Not to be cited without
permission of the authors[1]

Ne pas citer sans
autorisation des auteurs[1]

Canadian Atlantic Fisheries
Scientific Advisory Committee

Comité scientifique consultatif des
pêches canadiennes dans l'Atlantique

CAFSAC Research Document 92/115

CSCPCA Document de recherche 92/115

Larval Settlement Patterns of the Giant Scallop *(Placopecten magellanicus)* in Passamaquoddy Bay, New Brunswick

by

S.M.C. Robinson, J.D. Martin, R.A. Chandler, G.J. Parsons, and C.Y. Couturier
Dept. of Fisheries and Oceans
Biological Sciences Branch
Invertebrates Fisheries Section
Biological Station
St. Andrews, New Brunswick E0G 2X0

[1]This series documents the scientific basis for fisheries management advice in Atlantic Canada. As such, it addresses the issues of the day in the time frames required and the Research Documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

[1]Cette série documente les bases scientifiques des conseils de gestion des pêches sur la côte atlantique du Canada. Comme telle, elle couvre les problèmes actuels selon les échéanciers voulus et les Documents de recherche qu'elle contient ne doivent pas être considérés comme des énoncés finals sur les sujets traités mais plutôt comme des rapports d'étape sur les études en cours.

Research Documents are produced in the official language in which they are provided to the secretariat by the author.

Les Documents de recherche sont publiés dans la langue officielle utilisée par les auteurs dans le manuscrit envoyé au secrétariat.

Abstract

The objective of this study was to test the null hypothesis: there are no consistent inter-annual spatial and temporal settlement patterns of scallop larvae (*Placopecten magellanicus*) in the Passamaquoddy Bay area. Spat collection bags were placed in a uniform grid pattern in Passamaquoddy Bay and surrounding areas to collect settling scallop larvae during the fall of 1989, 1990, and 1991. During the course of the study, temperature/salinity profiles were taken throughout the area, horizontal and vertical transects were performed around the Bay for chlorophyll a, and samples for scallop larvae were taken. The results refuted the null hypothesis and showed very consistent inter-annual spatial patterns of scallop spat settlement with the northern part of Passamaquoddy Bay having the highest settlement rates and mean shell heights. The spatial pattern of spat settlement closely reflected the known oceanographic properties of the area and were consistent with observations on scallop larval densities and observed chlorophyll a levels. It is postulated that the northern part of Passamaquoddy Bay may be acting as a larval nursery area for the scallop populations in the area.

Résumé

La présente étude visait à vérifier l'hypothèse nulle selon laquelle il n'y a pas de régimes spatiaux et temporels inter-annuels réguliers dans l'implantation des larves de pétoncle (*Placopecten magellanicus*) dans la baie de Passamaquoddy. On a installé des sacs collecteurs de naissain selon un quadrillage uniforme dans cette baie et ses alentours afin de recueillir du naissain de pétoncle en phase d'implantation au cours de l'automne, cela en 1989, 1990 et 1991. Au cours de l'étude, on a également établi des profils de la température et de la salinité dans la région, échantillonné la clorophylle-a le long de transects horizontaux et verticaux dans la baie et prélevé des échantillons de larves de pétoncle. Les résultats obtenus réfutent l'hypothèse nulle et révèlent que l'implantion du naissain de pétoncle obéit à des régimes spatiaux inter-annuels très réguliers, le plus haut taux d'implantation et la plus grande hauteur moyenne de coquille étant observés dans le nord de la baie de Passamaquoddy. Le régime spatial de l'implantation du naissain reflète étroitement les propriétés océanographiques connues de la région et concordent avec les densités de larve et les niveaux de chlorophylle-a observés. On formule l'hypothèse que la partie nord de la baie agit peut-être comme nourricerie des larves de toute la population de pétoncle des environs.

Introduction

Fishery biologists have often hypothesized that the recruitment gate to many of the various marine stocks is to be found in the early life history stages. This is primarily because huge numbers of larvae produced by spawning adults give the potential for large fluctuations in the number of recruits to the fishable stocks if mortality rates in the early stages vary markedly. This idea was initially suggested by Hjort (1914) for Norwegian stocks of herring and has since been applied to other stocks and species. Prevailing oceanographic conditions have been thought to be important in this process as water currents provide the major source of transportation and food for the developing larvae. This view of the role of hydrography in the early developmental stages has been shown to be important to pelagic fishes (Cushing, 1986, Lasker, 1975), echinoderms (Pedrotti and Fenaux, 1992), coral reef fauna (Milicich et al., 1992), and infaunal and epifaunal benthos (Thouzeau, 1991).

Dickie (1955) was one of the first to suggest that recruitment success of stocks of sea scallops, *Placopecten magellanicus*, was determined at larval and early juvenile stages. He suggested that poor years of recruitment were due to the advection of larvae out of the favourable settlement areas. Since then, other researchers have examined the relationship between *P. magellanicus* and the local hydrographic conditions (e.g. Caddy, 1979; Naidu and Anderson, 1984; Tremblay and Sinclair, 1988; 1990; 1992) with the aim of explaining some of the recruitment mechanisms. Similar work has also been done by Boucher (1985) and Thouzeau (1991) on another pectinid, *Pecten maximus*.

Sampling newly settled post-larvae has usually been accomplished with the use of Japanese-type spat collectors; onion bags which have been filled with polyethylene strips or monofilament gill netting. Some studies have shown that larvae collected in spat bags generally reflected bottom sediment type and that the patterns could be partly explained by hydrographic mechanisms (Thouzeau, 1991). Sause et al. (1987) suggested there may be a relationship between the number of spat settling in the collection bags and recruitment to the adult population of the scallop, *Pecten alba*, in Australia. A contrasting study on *Pecten fumatus* in Australia showed that while there was a positive relationship between the number of larvae settling on the collectors and spawning biomass, there was no relationship between the number settling in the bags and the number of juveniles the following year (Young et al., 1989).

Identification of new recruits coming into the commercial scallop fishery in the Scotia-Fundy region is accomplished through standard research survey cruises every year. The type of sampling done (using Digby drags; see Robinson and Chandler, 1990 for details) generally allows resolution of the 2 or 3 year old age-class. If the magnitude of a recruitment pulse could be detected earlier, planning for management could be advanced by up to 2 years.

There appear to be conflicting views on the value of annual spat settlement information based on the Australian work. Therefore, the recruitment process is undoubtedly more complex than it first appears and to understand the process one must start at a very basic level. We decided to examine these relationships in Passamaquoddy Bay because: 1) there is a wide range of physical environments available, 2) the area has supported a small, local, scallop fishery for many years and 3) the area is in close proximity to a fisheries laboratory which allows for more intensive and detailed work.

The primary objective of this study was to test the null hypothesis: that there are no consistent inter-annual settlement patterns of scallop larvae in the Passamaquoddy Bay area. A secondary objective was to examine some of the local oceanographic features of Passamaquoddy Bay.

Materials and Methods

Study Site

Passamaquoddy Bay (45°5' N, 66°58' W) is located on the southwest side of the Bay of Fundy near the border of Canada and the United States. It is a semi-enclosed bay with two major entrances to the Bay of Fundy; Letete Passage on the eastern side and Western Passage on the western side (Fig. 1). The area is characterized by semidiurnal tides with a mean tidal amplitude of 7 m (Trites and Garrett, 1983). Water currents through the passages can attain speeds of 2 m/s. Flushing time has been estimated by Ketchum and Keene (1953) to be 9 days for the St. Croix River estuary and 15 days for Passamaquoddy Bay. Two cyclonic eddies are present in Passamaquoddy Bay, a strong one in the eastern part and a weaker one on the western side. These are significantly affected by wind patterns (Trites and Garrett, 1983). During the summer months, the wind direction is predominantly from the southwest and it shifts clockwise to the northwest as winter approaches (Schroeder et al. 1990).

For this study, Passamaquoddy Bay and the coastal area outside the Bay were divided into 25 sampling stations using a two-mile grid criteria (Fig. 1). The area was post-stratified into four subareas; St. Croix River estuary, Passamaquoddy Bay north, Passamaquoddy Bay south, and the outside coast.

Hydrographic Measurements

Water column profiles of temperature and salinity were taken monthly at each of the 25 stations with a Seabird SBE 19 CTD. This was an internally recording CTD which was capable of downloading the data into a microcomputer via an RS232 port. The temperature and salinity information at each depth interval was then converted to give density (sigma -t).

Chlorophyll a Measurements

Chlorophyll a concentrations were measured *in situ* with a Turner Model 450 fluorometer with a flow-through door according to the protocol of Parsons et al. (1984). Output from the fluorometer was recorded with a Fisher Recordsall chart recorder. Sea water was provided to the fluorometer with a Briggs and Stratton impeller-type water pump with 10 m of intake hose. Vertical samples for chlorophyll a were taken by lowering the weighted end of the intake hose over the side using a measured line. The sampling depth for the horizontal transects was determined with prior vertical profiles to determine the chlorophyll maximum (the depth at which the highest chlorophyll a concentration occurred). Two horizontal transects were performed, one at 1 m on September 18, 1992 and the other on September 19, 1992 at 4 m. During the course of the vertical profiles and the horizontal transects, 2 L samples of seawater were regularly taken, filtered onto Whatman GFF filters, and frozen for later calibration of the trace on the chart recorder. The filters were analyzed according to the procedure in Parsons et al. (1984) and were calibrated with a standard curve for chlorophyll a on the fluorometer.

Scallop Larval Collections

Vertical plankton tows were taken, using a 0.166 m^2 plankton net with 64 µm mesh netting and a flow meter, during the fall of 1992 at several sampling sites in Passamaquoddy Bay. The larvae were initially preserved in buffered 1% formalin in seawater, transferred to 70% ethanol, and stored for later analysis. Vertical profiles of larvae at specific depths were taken by pumping 1 m^3 of seawater through the plankton net using the water pump. The larval samples were treated as above. To count the larvae, a sample was stirred so the larvae were all suspended and four 1 mL aliquots were removed. The total number of bivalve and scallop larvae were counted using a dissecting microscope. Larval densities for the vertical hauls with the plankton net were calculated per square meter using the data from the flow meter on the net which measured the amount of water filtered.

Scallop Spat Collections

Scallop spat were collected with Japanese onion bag collectors filled with 500 g of monofilament gill netting. At each station, three bags were suspended in the water column from a rope 3 to 5 m off the bottom by means of a subsurface float attached to anchoring blocks (Fig. 2). A float at the surface marked the position of the collector. The bags were deployed at the end of August each year and retrieved in the latter part of December. The bags were then transported to the laboratory where the monofilament netting of each bag was vigorously washed in a large tub of water (20 to 30 L). The juvenile scallops and other associated invertebrates in the tub were then passed through a nested series of sieves where the larger organisms were removed. The scallop spat were then counted and removed from the sample by hand using a magnifying glass or a dissecting microscope (depending on the spat size) and preserved in 70% ethanol. A subsample of 100 spat was later measured with an ocular micrometer in a dissecting microscope for shell height to the nearest 0.1 mm.

Results

Hydrographic Measurements

Six sampling stations were chosen as representative of the general area. Stratification of the water mass during May to September increased towards the upper part of Passamaquoddy Bay based on the sigma-t profiles (Fig. 3). The area outside Passamaquoddy Bay, Station 21, showed complete mixing of the water column except during May. Station 25 in Letete Passage also showed complete mixing of the water column for all the months sampled. Stratification of the water column began to occur in the centre of the northern part of Passamaquoddy Bay (Station 14) in June at approximately 8 m. The stratification was even more intense at the head of the Bay near Station 10. Here stratification was present in May and lasted through October with a depth of mixing to 8 m. In the St. Croix River estuary (Station 4), there was some stratification occurring in May, but the water column at this point in the estuary appeared to be mostly vertically mixed throughout the year. In the southern part of Passamaquoddy Bay (Station 6), some stratification occurred during the summer months, but it was not as extreme as that found in the northern part of the Bay.

Chlorophyll a Measurements

The vertical profiles taken on August 17, 21, and 22, 1992 to determine the chlorophyll maxima in the water column showed that the highest concentrations of chlorophyll a were found in the northern part of Passamaquoddy Bay (Fig. 4). The St. Croix River estuary and the outside coast generally had maxima which ranged from 1 to 2 µg/L, the southern part of Passamaquoddy Bay ranged from 2 to 4 µg/L, and the northern part of the Bay ranged from 2 to 5 µg/L.

Two horizontal transects were performed through the lower end of the St. Croix River estuary, the upper part of the southern section of the Bay and the northern section of the Bay at 1 m on September 16, 1992 and at 4 m on September 17, 1992. This was a period of a large phytoplankton bloom. The average level of chlorophyll a measured was about 2 µg/L, but readings in the patches often went off scale with values much higher than 8 µg/L (Fig. 5). The largest patch was found in the northern part of the Bay just before the reference mark C. The concentration of chlorophyll a in this sample measured 175 µg/L. The largest amount of variation was found along the 1 m transect as patches of phytoplankton were encountered. The 4 m transect showed the same general trends in the distribution of the chlorophyll a, but with less variation (Fig. 6). The highest concentrations were near Stations 6, 7 and 8 and near the upper part of the northern part of the Bay. The average chlorophyll concentration at 4 m was about 2 µg/L, but there was an increasing trend of higher phytoplankton levels towards the northern part of the Bay at 4 m from reference point C (2 µg/L) to D (4.5 µg/L).

Larval Studies

Total bivalve larvae per m^2 tended to be higher in the northern part of Passamaquoddy Bay than in any other areas (Fig. 7). The highest densities were over 10,000 per m^2 at Station 5 and Station 15. Patterns for scallop larvae were similar to the total bivalve larvae with the highest densities also in the northern part of the Bay. Some stations had over 1,000 scallop larvae per m^2.

Two vertical samples were taken for scallop larvae on September 18, 1992 (Fig. 8). Larvae were found to be concentrated at the chlorophyll a maximum at 3 m for Station 15. More than twice as many larvae per m^3 were found at 3 m than at either 0.5 m or 7 m. The second sample was taken between Station 10 and 14 in an extremely large patch of the ciliate, *Mesodinium rubrum*. No scallop larvae were found in the chlorophyll a maximum which was in the top 1 to 2 m or just below the maximum at 5 m.

Spat Settlement

The spatial patterns of spat settlement in the collecting bags were consistent from 1989 to 1991 as the area of highest settlement of scallop spat was the northern part of Passamaquoddy Bay (Figs. 9, 10, 11). In 1989, the highest mean densities found were 1,055 (±110) individuals per bag compared to 2,985 (± 193) in 1990 and 1,577 (±224) in 1991.

The pattern in mean shell height of scallop spat between years was also consistent with some stations having greater mean heights than others (Fig. 12). Stations 10, 11, 12, and 13 tended to have the largest individuals while 15, 16, 17, and 18 usually had the smallest.

There were also consistent patterns inter-annually in spat number and mean shell height (Fig. 13) when the stations were grouped by areas (see Fig.1). The St. Croix River estuary always had the lowest number of larvae settling while the northern part of Passamaquoddy Bay had the highest. The outer coastal area and the southern part of Passamaquoddy Bay were intermediate. The northern part of the Bay also consistently had the largest individuals. 1990 also had the largest spat and highest numbers compared to the other years.

Discussion

The results from this study support the hypothesis that the early life history stages of the giant scallop in the Passamaquoddy area are tightly linked to local hydrographic conditions. The inferred residual circulation patterns at the surface in Passamaquoddy Bay by Chevrier and Trites (1960), based on drift bottle studies (Fig. 14), closely match the patterns of spat settlement we observed in this study. The wind patterns for the area (Schroeder et al., 1990) would also tend to concentrate any larvae in the surface layers in the northern Bay. This same linkage to oceanography has also been shown to varying degrees for *Placopecten magellanicus* on Georges Bank (Tremblay and Sinclair, 1992), *Chlamys patagonia* (Orensanz, 1991), and *Pecten maximus* (Boucher, 1985; Thouzeau, 1991).

The northern part of Passamaquoddy Bay stratifies during the summer and early fall as demonstrated by the CTD profiles that were taken throughout the year. This stratification was probably due to a combination of: the circulation patterns in the Bay which creates a gyre, the protected nature of the area which reduces mixing of the water by the wind, and the freshwater runoff from the rivers. Stratification may have some advantages to scallop larvae which feed on phytoplankton. If the water is stratified, then the depth of mixing near the surface will only be down to the pycnocline at ca. 8 m thereby allowing the algae in the water column to spend more of their time in the more intense euphotic zone; *sensu* Sverdrup (1953) and Riley (1942) on the development of the spring plankton bloom. Any algae inhabiting these stratified locations will then be more productive. The information on the chlorophyll a maxima from the vertical profiles at several of the sampling stations during

August 1992 supports this view of a more productive area in the northern part of the Bay. The horizontal transects show the same general pattern of an increase towards the upper part of the Bay, but the lack of coverage in the other areas make comparisons more difficult. The chlorophyll a levels found in this study were 2 to 5 times higher than that found for the Bay of St. Brieuc in France where *Pecten maximus* larvae and early juveniles were being studied (Thouzeau, 1991). It should also be noted that the data on chlorophyll a from this study were from a narrow window of time and may not show the entire picture of phytoplankton standing stock. Further sampling is being scheduled to address this point for the upcoming 1993 field season.

The larval samples in September indicate that scallop larvae are being concentrated in the northern part of Passamaquoddy Bay. They are being transported into the area by the water currents as assessment surveys have shown that the adult stocks are mainly concentrated in the southern part of the Bay, the outside coast, and in the St. Croix River estuary (Robinson, unpublished data). Although Passamaquoddy Bay has been estimated to have a flushing time of 15 days, it appears that the larvae are being retained in the upper part of the Bay to some extent. The retainment of larvae in gyres and stratified systems has been suggested or demonstrated for *Placopecten magellanicus* (Dickie, 1955; Caddy, 1979; Naidu and Anderson, 1984; Tremblay and Sinclair, 1988; 1992), *Pecten maximus* (Boucher, 1985; Thouzeau and Lehay, 1988; Thouzeau, 1991), and *Crassostrea virginica* (Mann, 1989).

The settlement of scallop spat in the onion bag collectors matched the distribution pattern of the scallop larvae. This suggests that the spat bags give an accurate picture of the relative amounts of settling larvae in the water column and the differences in the number of spat settling in the bags are not due to predation, etc. The numbers of post-larvae found in the collectors were generally high for *Placopecten* in the Scotia-Fundy region (M. Dadswell, pers. comm.). The close agreement in the relative numbers and sizes between stations and sampling sites for the three years studied indicate that the processes which shape the cohort of early life history stages are consistent from year to year, but differ in magnitude.

When the pieces of data are examined the following facts emerge: 1) the northern part of the bay has a gyre which has some retention ability and stratification; 2) the northern part may also have the highest food levels; 3) more larvae are found there and fewer adults; 4) more larvae are settling on spat bags there, and they are larger.

These facts suggest the area may function as a nursery for scallop larvae. It is possible that the larvae are maintained in the upper bay by physical mechanisms and then recruit to areas that are conducive to settlement when they are ready to metamorphose. The benefit that the larvae would gain from this system is higher growth rates, earlier settlement, and more time to grow on the sea bottom. Thouzeau and Lehay (1988) indicated that for *Pecten maximus*, the survival of juveniles on the seabed was a function of the size of the individuals over the first winter. If that is the case for *P. magellanicus*, the possible rapid growth experienced by the larvae in the upper Bay may give them a better chance of survival over the winter once they settle in the appropriate areas. Scallop larvae may also be sensitive to low food levels, particularly if they are transported into unfavourable areas. His and Seaman (1992) showed that larvae of the oyster, *Crassostrea gigas*, which have been starved for 4 to 5 days and then fed daily thereafter showed significant mortality effects. Those which had been starved for 6 to 8 days had almost 100% mortality despite the presence of suitable food items. These results mirror results from larval herring (*Clupea harengus*) and their "point of no return" (Blaxter and Hempel, 1963).

In conclusion, we have rejected the null hypothesis and demonstrated a tight link between the oceanography of an area and the early life history patterns of scallops. The picture which emerges resembles the concept of a retention area *sensu* Iles and Sinclair (1982) or the "member-vagrant hypothesis" of Sinclair (1987) where populations are maintained over time by interactions with the physical retention characteristics of an area. Future research will be directed at the benthic phase to determine the significance of the larval supply in the overlying waters to the successful recruitment of juveniles to the adult populations.

Acknowledgements

We thank Mr. Wayne Miner, skipper of the Pandalus III, for assistance in conducting the CTD casts and deploying scallop spat bags over the years. F. Cunningham drafted some of the figures. D. Robichaud reviewed an early draft of this manuscript and provided valuable suggestions.

References

Blaxter, J.H.S. and G. Hempel 1963. The influence of egg size of herring larvae (*Clupea harengus* L.) J. Conseil 28:211-240.

Boucher, J. 1985. Caractéristiques dynamiques du cycle vital de la coquille Saint-Jacques (*Pecten maximus*): hypothèses sur les stades critiques pour le recrutement. J. Cons. Int. Explor. Mer. C.M. 1985/K23/Sess. Q. 10p.

Caddy, J.F. 1979. Long-term trends and evidence for production cycles in the Bay of Fundy scallop fishery. Rapp. P.v. Reun. Cons. int. Explor. Mer 173:97-108.

Chevrier, J.R. and R.W. Trites 1960. Drift-bottle experiments in the Quoddy region, Bay of Fundy. J. Fish. Res. Board Can. 17:743-762.

Cushing, D.H. 1986. The migration of larval and juvenile fish from spawning ground to nursery ground. J. Cons. int. Explor. Mer 43:43-49.

Dickie, L.M. 1955. Fluctuations in abundance of the giant scallop *Placopecten magellanicus* (Gmelin), in the Digby area of the Bay of Fundy. J. Fish. Res. Board Can. 12:797-857.

His, E. and M.N.L. Seaman 1992. Effects of temporary starvation on the survival, and on subsequent feeding and growth, of oyster (*Crassostrea gigas*) larvae. Mar. Biol. 114:277-279.

Hjort, J. 1914. Fluctuations in the great fisheries of northern Europe viewed in the light of biological research. Rapp. P.-V. Reun. Cons. Int. Explor. Mer 20:1-228.

Iles, T.D. and M. Sinclair 1982. Atlantic herring: stock discreteness and abundance. Science 215:627-633.

Ketchum, B.H. and D.J. Keene 1953. The exchanges of fresh water and salt waters in the Bay of Fundy and in Passamaquoddy Bay. J. Fish. Res. Board Can. 10:97-124.

Lasker, R. 1975. Field criteria for survival of anchovy larvae: The relationship between inshore chlorophyll maximum layers and successful first feeding. Fish. Bull. 73:453-462.

Mann, R. 1989. Distribution of bivalve larvae at a frontal system in the James River, Virginia. Mar. Ecol. Prog. Ser. 50:29-44.

Milicich, M.J., M.G. Meekan and P.J. Doherty. 1992. Larval supply: a good predictor of recruitment of three species of reef fish (Pomacentridae). Mar. Ecol. Prog. Ser. 86:153-166.

Naidu, K.S. and J.T. Anderson 1984. Aspects of scallop recruitment on St. Pierre Bank in relation to oceanography and implications for resource management. CAFSAC Res. Doc. 84/29 15p.

Orensanz, J.M., M. Pascual and M. Fernandez 1991. Argentina. pp. 981-999. In: Shumway, S.E. (Ed.) Scallops: Biology, Ecology and Aquaculture. Elsevier , New York 1095 p.

Parsons, T.R., Y. Maita and C.M. Lalli. 1984. A Manual of Chemical and Biological Methods for Seawater Analysis. Pergammon Press, Oxford, New York, Toronto 173 p.

Pedrotti, M.L. and L. Fenaux. 1992. Dispersal of echinoderm larvae in a geographical area marked by upwelling (Ligurian Sea, NW Mediterranean). Mar. Ecol. Prog. Ser. 86:217-227.

Riley, G.A. 1942. The relationship of vertical turbulence and spring diatom flowerings. J.

Mar. Res. 5:67-87.

Robinson, S.M.C. and R.A. Chandler 1990. The Grand Manan scallop stock assessment 1988-1989. CAFSAC Res. Doc. 90/81 26 p.

Sause, B.L., D. Gwyther, and D. Burgess. 1987. Larval settlement, juvenile growth and the potential use of spatfall indices to predict recruitment of the scallop *Pecten alba* Tate in Port Phillip Bay, Victoria, Australia. Fish. Res. 6:81-92.

Schroeder, W.W., S.P. Dinnel, and W.J. Wiseman Jr. 1990. Salinity stratification in a river dominated estuary. Estuaries 13:145-154.

Sinclair, M. 1987. Marine Populations. An Essay on Population Regulation and Speciation. Univ. Washington Press, 252 p.

Sverdrup, H.U. 1953. On conditions for the vernal blooming of phytoplankton. J. Cons. int. Explor. Mer 18:287-295.

Thouzeau, G. and D. Lehay 1988. Variabilité spatio-temporelle de la distribution, de la croissance et de la survie des juveniles de *Pecten maximus* (L.) issues des pontes 1985, en baie de Saint-Brieuc. Oceanol. Acta 11:267-284.

Thouzeau, G. 1991. Experimental collection of postlarvae of *Pecten maximus* and other benthic macrofaunal species in the Bay of Saint-Brieuc, France. I. Settlement patterns and biotic interactions among the species collected. J. Exp. Mar. Biol. Ecol. 148:159-179.

Tremblay, M.J. and M.M. Sinclair 1988. The vertical and horizontal distribution of sea scallop (*Placopecten magellanicus*) larvae in the Bay of Fundy in 1984 and 1985. J. Northw. Atl. Fish. Sci. 8:43-53.

Tremblay, M.J. and M. Sinclair 1990. Sea scallop larvae *Placopecten magellanicus* on Georges Bank: vertical distribution in relation to water column stratification and food. Mar. Ecol. Prog. Ser. 61:1-15.

Tremblay, M.J. and M. Sinclair 1992. Planktonic sea scallop larvae (*Placopecten magellanicus*) in the Georges Bank region: Broadscale distribution in relation to physical oceanography. Can. J. Fish. Aquat. Sci. 49:1597-1615.

Trites, R.W. and C.J.R. Garrett. 1983. Physical oceanography of the Quoddy region. Can. Spec. Publ. Fish. Aquat. Sci. 64:9-34.

Young, P.C., R.B. Martin, R.J. McLoughlin and G. West. 1989. Variability in spatfall and recruitment of commercial scallops (*Pecten fumatus*) in Bass Strait. pp. 80-91. In:

Dredge, M.L.C., W.F. Zacharin and L.M. Joll (Eds.) Proceedings of the Australasian Scallop Workshop, Hobart, Australia.

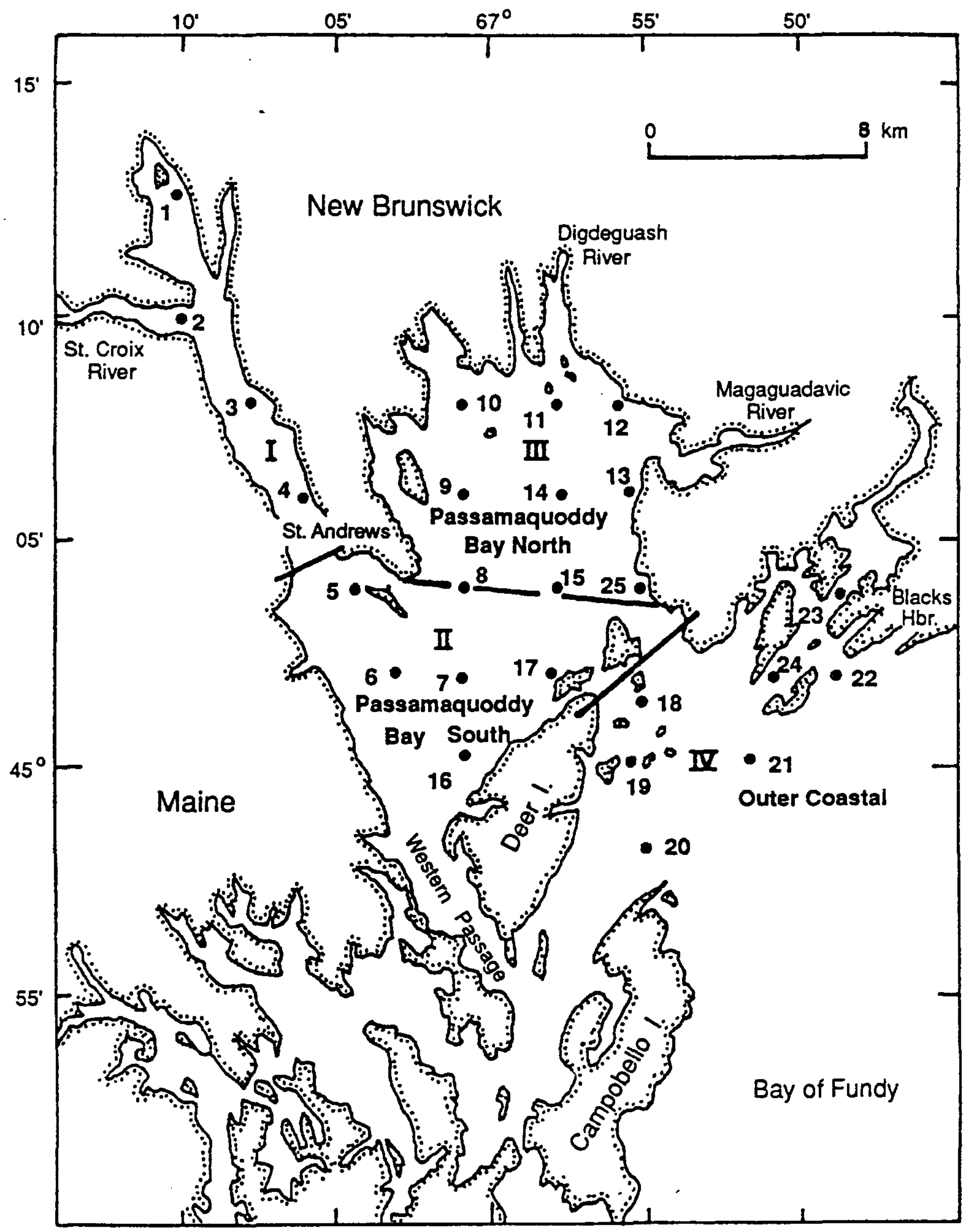


Figure 1. Map of the Passamquoddy Bay study site showing the sampling stations and the four subareas.

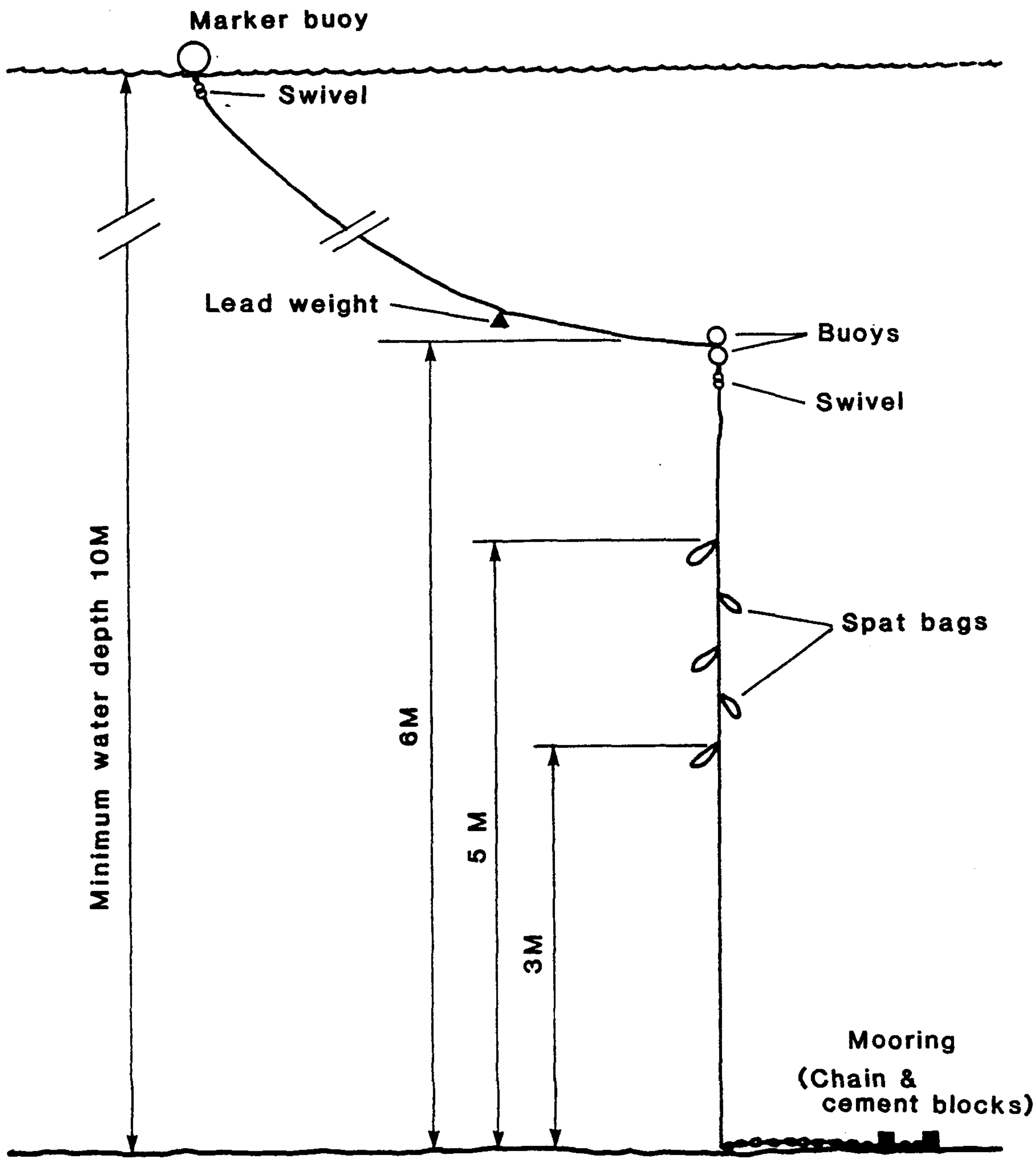


Figure 2. Diagram of the scallop spat collection device.

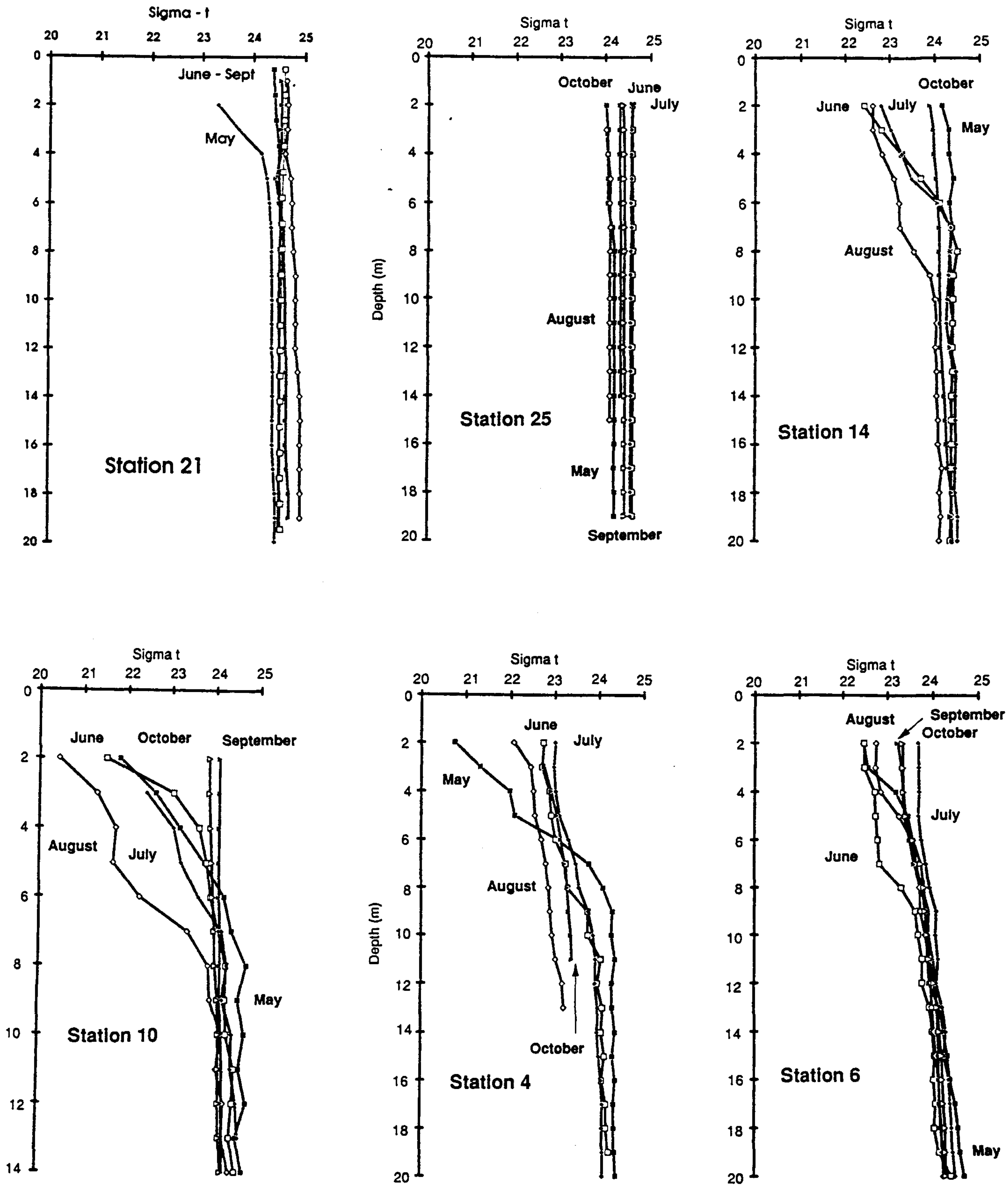


Figure 3. Sigma-t profiles from selected representative sampling stations in Passmaquoddy Bay and surrounding areas for the months May through October. See Figure 1 for sampling locations.

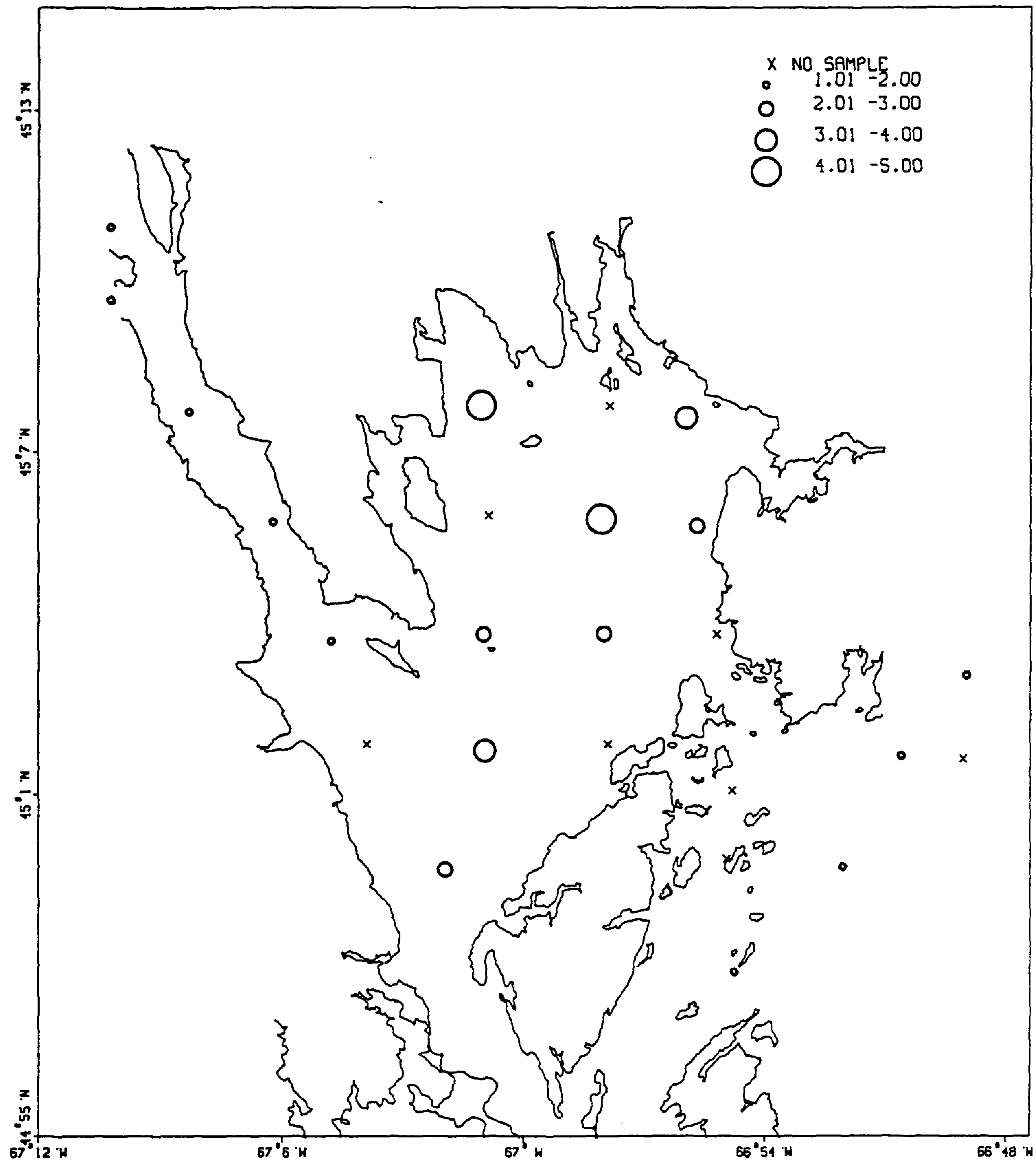


Figure 4. Maximum chlorophyll a (μg/L) values at the various sampling stations from vertical profiles done on August 17, 21, and 22 1992.

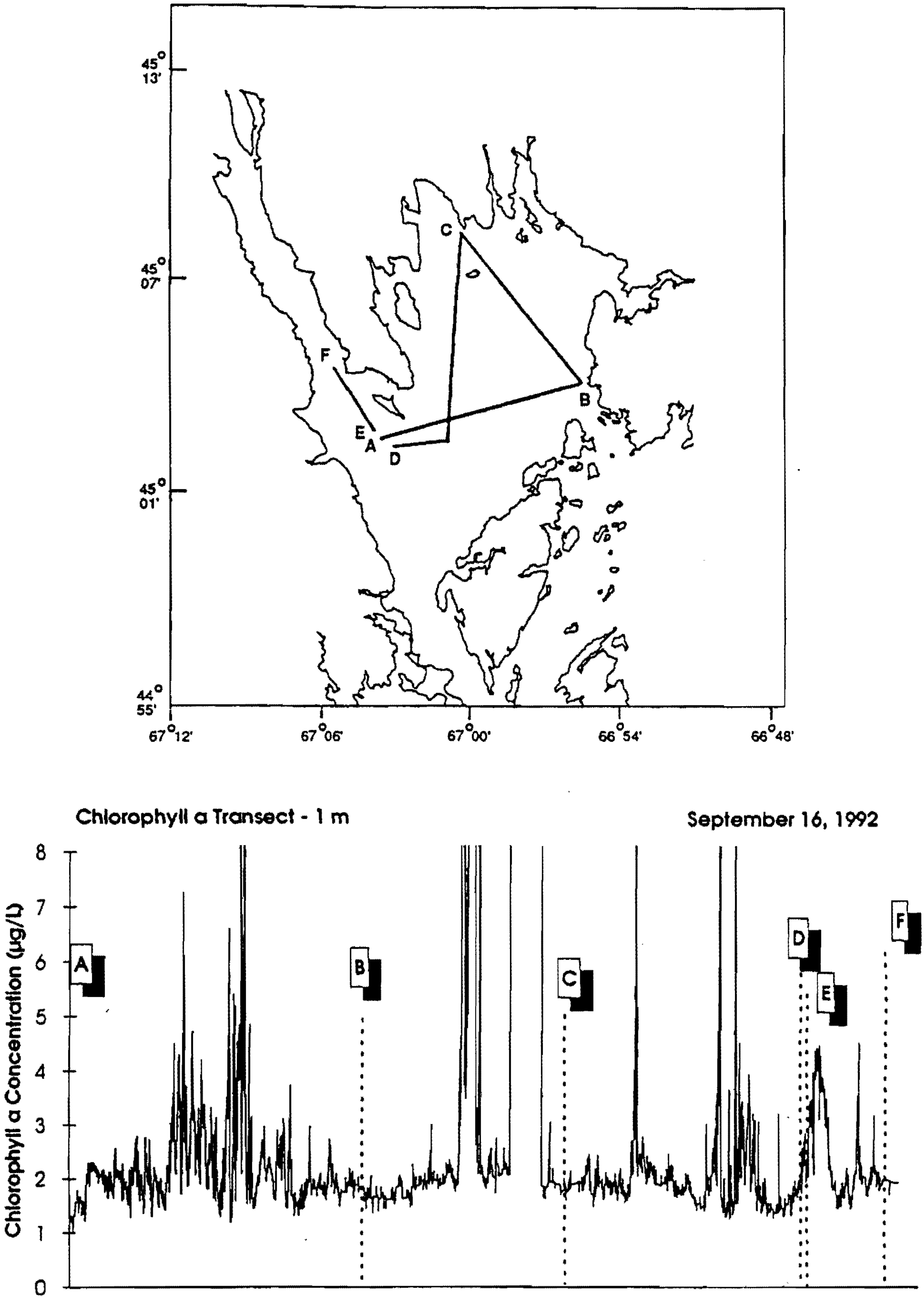
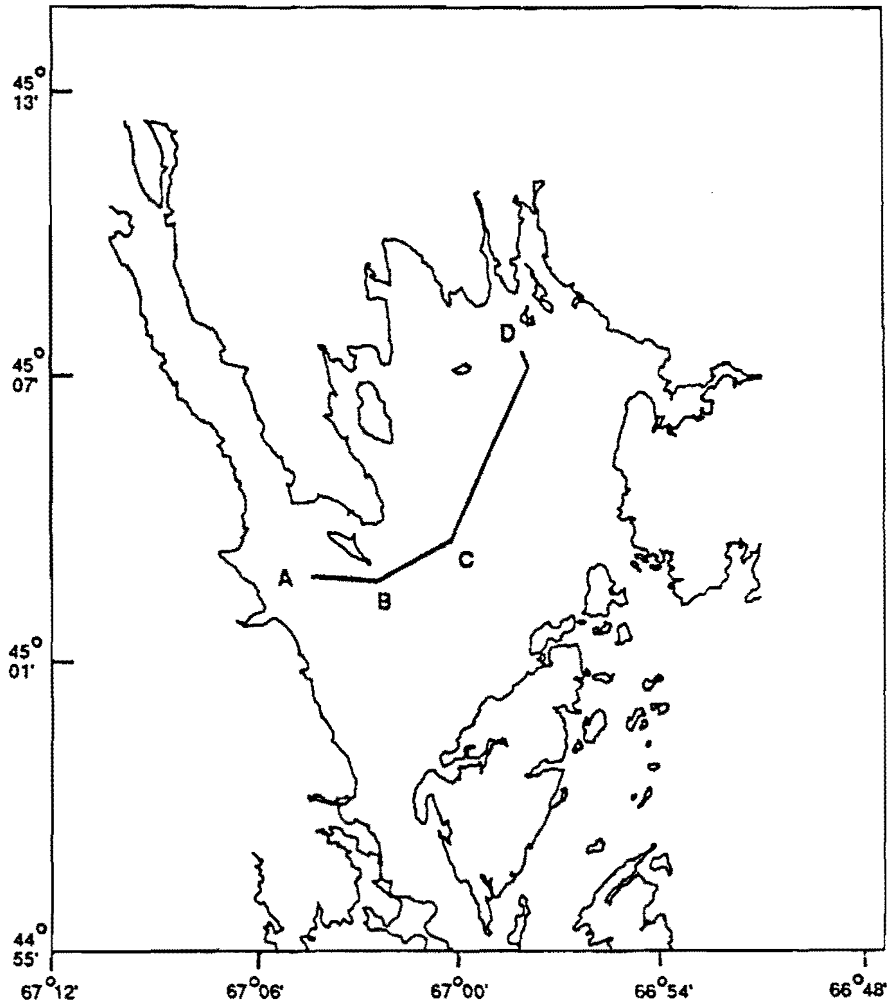


Figure 5. Horizontal transect for chlorophyll a (µg/L) done at 1 m on September 16, 1992. The reference letters on the cruise track correspond to the letters on the bottom trace.



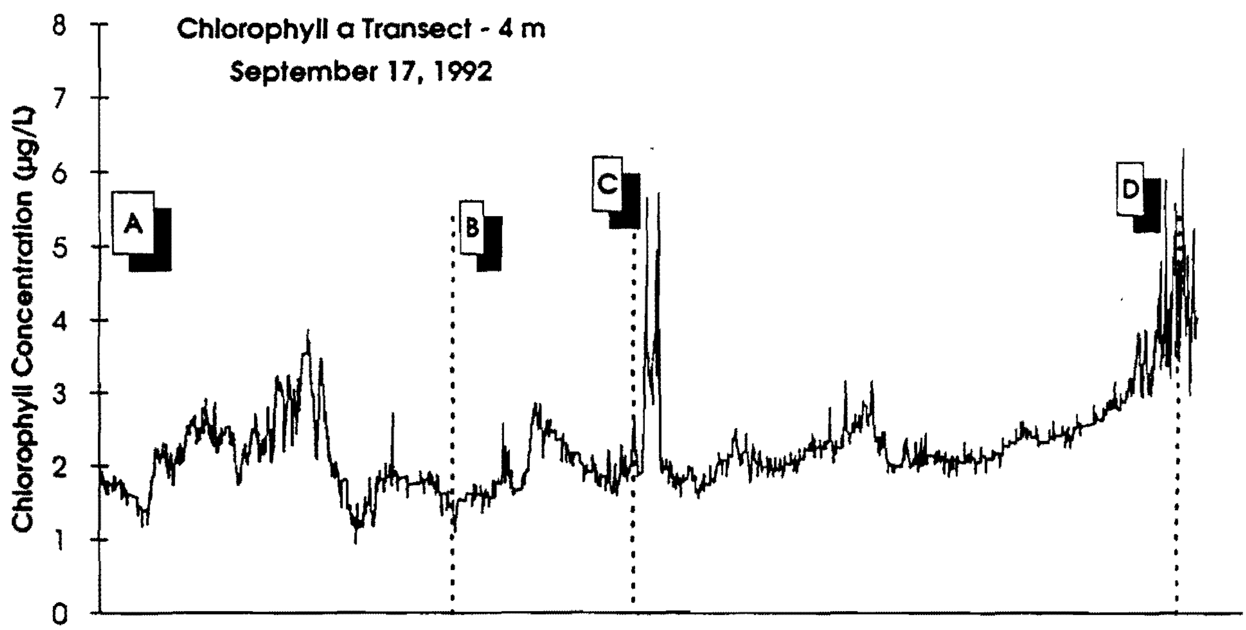


Figure 6. Horizontal transect for chlorophyll a (µg/L) done at 4 m on September 17, 1992. The reference letters on the cruise track correspond to the letters on the bottom trace.

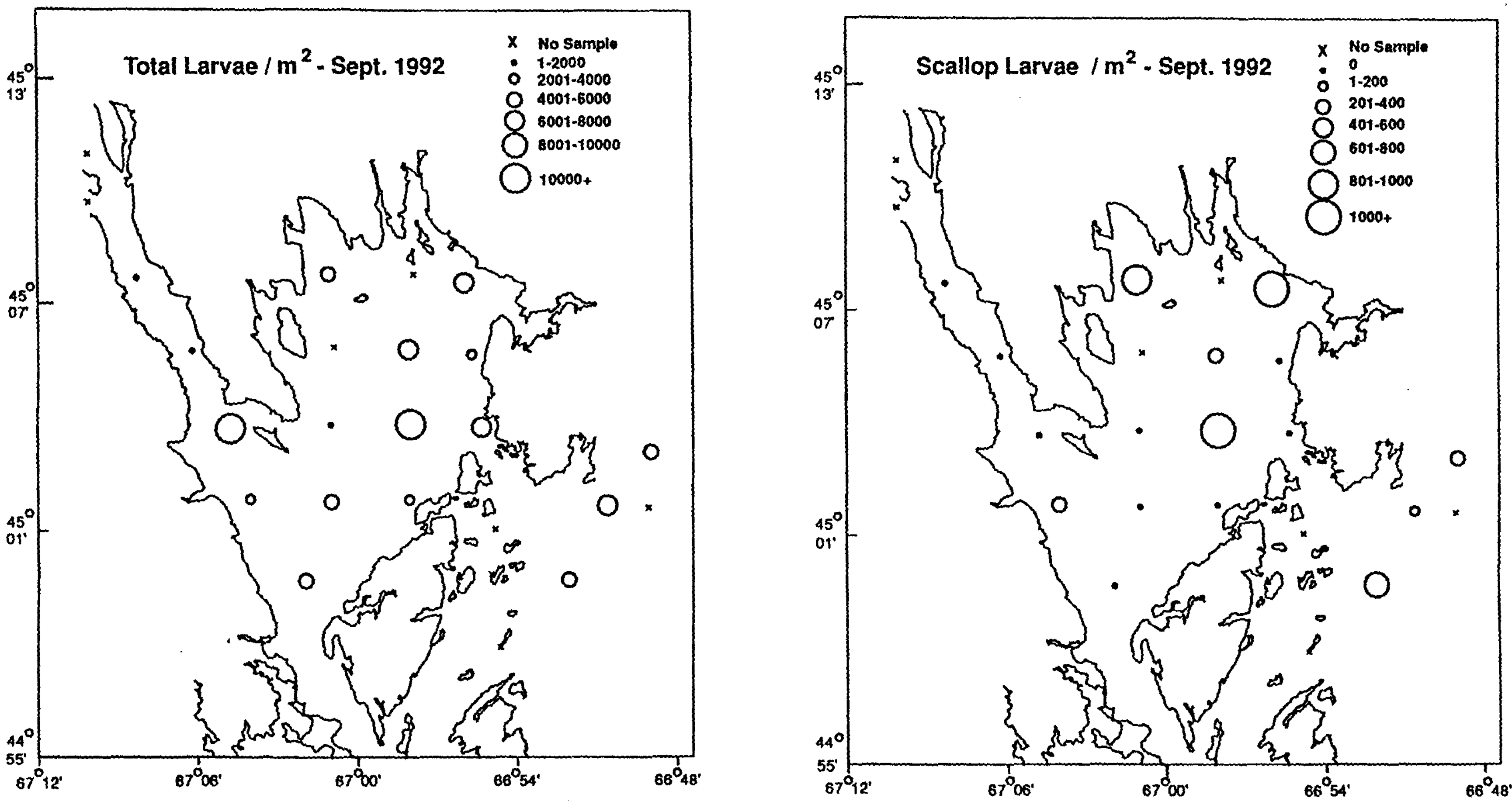


Figure 7. Densities of total bivalve larvae and scallop larvae at the various sampling stations in Passamaquoddy Bay during September 1992.

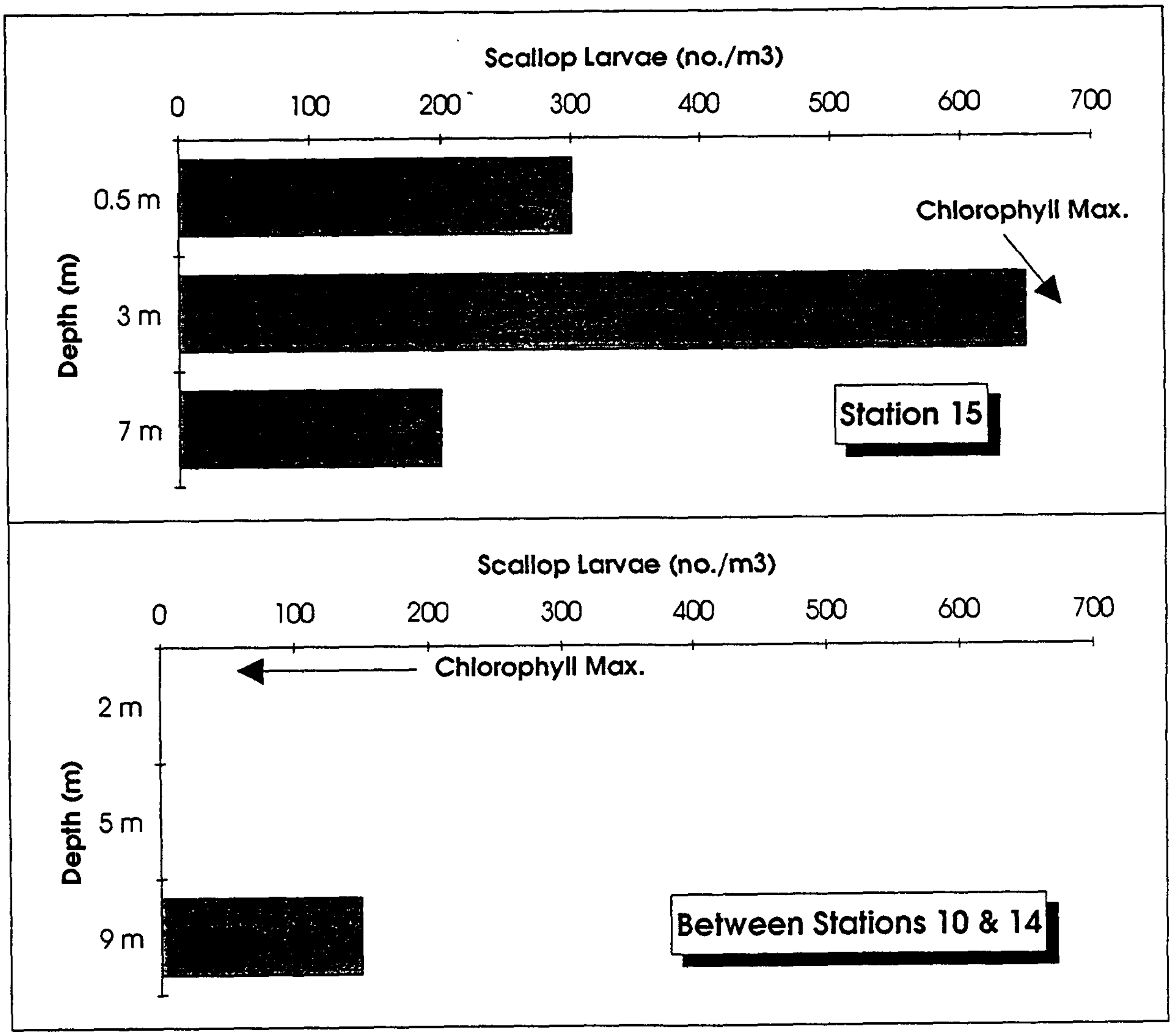


Figure 8. Densities of scallop larvae at different depths at two stations in Passamaquoddy Bay on September 18, 1992.

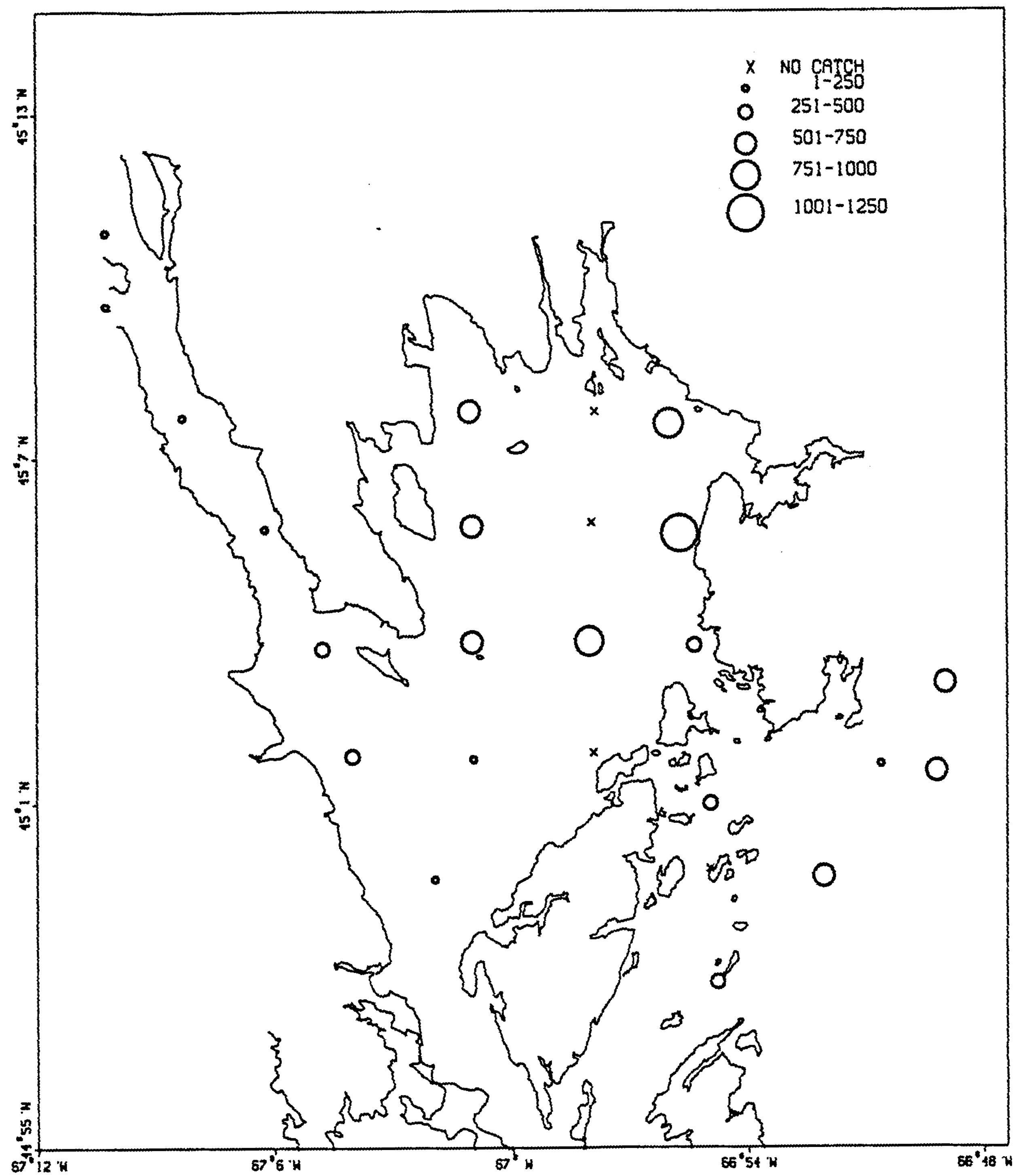


Figure 9. Mean number of scallop spat per bag recovered in December 1989 from the collection bags at the various sampling stations in Passamaquoddy Bay and outside coast. X denotes loss of sampling gear.

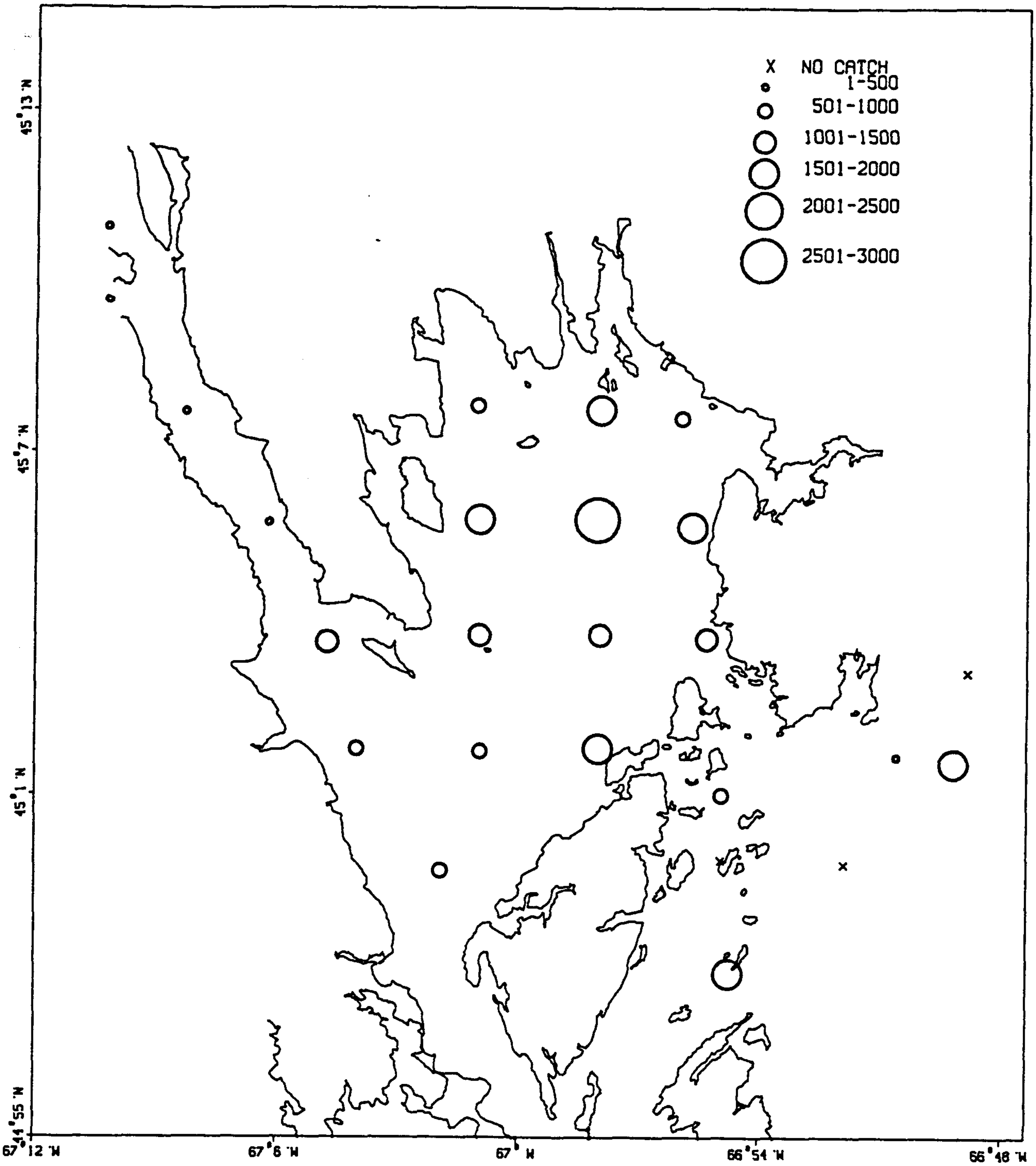


Figure 10. Mean number of scallop spat per bag recovered in December 1990 from the collection bags at the various sampling stations in Passamaquoddy Bay and outside coast. X denotes loss of sampling gear.

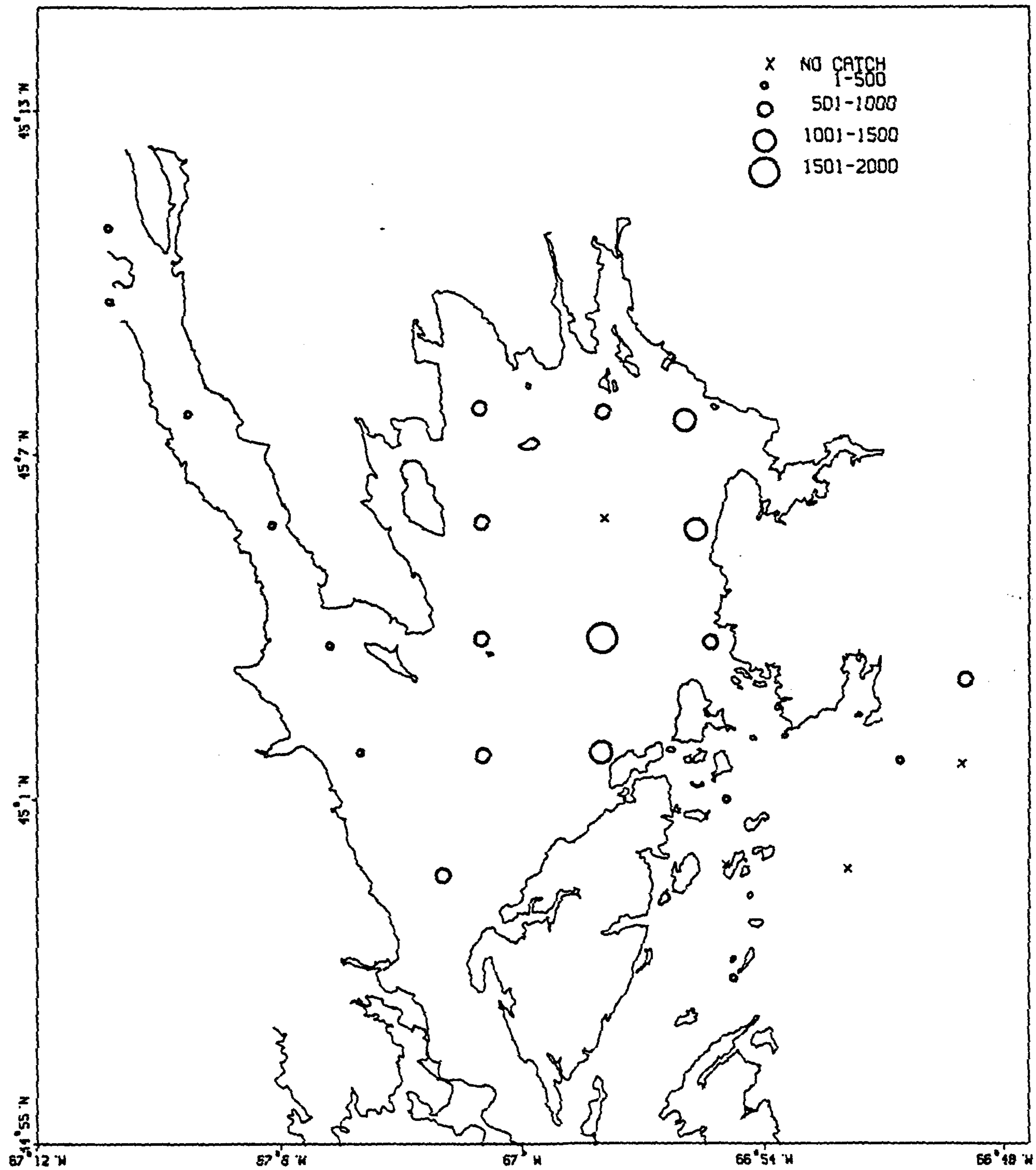


Figure 11. Mean number of scallop spat per bag recovered in December 1991 from the collection bags at the various sampling stations in Passamaquoddy Bay and outside coast. X denotes loss of sampling gear.

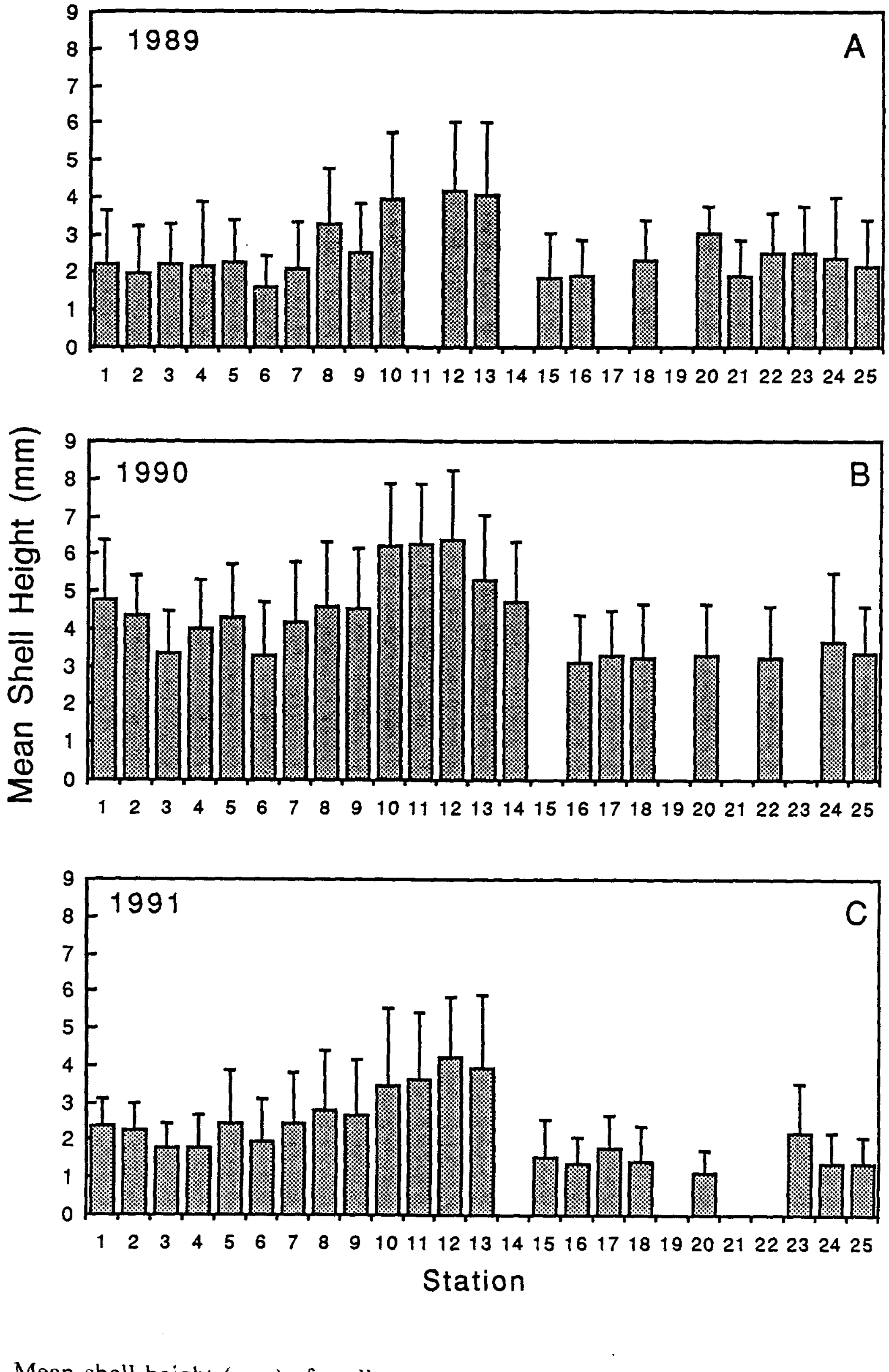


Figure 12. Mean shell height (mm) of scallops recovered from the spat bags in December at the various stations for the years 1989 to 1991. Bars represent one standard deviation.

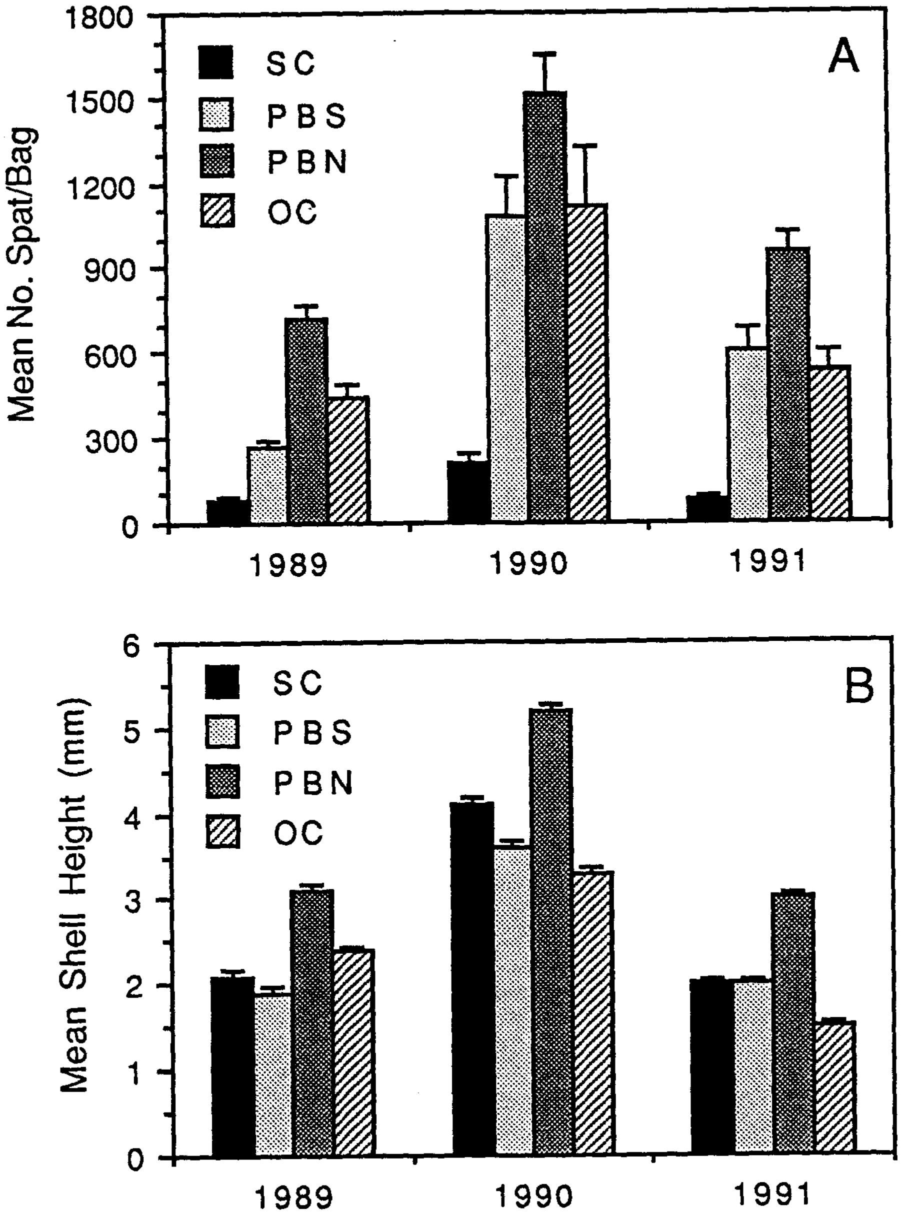


Figure 13. Mean numbers of spat per bag and mean shell height (mm) for the four subareas during the years 1989 to 1991. Bars represent one standard error. SC= St. Croix River Estuary, PBS=Passamaquoddy Bay South, PBN=Passamaquoddy Bay North, and OC=Outer Coast.

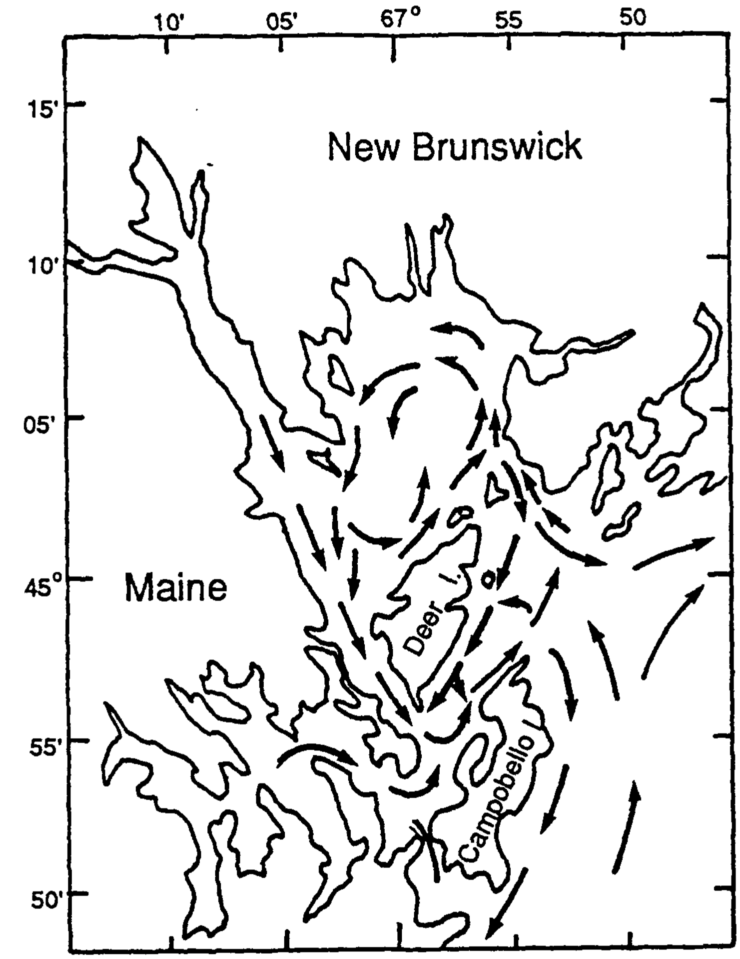


Figure 14. Residual surface circulation map of the Quoddy region. (Redrawn from Trites and Garrett, 1983)