THE PILE WORM, *Neanthes succinea* (Frey and Leukart)

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The nereid polychaete, *Neanthes succinea,* was first reported in the Salton Sea by Hartman (1936) from a collection made by S. F. Light in June 1935. Just how or when it was introduced is uncertain, but it may have been in 1930 when, according to records of the California Department of Fish and Game, "a few pile worms" were brought in from San Diego Bay. *Neanthes* is now abundant in the Sea, and the present fish fauna is largely dependent on its presence. Zenkevich (1951) discussed the value of *Neanthes* as a fish food.

It spends most of its life in burrows in the mud and among the masses of barnacles. Mature *Neanthes* leave their protective burrows at night and swim to the surface to spawn. The swimming, or epitokol, stage lasts only a few days and then the worm dies.

SPAWNING

Spawning or swarming of *Neanthes* can be observed at night because they are attracted to light. In the Salton Sea swarming follows the pattern recorded on March 20, 1955 in the boat channel at Fish Springs (Table 19). Observations began at 6:15 PM, Pacific Standard Time and ended at 11:15 PM. All of the worms attracted to a suspended light were collected, and collections per 15-minute period were kept separate.

When a female appeared she was soon surrounded by several males; spawning then occurred almost immediately and lasted only a few seconds. The eggs and sperm appeared as milky patches in the water. Immediately after shedding her eggs the female would sink out of sight, apparently completely spent. The male epitokes continued to swim. The duration of the male epitoke after spawning was observed in the laboratory where 9 of 17 were active 24 hours after collection; 7, after 48 hours; and 2, after 96 hours. Twelve of the 17 were dead

TABLE 19

Numbers of Neanthes Epitokes Collected at Fish Springs, Salton Sea on March 20, 1955

Time (PM)	Number of Epitokes Collected
6:15- 6:30	None (sunset)
6:[illegible]- 6:45	None
6:45	1
6:45- 7:00	24: 16 males, 8 females
7:00- 7:15	115: 101 males, 14 females
7:15- 7:30	215: 189 males, 26 females (maximum activity)
8:[illegible]- 8:15	87: 69 males, 18 females
9:[illegible]- 9:15	4: 3 males, 1 female
[illegible]-10:15	None
11:[illegible]-11:15	None

96 hours after collection, but one was still alive after 11 days. Half of the male epitokes lived for only 24 to 48 hours after collection, and, presumably, after spawning.

FERTILIZATION AND LARVAL DEVELOPMENT

The development of eggs, obtained from mature worms collected on the nights of February 15 and May 8, 1955, was observed in the laboratory where the temperatures ranged from 20 to 25 degrees C. The spherical eggs were 150-200 micra in diameter. Immediately following fertilization a gelatinous sheath surrounded the egg; this sheath began to swell and many sperm seemed to become entangled in it. After 80 minutes, the fertilization membrane was visible, and after an hour and a half the first polar bodies appeared. Twenty minutes later the first division occurred, and in another 30 minutes the second division. Within 13 hours the eggs had become ciliated, lost their gelatinous covering, and were free-swimming. The egg had developed into a trochophore larva after 24 hours, and in 36 hours had two larval segments with setae. In 54 hours, they possessed three seta-bearing segments.

The duration of the free-swimming planktonic period was difficult to determine because the change from the three- to the four-segmented stage seemed to be critical in their development. In laboratory rearing experiments, *Neanthes,* after reaching the three-segmented stage in two and one-half to three days, have lived for as long as 10 days without developing further. In nature it would seem that three to six additional segments were added in 10 to 14 days.

The eggs and larvae were planktonic. When they had six to nine adult segments they began to settle. By the time they reached the nine-segmented stage virtually all had settled to begin their bottom-dwelling period. Plankton and worms that had recently settled were studied to provide data showing time of spawning, changes in seasonal prevalence, and rate of growth.

PLANKTON

The number of eggs and planktonic larvae in a three-liter sample were ascertained during a two-year period at two stations off Fish Springs. At the station three miles offshore, samples were taken above the bottom (12 meters), at mid-depth (six meters) and at the surface. Near-shore samples were collected above the bottom (three meters) and at the surface (Figure 21).

This sampling revealed a spring peak of spawning (which occurred from March to June 1955) followed by reduced activity during summer, as indicated by fewer worms in the plankton. Spawning increased again in the fall (starting in September 1955), continued during winter, and culminated in another spring peak in April and May of 1956.

The spawning of *Neanthes* has been reported to follow a monthly cycle, always, according to Lillie and Just (1913), between full and new moon. This did not seem to be the case in the Salton Sea where eggs were found in samples taken at all phases of the moon. Eggs in the plankton can be assumed as evidence of spawning within the previous 24 hours; spawning thus occurred irregularly or continuously. The seemingly continuous spawning made it difficult to estimate the time

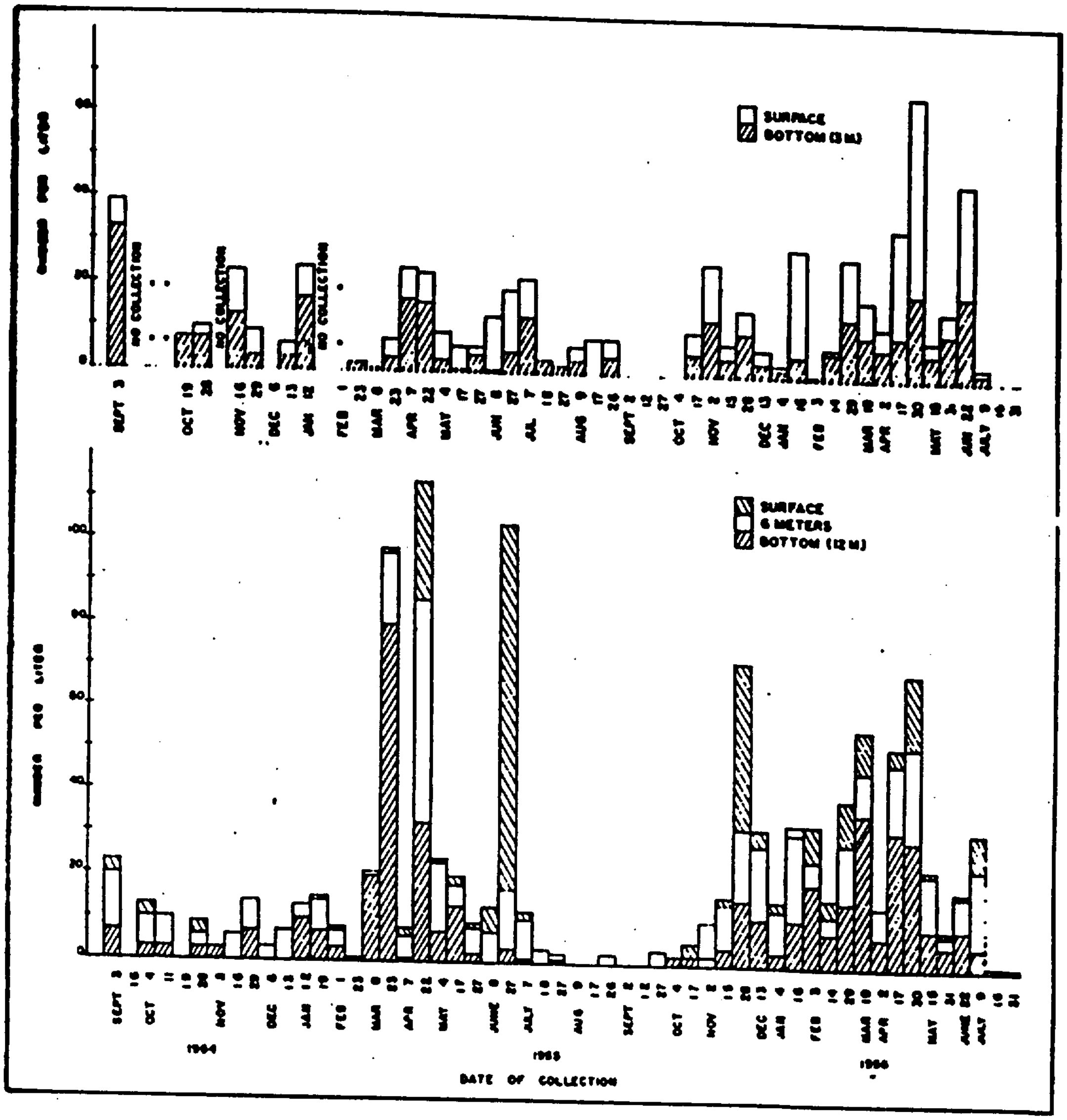

FIGURE 21. The number of eggs and planktonic larvae taken in a three-liter sample during a two-year period at two stations off Fish Springs, Salton Sea. At the station three miles offshore, samples were taken above the bottom (12 meters), at mid-depth (six meters) and at the surface. At the station near shore, samples were collected above the bottom (three meters) and at the surface.

Neanthes spent in the plankton, but the planktonic stage ended when, with attainment of six to nine segments, the worms settled to the bottom.

SETTLEMENT

Their settlement was studied by using one-gallon glass jars suspended beneath the surface at nine different locations in the Sea. The mouth of each jar had a diameter of 10.5 cm; the area through which the worms settled thus represented 83.5 cm^2, which is, roughly, 0.01 square meter. A few of the samples were collected at 10- and 90-day intervals, but most at 30-day intervals. That is the jars were usually removed and replaced monthly. The worms in the jars were counted, and as an estimate of their rate of growth, the number of segments per worm in representative portions of the sample was also determined.

Ten-Day Collections

Settling jars removed at 10-day intervals indicated irregular periods of maximum spawning each month. For example, 90 percent of the worms settling during March 1955 at the station 100 yards off Fish Springs did so during the last 10 days. On the other hand, at a station two miles south of Fish Springs only 22 percent of the number that settled during March did so during this same 10-day period (the last 10 days of the month). At this second station, maximum spawning was during the first 10 days, when 70 percent of the month's total accumulated. There may have been, as in the preceding examples, one period of maximum spawning in a month, or there may have been more than one, as in May, when, at the station 100 yards off Fish Springs, 10 percent of the month's total settled in the first 10 days, 45 percent during the second 10 days, and 45 percent during the last 10.

The 10-day collections thus showed no regularity in peaks of monthly spawning nor correlation with phases of the moon. The 10-day samples proved helpful in estimating rates of growth for the 30-day samples (see below); for example, if most of the worms had settled during the last 10 days of a 30-day period, the majority would have been smaller than if most had settled early in the month.

Thirty-Day Collections

The average numbers of worms in the 30-day settling jars (Table 20) verified the annual spawning cycle indicated by the plankton collections: a spring period of maximum spawning (reaching its peak in April and May) was followed by a summer period with reduced activity. In late fall, another peak of spawning occurred (in November 1955) which preceded a winter period of reduced activity. About 60 percent of the worms that settled in the jars during the year were spawned during the months March through June, 15 percent during July through October, and 25 percent during November through February.

Figure 22 shows the sizes of worms that settled in 30 days during the spring spawning three miles east of Fish Springs, above the deepest water of the Sea. The numbers of worms in the jars, the mean number of segments, and the maximum number of segments have been listed in Table 21. The increase from March to April and May, and the decrease at the beginning of summer were comparable to the trend shown by the plankton and by the average numbers settling each month for all stations.

TABLE 20

Average number of Neanthes in 30-Day Settling Jars in Salton Sea, 1955-1956

Month	Average Number of *Neanthes* per 30 Days	Month	Average Number of *Neanthes* per 30 Days
March	1,688	September	434
April	2,720	October	258
May	1,903	November	1,475
June	1,304	December	704
July	959	January	605
August	180	February	1,000

The increase in the mean number of segments from March to the maximum in June and July may be indicative of a faster growth rate, correlated with warming of the water. The increased prevalence of worms having more than 30 segments in May and June (Figure 22) may also have been due to a more rapid rate of growth. However, since the larger worms may have crawled in from surroundings it would seem

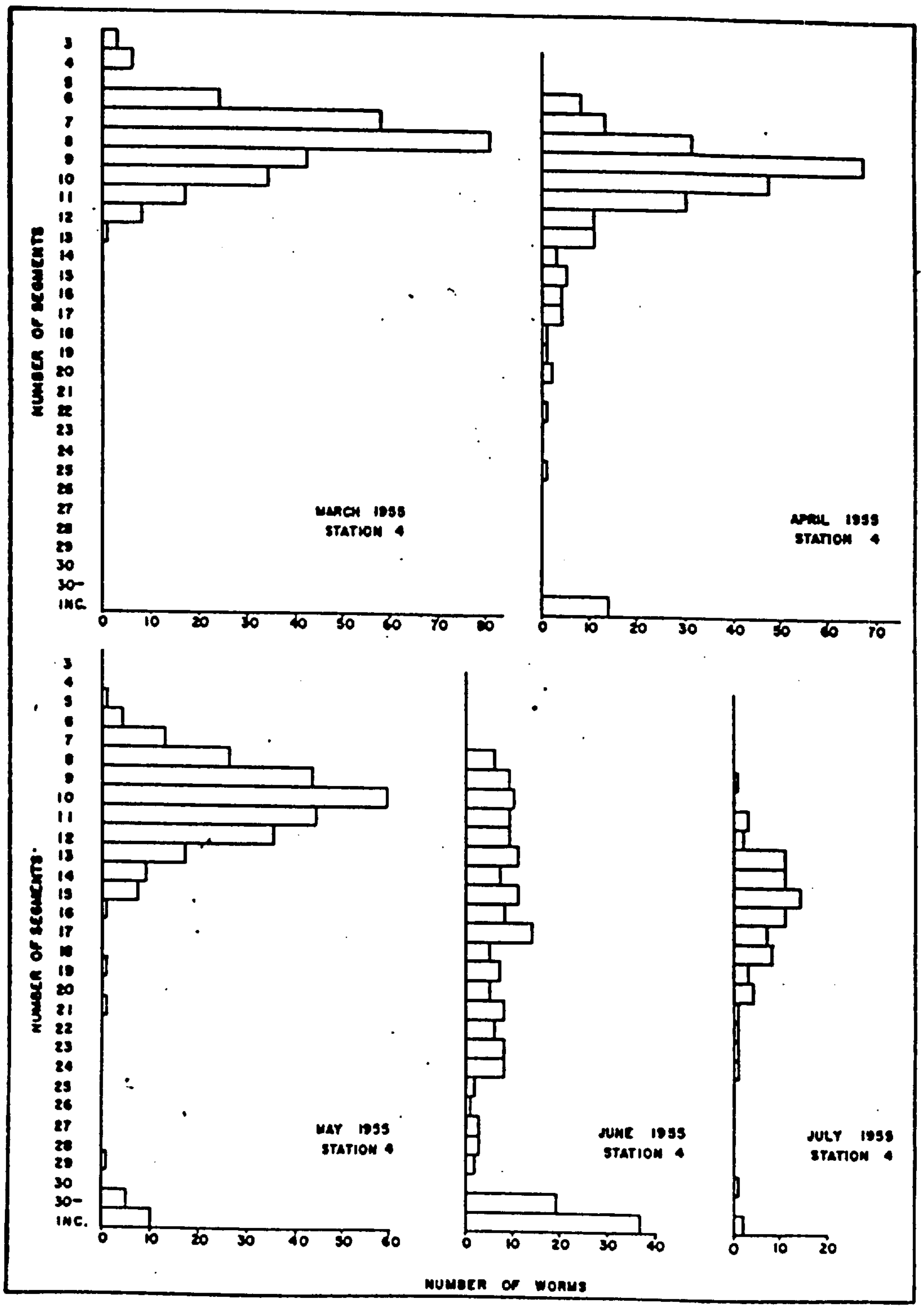

FIGURE 22. Size distribution of *Neanthes* settling in jars in a 30-day period during March to July, 1955. All collections made at a station three miles east of Fish Springs, above the deepest water of the Salton Sea.

TABLE 21

Number of Neanthes, Mean Segment Number, and Maximum Segment Number, in 30-day Settling Jars from 3 Miles East of Fish Springs, Salton Sea During Spring, 1955

Month	Number	Mean Segment Number	Maximum Segment Number*
March	1,040	8	13
April	3,119	9	18-22
May	3,372	10	16-21
June	991	16	25-29
July	344	15	20-24

* Only worms in lower size modal group included.

more justifiable to estimate the "usual" rate of growth from the start of the "tail" of the distribution, shown in Figure 22, rather than from the individuals having more than 30 segments.

If estimates are made in this way, the maximum of 13 segments in March indicates that the worms entering as six-to-nine-segmented larvae added four to seven segments during the month. In April and May, the maximum of about 20 segments would indicate that the settled larvae grew 11 to 14 segments during the month. In June, the segmental distribution tapered out between 25-29 which would indicate addition of 17-23 segments per month, which was the maximum observed in the deepest parts of the Sea. At the three-mile station in July, the number of worms decreased and their rate of growth seemed to decrease to about that observed for April and May. By August, *Neanthes* had disappeared from the bottom below depths of about 25 feet.

During spring and early summer, worms in the collections from shallow water near shore (e.g., Station 1, upper part of Figure 23) contained the same mean number of segments and the same maximum number as those found in the deeper water, indicating growth rate was uniform in various parts of the Sea.

Data for all the shallow-water stations during summer, fall, and winter were similar to those in the lower part of Figure 23, which shows the size distributions of worms collected in 30-day settling jars one-half mile north of Mullet Island. At this station in August, there were relatively few worms (336 total), and relatively few were small: half the worms had more than 30 segments. Although the distribution shows no real peak, if rate of growth is estimated from the "tail" of the size-distribution curve, it would be 25-30 segments per month. However, if rate of growth is judged from the size attained by 171 of 336 worms in the collection, it would be more than 30 segments per month. It is conceivable that those with more than 30 segments settled during a period of intensive spawning early in the month, and that the smaller worms were spawned later in the month (an interpretation is suggested in the discussion of the 10-day collections).

There may be a correlation between growth rate and temperature. It was not until November that the mean water temperature decreased to 20 degrees C., approximating those of the spring (Table 22).

By November, the size distribution (Figure 23) was about as it had been in March: there were many small worms, with a mean segment number of 7 and a maximum of 12. The growth rate was three to six

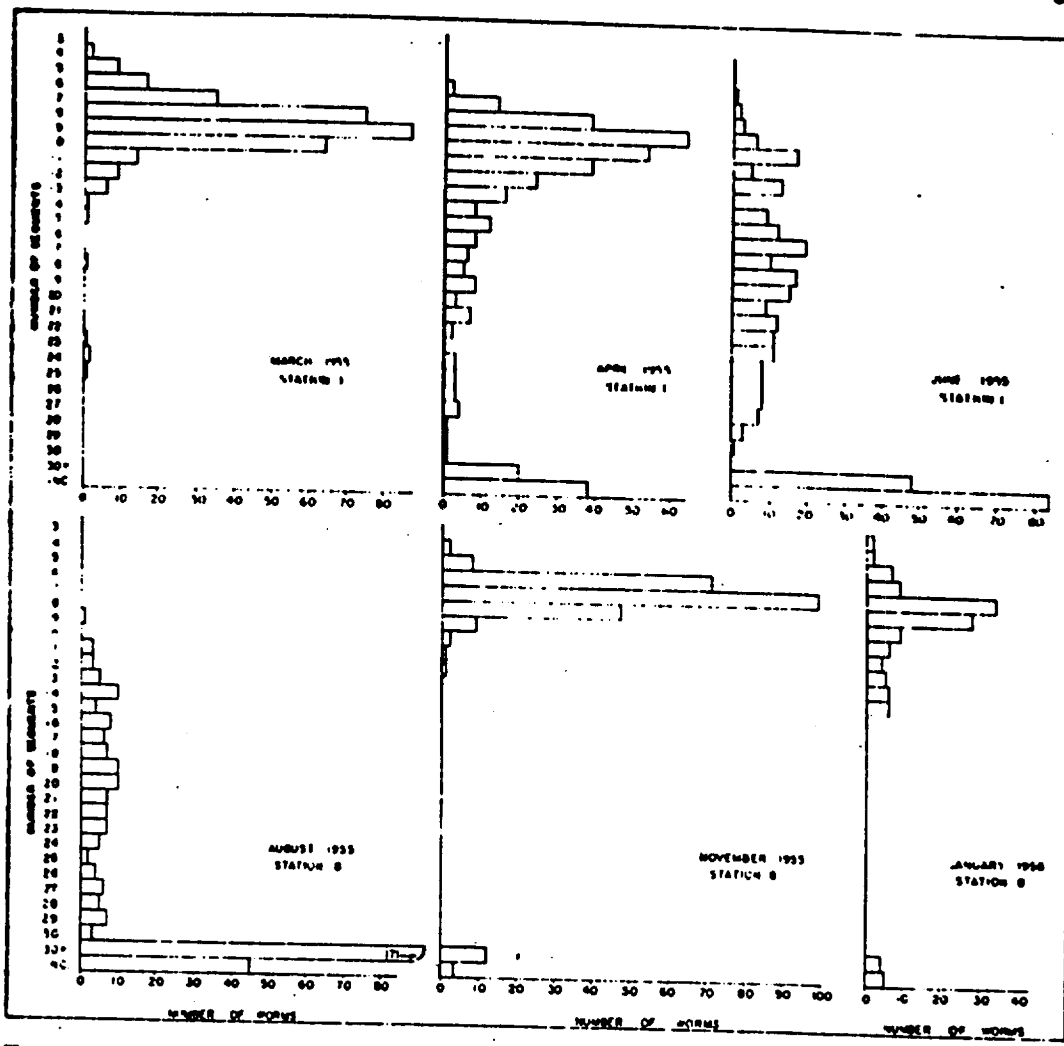

FIGURE 23. Size distributions of *Neanthes* settling in jars in a 30-day period during six different months in 1955 and 1956. All collections were made at a station one-half mile north of Mullet Island, Salton Sea.

segments per month. In November, worms having more than 30 segments were no longer numerous, as they had been in August, and, at some stations in September and October. In December and January, the growth rate was about as in November but there were far fewer worms: 387 compared to 1,099. These figures for fall and winter are in contrast to the greater number that settled during the spring spawning—in April 1955, 2,774 worms settled in the jar at Station 8.

TABLE 22

Mean Monthly Surface Temperatures in Salton Sea, 1955

Month	Temperature in Degrees C	Month	Temperature in Degrees C
January	13	July	30
February	14	August	32
March	18	September	31
April	21	October	27
May	23	November	20
June	27	December	16

The data from the 30-day settling jars showed the rate of growth was slow (three to seven segments per month) in early spring and during fall, but during the summer it was 25-30 segments per month, or even more.

Ninety-Day Collections

There were no sexually mature worms in any of the jars left for 30-day periods. Collections for 90-day periods contained a few epitokes showing that some *Neanthes* reach maturity within 90 days.

In judging maturity of *Neanthes* it should be mentioned that, based upon 114 epitokes (21 female, 93 male), the normal number of segments of mature males was 88 to 98 and for females, 103 to 125. For the males, 14, 34, and 40 to 50 segments were pre-natatory, natatory, and post-natatory; while for females there were 17, 26, and 60 to 82, respectively.

Although the number of pre-natatory and natatory segments was nearly constant, the number of post-natatory segments was more variable. Although most complete males had 40-50, individuals with 58, 64, and 85 were found. Among the females, although most had more than 60, one complete female had only 44. The counts of post-natatory segments were based on complete worms; the actual number varied, however, because terminal segments were often missing. Sexually functional worms may lack all the post-natatory and even some of the natatory segments. It was observed in an aquarium that the tails of *Neanthes* may protrude from their burrows. Loss of terminal segments may be due to "grazing" on the protruded tails by other *Neanthes* or by fish. The epitoke of *Neanthes* thus has at least 50 segments, and if complete, 90 to 100 or more.

The sizes of the worms that settled in a jar in three months, (March 3 to June 1, 1955) one-half mile north of Mullet Island are shown in Figure 24. The continuous distribution (up to a length of 80 segments), and the presence of three epitokes, of which two were males (one with 56 segments, the other with 62) and one female (with 79 segments) is evidence that during spring at least a few *Neanthes* reached maturity within 90 days.

The rate of growth can be estimated if it is assumed that the largest one-third of the worms had settled during the first 30 days of the 90-day period and that their growth was constant. The presence of 50 to 80 segments indicates a growth of 17 to 27 per month. Since this took place during March, April, and May when mean water temperatures were between 20 and 30 degrees C., it is conceivable that during July, August, and September, when mean water temperatures ranged from 30 to 35 degrees C., the growth rate may, indeed, have been greater than 30 segments per month, as was indicated by numerous individuals somewhat longer than 30 segments in 30-day collections—i.e., that made in August at Station 8, shown in the lower left of Figure 23.

Number Per Unit Area in Settling Jars

The settling jars showed that tremendous numbers of worms settled to the bottom. The minimum number in a 30-day collection near shore was 99 (Station 7, October); the maximum during the peak of spring spawning was 5,423 (Station 10, April). Since the area through which they settled was approximately 0.01 square meter, these figures repre-

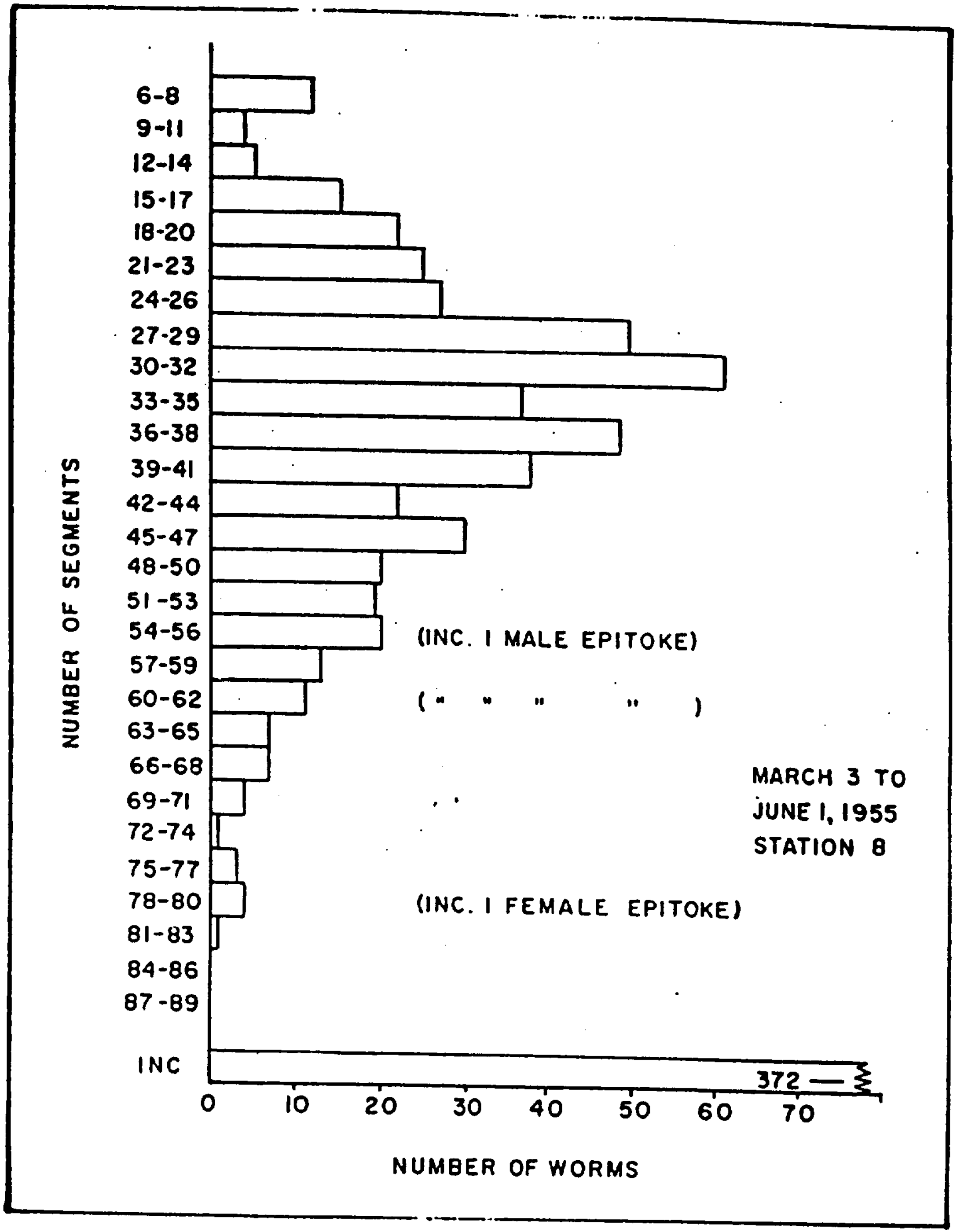

FIGURE 24. The size distribution of *Neanthes* settling in jars in the 90-day period, March 3 to June 1, 1955, at a station one-half mile north of Mullet Island, Salton Sea.

sent 10,000 to 540,000 worms per square meter of bottom, or 1 to 54 worms per square cm. The maximum number collected represented one worm per two square mm.

Measurements of small *Neanthes* showed immature worms, up to about 30 segments, were about 0.1 mm long per segment. That is, a 10-segmented worm was about 1.0 mm long; a 30-segmented one about 3.0 mm. So, because of their small size, great numbers can settle, and for about the first month of bottom-dwelling there was room for the maximum found in 30-day collections. However, mature *Neanthes* epitokes of 70-90 segments were four to five cm long (1¾ to 2¼ inches). Obviously there was insufficient area for all that settle to reach maturity. Samples of the bottom mud, screened to determine the number actually present, averaged about 6,500 per square meter, while the maximum was about 19,000.

BOTTOM SAMPLES

From bottom samples taken to study the sedimentation and Foraminifera of the Sea, Arnal (1957) concluded that "*Neanthes* lives only in littoral sediments, and is restricted to fine sand and silt material. None were found [*sic*] in coarse sand or in fine mud in the center of the Sea." Through the courtesy of Mr. Arnal, the samples he had taken were made available to us. *Neanthes* were in 58 of 78 of these taken at depths of 1 to 29 feet; none was in 21 collections from depths greater than 30 feet. However, none of Arnal's samples from greater than 30 feet had been taken in winter or spring. His collections thus showed only that *Neanthes* was absent from the bottom at greatest depths in summer and early fall.

Neanthes have been found in winter and late fall in the deepest part of the Sea. For example, three miles off Fish Springs (depth 40 feet) *Neanthes* were present in samples taken with an Ekman-type dredge on February 22, 1955, when there were 39 per 36 square inches, and, after being absent in summer, on October 25, 1955 when there were 17 per 36 square inches.

During the summer of 1955, routine dissolved oxygen determinations at the station three miles east of Fish Springs showed that the waters below about 20 feet became anoxic at times in June, July, August, and September. The periods of anoxia were usually short (especially in June) but were occasionally of sufficient duration to suggest that lack of oxygen might account for the worm's disappearance from the plankton and from the bottom in the deepest part of the Sea in July, August, and September.

In order to verify the apparent summer disappearance of *Neanthes* from the plankton and from the bottom at depths below about 25 feet, and to obtain an estimate of the actual mass of *Neanthes* in the bottom of the Sea, two series of bottom samplings were made during September and November of 1956. One series of samples was collected at the end of summer when anoxic conditions should have eliminated *Neanthes;* the second was taken during the fall peak of spawning after return of oxygen at the bottom.

An Ekman-type dredge, which samples a bottom area of 36 square inches, was used. The samples were preserved with formalin, sorted through a U. S. Standard Sieve series and stored in 70 percent isopropyl alcohol. The weight and the number of worms were determined. The weight was that of the preserved animals after excess moisture had been removed by placing them on filter paper for a short time.

Bottom samples were collected along transects from Fish Springs to Mortmar and from Durmid to Truckhaven on September 18, 1956 (Figure 25). *Neanthes* were absent in all five samples from depths below 30 feet, but were present in the five collected at less than 16 feet (Table 23). On September 21, 1956, samples were collected along a transect due south from Bombay Beach toward the southern shore of the Sea.

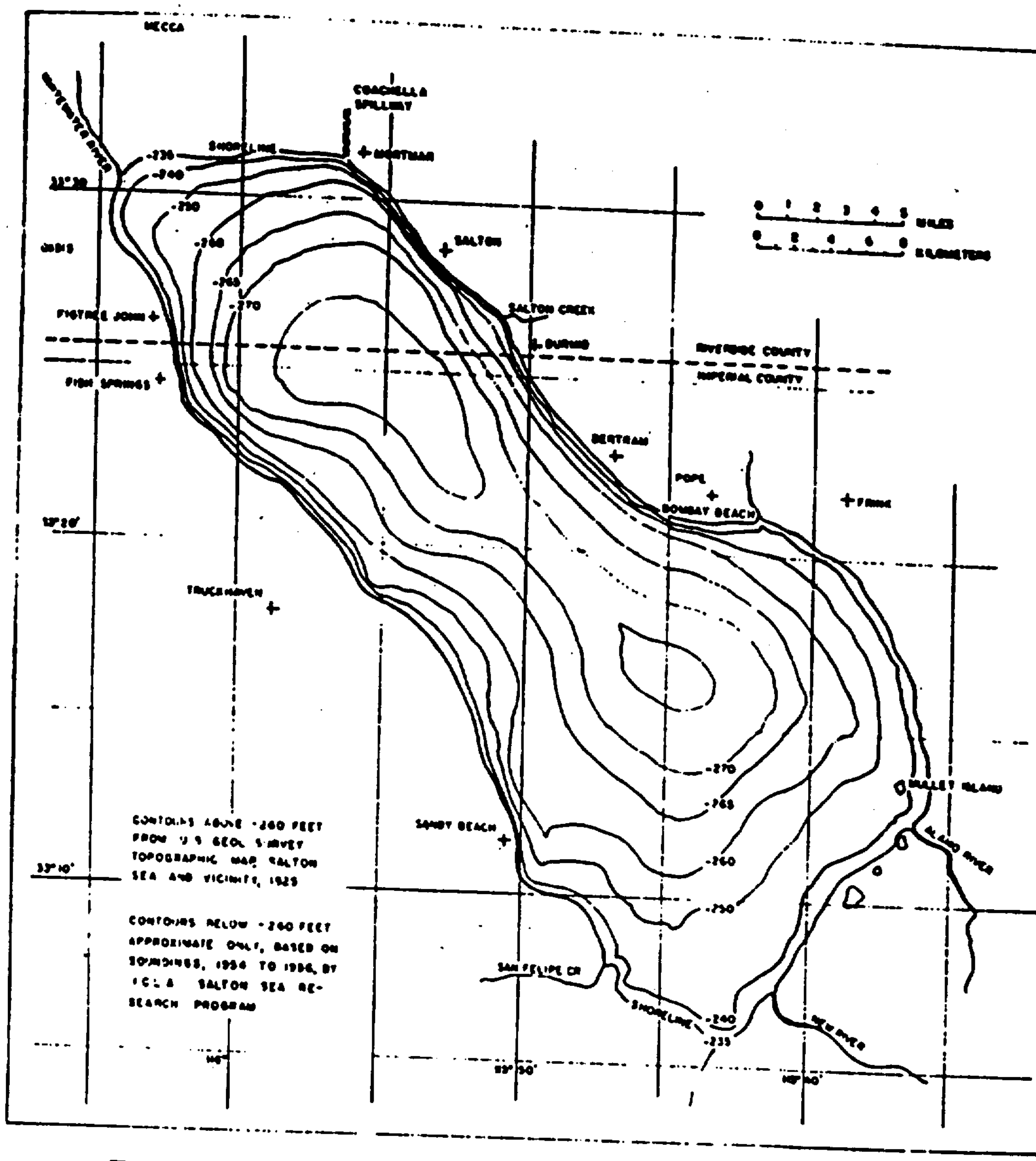

FIGURE 25. Bottom contours and local reference points, Salton Sea.

A few small *Neanthes* (ranging from one to five per 36 square inches) were present in the four bottom samples from deeper than 25 feet, but were numerous in two samples taken in 7 to 10 feet of water.

In a series of samples taken November 29, 1956 at approximately five-foot depth-intervals along a line from Fish Springs toward Mortmar, *Neanthes* were present in all collections made in from 5 to 36 feet (Table 24). It would thus seem that *Neanthes* was absent at these depths in September, but had returned by November.

Another series of samples was taken on December 3, 1956 along a transect from the spillway north of Mortmar to Oasis. *Neanthes* were in all of these samples which were taken at depths from 10 to 23 feet (Table 24).

Depth Distribution of *Neanthes*

It would seem from the data of Table 24 that the zone at the upper boundary of the depth that becomes anoxic in summer is the zone that, in fall at least, is the most productive of *Neanthes*. At nine stations in

TABLE 23

Numbers and Weight of Neanthes per Unit Area of Bottom in Collections Made in September 1956, Salton Sea

Location	Depth in Feet	*Neanthes* Number per 36 in²	Weight g/36 in²	Weight g/m²
September 18, 1956				
100 yd off Fish Springs	11	51	0.313	13.2
2 mi NE of Fish Springs	36	0	0	0
4 mi NE of Fish Springs	37	0	0	0
6 mi NE of Fish Springs	38	0	0	0
150 yd off Mortmar	13	441	1.587	67.2
150 yd off Mortmar	13	423	1.71	72.0
500 yd off Durmid	14	69	0.278	11.7
2 mi SW of Durmid	39	0	0	0
4 mi SW of Durmid	42	0	0	0
300 yd off Truckhaven	10	124	1.070	45.0
September 21, 1956				
200 yd off Bombay Beach	9	91	0.683	28.8
2½ mi S of Bombay Beach	37	9	----	----
5 mi S of Bombay Beach	39	1	----	----
7½ mi S of Bombay Beach	35	5	----	----
10 mi S of Bombay Beach	26	3	----	----
Southern Shore	7	69	0.184	7.75
Second Sample, No. 6	7	62	0.296	12.5

TABLE 24

Numbers and Weight of Neanthes per Unit Area in Collections Made in November and December 1956, Salton Sea

Location	Depth in Feet	*Neanthes* Number per 36 in²	Weight g/36 in²	Weight g/m²
November 29, 1956				
Fish Springs Jetty	5	109	.2495	10.5
150 yd NE of Fish Springs	10	174	.6712	28.2
300 yd NE of Fish Springs	16	215	.3361	14.1
500 yd NE of Fish Springs	20	231	1.8060	75.9
1 mi NE of Fish Springs	30	77	.2825	12.0
4.5 mi NE of Fish Springs	36	39	.1067	4.5
S of Mortmar	10	261	.2838	12.1
1½ mi NW of Mortmar	10	189	.4095	17.2
1½ mi NW of Mortmar	10	166	.4081	17.1
December 3, 1956				
400 yd true S of spillway	10	189	.3307	14.0
200 yd from spillway	20	222	.8187	34.4
3 mi SW of spillway	23	118	.7115	30.0
6 mi SW of spillway	20	115	.9155	38.5
200 yd offshore E of Oasis	10	98	.3770	15.8
200 yd offshore 3 mi N of Fish Springs	10	167	.3177	13.3

water shallower than 16 feet, the weights of worms in 36 square inches of bottom ranged from 0.2495 to 0.6712 grams, and averaged 0.376. At depths of about 20 feet, the weights ranged from 0.5903 to 1.8060 grams for an average of 0.968. At greater depths (exceeding 30 feet) the range was 0.1067 to 0.2825 for an average of .1946 (three samples). The bottom that becomes anoxic and unsuitable for the worm in summer is black organic mud, covered with a mat of bacteria and detritus. The bottom at about 20 feet is a brownish sand with an admixture of barnacle shells. The shallowest areas near shore are silt or clay or sand, black or brown in color, and covered with a mat of blue-green algae and diatoms. This mat may become detached, and eventually settles in deeper water or is thrown on the shore by wave action. Arnal (1957) found that the shallower zone near shore had the least organic matter (one to two percent) but with depth it increased in the bottom mud to a maximum of five to six percent. The bottom below a depth of 25 feet evidently became anoxic during the time of degradation of the great amount of phytoplankton and zooplankton produced in the spring due to the bacterial decomposition of the increased amounts of settled organic matter. *Neanthes,* therefore did better in the intermediate depths, where the amount of organic matter was two to four percent, than in the zone near shore, where there was less food (organic matter one to two percent), or at greater depths where, although there was a rich food supply, the amount of organic matter (five to six percent) was so great that oxygen was not available for prolonged periods in summer.

The lengths of the anoxic periods were important. In shallower water, oxygen frequently was depleted at dawn during summer. But the anoxic condition lasted only a few hours each day. In laboratory experiments conducted July 21-26, 1955, some *Neanthes* survived 24 to 27 hours in oxygen-depleted water. It would thus seem that *Neanthes* can tolerate absence of oxygen for about one day, but cannot endure anoxia for longer periods.

Neanthes, therefore, were absent from the bottom below about 25 feet during July, August, and September. From October to June, after the organic matter had been degraded, the deepest zone again had sufficient oxygen to support them. During this period, they could make use of the richest food supply in the Sea.

Standing Crop of *Neanthes*

It can be calculated from the bottom contours (Figure 25) that 30 percent of the Sea lies above −250 feet, 14 percent lies between −240 and −260 feet, and 56 percent lies below −260 feet. This means that with the surface elevation at −235 feet, 30 percent of the 220,000 surface acres is shallower than 15 feet, 14 percent lies at depths between 15 and 25 feet, and 56 percent is deeper than 25.

These depths delimit, approximately, the three distributional zones of *Neanthes:* that of greatest productivity between 15 and 25 feet, the less productive shore area, and the deep zone from which *Neanthes* is excluded in summer and early fall.

The surface area of the Sea at −235 feet is 220,000 acres, or 890×10^6 m^2. The three zones (shore, intermediate, and deep) contain respectively 265×10^6, 125×10^6, and 500×10^6 m^2.

The weight of worms found in bottom samples (Table 24) in late fall can be used to indicate the standing crop of *Neanthes* at that season. In the deepest part of the Sea (depths greater than 30 feet), this was about 8 grams/m^2. The 500×10^6 m^2 of this zone would contain 4×10^6 kilograms of *Neanthes*. In the most productive zone (between 15-25 feet) the average weight of *Neanthes* was about 40 grams per m^2, so this zone would contain 5×10^6 kilograms of worms. The shallower shore area (less than 15 feet deep) contained an average of about 16 grams per m^2, or about 4.2×10^6 kilograms of worms.

The entire Sea, on this rough estimate, would contain 13.2×10^6 kilograms of *Neanthes*. Since there are 907 kilograms per ton, there would be 14,500 tons of *Neanthes* in the bottom of the Sea in fall. This represents about 125 pounds per acre. Previously it was estimated, on the basis of numbers in settling jars, that about 25 percent of the annual spawning took place in fall and winter, 60 percent in spring, and 15 percent in summer. If this proportion applied to the numbers on the bottom, it may be that the standing crop in spring averages about 300 pounds per acre, and in summer about 75.