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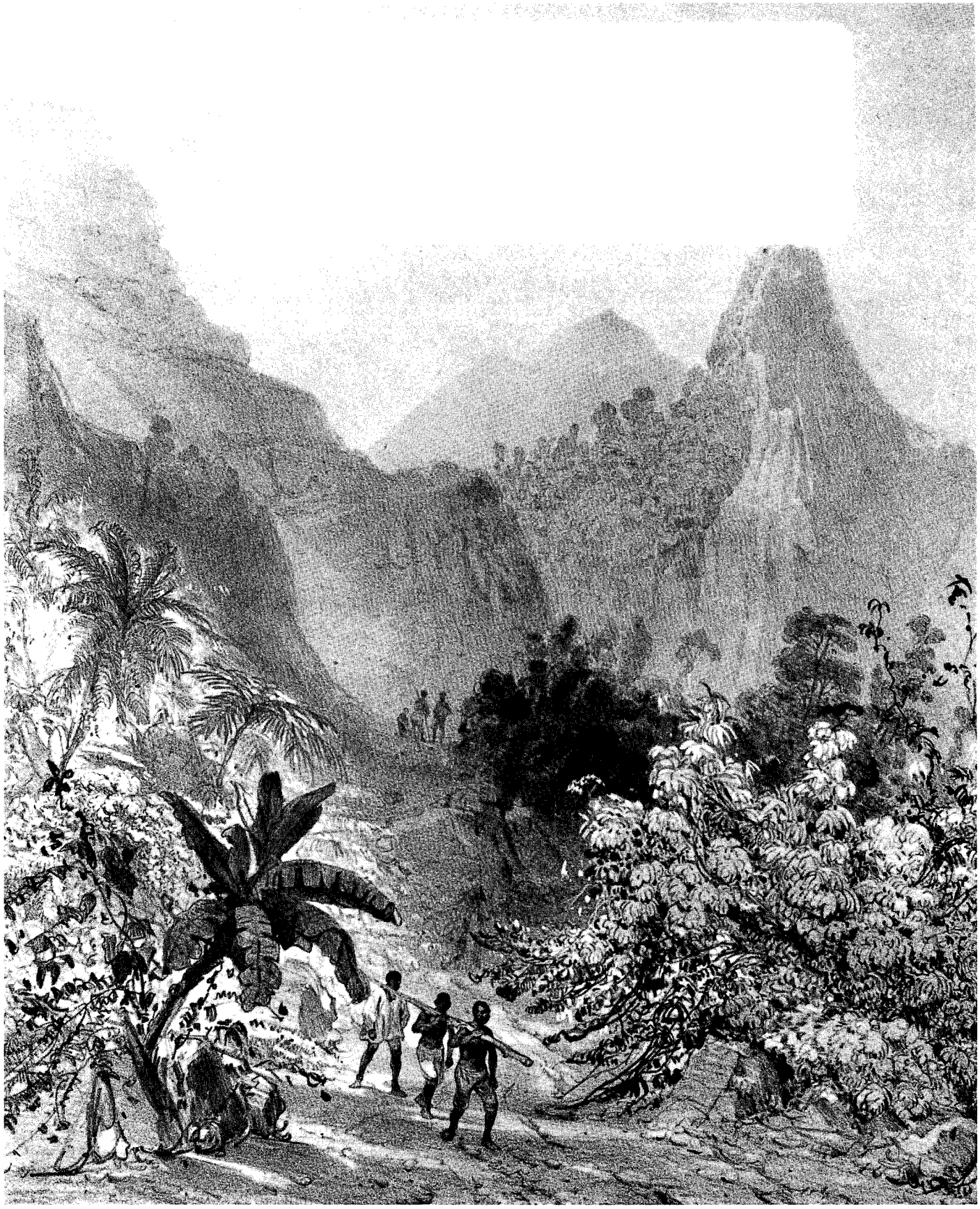

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ZOOPLANKTON POPULATIONS AND WATER CHEMISTRY FROM A SHALLOW (4.3 m) AND DEEP (600 m) PUMPED WATER DISCHARGE, KEAHOLE, HAWAII

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INTRODUCTION

The recent installation of the shallow (4.3 m) and deep (600 m) coastal water supply pipes and support facilities at the University of Hawaii's Natural Energy Laboratory of Hawaii (NELH) at Keahole, Hawaii provides a new and unique research opportunity. A one month pilot study, funded by the University of Hawaii Sea Grant program, was initiated to conduct simultaneous deep and shallow water basic biological and chemical research. Zooplankton, water chemistry and related oceanographic parameters were assayed at a well-defined site over specific periods of time and in measurable volumes of water. The results of these measurements provide insight not only into diurnal fluctuations in the zooplankton community, but also into zooplankton patchiness. Simultaneous measurements of water chemistry, including suspended sediments and nutrients, complement the biological studies and provide a first order estimate of the water/biota relationships in the shallow waters and at 600 m off Keahole Point. In addition to contributing to basic zooplankton population biology research, such information is applicable to entrainment and impingement in ocean thermal energy conversion (OTEC) or conventional power plant intake systems and to determining the suitability of the water supply for aquaculture developments.

Zooplankton and phytoplankton have traditionally been sampled at sea by towed nets of varying mesh sizes. Quantitative analyses of these samples for population characteristics and depth distributions are subject to errors inherent in the sampling methods. Accurate measurements of the volume filtered are affected by net clogging and its subsequent effect on flowmeters. Precise sampling depths are difficult to maintain and nearly impossible to reproduce due to variations in the towing speed of the ship, currents, and weather conditions. In addition to the potential mechanical sampling errors, estimates of population densities and water column distributions are most significantly impaired due to behavioral factors, i.e. clumping or "patchiness" of the populations, and avoidance of the nets by the faster-swimming plankters.

Over the years, numerous devices have been tried, tested, and developed in an effort to reduce these mechanical problems. Flowmeters of multiple shapes and sizes have been attached in front of, behind and inside the plankton nets. Electronic devices have been employed to monitor depths of sampling, and paired nets (so-called Bongo nets) have been used to estimate patchiness. (An overview of these methods and sampling devices is found in the UNESCO Press (1968) report, "Zooplankton Sampling.") Despite the advances that have been made in equipment, certain problems remain inherent to the use of towed nets, most notably patchiness of distribution, avoidance of the nets, and precise measurements of the volume filtered.

To circumvent these problems, pumps have been employed in surface waters with various methods of estimating the volumes so obtained (Barnes, 1949). Aron (1958) cited 17 studies from 1897 to 1957 dealing with plankton pumps, including the first documented attempt at extensive pump sampling by Hensen in 1887. Aron's conclusion is of interest: "The pump appears to be an ideal tool for investigating both horizontal and vertical plankton distribution." The development of suitable pumps has been examined by Gibbons and Fraser, 1937; Harvey, 1966; Beers et al., 1967; Singarajah, 1969; and Lenz, 1972. Most recently, studies by Leithiser et al. (1979) comparing a high-volume pump with conventional plankton nets for collecting fish larvae entrained in power plant cooling systems have shown that the nets greatly undersampled both total numbers and particularly large larvae as compared to the pump collections. Their findings suggest that "the conclusions regarding ichthyoplankton entrainment based on data obtained with conventional plankton nets may be of questionable validity."

Alternatives to standard impeller-driven pumps were sought to minimize destruction or maceration of the plankters. These alternatives have included siphon systems (Harvey, 1966) and vacuum systems (Lenz, 1972). Previous pumped methods of sampling have suffered severe limitations primarily due to the mechanical-logistical problems of handling long pipes or non-collapsable hoses on-board ships, and the corrosion problems associated with the use of pumps in sea water. A major problem acknowledged by Aron and others is the size of the pump needed for deep water sampling and the physical-mechanical problems of suspending a pipe or hose at a specific depth from a ship. The deepest pump samples reported to date were taken at 85 m (Judkins, 1980). Our present zooplankton studies from the cold water intake at NELH provide the first such pumped collections obtained from the deep 600-m (2000-foot) mid-water environment.

MATERIALS AND METHODS

As part of its continuing ocean thermal energy and aquaculture research program, NELH has installed a shallow (warm) and deep (cold) water supply system consisting of three 30.5 cm (12 in) diameter PVC pipelines that extend from the laboratory facilities approximately 125 m (400 ft) across the raised lava-reef platform and into the sea (Fig. 1). The two shallow water pipes extend 12 m (40 ft) seaward of the shoreline, with their intakes at a depth of 4.3 m (14 ft) below the sea surface, and 1.8 m (6 ft) above the bottom (total water depth: 6 m (20 ft))*. The single deep water pipe is of the same 30.5 cm (12 in) diameter but extends seaward approximately 1680 m (5500 ft), with the entrance end tethered 21 m (70 ft) off the sea bottom at a depth of 2000 ft. Actual length of the deep, cold water pipe is 1800 m (5900 ft). The deep pipe is completely open at its lower end, but the shallow pipe is covered with a multi-holed cap (the holes are irregular, but are approximately 2-5 cm across) to exclude large animals and rocks. Each of the three systems discharges into separate 1000-gallon header tanks to maintain a constant gravity flow to the laboratory units. All piping systems and the header tanks are non-metallic to eliminate metal-ion contamination. The surface water pumps have Fybrock impellers (an inert plastic), and the deep water pump is stainless steel.

At the time of our collections, water was supplied at rates of approximately 450 gpm (0.028 m^3/sec)** for each of the shallow water pipes and 340 gpm (0.021 m^3/sec) for the deep water supply pipe. At a pumping rate of 340 gpm, the velocity of the water in the pipe is approximately 30 cm/sec, and the residence time of the water in the pipe is about 86 to 95 min (NELH Staff, personal communication). The relatively long transit time in the deep water pipe thus affects the interpretation of the data collected. Time of collection of samples from the deep water pipe are corrected for a travel time of 90 min. The deep water samples thus represent conditions existing in the bottom waters some 1½ hours previous to the time of collection. No comparable problem existed in the much shorter surface water intake. At a pumping rate of 450 gpm, the velocity of

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*The shallow water intake pipe has now been extended to 260 feet offshore, with the subsurface intake at 20 feet below the sea surface and 300 feet off the bottom, to reduce inflow of detritus and sand during periods of high surf.

**Sampling duration and frequency were selected to facilitate examination of diurnal variation and on the assumption of a pump flow rate of 500 gpm. This flow rate was later found to be in error.

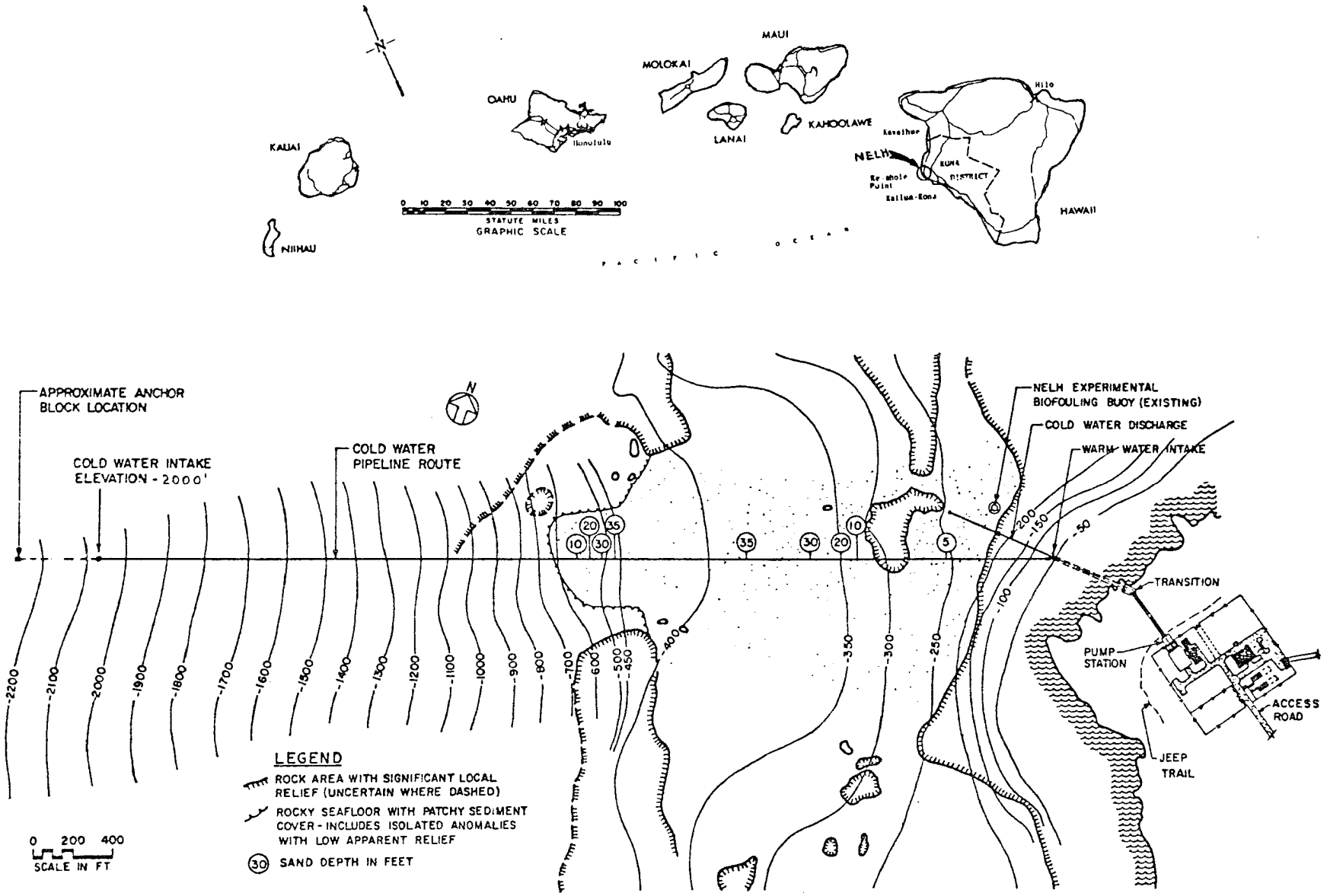


Figure 1. Natural Energy Laboratory of Hawaii.
Site plan showing route of intake pipes.

the water through the 192 m, 30.5 cm diameter pipe was approximately 39 cm/sec and the residence time of the water in the shallow pipe was only about 8 min.

Water samples for micronutrient analysis were collected in 60 ml polyethylene bottles from the header tanks directly below the mouths of the discharge pipes, and were immediately frozen. Six samples were collected the first week (July 13-14, 1982) from the shallow pipe only, due to a malfunctioning pump on the deep pipe during the first week (see p. 5). Six samples were collected the second week (July 20-21, 1982) from each of the two pipes, and three deep samples and one shallow sample were collected the third week (July 27-28, 1982). The samples were analyzed on a Technicon Autoanalyzer II using standard methods for automated micronutrient analysis, to determine concentrations of phosphate (PO_4), nitrite + nitrate (NO_2 + NO_3), ammonia (NH_4), and silica (Si).

Pairs of samples for particulate analysis were obtained by filtering 400 ml and 800 ml of water from the shallow and deep water discharges, respectively, through precombusted (500°C for 4 hr) GFC glass fiber filters (pore size ca. 1μ). Six pairs of shallow samples were collected the first week, and four pairs of shallow and five pairs of deep samples (one of the deep sample pairs had only one filter) were collected the second week. The samples were analyzed on a Hewlett-Packard 185B carbon-hydrogen-nitrogen analyzer. One of each pair of filters was precombusted at 500° C for 4 hr to remove organic material, producing a value for particulate inorganic carbon (PIC). The other filter produced a value for total particulate carbon (TPC) and particulate nitrogen (N). Particulate organic carbon (POC) was thus determined as the difference between the two filters: POC = TPC - PIC.

Water temperature was measured at the time of sampling, using a hand-held thermometer in the header tanks directly in the flow of water from the pipes.

The preliminary and short-term nature of this study dictated the use of considerable "borrowed" equipment. Simultaneous deep and shallow water zooplankton samples were taken with 183μ mesh nets, as they were the only nets available in duplicate. Nets were tied over the discharge outlets from one of the two surface water intakes and the single deep water intake where their flows discharged into their respective warm and cold water header tanks. Each sample was collected for approximately 2 hours*, after which the net was carefully washed down and the zooplankton washed into a funnel-type plankton concentrator of 64μ mesh, then transferred to 30 ml jars and preserved in 5 percent formalin. Environmental data recorded for each collection included water temperature, weather and wind speed. Three 24-hour sample series of 10 samples each were collected at weekly intervals: on July 13-14 (week 1); 20-21 (week 2); and 27-28 (week 3), 1982. Four samples were taken during the daytime, four at night, and one each at dawn and dusk. Because of pump problems on the deep water pipe, the first series sampled only the shallow discharge. The second and third series sampled the discharges from both the shallow and deep water pipes.

An additional series of samples taken on July 29, 1982 investigated relative catching efficiencies of the shallow pipe, using a 505μ-mesh zooplankton net, while simultaneously an identical net (1 m mouth diameter) was towed about 100 m offshore of Keahole Point at a depth of 10 m for a series of four 15-min tows. Because of a strong north-flowing current off Keahole Point, the boat from which the offshore samples were taken was

*See second note, p. 2.

almost stationary with respect to the shore; thus the water sampled was quite close to the depth and location of the shallow water intake. The speed of the net through the water was estimated as 1.0 m/sec. The sample volume of each tow was calculated to be 700 m^3 (a malfunction of the flowmeter prevented a direct flow measurement).

Several difficulties were experienced with the first week's collections. The pump for the deep water pipe system was out of operation and could not be replaced due to heavy surf and generally adverse weather conditions. Sand and organic debris put into suspension by the high surf was sucked into the shallow intake pipe, contaminating the shallow water samples. It proved to be impractical to separate the zooplankton from the sand and sticky detritus, so the first week's zooplankton samples were not analyzed. Fortunately the weather conditions improved, and the deep water pump was repaired, so that the paired surface and deep water samples collected during weeks 2 and 3 were quite amenable to standard aliquot sorting and counting analysis.

Zooplankton taxa were identified and counted using a binocular stereo microscope. Identifications were carried to the species level only for larval fishes and some copepods. Most copepods were identified to genus. Other zooplankton groups were not usually identified below order or family level. Whole samples were counted when total numbers were small; more often a 1/4 to 1/32 aliquot was counted, so that 100-200 of the most abundant taxon was usually represented in the aliquot.

RESULTS AND DISCUSSION

Concentrations of micronutrients and particulates are summarized in Table 1. As expected, micronutrient values were much lower in the shallow water (4.3 m) than in the deep water (600 m), due to nutrient depletion by phytoplankton above the thermocline. The micronutrient values of week 1 were similar to those of week 2, but the standard deviations were lower during the first week than the second. The more uniform distribution was probably the result of a well-mixed surface layer due to the high surf and strong currents observed during that first period. The scatter in micronutrient values during the second week may represent less mixing and more influence of phytoplankton grazers. Mean values from the limited sample series of the third week were generally similar to those from the first two weeks.

Particulate values were much higher in the shallow water than in the deep water, due to the suspension of shallow sediment by breaking waves near the shallow pipe intake. The higher particulate values in week 1 compared to week 2 reflected the unusually high surf during week 1. The values for micronutrients and particulates were similar to values obtained at NELH in August-September, 1982 (T. Daniel and T. Walsh, personal communication).

No obvious correlations were observed between variations in chemical parameters, temperature, and zooplankton abundance.

A list of the 66 zooplankton taxa and the percent frequency of their occurrence in the surface, deep and offshore collections is given in Table 2. Forty-three taxa were taken in the shallow water collections, representing 7 phyla. Five of the 43 taxa were present in 90 percent or more of the 25 surface samples, while 6 taxa were taken in one sample only. As was expected, copepods and other crustacea were the dominant zooplankters. The only other abundant animal group was larval polychaetes, which were taken in all samples.

Table 1. Results of water chemistry analysis.

		No. of samples	Micronutrients (µg-at/l: mean ± standard deviation) PO_4	$NO_2 + NO_3$	NH_4	Si
Week 1 (13-14 July 1982)	shallow	6	0.146 ± 0.027	0.316 ± 0.075	0.485 ± 0.021	5.751 ± 2.953
	deep	0	---	---	---	---
Week 2 (20-21 July 1982)	shallow	6	0.216 ± 0.022	0.547 ± 0.209	0.262 ± 0.115	10.142 ± 6.221
	deep	5	3.207 ± 0.104	38.797 ± 2.142	0.102 ± 0.047	88.642 ± 5.984
Week 3 (27-28 July 1982)	shallow	1	0.18	0.62	---	7.17
	deep	3	3.047 ± 0.103	37.500 ± 1.711	---	70.910 ± 3.826

			Particulates (µg-at/l: mean ± standard deviation) TPC	N	PIC	POC
Week 1 (13-14 July 1982)	shallow	6	10.225 ± 2.500	0.800 ± 0.218	3.296 ± 1.313	6.276 ± 2.465
	deep	0	---	---	---	---
Week 2 (20-21 July 1982)	shallow	6	5.631 ± 2.476	0.761 ± 0.601	1.910 ± 0.475	2.968 ± 1.575
	deep	5	1.201 ± 0.284	0.279 ± 0.215	0.270 ± 0.095	0.690 ± 0.207

Table 2. Percent of total samples containing species of zooplankton in the shallow, deep, and offshore samples.

TAXON	SHALLOW[1]	DEEP[2]	OFFSHORE[3]
CNIDARIA			
Medusa	---	---	33
Siphonophore	---	---	67
NEMATODA	16	---	---
CHAETOGNATHA	16	10	100
ECHINODERMATA			
Ophiactis larva	24	---	---
Holothurian larva	4	---	---
Unid. larva	---	---	33
MOLLUSCA			
Bivalve larva	4	5	---
Gastropod larva	4	---	---
Pteropod	---	---	33
ANNELIDA			
Polychaete larva	100	10	---
ARTHROPODA			
Pycnogonida	68	---	---
Crustacea			
Branchiopoda			
Cladocera	---	---	33
Copepoda			
Apseudis	44	5	---
Candacia	84	5	100
Copilia	---	---	33
Corycaeus	96	20	67
Eucalanus	20	60	33
Euchaeta	96	75	100
Labidocera	52	---	67
Lophothrix	---	60	---
Macaudreivella	---	85	---
Macrostellata	---	45	---
Neocalanus	16	---	---
Oncaea	72	55	67
Pleuromamma			
P. abdominalis	---	90	---
P. piseki	8	65	---
P. xiphias	16	100	33
Sapphirina	24	---	100
Scolecithrix	76	15	67
Undinula	92	25	100

[1] n = 25 surface samples.

[2] n = 20 deep samples.

[3] n = 3 offshore samples.

Table 2, continued.

TAXON	SHALLOW[1]	DEEP[2]	OFFSHORE[3]
ARTHROPODA			
Crustacea			
Copepoda			
Sp. 101	8	95	---
Sp. 103	---	100	---
Sp. 104	4	---	---
Sp. 105	16	95	---
* Sp. 106	---	15	---
* Sp. 107	---	5	---
* Sp. 108	---	5	---
* Sp. 109	---	10	---
* Sp. 110	4	---	---
* Sp. 111	---	5	---
* Sp. 113	---	35	---
Unid. Cyclopoid	20	---	---
Ostracoda	12	90	33
Peracarida			
Mysid	84	5	100
Caprellidae	12	---	---
Unid. Amphipod	100	5	33
Isopod A	64	---	---
Isopod B	40	---	---
Tanaidacea	16	---	---
Stomatopoda	---	5	---
Euphausiacea	---	---	33
Decapoda			
Lucifer	8	---	100
Penaeid larva	68	---	---
Crab Zoea	36	---	33
Brachyurid larva	4	---	---
Unid. megalops	48	---	---
Unid. larva	12	---	---
CHORDATA			
Urochordata			
Doliolid	---	---	67
Oikopleura	---	---	100
Osteichthyes			
Bathygobius fuscus	12	---	---
Foa brachygramma	---	---	33
Tripterygion atriceps	16	---	---
Myctophidae	---	25	---
Unid. larval fishes	12	30	---
MISCELLANEOUS			
Unid. eggs	20	15	67

*Not counted in all deep samples

The deep water samples were much cleaner than the shallow samples, with no appreciable macroscopic detritus, although small amounts of sand (less than 1 gm) were also present in these samples. The predominant zooplankters were copepods; other crustacea (euphausiids, larval decapods, etc.) were also present, as well as a few small mesopelagic fish (myctophids) and several unidentified larval fish. Jelly type organisms were very rare. Many of the animals were moderately to seriously damaged by passage through the pipe and pump. This was surprising, as initial pre-study test samples from the deep water pipe taken in April, 1982 indicated very little damage to the organisms. The reason for this apparent difference in the sample condition is not readily explained. The pre-study samples and the present collections are both so small that the difference in sample condition may not be significant.

Identifications were particularly difficult for the deep water collections. The deep water zooplankton is poorly described in the literature, and the preliminary nature of this study did not justify the time or funds to conduct the lengthy examinations that would be necessary for identifications to the species level. Numbers were assigned to unidentified species, and representative samples for each species number were transferred to separate vials for later identifications. As of this date, some 33 taxa have been identified, including 11 copepods presently noted only by number. At least 11 of the deep water taxa were not present in the shallow water collections. This number will most likely be adjusted upward after more precise taxonomic studies have been completed. Six taxa occurred in 90 percent or more of the 20 deep water samples, while 12 taxa were identified in 10 percent or less of the samples. These numbers however must be considered preliminary, as further identifications may alter the counts.

The distribution and abundance in time of those taxa present in quantities of at least 1.0 /m^3 or greater in the shallow water collections for weeks 2 and 3 are presented in Figs. 2-13. Similar distributions for the deep water species occurring in numbers of at least 0.1 /m^3 are shown in Figs. 14-16. Times are plotted as the midpoint of the sampling interval. Diurnal variations are readily observed in many species in both the deep and shallow water collections. It should be noted that the times of the deep water collections have been corrected to actual times of water intake into the bottom of the pipe to account for the approximately 90 min travel time through the 1800-m cold water pipe.

Evaluation of the sampling method

At the flow rates in use during our collections (approximately 100 m^3/hr), and the numbers of species present per m^3, the 2-hour sampling time gave minimal numbers for estimating abundance. This was particularly true for the deep water samples, where the flow rate was approximately three-fourths that of the shallow water pipe. Many of the less-abundant species were represented by fewer than 5 individuals per sample, making meaningful statistical analysis difficult if not impossible. Prior to undertaking any long-term studies of the zooplankton from the intakes at NELH, a series of samples of varying volumes should be taken to determine the optimum sampling volume (duration) necessary for statistical significance. Our samples were confined to about 2-hour periods; hence we have insufficient data in both the smaller and larger volumes (shorter and longer sampling periods) to allow the construction of a curvilinear regression line indicating number of species as compared to sample durations (volume filtered). To provide adequate data for statistically valid estimates of zooplankton population parameters, Cassie (1968) has suggested that some number between 10 and 100 individuals per species should be sampled. Our data suggest that the required number of individuals could be achieved for the majority of the samples if the sampling volumes were doubled; i.e., 400 m^3 of

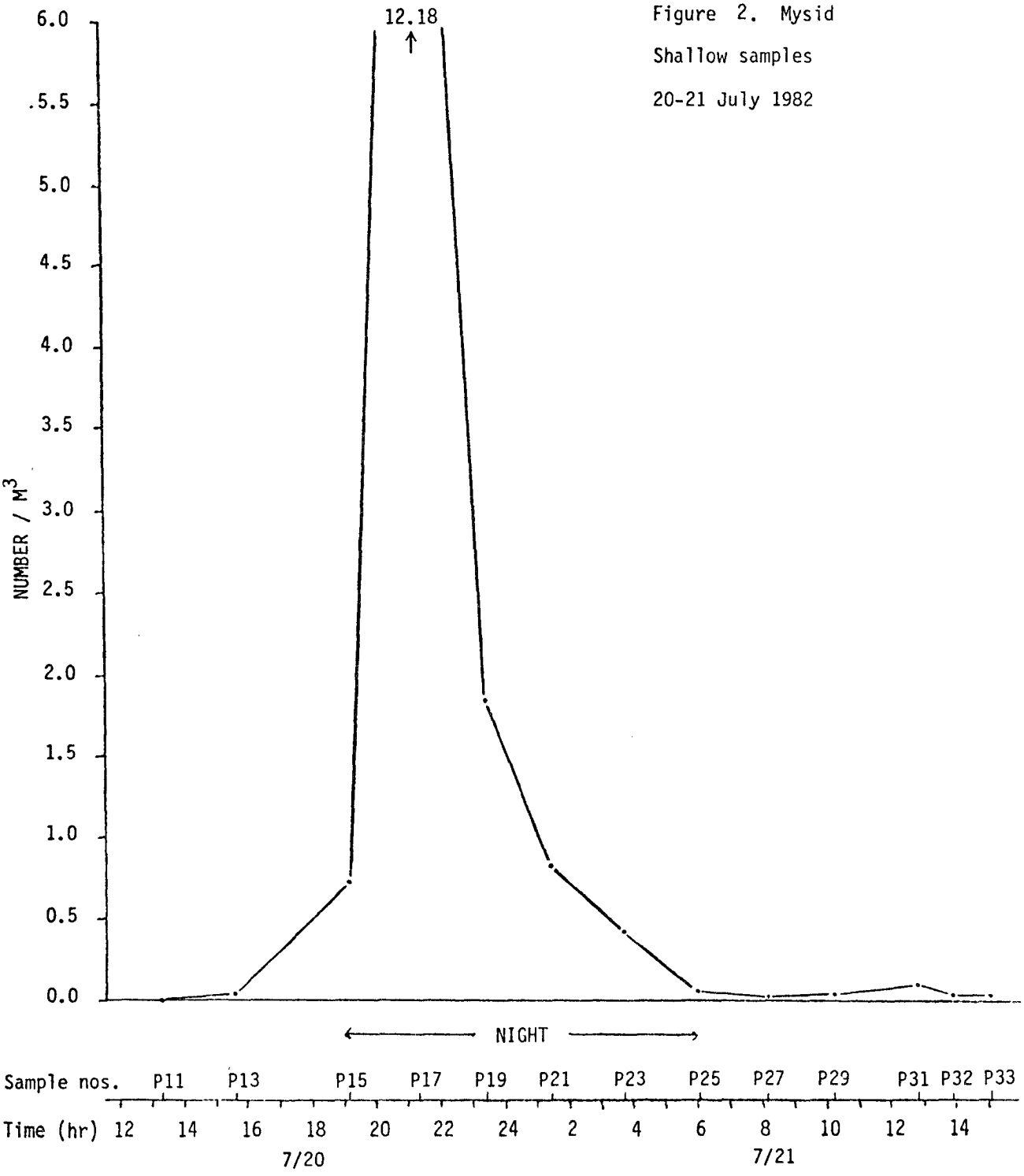


Figure 2. Mysid

Shallow samples

20-21 July 1982

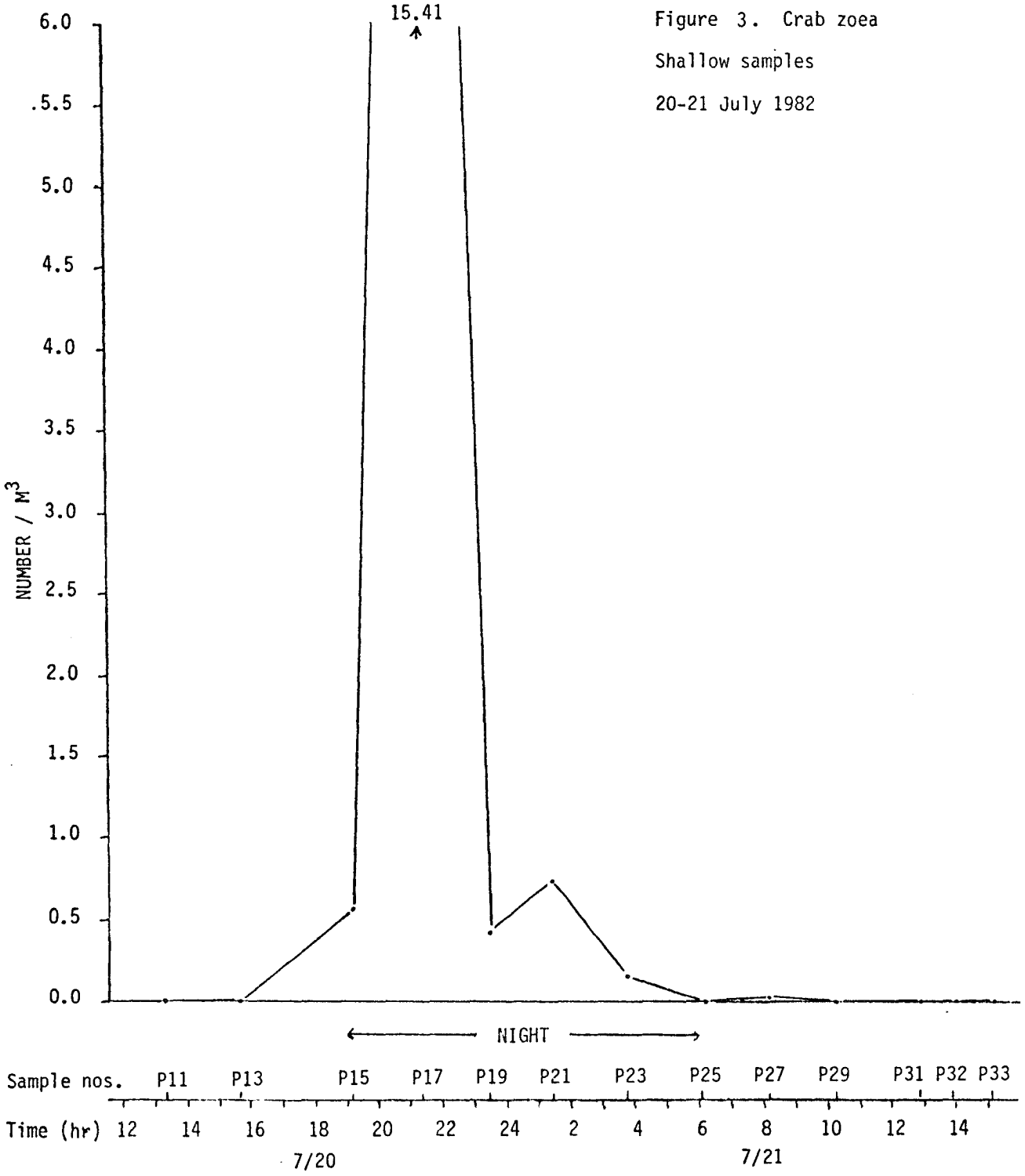


Figure 3. Crab zoea

Shallow samples

20-21 July 1982

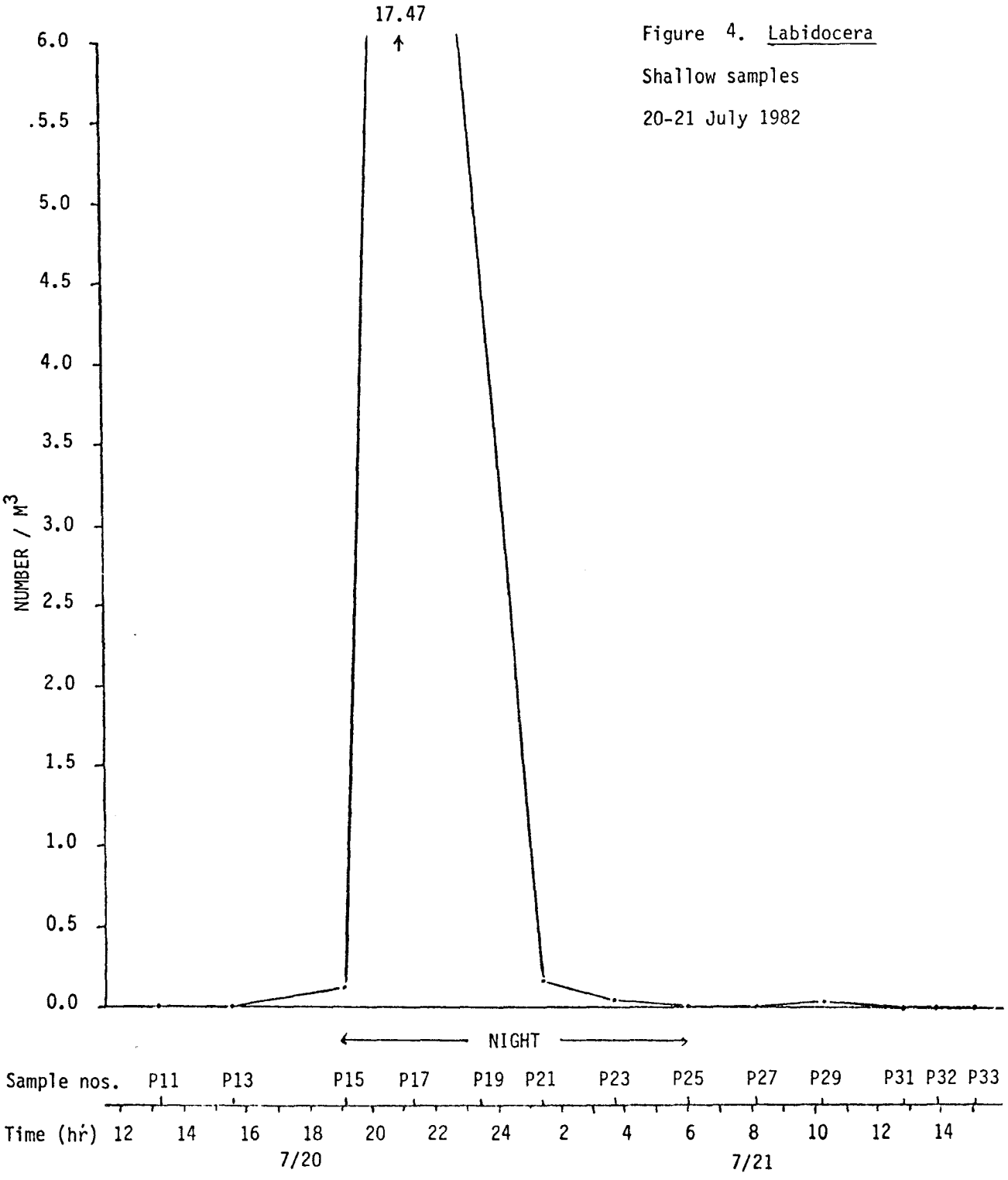


Figure 4. Labidocera

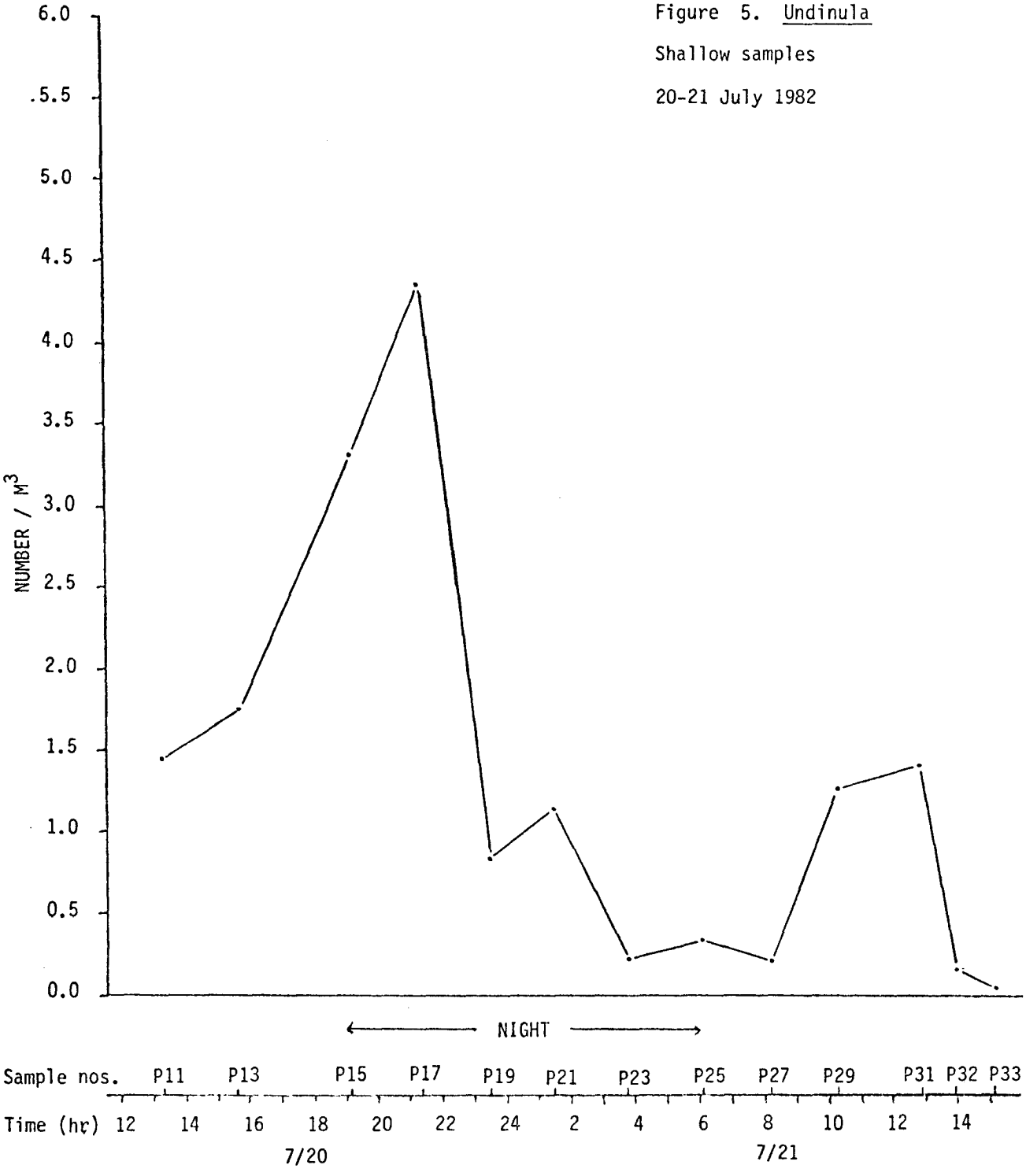
Shallow samples

20-21 July 1982

Figure 5. Undinula

Shallow samples

20-21 July 1982



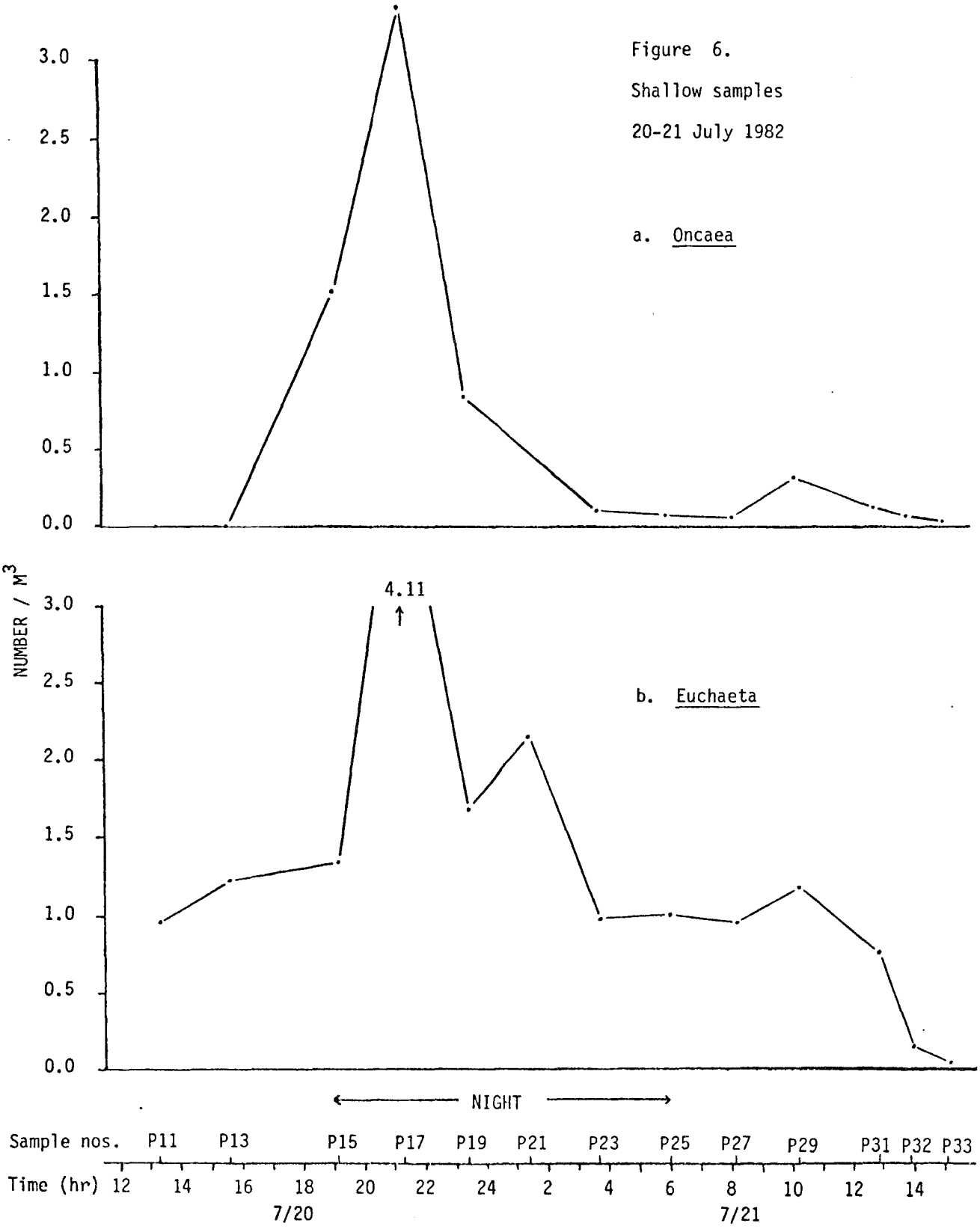


Figure 6.

Shallow samples

20-21 July 1982

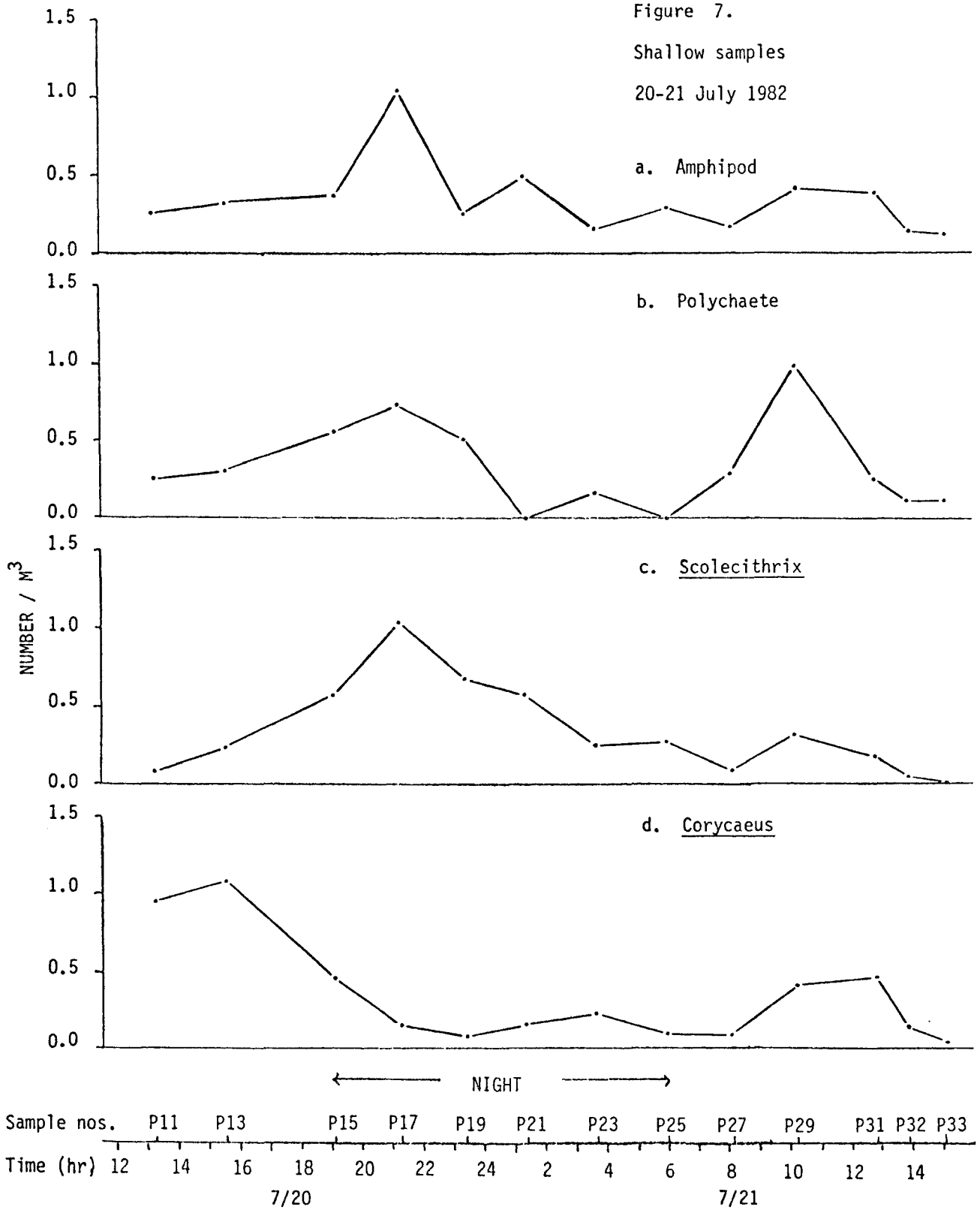


Figure 7.

Shallow samples

20-21 July 1982

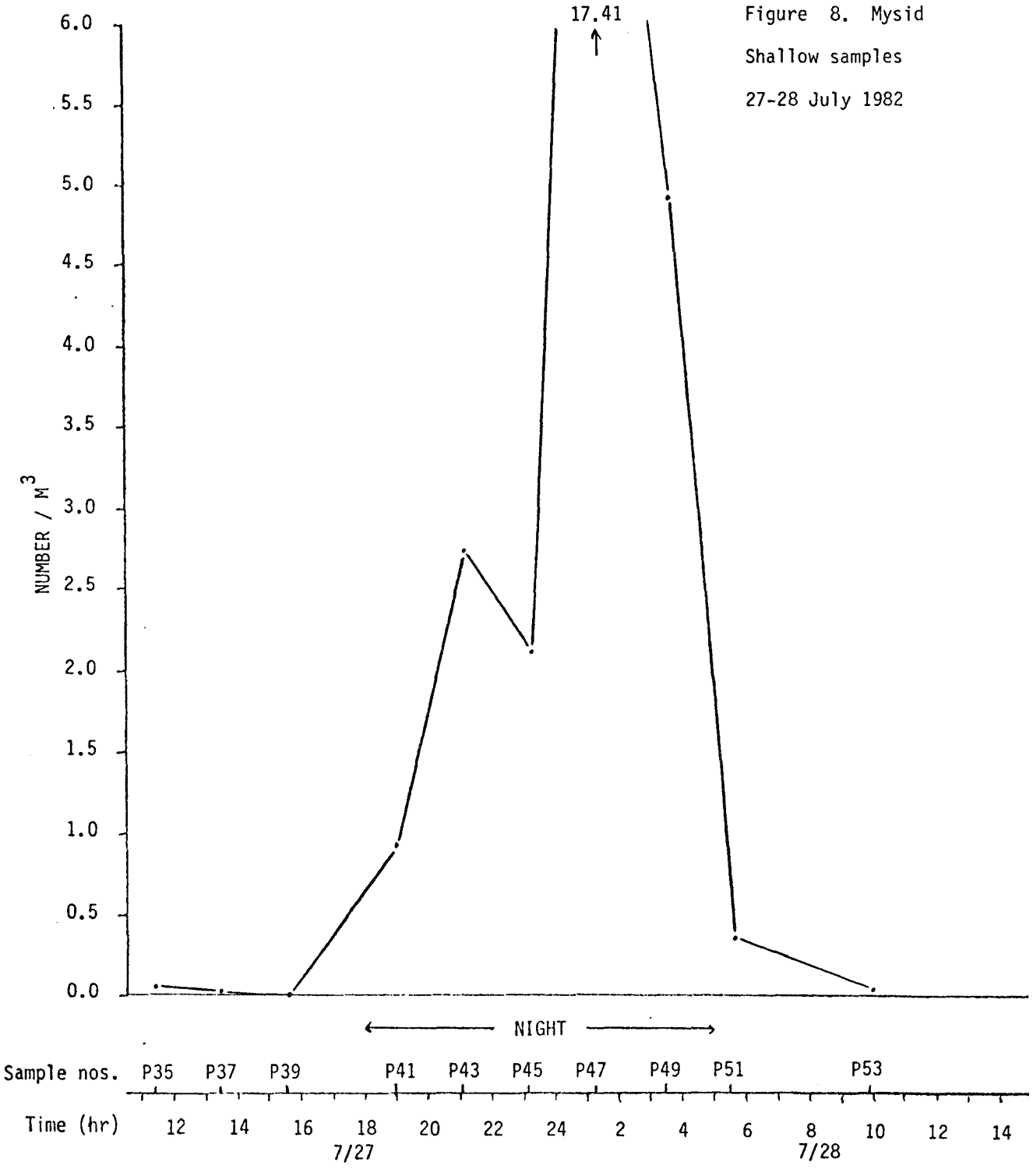


Figure 8. Mysid

Shallow samples

27-28 July 1982

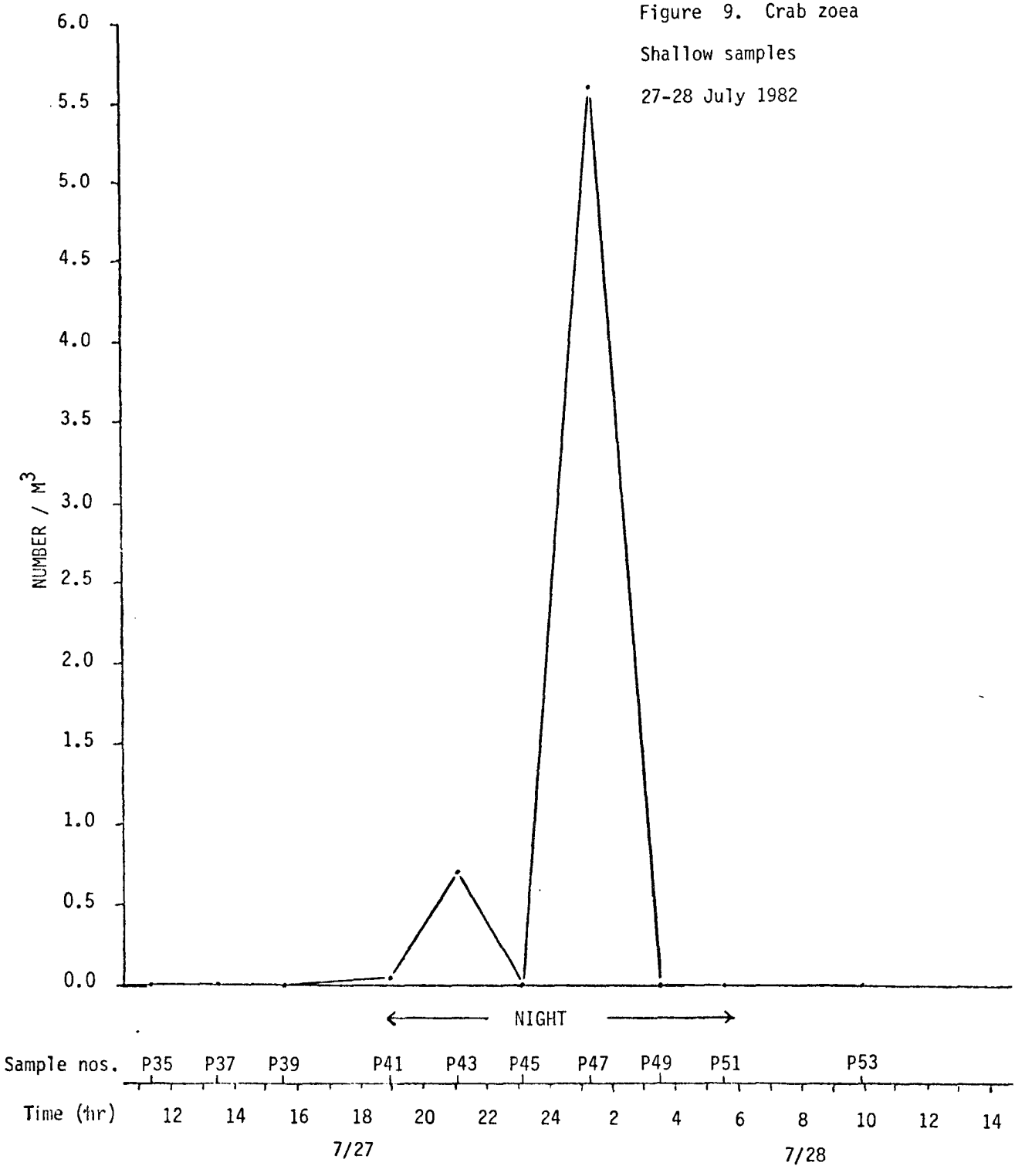


Figure 9. Crab zoea

Shallow samples

27-28 July 1982

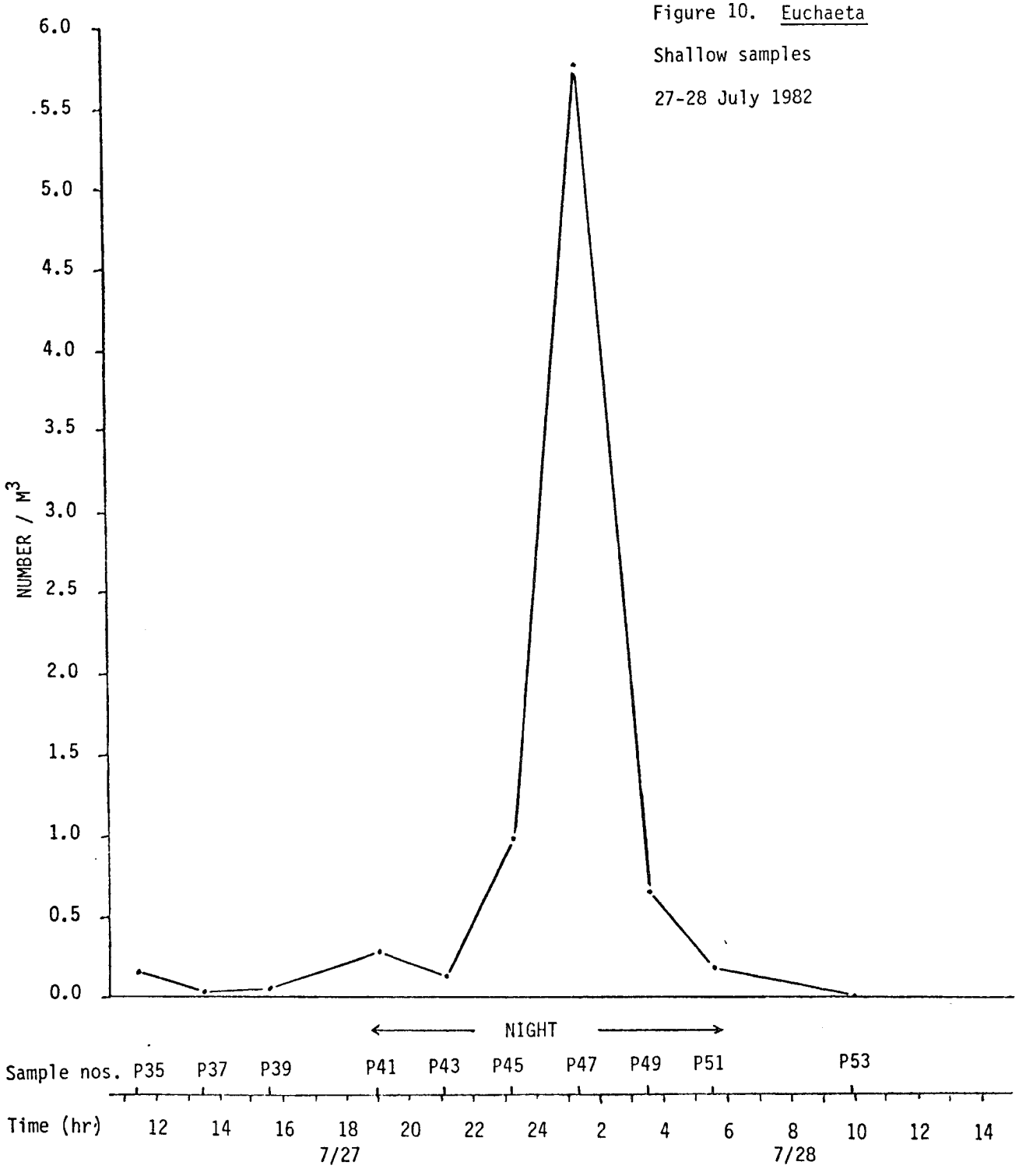


Figure 10. Euchaeta
Shallow samples
27-28 July 1982

Figure 11. Labidocera

Shallow samples

27-28 July 1982

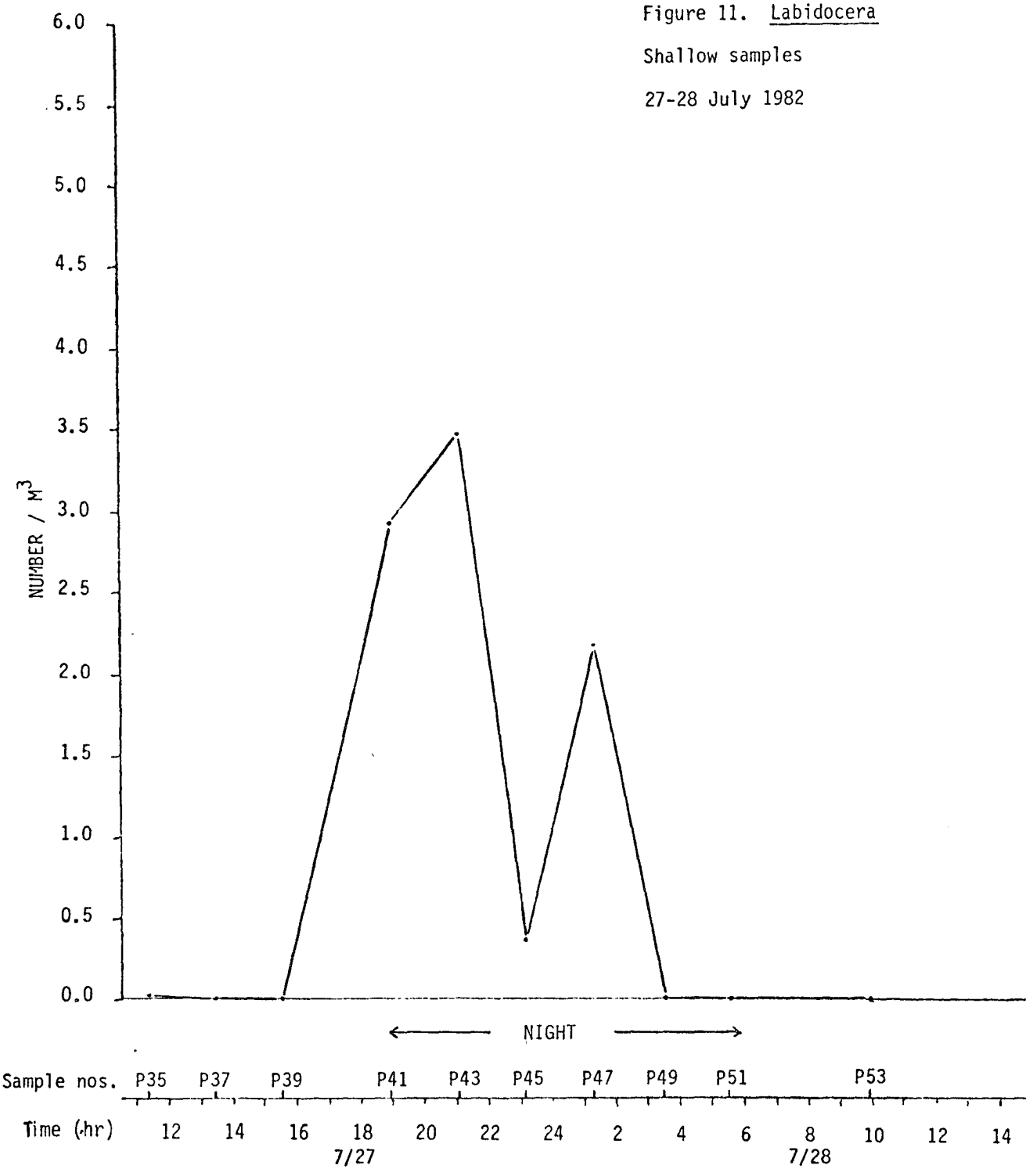


Figure 12.

Shallow samples

27-28 July 1982

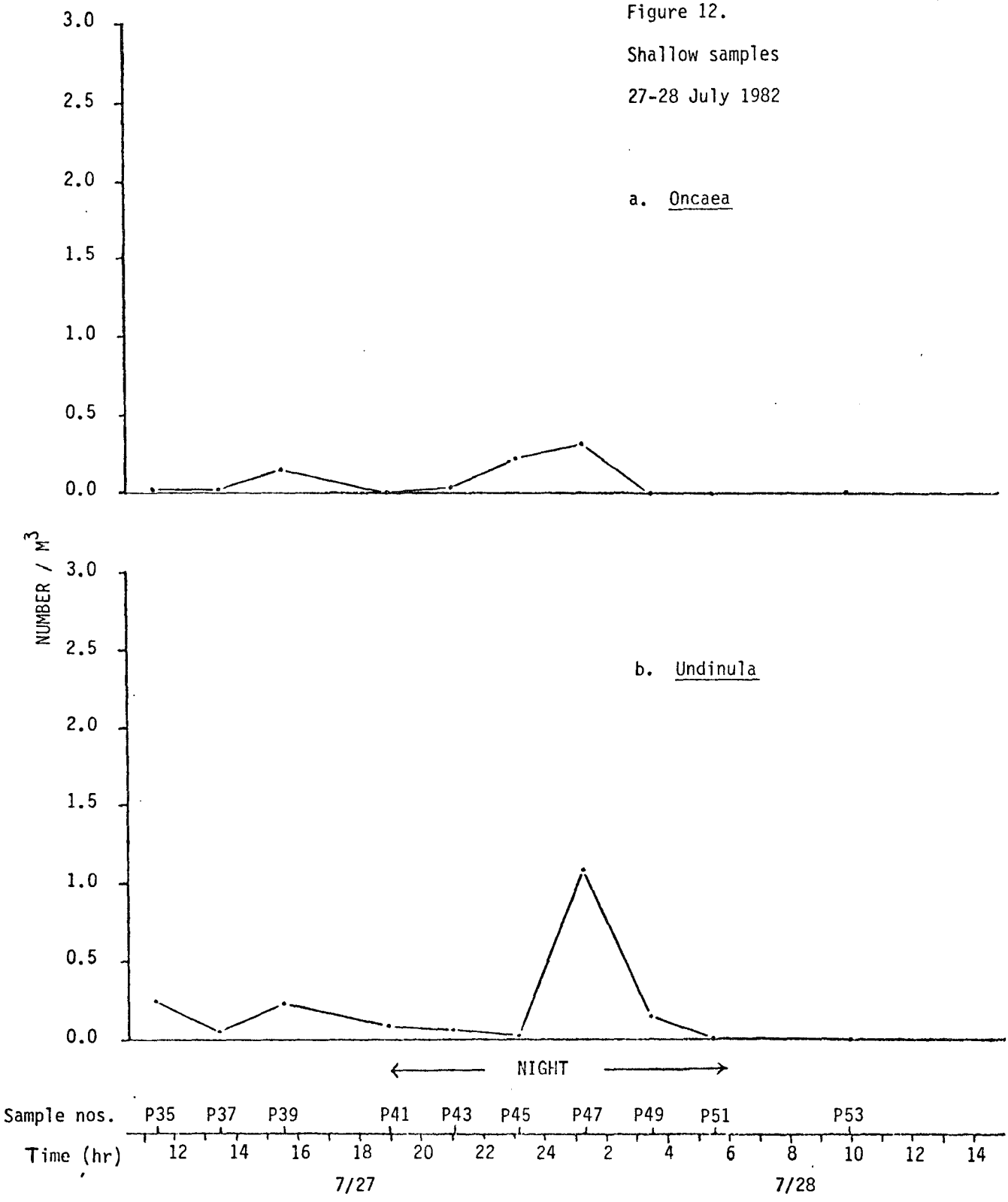


Figure 13.

Shallow samples

27-28 July 1982

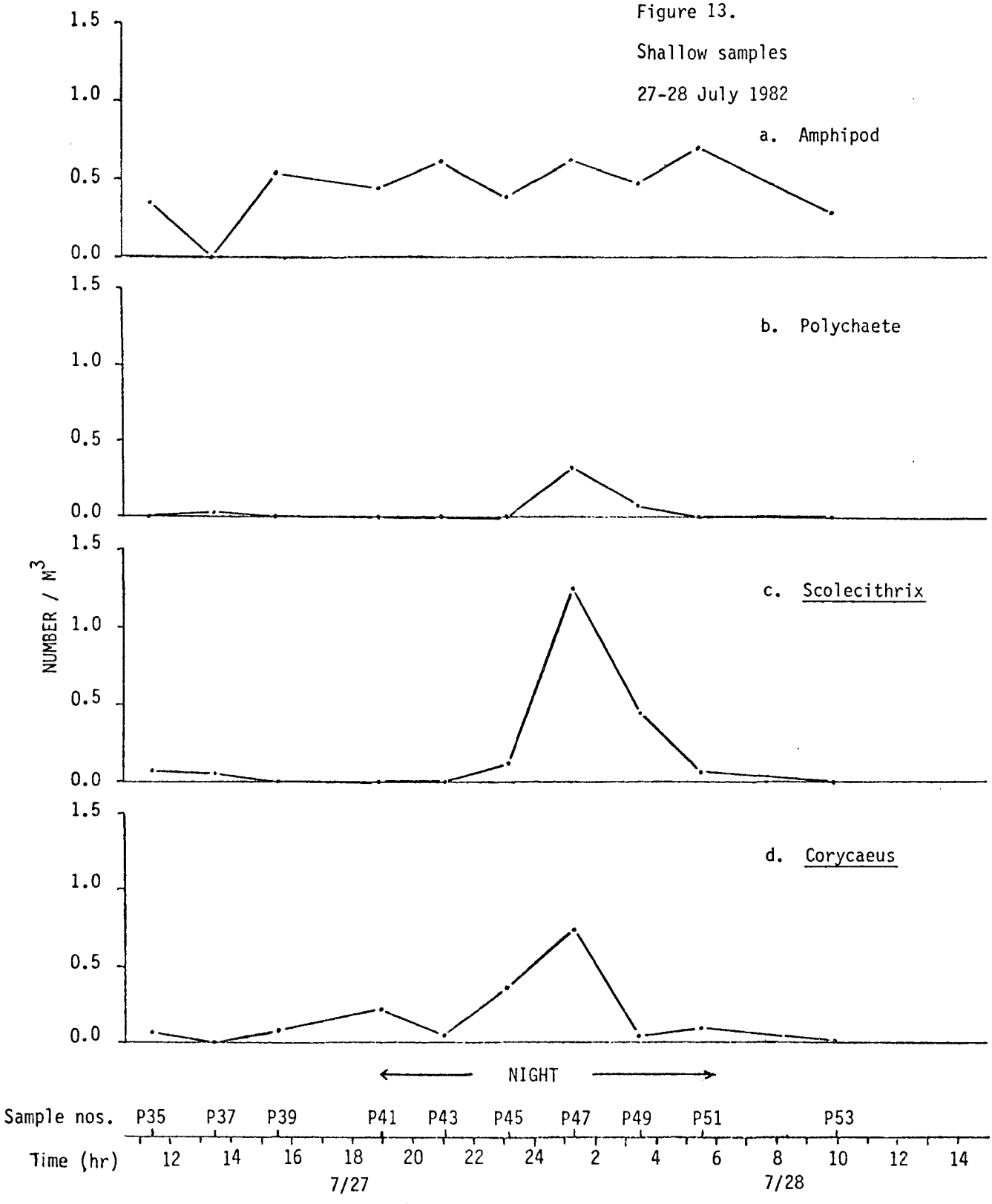


Figure 14. Undinula
Deep samples
20-21 July 1983

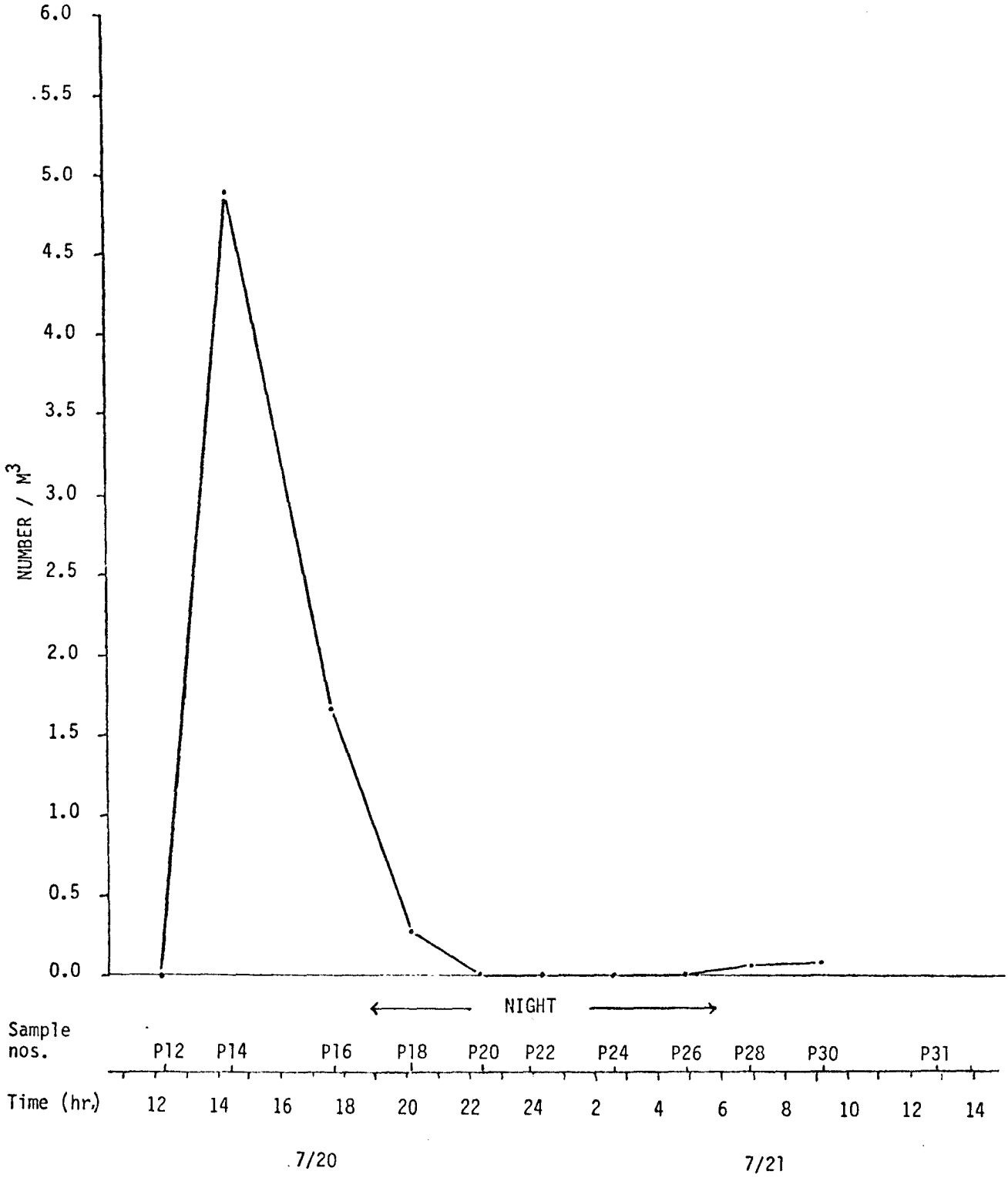


Figure 15.
Deep Samples
20-21 July 1982

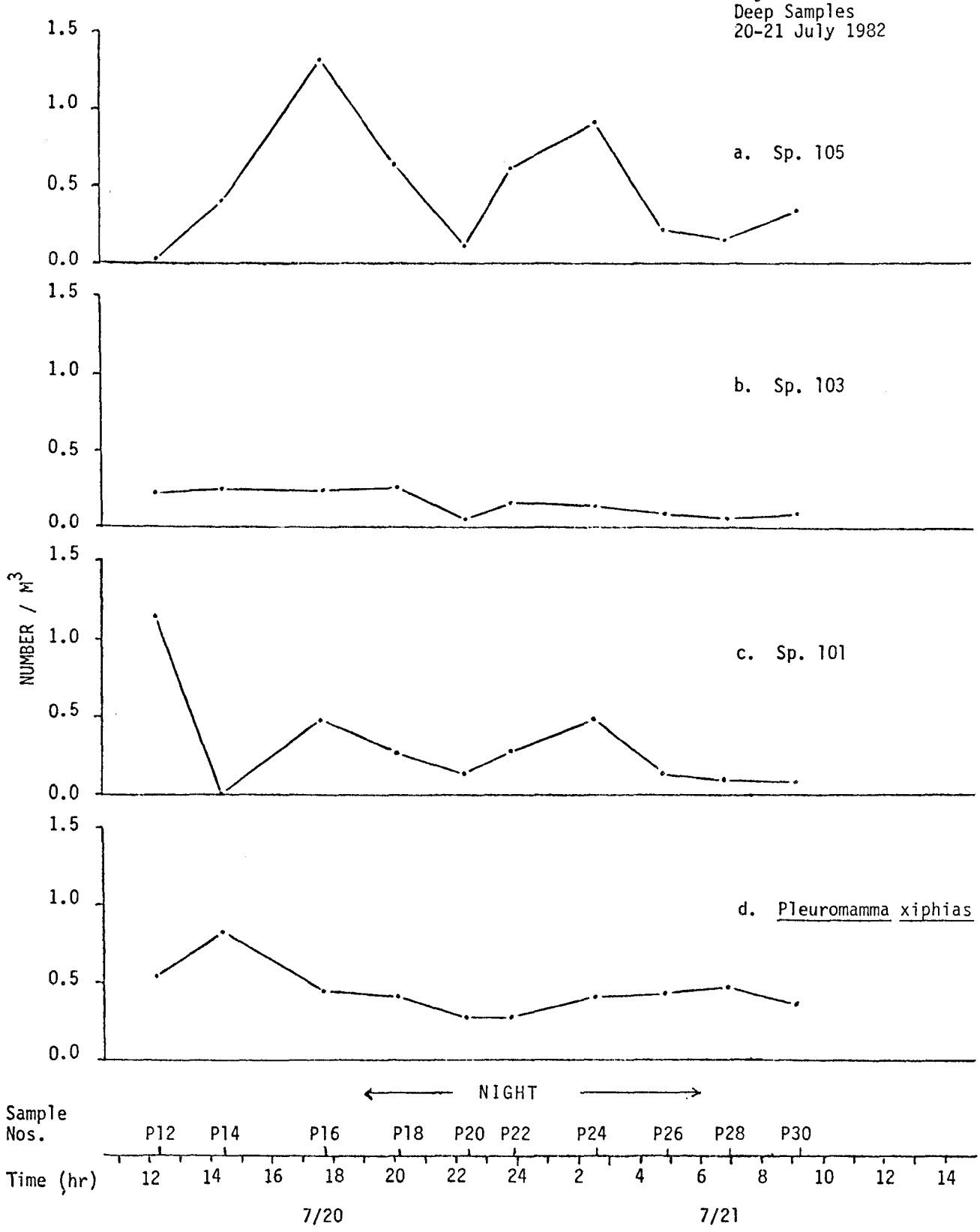
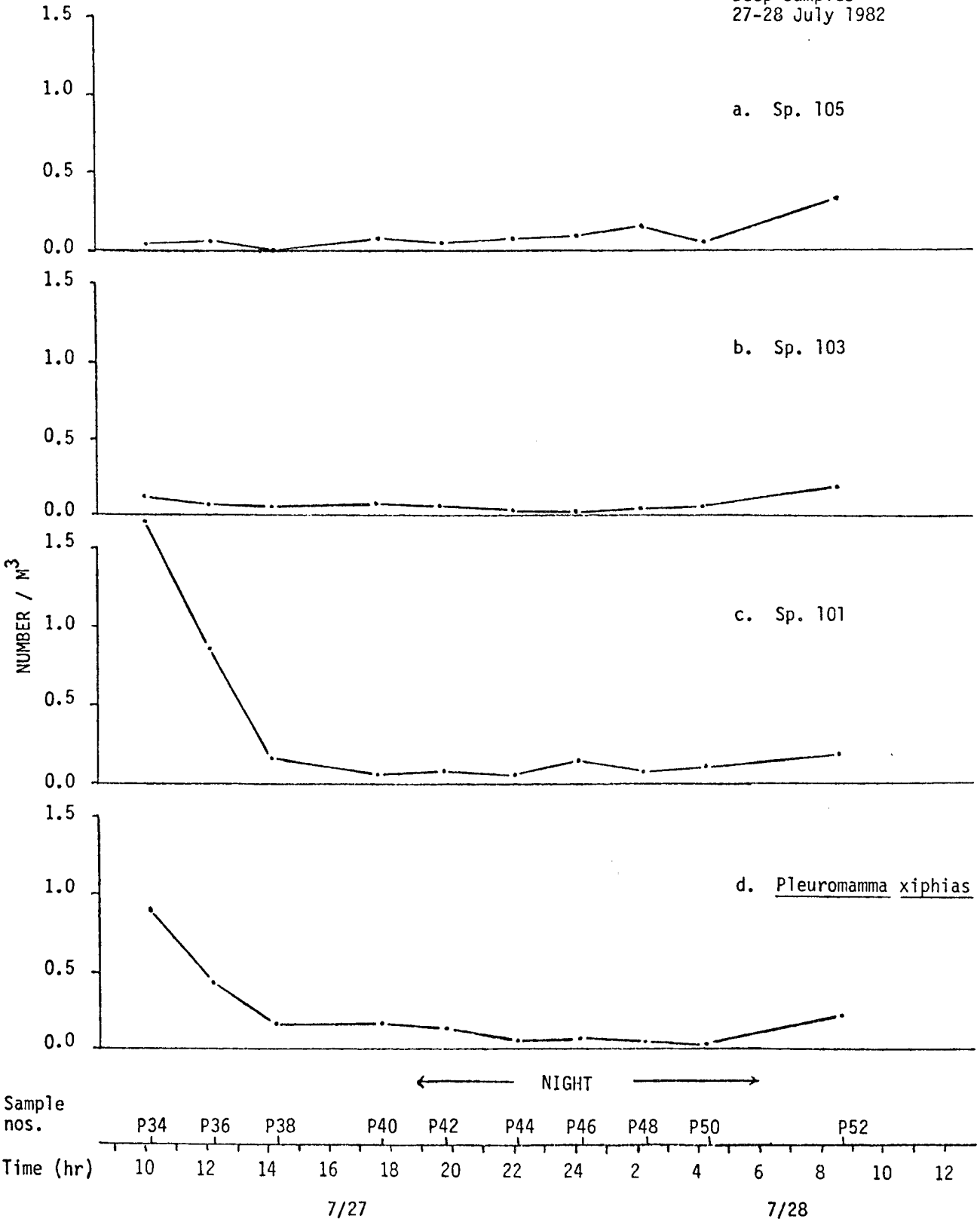


Figure 16.
Deep Samples
27-28 July 1982



water filtered instead of 200 m^3. Such an assumption would only be valid, however, if one assumed a random distribution of zooplankters. Such is not the case. The "patchy" distribution of zooplankton is well recognized (e.g. Wiebe and Holland, 1968). Hence, one must use caution in recommending a simple doubling of the sampling effort. As was mentioned in the introduction, one of the unique aspects of pumped-water plankton collections is the ability to replicate samples accurately in volume and in location. It was postulated that this replicatory capability would permit yet another approach to the estimation of patchiness in zooplankton. If, for example, one can determine the size of the particular universe being sampled, one could potentially estimate a minimum patch size for a particular species. Recognizing that the following calculations are speculative, we submit them not to suggest their accuracy for precise determinations, but to suggest an approach that might be used for future longer-term studies.

The distribution of zooplankton is affected by inter- and intra-specific biological parameters, water currents and chemistry (Haury, 1982; Parsons et al., 1977). Current measurements obtained by Freye et al. (1981), Noda et al. (1979, 80, 81), and Bathen (1975, 77) in the vicinity of the deep water intake pipe indicated that the deep water currents at Keahole are highly variable both in speed and direction, with values ranging from 0.1 to 1 kt (5-50 cm/sec.) and directions sometimes oscillating through 180°. Specific values for the deep water currents are of special interest with respect to estimating patchiness either in the biota or nutrients. One would like to know, for example, if our samples represented the biota or nutrients in a spherical volume centered on the pipe intake, or if we have sampled a narrow "current stream" flowing past the end of the pipe. In the first case, if the bottom current is very small relative to the intake velocity, then we can assume that we are sampling a volume more or less equidistant from the end of the pipe and proportional to the volume of water pumped. Assuming that 1 kt = 50 cm/sec or 1800 m/hr, then a bottom current of 1 kt would produce a flow past the end of the pipe of approximately 1800 m/hr, or 3600 m over the 2-hour sampling time. Measured currents on the bottom (Bathen, 1977; Freye et al., 1981), indicate that current speeds are closer to 0.1-0.2 kt (5-10 cm/sec) or 1/10th of the 1800 m; i.e. 180-360 m in horizontal distance from the pipe. Bathen also measured short term (of the order of 2 hours or less) reversals in the current direction, so we might assume that under minimal bottom current conditions and assuming a 30 cm/sec pipe intake current, the distance sampled would be within a 300 meter radius of the intake. On the average, however, the flow in the pipe is 3-4 times the current speed, and one can reasonably conclude that the sample comes from a relatively small volume of water adjacent to the pipe. In such a case, assuming an average sample volume of about 200 m^3 in the 2 hour sampling period, we would have sampled an area approxmately 7.2 m in diameter extending radially outward from the intake pipe.

$$r = \sqrt[3]{\frac{V}{\frac{4}{3}\pi}}$$

$$r = \sqrt[3]{\frac{200\ m^3}{4.189}}$$

$$r = 3.6\ m$$

$$d = 2r = 7.2\ m$$

For the deep water pipe, the intake of the pipe has been determined by direct measurement (by the U.S. Navy submersible "Turtle") to be 70 ft (21 m) off the bottom. Assuming that the above calculations are approximately correct, then the area of influence of the intake pipe would extend to within approximately 17 m of the bottom.

Some of the deep water plankton samples contained small amounts of sand, presumably put into suspension during periods of maximum bottom currents. Samples containing sand may represent collections from the "stream" flowing past the end of the pipe and therefore could theoretically come from as far as 360 m from the pipe, in contrast to the samples lacking sand, which may represent the population in the 7.2 m sphere.

Diurnal variation

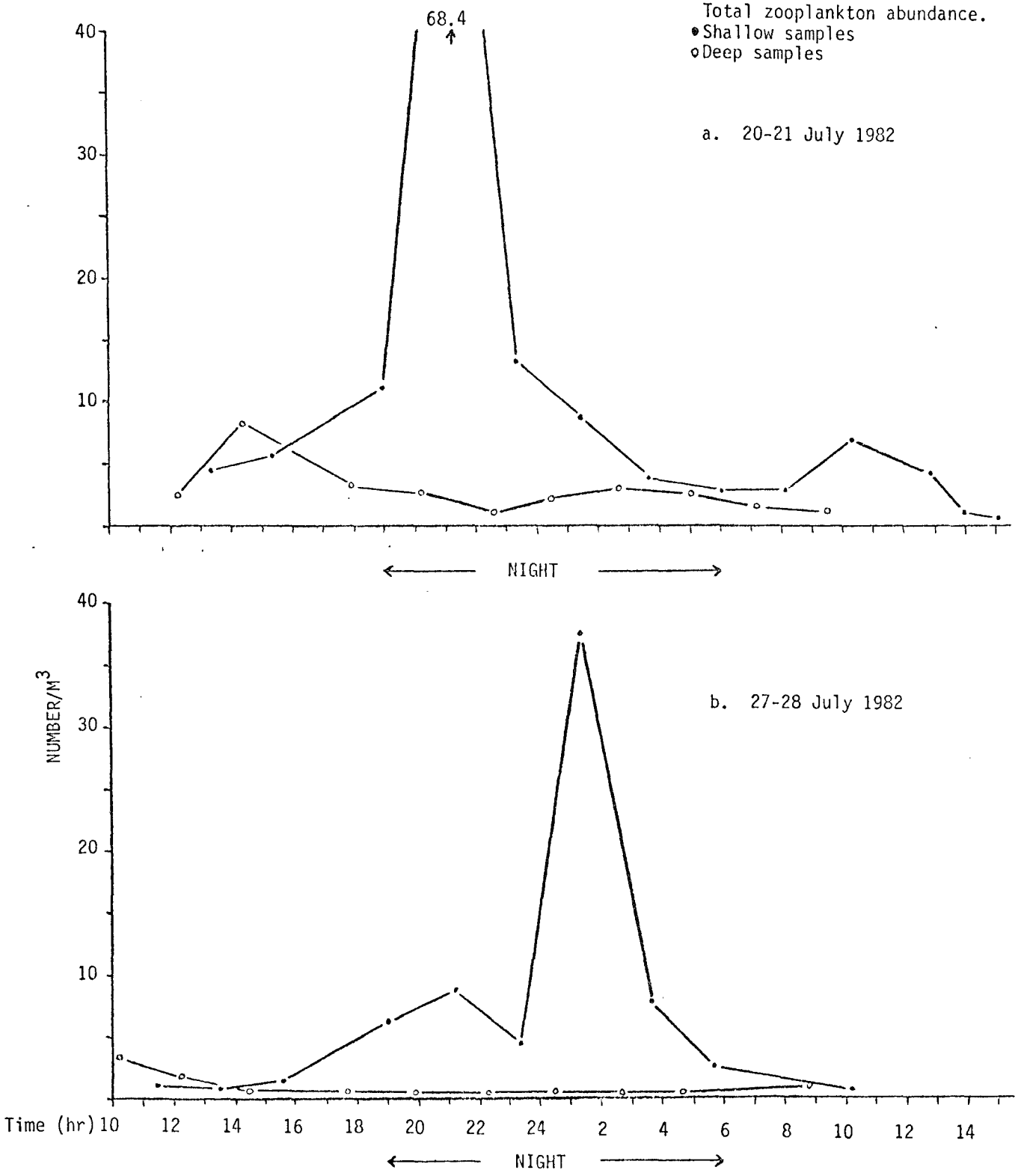
The diurnal variation of the total zooplankton population for weeks 2 and 3 is shown in Fig. 17. As expected, the variation was most pronounced in the shallow collections. Taxa showing most prominent day/night variation included mysids (Figs. 2 and 8), crab zoeas (Figs. 3 and 9), Corycaeus (Figs. 7d and 13d), Euchaeta (Figs. 6b and 10), Labidocera (Figs. 4 and 11), Oncaea (Figs. 6a and 12a), and Scolecithrix (Figs. 7c and 13c). With the exception of Corycaeus, each of these taxa showed a prominent peak in numbers at approximately 2100 hr during the July 20-21 (week 2) collections. Sunset was at 1900 hr. Corycaeus showed a decrease in abundance for that time. The shallow water samples taken during week 3 (July 27-28, 1982) showed somewhat similar peaks. Polychaetes (figures 7b and 13b), mysids, crab zoeas, Corycaeus, Euchaeta, Labidocera, Oncaea, Scolecithrix, and Undinula all peaked at 0130 hr. Again, sunset was at about 1900 hr.

A probable explanation for the time difference of the peak in abundance between the second and third week samples is the phase of the moon. During week 2 the moon was new, and there was essentially no moonlight. In contrast, during week 3 the moon was at first quarter and set at 0030 hr. Significant amounts of moonlight affected the vertical distribution of the zooplankton until about 2300 hr, so zooplankters peaked about 2 hours after moonset, a delay closely approximating the darkness/peak relationship observed in the second week's samples. It should be noted that the distribution of the neustonic copepod Labidocera in the week 3 shallow water samples actually showed two peaks, the first at 2100 and the second at about 0130. Perhaps the first peak was in response to sunset (at 1900) and the second in response to moonset.

Both parametric and non-parametric statistical tests (Students "t", Wilcoxon, Kruskal-Wallis) were employed on the combined weekly samples to test the significance of the day-night distributions. Amphipods, crab zoeas, mysids, shrimp, Candacia, Euchaeta, Labidocera, Oncaea, and Scolecithrix all showed significant day/night variation at the 90 percent confidence level.

Diurnal variation was not so pronounced in the deep samples, but the five most abundant species each showed a decrease in abundance in the samples taken after dark (Figs. 14 to 16). In the samples taken during week 2, Pleuromamma xiphias, Undinula, and copepod species 101, 103, and 105 each exhibited a decreased abundance at about 2200 hr. Undinula was not present in the deep water samples taken during the third week's collections. The other four species showed some decrease in abundance during the nighttime hours, but the differences were not so pronounced as in the second week's collections.

Figure 17.
Total zooplankton abundance.
• Shallow samples
o Deep samples



The average numbers of zooplankton taken in the shallow and deep water samples for each week (Fig. 18) show a marked difference in day-night abundance. The deep samples have higher abundances in the daytime than at night, while the opposite is true of the shallow samples. This difference is undoubtedly caused by the vertical migration of mesopelagic zooplankton into shallower water at night, depleting the deep population and enriching the shallow population. Very few of the deep (600 m) species are migrating to the depth of the shallow pipe (4.3 m) (one copepod genus that does occur in both sets of samples is Euchaeta); rather, the deep zooplankton is most likely migrating to intermediate depths, perhaps 200-300 m, while the migrants appearing in the shallow night samples may be mostly from 100-200 m. We have discussed the surface or shallow water samples in contrast to the deep water collections. One must keep in mind that the location of the "surface" collection is not really at the surface but at 4.3 m (14 ft). Presumably those species showing marked diurnal variation are not confined to the modest water column directly below the surface intake (a distance of but 1.7 m) during the day. It is most probable that the increase in plankton concentration observed in the nighttime samples represents primarily an upslope or onshore movement of zooplankters from deeper water.

There appears to be little correlation between the abundance of the various species and the tide cycle in either of the two sampling periods or the two sampling depths. Only one species, copepod species 105 taken in the deep water samples during the second week, seemed to be strongly correlated with the tidal cycle (Fig. 19). Additional samples would be required prior to any conclusions as to the relationship between tidal cycles, zooplankton abundance and possible internal waves.

Comparison of species and abundance of zooplankton taken in offshore tows with simultaneously collected pumped samples

One of the primary goals of this pilot study was to examine the relative catching efficiencies of standard towed nets as compared with the pumped samples. Such a comparison would provide a first-order approximation of entrainment of zooplankters into intake pipes in tropical waters. Previous studies by Leithiser et al. (1979) in Carlsbad, California had shown that estimates of entrainment based on nets placed in the intake channels of power plants led to a significant underestimation of the species and numbers of ichthyoplankton actually entering the intakes. Because of plans for future OTEC plants and the ongoing energy and aquaculture-related studies at NELH, comparisons of towed and pumped samples were of considerable interest.

Table 3 compares estimates of zooplankton abundance from shallow pipe samples with simultaneously-collected samples from a conventional towed plankton net. The towed net is evidently a more efficient zooplankton sampler than the shallow pipe intake, based on the fivefold difference in zooplankton density. The towed net also produced a more diverse collection than the pipe (27 taxa vs. 15). Chaetognaths were present to some extent in the offshore tows, but not in particularly significant quantitites. Considering their usual ubiquitous presence, their minimal numbers in the offshore tows and their absence from the pumped samples is surprising. No explanation for this distribution is obvious at this time.

One of the most noticeable features of Table 3 is the striking difference in species composition between the pipe samples and the towed samples. Of the 35 taxa collected, only 7 occurred in both sample sets. Since intake velocities were presumably much higher for the towed net than the mouth of the pipe (the speed of the towed net was estimated at 100 cm/sec and the intake velocity of the shallow pipe was assumed to be less than

Figure 18. Day-night (D-N) differences in total zooplankton abundance.

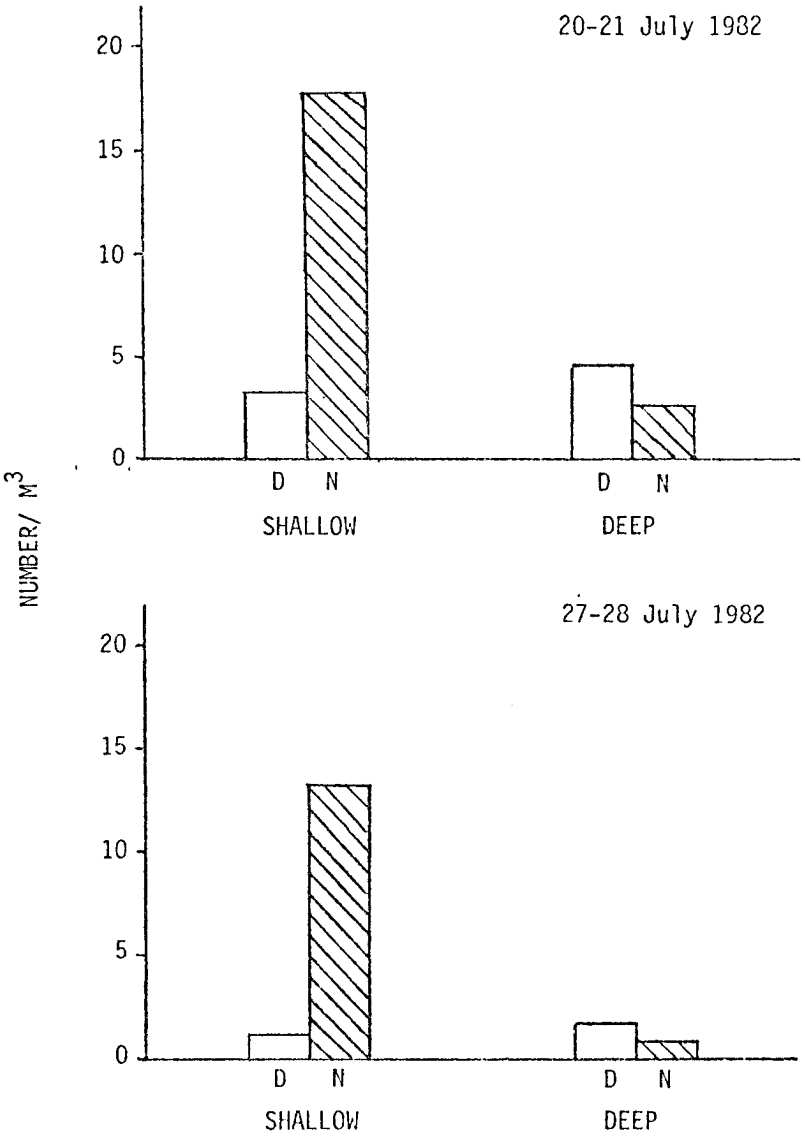


Figure 19. Unidentified copepod Sp. 105, abundance compared with tide cycle. Deep water samples, 20-21 July 1982.

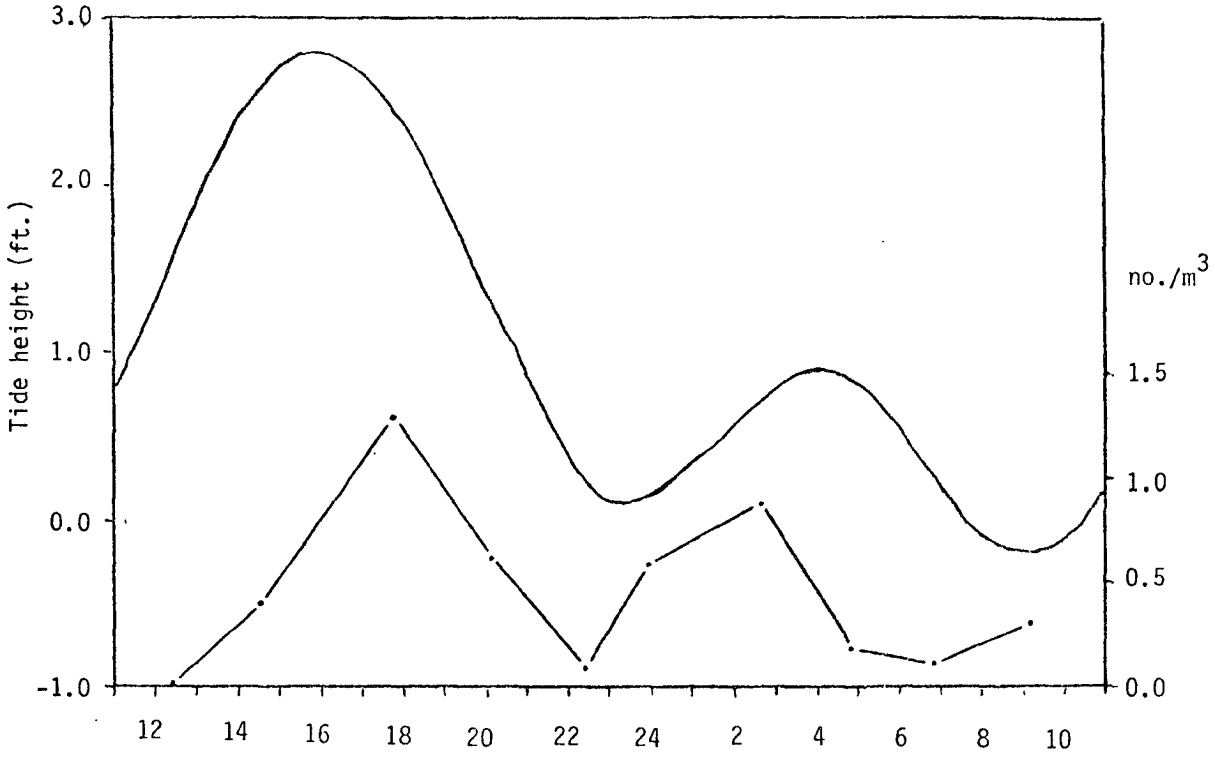


Table 3. Comparison of towed net samples with shallow pipe samples, 29 July 1982.

Taxon	Avg. no./m^3, P54, 55 (shallow pipe)	%	Avg. no./m^3, P57, 58, 60 (tows)*	%
Amphipod	0.341	35.9	0.019	0.5
Barnacle larva	0.038	4.0	---	---
Crab Zoea	---	---	0.008	0.2
Candacea	0.005	0.5	0.156	3.7
Chaetognath	---	---	0.145	3.5
Cladocera	---	---	0.034	0.8
Copilia	---	---	0.004	0.1
Corycaeus	0.058	6.1	0.095	2.2
Decapod megalops	0.010	1.1	---	---
Doliolid	---	---	0.011	0.3
Echinoderm larva	---	---	0.004	0.1
Egg	---	---	1.459	34.8
Eucalanus	---	---	0.023	0.5
Euchaeta	0.212	22.3	0.370	8.8
Euphausiid	---	---	0.004	0.1
Foa brachygramma	---	---	0.004	0.1
Isopod A	0.014	1.4	---	---
Isopod B	0.034	3.6	---	---
Labidocera	---	---	0.156	3.7
Lucifer	---	---	0.023	0.5
Medusae	---	---	0.004	0.1
Mysid	---	---	1.006	24.0
Neocalanus	0.005	0.5	---	---
Oikopleura	---	---	0.080	1.9
Oncaea	0.005	0.5	0.118	2.8
Ostracod	---	---	0.168	4.0
Pleuromamma xiphias	---	---	0.008	0.2
Polychaete	0.125	13.2	---	---
Pteropod	---	---	0.008	0.2
Pycnogonid	0.005	0.5	---	---
Sapphirina	---	---	0.076	1.8
Scolecithrix	0.010	1.1	0.065	1.5
Shrimp	0.053	5.6	---	---
Siphonophore	---	---	0.030	0.7
Undinula	0.034	3.6	0.118	2.8
TOTAL	0.949		4.196	

*Assuming each tow filtered 700m^3 of water.

30 cm/sec), one might expect the faster-swimming organisms, such as large crustacea, to be relatively more abundant in the towed samples than in the pipe samples. One might also expect slow-swimming or non-motile organisms, such as medusae or eggs, to be equally common in both sample sets. Neither expectation is satisfied. Such presumably strong swimmers as decapod megalops and shrimp were taken only by the pipe, while eggs and slow-swimming medusae were taken only by the towed net.

The criteria determining whether a given organism is more likely to be captured by a towed net or by the pipe intake are more complicated than mere avoidance ability. For example, it is quite possible that the 9 taxa taken preferentially by the pipe (amphipod, barnacle larva, decapod megalops, isopod A, isopod B, Neocalanus, polychaete, pycnogonid, and shrimp) may all be benthopelagic or demersal organisms attracted to a solid substrate. More detailed identifications to the genus or species level may confirm or refute this hypothesis.

The profound difference between the pipe samples and the towed samples has important implications for studies on entrainment of zooplankton into pipes, such as power plant cooling intakes or OTEC systems. The standard method of zooplankton collection for such environmental assessment has always been towed plankton nets. Our study indicates that such zooplankton collections may completely misrepresent the actual plankton populations affected by entrainment. Intake pipes and towed nets both sample zooplankton non-randomly (although a towed net probably approaches randomness more closely than an intake pipe). Additional studies on the selectivity of intake pipes for different plankton taxa might lead to special designs of intake heads that allow the escape of commercially-important groups such as fish and decapod larvae.

SUMMARY AND RECOMMENDATIONS

Zooplankton and water chemistry samples were taken from the shallow and deep water discharge pipes at the Natural Energy laboratory at Keahole Point, Hawaii. Approximately 200 m^3 were filtered for each 2-hour sampling period over a 24-hour period, at weekly intervals for three weeks in July, 1982.

Three standard 1-m plankton tows were taken in the offshore waters near the shallow water intake pipe. Simultaneous onshore collections were taken from the shallow water discharge pipe to compare relative catching characteristics between the two methods.

Of the 66 taxa taken in the study, 43 were found in the shallow water discharge, 33 were taken in the deep water discharge, and 27 were taken in the offshore tows.

Significant diurnal variation at the 90 percent confidence level was observed in many of the taxa taken in the shallow pipe collections. Diurnal variation in the taxa taken in the deep pipe collections was less pronounced, but a few species, notably Oncaea, Pleuromamma xiphias, Macrostellata and copepod sp. 103, demonstrated significant day/night differences in abundance over the 24-hour sampling periods. Zooplankton per m^3 increased in the shallow water samples taken after dark, while the deep water collections showed a significant decrease in total numbers per m^3.

The diurnal response of the shallow and deep water species appeared to be dependent on the time of moonrise and moonset. In at least one species, Labidocera, taken in the shallow water collections, two peaks in abundance were noted; one occuring at sunset and another at moonset.

Only one species, copepod sp. 105 taken in the deep water collections, showed any correlation between its distribution and the tidal cycle.

Micronutrients were more concentrated in the deep water than in the shallow water, as expected. Particulate matter was more abundant in the shallow samples in the first week than in the second, due to the abnormally high surf. The distribution of the zooplankton did not appear to be correlated with any of the measured variations in water chemistry.

The study now completed was specifically designed as a pilot project to test the effectiveness of pumped zooplankton sampling techniques and to provide the basis for recommendations for future biological and chemical studies related to the continuing energy and aquaculture research programs at NELH, as well as the development of OTEC plants in Hawaiian waters. Recommendations from this pilot study are as follows:

1. It is imperative that precision flow meters be placed on both the shallow and deep water pipes, and that water flow be monitored continuously. The value of NELH as a tool for environmental impact analysis, energy and aquaculture development, and basic research in chemistry and biology depends critically on accurate and precise knowledge of water flow through the system.

2. The 200 m^3 sampling volume is not adequate for a statistically valid sample of the less-abundant species. A series of samples from 100 m^3 to 2000 m^3 should be taken over a period of several days to determine an optimum volume for statistically significant numbers of 90-95 percent of the species taken.

3. Additional statistical analysis should be performed on the existing data. To date, only analysis of day/night variation has been done. The data should be examined for correlation among the various taxa to identify co-occurring species groups.

4. Further species identifications would greatly enhance the value of the collections. It would be interesting to know if the zooplankton taken by the deep pipe is all mesopelagic, or if some species are associated with the bottom. Since the bathyal zooplankton fauna is very poorly known, new species might well be discovered. Much of the zooplankton taken by the shallow pipe may be associated with the bottom, and some (e.g., pycnogonids) may even be meiobenthic fauna living inside the pipe itself.

5. On the basis of the present data and that collected in recommendation 2 above, certain key species should be selected for long-term monitoring. These key species would include species, such as larval fish, known to be of direct importance to man, or species known to be of primary importance in the food chain of species important to man. A longer-term investigation would be scientifically interesting in a number of ways. The present results represent only conditions in midsummer. While seasonal zooplankton data are available for the area (e.g., Noda et al., 1981), they are based on towed net samples. Pipe samples should be considerably different. In particular, it seems likely that planktonic larvae of important fouling organisms may be taken preferentially by the pipe. These larvae are probably produced at intervals depending on the spawning habits of the adults.

6. Another useful experiment would be a repeat of the comparative towed net vs. shallow pipe sampling with a working flowmeter. It would also be informative to rig a duplicate of the shallow water pipe intake head in a laboratory tank and measure actual intake velocities through the various-sized holes. It would then be possible to be more specific as to zooplankton avoidance capabilities, based on values from the literature or actual laboratory experiments. Another interesting but more expensive and difficult investigation would be to repeat the towed net vs. pipe sampling with the deep pipe, using closing nets from a larger ship (the shallow water tows were done quite easily from a small boat). Since entrainment into an OTEC pipe would be from the mesopelagic zone, such an investigation would provide valuable baseline data for environmental impact analysis for future OTEC plants.

7. A series of samples should be taken from the shallow and deep water pipes at varying pumping rates to compare catching/avoidance abilities of various species at different flow rates. The species selectivity of the intake is related to the velocity of the water entering the intake, the area of current influence away from the intake pipe, the size and shape of the intake ports, the swimming speed of zooplankters, and the escape/avoidance reactions of various individual species. Estimates of the effects of OTEC system on zooplankton populations must therefore take these factors into consideration when attempting to predict the environmental consequences and significance of OTEC development. Small-scale laboratory studies have been conducted using shallow water species to provide first-order estimates of some of these factors. Use of the NELH facilities would permit similar field-scale experiments to complement earlier laboratory work.

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