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Telemetric Investigation of Vertical Migration of *Nautilus belauensis* in Palau[1]

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ABSTRACT: Sonic transmitters coupled to depth-sensitive strain gauges and attached to shells of *Nautilus belauensis* in Palau, Western Caroline Islands, established net vertical movement between 85 and 467 m, and lateral movement of about 3 km over a period of 7 days and nights. Generally, the animals were found in deep water during daytime and moved to shallower water at night.

MOST GENERAL REFERENCES ON the ecology and behavior of *Nautilus* indicate that these animals become active at night and move from deep to shallow water (Morton 1967, Barnes 1974, Yonge and Thompson 1976). This assumption can be traced to Arthur Willey, who conducted field research on *Nautilus* in the late 19th century: "I came to the conclusion in New Britain, which I afterwards confirmed in the Loyalty Islands, that the feeding-ground is not the breeding-ground of the Nautilus—or, in other words, that the nautilus migrates in shoals nocturnally from deeper into shallower water in quest of food.... In (the Loyalty Group) Nautilus migrates at night from deep water into as little as three fathoms" (Willey 1899:7–8). While Willey provided only sketchy details on how he arrived at this conclusion, his comments have been accepted as fact in virtually all subsequent literature on *Nautilus*.

Recently, Ward, Greenwald, and Magnier (1981) and Ward (1982) have noted that Willey's assumptions have never been confirmed by direct observation and suggested that perhaps *Nautilus* is better described as a slowly foraging organism of the deep nektobenthos rather than an active animal covering wide depth ranges.

This study was undertaken in an attempt to resolve this issue and to obtain data on the daily movements of individual *Nautilus* in its natural environment. Due to the depths at which *Nautilus* occurs, 50–260 m (Saunders and Wehman 1977), direct observation of this organism is impractical. The approach used here was to utilize sonic transmitters to track the movements of the *Nautilus*. We believe this is the first time this technique has been used successfully on any marine invertebrate.

MATERIALS AND METHODS

Nautilus belauensis (Saunders 1981*a*) was trapped along fringing reefs in Palau using baffle-type fish traps suspended along the reef face for 1–3 days. The animals used in this research were adult males (ca. 190 mm shell diameter). They were collected at approximately 200–300 m depth on the afternoon of 19 June 1982 by Bruce Saunders who inscribed a number on the shell of each animal (#3028 and #3040) as part of an ongoing tag-recapture study of *Nautilus* in Palau. The animals were trapped seaward of the southeast reef face of Augulpelu Reef and were maintained in chilled seawater (18°C) on board the boat until tagged. After the transmitters were attached, the animals were released about 2 km west of their capture site (Figure 1).

The two transmitters used in this study were designed to provide depth information and to indicate lateral movement of the *Nautilus*. Design specifications were determined after testing a prototype model on *Nautilus* in Palau

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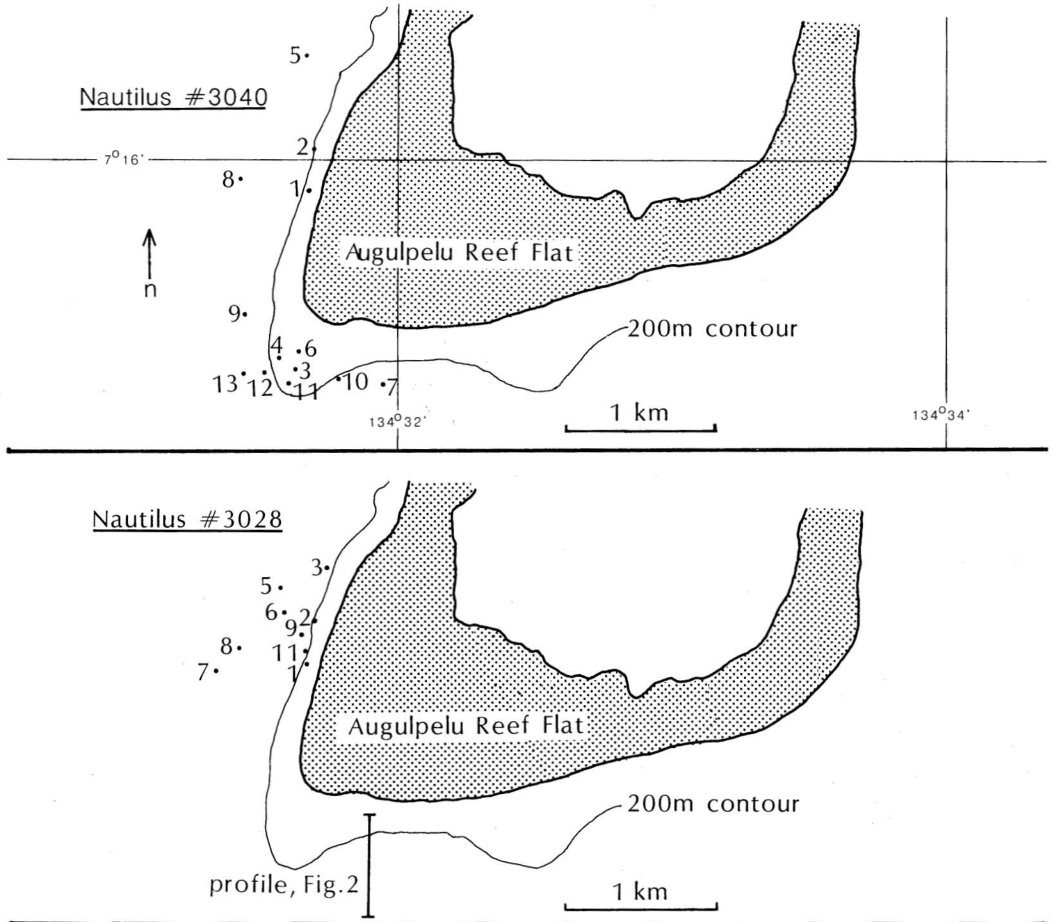

DATE	LOCATION	TIME #3040	TIME #3028
June 19	1	1834	1834
June 20	2	1125	1130
	3	1725	1740
	4	1820	------
June 22	5	0834	0839
June 23	6	1804	1819
June 24	7	0715	0734
June 25	8	0845	0845
	9	1633	1642
	10	1734	------
	11	1835	1810
June 26	12	0534	------
	13	0632	------

FIGURE 1. Lateral movements of *Nautilus* #3040 and #3028 from 19–26 June 1982. Location #1 was the release site for both animals.

in 1978 (Carlson and deGruy 1978). Transmitters consisted of a crystal frequency-controlled thick-film hybrid microcircuit with the pulse rate determined by a four element resistive strain-gauge depth-sensor. One transmitter operated at 38.4 khz and the other at 40.0 khz. Power for the logic portion of the circuit was provided by a 6.0 v lithium battery, and the output portion of the circuit was powered by a 3.9 v lithium battery. The transmitters had a range of 1–1.5 km under good conditions and a seven day lifespan.

Nautilus are almost neutrally buoyant in seawater (Ward, Greenwald, and Greenwald 1980) and the transmitters were also designed to be neutrally buoyant. Each was constructed on a glass-epoxy substrate and encapsulated in a mixture of Eccobond 55 Epoxy and glass microballoons to provide neutral buoyancy as well as rigidity to the transmitters. Each transmitter was approximately 8.5 cm × 6.5 cm × 6.5 cm.

Transmitters were calibrated by attaching them to a weighted line and lowering them to 200 m. At periodic intervals the pulse rates (in milliseconds) and depths were recorded. Since the pulse rate of the strain-gauge depth-sensor was designed to vary linearly with depth, a straight line could be fitted to the data ($r = .98$) and extrapolated for depths greater than the 200 m calibration depth.

Transmitters were molded to fit the contour of the *Nautilus* shell and were secured to the top of the shell by a thin strip of duct tape. Both animals were released simultaneously at a depth of 15 m at 1834 hrs, 19 June 1982 (Figure 1, location #1). They were followed by divers to a depth of 45 m and observed until they disappeared from view at a depth of about 55 m. Both animals appeared to swim normally, away from the reef face toward deeper water.

Signals from the transmitters were monitored using a CAI (Communications Associates, Inc.) receiver, model CR-40, with a preamplified, staff-mounted, unidirectional hydrophone. An audible signal and an LCD readout of the pulse rate in milliseconds were produced. The location of each animal could be determined by swiveling the hydrophone 360 degrees. When the animal was beneath the

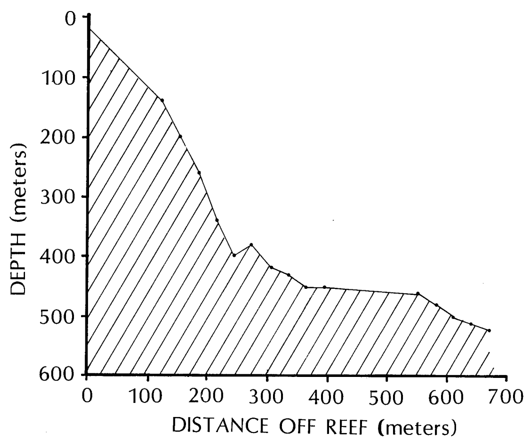

FIGURE 2. Reef profile at Augulpelu Reef, Palau (see Figure 1 for location of profile).

boat the audible signal was equally strong regardless of the direction of the hydrophone. Some imprecision in determining location resulted because the signals were picked up by the receiver through a cone-shaped area with an angle of 11°. This error increased with depth, ranging from a radius of 8.2 m to 45.0 m, corresponding to the minimum and maximum depths recorded for the *Nautilus*. This error was not considered significant when plotting positions in Figure 1. An approximate position of the boat was determined in the field by comparing reef features with a nautical chart of Augulpelu Reef. This information was later corroborated with compass headings taken on five points on shore and on the reef in determining the final positions shown in Figure 1.

A profile of the reef in the area where the *Nautilus* were released was made using a Fuso Marine fathometer. The location of this profile is indicated in Figure 1. Distance was determined by paying out a rope tied at one end to the reef and then taking fathometer readings at marked intervals along the rope. Only one data set was obtained by this method for generating the reef profile in Figure 2.

Ocean temperatures were obtained by using a maximum-minimum thermometer lowered to specific depths and then retrieved (Figure 3).

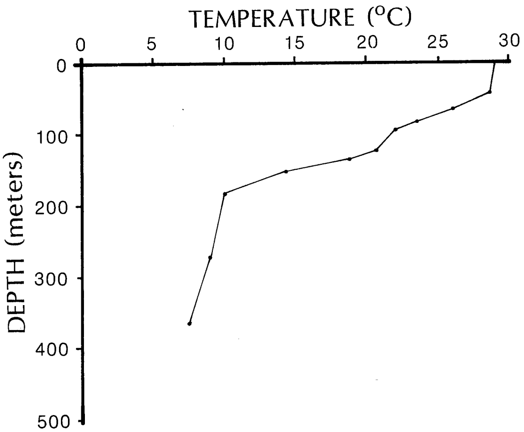

FIGURE 3. Temperature profile at Augulpelu Reef, Palau.

RESULTS

Although a severe tropical storm, "Ruby," prevented continuous 24 hr monitoring, data were collected at different time intervals through 6 days of the 7-day tracking period.

The transmitter on *Nautilus* #3040 functioned properly throughout the tracking period. However, the transmitter on animal #3028 malfunctioned after the first night, producing an unvarying, rapid pulse rate throughout the week corresponding to a depth "above" sea level when compared to its calibration data. As a result, the depth of # 3028 could not be determined but the signal was useful in fixing its position.

A record of the vertical movements of *Nautilus* #3040 (Figure 4) shows that during the mid-mornings of 22, 24, and 25 June the animal was located in deep water (ca. 400–450 m) and during the evenings of 20, 23, and 25 June it was found in shallow water (ca. 100 m). During the period following sunset on 25 June this animal was tracked moving rapidly from deep water into shallow water (341 m to 85 m in 4.25 hrs) and, on the following morning, before sunrise, the animal returned to deep water (161 m to 340 m in 3 hrs). These data strongly suggest migration into shallow water at night and a return to deep water during the day. However, data which do not fit this general pattern were recorded around midday on 20 June and between 0300 and 0400 hrs on 26 June. The maximum depth recorded for animal #3040 was 467 m (25 June, 0920 hrs) and the minimum depth was 85 m (25 June, 2034 hrs).

Nautilus #3040 moved laterally about 3 km along the reef face (Figure 1), whereas animal #3028 was less active, remaining within 1 km of the release point (Figure 1). In general, both animals were located farther away from the reef face in the daytime and closer to the reef at night, but their exact proximity in relation to the ocean floor was not determined.

DISCUSSION

It is clear from this study that *Nautilus* is an active animal, capable of traversing large distances both vertically and horizontally in short periods of time. Willey's hypothesis is supported by our data which indicate that *Nautilus* moves into shallow water during the night and returns to deeper water in the daytime. While the general pattern of movement seems clear, there are some apparently anomalous data. On 20 June between 1100 and 1300 hrs *Nautilus* #3040 was located in relatively shallow water when it was expected to be in deep water. This may be the result of orientation problems and acclimation because the animal had been released only a few hours earlier. However, on 26 June between 0327–0404 hrs, the *Nautilus* was tracked moving 131 m upward before beginning a predawn descent. Minor vertical movements also occurred at various other times during the 7-day period suggesting either that *Nautilus* undergoes several vertical movements during the day and night or that they are simply following bottom contours (Figure 2). Another possibility is that varying light levels during the stormy weather affected the movements of the animal, but we do not have appropriate data to test this hypothesis.

The upward movement of *Nautilus* may be temperature limited. At 85 m, the shallowest depth recorded for the *Nautilus*, the temperature was approximately 24°C; aquarium studies indicate that *Nautilus* cannot survive at temperatures exceeding 25°C for extended periods (Carlson 1979). This coincides with results of Saunders (1981*b*: p. 6) who noted

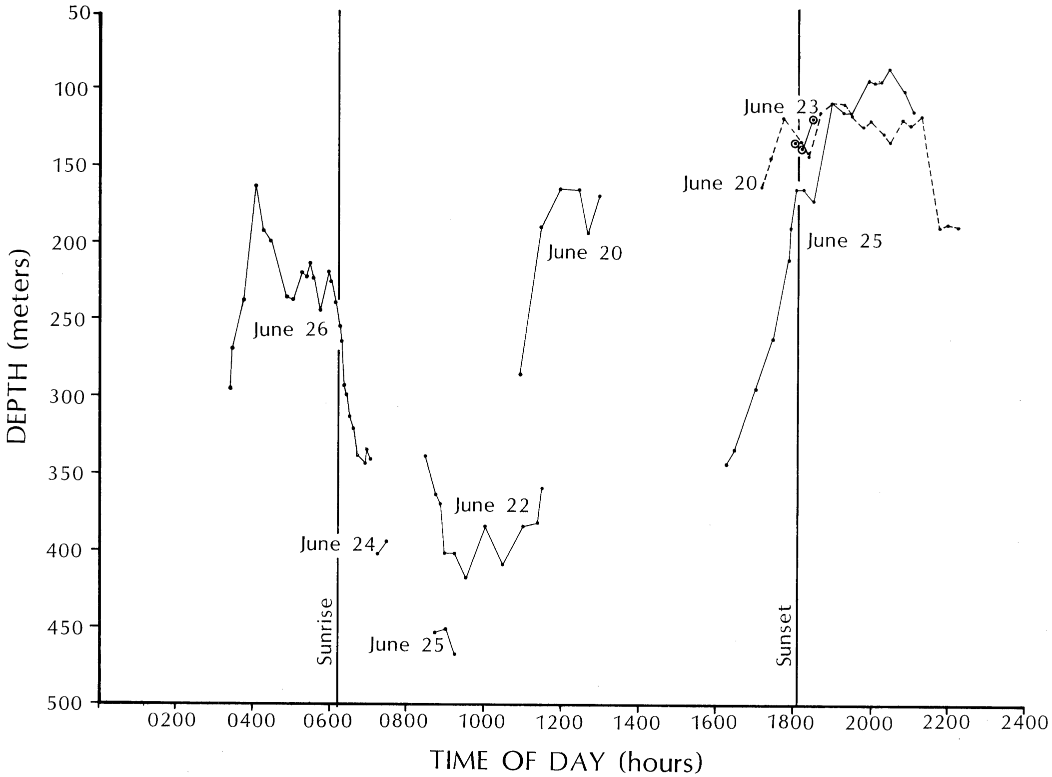

FIGURE 4. Daily vertical movements of Nautilus #3040, 19–26 June 1982, at Augulpelu Reef, Palau.

that *Nautilus* in Palau are not caught in traps set at depths less than 70 m.

Extensive movements of *Nautilus* over long periods of time around the Palau archipelago have been documented through tag-recapture techniques (Saunders and Spinosa 1979). Their study revealed an average distance traveled ranging from .45 km/day over 322 days to .8 km/day over 5 days. Our data indicate that *Nautilus* can travel up to .8 km/hr although the average, .17 km/hr, is much less. This maximum rate is almost exactly equivalent to the swimming rate calculated by Ward et al. (1977), who measured *N. pompilius* swimming in the field at a maximum rate of .25 m/sec = .9 km/hr. The much lower long-term figures obtained by Saunders and Spinosa are undoubtedly related to back-tracking: *Nautilus* #3040 and #3028 moved back and forth along the reef face many times rather than continually moving in one direction.

The influence of tidal currents in assisting or impeding the movement of *Nautilus* could not be determined directly. However, if passive transport by currents was a primary factor in movement, then one would expect the patterns for both *Nautilus* #3040 and #3028 to be similar. This was not the case. At the time of release and again 6 days later both animals were at the same location on the reef (Figure 1, position 8), but at other times their positions differed by as much as 1.8 km.

These results clearly indicate that *Nautilus* is a wide-ranging animal capable of making large vertical movements through a wide range of temperatures and able to traverse relatively great distances laterally in short periods of time. Further studies of this type will be conducted to determine how general these results are and if there are differences in the magnitude and direction of these movements among age groups and between sexes.

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