FRI-UW-9203
December, 1991

FISHERIES RESEARCH INSTITUTE
SCHOOL OF FISHERIES WH-10
UNIVERSITY OF WASHINGTON
SEATTLE, WA 98195

PORT MOLLER KING CRAB STUDIES

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ANNUAL REPORT

FOR

ALASKA OUTER CONTINENTAL SHELF ENVIRONMENTAL ASSESSMENT
PROGRAM, NOAA, U.S. DEPARTMENT OF COMMERCE;
AND ANCHORAGE OFFICE, MINERALS MANAGEMENT SERVICE,
U.S. DEPARTMENT OF THE INTERIOR

Approved

Submitted 3-27-92 R.C. Francis
Director

ABSTRACT

A suite of biological sampling was undertaken to study the population status of king crabs in the Port Moller estuarine complex (Port Moller and Herendeen Bay) in the southeastern Bering Sea. Samples were collected between 25 April and 30 July 1990; methods included zooplankton sampling, benthic trawling and dredging, commercial crab pots, and intertidal surveys. Larvae, juveniles, and adults of both red (RKC) and blue (BKC) king crabs were found. Larvae of both species were concentrated in the Portage Creek arm of Herendeen Bay, a few were found in outer Herendeen Bay and Hague Channel, and virtually none were found in Port Moller. A stochastic larval development model was developed and used to simultaneously estimate hatch times, stage durations, and mortality rates for the two species. Peak hatch was calculated to be on 5 May for RKC and 6 May for BKC. Average zoeal durations (stages Z1 to Z4 combined) were 47 days for RKC and 53 days for BKC. Instantaneous larval mortality rates (calculated by assuming no export of larvae from Herendeen Bay) were $0.095\ d^{-1}$ for RKC and $0.075\ d^{-1}$ for BKC. Larval transport to or from the estuary could not be readily assessed without information on water circulation patterns. Juveniles of both species were found on rocky substrates in inner Herendeen Bay, but no estimates of juvenile abundance were possible. Adult RKC were caught in substantial numbers in inner Herendeen Bay, with a few caught in Hague Channel and none in Bristol Bay near the Port Moller entrance. Males and females were spatially segregated within inner Herendeen Bay. Five BKC (4 male, 1 female) were caught in inner Herendeen Bay. Fecundity estimates for female RKC ranged from 15,000 to 130,000 eggs, with a relationship of egg number (Y) to carapace length (X) of $Y = 2170X - 135{,}500$. Juvenile and adult Tanner crab were also caught, and some results for this species are reported. Results provide background information that may be used in assessing local environmental effects of oil and gas development or other environmental problems.

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ACKNOWLEDGMENTS

We thank other participants in the University of Washington field crew (Bing Shi and Rick Nemeth) for their dedicated efforts. The herring crew from Triton, Ltd. (Mike McGurk and Dave Warburton) provided invaluable cooperation, thus allowing more extensive larval sampling than otherwise would have been possible. We thank the skippers and crews of the vessels involved in the field effort: NOAA Vessel 1273 (John Dermody and Pat Harman, skippers), the chartered gillnetter *Dawntreader* (Fred Dyson, skipper), and the crabber *Cascade* (Bob Miller, skipper). We are grateful for the support of the Alaska Crab Coalition (particularly Arni Thompson), especially for the provision of the *Cascade*, without which adult sampling would have been impossible, and we thank everyone at OCSEAP Anchorage (Lyman Thorsteinson, Laurie Jarvela, and John Dermody) for help along the way. This program has benefited from cooperative interaction with, and logistical support provided by, the Alaska Department of Fish and Game, the National Marine Fisheries Service, and the Alaska Crab Coalition, which together have enhanced our program on behalf of OCSEAP-MMS program needs.

This study was funded by the Minerals Management Service of the Department of the Interior, through an interagency agreement with the National Oceanic and Atmospheric Administration, Department of Commerce, as part of the Alaska Outer Continental Shelf Environmental Assessment Program (OCSEAP).

KEY WORDS

blue king crab, *Chionoecetes*, environmental assessment, larval development, larval transport, *Paralithodes*, population biology, red king crab, southeastern Bering Sea, Tanner crab

INTRODUCTION

Over the last 20 years, abundance of king crabs (*Paralithodes* spp.) has varied tremendously in the southeastern Bering Sea. Current explanations of such fluctuations are tenuous because many aspects of the ecology and distribution of various life history stages are poorly studied. For both red (*P. camtschatica*, "RKC") and blue (*P. platypus*, "BKC") king crabs, research has focused on adult and sub-adult stages. The limited work on larvae and juvenile stages points to substantially different distributional patterns than for older animals (Sundberg and Clausen 1977, Armstrong et al. 1981; McMurray et al. 1984). In particular, small juveniles of both species occur nearshore in benthic substrate that provides refuge from predation, while adults typically occur on more open substrates farther offshore.

Use of coastal lagoons and embayments by RKC has long been a question, and the Port Moller Complex (PMC) has been of particular interest. Commercial and subsistence crab fishing has occurred in Herendeen Bay, and both red and blue king crab are known to occur in the bay. BKC are of particular scientific interest because of their disjunct distribution, being known from the Pribilof, St. Matthew, and St. Lawrence islands, and in deep bays of Kodiak Island and Southeast Alaska.

The PMC is a large inlet adjacent to Bristol Bay (Fig. 1) and is near the North Aleutian Basin oil and gas lease area. This area is thought to be of prime importance as a nursery for juvenile crabs, which has prompted the Minerals Management Services (MMS) to fund research on crab populations in relation to oceanography in the PMC. Reconnaissance studies completed in 1989 confirmed the presence of both RKC and BKC in the complex, where they were found mainly in inner Herendeen Bay (Armstrong et al. 1990).

The focus of the 1990 studies was to:

1. document the spatial and temporal distributions of king crab larvae and estimate larval dispersion and mortality,
2. estimate larval exchange between the estuary and Bristol Bay,
3. evaluate estuarine habitat use by juvenile king crab,
4. describe spatial and temporal patterns in juvenile and adult king crab abundance, and
5. describe physio-chemical attributes of the PMC that would enhance crab survival compared to the broad adjacent area in Bristol Bay.

While the focus of the study was on king crabs, numerous Tanner crab (*Chionoecetes bairdi*) were also caught in the sampling. Because Tanner crab are also commercially important, data on juveniles and adults of this species are included. However, this species was not sorted from larval samples and no larval data are reported.

METHODS

FIELD

The survey for king crab larvae was conducted jointly with the herring survey performed by Triton, Ltd. (Vancouver, British Columbia). Sampling commenced 25 April 1990 and continued through 30 July. Until mid-June the survey was conducted from the 36-foot (11-m) NOAA Vessel 1273, then from the chartered gillnetter *Dawntreader*. Larval samples were collected weekly at 21 stations throughout the estuary. About 600 larval samples were collected. Stations are listed in Table 1, and their locations are shown in Figure 2.

Sampling consisted of double-oblique tows of a 60-cm bongo net from the surface to within 5 m of the bottom. Early in the season, both nets had 333-µm mesh. In mid-season, a combination net with 333-µm mesh on one side and 505-µm mesh on the other was used. After 23 June, both nets had 505- µm mesh. All king crab larvae were retained by the larger mesh; the initial use of 333-µm mesh was strictly for purposes of the concurrent larval herring study. Catch from both sides of the net were combined into one sample, except when different meshes were used. Tow distances were recorded with a flowmeter (General Oceanics Model 2030) mounted inside the net mouth. A limited number of samples were collected with a 1 x 1 m Methot net with a 1000-µm mesh. In addition, 24-h series of vertically stratified samples were obtained with a Tucker trawl, twice in Herendeen Bay and once in Port Moller, with the intention of identifying vertical migratory behavior of king crab larvae. All zooplankton samples were preserved in 5% buffered formalin in seawater. For analysis, tow distances were later converted to volume sampled by multiplying by the combined net opening area. Larval catch was then converted to density per 1,000 m^3 by dividing numbers caught by volume filtered, or to density per 100 m^2 of surface by multiplying numbers per volume by bottom depth for the station.

Juvenile king crab were sampled via three methods: benthic trawling, use of a rock dredge, and intertidal sampling. Sites sampled are listed in Table 2. Trawling was conducted mainly with a 3-m beam trawl (Gunderson and Ellis 1986); a small otter trawl was used at one station. Rocky areas were sampled with a small (39 x 15 cm) rock dredge. At low tide, transects parallel to the water's edge were walked to search for juvenile king crab on the surface and under movable rocks. For all three methods, all king crab encountered were identified to species, sexed, and measured (carapace length, CL) using vernier calipers. Other commercially important crab species encountered were also recorded.

Adult king crab were sampled using commercial crab pots from the vessel *Cascade* provided by the Alaska Crab Coalition. During 21-27 June, pots were set in 111 locations, with 65 locations in Herendeen Bay, 25 locations in Hague Channel, and 21 locations along a transect outside the estuary in Bristol Bay. Locations within the estuary are shown in Figure 3. A total of 132 pots were set (1-3 sets per location). Crabs caught were sexed and measured to the nearest mm CL, and eggs and shell condition were recorded. A total of 1,963 crab (1,615 males, 348 females) were tagged using two types of tags. About half the males were tagged with NMFS isthmus tags inserted through the isthmus and tied into muscle; the remaining males and all females were tagged with Floy anchor tags inserted through the carapace above the branchial area. Anchor tags are expected to be lost on molting, while the isthmus tags should be retained. We are currently participating in a joint National Marine Fisheries Service–Alaska Department of Fish & Game (NMFS-ADFG) tag recovery program, which offers rewards for tags returned by commercial crabbers. Twenty-five adult female RKC were collected and shipped to ADFG (Gordon Kruse, Juneau) for electrophoretic analysis.

LABORATORY

Larvae

Plankton samples were completely sorted for king crab larvae, which were identified to species and larval stage using published descriptions and keys (Sato 1958; Hoffman 1968; Haynes 1984), as modified by G. C. Jensen et al. (unpubl. data). Larvae were transferred to and stored in a 70% ethanol/5% glycerol solution. On the basis of the larval development, the sorting effort was focused on samples collected from late April through the first week in July. Later samples were spot-checked to be sure that no larvae were present so late in the season. No larvae were found in early-season samples from Port Moller Bay, so later samples from that area were only spot-checked to be sure the pattern held. The processed samples included 246 bongo net, 40 Tucker trawl, and 2 Methot net samples.

Fecundity

Gravid female RKC (n=25) and Tanner crab (n=23) were frozen and shipped back to the lab where they were thawed and measured, their stomachs removed and preserved, and eggs removed. One subsample of two hundred eggs was taken from each egg mass. Subsample and remaining egg mass were dried to constant weight, and total number of eggs was calculated as:

$$N_T = \frac{N_S}{W_S} \cdot W_R + N_S,$$

where N_T is total number of eggs, N_S is number in subsample, W_S is subsample weight, and W_R is weight of remaining egg mass. Egg number and carapace length (RKC) or width (Tanner) were then subjected to a simple regression analysis, and the slope was tested for significance. Results were compared to data for the same species previously reported by other investigators.

DATA MANAGEMENT AND ANALYSIS

Following completion of field work and laboratory analyses, data were coded into computer files for analysis. Coded data were verified by hand-checking against field and laboratory data sheets, and corrected data were archived on 9-track tape at the University of Washington Academic Computer Center. Most analyses were carried out using Microsoft Excel on MS-DOS-based personal computers, but more complicated statistical analyses were performed using S-Plus (Statistical Sciences Inc., Seattle, WA) on UNIX-based workstations.

LARVAL MODELS

Hatch times, larval development rates, and larval mortality rates were estimated for both species via a dynamic cohort model. Such models have been used extensively in larval insect work (Manly 1974; Stedinger and Shoemaker 1985), and copepod dynamics (Parslow et al. 1979; Sonntag and Parslow 1981). Recently, Shirley and Shirley (1989a) have applied an instar analysis technique to estimating mortality of RKC larvae in Auke Bay, Alaska. The technique they used is simpler than the cohort model approach in that it does not account for variability of hatch times and stage durations.

The model we used consists of two components: a biological model that describes the dynamics of larval stages from hatch through the four zoeal stages, and a sampling model that describes the probability distributions of sampling error. Both models are described in detail in Appendix A. The biological model contains parameters that characterize larval dynamics: time of hatch, total number hatched, durations of the larval stages, and mortality rates. The model is quite similar to the "lag-Manly" model described in Parslow et al. (1979); the only differences are that we allowed individual variation in stage durations and we specified a common mortality rate for all larval stages. Biological parameters are defined in Table 3. The sampling model differs substantially from that used by Parslow et al. (1979). They used simple nonlinear least squares to fit parameters to the data. In our view, this is unjustifiable for our data, where sample sizes are relatively small. Instead, we have used a technique first applied in fisheries work by Fournier and Archibald (1982) which separates the sampling error into two components: error in measuring total abundance, and error in estimating stage composition of the sample. The first type of error is typically modeled as log-normal or (almost equivalently) as normal with constant coefficient of variation. The second error is multinomial if all stages are identified accurately and sampled randomly within the total catch.

This model was fit to the field data using numerical maximum likelihood estimation. The estimation procedure used a "simplex" function minimization algorithm (Press et al. 1986) interfaced to S-Plus. Approximate parameter standard errors and correlations were calculated from the inverse of an approximate information matrix evaluated at the estimates.

RESULTS

LARVAE

Geographic Distribution and Abundance

King crab larvae were present in the bongo samples from the beginning of the survey in late April until early July. RKC larvae were found throughout the PMC; however, large densities were only observed in the inner parts of Herendeen Bay. Of the total number of RKC larvae, 94.7% were found in Herendeen Bay, 5.2% in Johnson Strait and Hague Channel, and 0.1% in Port Moller. BKC larvae were only found in the inner parts of Herendeen Bay. The overall ratio of RKC to BKC larvae was 7:1.

King crab have five larval stages: four zoeal stages (Z1-Z4) and a megalopal stage. The highest abundance of RKC larvae was observed May 12 at Station 36 in Herendeen Bay, with a density of 6,773 larvae per 100 m^2, of which 5,823 were Z1 and 950 Z2 larvae. Densities of the subsequent zoeal stages and the megalopal stage peaked every 1 to 2 weeks in the following 10 weeks until early July, when only a few megalopae were observed. Abundances of BKC larvae showed the same trends with the highest density of 1,280 larvae per 100 m^2 (1,218 Z1 and 62 Z2) on May 12. The total abundances of RKC and BKC larvae in the period of May through June are shown in Figures 4 and 5.

Vertical Distribution

Tucker trawl samples indicated a pattern of vertical migration by king crab larvae, which primarily existed in the upper 40 m of the water column (Fig. 6). The highest densities were found during the day at a depth of 30-40 m which coincides with the thermocline (Fig. 7). At night, larvae occurred predominantly at depths of 10-20 m.

Larval Development and Mortality

The dynamic cohort model was fit to zoeal density data from the three innermost Herendeen Bay stations (35, 36, and 37). The fit of the model to these data for RKC and BKC are shown in

Figures 8 and 9. Parameter estimates are given in Table 4. Initial fits indicated strong outliers on day 173 for both species, which were excluded from the estimates presented here. For both species, hatch peaked during the first week in May (day 125 for RKC, day 126 for BKC), and the hatch distributions had a standard deviation of about 4 days. Average stage durations ranged from 10.5 to 12.1 days for RKC, and 10.5 to 16.3 days for BKC (although the last estimate had quite a large standard error). Total average zoeal duration (from hatch until molt to megalopa) was 47 days for RKC and 53 days for BKC. Instantaneous natural mortality rates were estimated as $Z=0.095 \cdot d^{-1}$ and $Z=0.075 \cdot d^{-1}$ for RKC and BKC, respectively, corresponding to average net survival from hatch to megalopa of 1.2% for RKC and 1.9% for BKC. These rates are, of course, subject to the assumption that there is no larval export from (or import to) inner Herendeen Bay.

Juveniles

Seventy-seven RKC, 7 BKC, and 39 Tanner crab were collected in trawl, dredge, and intertidal samples. Trawling for juvenile king crab was not as effective as had been expected, catching a total of only 4 king crab (3 red, 1 blue) and 36 Tanner crab. This is probably because the trawl is only effective on soft bottoms, while juvenile king crab are generally found in rock or shell habitats. The small rock dredge captured only three juvenile RKC and three Tanner crab. This low catch is not surprising considering the small size of the dredge used, which could sample very little habitat area. Surveys in low intertidal rocky areas found 70 RKC and 6 BKC. In addition, 102 carapaces of larger (90 to 125 mm CL) RKC were collected from high intertidal drift lines. No Tanner crab were found in intertidal samples.

Geographic Distribution and Abundance

All crab collected in trawl, dredge, and intertidal samples were found in Herendeen Bay; none were found in Port Moller. Of the 72 RKC found in intertidal surveys, 66 were located near Bold Bluff Point, 3 at Bluff Point, and 1 at Gull Island. All crab found in intertidal surveys were on rocky substrates. The trawl and dredge samples covered a variety of substrates. In these samples, most RKC (91%) occurred on rock/sand substrates with 3% on plain rock and 6% on mud mixed with shell or rock (Fig. 10); all BKC were collected from rock/sand substrates; and Tanner crab occurred on rock (55%), mud (41%), and gravel (4%) substrates, but not on sand (Fig. 11).

Size Composition

In the trawl, dredge, and intertidal samples, juvenile RKC ranged mainly from 5 to 30 mm CL with a few larger individuals; BKC ranged from 5 to 30 mm CL; and Tanners ranged from 12 to 131 mm CW (Figs. 12-14).

ADULTS

Geographic Distribution and Abundance

Unexpectedly high concentrations of adult RKC were encountered in Herendeen Bay. A total of 2,021 males and 1,137 females were caught by pots in Herendeen Bay, and 3 males were caught in Hague Channel. No king crab were caught in the 21 samples outside the estuary. Five BKC (4 male, 1 female) were also caught in Herendeen Bay. Most adult crab were caught in a relatively shallow (15- to 70-m) belt around Herendeen Bay, while three males were found in deeper (70- to 100-m) water. This contradicted initial expectations that adults would be in deeper water. There was also a remarkable pattern of spatial segregation of the sexes. Samples in the western portion of Herendeen Bay consisted almost entirely of females with a few small males, while samples to the east were largely males (Fig. 15).

Size Composition

Size distributions of the RKC are shown in Figures 16 and 17. Most males were of sub-legal size (below 137 mm CL). The size distribution of Tanner crab is shown in Figure 18.

Fecundity

A large proportion (84%) of the females caught were carrying eggs. The size at 50% ovigery for RKC was between 85 and 90 mm CL (Fig. 17). Total number of eggs estimated for RKC ranged from 15,000 to 130,000, with an average of 78,800 eggs (SD=27,100). Carapace length ranged from 84-129 mm ($\bar{X}$=101 mm, SD=10.1). The regression equation that describes the relationship of egg count to carapace length is

$$Y = 2170 \cdot X - 135{,}500,$$

which is statistically significant ($p<0.001$). (One outlier—a large female with very low egg count—was dropped from the regression).

Total number of eggs estimated for Tanner crab ranged from 39,000 to 400,000 with an average of 186,900 and a standard deviation of 76,900. Carapace width ranged from 77-110 mm with an average of 94 mm, and a standard deviation of 12.1. The regression equation that describes the relationship of egg count to carapace length is

$$Y = 4007 \cdot X - 190{,}300$$

which is significant ($p=0.004$).

DISCUSSION

LARVAE

The distribution of king crab larvae throughout the spring of 1990 indicates that most of the crab remain in inner Herendeen Bay. BKC larvae were only found in Herendeen Bay, and the distribution of RKC larvae decreased from high densities in inner Herendeen Bay to very low densities at the entrance of the PMC. Taken in conjunction with the observed concentration of ovigerous females in that area, this suggests that Herendeen Bay may be a king crab larval retention area. This is particularly likely for BKC, for which no nearby sources of larvae are known. We are pursuing use of the physical transport model developed by the herring project (Triton, Ltd., and Edinger Assoc.) to test hypotheses regarding king crab larval transport in and out of the estuary; this will help to clarify the relationship of the Herendeen Bay stock with Bristol Bay stocks. Initial results from this model (Edinger and Buchak 1991) indicate that while Herendeen Bay as a whole has a high flushing rate ($0.512 \cdot d^{-1}$), the rate for the inner part of the bay is quite low (ca. $0.016 \cdot d^{-1}$ for near-surface water). If larvae behave as passive, neutrally buoyant particles, this flushing rate can be interpreted as the instantaneous rate of larval emigration from the bay and can be used to correct the calculated natural mortality rates. Applying this correction to the zoeal mortality rates reported above, we obtain $Z=0.079 \cdot d^{-1}$ for RKC and $Z=0.059 \cdot d^{-1}$ for BKC, resulting in roughly double the net zoeal survival calculated without the correction.

The larvae existed primarily in the upper 40 m of the water column and exhibited a diel migration rising to the shallower waters during the night and descending to deeper waters during the day. Other studies from the Bristol Bay area have found similar diel migration of RKC and BKC larvae (McMurray et al. 1984, Armstrong et al. 1981, 1987). However, one study from Auke Bay, Alaska, found RKC larvae which exhibited a reverse diel migration, rising to the surface after sunrise and descending below 30 m after sunset (Shirley and Shirley 1989b).

Predictions from the larval model (Appendix A) indicate that king crabs in Herendeen Bay hatched most eggs over a 2-week period centered on 5 May (RKC) or 6 May (BKC). This is about the middle of the range of hatch times (early April to late May) estimated by Armstrong et al. (1981) for RKC in the SE Bering Sea. It is also in the middle of the range of peak ZI abundance reported by Shirley and Shirley (1989a) for Auke Bay sampling in 1985-1988. The king crab larvae in Herendeen Bay had completed zoeal development in less than two months, with zoeal durations ranging from 10.5 to 16 days per stage. These development rates are much faster than rates estimated by Armstrong et al. (1981) for the SE Bering Sea, and they are toward the fast end of the range of development times reported by Shirley and Shirley (1989a). This probably reflects the effect of relatively warm (4-7°C in May, 8-10°C in June) surface waters in Herendeen Bay during the larval period, but may also be influenced by food supply or other factors. RKC larval mortality rate ($Z=0.095 \cdot d^{-1}$) was considerably higher than the average rate ($0.045 \cdot d^{-1}$, based on 14-d stage duration and 53.6% average survival per stage) reported by the Shirleys for Auke Bay, although it was within their reported range of variation.

Larval abundance estimates could be affected by net performance problems, especially net avoidance or extrusion of larvae through the net mesh. Laboratory studies (T. Shirley, Univ. Alaska, pers. comm.) have shown that all king crab larval stages are fully retained by 505 μm mesh, so extrusion is not a problem in this study. Net avoidance could be a problem for which we have no reliable means of correction. Net avoidance can be estimated by three methods: comparing catch in paired day and night samples, comparing catch in nets of different mouth size, and by theoretical calculation from swimming speed and net performance characteristics. To our knowledge, there have been no studies of net avoidance for these species. In our own sampling, only one day-night series was completed within the larval season (Fig. 6); the resulting samples show no substantial difference between total numbers caught during day and night. No net comparison sampling was completed during the larval season. While we have no reliable net performance data to use in theoretical calculations of net avoidance, the slow swimming speeds of king crab larvae (maximum of about 2 cm s^{-1}, Shirley and Shirley 1988) suggest a very limited ability to escape nets.

JUVENILES

Few conclusions can be reached from the limited samples of juveniles obtained during field work. Early juvenile king crab were primarily found in rocky habitats, which is consistent with previous descriptions of habitat requirements for the two species. These rocky habitats occur primarily in inner Herendeen Bay on steep slopes. We were unable to assess the subtidal extent of this habitat within the estuary.

The size distribution of early juvenile RKC in 1990 is quite similar to that observed in 1989 (Armstrong et al. 1990). Two size modes are apparent, one between 5 and 10 mm CL, the other between 20 and 30 mm CL. These probably represent 1- and 2-year-old crab, respectively. If these ages are correct, this indicates growth of 15-20 mm during the second year of life.

ADULTS

The presence of a fairly large, reproductive stock of RKC in Herendeen Bay was unexpected. The questions of origin of these crab, and of their relation to Bristol Bay stocks, remain unanswered. Some information may come from ADFG's electrophoresis work and from larval data analysis, particularly from application of the circulation model being developed by Triton, Ltd., and J.E. Edinger Associates.

The size at 50% ovigery is very close to that found during NMFS Bristol Bay surveys in 1990, as was the percent of females with eggs above that size (B. Stevens, NMFS, Kodiak, Alaska, pers. comm.). Comparison of the RKC fecundity estimates with findings reported by other investigators indicates that the total number of eggs estimated in this study appears to be smaller than previous reports by Nakazawa (1912), Marukawa (1933), Wallace et al. (1949), Rodin (1970), Fukuhara (1985), and Haynes (1968) (Table 5). Our small sample size precludes any conclusion on the causes for this difference. As with our results, Sasakawa (1975, BKC), Haynes (1968), and Wallace et al. (1949) reported a high variability in fecundity estimates, which they attribute to the reproductive stage of the female (primiparous or multiparous) and the age of clutch of each female when collected. Kawasaki (1972), Matsuura and Takeshita (1985), and Takeshita et al. (1972) have shown that egg numbers are also related to the age of the female and the developmental stage of the clutch. Otto et al. (1982), Sasakawa (1975), and Somerton and MacIntosh (1985, BKC) all describe a positive curvilinear function between egg number and carapace length, although only Somerton and MacIntosh (1985) state a statistical significance for their findings. The linear regression equation stated by Haynes (1968) is listed in Table 6 and is similar to our equation in both slope and intercept. Kawasaki (1972) reported both a rectilinear and curvilinear relationship for egg number to crab size and age respectively.

Number of eggs and carapace width estimates for Tanner crab appear to be very similar to that reported by Hilsinger (1976), Somerton and Meyers (1983), and Paul (1982) (Table 7). Again, variability was high in both our findings and all other studies, which the above authors attributed to female mating stage and brooding time. A positive curvilinear relationship between number of eggs and carapace width was described by Somerton and Meyers (1983), Hilsinger (1976), and Paul (1982). Linear regression equations for summer and spring sampling reported by Hilsinger (1976) are listed in Table 8 and are comparable to our equation.

From larval dynamics and adult fecundity estimates, we can make a rough calculation of spawning stock size using a larval production method (Nichols et al. 1987). The only substantial larval densities were found in the Portage Creek arm of Herendeen Bay. If we assume that this area contains all the king crab larvae hatched in the bay, then the output of the larval dynamic model can be used to calculate numbers of eggs hatched, and fecundity data may be used to calculate approximate number of spawning females. For RKC, the model predicted a mean hatching density of about 5.01×10^5 ha^{-1} of surface area. The area of Portage Creek arm (using a line from Shingle Pt. to Bold Bluff Pt. as the outer limit) is about 2,540 ha, so total estimated hatch is 1.27 x 10^9 eggs. The average fecundity from our sampling was 7.88 x 10^4 eggs per female, so we estimate a total of about 16,000 spawning females in Herendeen Bay. A similar calculation for BKC can be made, although we have no direct fecundity information for that species. Calculated egg density is 5.4 x 10^4 ha^{-1}, and total hatch is 1.37 x 10^8 eggs. Applying Sasakawa's (1975) estimate of average fecundity for the species (120,000), total number of spawning females is expected to be about 1,100. In other areas, BKC have been found to spawn biennially, so the total adult female population would be twice this number.

The estimates above depend on several assumptions, including no emigration of larvae, uniform larval densities throughout the area, and application of June fecundity measurements (or measurements from the literature) to the May hatch (i.e., that fecundity is relatively constant from year to year). Planned work with circulation modeling should provide insight into the first two assumptions.

GENERAL

The discovery of reproductive stocks of red and blue (as evidenced by the presence of larvae and juveniles) king crab in Herendeen Bay was unexpected. The suggestion that this may be a larval retention area is important because these stocks may be isolated from other stocks of the two species, and thus may be insulated from environmental impacts to stocks along the North Aleutian Shelf and elsewhere. Significant questions remain about the size and reproductive potential of these stocks, and about their relationship with stocks outside the estuary.

APPLICATION OF STUDY TO ENVIRONMENTAL ASSESSMENT

This report provides basic biological information about crab stocks in Herendeen Bay that could be used in a variety of environmental assessments. Problems that could impact local crab stocks include potential oil and gas development, fishing vessel and fish processor pollution, coastal development (breakwaters, dredge and fill, etc.), major fishing efforts, and regional climatic change.

As an example, potential oil impacts on king crab stocks in Herendeen Bay could come from two sources: (1) from a drilling rig or tanker accident in Bristol Bay with the resulting slick being transported into the PMC by currents and tides, and (2) from localized spills from an oil transshipment facility located inside the complex. In either case, surface slicks would have an obvious detrimental impact to young juveniles living in the rocky intertidal/shallow subtidal zone, and this habitat could be fouled for many years. Additionally, larvae would be affected if concentrations of water-soluble petroleum hydrocarbons are substantial, and some larval stages (especially megalopae) could suffer direct exposure to surface slicks during near-surface periods of their diel migration. Subtidal juvenile and adult king and Tanner crabs could be at risk if a significant portion of the oil sinks to subtidal sediments. Reproductive potential could be especially affected, both through direct exposure of extruded egg masses to benthic oil and through concentration of ingested hydrocarbons in lipid-rich developing eggs. Both juveniles and adults could also suffer impairment of foraging success because oil can disrupt detection of food (Hyland and Miller 1979) and pollutants may adversely affect the molting process (Peddicord and McFarland 1976). Indeed, populations of the fiddler crab, *Uca pugnax*, suffered population declines due to oil sediments following the 1969 West Falmouth oil spill (Krebs and Burns 1977).

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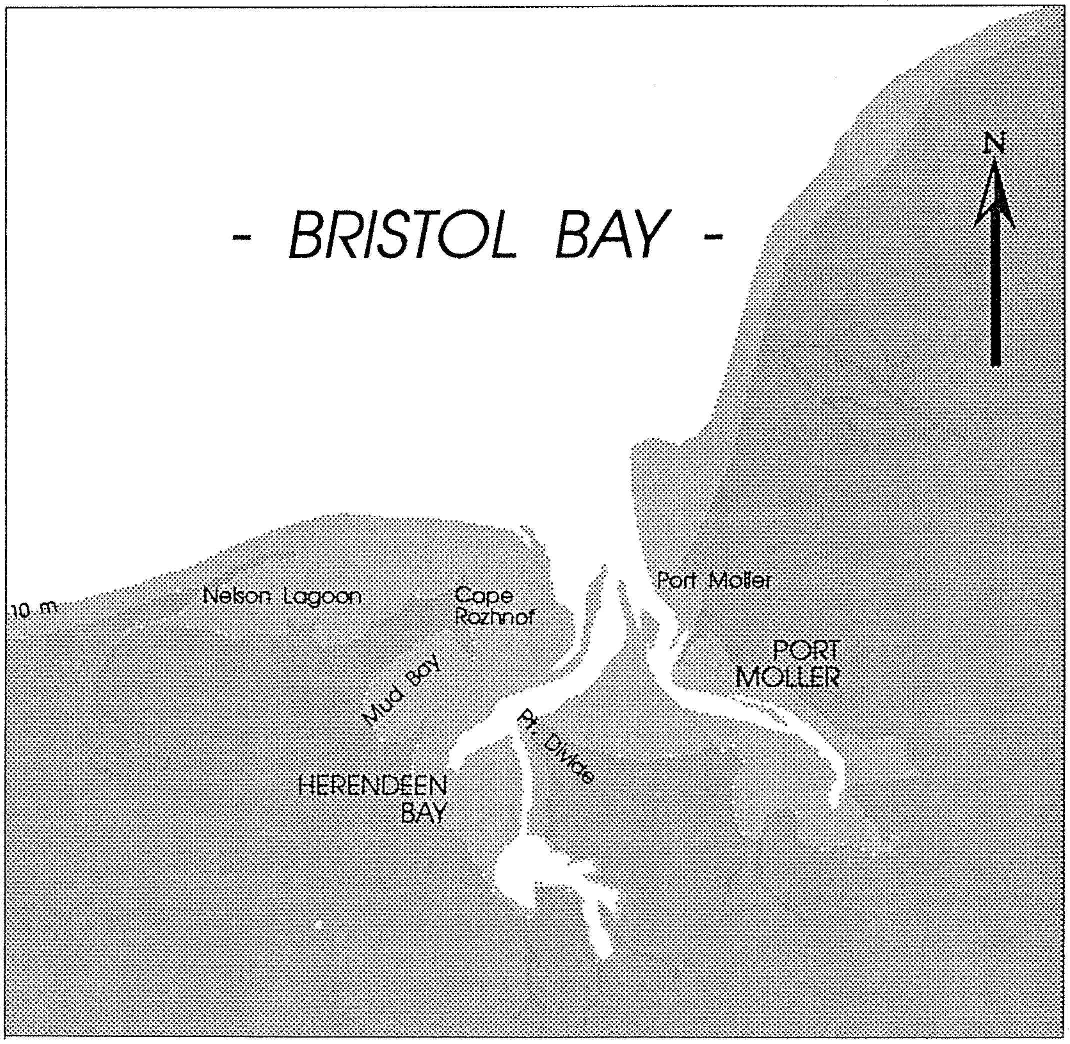

Figure 1. Chart of southern Bristol Bay showing Port Moller and Herendeen Bay. Dark shading—land; light shading—shallow water (<10 m); white—deep water.

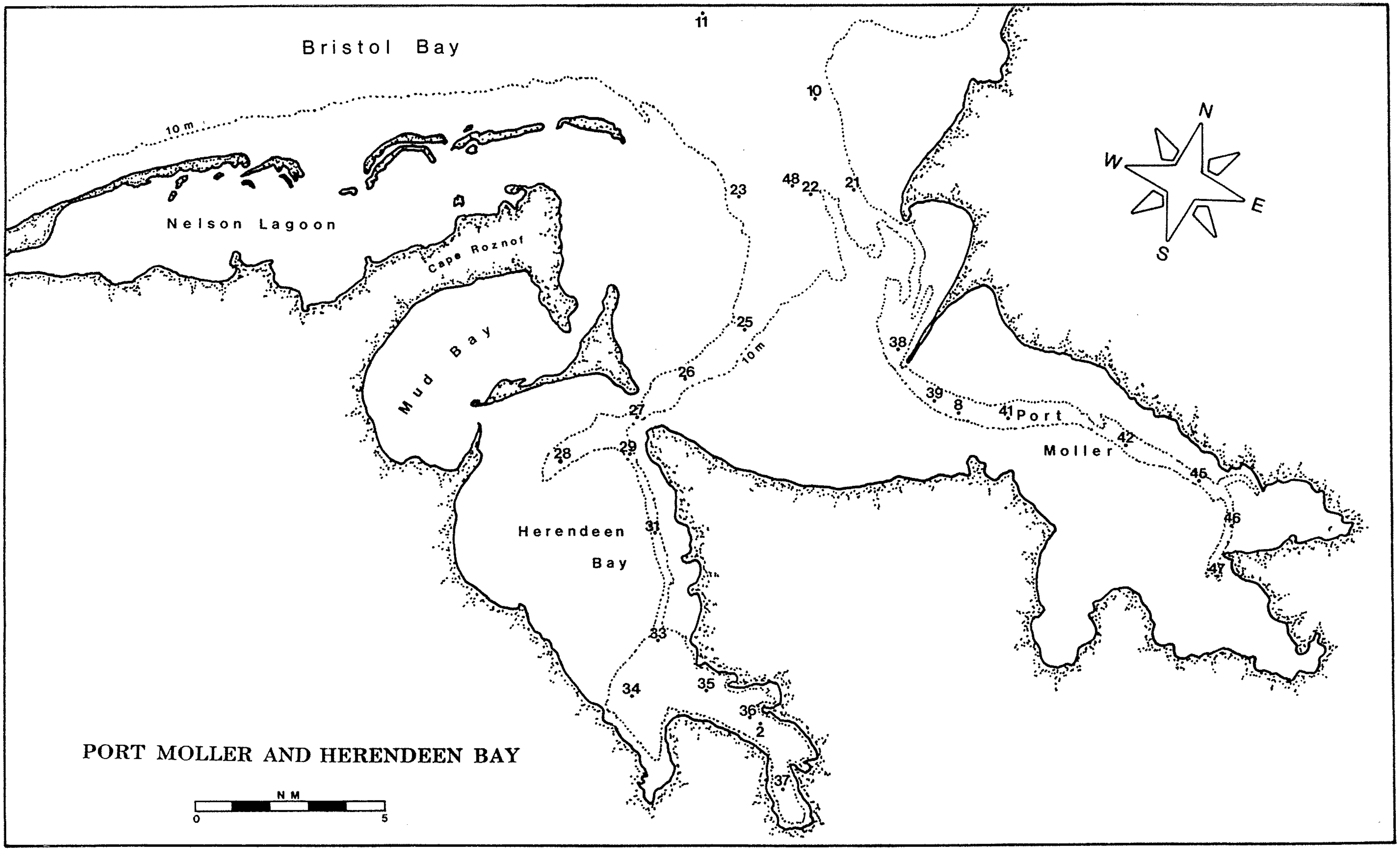

Figure 2. Locations of larval survey stations.

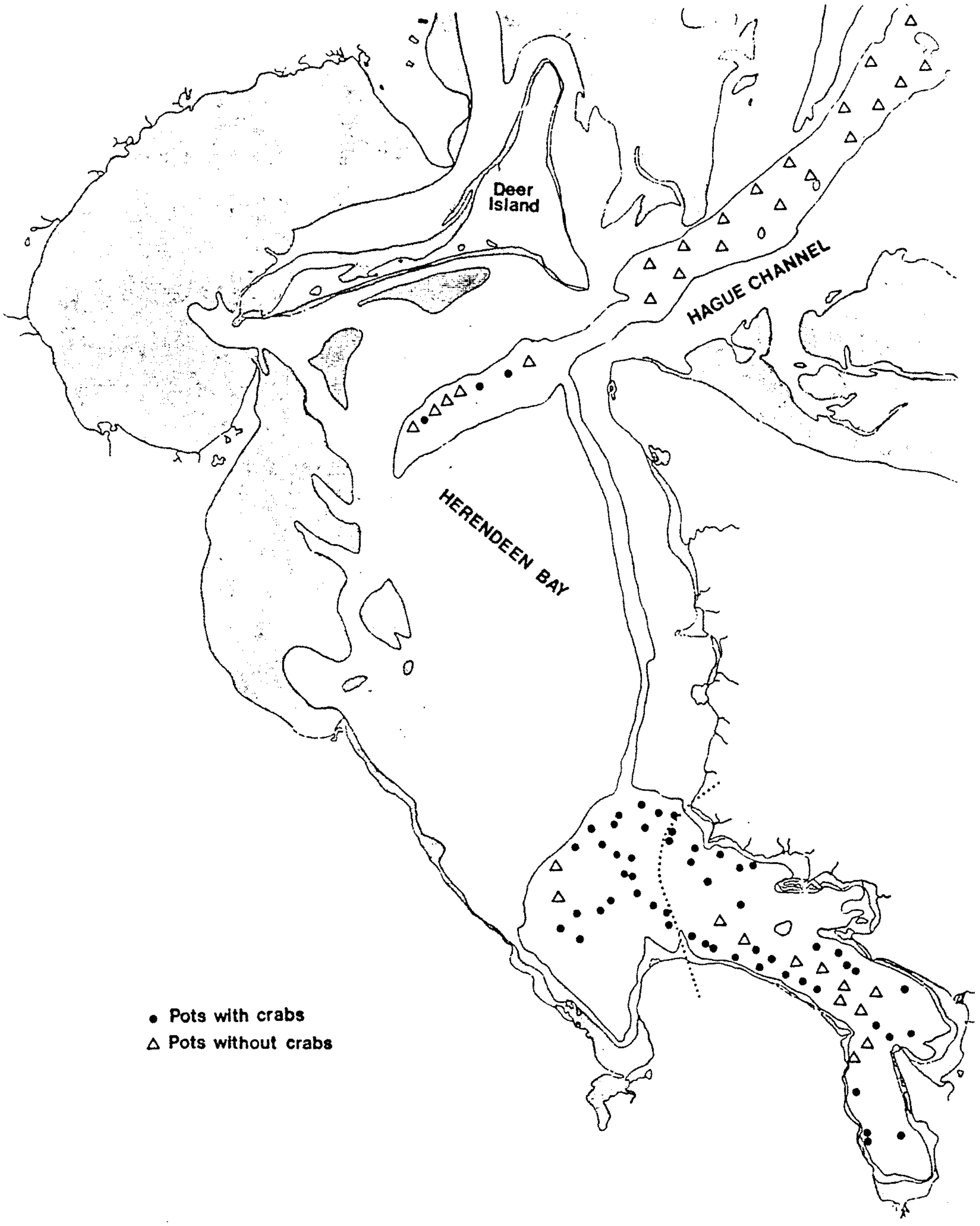

Figure 3. Locations of king crab pot samples in Herendeen Bay and Hague Channel. Dots—pots with king crab; triangles—pots with no king crab. The dotted line divides female-dominated (west) and male-dominated (east) areas.

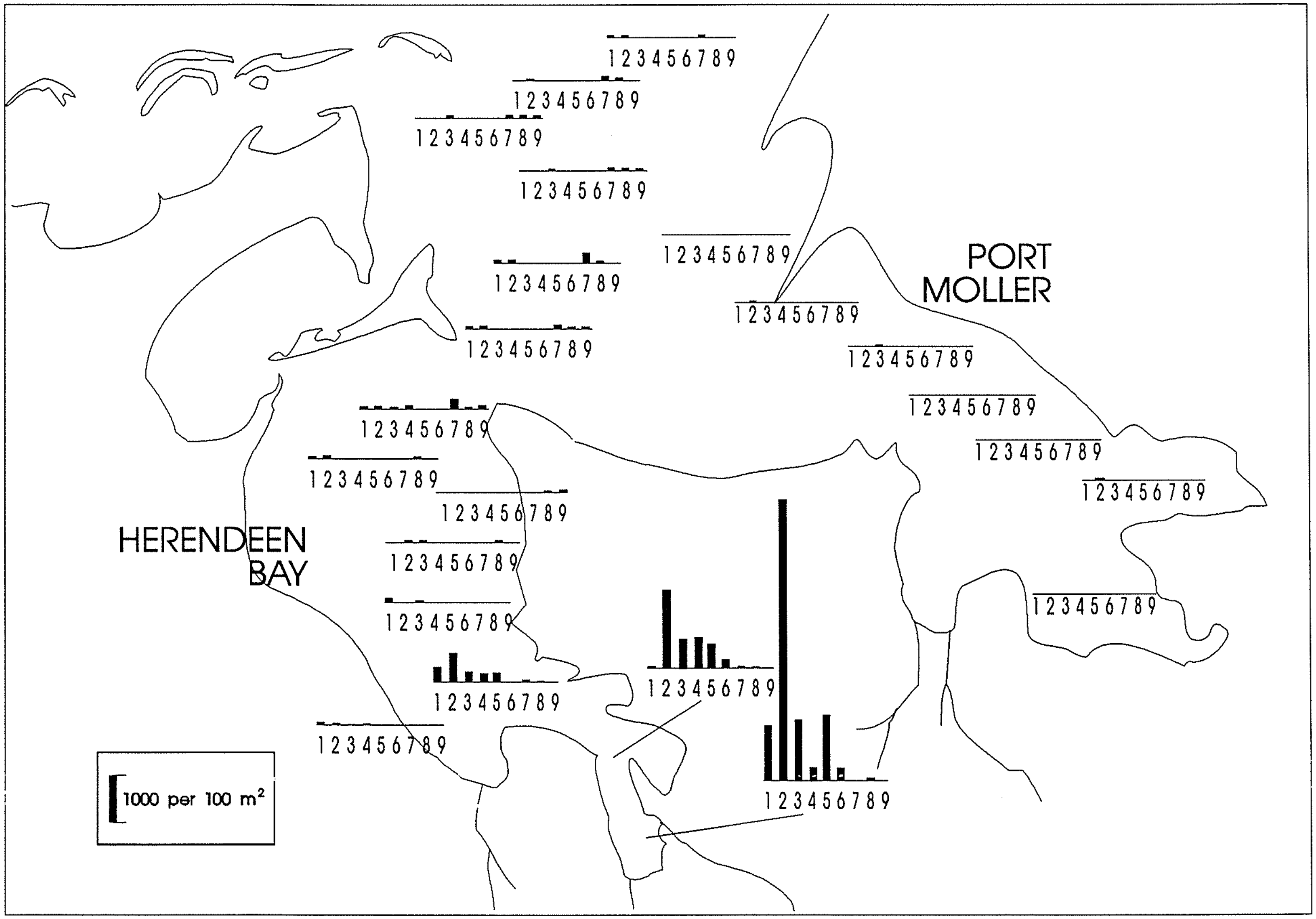

Figure 4. Red king crab larval abundance by week and sample location. Weeks are numbered consecutively from 1 May 1990.

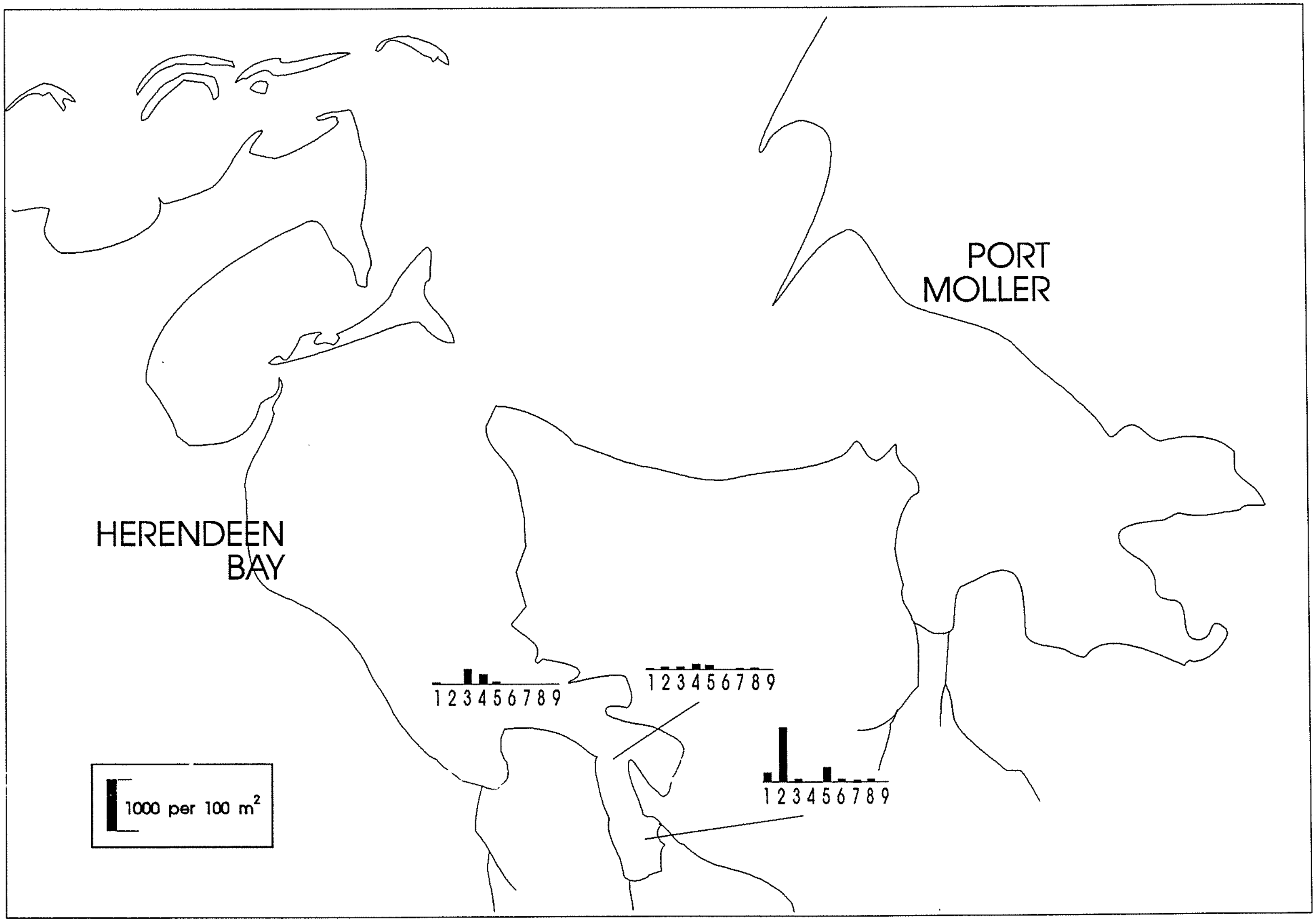

Figure 5. Blue king crab larval abundance by week and sample location. Weeks are numbered consecutively from 1 May 1990.

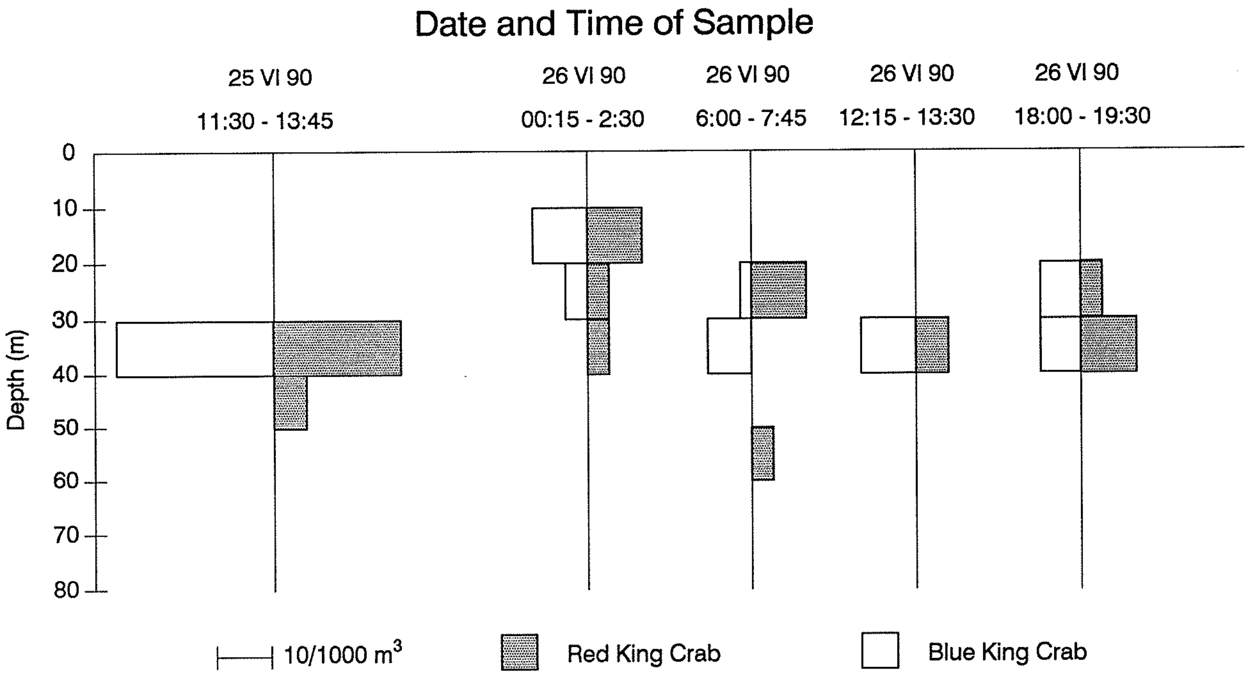

Figure 6. Diurnal depth distributions of king crab larvae at Station 36, 25-26 June 1990.

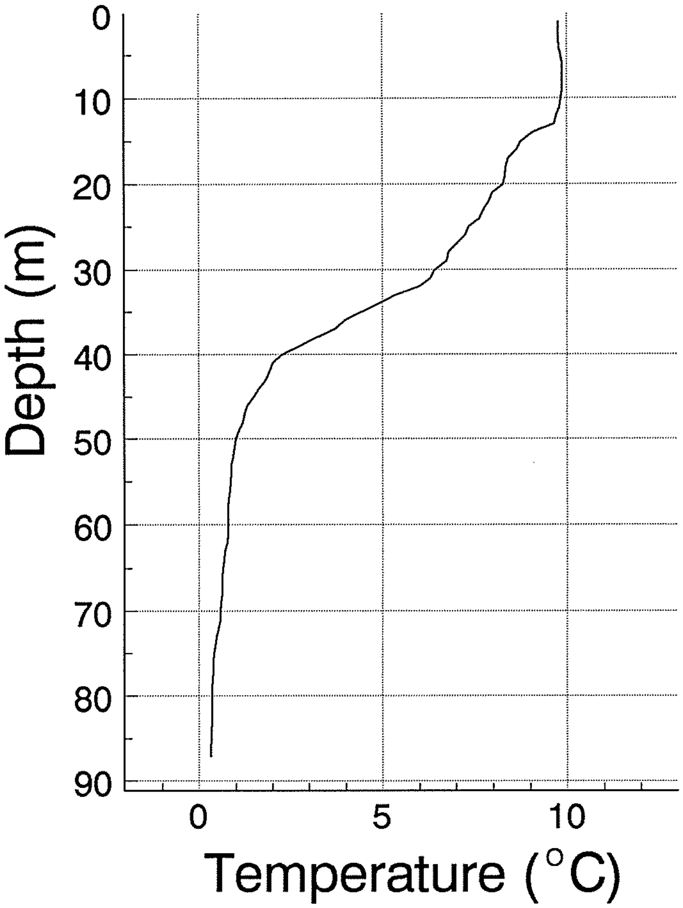

Figure 7. Temperature profile at Station 36, 26 June 1990.

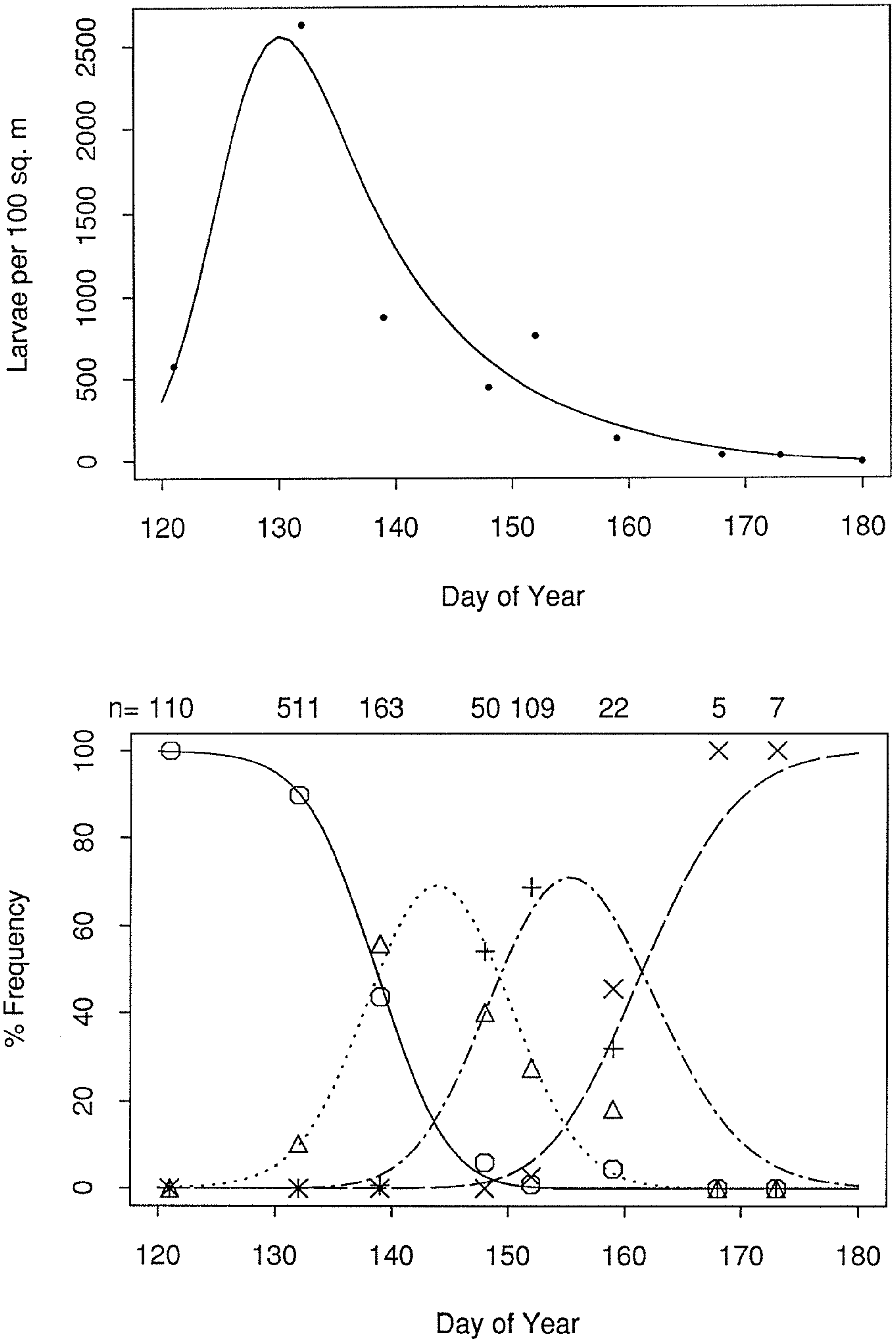

Figure 8. Temporal pattern of red king crab zoeal density, average for stations 35, 36, and 37. Upper: total zoeal density (No. per 100 m^2), predicted (line) and observed (dots). Lower: percent frequency by stage, predicted (lines) and observed (symbols); "n" is the total number of larvae captured on each sample day. Stages are Z1 (solid line, octagon), Z2, (dotted line, triangle), Z3 (dot-dash line, "+"), Z4 (dashed line, "x").

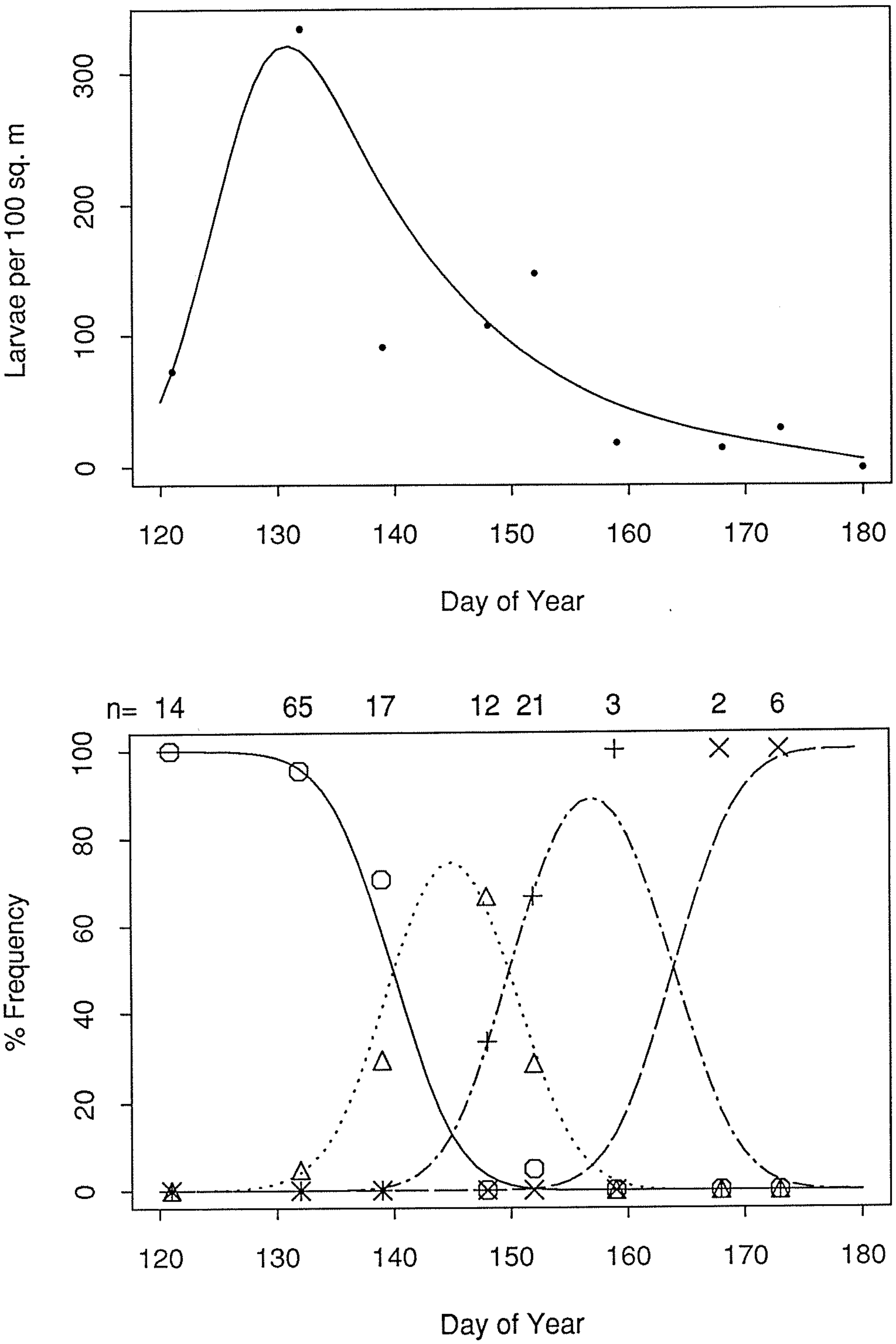

Figure 9. Temporal pattern of blue king crab zoeal density, average for stations 35, 36, and 37. Upper: total zoeal density (No. per 100 m^2), predicted (line) and observed (dots). Lower: percent frequency by stage, predicted (lines) and observed (symbols); "n" is the total number of larvae captured on each sample day. Stages are Z1 (solid line, octagon), Z2, (dotted line, triangle), Z3 (dot-dash line, "+"), Z4 (dashed line, "x").

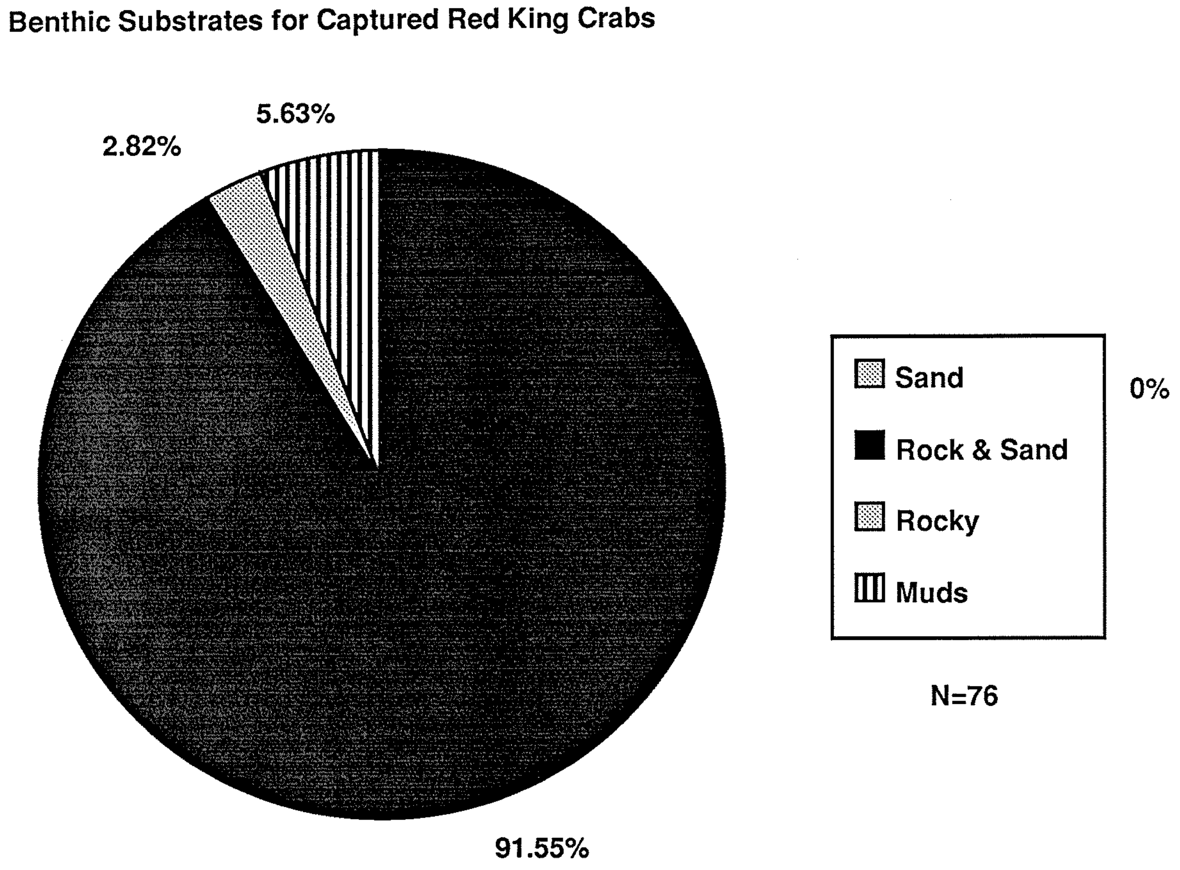

Figure 10. Frequency of benthic substrates where red king crab were caught in trawl and dredge samples.

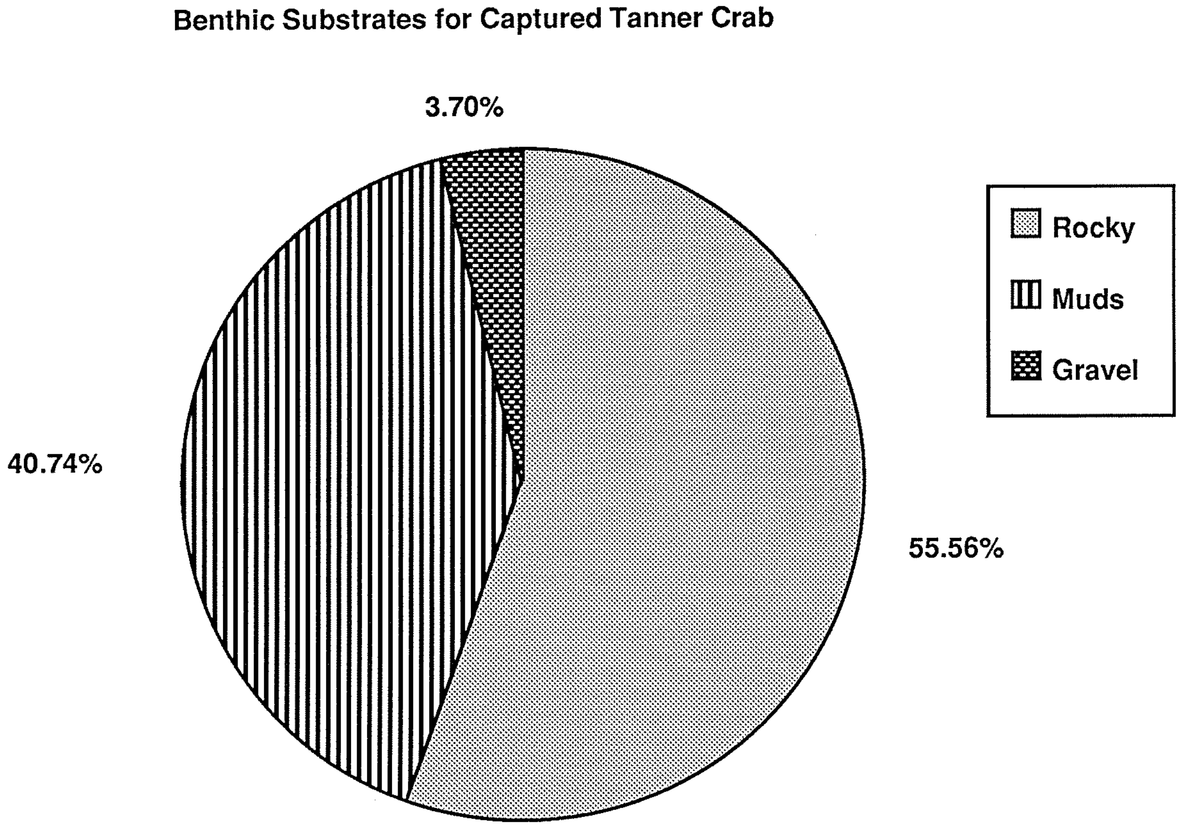

Figure 11. Frequency of benthic substrates where Tanner crab were caught in trawl and dredge samples.

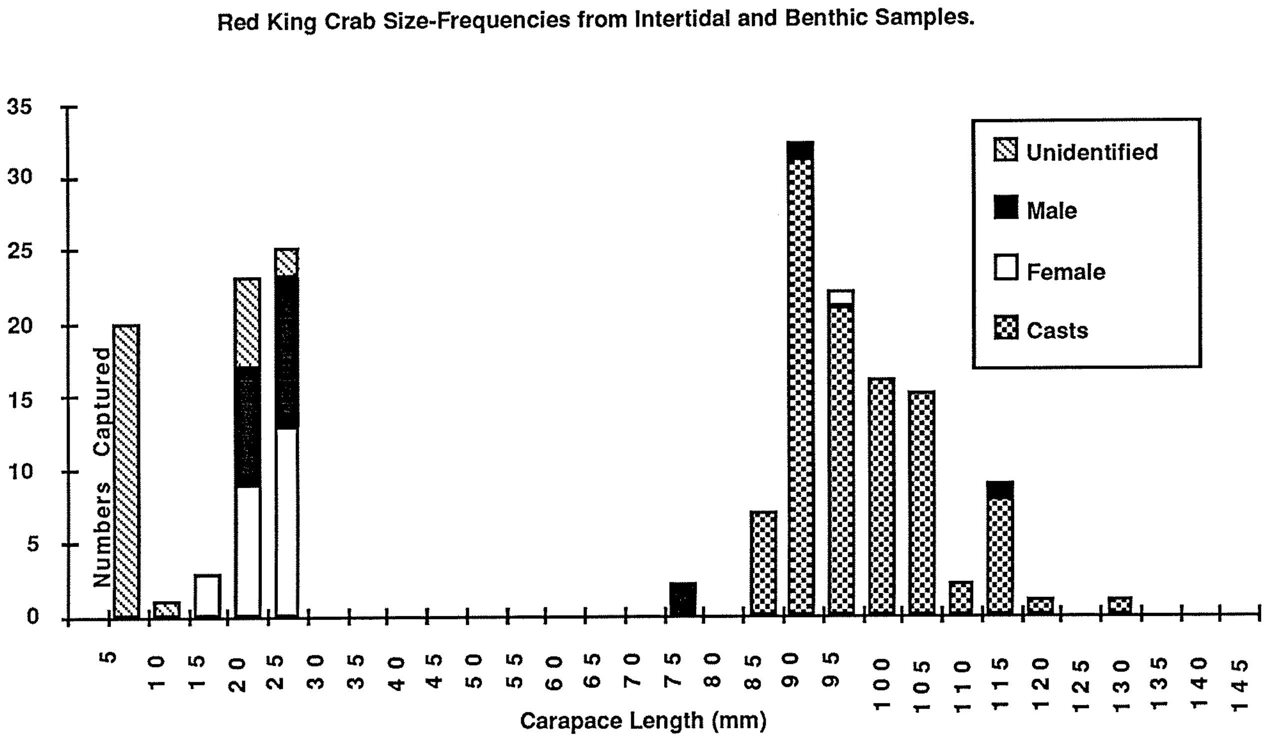

Figure 12. Size distributions of red king crab caught in trawl, dredge, and intertidal samples.

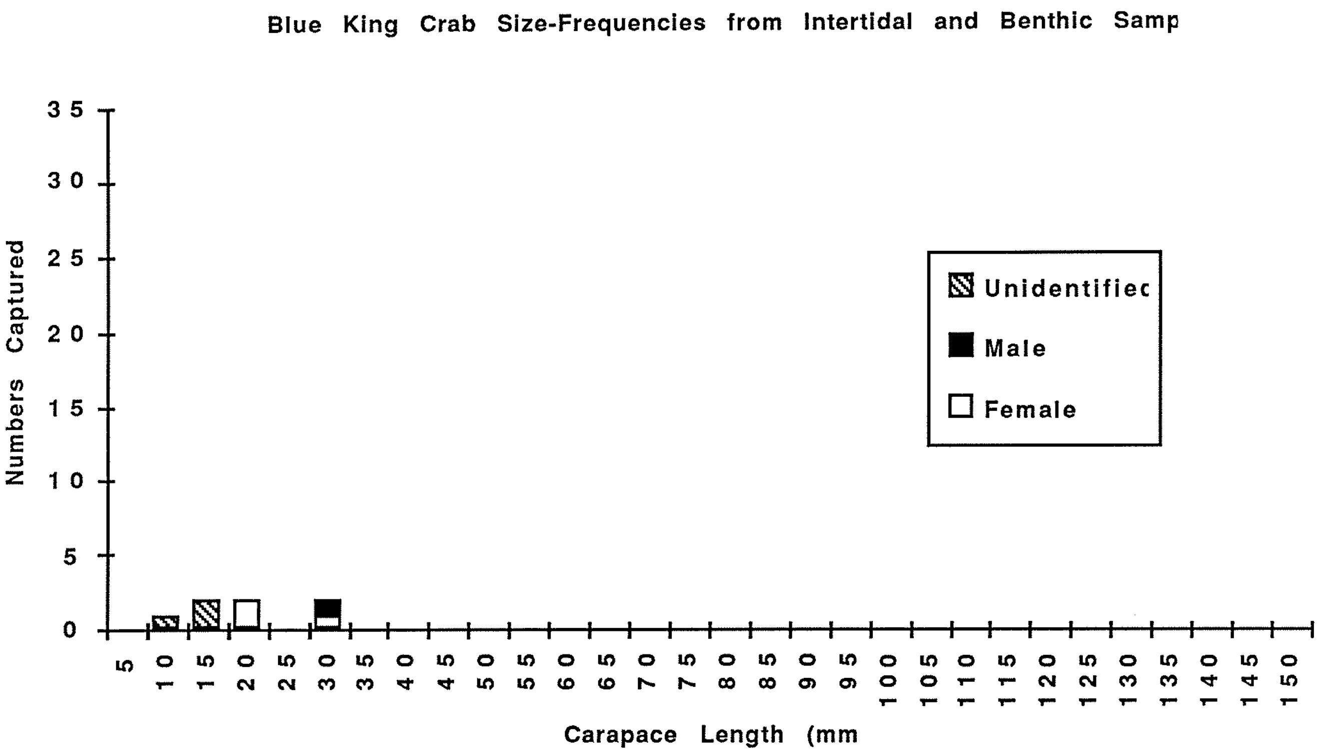

Figure 13. Size distributions of blue king crab caught in trawl, dredge, and intertidal samples.

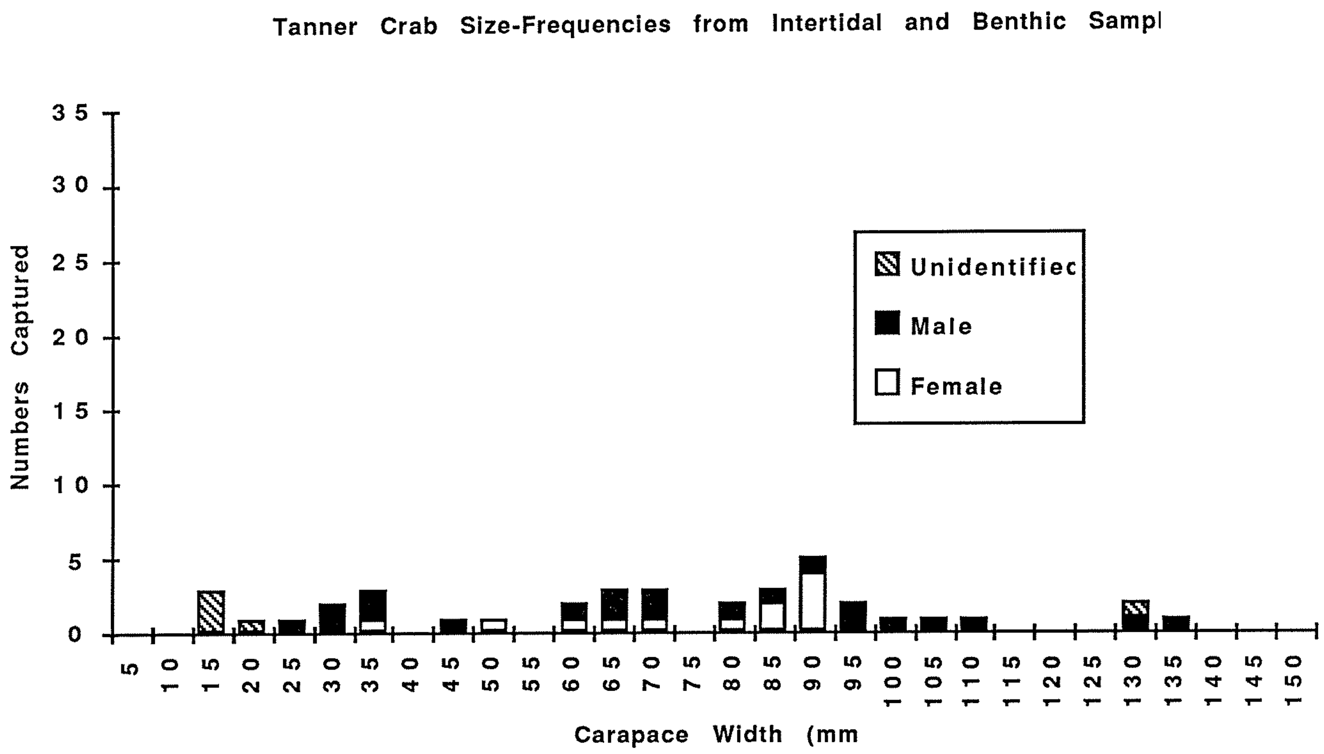

Figure 14. Size distributions of Tanner crab caught in trawl and dredge samples.

Figure 15. Sex composition of adult red king crab caught in pots, over 1 x 1/2 minute grid cells. Bars represent total numbers caught by all pots in that grid cell.

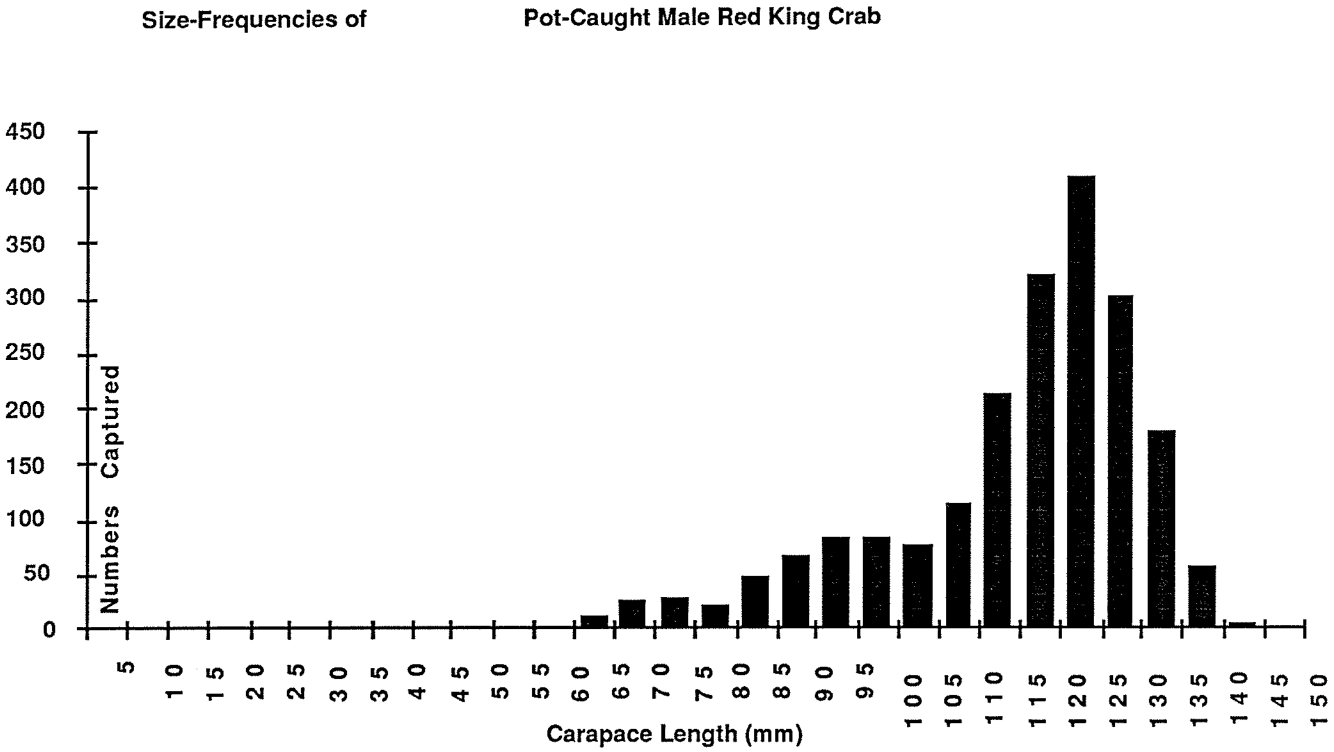

Figure 16. Size distributions of adult male red king crab caught in crab pots.

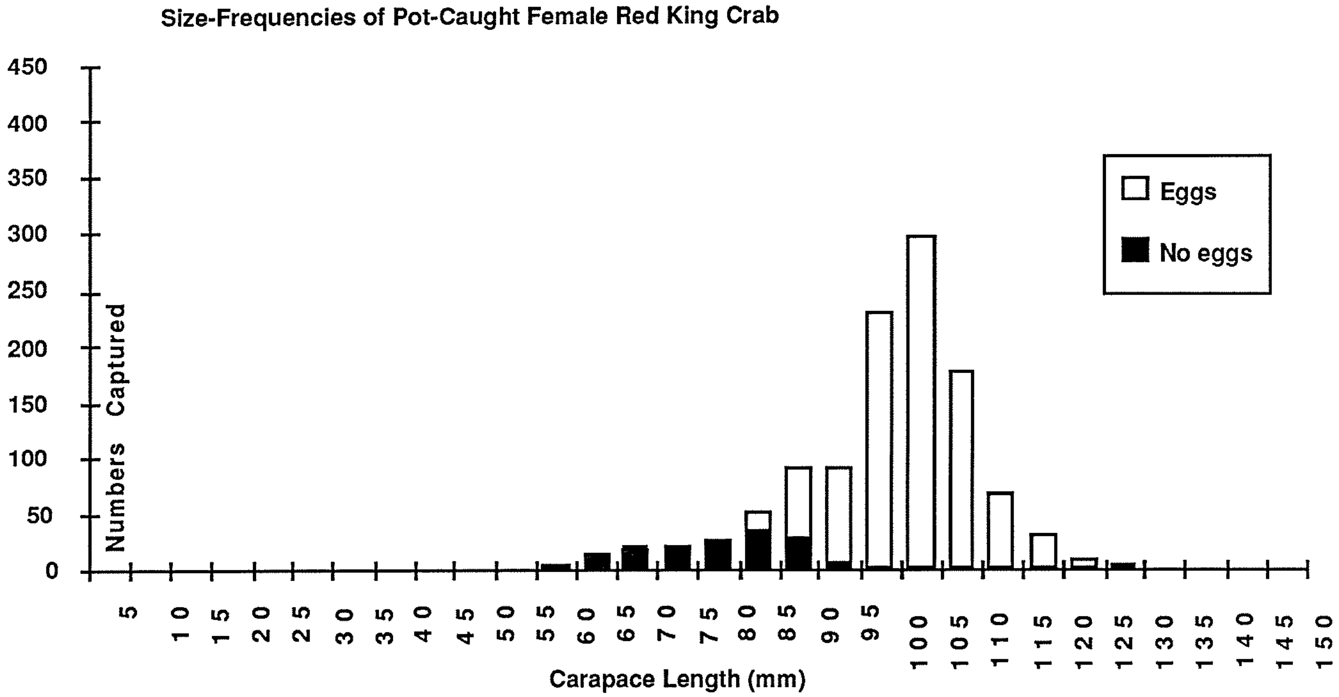

Figure 17. Size distributions of adult female red king crab caught in crab pots.

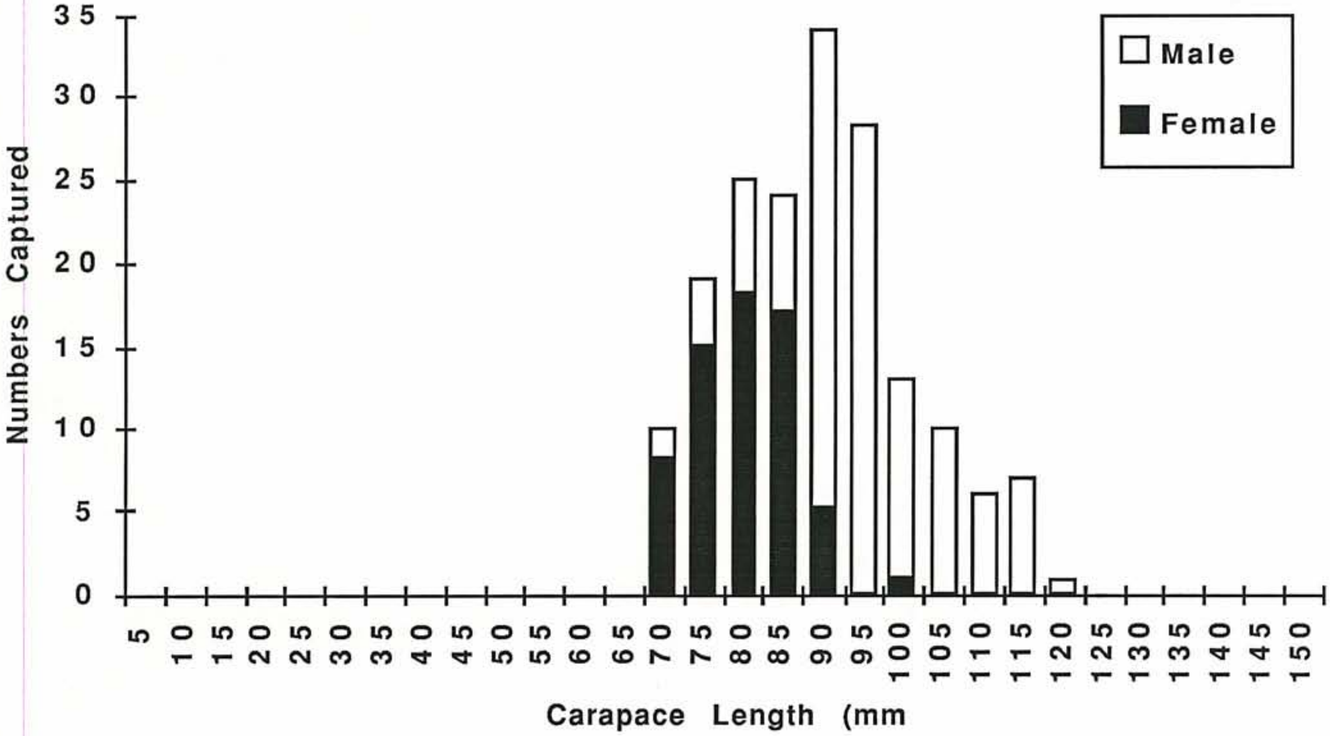

Figure 18. Size distributions of adult Tanner crab caught in crab pots.

Table 1. Larval sampling stations.

Station	N. Latitude		W. Longitude	
2	55°	44.7'	160°	42.0'
3	55	46.2	110	46.9
7	55	55.4	160	43.4
8	55	53.1	160	32.7
9	55	57.1	160	40.8
10	56	1.6	160	40.0
11	56	4.4	160	44.4
12	55	52.2	160	22.6
21	55	59.1	160	36.4
22	55	59.1	160	39.1
23	55	59.1	160	42.6
25	55	57.1	160	40.6
26	55	55.3	160	43.6
27	55	53.4	160	48.1
28	55	52.3	160	51.8
29	55	51.2	160	47.6
31	55	49.1	160	46.9
33	55	46.9	160	47.2
34	55	44.8	160	47.8
35	55	45.6	160	44.7
36	55	44.7	160	42.0
37	55	42.9	160	41.4
38	55	56.0	160	35.2
39	55	53.6	160	32.6
41	55	53.4	160	28.4
42	55	52.7	160	24.4
45	55	51.8	160	21.8
46	55	50.0	160	19.4
47	55	48.2	160	18.5
48	56	0.7	160	39.0
49	56	1.9	160	42.3

Table 2. Benthic and intertidal samples collected. HB = Herendeen Bay, HC = Hague Channel, PM = Port Moller

			Location				
Gear Type	Sample	Date	N Lat.		W Long.		Description
Beam Trawl	1	10-Jun-90	55°	51.7'	160°	21.9'	
	2	10-Jun-90	55	53.5	160	28.5	
	3	10-Jun-90	55	56.0	160	35.2	
	4	11-Jun-90	55	53.2	160	53.3	HC, E end
	5	11-Jun-90	55	46.8	160	47.5	HB, Deer Valley Arm
	6	11-Jun-90	55	46.8	160	47.5	HB, Bold Bluff Pt.
	7	11-Jun-90	55	45.4	160	43.7	HB, Crow Pt.
	8	11-Jun-90	55	44.7	160	42.3	HB, Off Crow Pt.
	9	11-Jun-90	55	43.4	160	41.3	HB, Off Gull Pt.
	10	12-Jun-90	55	43.0	160	41.8	HB, Portage Ck. Arm
	11	12-Jun-90	55	43.5	160	40.9	HB, Gull Pt.
	12	12-Jun-90	55	45.2	160	42.0	HB, Crow Pt.
	13	12-Jun-90	55	46.0	160	43.3	HB, S side Bluff Pt.
	14	12-Jun-90	55	45.3	160	45.4	HB, Bold Bluff Pt.
	15	17-Jun-90	55	43.5	160	40.9	
	16	24-Jun-90	55	43.9	160	40.5	HB, N of Gull Pt.
	17	24-Jun-90	55	42.3	160	41.1	
	18	24-Jun-90	55	45.2	160	45.5	HB, Bold Bluff Pt.
	19	16-Jul-90	55	56.9	160	34.2	PM, N of Harbor Spit
	20	16-Jul-90	55	57.9	160	34.4	PM, N of Harbor Spit
	21	16-Jul-90	55	55.1	160	35.6	PM, N of Harbor Spit
	22	16-Jul-90	55	51.6	160	22.3	
	23	16-Jul-90	55	53.4	160	29.6	
	24	16-Jul-90	55	53.2	160	29.7	
	25	16-Jul-90	55	53.3	160	28.9	
	26	16-Jul-90	55	53.3	160	31.0	
Otter Trawl	1	11-Jun-90	55	45.8	160	42.5	HB, Mine Harbor
Rock Dredge	1	17-Jun-90	55	46.0	160	43.2	HB, S of Bluff Pt.
	2	23-Jun-90	55	45.1	160	42.4	
	3	23-Jun-90	55	45.2	160	42.6	
	4	23-Jun-90	55	44.6	160	43.1	
	5	23-Jun-90	55	44.6	160	43.3	
	6	23-Jun-90	55	43.6	160	42.4	
	7	24-Jun-90	55	43.9	160	40.6	HB
	8	24-Jun-90	55	44.2	160	41.5	HB, Gull Pt.
	9	24-Jul-90	55	42.4	160	42.2	
	10	24-Jul-90	55	42.4	160	42.0	
	11	24-Jul-90	55	43.3	160	42.4	
	12	24-Jul-90	55	43.6	160	42.4	
Intertidal	1	11-Jun-90	55	46.3	160	43.7	HB, Bluff Pt.
	2	12-Jun-90	55	45.5	160	46.2	HB, Bold Bluff Pt.
	2.5	20-Jun-90	55	46.3	160	43.7	HB, Bluff Pt.
	3	21-Jun-90	55	45.5	160	46.2	HB, Bold Bluff Pt.
	4	21-Jun-90	55	45.5	160	46.2	HB, Bold Bluff Pt.
	5	21-Jun-90	55	45.5	160	46.2	HB, Bold Bluff Pt.
	6	22-Jun-90	55	45.5	160	46.2	HB, Bold Bluff Pt.
	7	23-Jun-90	55	41.6	160	45.7	HB, Gull Isl.
	8	25-Jun-90	55	44.0	160	40.8	HB, Gull Pt.

Table 3. Biological parameters of the larval cohort model.

Parameter	Definition
N_0	Number hatched
μ	Mean hatch time (day of year)
σ	Standard deviation of hatch time (days)
D_1	Stage duration, 1st Zoea (days)
D_2	Stage duration, 2nd Zoea
D_3	Stage duration, 3rd Zoea
D_4	Stage duration, 4th Zoea
CV	Coefficient of variation for durations
Z	Instantaneous mortality rate (per day)

Table 4. Estimates of biological parameters of the dynamic cohort model.

		RKC		BKC	
Parameter	Units	Value	S.E.	Value	S.E.
N_0	per 100 m^2	5009	161	540	40
μ	d	125	<0.01	126	0.02
σ	d	4.11	0.31	4.40	0.51
D_1	d	12.0	0.4	12.2	0.9
D_2	d	10.5	0.6	10.5	1.4
D_3	d	12.1	1.1	14.2	2.5
D_4	d	12.0	1.9	16.3	3.5
CV	%	22.1	3.8	24.7	7.6
Z	d^{-1}	0.095	0.002	0.075	0.004

Table 5. Fecundity estimates for red king crab.

		Carapace width (mm)			Car. length (mm)			Total No. of eggs			Study
Author	N	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD	area
Present study	25	108	92-131	9.15	101	84-129	10.1	78,367	15,000-130,000	27,094	Herendeen Bay
Nakazawa (1912)*			127-169						62,550-345,900		Hokkaido
Marukawa (1933)*			115-168						69,598-270,204		Hokkaido
Wallace et al. (1949)						128-145			148,349-446,639		Canoe Bay
Rodin (1970)*			94-171						55,408-444,651		Bristol Bay
Fukuhara (1985)	89		40-159						70,000-280,000		SE Bering Sea
Haynes (1968)**						98-175			77,000-333,000		Cook Inlet

*Cited in Fukuhara (1985).

**Calculated from regression equation.

Table 6. Size-fecundity regression equations for red king crab.

Author	Area	Equation	N	P
Present Study	Herendeen Bay	$Y = 2170X - 135,500$	24	<0.001
Haynes (1968)	Cook Inlet	$Y = 3,319X - 247,400$	90	
Kawasaki (1972)	Kamchatka	$Y = 2.3468X - 170$		

Table 7. Fecundity estimates for Tanner crab.

		Carapace width (mm)			Total No. of eggs			
Author	N	Mean	Range	SD	Mean	Range	SD	Area
Present Study	23	94.12	77-110	12.13	186,900	39,000- 400,000	76,900	Herendeen Bay
Hilsinger (1976) (summer)			79-115			24,000- 318,000		Prince William Sound & Gulf of Alaska
Hilsinger (1976) (spring)			87-110			34,000- 317,000		
Somerton et al. (1983) (primiparous)			73-101			50,000- 180,000		Pribilof Islands
Somerton et al. (1983) (multiparous)			65-110			40,000 350,000		
Paul (1982)	222		80-120			150,000- 350,000		

Table 8. Size-fecundity regression equations for Tanner crab.

Author	Area	Equation	N	P (slope only)
Present study	Herendeen Bay	$Y = 7.43X - 190{,}300$	23	0.0045
Hilsinger (1976)	Prince William Sound	$Y = 4610X - 275{,}800$		Significant between the two
		$Y = 2347X - 95{,}100$		

APPENDIX A: LARVAL DEVELOPMENT MODEL

The larval cohort model used is similar to the Manly (1974) larval insect model and the "lag-Manly" model used by Parslow and colleagues (Parslow et al. 1979; Sonntag and Parslow 1981) for copepod populations. The model follows the dynamics of a cohort from hatch through several larval stages, accounting for mortality, variation in hatch time among individuals, and variation in development rates among individuals. The model as applied has two components: a biological model, and a sampling model relating the biological model to observations.

BIOLOGICAL MODEL

The biological model makes the following assumptions:

1. Mortality is constant, equal for all stages, and independent of growth.
2. Development rate for an individual is constant in time and space.
3. The population is closed (specifically no advection or diffusion).
4. Individual differences in hatch time and development rate are normally distributed.
5. The population is sufficiently large that stochasticities average out.

Thus, we can define the following:

J = No. of larval stages
τ_j = time of transition from stage j to j+1 (τ_0 is hatch time)
$f_j(t)$ = probability density function (pdf) of τ_j
$F_j(t)$ = cumulative density function (cdf) of τ_j

Then, with no mortality, the population can be described as a renewal process (Cox 1962). The expected proportion of individuals in stage j at time t is

$$\bar{q}_j(t) = F_{j-1}(t) - F_j(t)$$

or, conditioning on τ_0

$$\bar{q}_j(t|\tau_0) = F_{j-1}(t|\tau_0) - F_j(t|\tau_0).$$

Adding simple exponential mortality from hatch, we define the probability that an individual is alive at time t, given τ_0, as

$$\bar{s}(t|\tau_0) = e^{-z\cdot(t-\tau_0)}.$$

The total expected proportion of individuals alive and in stage j at time t, conditional on τ_0 is

$$\bar{p}_j(t|\tau_0) = \bar{q}_j(t|\tau_0)\cdot\bar{s}(t|\tau_0).$$

For a cohort with varying individual hatch times, the total expected proportion of individuals alive and in stage j at time t is

$$\bar{p}_j(t) = \int_{-\infty}^{\infty} f_0(\tau_0) \cdot \bar{q}_j(t|\tau_0) \cdot \bar{s}(t|\tau_0) \cdot d\tau_0$$

$$= \int_{-\infty}^{\infty} f_0(\tau_0) \cdot [F_{j-1}(t|\tau_0) - F_j(t|\tau_0)] \cdot e^{-z\cdot(t-\tau_0)} \cdot d\tau_0$$

For a sufficiently large population, we can (by the law of large numbers) assume that actual instar proportions are equal to the expectations, i.e.,

$$n_j(t) = \bar{p}_j(t) \cdot N_0,$$

where $n_j(t)$ = the population of individuals in stage j at time t, and
N_0 = the total number hatched for the cohort.

Applying this general model to king crab zoea, the distribution of hatch times was assumed to be normal with mean μ and standard deviation σ. Durations for the four zoeal stages were also modeled as normal, with means D_i for each stage and a common coefficient of variation (CV) for all stages.

SAMPLING MODEL

Much population dynamics methodology has come from engineering systems analysis, where simple least squares is widely used to fit models to large data sets. This was the method used by Parslow et al. (1979) and Sonntag and Parslow (1981). However, most plankton populations are patchy, which leads to high sampling variability and high correlations in the data . Sampling populations classified by stage or age leads to further complications. For age-classified fish populations, Fournier and Archibald (1982) recognized that sampling error has two components: variation in total catch relative to overall population abundance, and error in age-frequencies within the sample relative to those in the population. The same considerations apply to stage-classified samples. Variation in total catch results from population patchiness and variation in sampling effectiveness. This variation has been modeled in several ways, including log-normal (Fournier and Archibald 1982), normal with constant CV, and normal with variance following Taylor's power law. If sampling is equally effective for all stages and the population stage structure is spatially homogenous, the sample stage-frequencies will be multinomial with expectations equal to the true population frequencies. (For a case where the spatial homogeneity assumption does not hold, Stedinger and Shoemaker [1985] applied a Dirichlet-multinomial model.)

As an initial application of our model, we used normal, constant CV error for total catch, and simple multinomial error for stage composition. We had no replicate samples from which to estimate CV, so CV was set to 50% based on experience with other data sets. Parameter estimates were found to be insensitive to choice of CV from 25% to 50%, although using a higher CV puts relatively more weight on stage composition data than on total catch.

Under this sampling model, the log-likelihood equation used to obtain parameter estimates is

$$L(\Theta|C) = \sum_{i}\frac{(C_i - \hat{C}_i)^2}{0.5\cdot\hat{C}_i} + \sum_{ij} c_{ij}\cdot\ln(p_{ij})$$

where i = index of sample times,
j = indexes stages,
$\mathbf{C}$ = the matrix of catches by stage at sample times,
C_i = total observed catches at sample times,
c_{ij} = observed catches by stage,
$\hat{C}_i$ = total predicted catches,
p_{ij} = predicted stage proportions, and
Θ = the vector of parameters defined in Table 3.