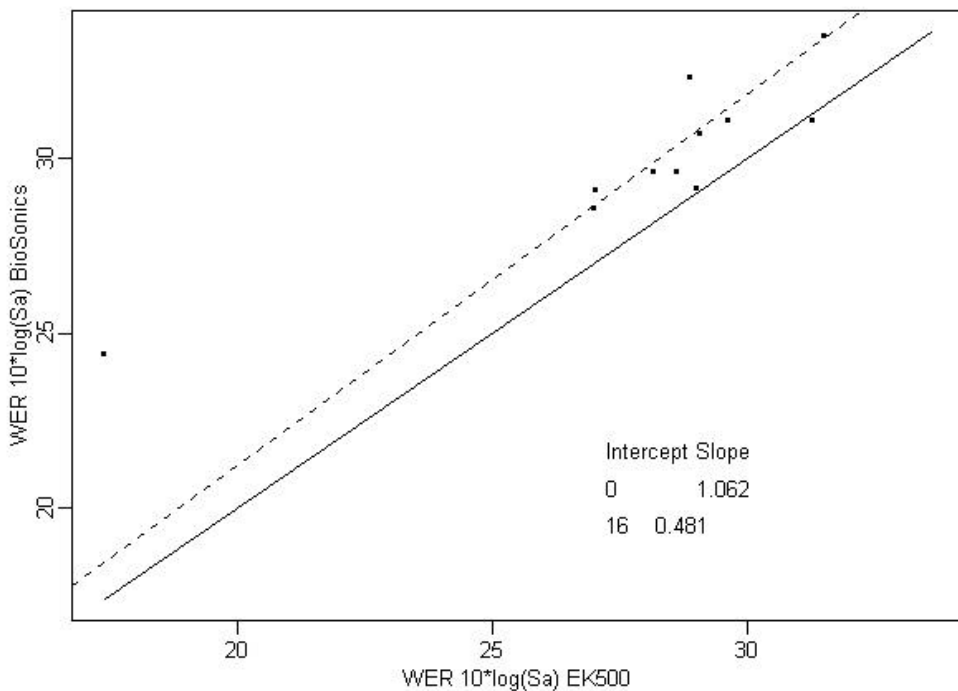
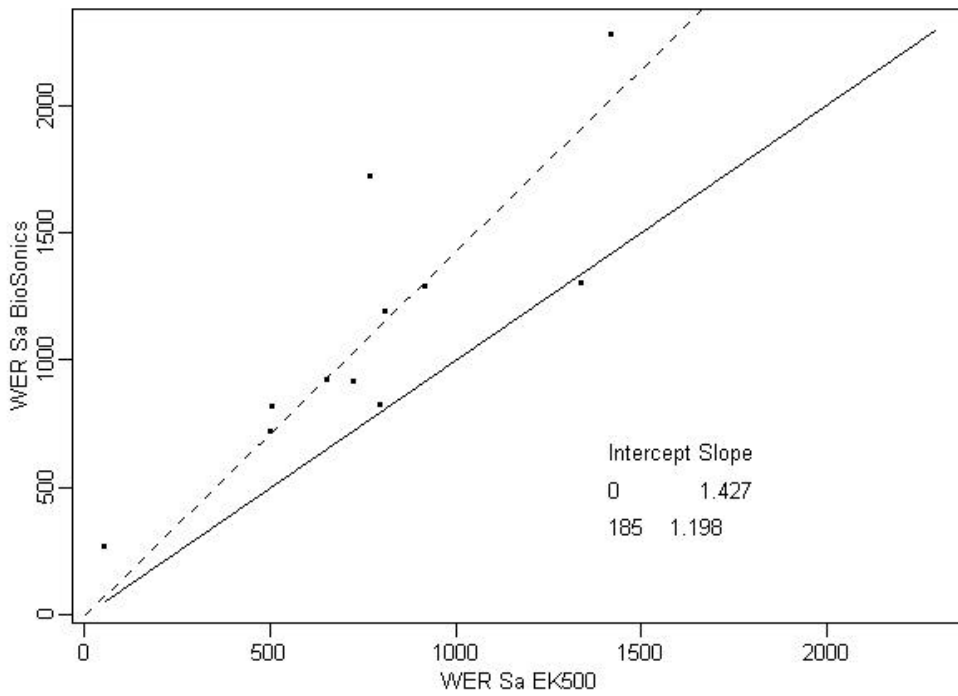


Figure 9. Results from the August 1995 intercalibration between BioSonics and Simrad acoustic systems on the W.E. RICKER. The solid line indicates 1:1 agreement. 9a) A linear least square fit to the Sa values from both systems indicates a slope of 1.43 (or 0.70 for the inverse). 9b) A fit to the logarithmic SA values indicates a slope of 1.06 (or 0.94 for the inverse).

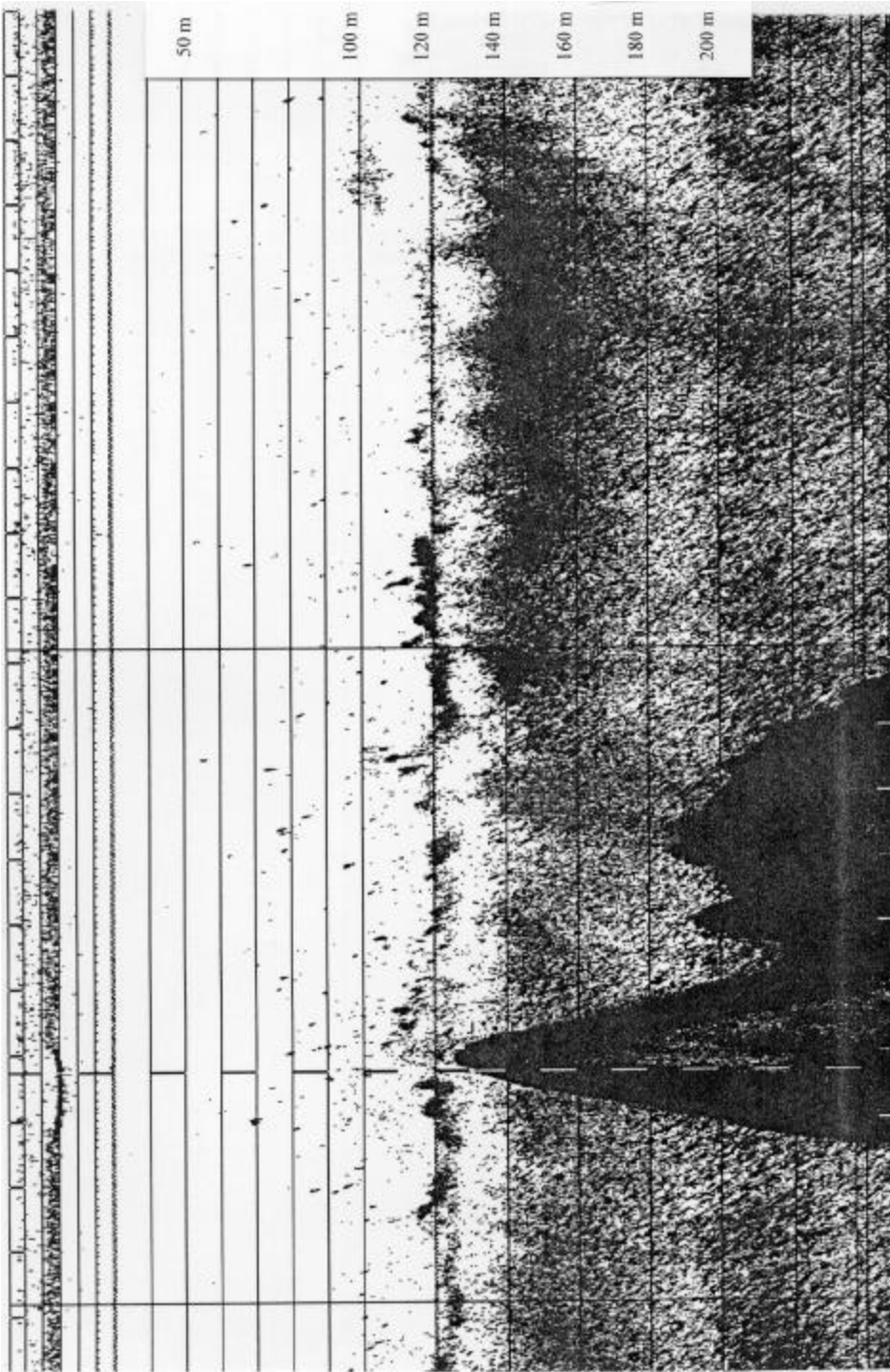


Figure 10. Black and white echogram recorded in 1993 on Transect A3 in Sabine Channel .

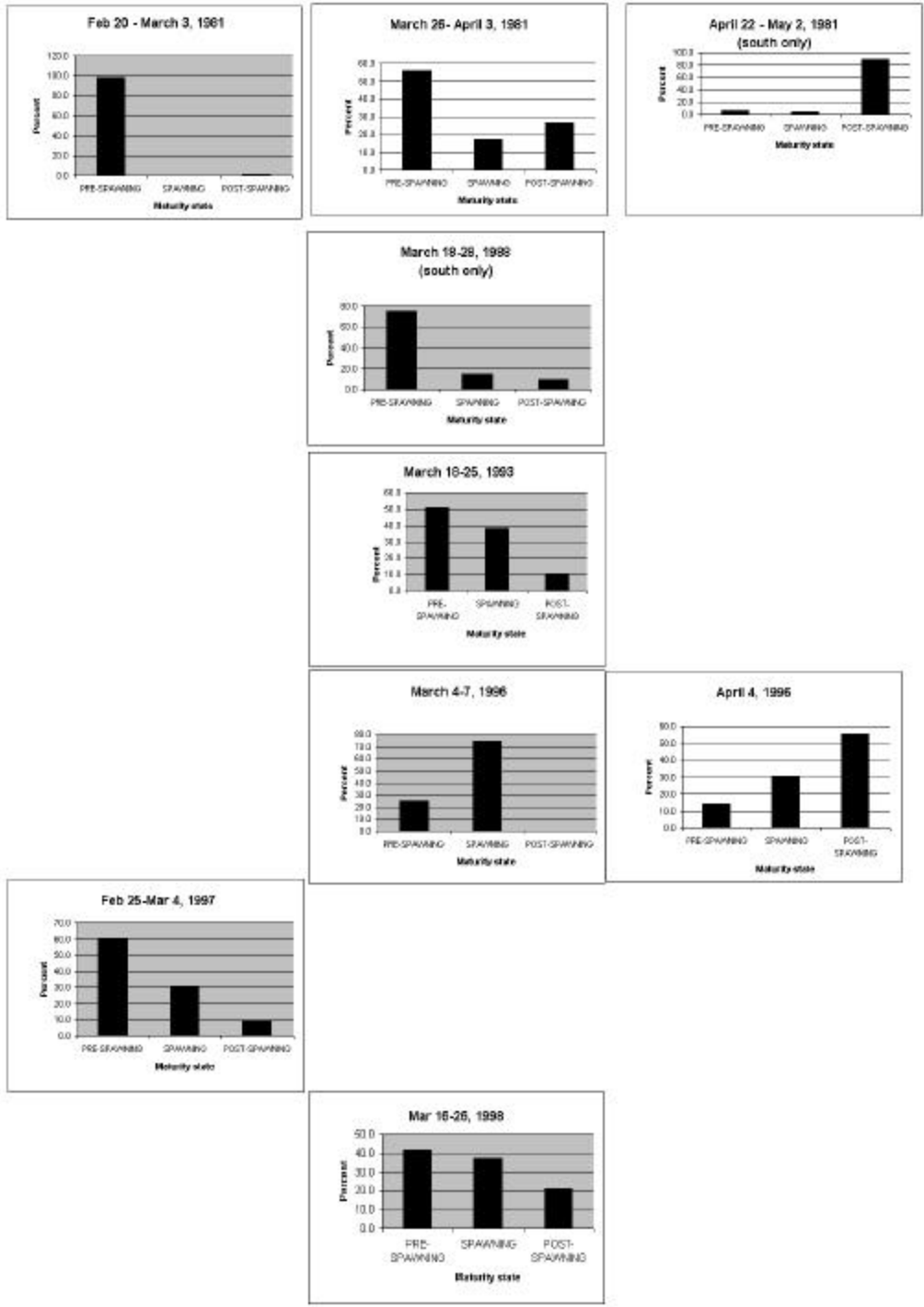


Figure 11. Comparison of Pacific hake maturity stages from the 1981 through 1998 Strait of Georgia surveys. Highlighted histograms are for hydroacoustic surveys. The three columns provide a rough indication of maturity timing by month within a season.

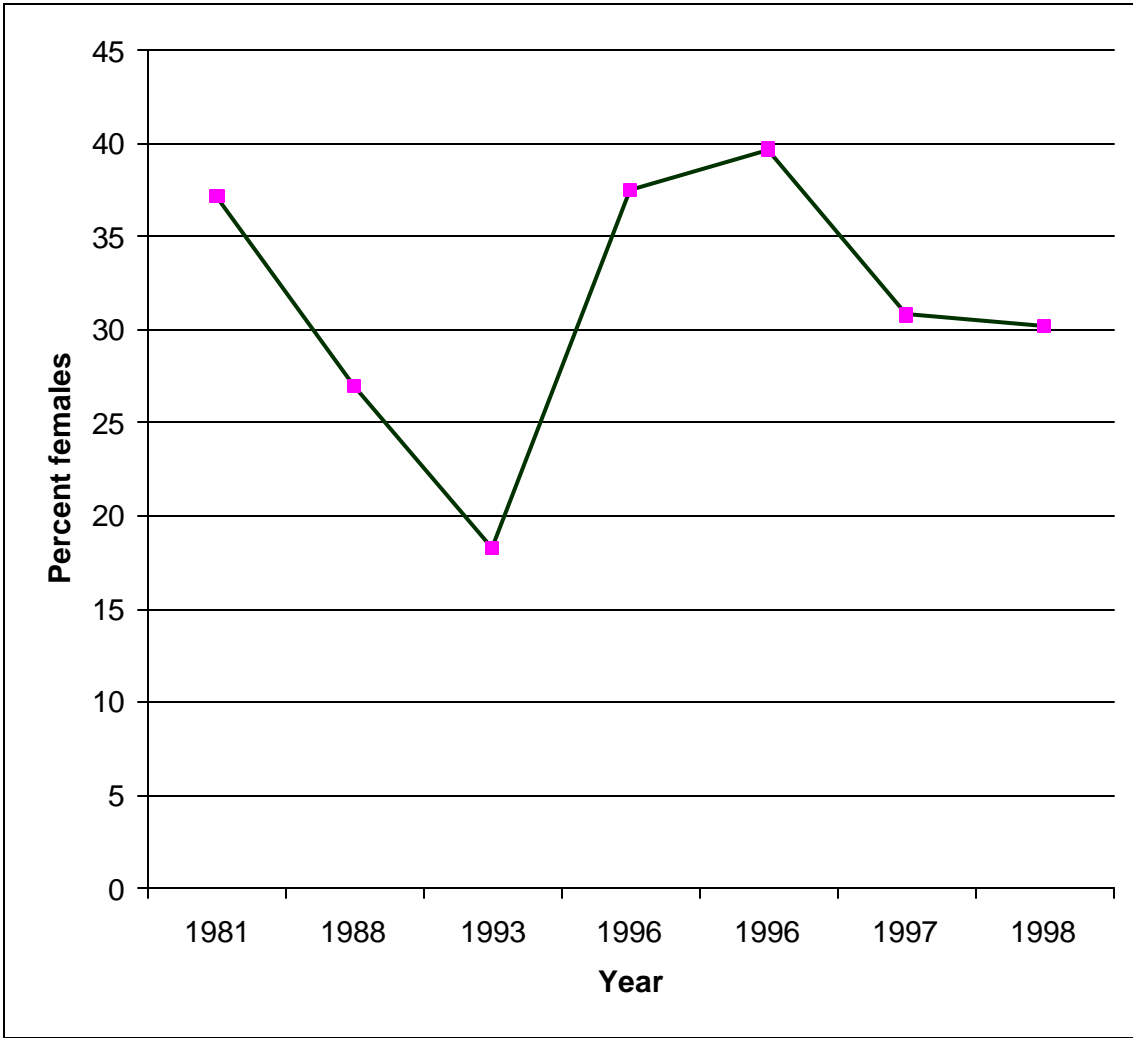


Figure 12. Percent of mature females in trawl catches from 1981 to 1998.

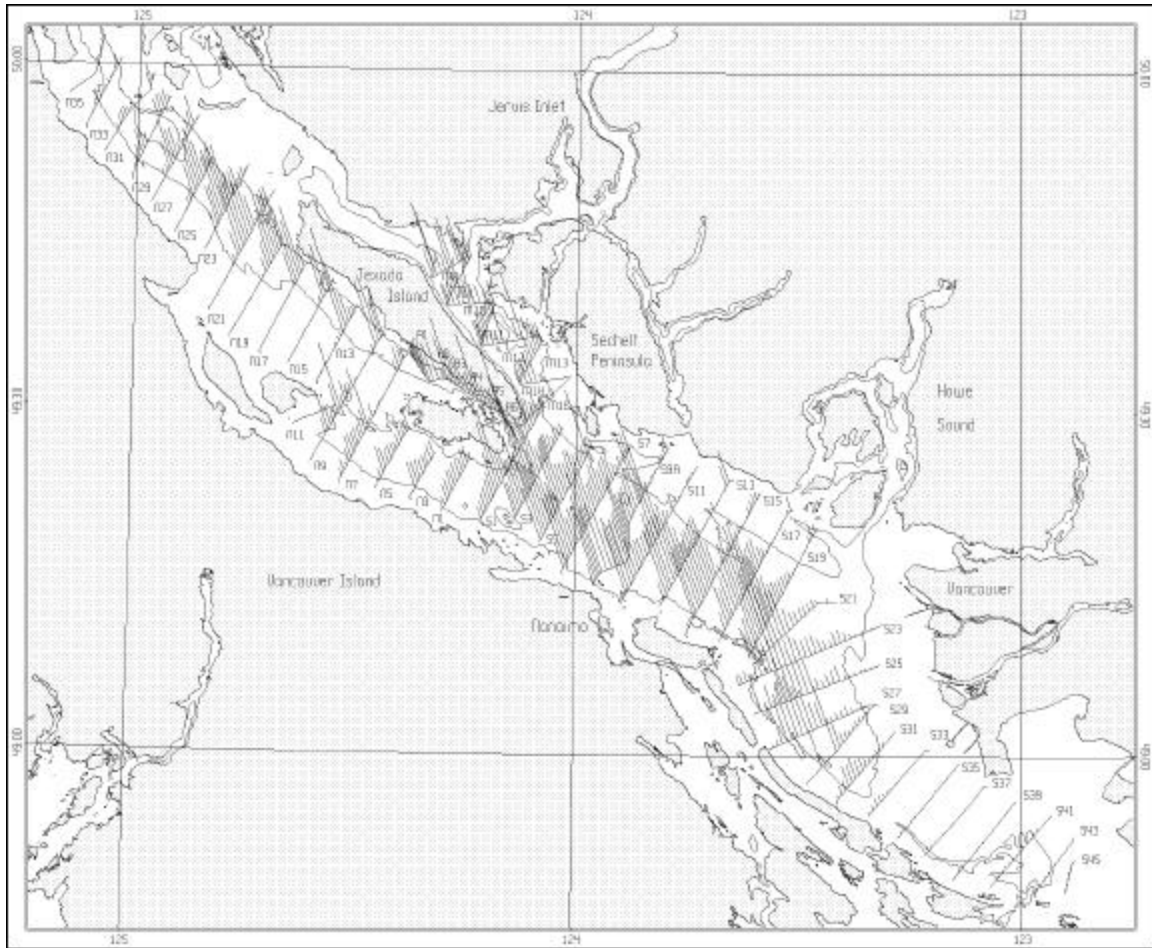


Figure 13a. Pacific hake distribution from the 1933 Strait of Georgia survey.

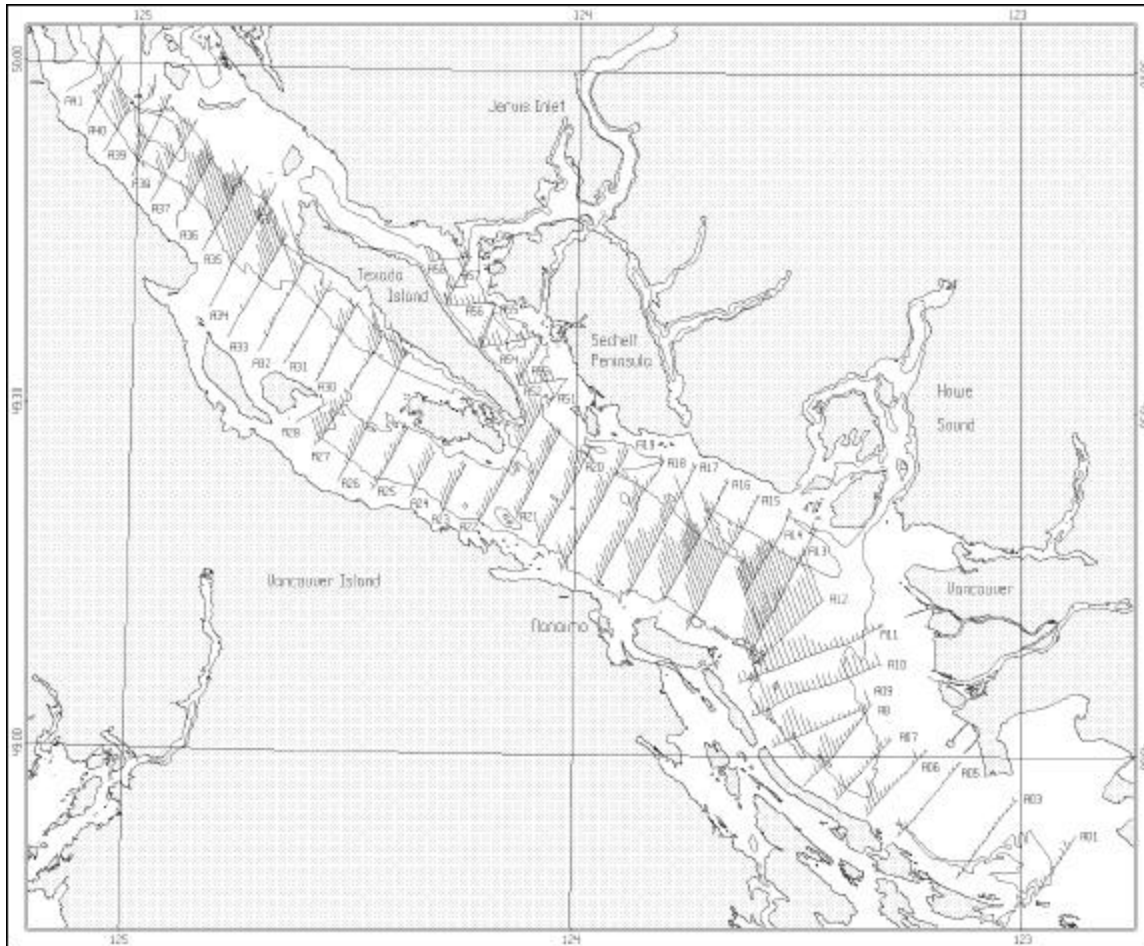


Figure 13b. Pacific hake distribution from the 1996 Strait of Georgia survey.

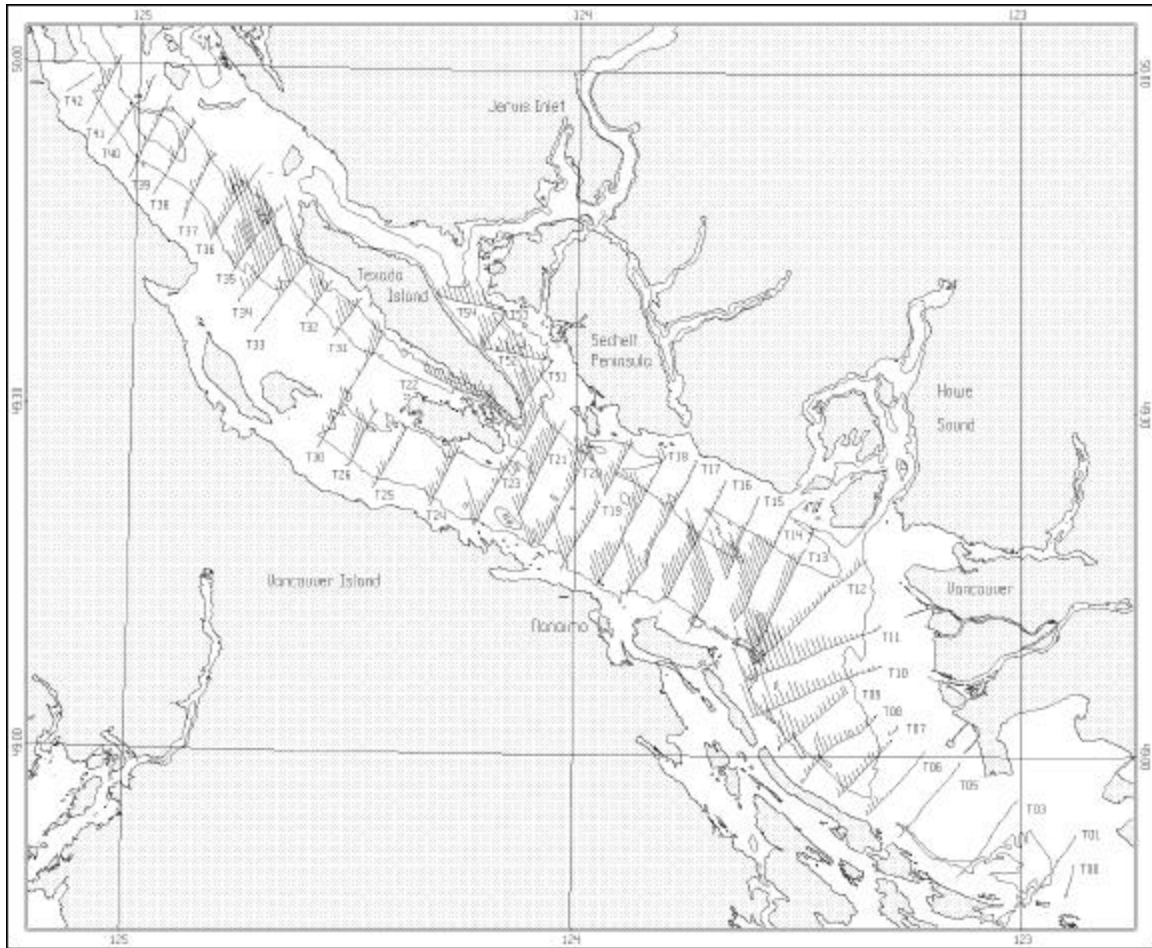


Figure 13c. Pacific hake distribution from the 1997 Strait of Georgia survey.

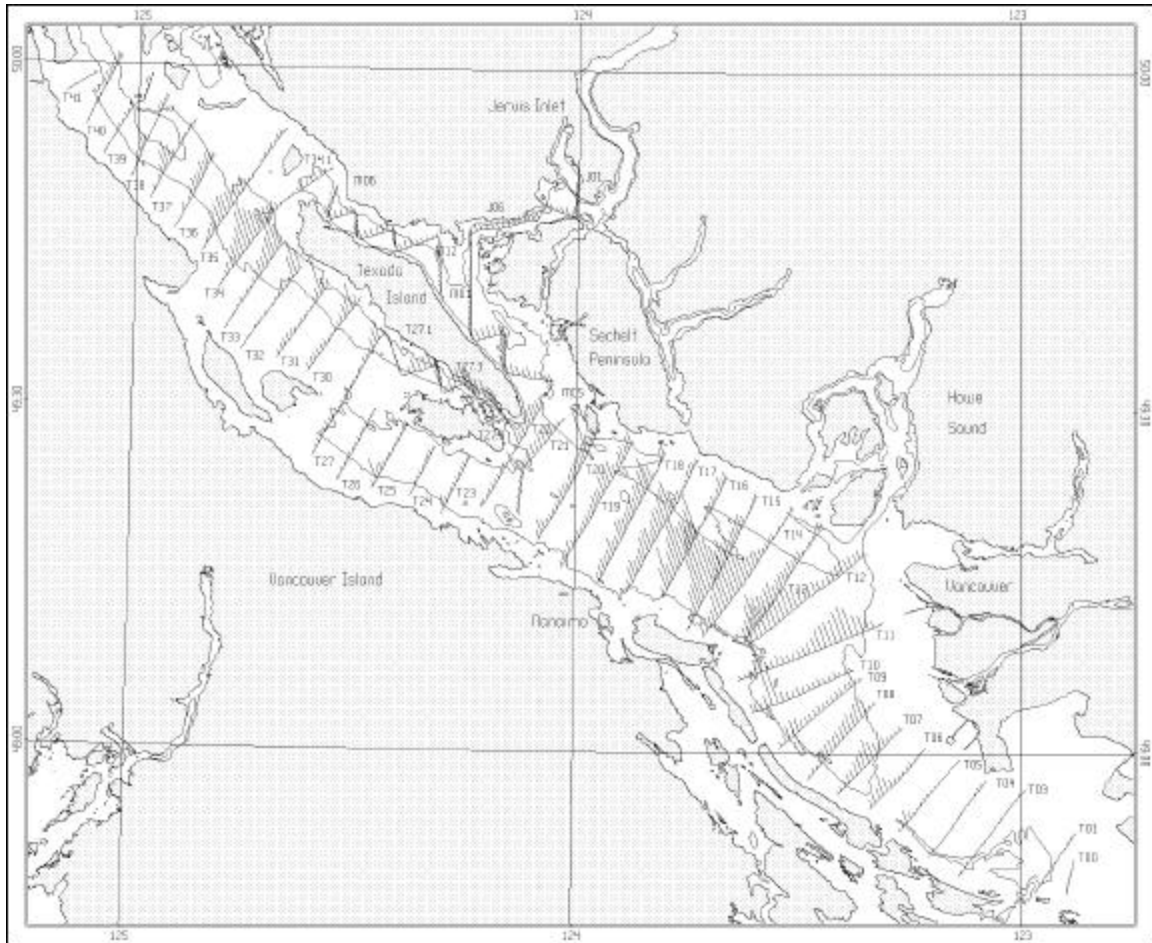


Figure 13d. Pacific hake distribution from the 1998 Strait of Georgia survey.

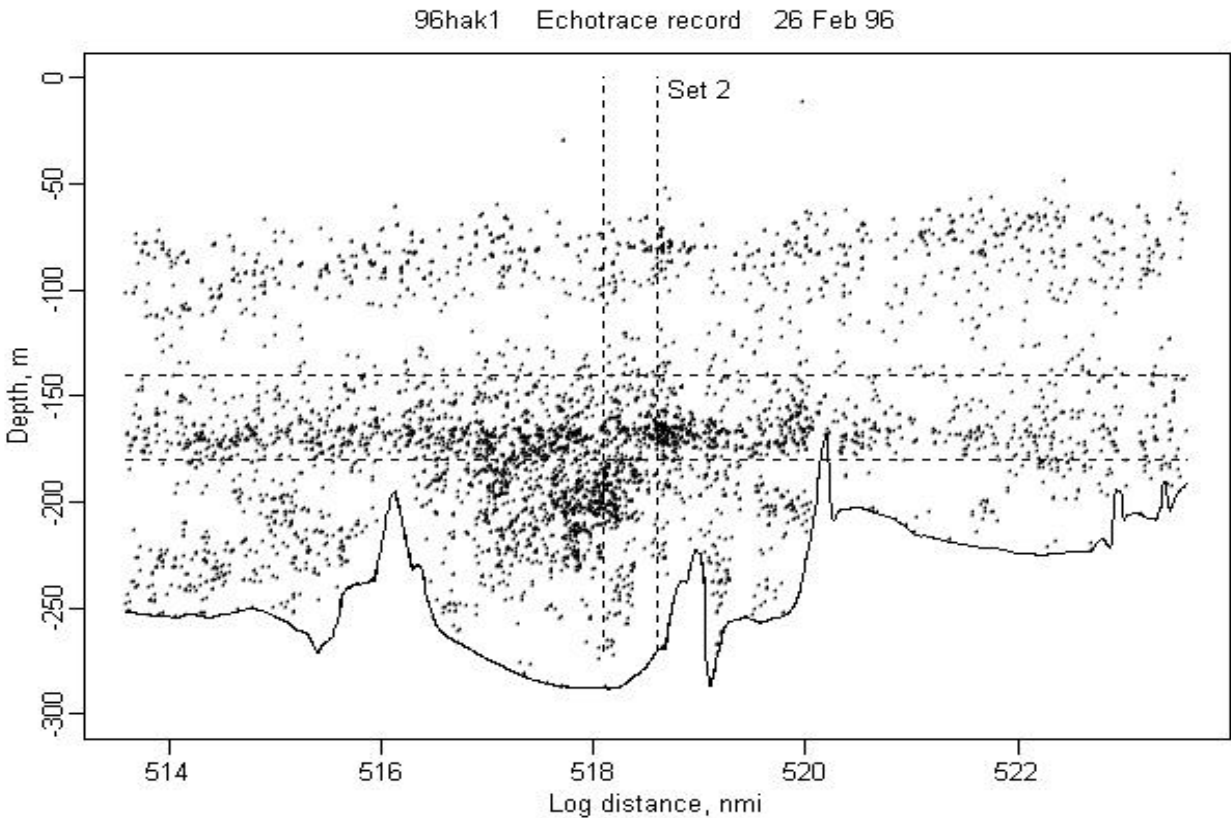


Figure A1-1. The echogram of detected single fish targets (echo traces) was obtained by plotting target depth versus log distance. The location of Set 2, is shown to allow close correlation of the target strength and fish length histograms.

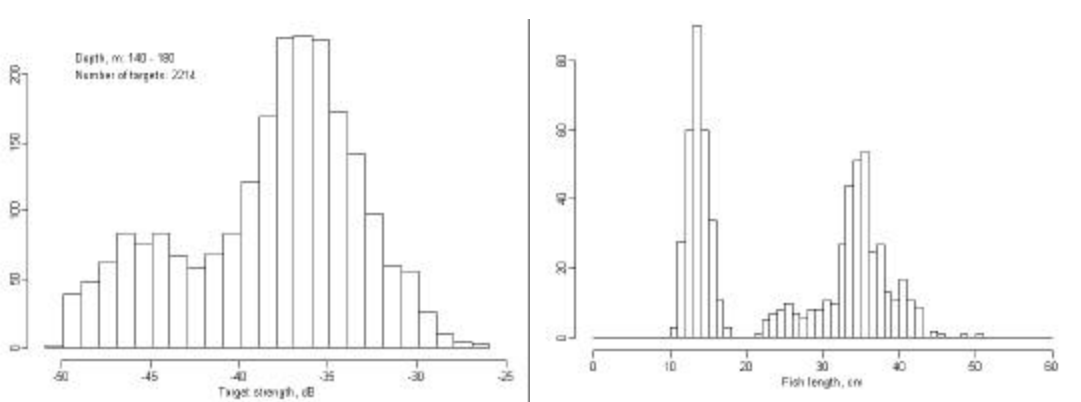


Figure A1-2. TS and fish length histograms from Set 2, February 26, 1996. The two distinct peaks in the fish length histogram are reflected in the TS histogram.

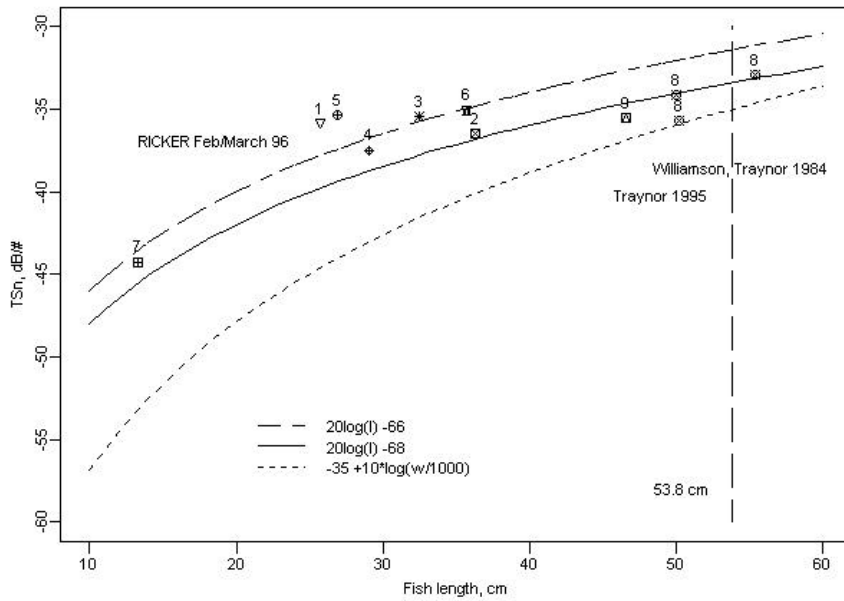


Figure A1-3. Measured TS Length relations (dB/# vs cm) from Kieser et al. (1996; dashed line), and Dorn (1996; solid line; data from Williamson and Traynor (1984) and Traynor (1995)). Dotted line shows the length dependent TS curve that corresponds to the constant TS per unit weight of $TS_w = -35$ dB/kg used in our previous hake surveys (Kieser et al. 1992). Vertical dashed line is intercept for 1 kg hake (53.8 cm).

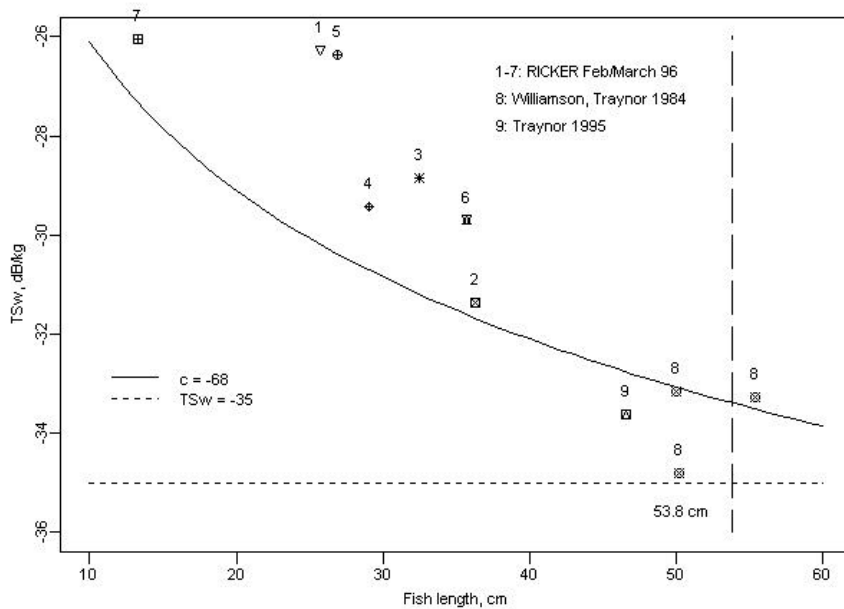


Figure A1-4. Measured TS Length relations (dB/# vs cm) from Dorn (1996; solid line; data from Williamson and Traynor (1984), and Traynor (1995)). The relation yields TS_w of -27.6 and -31.5 dB/kg for fish of 14 and 35 cm length, respectively. Dotted line indicates the constant or length independent TS_w of -35 dB/kg used in our previous hake surveys (Kieser et al. 1992). Vertical dashed line is intercept for 1 kg hake (53.8 cm).