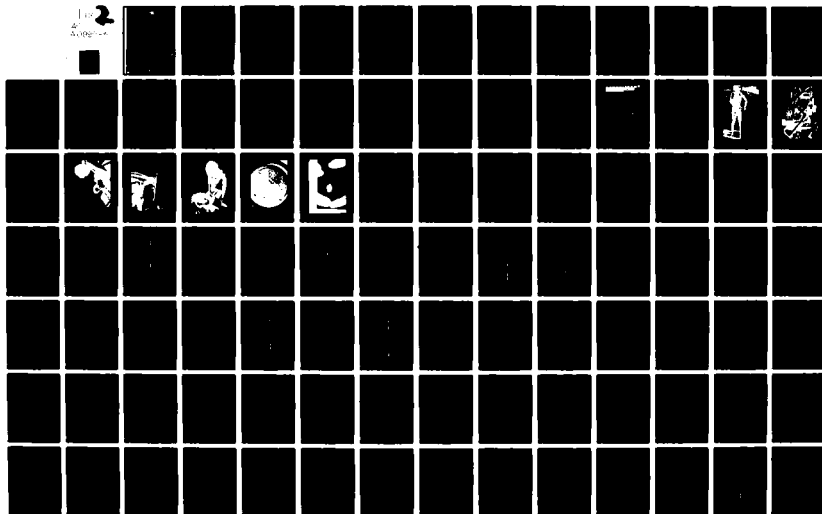


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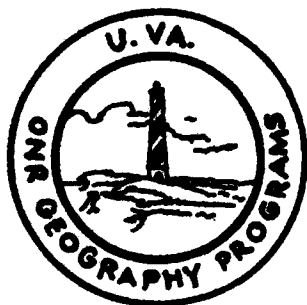


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THE RELATIONSHIP OF *EMERITA TALPOIDA*
TO BEACH CHARACTERISTICS



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MAY, 1981
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THE RELATIONSHIP OF *Emerita talpoida*
TO BEACH CHARACTERISTICS

Michael Lowell Bowman
Vienna, Virginia

B. S., Bridgewater College, 1979

A Thesis Presented to the Graduate
Faculty of the University of Virginia
in Candidacy for the Degree of
Masters of Science

Approved
28 April 1981
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May, 1981

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ABSTRACT

A model was developed which described the spatial and temporal variations of *Emerita talpoida* populations as a function of environmental and biologic factors and geomorphic attributes of the foreshore. The model was tested through field sampling at the Coastal Engineering Research Center (CERC) Field Research Facility, Duck, North Carolina, and at selected sites along the mid-Atlantic coast. The data indicate that the model accurately describes the spatial and temporal variations of *E. talpoida*.

The spatial distribution on the foreshore is influenced by environmental and geomorphic factors. *E. talpoida* populations generally increase in density across the foreshore toward the step. High density cells frequently lie within areas of reduced wave energy such as cusp troughs. Structures extending across the foreshore, e.g., the CERC pier, cause redistribution of *E. talpoida* and beach sediment as a result of their interaction with incident wave energy; the distribution is a function of the dominant wave regime. The depth distribution of *Emerita* was roughly lenticular with few *Emerita* found at depth high on the foreshore and the numbers increasing toward the step.

Onshore migration of the overwintering population occurred during a period of rapidly increasing water temperature in early April. Numbers generally increased

through spring and summer to a seasonal maximum in late summer and early fall. Large and often rapid fluctuations in the population are superimposed on the seasonal cycle. Many of these fluctuations are related to variations in environmental factors, e.g., wave energy and tide level, and probably reflect onshore and offshore migration of the population in response to energy conditions and feeding requirements.

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INTRODUCTION

The 295 barrier islands that rim the Atlantic and Gulf coastal plains comprise 19% of the coastline of North America (Dolan, et al., 1972). Because of the recreational and economic potential of the sand beaches and barrier islands, protection from erosion has become an important national issue. However, engineering projects must be undertaken with consideration of their impact on beach ecology. Sand beaches seem inhospitable to life to the casual observer but, upon closer examination, are found to harbor a wide range of organisms.

Emerita talpoida, the common mole crab, is a conspicuous swash zone inhabitant of sandy beaches along the Atlantic coast (Matta, 1977; Efford, 1976). In a study of beach nourishment impact on *Emerita* distribution, Hayden and Dolan (1974) pointed out the importance of *Emerita* to beach ecology and its usefulness as an indicator species of engineering project impact. Most studies have dealt with the west coast species, *E. analoga*.

One poorly understood aspect of the biology of *Emerita* is its distribution on the foreshore and particularly its tendency to form aggregations (localized patches of high population density) (Efford, 1965; Cubit, 1969; Pearse, et al., 1942). Numerous hypotheses have been proposed to explain this phenomenon based on either biologic (Efford, 1965) or physical arguments (Cubit, 1969). Information

relating the spatial and temporal variations of *E. talpoida* populations to physical characteristics of the foreshore is needed to further our understanding of the biology of this species.

This study was initiated to examine the relationship of *E. talpoida* to beach attributes such as grain size and beach slope and to the physical processes affecting the beach system. Studies of *Emerita* aggregations (Efford, 1965) have been conducted over small sections of beach. Sampling procedures used in this study were designed to obtain data on the spatial distribution of *E. talpoida* over a large area of beach. A model was developed to describe these interactions and tested through field sampling at selected sites along the mid-Atlantic coast. Questions to be addressed include:

1. What is the effect of sediment size on *Emerita* distribution on the beach?
2. What effect do environmental processes have on *Emerita* distribution on the beach?
3. What is the pattern of spatial and temporal variations of *Emerita*?

The results indicate that the across-the-beach and longshore distribution of *E. talpoida* are influenced by the action of environmental factors such as wave energy and approach, by geomorphic attributes of the foreshore, and by structures (e.g., piers) extending across the foreshore.

LITERATURE REVIEW

REPRODUCTION AND LIFE CYCLE

Mating of *Emerita* takes place from late spring through early summer. *E. analoga* females produce eggs repeatedly throughout the summer (Cox and Dudley, 1968). The eggs are carried for approximately one month, after which they are released as pelagic zoeae (Dudley and Cox, 1967). An average of 28 days is required for larval development from egg through six to seven pelagic zoeal stages to megalopa in *E. talpoida* (Rees, 1968). The mechanism which initiates the return of the megalopae to shore is undetermined, although Hunter (1972) reported a relationship between reproductive and development cycles and water temperature.

Emerita populations are sometimes distributed on the foreshore according to size. Within aggregations of *E. analoga* the smallest individuals (young and males) have been observed highest in the swash zone, with the larger females inhabiting the lower foreshore (Efford, 1965). The opposite pattern has been observed in *E. talpoida* populations (Bursey and Bonner, 1977). This discrepancy may result from interspecific differences related to feeding requirements and ability to tolerate stress.

PHYSIOLOGICAL RESPONSES

E. talpoida is a hyperosmoregulator (i.e., the body fluids are maintained at a higher concentration than the

external medium by osmosis), unlike *E. analoga* (Burse and Bonner, 1977). The oxygen consumption of *E. talpoida* larvae is almost twice that of similarly sized spider crab larvae due to the more rapid growth rate and energy utilization of *Emerita* (Schatzlein and Costlow, 1978). Furthermore, *E. talpoida* larvae exhibit a constant pattern of chromatophores throughout their successive stages, a characteristic which can be used diagnostically for identification (Shield, 1973).

An important adaptation which allows *Emerita* to remain within the active swash zone is its burrowing ability. Burrowing is initiated by tactile stimulation of the telson (Trueman, 1970) and can only occur within fluid sand (Pearse, et al., 1942). No other large filter-feeding organisms have developed the adaptations necessary to allow them to successfully fill the ecological niche that *Emerita* occupies (Efford, 1966). Efford (1966) reached four conclusions concerning the feeding pattern of *E. analoga*:

1. Water velocity affects feeding behavior and the antennal cleaning rate.
2. Food size and type affect the cleaning rate.
3. There is no evidence that *Emerita* can actively sort the filtered particles in the mouth and reject the sand particles while ingesting food material.
4. *E. analoga* can live and feed in standing water while *E. talpoida* cannot.

Emerita AND BEACH ECOLOGY, GEOMORPHOLOGY AND DYNAMICS

Emerita is a food source for terrestrial predators (Mueller, 1976; Fales, 1976; Wolcott, 1978). It is also a link between the subaqueous and subaerial food chains (Hayden and Dolan, 1974). Matta (1977) concluded that *E. talpoida* was the dominant organism in the swash zone of a beach near Duck, North Carolina.

Efford (1970) proposed a mechanism to account for the relative stability of sedentary *Emerita* populations. The majority of pelagic *Emerita* larvae remain near the shore from which they were hatched due to longshore currents and their associated countercurrents. The megalopae then drift passively to the beach and thus replenish the population.

There are two major hypotheses to explain aggregation formation. Efford (1965) proposes that biological factors are the causative force, while Dillery and Knapp (1970) and Cubit (1969) maintain that physical factors are the cause. Efford was unable to find any physical factors correlated with aggregation locations consistently enough to explain their presence. The biological factors he suggested included optimization of food resource exploitation, facilitation of mating through increased frequency of contact of males and females, and decreased predation by randomly searching shore birds.

Dillery and Knapp (1970) found that *Emerita* move with longshore currents and that aggregations were generally associated with beach cusps. Cubit (1969) also observed an association between aggregations and beach cusps. He reported that *Emerita* spontaneously burrow out of fluid sand. Cubit proposed a physical explanation of aggregation formation and migration across the foreshore based on his observations.

Cubit maintained that *Emerita* are kept within the swash zone by the physical action of surf at the lower edge and the fluid sand created by wave wash at the upper edge. To explain aggregation formation, he defined a convergence zone as the result of a net movement of the lateral component of wave velocity into an area and stated that *Emerita* would tend to be washed into these convergence zones. When the convergence area remained stationary through several tidal cycles, an aggregation would develop. Cubit's paper also alludes to the role of grain size in thixotropy (sand made fluid by water flowing through it) and the ability of *Emerita* to move in the sand.

THE *Emerita*/BEACH-ENERGY MODEL

Organisms of stressed environments are strongly influenced by the physical processes which control their environment. In the case of *Emerita*, these processes may be divided into two categories: (1) nearshore processes such as tides, waves, currents and water temperature; and (2) beach characteristics, such as beach morphology and sediment characteristics. Biological factors (e.g., predation, mortality, food availability and physiological requirements) also play an important role in determining *Emerita* distribution on the beach. This distribution is characterized by temporal and spatial variations on both small and large scales.

TEMPORAL VARIATIONS

The seasonal cycle of *E. talpoida* begins in early spring with the arrival on the beach of individuals that overwintered in the offshore zone in water two to four meters deep (Edwards and Irving, 1943). The stimulus for migration from offshore to the beach foreshore is probably associated with water temperature. Adult forms are common in the population in early spring since *E. talpoida* has a lifespan of approximately two years and continues to grow throughout the winter (Edwards and Irving, 1943). The seasonal cycle reaches its peak in late summer when there are large numbers of adults and megalopae present on the beach, and begins to decline in early autumn with the initiation of offshore

migration, which is completed by early winter. From winter through early spring no *Emerita* are found on the foreshore.

Rapid fluctuations in the population on the order of a day to a week or more are superimposed on the long-term, seasonal cycle. Episodic events, such as coastal storms, have an immediate effect on the pattern of temporal variation. Predation by fish, ghost crabs (*Ocypode quadrata*), and shore birds and mortality of *Emerita* also affect the temporal cycle. Food availability and eating habits play a more subtle role in the pattern of temporal variation. For example, the sharp reduction in *Emerita* populations observed along the entrances of inlets can be explained by the lack of sufficient swash action for feeding.

SPATIAL VARIATIONS

The spatial patterns of *Emerita* are more complex than the temporal patterns. Spatial variations occur in three dimensions (along and across the beach and with depth) and also vary on a large scale along the coast. Physical factors are the primary controlling agents.

The longshore variation of *Emerita* is largely controlled by longshore currents which are generated by waves breaking at an angle to the foreshore (Shepard, 1973). *Emerita* which are in nearshore waters are transported in the direction of the current. For example, *Emerita* located near the beach step may be suspended by surf action and subsequently

transported by longshore currents. The distance traveled before burrowing occurs is small, but over several tidal cycles the organisms may be moved considerable distances. *Emerita* could thus be concentrated in areas where longshore currents converge.

Variations of *Emerita* across the beach are related to tidal action, swash action, beach slope and sediment characteristics. *Emerita* migrate back and forth across the beach with the tides, generally remaining within the active swash zone. Populations reach maximum density in the middle and lower portions of the swash zone where they can actively feed. Relatively flat beaches allow a wide swash zone and relatively steep ones limit this zone to a narrow strip. Grain size is important in that it controls the ability of *Emerita* to move once it has burrowed through the surface layer of sand.

The distribution of *Emerita* with depth is closely related to grain size and the ability of a given grain size to be thixotropically fluid. *Emerita* can only burrow into the wet and fluid sand of the swash zone; they are unable to move in moist or dry sand. At high tide, *Emerita* can burrow into the sand of the upper foreshore. Those which burrow to a depth of a few centimeters migrate down the beach with the ebb tide, leaving those which burrowed deep into the beach stranded until the next high tide. This process occurs throughout the tidal cycle.

Most *Emerita* remain near the surface but some burrow deep into the beach. Thus, sampling during low tide would show few or no *Emerita* in the surface sand landward of the swash zone and very few at depth high on the foreshore, with the number at depth increasing and reaching a maximum toward the mid and lower swash zone. A sharp reduction in the population exists at the beach step due to intense turbulence caused by breaking waves. There is a maximum depth to which *Emerita* will burrow based upon grain size, water table depth and swash action (which combine to determine the thixotropic fluidity of the sand) and physiological requirements such as oxygen availability.

This study was designed to examine three aspects of this spatial and temporal model:

1. The spatial distribution of *E. talpoida* on the foreshore. What effect do physical attributes of the beach have on the distribution?
2. The temporal variations on rapid and seasonal scales.
3. The effect of environmental processes on the spatial and temporal variations of *E. talpoida* populations.

DESIGN

A data acquisition program which allowed systematic collection of biologic, environmental and geomorphologic data over a seasonal cycle was required to establish the covariation of *Emerita* populations with physical processes and beach geomorphology. A primary objective of this study was to examine *Emerita* distribution at a scale larger than has been used in previous studies. For example, Efford (1965) studied aggregations of *E. analoga* along a 380 meter length of beach. Although Saloman and Naughton (1978) sampled at eight stations along approximately 30 kilometers of beach at Panama City, Florida, they did not examine the spatial distribution of *E. talpoida*.

The Army Corps of Engineers Field Research Facility (FRF) at Duck, North Carolina, provides an ideal location for the collection of this type of baseline information (Figure 1). The FRF is a 1900 foot research pier which is used for the collection of numerous environmental data (CERC, 1980). A study of beach fauna including *E. talpoida* was conducted at this site by Matta (1977).

A series of parallel transects placed at 100 meter intervals was established at the FRF. Five transects were located north of the pier and five on its southern side (Figure 2). Transect locations were marked by stakes planted in the seaward face of the primary dune. Sampling

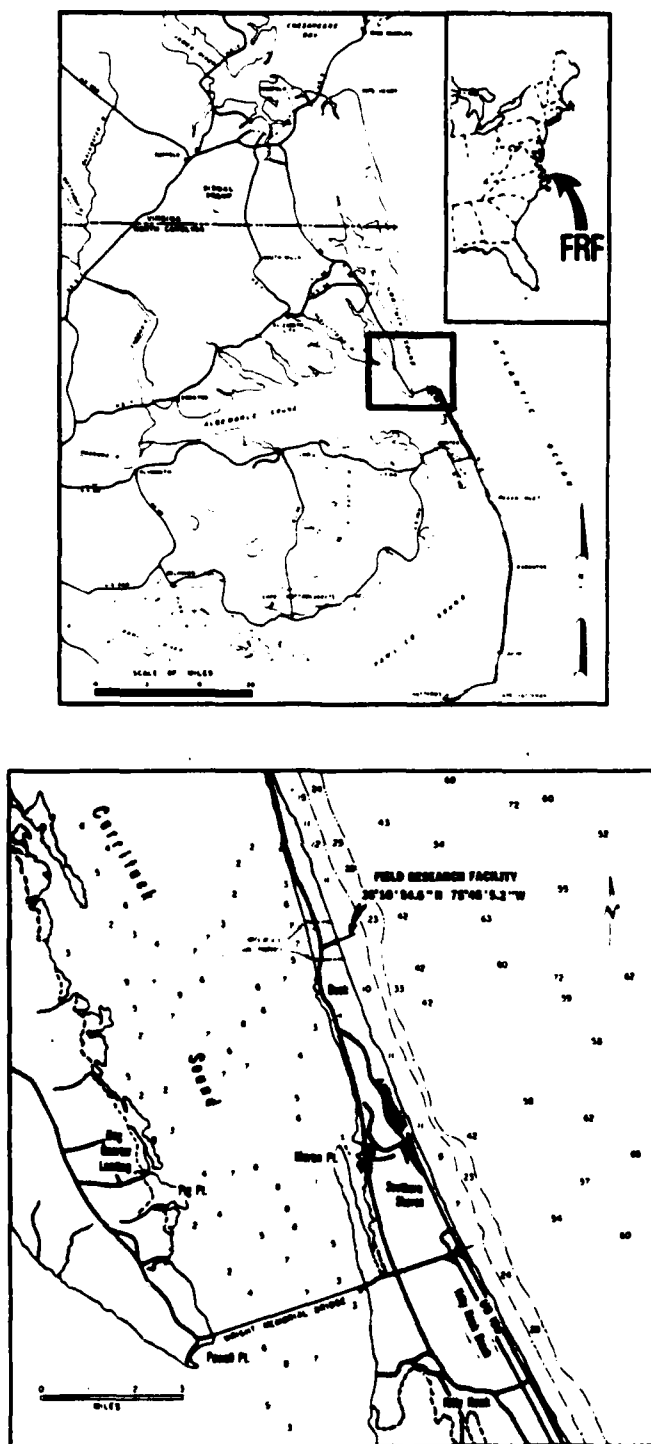


Figure 1. Location map for the CERC Field Research Facility, Duck, North Carolina.

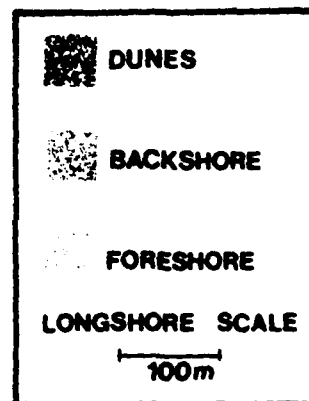
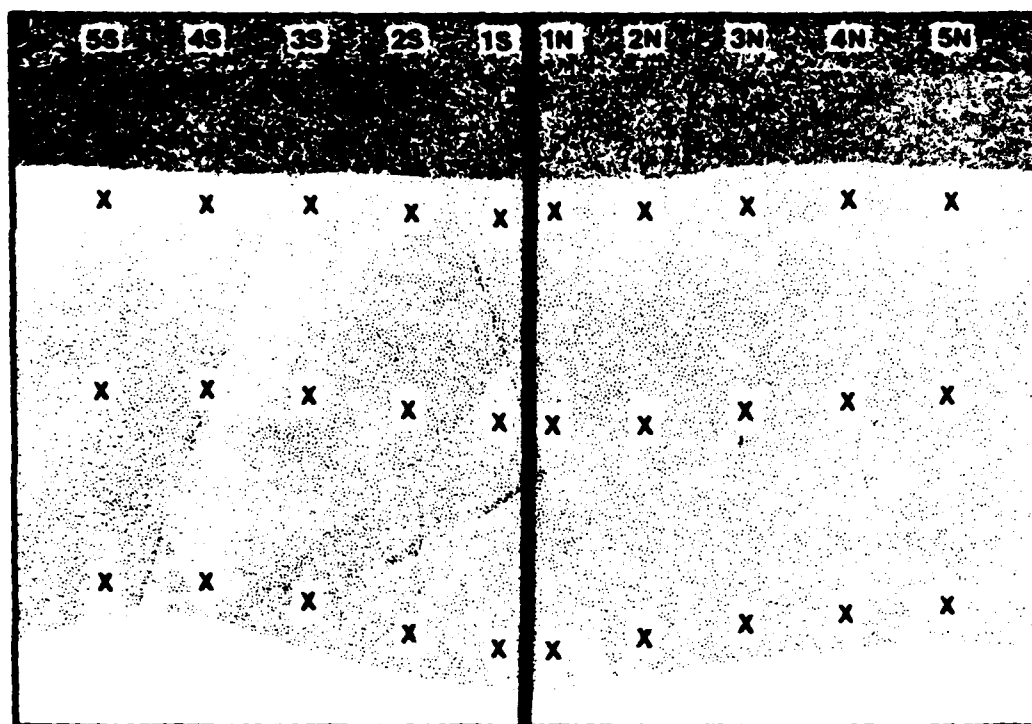


Figure 2. Transect locations at the FRF. The solid black line represents the pier, numbers along the top are the transect numbers. Core locations are marked. Distances across the foreshore are not to scale.

was conducted at biweekly intervals from mid-February through late May; at weekly to biweekly intervals from June through July; and at biweekly intervals from September through mid-November, 1980.

Biweekly sampling intervals throughout a seasonal cycle allow an assessment to be made of the temporal variations of *Emerita* populations, while at the same time filtering some of the high frequency fluctuations resulting from episodic events such as coastal storms. Cox and Dudley (1968) made semimonthly collections from March through September and monthly collections during the remainder of the year. Barnes and Wenner (1968) made biweekly collections from spring through early autumn.

Sampling was conducted between high tide and the following low tide to avoid relocation of *Emerita* during a rising tide (Barnes and Wenner, 1968; Efford, 1965). Normally sampling was conducted during the morning high-low tide cycle. Core samples were made with a device constructed of PVC pipe (I.D. 10.1 cm, sampling area 80.12 cm², Figures 3 and 4). The maximum depth of the cores was 25-30 cm. Three cores were taken along each transect: one each at the high tide, mid-tide and near the low tide line. Due to the constantly changing nature of beach width, slope and tide level, the actual position of each core

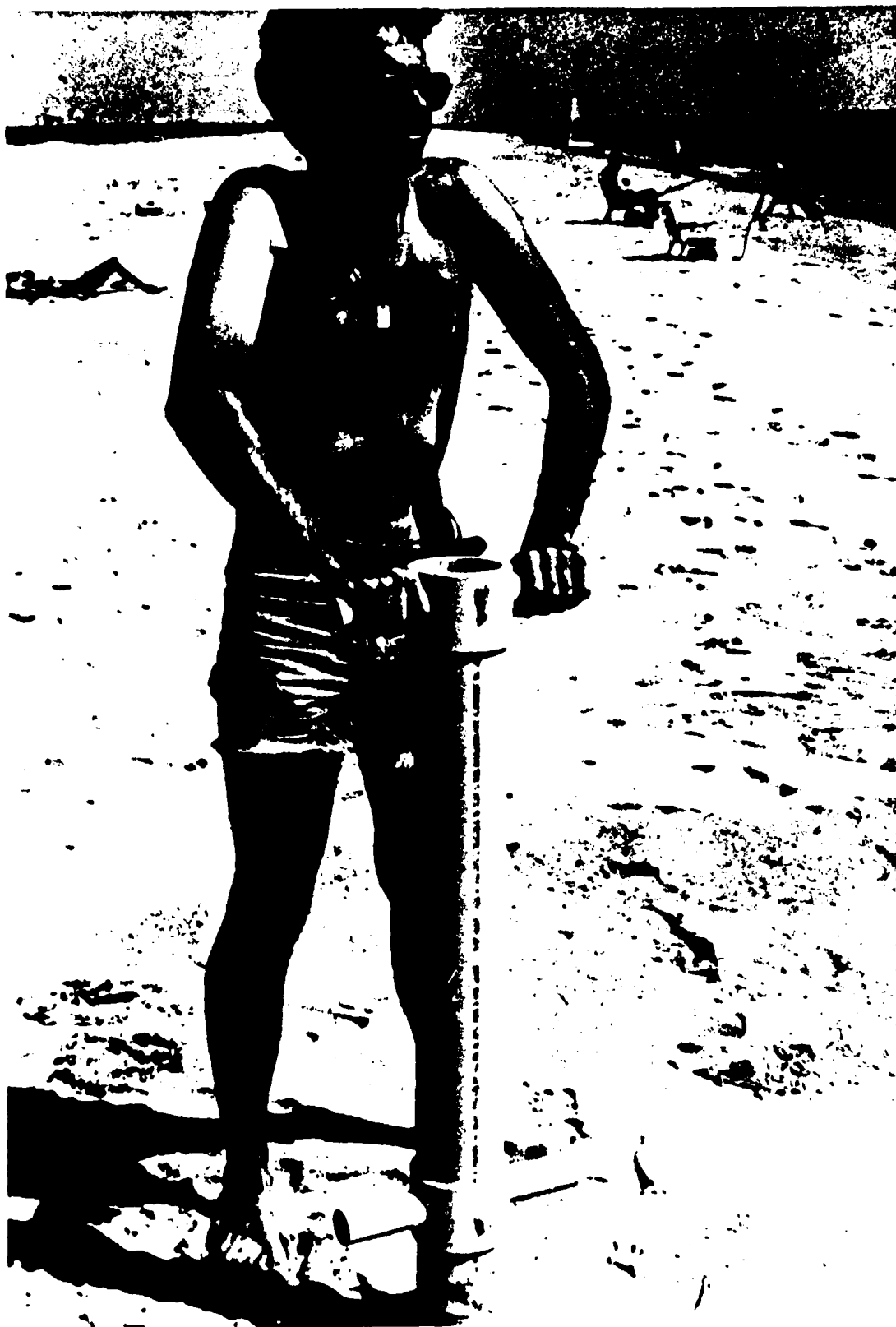


Figure 3. PVC pipe sampler.



Figure 4. Using the sampler in the surf zone.

along the transects changed from week to week but their relative positions remained constant as did their positions north or south of the pier.

At each core location an estimate was made of the mean grain size of the upper 5 cm of sand using the method of visual comparison with vials containing known sand sizes (Figure 5). The required accuracy of grain size estimates was not so high as to restrict grain size determination to laboratory methods. The method of visual comparison allows for a large number of samples to be processed in the field so that the actual standard error of estimate approaches that of more accurate laboratory methods that require more time and thus fewer samples (e.g., settling tubes). Beach slope measurements were made using an Abney level placed on a wooden stake which was oriented perpendicular to the waterline (Bascom, 1959; Figure 6). Finally, a core was taken and washed through a No. 6 (3.35 mm) sieve (Figure 7). The *Emerita* caught in the sieve (Figures 8 and 9) were counted by size class: small, less than 8 mm; medium, 8-15 mm; large, greater than 15 mm. Megalopae were counted as juveniles.

Sampling was also conducted throughout the summer at selected sites along the mid-Atlantic coast to determine the general applicability of the model. One criterion in selecting the sites was that they encompass a wide range of grain sizes from fine to coarse in order to assess the effect of sediment size on *Emerita* distribution; this goal



Figure 5. Estimating grain size by visual comparison with vials containing known grain sizes.



Figure 6. Measuring beach slope with an Abney level.



Figure 7. Washing core sample through sieve.



Figure 8. *Emerita* caught in sieve.

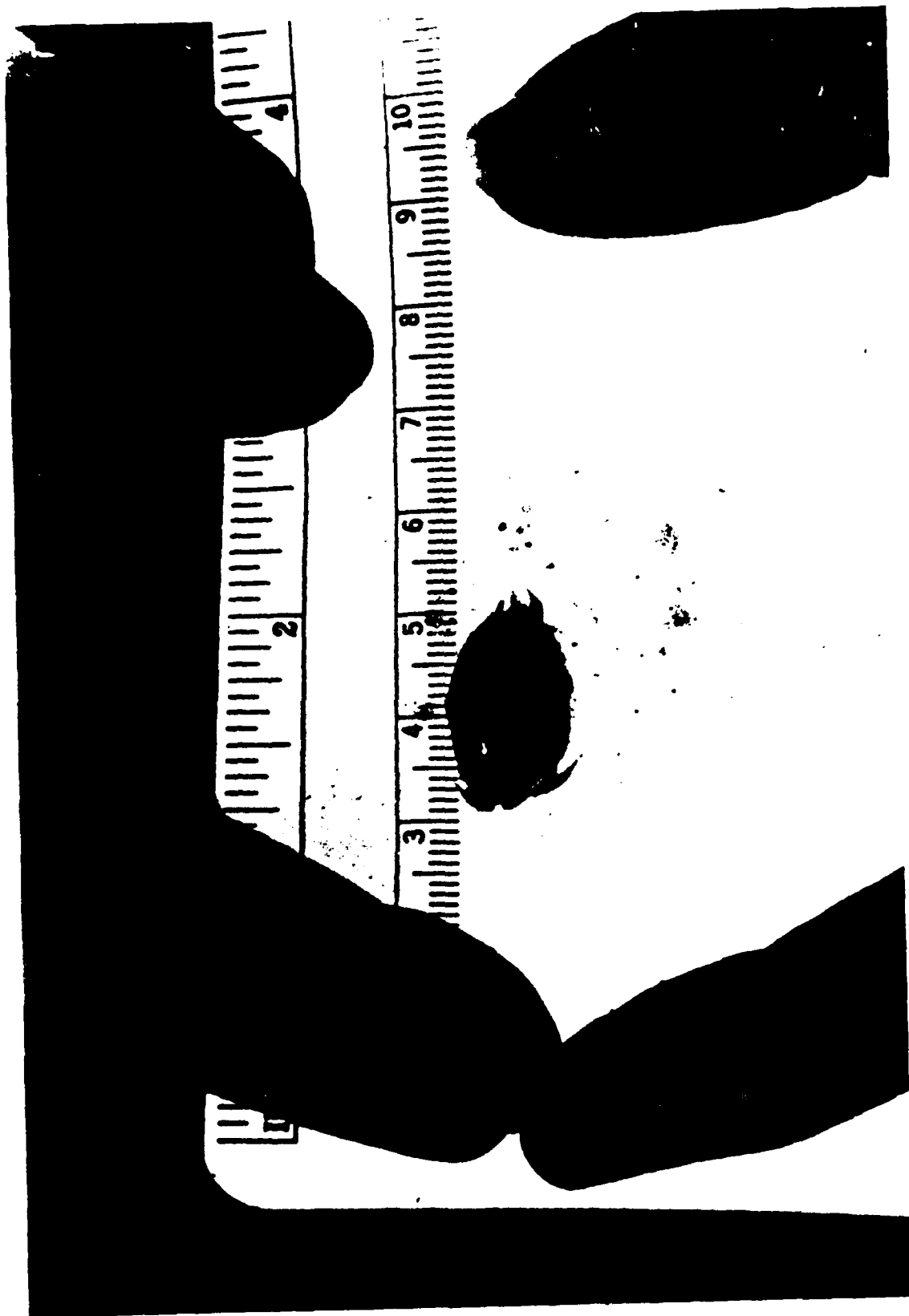


Figure 9. Large *Emerita*.

was only partially achieved. A total of three criteria were used: geographical distance from the FRF; expected sediment characteristics; and accessibility. These sites were Sandbridge, Virginia; Delaware Seashore State Park, Delaware; and Assateague Island National Seashore, Virginia.

Samples were to be taken at one meter intervals across the beach along a series of five meter parallel transects between high tide and the following low tide. This spacing would have provided high resolution data on small-scale spatial variations; however, this sampling plan proved to be beyond the capabilities of a single investigator. Therefore, samples were taken at one meter intervals along a single transect at each site, thus providing information on *Emerita* distribution with depth.

A beach slope measurement was made at each station. In this case, however, the core was removed from the PVC pipe sampler in approximately 5 cm thick layers. The mean grain size of each layer was estimated and the number of *Emerita* per layer was recorded.

THE DATA MATRIX

The sampling procedures described in the previous section generated a large and complex data matrix. Three types of data were collected at the FRF, each divided into subgroups. Biologic data (the number of *Emerita* per core) is subdivided into four size classes and three foreshore zones (ten core locations within each zone; see Figure 2). Geomorphic data consists of grain size and beach slope, divided into three foreshore zones. Environmental data provided by the FRF includes breaker height, wave approach, water temperature and longshore current speed and direction. Tide level was obtained from the N.O.A.A. 1980 Tide Tables.

Each day of sampling generated a single matrix. Analysis entailed calculating means and standard deviations for the various submatrices through time. Different combinations of submatrices allowed examination of the spatial and temporal variations of the data.

Sampling conducted at the Sandbridge, Virginia, Delaware and Assateague Island sites during the summer also generated large matrices. In this case biologic data is divided into four size classes and a varying number of 5 cm thick layers (generally 5 or 6) at each core location across the foreshore. Geomorphic data consists of beach slope at each core and grain size for every layer within a core. Environmental data are limited to breaker height,

which was estimated by the investigator. The biologic submatrices were used to construct plots of across-the-beach variation and depth distribution by combining data from all three sites. Distance across the foreshore was converted to a dimensionless relative foreshore width since the foreshore width varied between sites.

SPATIAL VARIATIONS

Spatial variations in each *Emerita* size class, grain size and beach slope were originally determined by calculating the mean and standard deviation for each of the variables at each core location from April 12 (initial appearance of *Emerita*) through November 14, 1980 (last day of sampling). These values were used to produce contour maps depicting the spatial distribution. Subsequent analysis of the environmental data revealed a significant difference in the direction of wave approach between the periods from April 12-August 15 and August 16-November 14, 1980.

Means and standard deviations for the variables were recalculated for these two periods. The contour maps which were then produced revealed major differences in *Emerita*, grain size and beach slope patterns which seemed to be related to wave approach. The control of the spatial distribution of these variables by wave approach is discussed in the Results Section.

TEMPORAL VARIATIONS

Temporal variations of each *Emerita* size class were determined by calculating the mean and standard deviation over each foreshore zone for each day of sampling. The means were plotted against time. The standard deviations, however, were generally greater than the mean due to the large spatial variability of the population on a given day. A table relating standard deviations to the mean appears in the Results Section. The environmental data listed in the opening paragraph of this section were also plotted as a function of time.

RESULTS

The spatial and temporal variations of *Emerita* result from the complex interactions of the organism with beach morphology and physical processes. In general, the spatial patterns of *Emerita* are controlled by beach morphology and wave energy, both of which are modified by the FRF pier structure itself. Contours of population density reveal differences in distribution related to the dominant direction of wave approach with the highest population densities associated with well-protected areas of the foreshore.

The temporal variations of *Emerita* fluctuate widely with a seasonal population maximum occurring in late summer and early fall. These fluctuations are associated with a combination of large waves/rising tide levels or small waves/falling tide levels. The time of initial appearance of *Emerita* on the foreshore was coincident with a sharp increase in water temperature. Some differences are also observed between foreshore zones and size classes.

WAVE ENERGY AND BEACH MORPHOLOGY

Along the mid-Atlantic coast the waves arrive primarily from the northeast in winter and east and southeast in summer. A relationship exists between beach morphology and wave energy. Wave energy varies roughly with the square of

wave height. High energy waves in winter cut the berm back which results in a steeper beach. The excess sand is transported to the bar (Bascom, 1980). During the summer, low energy waves move sand from the bars to the foreshore, building the beach seaward leading to gentler slopes. Thus, grain size and beach slope, two easily measured geomorphic attributes, would be expected to reflect the dominant wave regime.

Wave Energy

Figure 10 shows the temporal record of wave approach at the FRF. From April 1 through August 15 the dominant wave approach is from the southeast; after August 15 the waves arrive from the east, parallel with the pier. These two periods represent the summer wave regime and the transitional regime between summer and winter. Table 1 gives statistics for these two regimes.

Bascom (1980) defines wave energy orthogonals as wave rays drawn perpendicular to the wave front. Orthogonals show the direction of wave energy transport. When the orthogonals parallel the pier, i.e., the wave trains arrive from the east, as they do after August 15, the incident wave energy will be reduced (attenuated) by dissipation around the pier pilings in the form of turbulence. Energy attenuation will occur over a relatively short length of beach (Figure 11a). However, when the energy orthogonals are not parallel with the pier, as is the case before

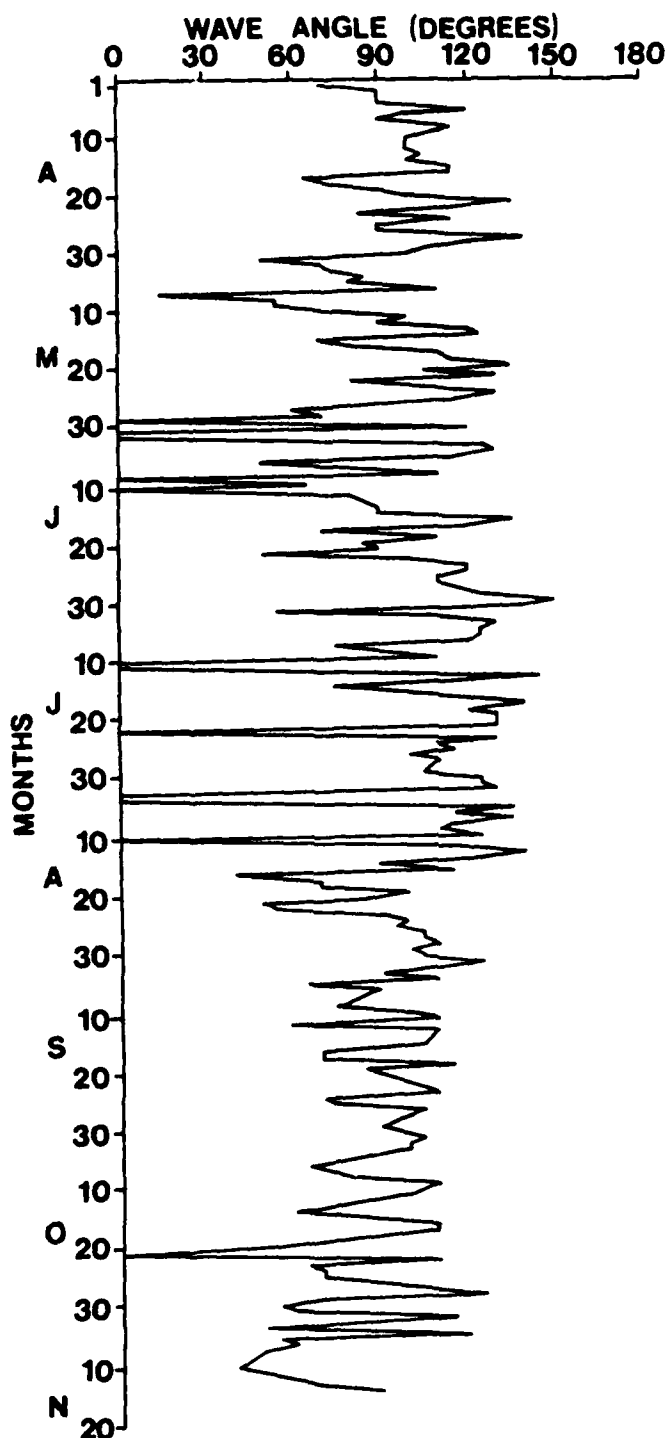


Figure 10. Temporal record of wave approach at the FRF. 0 degrees is approximately north, 90 degrees is approximately east. Days on which the sea was calm are recorded as 0 degrees.

Table 1. Wave Approach Statistics, FRF, 1980.

<u>Period</u>	Wave Approach Mean $\pm$ S.D. (Degrees)	Number of <u>Cases*</u>
4/1 -8/15	103.3 $\pm$ 24.7	123
8/16-11/14	85.8 $\pm$ 22.7	70
4/1 -11/14	96.9 $\pm$ 25.4	193

The difference in mean wave approach between the two wave regimes is significant at the .01 level of the t-test.

*Days when the sea was calm, i.e., wave approach is 0 degrees in Figure 10, were excluded.

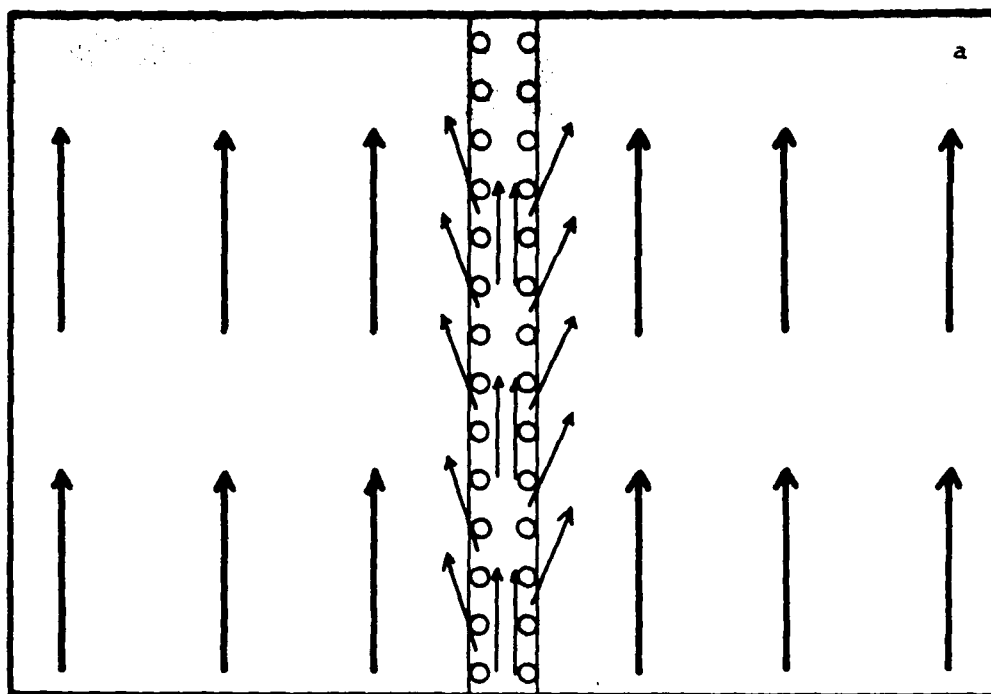


Figure 11a. Small zone of energy attenuation when waves arrive parallel with the pier.

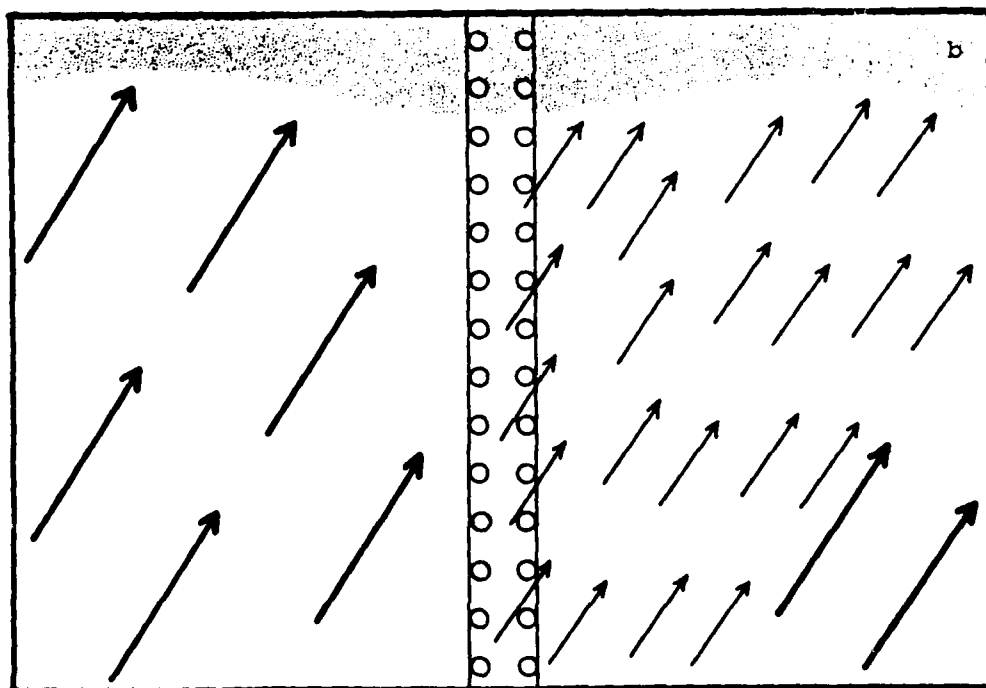


Figure 11b. Large zone of energy attenuation when waves are not parallel with the pier.

August 15, the incoming energy will be significantly attenuated (Figure 11b). This "pier effect" will be evident in geomorphologic data and will directly affect *Emerita* distribution. Pier effects will be most noticeable on the north side of the pier during the summer regime and will be confined to the area immediately north and south of the pier during the transitional regime.

Beach Morphology

Figure 12a shows the mean grain size contours for the summer wave regime. Grain size distribution is cellular south of the pier; on the north side it is relatively constant across the beach. The cell of fine sand (0.35 mm) in the upper and middle foreshore immediately north of the pier is a consequence of decreased wave energy resulting from turbulence around the pier pilings. The energy available for sediment transport is reduced, allowing only finer sediment to be transported and deposited. A t-test performed on these data shows that the sediment in the upper foreshore south of the pier is significantly larger than that north of the pier ($\alpha = 0.05$). The difference in grain size in the mid and lower foreshore on either side of the pier is not statistically significant (Table 2a).

Figure 12b suggests that the pier structure plays an important role in the sorting of the beach sediment, characterized by the standard deviation. The largest

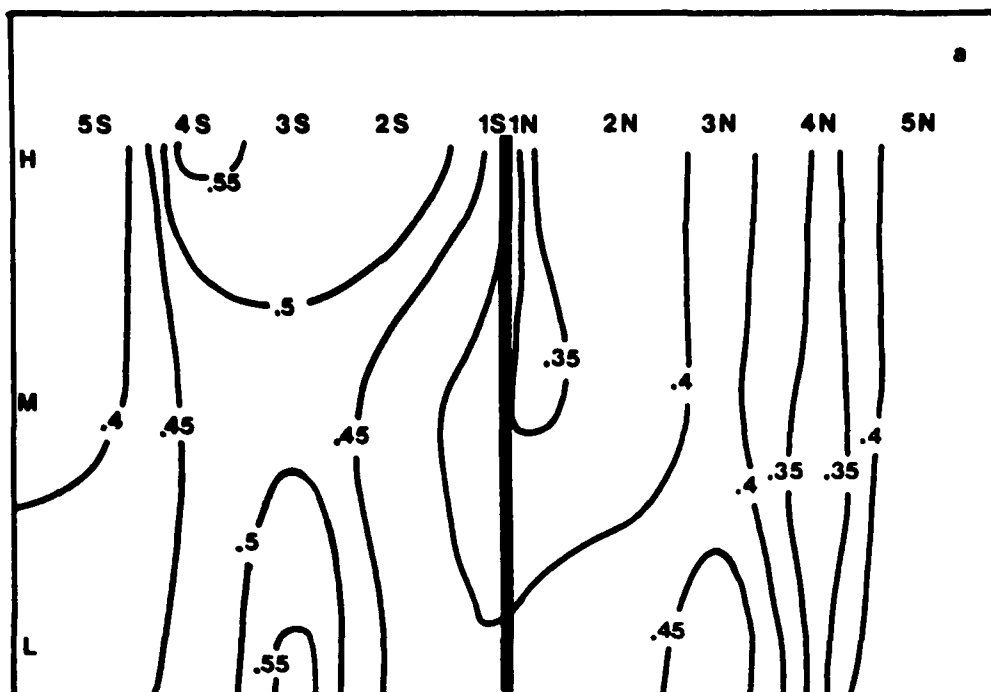


Figure 12a. Grain size mean in mm, summer wave regime.*

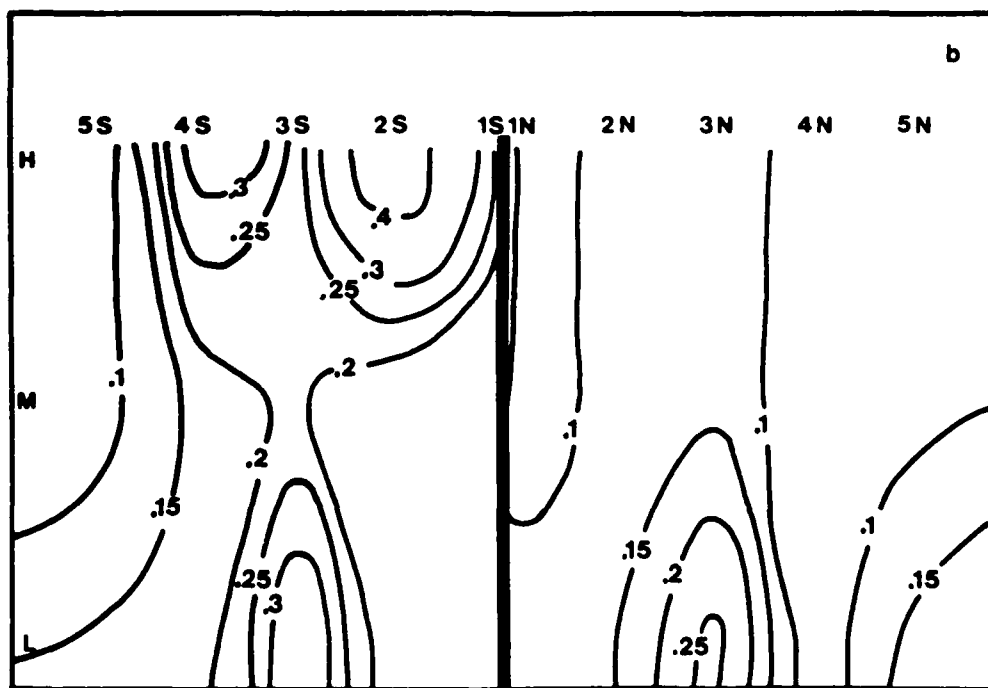


Figure 12b. Grain size S.D.*

*Letters along the left side indicate the foreshore zone (upper, mid and lower). Transect locations are indicated across the top. Distance between transects is 100 meters.

Table 2a. Grain Size Mean, CERC FRF, Duck, North Carolina.

<u>Fore-shore Zone</u>	<u>Summer Wave Regime</u>		<u>Statistical Difference*</u>
	<u>South of Pier (mm)</u>	<u>North of Pier (mm)</u>	
Upper	.493	.384	S>N**
Mid	.427	.382	NS***
Lower	.461	.421	NS***
	<u>Transitional Wave Regime</u>		
Upper	.587	.445	S>N**
Mid	.632	.512	S>N**
Lower	.794	.689	NS***

Table 2b. Grain Size S.D., CERC FRF, Duck, North Carolina.

<u>Fore-shore Zone</u>	<u>Summer Wave Regime</u>		<u>Statistical Difference*</u>
	<u>South of Pier (mm)</u>	<u>North of Pier (mm)</u>	
Upper	.279	.091	S>N**
Mid	.150	.092	S>N**
Lower	.191	.158	NS***
	<u>Transitional Wave Regime</u>		
Upper	.259	.128	S>N**
Mid	.203	.143	NS***
Lower	.203	.257	NS***

*Computed by the t-test, $\alpha = 0.05$

**S>N--south side > north side

***NS--not significant.

standard deviations, i.e., the sand most poorly sorted through time, occur on the south side of the pier where the wave energy is not attenuated. Table 2b shows that there is a significant difference in sorting in the upper and midforeshore between the north and south side of the pier; the north side is better sorted. The sorting in the lower foreshore is statistically equivalent on either side of the pier.

A more complex pattern of grain size distribution occurs during the transitional wave regime (Figure 13a). The mean grain size is relatively constant across the foreshore for approximately 200 meters south and 100 meters north of the pier. Cells of coarse sand are found in the lower foreshore. The 200 meter strip south of the pier is indicative of wave energy arriving from the north side of the pier. Farther away from the pier on either side the distribution becomes more zonal with grain size increasing toward the lower foreshore. The sediment is significantly coarser in the upper and midforeshore south of the pier; the difference is not significant in the lower foreshore (Table 2a). Sediment sorting, compared with the summer regime, has become nearly equal on either side of the pier (Figure 13b). The cell of poorly sorted sand in the upper foreshore 100 meters south of the pier results in the significant difference given in Table 2b. The difference in sorting in the mid and lower foreshore between the north and south sides of the pier is not statistically significant.

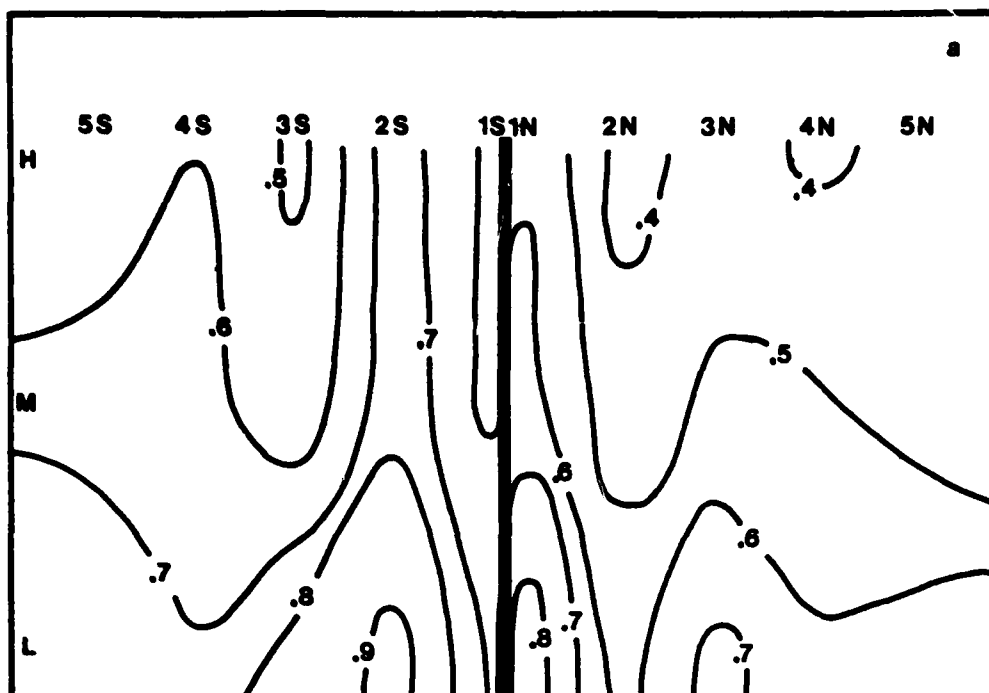


Figure 13a. Grain size mean in mm, transitional wave regime.*

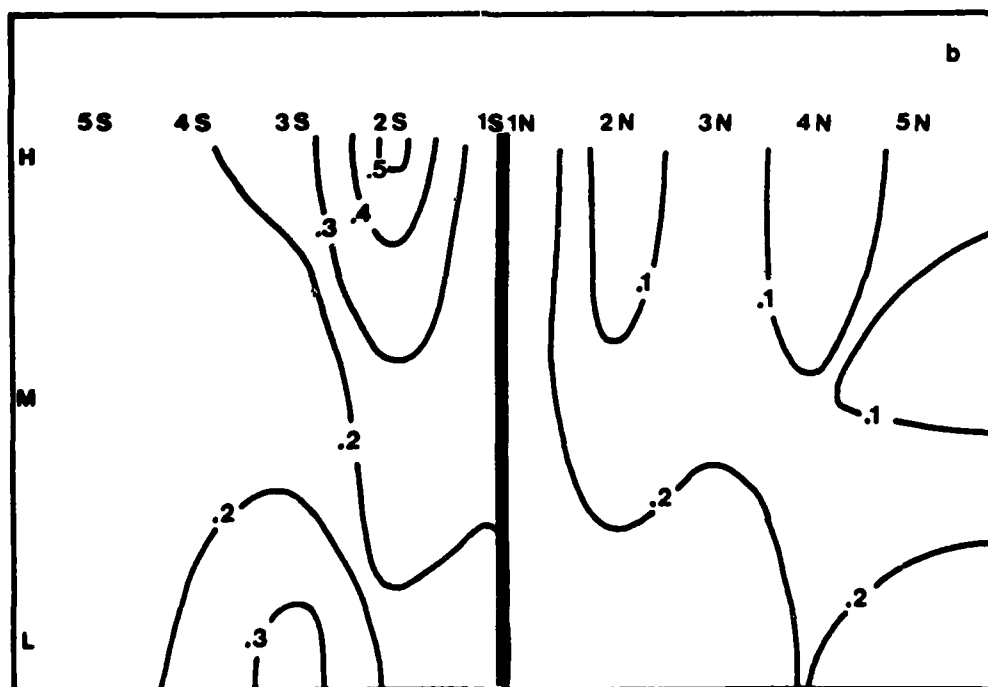


Figure 13b. Grain size S.D.*

*Letters along the left side indicate the foreshore zone (upper, mid and lower). Transect locations are indicated across the top. Distance between transects is 100 meters.

The t-test was also used to determine whether differences in grain size and sorting before and after August 15 are significant. The mean grain size shows no significant difference in the upper foreshore on either side of the pier between the two wave regimes. However, the mean is greater at the 0.05 level during the transitional regime in the mid and lower foreshore on both sides of the pier. This could be indicative of greater wave energy resulting in the transport of fine sand offshore. The standard deviations are not significantly different in the upper foreshore, although north of the pier the standard deviation is larger, i.e., the sand is more poorly sorted, after August 15. In the midforeshore the difference between the two wave regimes is significant at the 0.01 level; the sand is more poorly sorted during the transitional regime. In the lower foreshore south of the pier the difference in standard deviation is not significant, while north of the pier it is significant at the 0.05 level.

These statistical comparisons support the "pier effect" hypothesis. The sediment is finer and better sorted north of the pier during the summer wave regime. During the transitional regime the sand on both sides of the pier becomes coarser and more poorly sorted, although to a lesser degree on the north side of the pier.

The contours of the mean beach slope show several interesting attributes which provide further evidence of

the interaction of the pier structure with incident wave energy and beach morphology. During the summer wave regime (Figure 14a) south of the pier the slope increases from the upper to midforeshore and remains constant across the lower half of the foreshore. The standard deviations (Figure 14b) south of the pier are relatively small, indicating stable conditions. The large standard deviations under and immediately south of the pier in the upper foreshore may be associated with a combination of increased surf turbulence in this area during high tide and periods of large waves which can cause rapid changes in beach topography.

The feature north of the pier provides graphic evidence of the effect of wave direction. Shepard (1973) describes giant cusps whose "projecting points are spaced at intervals of a hundred or more meters." The feature shown in these contour maps resembles one horn of a large cusp system. During the summer regime (Figure 14a) the crest and troughs are parallel with the dominant direction of incident wave energy--the southeast. During the transitional regime (Figure 15a) this geomorphic feature is oriented to the east, again parallel with the incident wave energy. A region of smaller slope in the upper and midforeshore immediately south of the pier reflects the attenuation of wave energy which now arrives from slightly north of the pier. The pattern of standard deviations is complex (Figure 15b). The largest standard deviations are

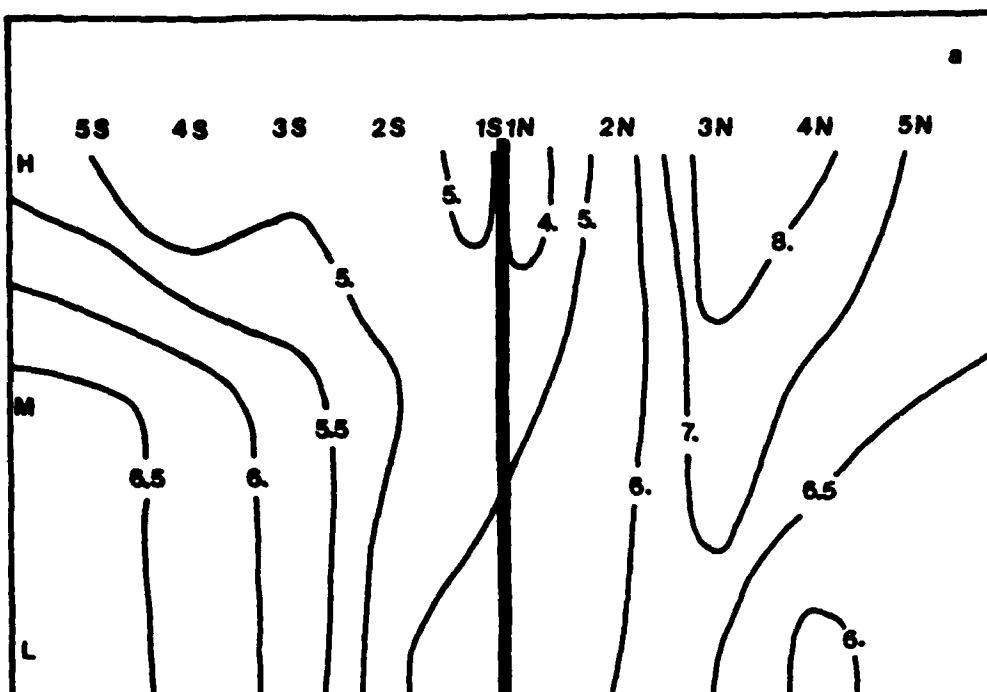


Figure 14a. Slope mean in degrees, summer wave regime.*

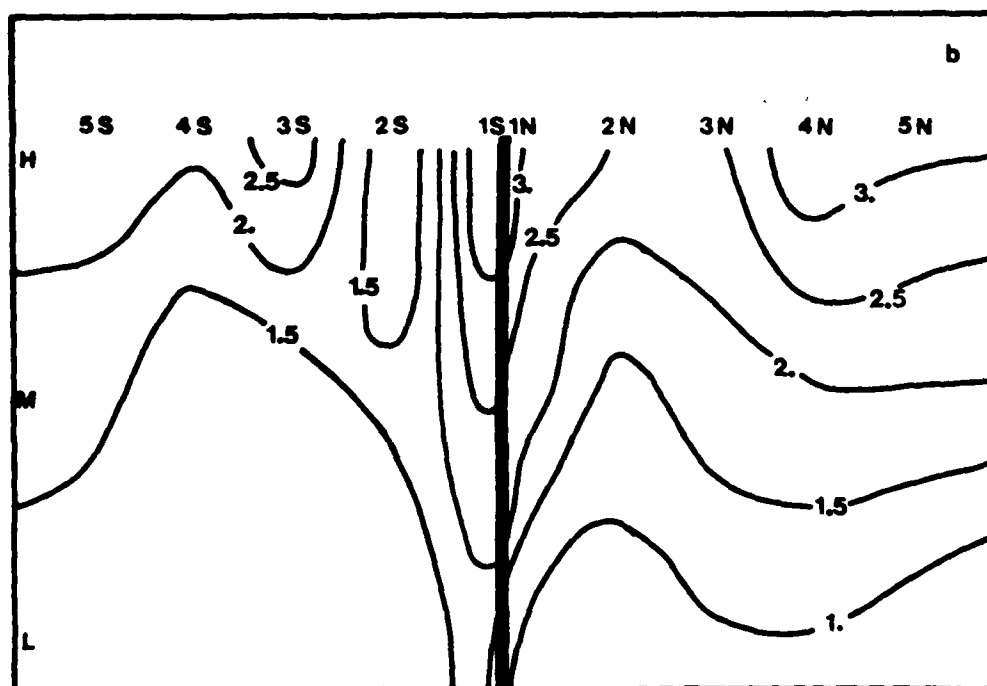


Figure 14b. Slope S.D.*

*Letters along the left side indicate the foreshore zone (upper, mid and lower). Transect locations are indicated across the top. Distance between transects is 100 meters.

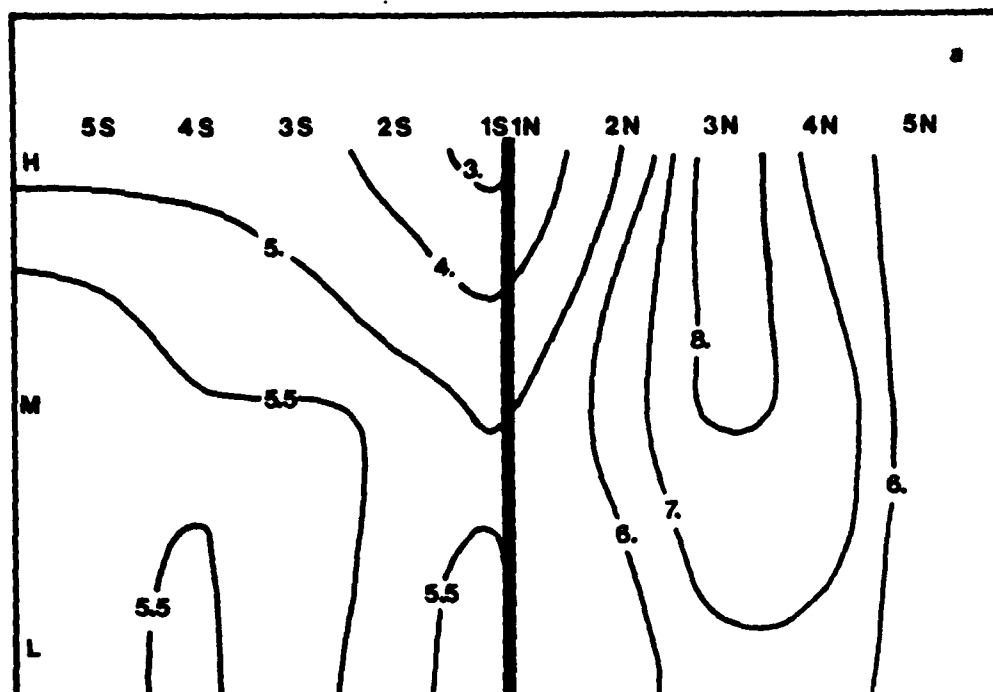


Figure 15a. Slope mean in degrees, transitional wave regime.*

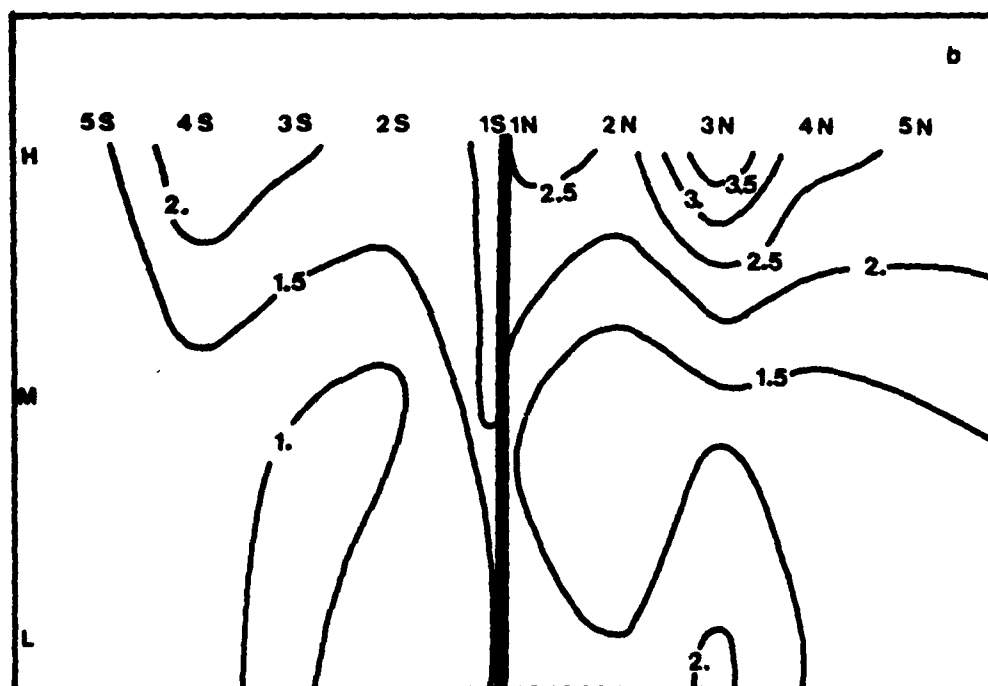


Figure 15b. Slope S.D.*

*Letters along the left side indicate the foreshore zone (upper, mid and lower). Transect locations are indicated across the top. Distance between transects is 100 meters.

associated with the crest of the cusp, suggesting that it is relatively unstable and easily affected by large waves.

Emerita and Grain Size

To assess the relationship of *Emerita* to grain size the number of *Emerita* per core is plotted against grain size (Figure 16) using the entire February through November FRF data set. The skewed distribution appears to have a peak around 0.5-0.6 mm. A frequency distribution of grain size for the same data set (Table 3) shows that the grain size of 66% of all cores taken lies between 0.25 and 0.5 mm. Only 9% of the cores have a mean grain size between 0.5 and 0.6 mm. These data lead to the conclusion that the peak in the *Emerita*/grain size distribution is not merely a result of the underlying grain size distribution. Rather, *Emerita* preferentially inhabit sand within a relatively narrow grain size spectrum. It is quite likely that this window is related to the ability of *Emerita* to burrow in various grain sizes.

Emerita and Beach Slope

The *Emerita*/beach slope distribution is also plotted (Figure 17) and has a peak between 5.6 and 7.0 degrees. The frequency distribution of beach slope (Table 4) shows that slopes of 5.0, 6.0 and 7.0 degrees comprise 60.2% of all the cores. The mean slope is 5.76 degrees and the median is 5.8 degrees, both of which lie within the peak

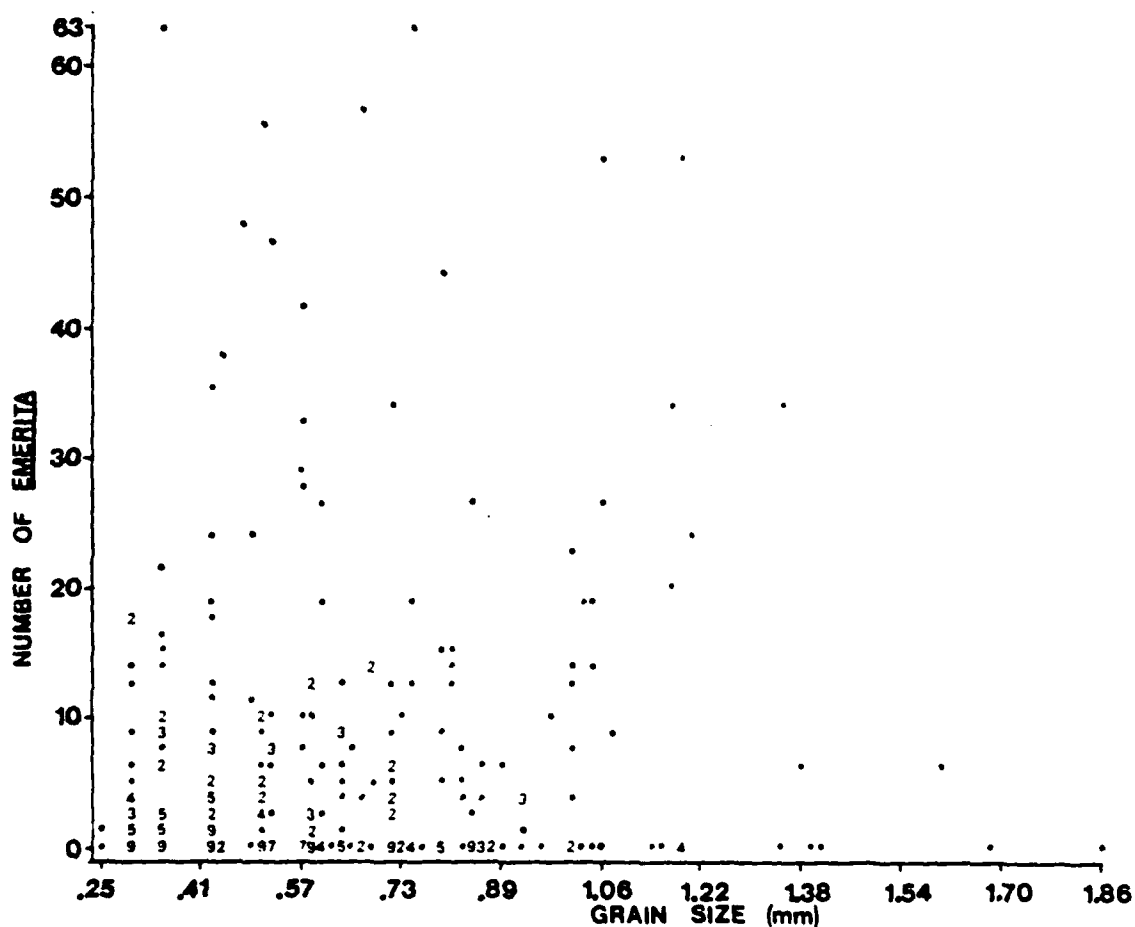


Figure 16. Number of *Emerita* per core vs. grain size. Numerals indicate the number of points at a locus; single points are represented by dots. A "9" represents nine or more points. To convert number of *Emerita* per core to number per m^2 multiply by 124.9.

Table 3. Grain Size Frequency Distribution and Statistics.

Grain Size (mm)	Absolute Frequency	Relative Frequency (%)	Cumulative Frequency (%)
.25	2	0	0
.30	98	17	18
.35	109	19	37
.42	117	21	57
.44	3	1	58
.47	1	0	58
.49	3	1	58
.50	41	7	66
.53	14	2	68
.57	13	2	70
.59	23	4	74
.60	4	1	75
.61	4	1	76
.62	1	0	76
.63	13	2	78
.65	2	0	79
.67	4	1	79
.68	3	1	80
.69	1	0	80
.71	23	4	84
.72	3	1	85
.73	1	0	85
.74	2	0	85
.75	7	1	86
.77	1	0	86
.80	9	2	88
.81	3	1	89
.83	4	1	89
.84	11	2	91
.86	5	1	92
.88	2	0	92
.89	2	0	93

Table 3 (cont.)

Grain Size (mm)	Absolute Frequency	Relative Frequency (%)	Cumulative Frequency (%)
.92	5	1	94
6	1	0	94
.94	1	0	94
1.00	7	1	95
1.02	2	0	96
1.04	3	1	96
1.05	3	1	97
1.07	1	0	97
1.14	1	0	97
1.15	1	0	97
1.16	2	0	98
1.19	5	1	98
1.20	1	0	99
1.35	2	0	99
1.37	1	0	99
1.40	1	0	99
1.41	1	0	99
1.61	1	0	100
1.68	1	0	100
1.86	1	0	100
Mean	.514	Skewness	1.825
Median	.421	Kurtosis	4.250
Mode	.420	Std Deviation	.239
Std Error	.010	Variance	.057

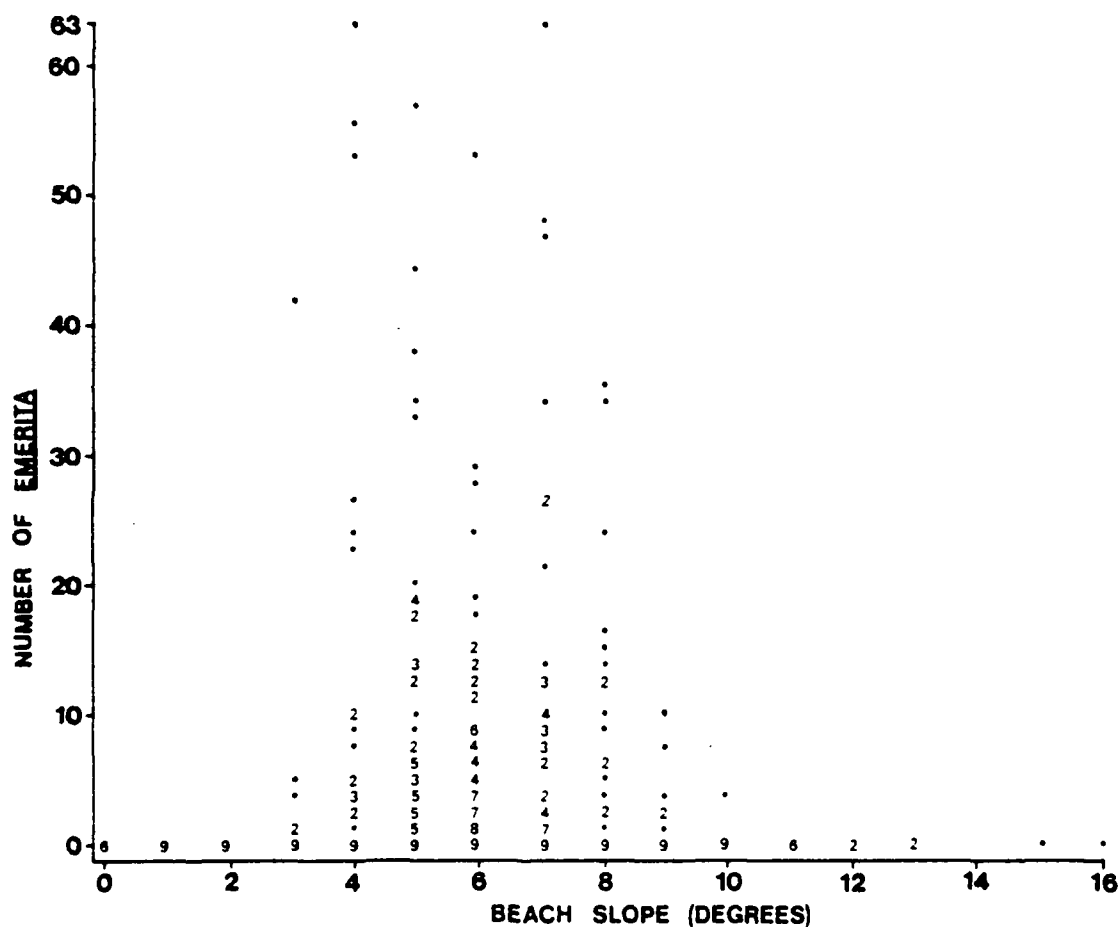


Figure 17. Number of *Emerita* per core vs. beach slope. Numerals indicate the number of points at a locus; single points are represented by dots. A "9" represents nine or more points. To convert number of *Emerita* per core to number per m^2 multiply by 124.8

Table 4. Beach Slope Frequency Distribution and Statistics.

<u>Slope (Degrees)</u>	<u>Absolute Frequency</u>	<u>Relative Frequency (%)</u>	<u>Cumulative Frequency (%)</u>
0.0	6	1.1	1.1
1.0	17	3.0	4.0
2.0	20	3.5	7.5
3.0	27	4.7	12.3
4.0	62	10.9	23.2
5.0	113	19.8	43.0
6.0	132	23.2	66.1
7.0	98	17.2	83.3
8.0	50	8.8	92.1
9.0	22	3.9	96.0
10.0	11	1.9	97.9
11.0	6	1.1	98.9
12.0	2	.4	99.3
13.0	2	.4	99.6
15.0	1	.2	99.8
16.0	1	.2	100.0
Mean	5.761	Skewness	.221
Median	5.803	Kurtosis	1.723
Mode	6.000	Std Deviation	2.181
Std Error	.091	Variance	4.755

region of the *Emerita*/beach slope distribution. From this information and the symmetric nature of the *Emerita*/beach slope distribution the conclusion is reached that *Emerita* do not preferentially inhabit a region with a specific slope.

Emerita SPATIAL DISTRIBUTION

The spatial distribution of *Emerita* at the FRF is influenced by the pier and its effects on the beach environment. The contour maps show that: (1) *Emerita* are most abundant in the lower half of the foreshore within the active swash zone; (2) *Emerita* populations are greater in areas of lower wave energy--in this case the relatively low energy beach north of the pier and particularly in the troughs of the large cusp; and (3) *Emerita* populations are highly variable in time and space, as shown by the standard deviations.

Contour maps and discussion for each size class appear in Appendix A. A zonal pattern is present south of the pier; the large and medium classes also show rhythmicity. Population densities are greatest north of the pier. The different locations of high density cells and the unique distribution of the standard deviation for each size class suggest that each size class responds differently to environmental factors and pier effects.

Summer Regime

The contours for the mean number of *Emerita* during the summer wave regime (Figure 18a) depict the effect of the pier. South of the pier a zonal distribution is present with the population density increasing toward the lower foreshore. The sinusoidal contours observed in the mid-foreshore may be associated with cusps although none are indicated on the slope contour map (Figure 14a). The pier structure interrupts this zonal pattern and causes a steep gradient immediately to its north. The population density is greater north of the pier, particularly in the upper and midforeshore. The high density cells in the midforeshore probably indicate the presence of aggregations during some of the sampling periods. This is supported by the standard deviation map (Figure 18b) which shows a standard deviation greater than the mean at all core locations at which *Emerita* were found. Thus, *Emerita* populations are highly variable both spatially and temporally. There is no readily apparent correspondence between the distribution of *Emerita* and grain size (Figure 12a). However, comparison of Figure 18a with Figure 14a shows that the high density cells in the midforeshore lie within the troughs of the large cusp, which are areas of lower wave energy.

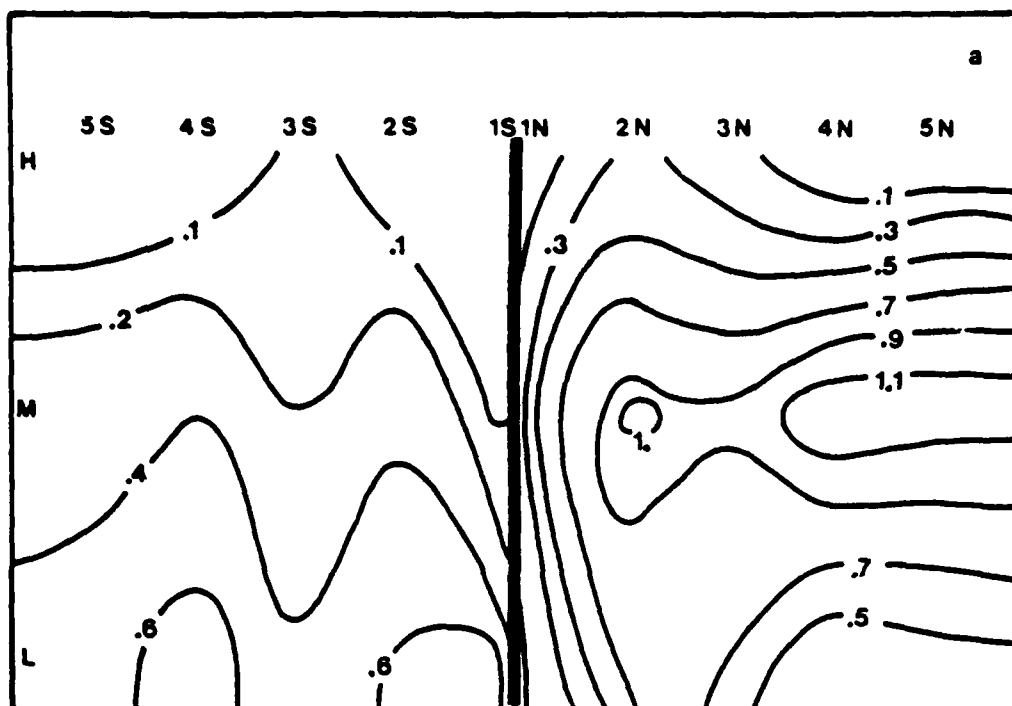


Figure 18a. Mean number of *Emerita*, summer wave regime.*

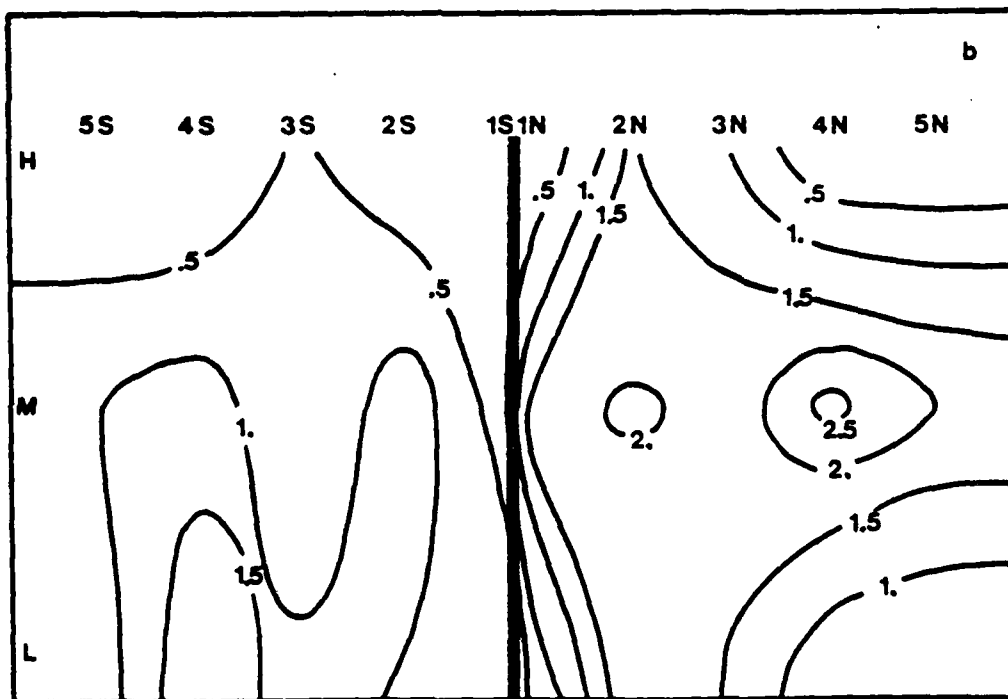


Figure 18b. S.D.*

*Letters along the left side indicate the foreshore zone (upper, mid and lower). Transect locations are indicated across the top. Distance between transects is 100 meters. To convert number of *Emerita* per core to number per m^2 multiply by 124.8.

Transitional Regime

During the transitional wave regime the distribution of *Emerita* is more uniform both along and across the beach. Pier effects are limited to a short length of beach on either side of the pier. The mean (Figure 19a) increases across the beach toward the lower foreshore and lacks the steep gradient parallel with the pier which was evident during the summer regime. In contrast with the earlier period, densities are now comparable on both sides of the pier. The cells in the lower foreshore north of the pier lie in areas of medium or coarse sand (Figure 13a) and within the troughs of the large cusp (Figure 15a). The standard deviations (Figure 19b) are generally greater than twice the mean, indicating the continuing variability of the population. Also, the densities are greater during the transitional regime, supporting the hypothesis that the population reaches a peak during this period.

The four size classes show the zonal distribution to varying degrees (Appendix B). The large and medium classes apparently are only slightly affected by the presence of the pier. Some high density cells of these classes are spatially coincident, suggesting the presence of aggregations of large and medium *Emerita*. The zonal distribution of the small and juvenile *Emerita* is interrupted by the pier; turbulence under the pier structure may be a factor. The small size class has the greatest densities of any of the classes throughout the year during this regime.

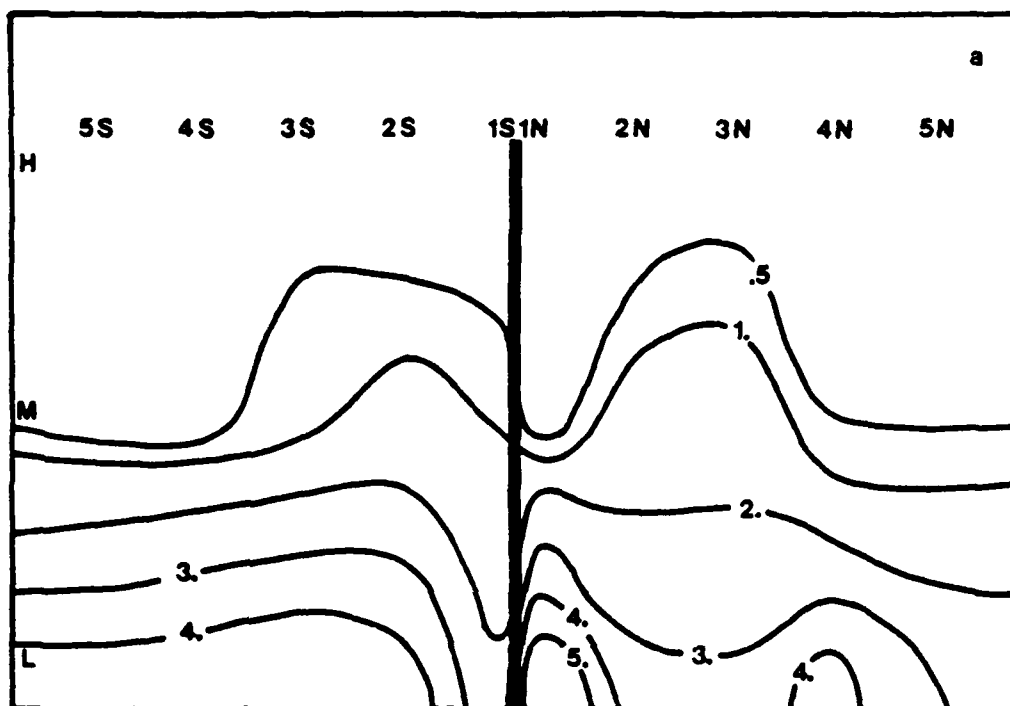


Figure 19a. Mean number of *Emerita*, transitional wave regime.*

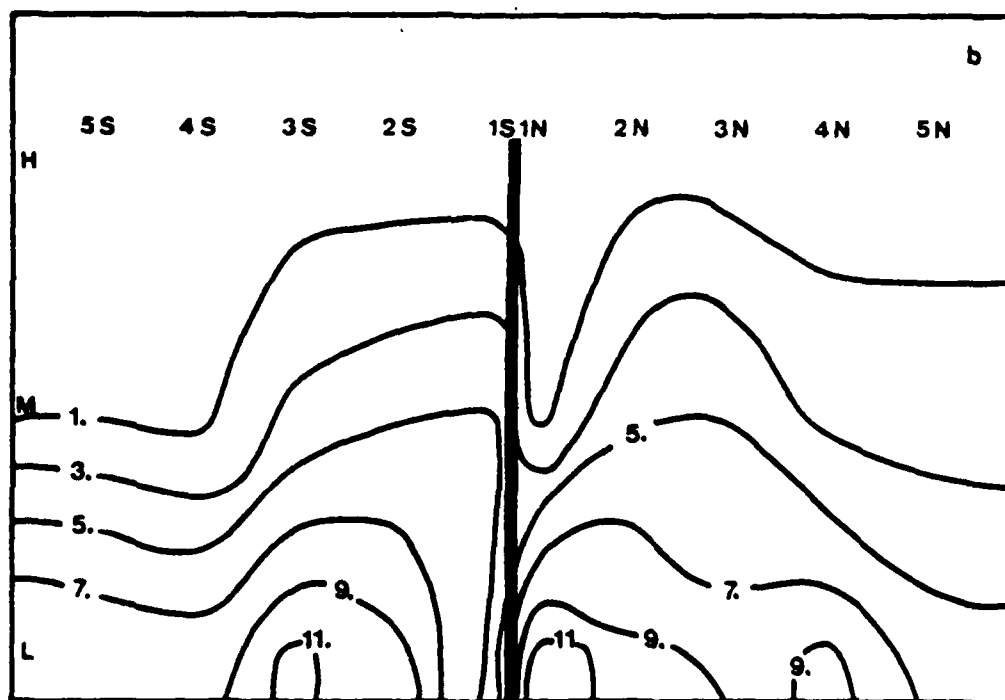


Figure 19b. S.D.*

*Letters along the left side indicate the foreshore zone (upper, mid and lower). Transect locations are indicated across the top. Distance between transects is 100 meters. To convert number of *Emerita* per core to number per m^2 multiply by 124.8.

Emerita Depth Distribution

The data collected at the Sandbridge, Virginia, Delaware and Assateague Island sites have been combined in Figures 20 and 21. Distance across the beach is expressed as the relative foreshore width; this circumvents the problem of sampling on beaches of different width and allows comparison with the data collected at the CERC pier, which is also presented with a relative across-the-beach scale. These data should be considered preliminary; further sampling is necessary to provide a richer data set.

Figure 20 is a high resolution representation of the distribution of *Emerita* across the beach. It shows very few *Emerita* high on the foreshore, a pattern predicted by the model and supported by the low resolution results presented above. At approximately halfway across the foreshore the mean number of *Emerita* increases sharply and remains at a relatively high level until the 0.75 relative foreshore width is reached. Examination of the field observations reveals that the upper limit of the active swash zone in almost all cases lay within this section of the foreshore. The peaks in the upper line (maximum number of *Emerita*) in Figure 20 probably indicate the presence of an aggregation during one of the sampling periods. The decline in the mean number of *Emerita* in the lower foreshore near the step is probably a result of surf turbulence.

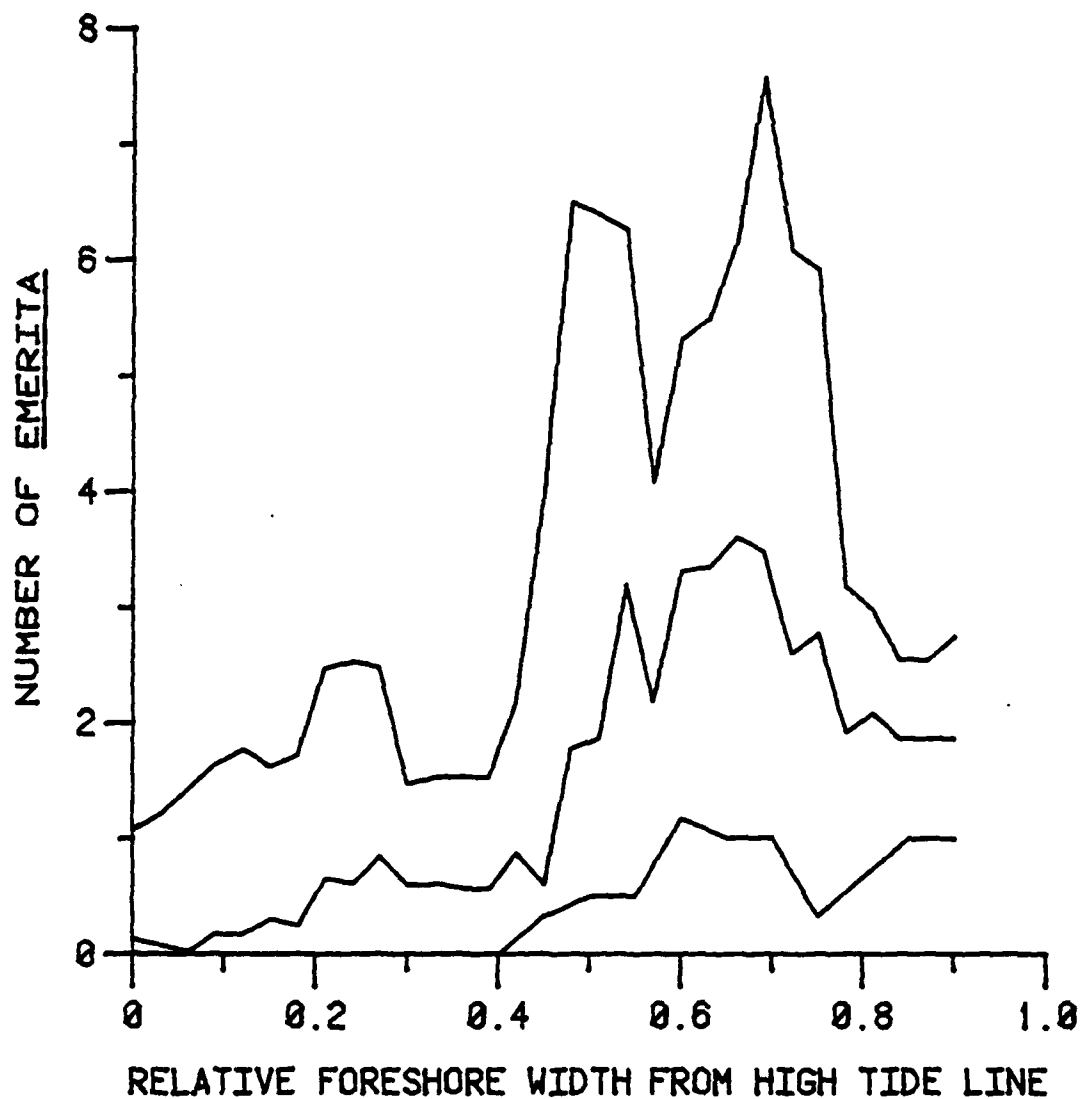


Figure 20. Number of *Emerita* per core vs. relative foreshore width. 0 is the high tide line, 1 is the step. The upper line is the maximum number of *Emerita*, the center line is the mean number, and the lower line is the minimum number found at a given foreshore width. To convert number of *Emerita* per core to number per m^2 multiply by 124.8.

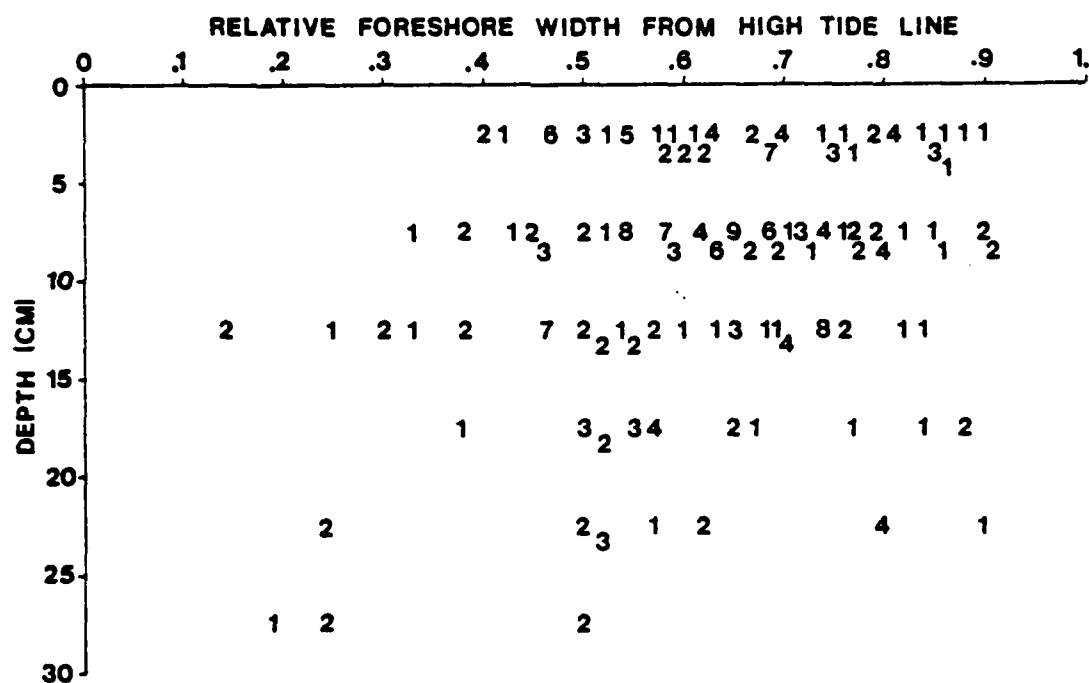


Figure 21. Depth distribution of *Emerita*. Numerals indicate the number of *Emerita* found at a given relative foreshore width within a 5 cm layer of sediment. 0 along the horizontal axis is the high tide line, 1 is the step.

The depth distribution of *Emerita* is shown in Figure 21. *Emerita* which are found high on the foreshore occur at depth; they are found nearer the surface toward the midforeshore. This pattern is also predicted by the model. From 0.4-0.9 relative foreshore width *Emerita* are found from the surface to 25-30 cm depth. This depth seems to indicate a maximum which is controlled by the ability of *Emerita* to burrow, its ability to survive over a tidal cycle without feeding (*E. talpoida* can feed only in the presence of moving water), and the water table depth. The lenticular distribution discussed in the model is roughly followed. Knox and Boolootian (1963) observed a similar pattern in *E. analoga* populations.

Emerita TEMPORAL DISTRIBUTION

The temporal pattern of *Emerita* is marked by a general increase in numbers from early spring to a seasonal maximum in late summer and early fall. Rapid fluctuations are superimposed on this cycle. Some of these fluctuations are apparently associated with changes in wave height, caused by storms, and tide level. Each size class behaves somewhat differently to environmental stress, suggesting that a threshold mechanism may be important in the temporal variations of the species. Different temporal patterns are observed in each foreshore zone. The standard deviations are generally several times greater than the mean; Table 5 gives the relationship between the two.

Table 5. Standard Deviations for *Emerita* by Size Class and Beach Zone as a Function of the Mean.

<u>Class</u>	<u>Foreshore Zone</u>		
	<u>Upper</u>	<u>Mid</u>	<u>Lower</u>
Juvenile	---	2.48-3.33	1.89-2.37
Small	3.02-3.33	1.28-3.33	1.41-3.33
Medium	2.48-3.33	1.37-3.33	1.27-3.33
Large	2.38-2.94	1.37-3.33	1.19-3.33
Total	1.76-3.33	0.84-3.33	0.87-1.77

The temporal curves for the entire *Emerita* population are best suited for illustrating the general influence of climatic events. Wave energy and tide level are dominant in determining population fluctuations. Population increases often occur during periods of low to moderate wave energy and/or falling tide levels. Declines in the population occur during periods of high energy and/or rising tide levels. Water temperature plays a role in the initial appearance of *Emerita* on the foreshore. Some of the fluctuations in the temporal curves are undoubtedly related to biological factors such as predation and mortality; these factors, however, cannot be addressed with this data set. The large standard deviations shown in Table 5 reflect the spatial variability of *Emerita* on a given day.

Emerita were present in the upper foreshore only during the month of May, 1980 (Figure 22a). The large, medium and small size classes were represented (Appendix C). Comparison of Figure 22a with Figures 24a and 24b shows that this peak immediately followed moderate wave energy conditions and occurred between spring high and low tides. This peak may represent movement of some *Emerita* out of the more highly stressed mid and lower foreshore. The upper foreshore does not appear to be a suitable area for *Emerita* for the remainder of the seasonal cycle. However, it is important to reemphasize that the data was collected between high tide and the following low tide; normally

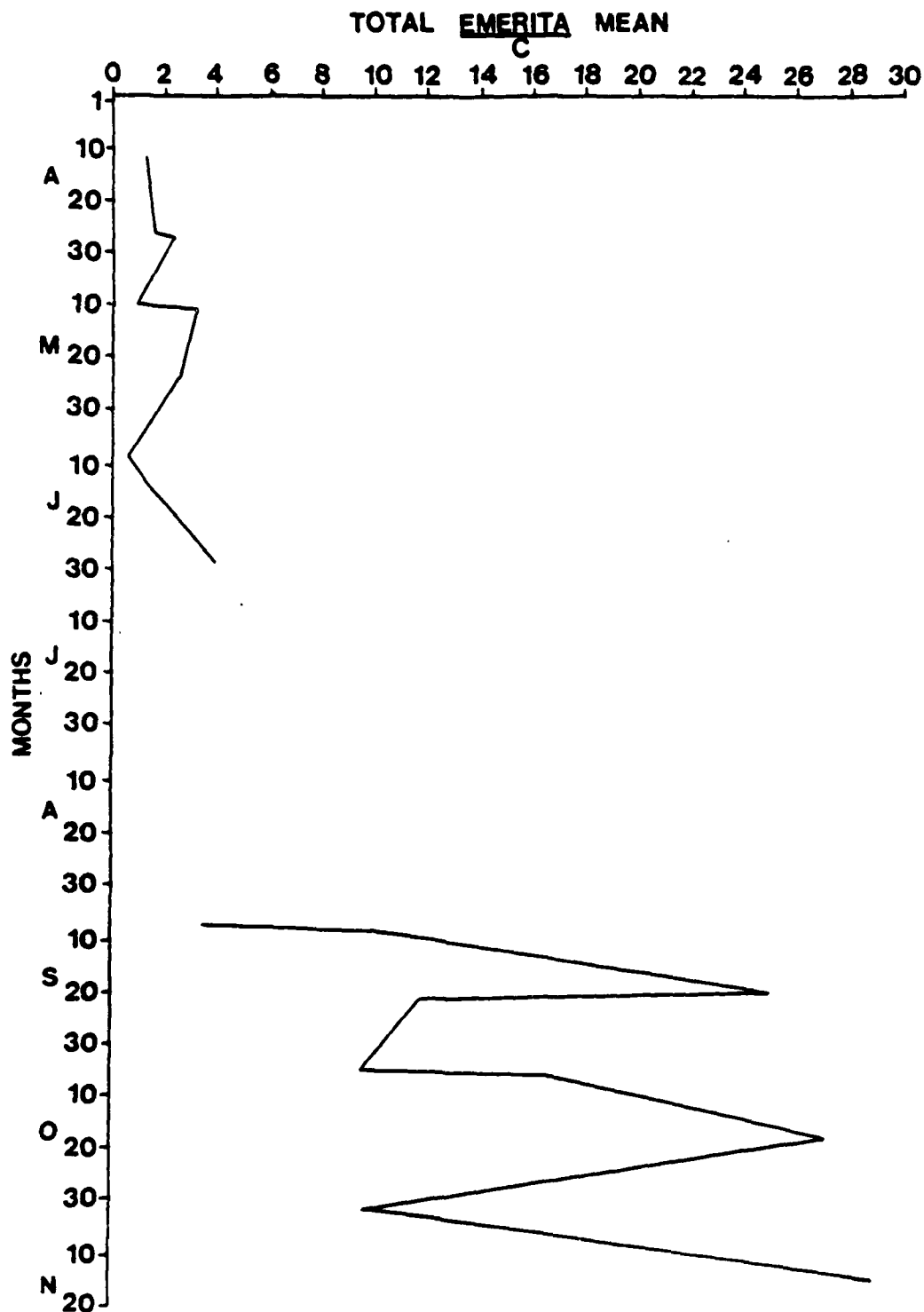


Figure 22. Temporal record of the entire *Emerita* population.
(cont.) Horizontal scale is the mean number of *Emerita* per core averaged over 10 cores. The gap in the record from late June through early September represents missing data.

c. Lower foreshore.

To convert number of *Emerita* per core to number per m^2 multiply by 124.8.

sampling was timed to end at or near the time of low tide. Since *Emerita* migrate across the foreshore with the tides, they would be found in the upper foreshore during high tide.

Water Temperature

The initial appearance of *Emerita* in samples in the mid and lower foreshore on April 12, 1980 (Figures 22b and 22c) coincided with a sharp increase in water temperature. Low water temperatures in February ($\bar{x} = 3.5^{\circ}\text{C}$) and March ($\bar{x} = 4.8^{\circ}\text{C}$) were followed by a rapid rise in water temperature which continued through late April (Figure 23 and Table 6). This rise probably resulted from the advection of warm Gulf Stream water toward the shore.

E. talpoida have been noted to overwinter offshore at Woods Hole, Massachusetts (Edwards and Irving, 1943). The Duck FRF data suggest this is also the case for coastal North Carolina. A causal relationship between water temperature and onshore migration cannot be established from these data; years of record would be required. However, they do suggest a mechanism which could explain seasonal onshore and offshore migration and that could be tested through yearly sampling.

Edwards and Irving (1943) found that the metabolic activity of *E. talpoida* is adjusted to the low water temperatures during winter so that it can actively feed and grow during this offshore phase of its life cycle.

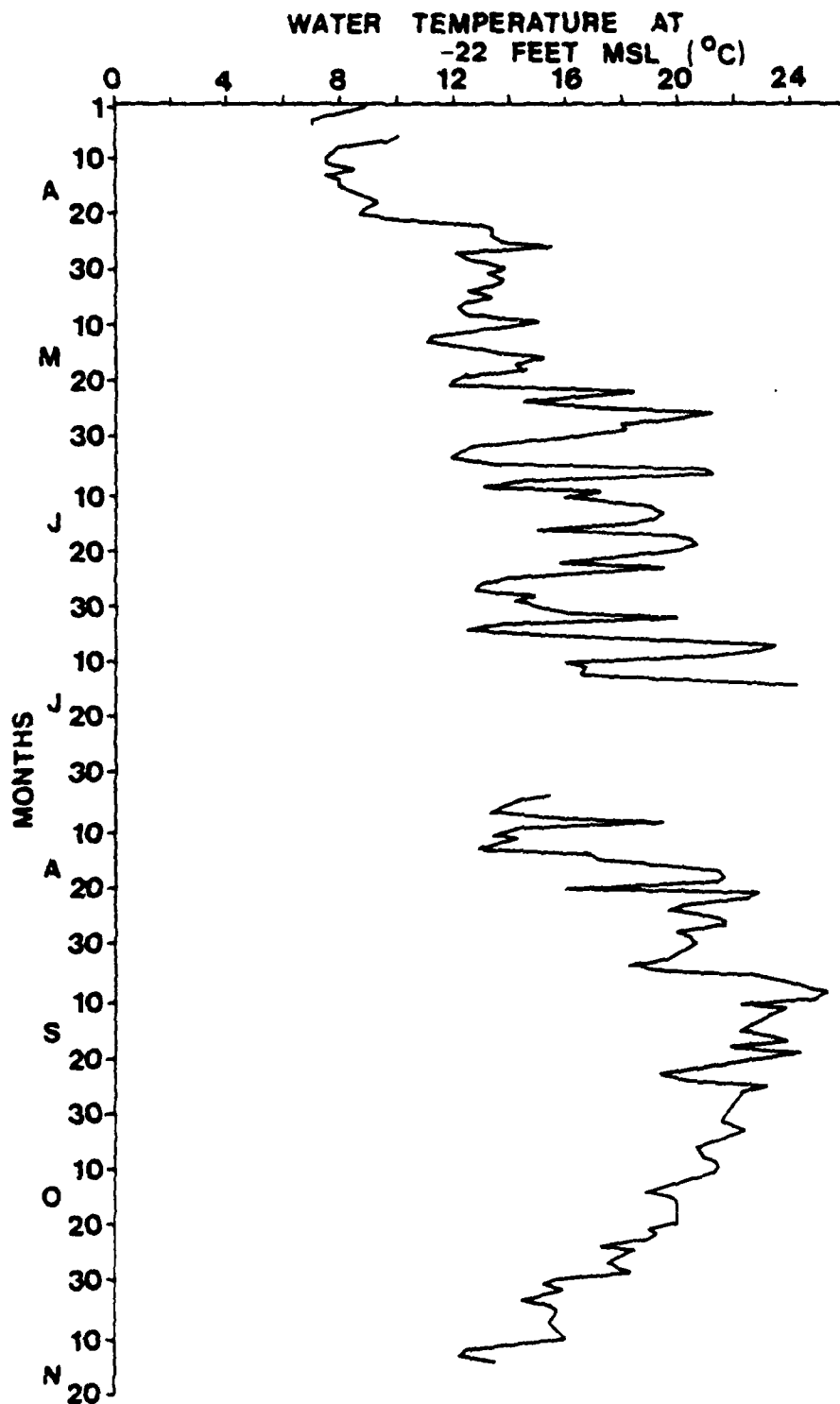


Figure 23. Temporal record of water temperature at the FRF. Gaps in the record indicate missing data.

Table 6. Water Temperature at -22 ft MSL at the FRF.

<u>Period</u>	<u>Mean $\pm$ S.D.</u>	<u>Range</u>
February, 1980	3.5 $\pm$.97°C	2 - 5.7°C
March	4.8 $\pm$ 1.8°C	1.5 - 7.5°C
April 1-12	8.1 $\pm$ 0.9°C	7.0 - 10.0°C
April 12-20	8.4 $\pm$ 0.5°C	7.5 - 9.3°C
April 20-22	10.5 $\pm$ 2.2°C	8.7 - 13.0°C
April 22-30	13.4 $\pm$ 0.9°C	12.1 - 15.5°C

If the migration response is controlled in some manner by water temperature, then it would be triggered when the ambient water temperature reaches the critical value required for onshore or offshore migration. Alternatively, advection of warm water toward the shore could physically transfer *Emerita* from regions where they had already returned to shore and at the same time cause the overwintering population to begin onshore migration as a result of the rapidly increased temperature. Once *Emerita* has passed out of the overwintering phase it is not affected by the large temperature variations which commonly occur in nearshore waters (Figure 23). Edwards and Irving (1943) found that *E. talpoida* rapidly adapts to temperature changes of as much as 10°C.

Wave Energy and Tide Level

The increase in the *Emerita* population in the midforeshore from April 12-May 10 is due mainly to onshore migration. This period is one of relatively low wave energy (Figure 24b and Table 7) and lies, predominantly, between the dates of spring high and low tides (Figure 24a). Most of the remaining population fluctuations in this area of the foreshore are also related to changes in wave energy and/or tide level. Table 8a shows that population increases occur during periods of falling tide level and low or moderate wave energy. This pattern is also evident in the lower foreshore (Figure 22c and Table 8b); the

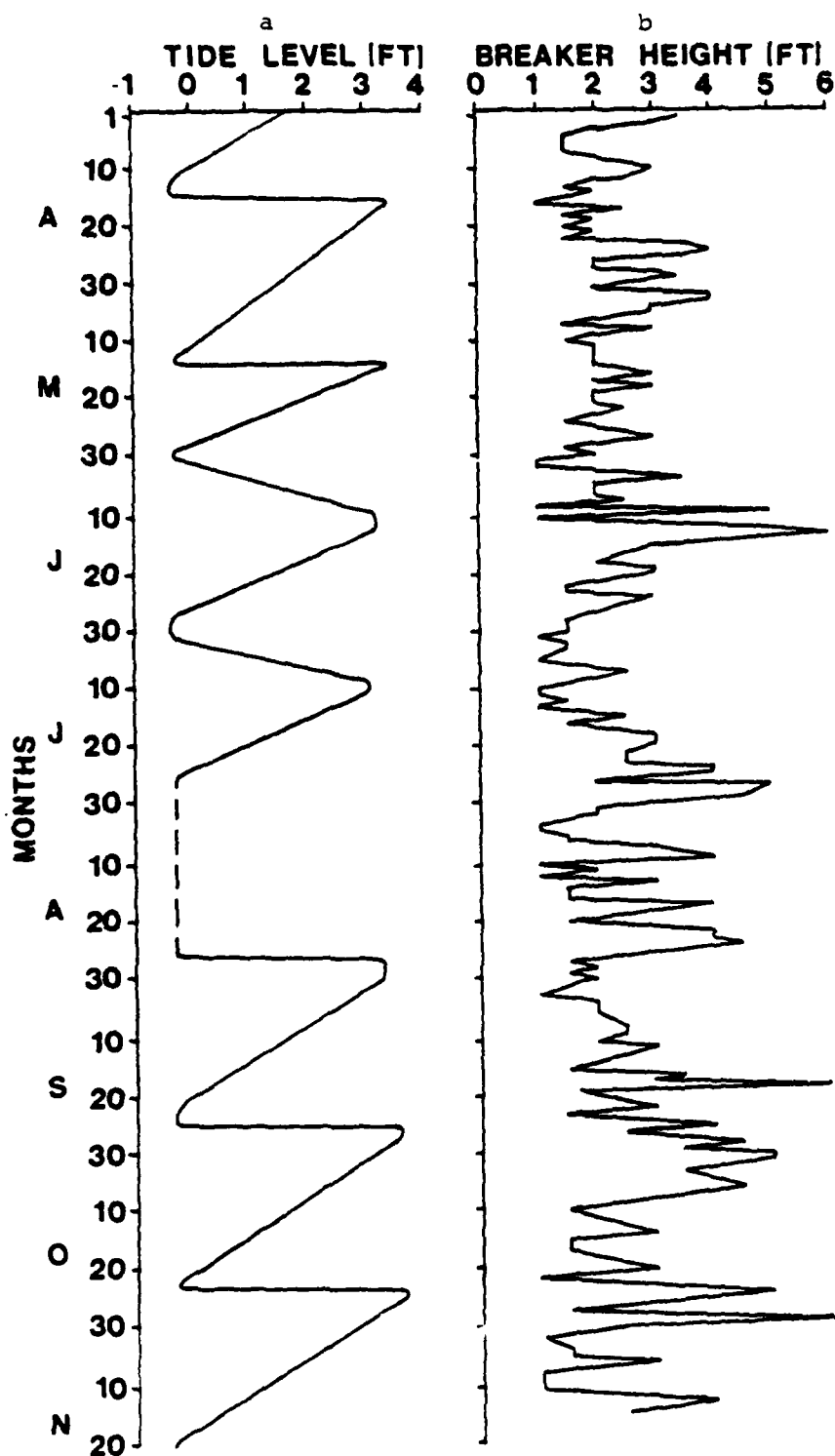


Figure 24a. Temporal record of the tide level for the area of Kitty Hawk, N.C. Data taken from the 1980 Tide Tables published by N.O.A.A. Dashed line indicates a probable error in the tables.

b. Temporal record of breaker height at the FRF derived from daily observations made at the pier.

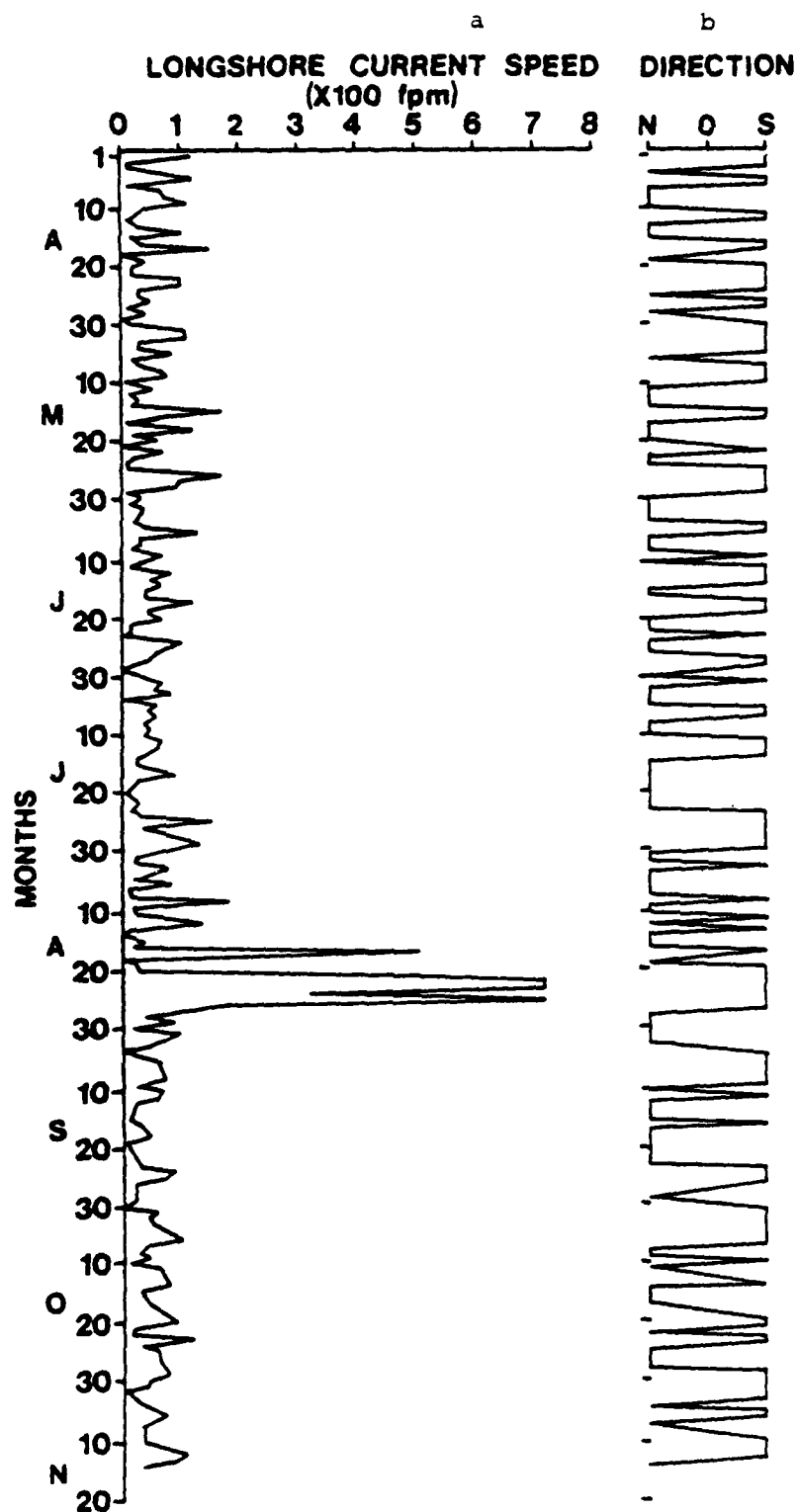


Figure 25a. Temporal record of longshore current speed at the FRF derived from daily observations made at the pier.

b. Temporal record of longshore current direction at the FRF. 0 indicates no longshore current.

Table 7. Mean Breaker Heights.

<u>Period</u>	<u>Breaker Height (ft)</u> <u>(Mean $\pm$ S.D.)</u>	<u>Range (ft)</u>
April 12-26, 1980	2.1 $\pm$ 0.9	1.0 - 4.0
April 12-May 10	2.4 $\pm$ 0.9	1.0 - 4.0
April 26-May 10	2.6 $\pm$ 0.8	1.5 - 4.0
April 26-May 24	2.4 $\pm$ 0.7	1.5 - 4.0
May 24-June 8	2.0 $\pm$ 0.7	1.0 - 3.5
June 8-29	2.7 $\pm$ 1.4	1.0 - 6.0
September 6-20	2.8 $\pm$ 1.3	1.5 - 6.0
September 20-October 5	3.5 $\pm$ 1.2	1.5 - 5.0
October 5-18	2.4 $\pm$ 1.1	1.5 - 4.5
October 18-November 1	3.7 $\pm$ 3.0	1.0 - 6.0
November 1-14	2.1 $\pm$ 1.1	1.0 - 4.0

Table 8a. Comparison of *Emerita* Population Fluctuations with Environmental Variations, Midforeshore.

<u><i>Emerita</i> Fluctuation</u>	<u>Wave Energy</u>	<u>Tide Level</u>	<u>Predominant Wave Approach</u>
Increase from 4/12-5/10	Low	Falling	E and SE
Decline from 5/24-6/8	Low	Rising	E
Increase from 9/20-21	Moderate	Falling	E
Decline from 10/4-5	High	Falling	E
Increase from 10/5-18	Moderate	Falling	SE
Decline from 10/18-11/1	High	Rising	E

Table 8b. Comparison of *Emerita* Population Fluctuations with Environmental Variations, Lower Foreshore.

Decline from 4/27-5/10	Moderate	Falling	E
Increase from 6/8-29	Moderate	Falling	SE
Increase from 9/7-20	Moderate	Falling	E
Decline from 9/20-10/5	High	Rising	E
Increase from 10/5-18	Moderate	Falling	E
Decline from 10/18-11/1	High	Rising	E
Increase from 11/1-14	Low	Falling	E

most rapid population declines occur during periods of high energy and rising tide level.

The fluctuations of the four size classes are similar to those discussed above (Appendix C). The medium and small classes show some tendency to migrate between fore-shore zones. Although data is lacking for July and August, observations made at the other sites during the summer indicate that the maxima in September and October for each size class are the seasonal maxima.

CORRELATIONS BETWEEN VARIABLES

Table 9 gives correlation coefficients for the biologic, environmental and geomorphic variables for both wave regimes. Few coefficients are found in Table 9b (transitional regime) because environmental data were not available for the sampling dates.

Summer Regime

The correlation coefficients in Table 9a suggest that changes in *Emerita* numbers in adjacent fore-shore zones are coupled. Population increases in the upper foreshore correspond with increases in the midforeshore. Increases in the midforeshore, however, correspond with population declines in the lower zone. These patterns probably reflect migration of *Emerita* from one zone to another and support the temporal data in Appendix C.

Table 9. Pearson Correlation Coefficients for *Emerita*, Environmental and Geomorphic Data.

Variables

1. Total *Emerita* mean, upper foreshore.
2. Total *Emerita* mean, midforeshore.
3. Total *Emerita* mean, lower foreshore.
4. Tide level.
5. Wave height.
6. Wave approach.
7. Current speed.
8. Current direction.
9. Water temperature at -22 ft MSL.
10. Slope mean, upper foreshore.
11. Slope mean, midforeshore.
12. Slope mean, lower foreshore.
13. Grain size mean, upper foreshore.
14. Grain size mean, midforeshore.
15. Grain size mean, lower foreshore.

There is little tendency for *Emerita* numbers to be linearly correlated at a significance level equal to or less than 0.1 with environmental or geomorphic variables. The spatial distribution of the population, however, has been shown to be influenced by these variables. Correlation coefficients between biologic and environmental and geomorphic variables might be significantly correlated, although perhaps not strongly, if matrices were produced for the north and south sides of the pier.

Table 9a shows that *Emerita* migrate from the upper foreshore during periods of high tide levels. The population in the lower foreshore is positively correlated with wave approach; the population increases as the direction of incident wave energy rotates toward the southeast. This reflects the higher *Emerita* densities found north of the pier during this regime.

The population in the upper and midforeshore increases with increasing slope in the lower foreshore. As the slope in the lower foreshore increases, the wave energy is expended across a narrower section of beach, i.e., the energy density increases. *Emerita* then migrate out of the lower zone to the upper zones. Conversely, decreasing slopes result in a lower energy density and *Emerita* then migrate to these areas. This relationship was evident when the contours of *Emerita* and beach slope were compared. High density cells of *Emerita* were located in the troughs of the large cusp.

Tide level is positively correlated with wave height and negatively correlated with slope in the upper and lower foreshore. Wave height is positively correlated with slope in the upper foreshore. This pattern suggests that high tide levels allow onshore transport of sediment from the nearshore subaqueous zone, resulting in gentler slopes. High wave events, however, cause rapid offshore sediment transport, resulting in steeper slopes. Furthermore, the finer grain sizes are transported as shown by the positive correlations between wave height and grain size in the mid and lower foreshore.

The coupling of adjacent foreshore zones observed for *Emerita* is also apparent for beach slope. Slope is positively correlated between the upper and midforeshore and between the mid and lower foreshore. The lower two zones are more strongly correlated than the upper two. The slope and grain size in the upper foreshore are positively correlated, although not strongly. As the slope increases the grain size also increases. This relationship is not apparent the mid or lower foreshore.

Grain size is positively correlated between the mid and lower foreshore. This reflects the fact that these two zones are subject to swash action for a longer portion of each tidal cycle than is the upper foreshore. These two zones also receive the major portion of wave energy inputs during high wave events. The relationship of wave energy to sediment transport is described above.

Transitional Regime

The *Emerita* population undergoes wider fluctuations during this period than during the summer regime. This may be responsible, in part, for the lack of significant correlations between the biologic variables. The negative correlation coefficients between wave height and beach slope in the upper and midforeshore do not correspond with those of the earlier period.

Geomorphic variables show correlations similar to those calculated for the summer regime. Beach slopes in the mid and lower foreshore are positively correlated. Beach slope and grain size in the upper foreshore are more strongly correlated than during the earlier regime, perhaps as a result of generally higher wave energies. During this transitional regime grain size is positively correlated between both the upper and midforeshore and the mid and lower foreshore. Again, this probably reflects higher wave energies which now affect all three foreshore zones.

DISCUSSION

The debate over the causes of *Emerita* aggregations has continued in the literature for two decades; however, the distribution of *Emerita* on a larger scale has not been addressed to date. The results presented in this thesis indicate that the across-the-beach and longshore variations of *E. talpoida* are influenced by physical processes (e.g., wave energy and approach) and geomorphic attributes of the foreshore (e.g., grain size and beach slope).

The migration of *Emerita* across the foreshore with the tides has been well documented (Barnes and Wenner, 1968; Cubit, 1969; Efford, 1965). Efford (1965) included a 1912 observation by Weymouth and Richardson that *E. analoga* are distributed on the foreshore according to size; the youngest individuals are found highest in the swash zone and the oldest, and largest, females are found nearest the step. These data do not support that observation. Instead, *E. talpoida* are distributed zonally across the foreshore with the greatest densities occurring near the step. The contour maps for both wave regimes show that each size class exhibits this pattern.

Anomalies in this zonal distribution do occur. This is evident in Figure 18a where high density cells are observed in the midforeshore. These cells are related to the presence of cusp troughs in these locations. Due to gentler

slopes in these regions, swash energy is expended over a greater width of beach; therefore the energy density is lower. Cubitt's (1969) observation that aggregations are often associated with cusp embayments can be explained in terms of the lower energy, and thus less stressful, conditions found in these areas. The rhythmicity observed south of the pier in Figure 18a may be indicative of greater *Emerita* densities in cusp embayments. Higher resolution sampling of the type used in this study could provide useful information on this phenomenon.

Efford (1965) noted that aggregations often consist of organisms of approximately the same age group. This observation is supported by these data. High density cells in the contour maps of both the mean number of *Emerita* and the associated standard deviations are interpreted as reflecting the presence of aggregations. It is apparent that aggregations are often composed of two, and sometimes three, size classes; they may also consist of a single size class.

Perhaps the most striking feature of the contour maps is the redistribution of *Emerita* and sediment which results from the interaction of the pier structure with incident wave energy. The extent of this interaction is a function of the wave regime. When the dominant wave approach is from the southeast quadrant a large wave energy shadow is present north of the pier. When the

dominant wave approach is from the east, i.e., parallel with the pier, the energy shadow is much more limited but lies immediately to the north or south of the pier. Since *Emerita* are absent from the foreshore during the winter months when the waves are primarily from the northeast, pier effects during this period will be limited to beach morphology and sedimentology. It is likely that during the winter wave regime the sediment north of the pier will be coarser than that to the south. *Emerita* densities are greater in the energy shadow, particularly during the summer wave regime, due to attenuation of the incident wave energy. Knox and Booloontian (1963) noted that *E. analoga* was more numerous on a section of beach sheltered by a series of piers than on open, exposed beaches. Sampling along other piers, and along groin fields, would provide the data needed to test this hypothesis relating *Emerita* distribution to incident wave energy.

E. talpoida populations overwinter offshore along the mid-Atlantic coast. Onshore migration begins in early spring; *Emerita* were first observed at the FRF on April 12, 1980. The initial appearance of *Emerita* on the foreshore occurs during a period of rapidly increasing water temperature (Figure 23). The number of *Emerita* on the foreshore generally increases to a seasonal maximum in late summer and early fall. The growth curve for *E. talpoida* derived by Edwards and Irving (1943) shows that the population at

Woods Hole resides offshore from early November through early April and on the foreshore from early April through early November. The results presented here support their observation.

The temporal record of *Emerita* exhibits wide, and often rapid, fluctuations. Standard deviations are generally greater than the mean and reflect the spatial variability of the population on a given day. Some of the population fluctuations are associated with high wave conditions. In general, increases in the population occur during periods of low to moderate wave conditions and/or falling tides; population declines occur during periods of high wave energy and/or rising tides.

A possible mechanism to explain these fluctuations involves the migration of some of the population from the foreshore to the nearshore subaqueous zone and is related to the feeding requirements of *E. talpoida*. This species can feed only in moving water (Efford, 1966). Efford (1966) observed that the antennal cleaning rate of *E. analoga* is a function of the velocity (or force) of the water. The rate increases linearly with the logarithm of velocity between velocities of 0.02-0.32 m/s; above and below these limits the rate is constant. An energy threshold exists above which *E. talpoida* is intolerant, i.e., conditions are too stressful. Rising tide levels cause the surf zone (i.e., high energy conditions) to move higher on the beach.

During periods of falling tide level and/or low to moderate wave energy, conditions in the swash zone are optimal for *Emerita* feeding and population increases are observed.

During periods of rising tide level and/or high wave energy, conditions in the swash zone are too stressful for *Emerita* to feed and they migrate temporarily to the nearshore sub-aqueous zone, where they can actively feed due to the slight oscillatory motion of water at the bottom. The correlation matrix for the summer wave regime suggests that some of the population may also migrate to the upper areas of the foreshore. Migration between foreshore zones is also suggested by the temporal records of the medium and small size classes, which show correspondence between declines in one zone and increases in the adjacent zone.

SUMMARY

1. The spatial distribution of *E. talpoida* on the foreshore is influenced by environmental factors (e.g., wave energy and approach) and geomorphic attributes (slope and grain size).
2. *E. talpoida* populations are distributed zonally on the foreshore with density increasing toward the beach step. High density cells tend to be found in regions of lower wave energy, e.g., cusp troughs.
3. Aggregations may be composed of one, two or three size classes.
4. Physical structures located across the foreshore cause extensive redistribution of *Emerita* and sediment. This redistribution results from the interaction of the structure with incident wave energy and varies depending on the dominant wave approach.
5. The temporal pattern of *E. talpoida* is characterized by rapid and often large fluctuations and large standard deviations. These fluctuations are related to changes in wave energy and tide level. Water temperature apparently plays a role in the initial appearance of *Emerita* on the foreshore in early spring. The seasonal maximum of the population occurs in late summer and early fall.

APPENDIX A
SPATIAL DISTRIBUTION

SUMMER REGIME

Large Size Class. The large size class has a high density cell in the midforeshore north of the pier (Figure A-1a). The large standard deviation in this location (Figure A-1b) indicates the large temporal variability of the cell. Standard deviation maxima also occur in the midforeshore immediately north of the pier and 300 m south of it. No features in the contour map of the mean (Figure A-1a) correspond with these maxima. These cells probably represent aggregations which were present during only a few sampling periods.

Medium Size Class. The medium size class has a pair of high density cells north of the pier, with correspondingly large standard deviations (Figures A-2a and A-2b). These peaks lie directly within the troughs of the large cusp (Figure 14a). The peak along the 4N transect coincides with the peak in the large size class, providing further evidence of the presence of an aggregation at this location. Two cells of large standard deviation occur south of the pier. These features do not correspond with any for the large size class, suggesting that each size class of *Emerita* responds separately to environmental factors and can form aggregations independently of other size classes.

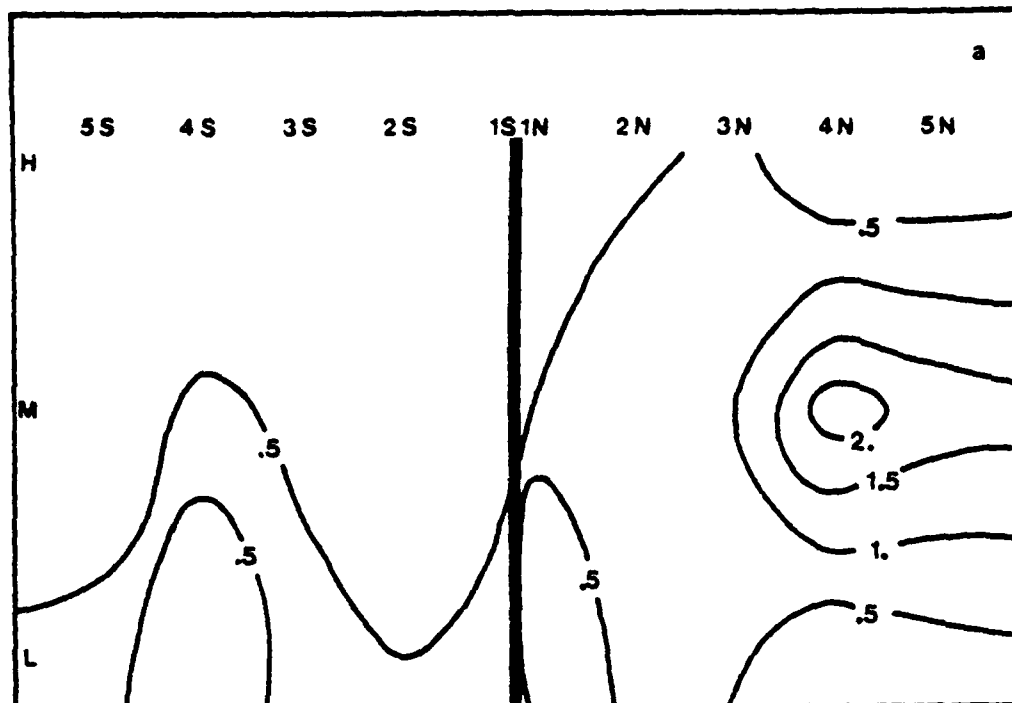


Figure A-1a. Large *Emerita* mean, summer wave regime.*

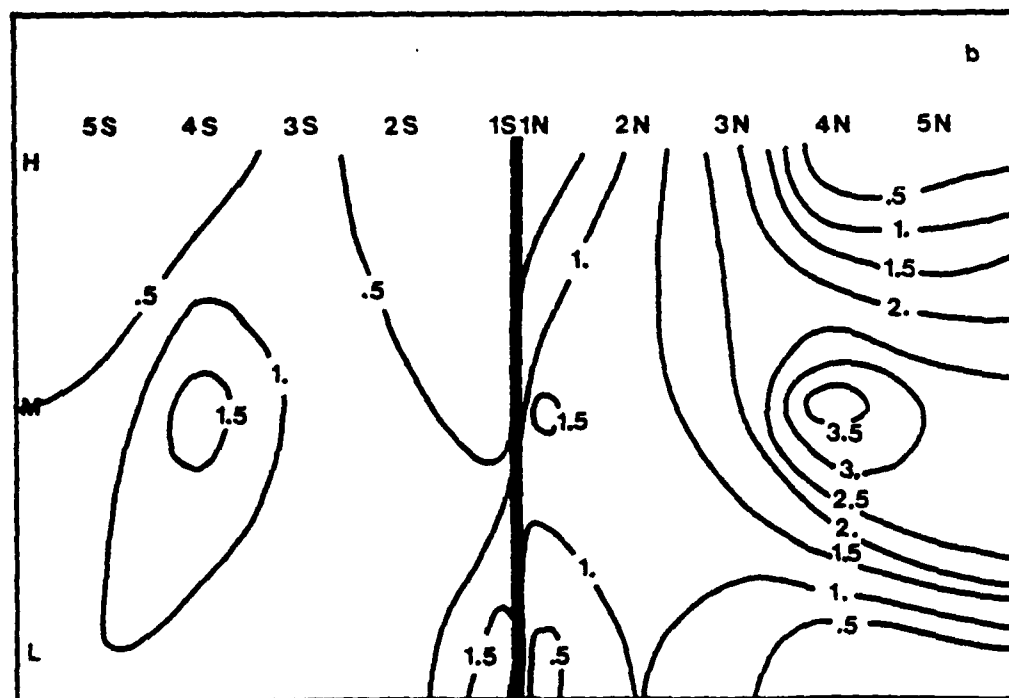


Figure A-1b. Large *Emerita* S.D.*

*Letters along the left side indicate the foreshore zone (upper, mid and lower). Transect locations are indicated across the top. Distance between transects is 100 meters. To convert number of *Emerita* per core to number per m^2 multiply by 124.8.

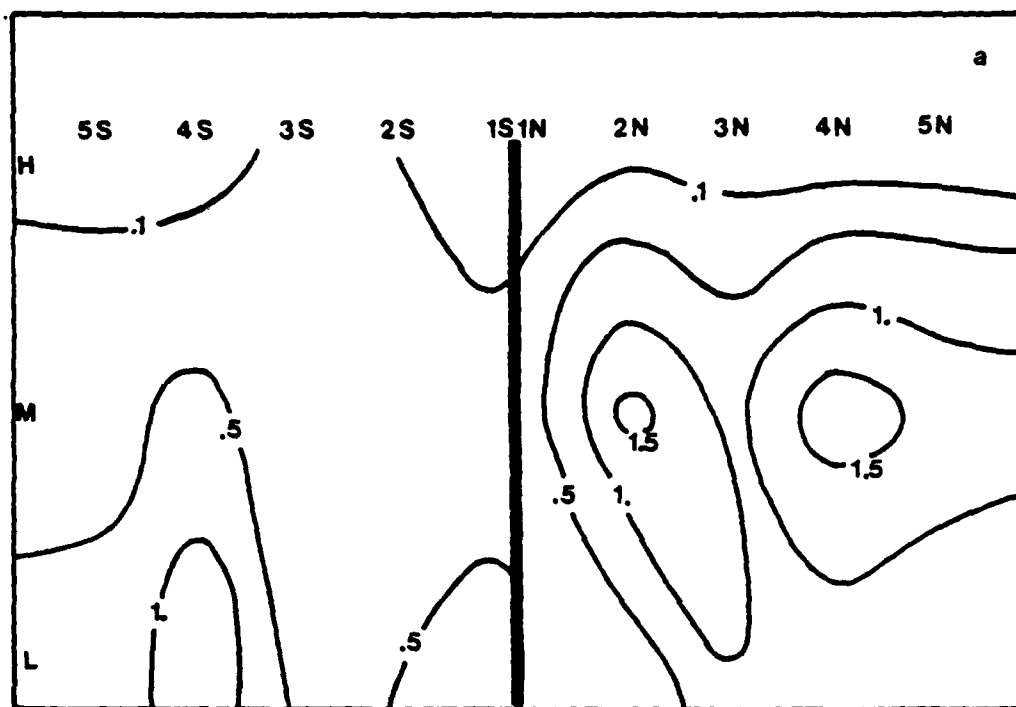


Figure A-2a. Medium *Emerita* mean, summer wave regime.*

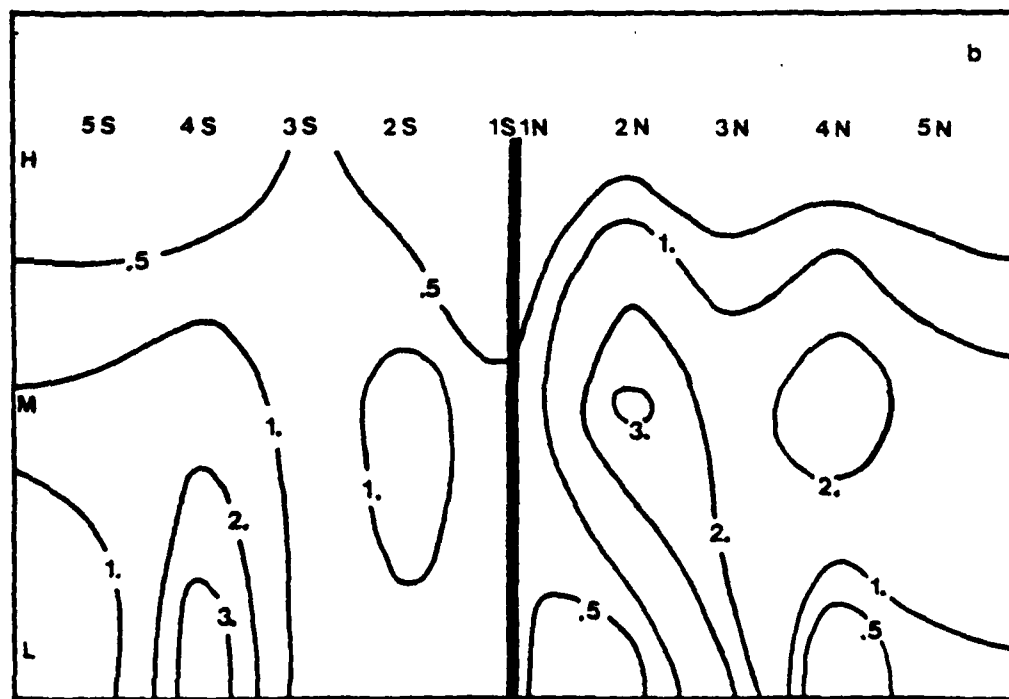


Figure A-2b. Medium *Emerita* S.D.*

*Letters along the left side indicate the foreshore zone (upper, mid and lower). Transect locations are indicated across the top. Distance between transects is 100 meters. To convert number of *Emerita* per core to number per m^2 multiply by 124.8.

Small Size Class. The small size class also shows its greatest densities north of the pier (Figure A-3a). A large high density cell occurs in the mid and lower foreshore north of the pier, and several cells occur in the lower foreshore south of the pier. These features bear little correspondence to any for the large and medium classes. The standard deviations (Figure A-3b) are equal to or less than the mean in three locations (transects 2S, 4N and 5N), all in the lower foreshore. *Emerita* density was less variable through time at these locations. Each of these sites exhibits medium, well-sorted sand (Figures 12a and 12b) and slight to moderate slopes (Figures 14a and 14b).

Juvenile Size Class. The juvenile size class shows very low density during the summer regime (Figure A-4a). They were found exclusively in the lower foreshore immediately south of the pier and 100 m to its north. This pattern suggests that the earliest megalopae arriving at the foreshore stay within the active swash zone to a greater degree than the other classes.

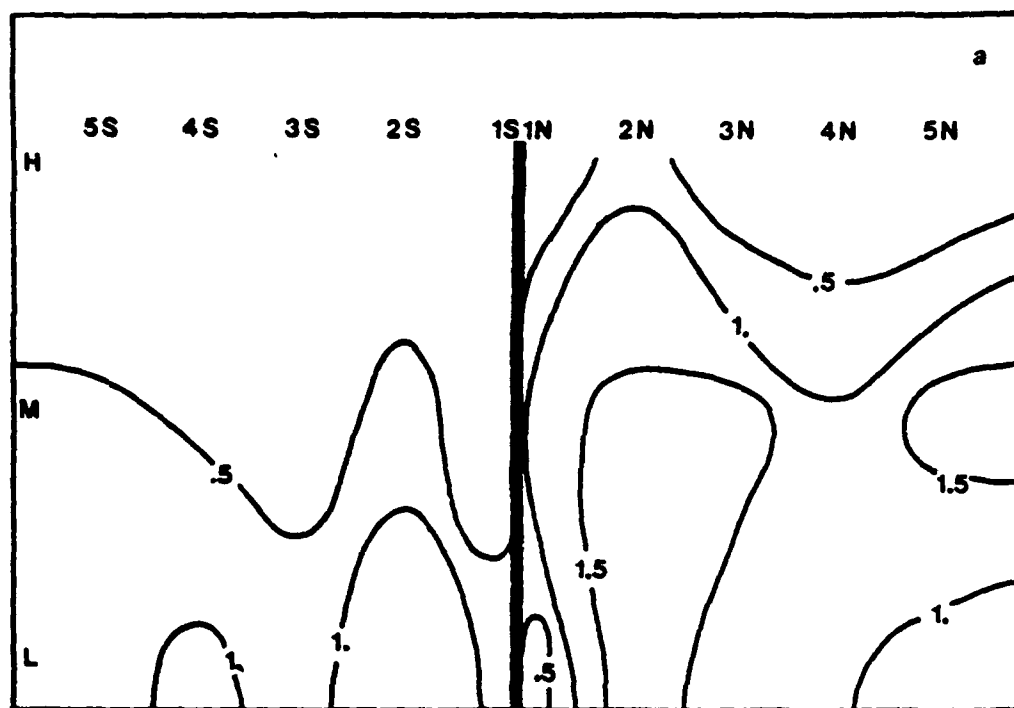


Figure A-3a. Small *Emerita* mean, summer wave regime.*

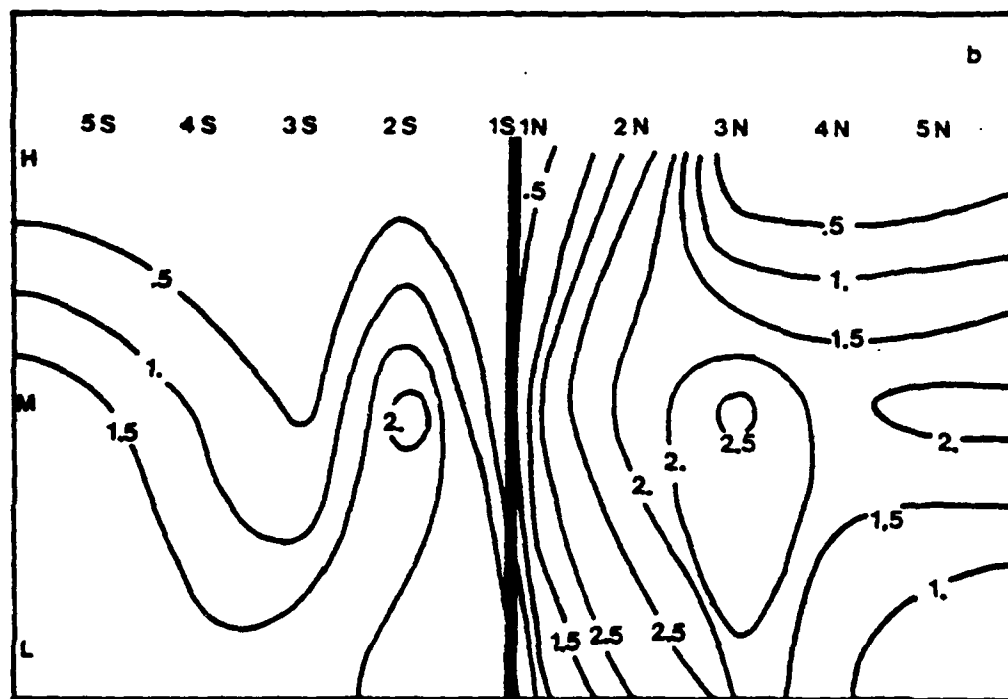


Figure A-3b. Small *Emerita* S.D.*

*Letters along the left side indicate the foreshore zone (upper, mid and lower). Transect locations are indicated across the top. Distance between transects is 100 meters. To convert number of *Emerita* per core to number per m^2 multiply by 124.8.

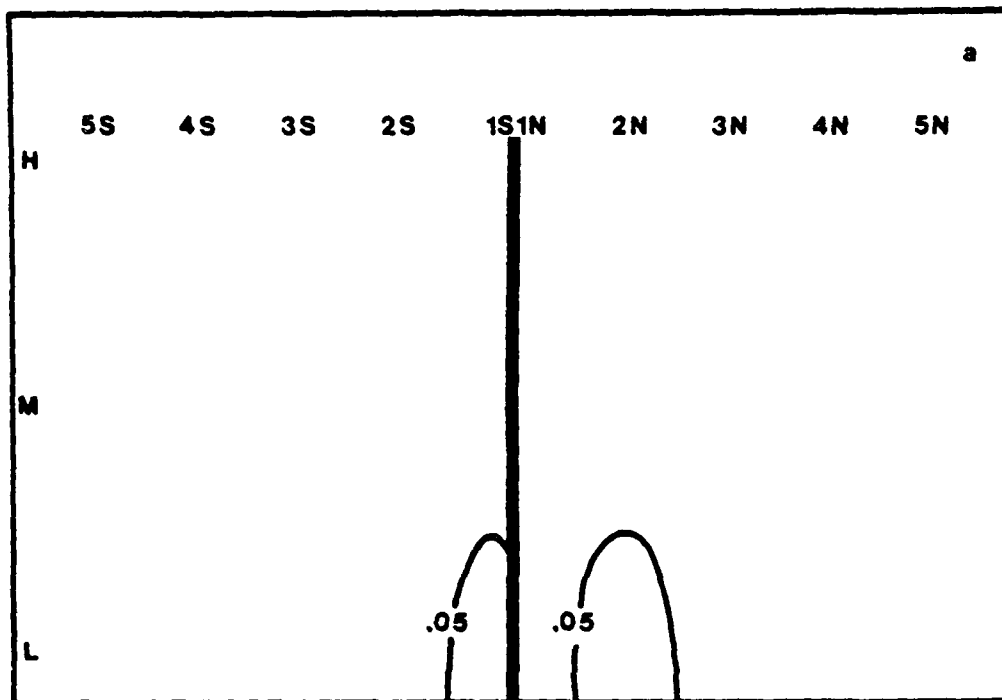


Figure A-4a. Juvenile *Emerita* mean, summer wave regime.*

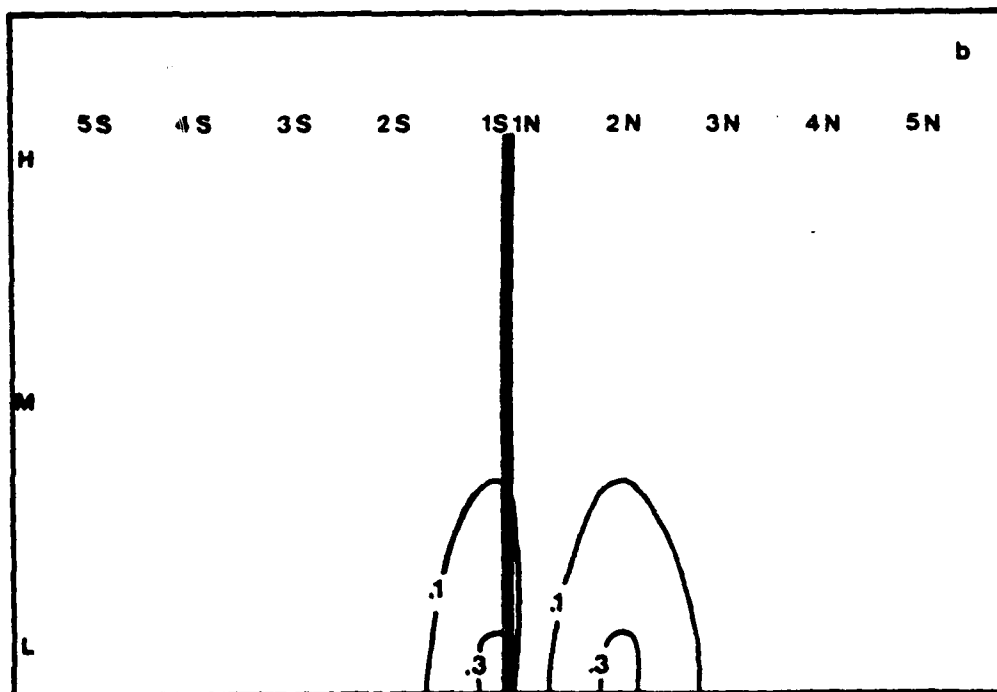


Figure A-4b. Juvenile *Emerita* S.D.*

*Letters along the left side indicate the foreshore zone (upper, mid and lower). Transect locations are indicated across the top. Distance between transects is 100 meters. To convert number of *Emerita* per core to number per m^2 multiply by 124.8.

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APPENDIX B
SPATIAL DISTRIBUTION

TRANSITIONAL REGIME

Large Size Class. The large size class exhibits a zonal pattern on both sides of the pier with high density cells in the lower foreshore (Figure B-1a). The standard deviations for these cells are equal to or less than the mean (Figure B-1b), suggesting that these cells are relatively stable aggregations. The two cells north of the pier lie on the sides of the cusp in a relatively low energy environment. The pier seems to have very little effect on the distribution of this class.

Medium Size Class. The medium size class also shows the zonal pattern on both sides of the pier (Figure B-2a). The cells in the lower foreshore correspond with those in the large size class, indicating that these are aggregations composed of these two size classes. Pier effects are most noticeable in the standard deviations (Figure B-2b), which are in all cases greater than the mean, and are generally greater than the standard deviations for the large size class. One conclusion to be drawn from this pattern is that the medium size class is more variable than the large size class and is more susceptible to environmentally induced variations.

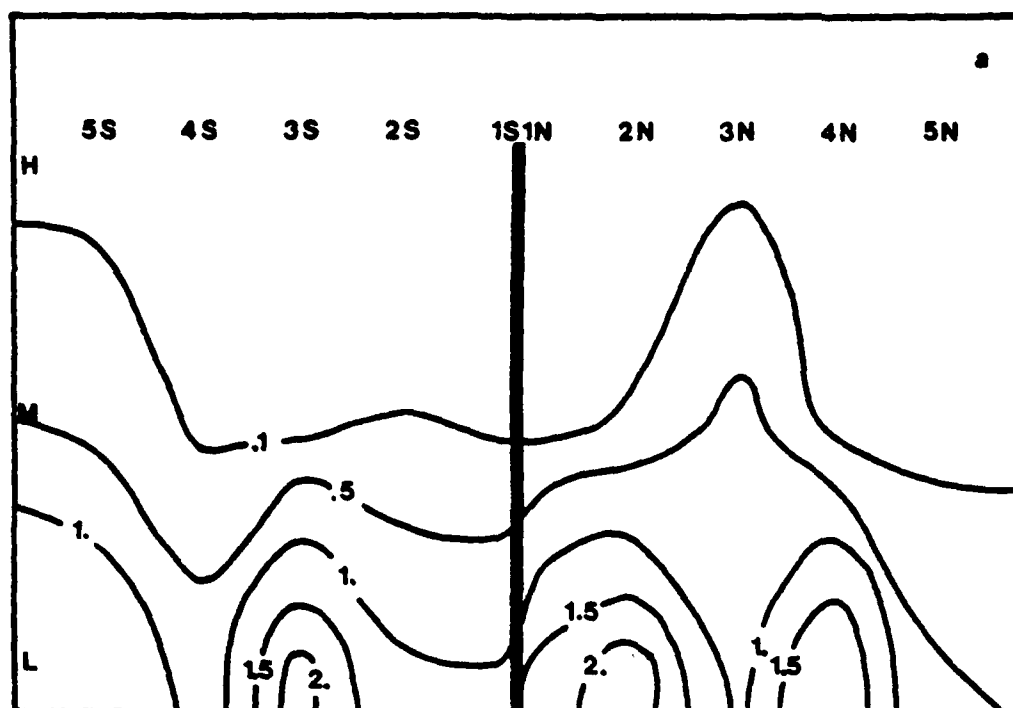


Figure B-1a. Large *Emerita* mean, transitional wave regime.*

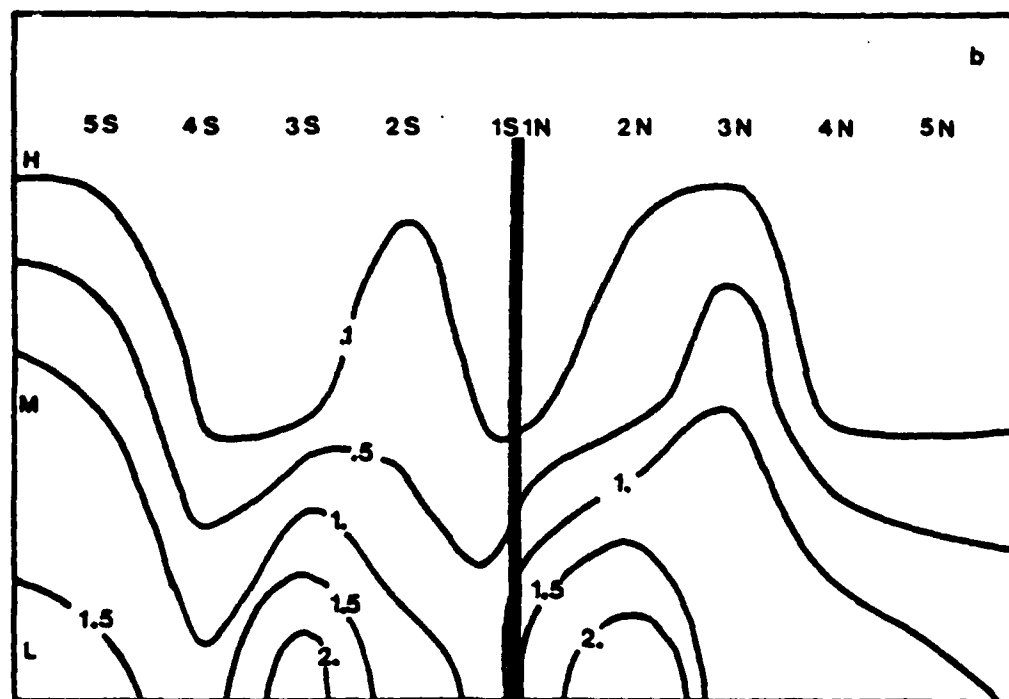


Figure B-1b. Large *Emerita* S.D.*

*Letters along the left side indicate the foreshore zone (upper, mid and lower). Transect locations are indicated across the top. Distance between transects is 100 meters. To convert number of *Emerita* per core to number per m^2 multiply by 124.8.

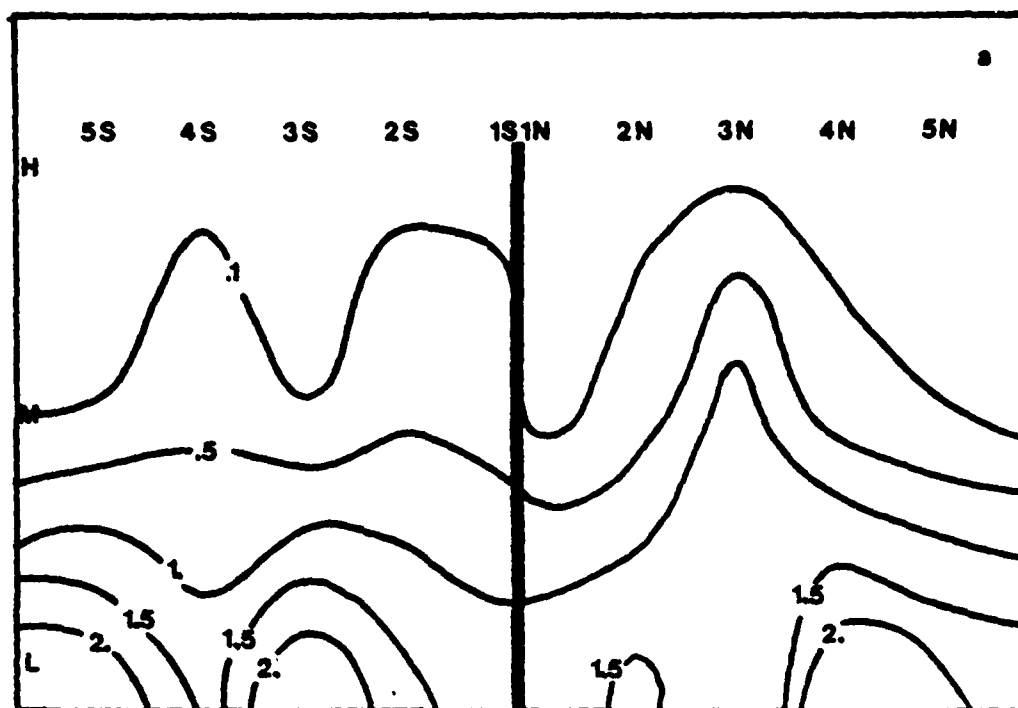


Figure B-2a. Medium *Emerita* mean, transitional wave regime.*

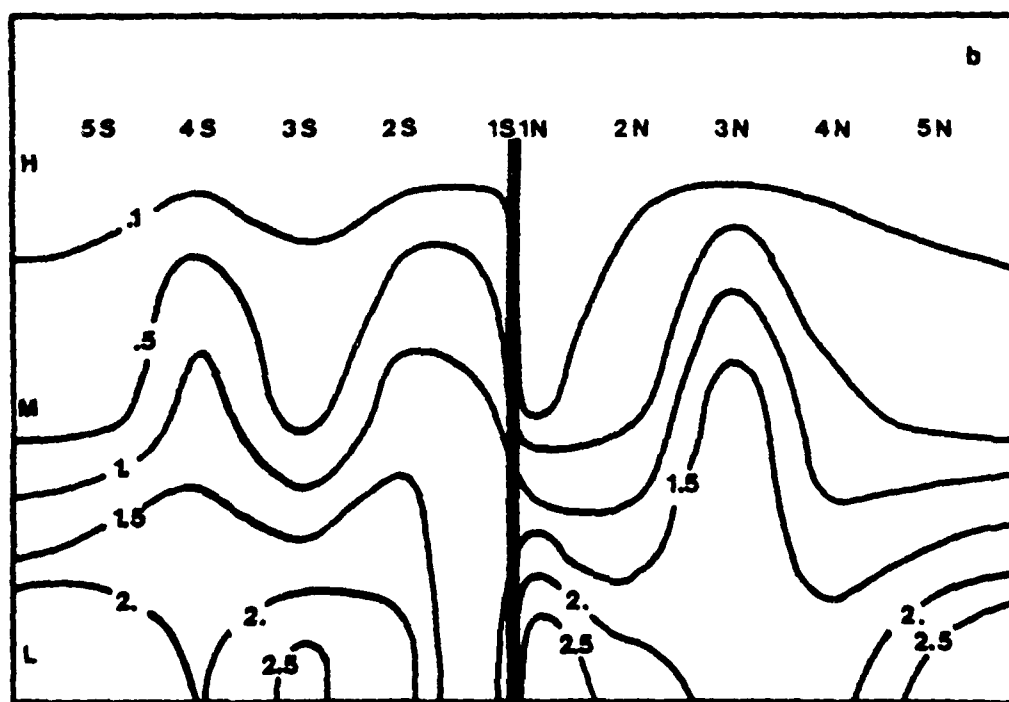


Figure B-2b. Medium *Emerita* S.D.*

*Letters along the left side indicate the foreshore zone (upper, mid and lower). Transect locations are indicated across the top. Distance between transects is 100 meters. To convert number of *Emerita* per core to number per m^2 multiply by 124.8.

Small Size Class. The small size class exhibits the greatest densities of any of the classes (Figure B-3a). The zonal distribution is interrupted by the pier; turbulence may be a factor. In the midforeshore the densities are greater in the 200 m strip north and south of the pier than they are farther away. This can be explained by considering that the wave approach oscillates around 90 degrees during this period. Large waves occurring on days with waves from the northeast quadrant would drive *Emerita* into the wave energy shadow south of the pier (for example, see Figures 10, 24b, 25a and 25b on June 9 and 13); those events occurring on days with waves from the southeast quadrant would drive *Emerita* to the north side of the pier (for example, see Figures 10, 24b, 25a and 25b on September 18 and October 25).

This mechanisms does not require *Emerita* to take an active role; they would be passively transported by the longshore currents generated when the waves break at an angle to the beach. The pier shadow extends for a limited distance to the north or south and beyond that distance the beach is subject to nonattenuated wave energy. The high density cell in the lower foreshore north of the pier lies in the southern trough of the cusp. The very large standard deviations (Figure B-3b) are indicative of the highly variable nature of this size class.

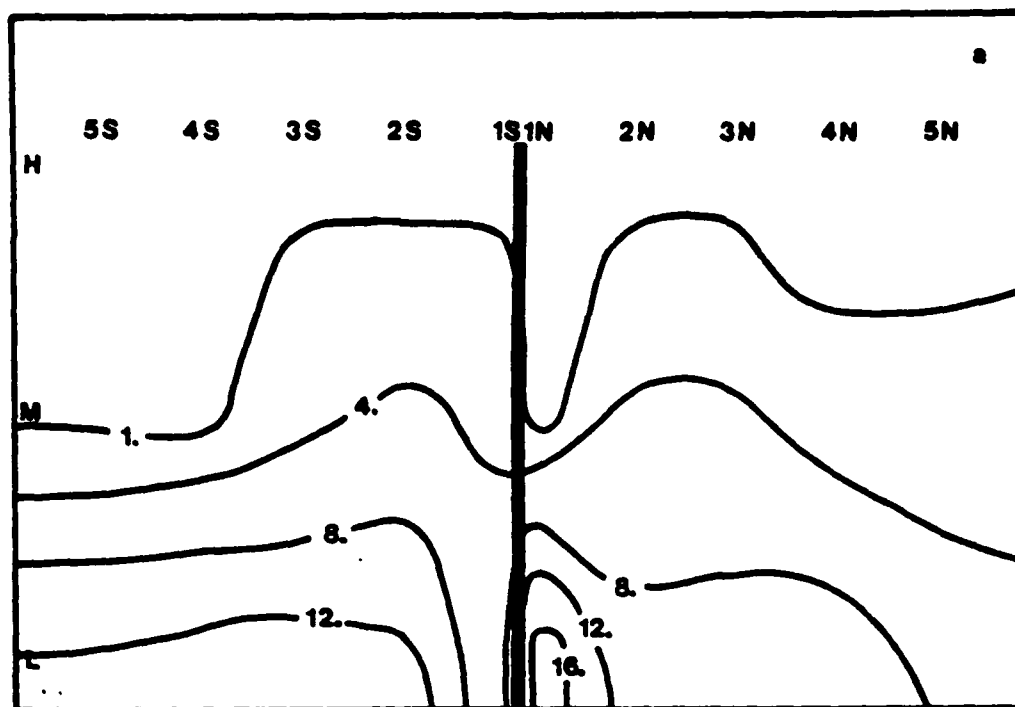


Figure B-3a. Small *Emerita* mean, transitional wave regime.*

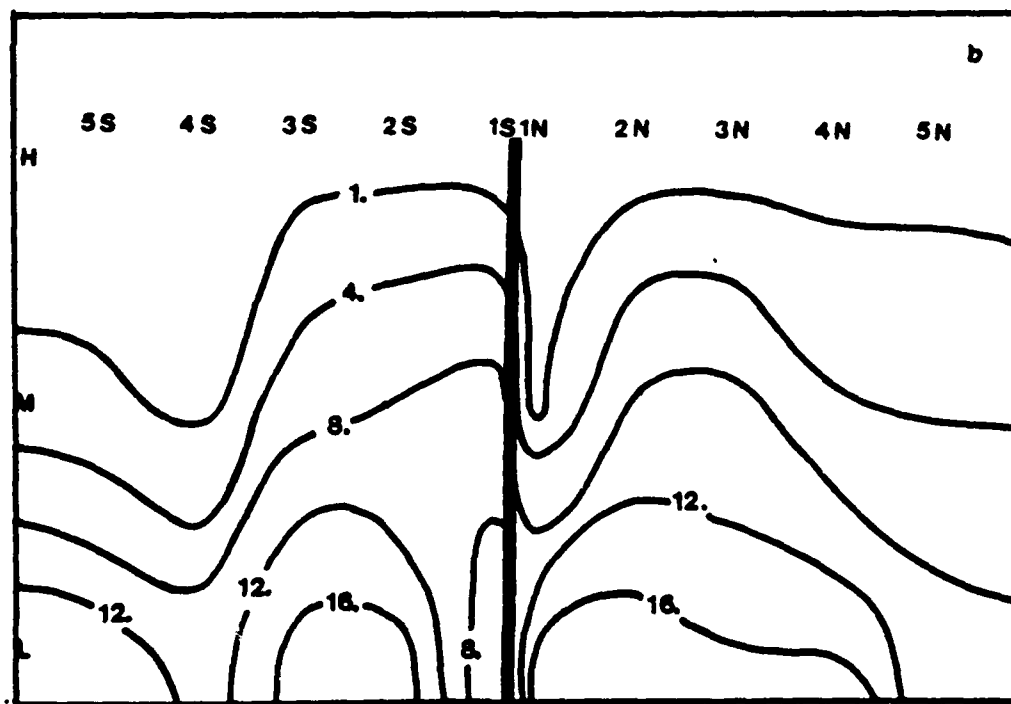


Figure B-3b. Small *Emerita* S.D.*

*Letters along the left side indicate the foreshore zone (upper, mid and lower). Transect locations are indicated across the top. Distance between transects is 100 meters. To convert number of *Emerita* per core to number per m^2 multiply by 124.8.

Juvenile Size Class. The cells which the juvenile size class exhibits in the lower foreshore (Figure B-4a) are associated with relatively small slopes (Figure 15a). There is a sharp reduction in population density at the pier which may be a result of wave turbulence. North of the pier megalopae are found in the midforeshore along the south side and crest of the cusp horn. The standard deviations (Figure B-4b) show that the number of megalopae is highly variable through time. Megalopae were not observed after October 4, 1980 in the midforeshore and after September 22, 1980 in the lower foreshore.

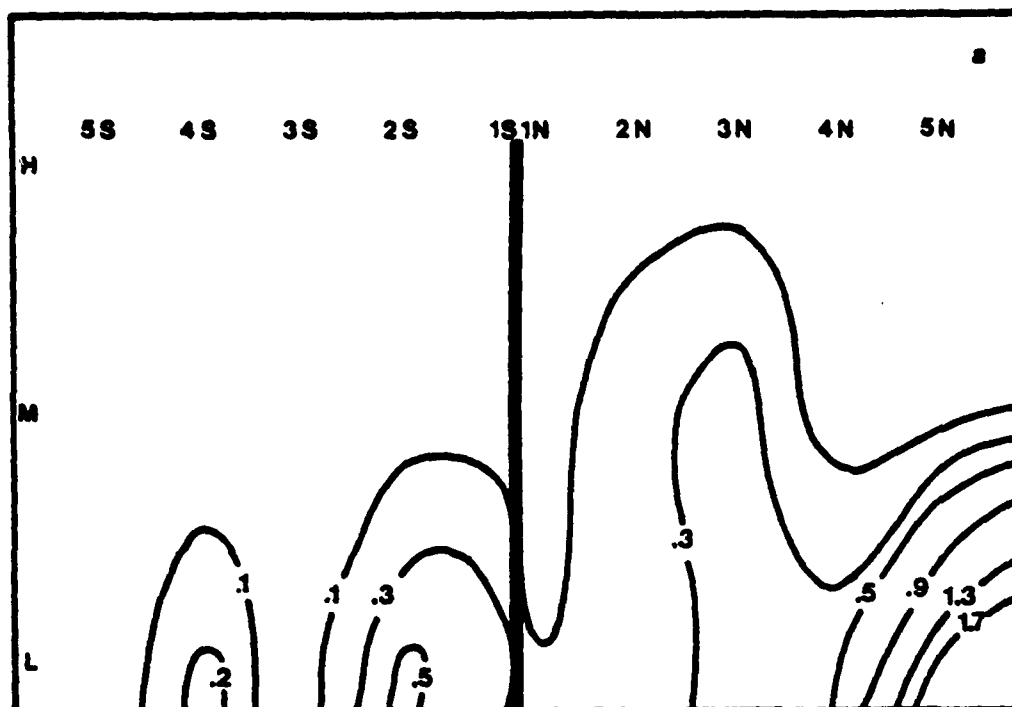


Figure B-4a. Juvenile *Emerita* mean, transitional wave regime.*

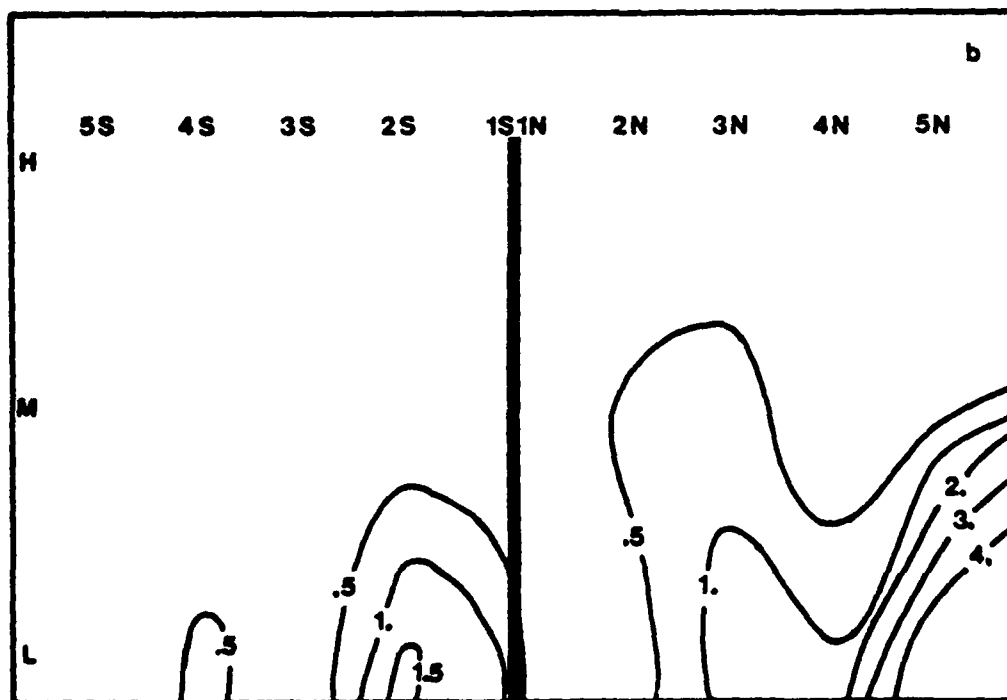


Figure B-4b. Juvenile *Emerita* S.D.*

*Letters along the left side indicate the foreshore zone (upper, mid and lower). Transect locations are indicated across the top. Distance between transects is 100 meters. To convert number of *Emerita* per core to number per m^2 multiply by 124.8.

APPENDIX C
TEMPORAL DISTRIBUTION

Large Size Class. The large size class shows a single, early season peak in the upper foreshore (Figure C-1a). Rising tide levels occur during this period and the wave energy is low to moderate. The midforeshore (Figure C-1b) shows steadily increasing numbers from April 12-May 24, which covers two periods of rising tide level and low to moderate wave energy. Some of this increase in numbers can be attributed to onshore migration of the overwintering population. In the late season a small peak is observed in October; the decline after October 18 corresponds to high energy conditions and rising tide levels. In the lower foreshore (Figure C-1c) twin peaks are observed in the early season; the second decline occurs over a period of rising tide levels.

Medium Size Class. The medium size class exhibits a small peak in the upper foreshore (Figure C-2a) in early May during a period of moderate wave energy and falling tide levels. The size class is absent from the upper foreshore for the remainder of the seasonal cycle. The pattern in the midforeshore (Figure C-2b) in the early season resembles that of the large size class. The size class increases steadily from mid-April to May 24. The decline in numbers from May 24-June 8 occurs during rising tide levels and low energy conditions. The population increases

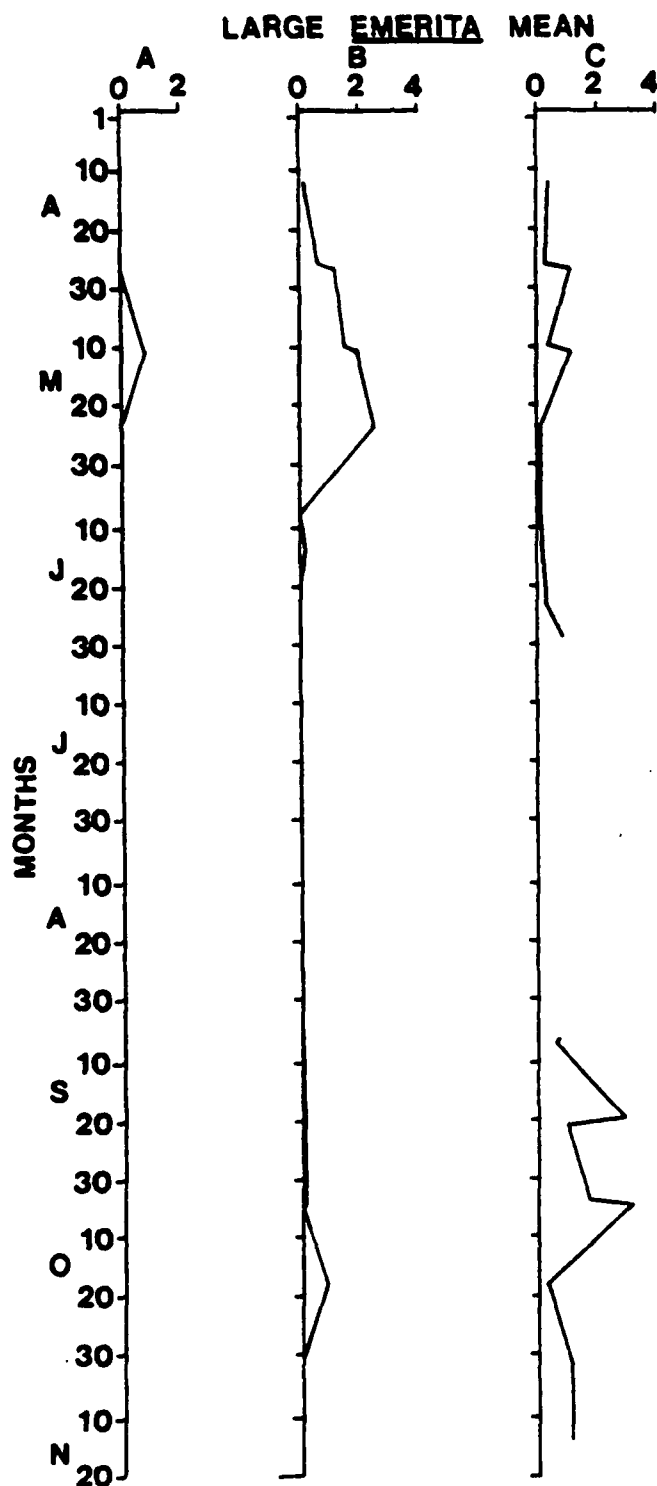


Figure C-1. Temporal record of the large *Emerita*. Horizontal scale is the mean number per core averaged over 10 cores. The gap in the record from late June through early September represents missing data.

- a. Upper foreshore.
- b. Midforeshore.
- c. Lower foreshore.

To convert number of *Emerita* per core to number per m^2 multiply by 124.8.

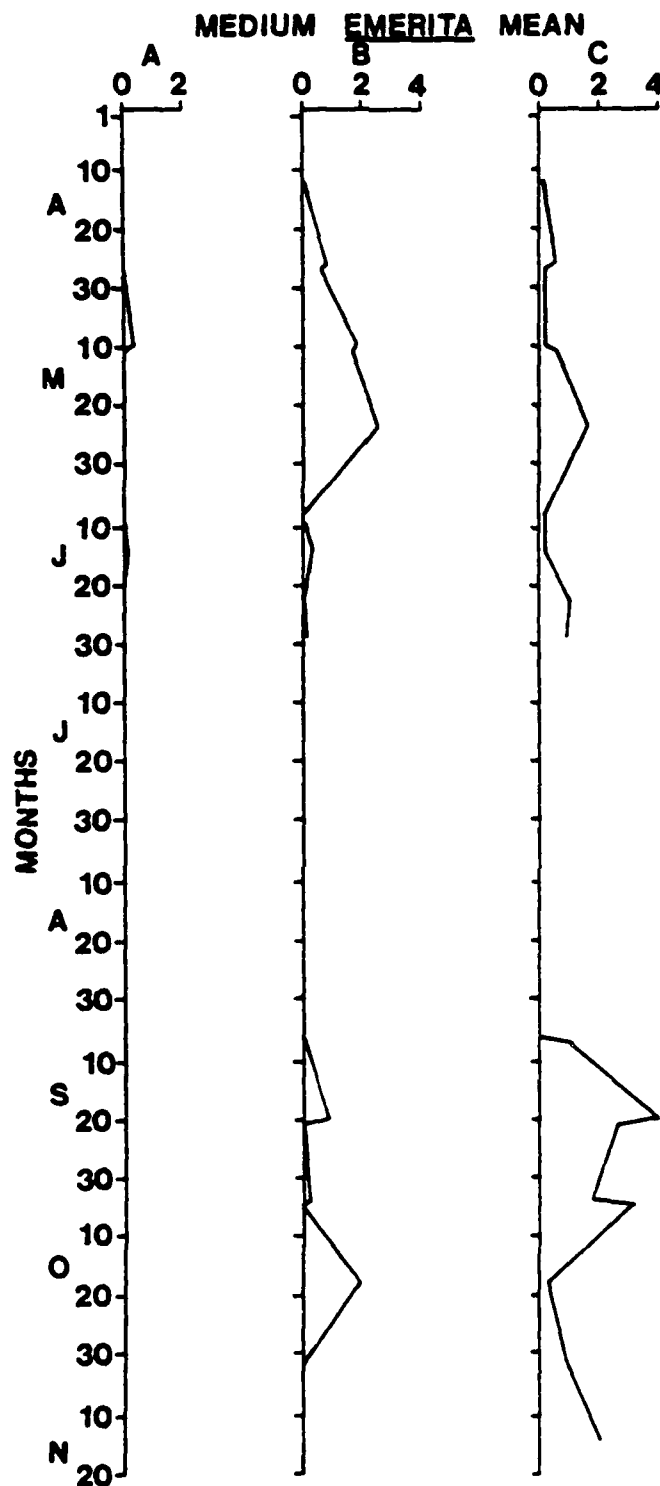


Figure C-2. Temporal record of the medium *Emerita*. Horizontal scale is the mean number per core averaged over 10 cores. The gap in the record from late June through early September represents missing data.

- a. Upper foreshore.
- b. Midforeshore.
- c. Lower foreshore.

To convert number of *Emerita* per core
to number per m^2 multiply by 124.8.

observed from September 7-20 and October 5-18 occur during low to moderate energy conditions and falling tide levels. These same patterns also occur in the lower foreshore (Figure C-2c), although there are some differences between this zone and the previous one. The decline in the lower foreshore from September 21-October 4 corresponds to a slight increase in the midforeshore. Also, the decline in the lower foreshore from October 5-18 corresponds to an increase in the midforeshore.

Small Size Class. The small size class also exhibits an early season peak in the upper foreshore followed by a sharp decline and absence for the remainder of the season (Figure C-3a). The increase in numbers in the midforeshore (Figure C-3b) from April 12-May 10 occurs during low energy and falling tide conditions. The sharp decline from May 10-11 corresponds to a sharp increase in the lower foreshore and may represent migration of small *Emerita* from the mid to lower foreshore. The population increases in the midforeshore from September 20-21 and October 5-18 correspond with low to moderate wave energy and falling tide periods and the declines from October 4-5 and October 18-November 11 occur during high energy and/or rising tide periods. The patterns of this size class in the lower foreshore (Figure C-3c) are the same as discussed earlier for the entire population.

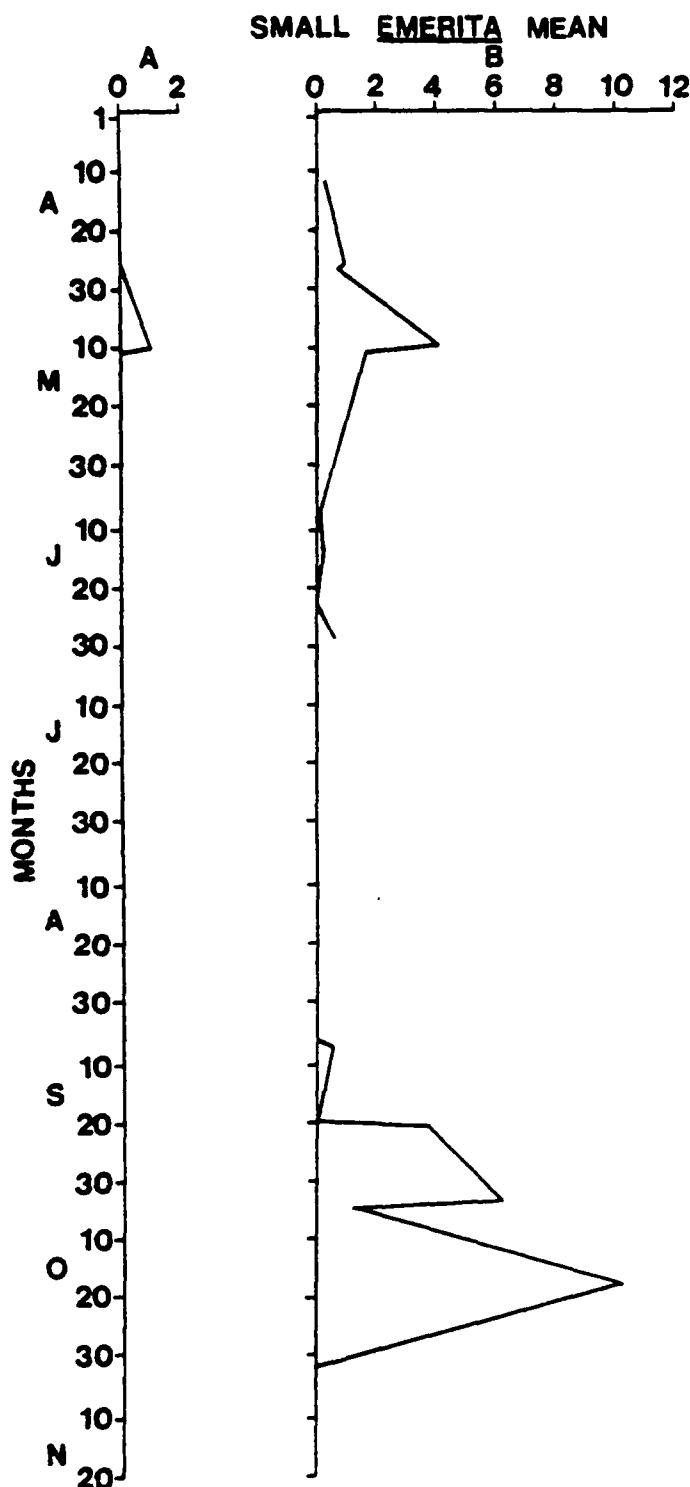


Figure C-3. Temporal record of the small *Emerita*. Horizontal scale is the mean number per core averaged over 10 cores. The gap in the record from late June through early September represents missing data.

- a. Upper foreshore. To convert number of *Emerita* per core
b. Midforeshore. to number per m² multiply by 124.8.

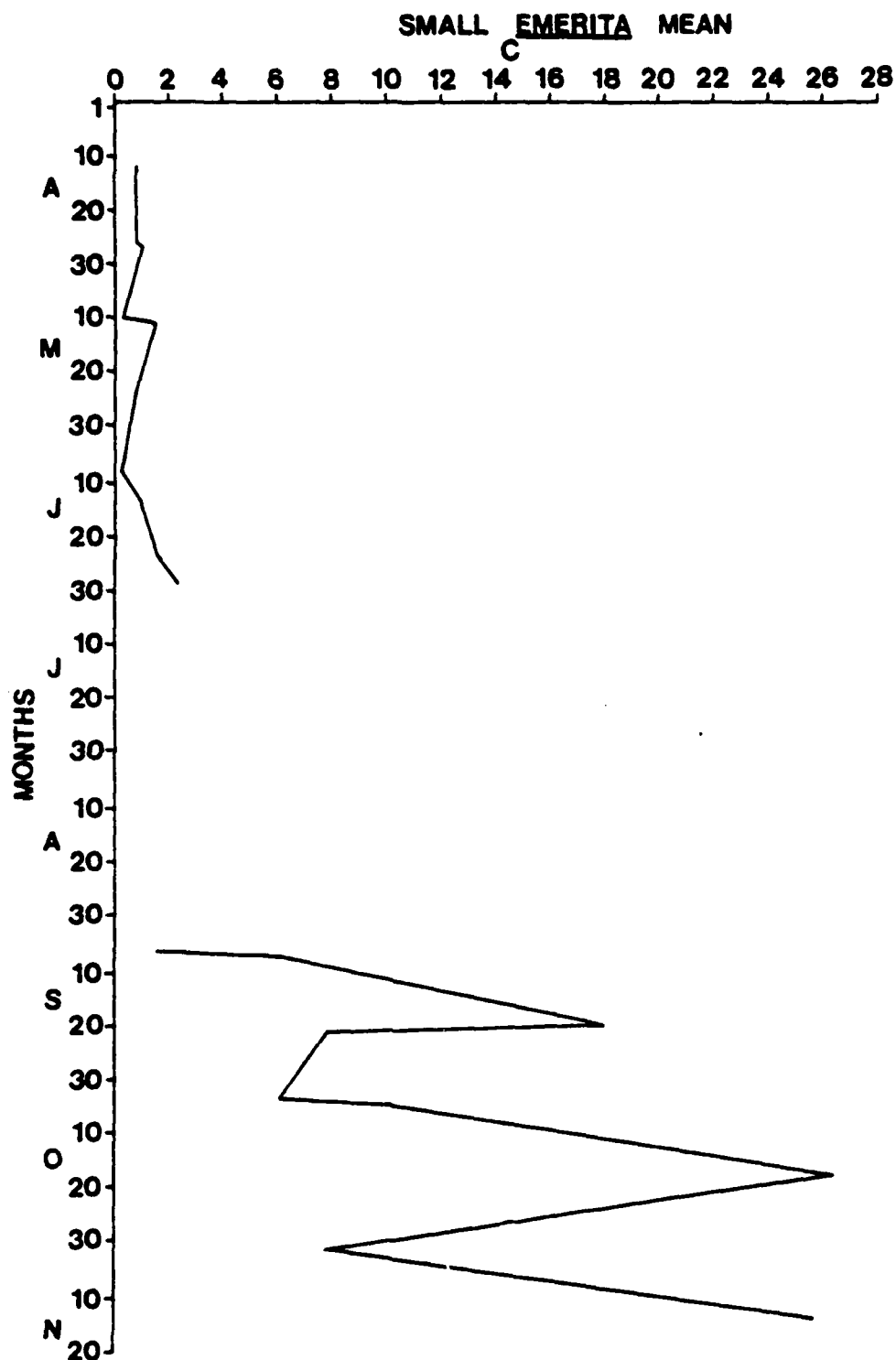


Figure C-3. Temporal record of the small *Emerita*. Horizontal scale is the mean number per core averaged over 10 cores. The gap in the record from late June through early September represents missing data.

c. Lower foreshore.

To convert number of *Emerita* per core to number per m^2 multiply by 124.8.

Juvenile Size Class. Megalopae were entirely absent from the upper foreshore from April 12-November 14. Their first appearance in the midforeshore (Figure C-4a) was in early September. However, sampling at other sites during the summer indicated that megalopae were abundant from late spring through late summer. This is not evident in these figures due to the lack of data for July and August. Figure C-4b does show that megalopae first appeared at this site in late June in the lower foreshore. The decline in numbers after September 8 results from the maturation of megalopae to small *Emerita*.

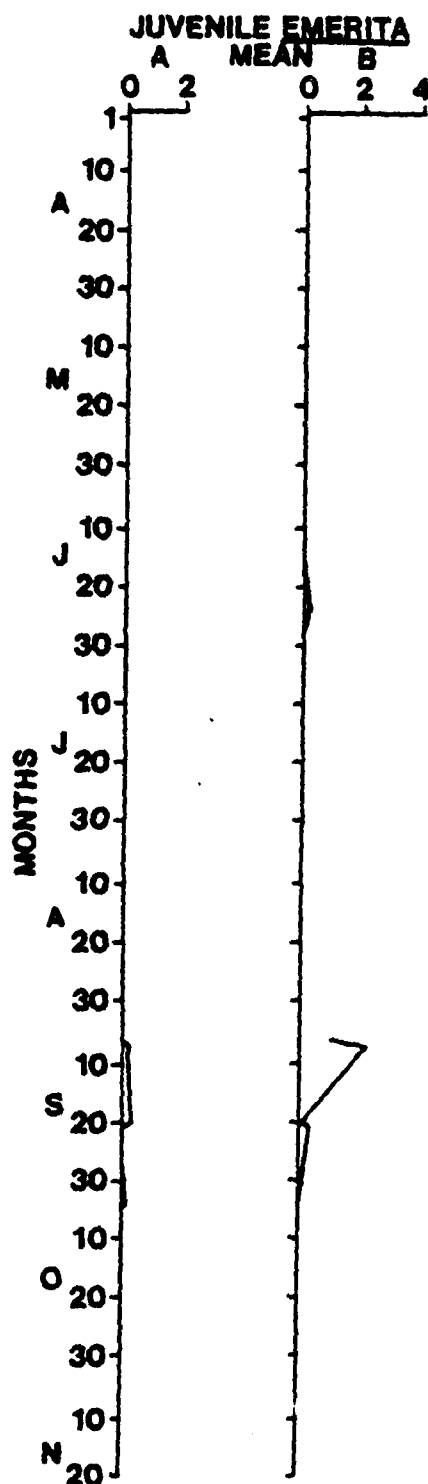


Figure C-4. Temporal record of the juvenile *Emerita*. Horizontal scale is the mean number per core averaged over 10 cores. The gap in the record from late June through early September represents missing data. No megalopae were found in the upper foreshore.

- a. Midforeshore.
 b. Lower foreshore.
- To convert number of *Emerita* per core to number per m^2 multiply by 124.8.

APPENDIX D

RECOMMENDATIONS FOR FUTURE STUDY

Further study of *E. talpoida* is needed to address questions raised in this thesis and to explore the ecology of this species in greater detail. The following recommendations may aid future students in developing research programs capable of yielding valuable results in the area of beach ecology and processes.

Any future study should include a control site on an exposed beach free of the influence of any structure such as the CERC pier. The use of a sampling grid similar to that used in this thesis would allow the data to be compared directly with those presented here. A similar grid system should also be used at the FRF. The wealth of environmental data collected at the pier makes it a prime location for any study concerned with environmental processes in the nearshore and foreshore zones. A high resolution sampling grid should also be established on a series of beach cusps. Furthermore, sampling in the nearshore subaqueous zone should be conducted to test the hypothesis that there is a dynamic onshore-offshore pool of *Emerita*.

Additional study of the distribution of *E. talpoida* in very fine and very coarse sediments is needed. This would require selection of specific sampling sites with the proper sediment characteristics. The distribution of *Emerita* with depth is also worthy of further study.

Several specific suggestions concerning sampling procedures can be made. Sampling for *Emerita* should be conducted between high and low tides. Sampling should also be conducted daily for an extended period to allow detailed examination of the temporal fluctuations of *Emerita*. A smaller mesh sieve should be used to separate *Emerita* from sediment. For the majority of the season a No. 6 (3.35 mm) sieve works very well. It is, however, too coarse for use in late summer and early fall when large numbers of very small (1-4 mm) *Emerita* are present on the foreshore. A small mesh screen should be placed over the mouth of the water container used to wash sediment through the sieve. On several occasions the author poured water containing *Emerita* into the sieve. This is one source of experimental error easily corrected. An Abney level is highly recommended for measuring beach slope. Its design makes it much more efficient to use than a Brunton compass, which also suffers from occasional internal fogging.

Questions which might be addressed in future studies include the following. Is the model presented in this thesis applicable to other sites? How are *Emerita* distributed in beach cusps? How does the distribution of *Emerita* at the CERC FRF compare with its distribution on exposed beaches not influenced by man-made structures? Future studies should continue to monitor pier effects on beach geomorphology.

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**NO
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