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REPORT ON ACOUSTIC TELEMETRY EXPERIMENTS DURING 1977

SWORDFISH

by

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This report covers experiments with swordfish conducted during 1977. The background and theory prompting these experiments was discussed in the research proposal which led to our 1977 contract and the section on swordfish from that proposal is included as an appendix. This report is not intended to be a finished paper. I have attempted to discuss all of the phenomena we observed and have included explanations and theories even when the evidence on hand was insufficient to support a positive statement in an article in a reviewed journal. This is a document which we will build on and I hope that in the future some of the gaps will be filled.

The material has been divided into the following sections:

1. Equipment. A general discussion.

2. Movements. A narrative of the capture and tagging of the 7 swordfish and an account of where they went as we followed them. The vessels and specific equipment used are discussed here.

3. Depth. We used depth telemetry as our primary tool and have made many inferences about the fish and its environment from the depth data.

4. Buoyancy. Some ideas on buoyancy based on the rapid vertical movements seen in the depth records.

5. Light. Light appears to be an important stimulus for swordfish.

6. Oxygen. The depth range of swordfish in the Baja California area appears to be limited by an oxygen minimum layer.

7. Temperature. We have extensive temperature data from our many XBT's and in some experiments by direct telemetry from the swordfish.

This work was supported by a grant from the Culpepper Foundation and by contract No. 03-7-043-35108 from the National Marine Fisheries Service. The report should not be widely circulated and permission should be obtained before quoting it.

1. EQUIPMENT

Transmitters:

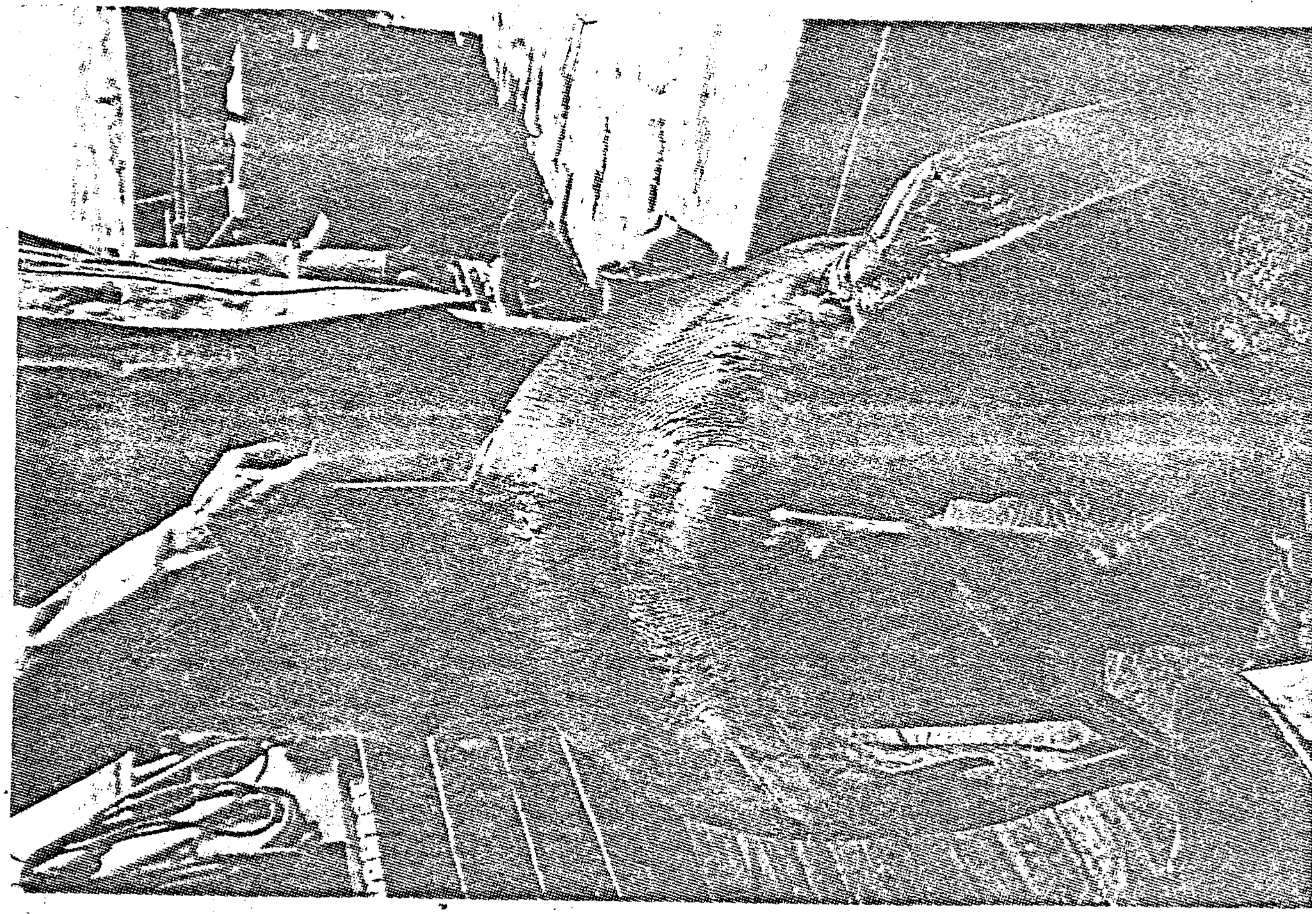
Our basic transmitter measures 5.5 x 1.75 x 1.25" and weighs 4 oz in water. It is powered by 5 lithium cells which provide the greatest energy density of any commercially available battery. An electronic circuit and a ceramic transducer convert the electrical energy to sound. We were able to hear one version of this transmitter at a distance of 3 1/2 miles in Vineyard Sound and a less powerful model operated for as long as a week at a useful power level. The transmitters are cast in a strong epoxy plastic and we have tested them to pressures equivalent to that at a depth of 4000 feet in the ocean.

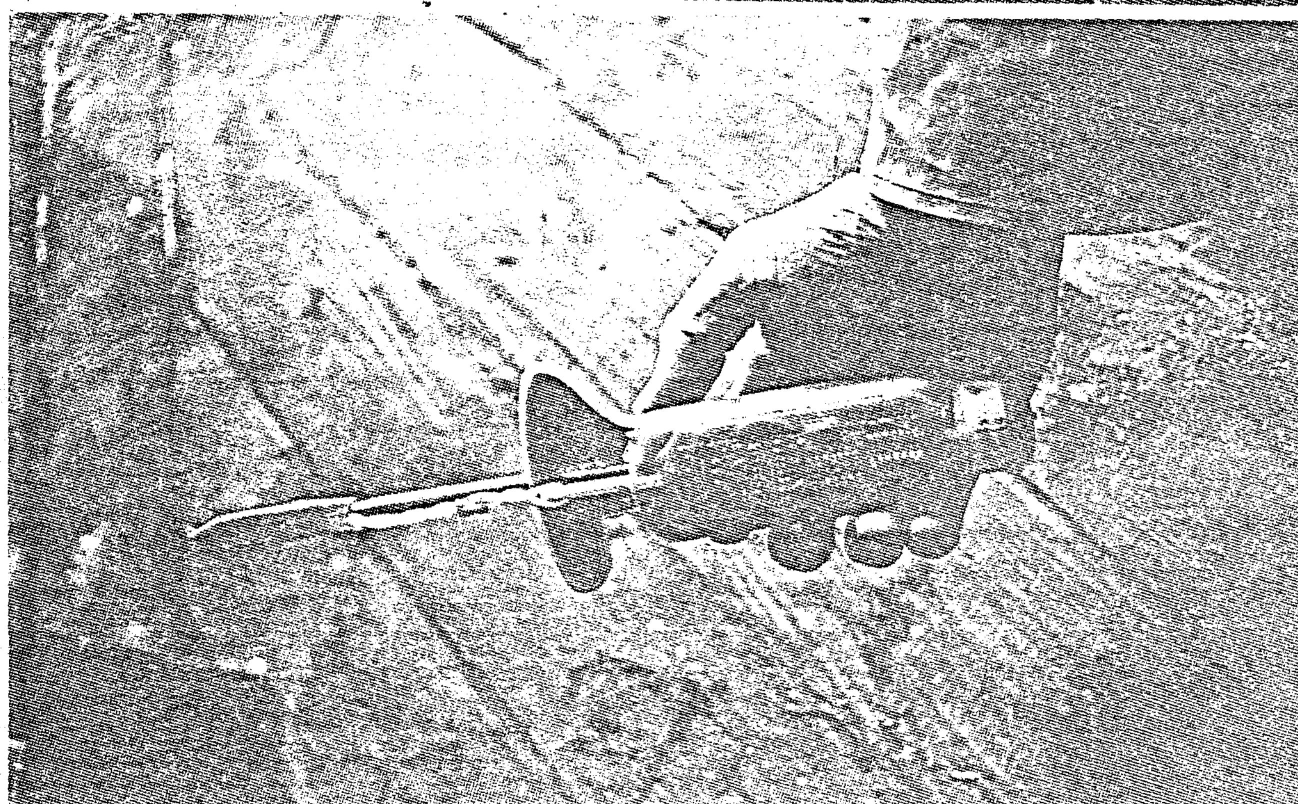
At present there are two types of instruments. One incorporates a thermistor and transmits water temperature; the other has a strain gauge pressure sensor and transmits depth. The information is sent as a variable pulse rate such that the faster it beeps, the greater the temperature or depth. The two kinds of information are broadcast at slightly different frequencies, 32 and 34 kHz, so that we can separate the signals in experiments which involve two transmitters on the same fish.

A small stainless steel dart is tied to the end of the transmitter with heavy monofilament line. Heavy rubber bands are used to hold the transmitter onto an adapter which is fastened to a standard harpoon iron. The adapter has a stop which limits the penetration of the dart to a few inches. Figure 1 shows the transmitter in position and the holding power of the dart.

Figure 1a. Transmitter and harpoon dart on adapter. The adapter attaches to a standard Lily iron and provides a way of controlling penetration of the dart and a flat surface to which the transmitter is strapped with heavy rubber bands.

Figure 1b. The small dart has considerable holding power. We could life and shake this 60 lb blue shark without it pulling out.





Receiving:

Aboard the tracking vessel the signal is picked up by a directional hydrophone, amplified by a preamplifier in the hydrophone and fed into an ultrasonic receiver. The receiver can be tuned to accept the signal and reject noise at other frequencies. The hydrophone is strongly sensitive in one direction and is mounted so that it can be rotated. Tracking the fish is simply a matter of turning the hydrophone to find the strongest signal and steering in that direction.

Mounting the hydrophone on the tracking vessel has always been a problem. The best method would be to have the hydrophone on a retractable shaft which could be pulled up into a well in the vessel's hull when not in use. This is impractical because the limited amount of time that we would use any vessel would not justify the expense. Our most satisfactory mounting uses a streamlined fin to hold the hydrophone in the water ahead of the bow. This is the quietest position to listen from. It keeps the hydrophone looking away from the ship and at the greatest possible distance from the propellers, which are usually a strong source of noise.

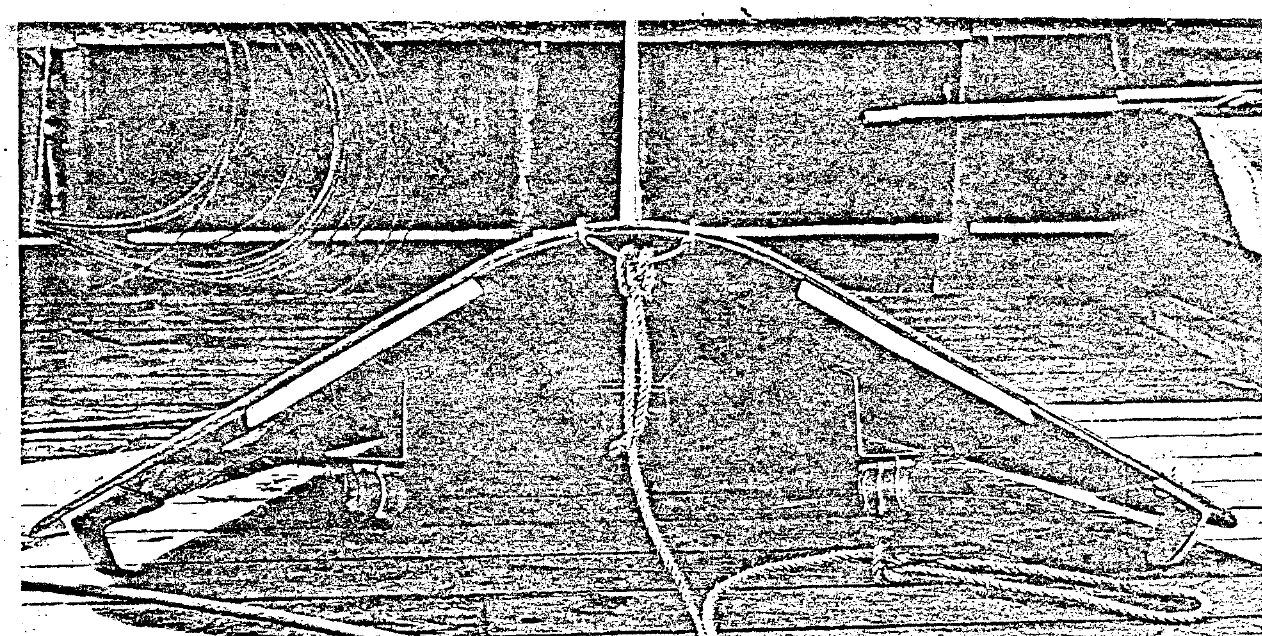
Every new vessel is a new problem. We were offered an opportunity to work on the Polish vessel, *WIECZNO*. She is a far-seas side trawler, approximately 170' long with a high bow and a graceful sheer. The high bow of *WIECZNO*, coupled with the bureaucratic difficulties of getting permission to weld any scaffolding onto the hull, prompted us to try a different type of hydrophone mounting. We used a "V" fin, which is sort of an underwater kite or depressor and is towed from a ship on a cable which it pulls down deep into the water at a steep angle. On the bottom of the "V" fin we mounted three hydrophones: a highly directional one which pointed straight ahead and two hydrophones with a broad sensitivity pattern mounted on each side at a 30° angle to the mid line as shown in Figure 2. The signals were amplified in the "V" fin and led up a multiple conductor cable to the bridge. Here we had a separate ultrasonic receiver for each of the two side-looking hydrophones and listened to the signal from both through stereo headphones. This was a crude binaural listening system. When the source of the signal was directly in front of the "V" fin, it was perceived in the center of the listener's head. As it moved off to one side, the perception of the sound shifted to that side. With this system we could tell which way to steer the boat in order to bring its course on a line toward the target.

2. MOVEMENTS

Our first attempt at acoustic telemetry from swordfish was during a NMFS shark-tagging cruise aboard the Polish research vessel, *WIECZNO*, out of Gydnia. The cruise had been arranged through the NMFS and Chuck Stillwell of the Narragansett Laboratory went as chief scientist.

The *WIECZNO* cruise was to be from 18 to 29 November and the working area was restricted to between Cape Hatteras and Georges Bank. This is a tough time of year to fish. It is difficult to find the appropriate water temperature gradients and swordfish are scarce. We went south to near Hatteras and began setting our gear. The weather was rough, but

Figure 2. This "V" fin was used to support our tracking hydrophones during the Wieczno cruise. The central hydrophone has a narrow sensitivity pattern pointed directly ahead. The side hydrophones had a broad pattern and were used with a binaural receiver.



the ship and the men were excellent for this type of fishing and we were able to work with ease when it would have been very difficult on a smaller ship.

We caught several live swordfish and put a depth transmitter into a small one weighing perhaps 50 lbs. It went to the bottom in 211 m of water and stayed there. Within the several mile error of our navigation it did not move during the next 27 hours and we abandoned it, feeling that it was dead or so severely injured that it would take a long time to recover and resume its normal activities.

Swordfish #2:

In the spring of 1977 we went to Cabo San Lucas in Baja California Mexico, where we had chartered the 65' swordfish harpoon boat, *SEA WORLD*, out of San Diego (Figure 3). The vessel was owned by Mr. Milton Shedd who was aboard and the charter included the services of Shedd's swordfish spotting plane. Shedd, his captain, Bob Vile, and the pilot, Pat Utley, made a very competent team, harpooning some 17 swordfish with California Fish and Game Service tags and never failing to get a transmitter into a swordfish for us when and where we wanted it.

While the vessel was still in San Diego we rigged our bow hydrophone on it for tracking. The mounting is shown in Figure 4. A streamline fin holds the directional hydrophone in the water. The hydrophone is fastened to a shaft which runs the length of the fin and allows it to be rotated by a rope and pulley system. The fin is quite streamlined and rudders with the water flow. This eliminates the large forces which

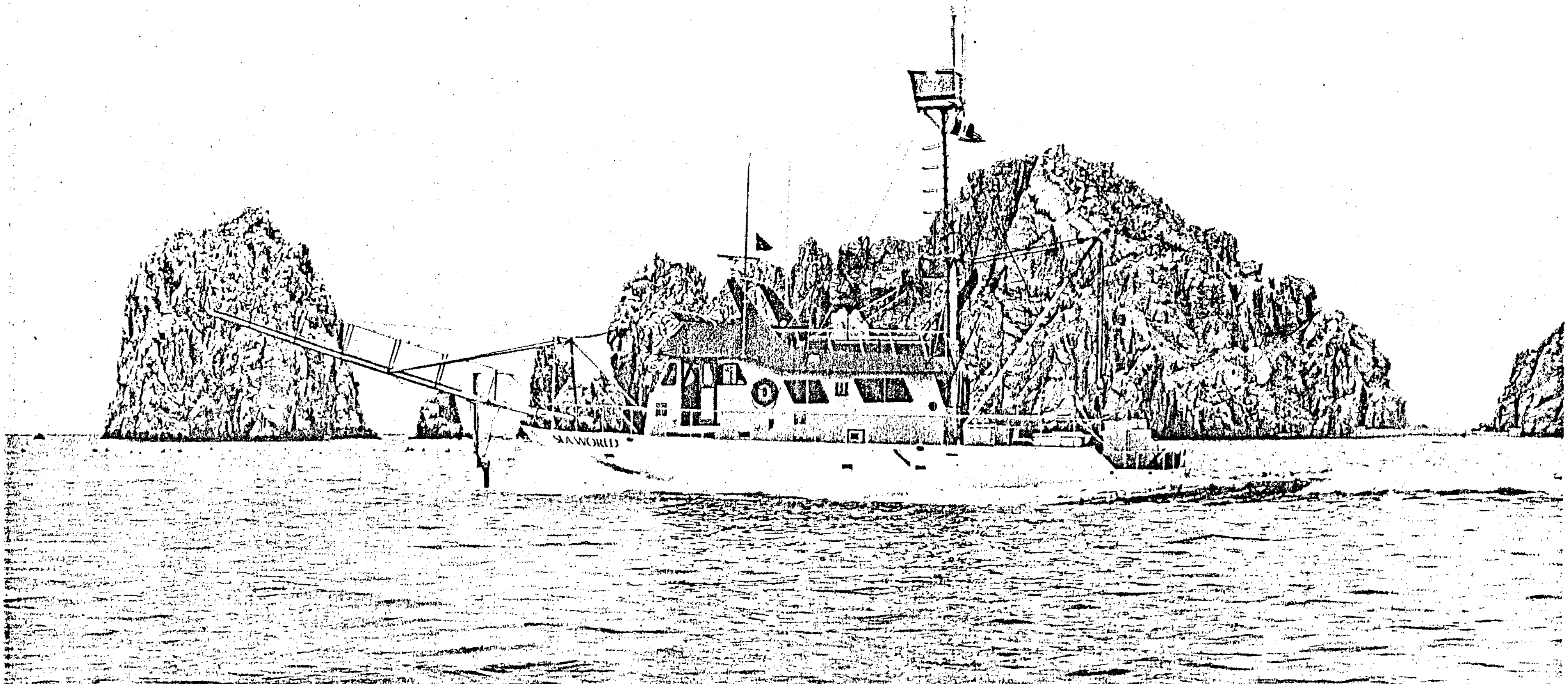


Figure 3. Sea World, shown here at the entrance to Cabo San Lucas harbor, is a 65' fiberglass hull, twin diesel yacht heavily loaded with three live bait tanks and a 40' harpooning stand.

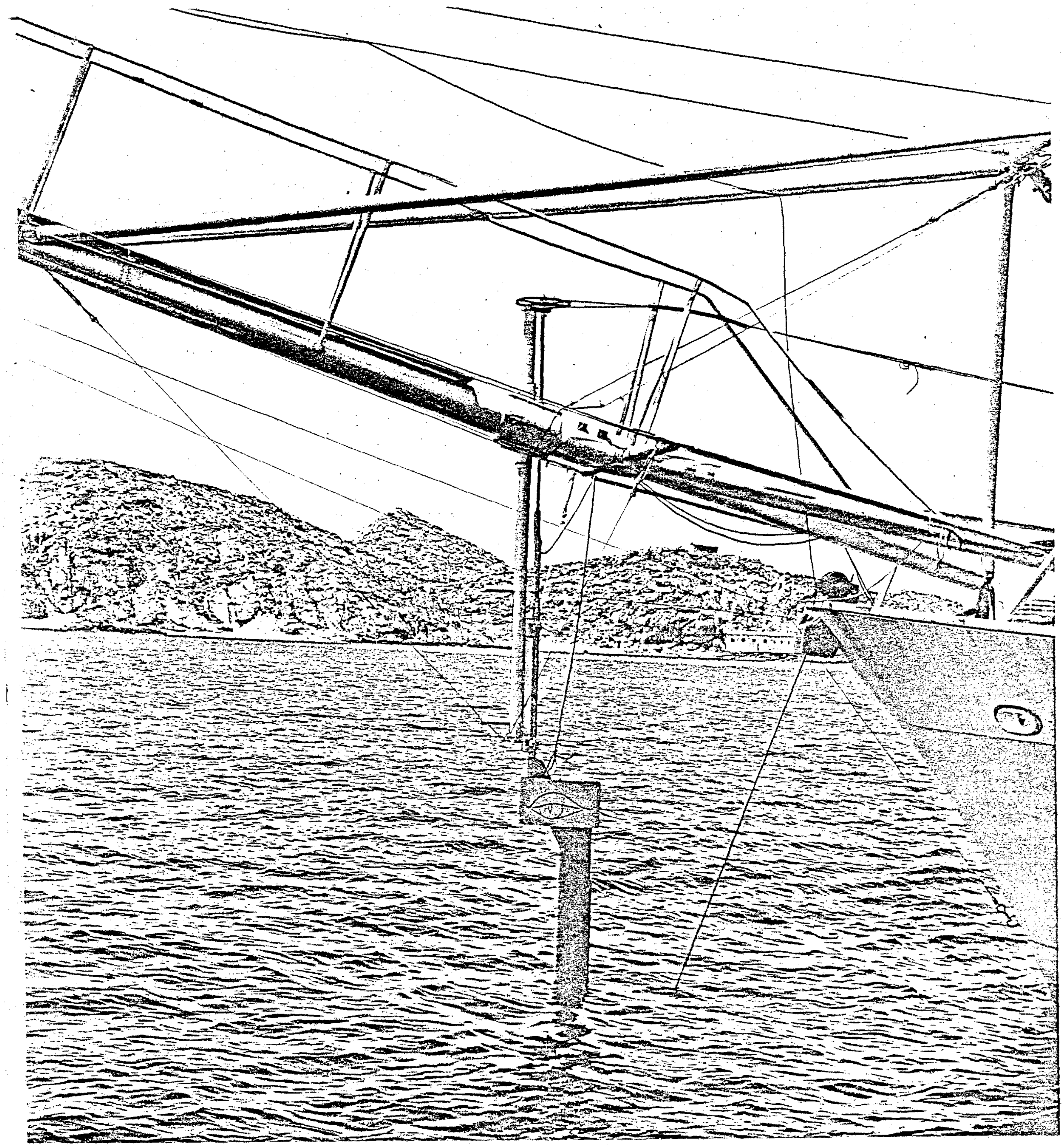


Figure 4. Our hydrophone fin in position on "Sea World". The hydrophone itself is 4' underwater at the end of the streamline black fin. It can be rotated by a rope and pulley arrangement. The hydrophone fin is removed from the vertical support when not in use.

would come to bear on a streamlined fixed fin as it was forced sideways with the yaw of the boat (Figure 5).

Shedd, who had fished for many years in the Cabo San Lucas area at the tip of Baja California, suggested that there were two groups of swordfish in this area: large fish which were found offshore in more than 500 fathoms of water and somewhat smaller fish which could be taken on an inshore bank in about 50 fathoms. Our first experiments were in the latter area.

Swordfish #2 weighed about 150 lbs and was harpooned with a depth transmitter on the morning of 19 April. It returned to the surface for 20 minutes after being struck and clearly seemed to be in good condition and unaffected by our transmitter. During the five days we followed this swordfish, it showed a clear cyclical pattern of movement. During the day it would occupy the same area in about 50 fathoms of water 5 miles out from land. Several hours before sunset it would move offshore and by sunset it would be in several hundred fathoms of water. During the night it remained in deep water, 1000 fathoms and went as far as 20 miles offshore. At the first sign of dawn, as soon as the sky started to lighten, it would swim inshore and return to the same area on the bank. This fish was clearly moving between two positions: on the bank near the bottom during the day and offshore on the surface over deep water at night (Figure 6). While on the bank the swordfish changed position slowly (except on 22 April when it swam along the 50 fathom contour at about 1 knot). When it reached its offshore position at night it moved slowly or remained in one spot. In moving between

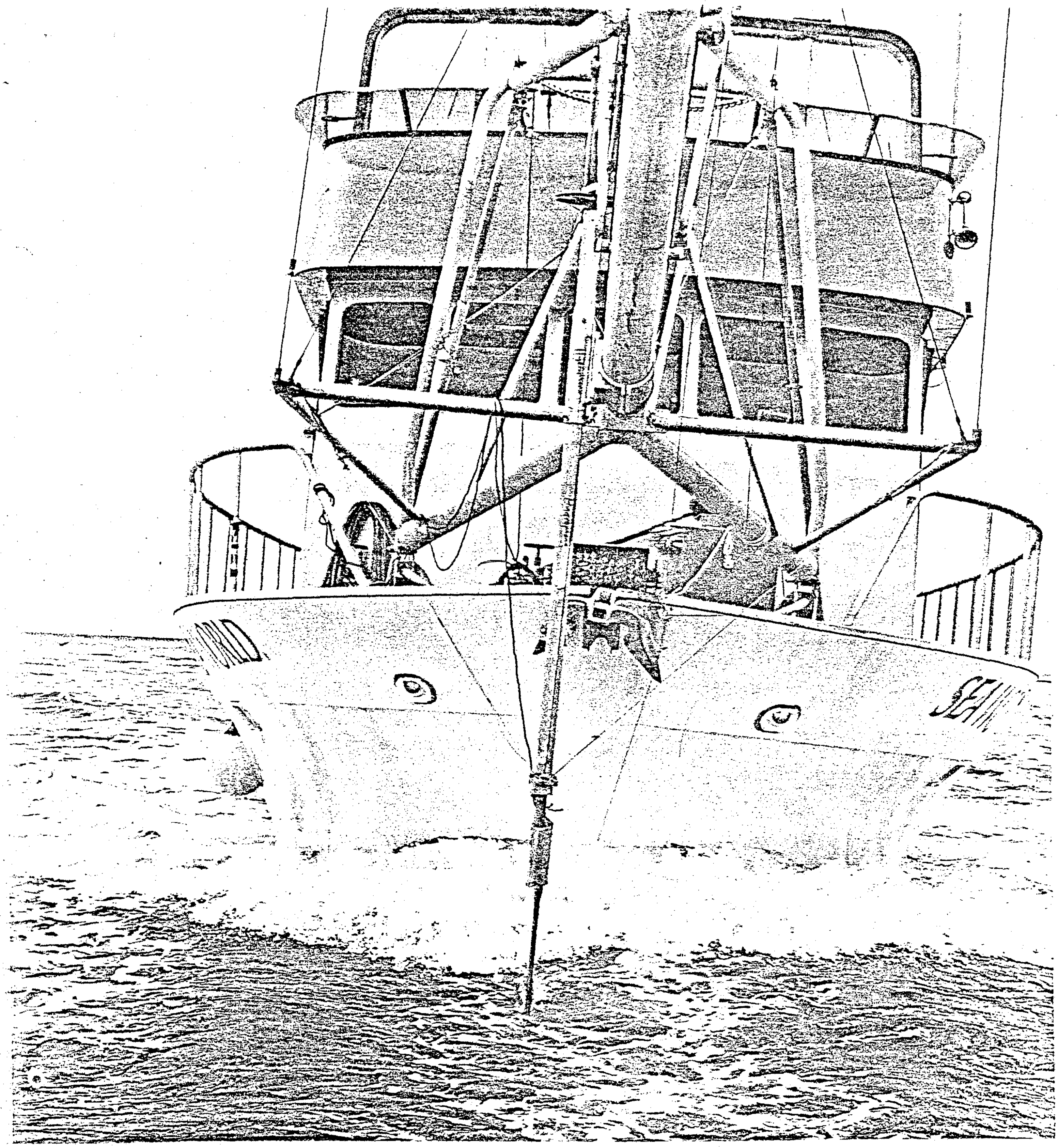
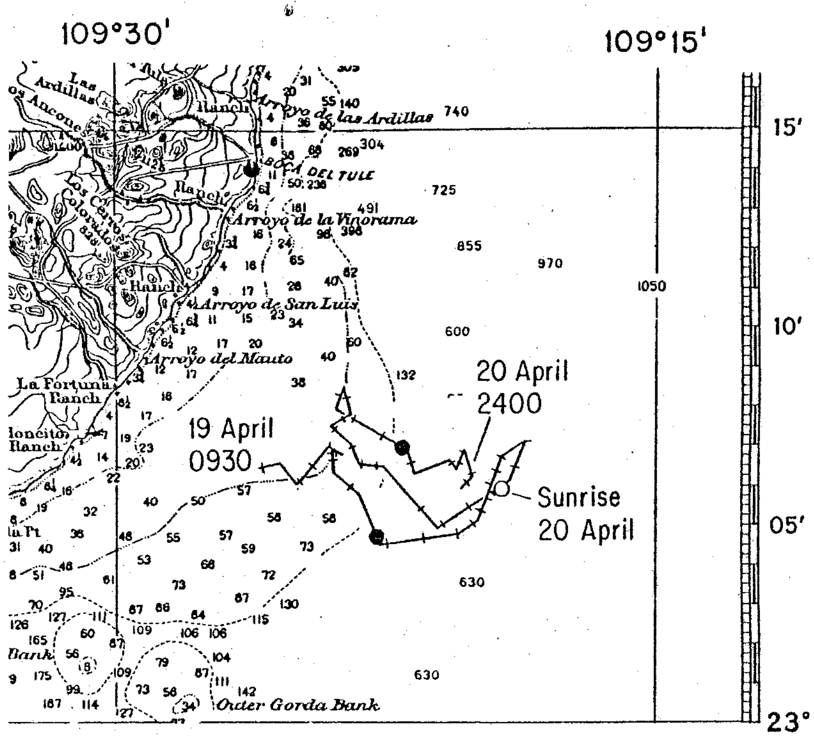


Figure 5. Sea-World underway with the hydrophone fin in position. The vessel had an impressive bow wave. While tracking Swordfish #3 the main tube of the harpoon stand broke just behind the hydrophone mount when the end of the stand dipped into a large wave.

Figure 6. Swordfish #2 moved between deep water and the 50 fathom curve on a bank during each of the five days we followed it. The track is seperated into 4 panels for clarity. Just before dawn every morning the fish would turn toward shore and leave the deep water. In the late afternoon, sometime before sunset, it would leave the bank and turn offshore. Compare with the depth record for this fish in figure 17. ● = sunset, 0 = sunrise, tics at 1 hour intervals.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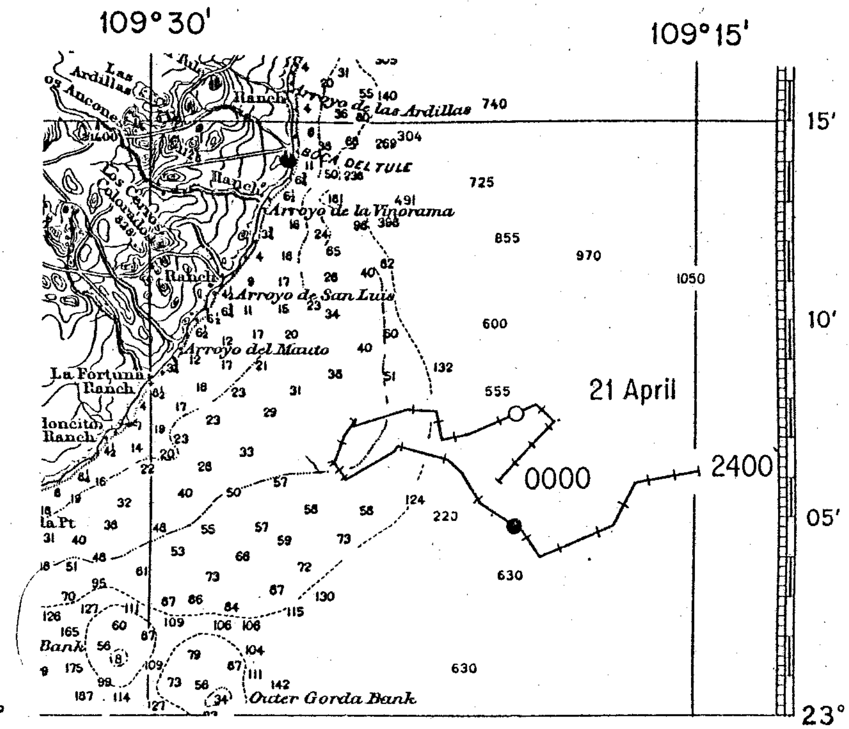
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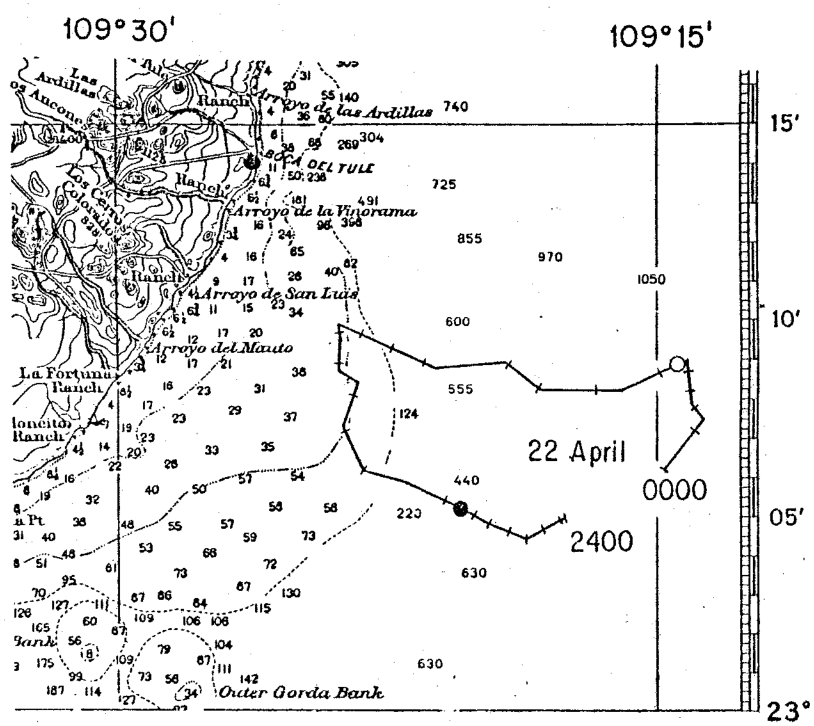
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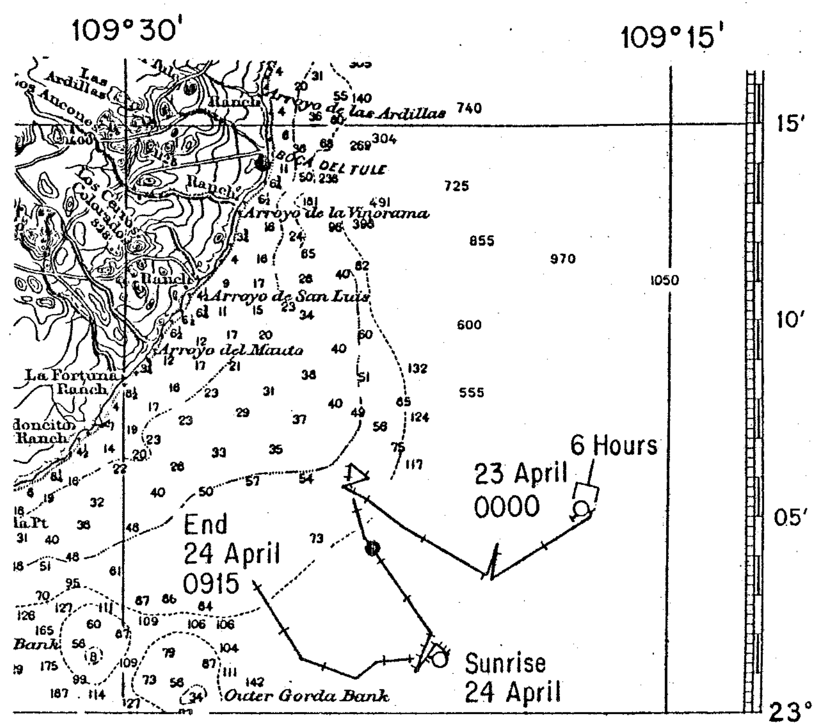
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Sunrise
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the two positions, however, it swam faster, at speeds of 1 to 2.5 knots.

The position and speed of the fish were recorded by plotting the position of our vessel using radar fixes on the shore. Because it is difficult to locate on a chart the precise position of a peak or cliff used as a landmark on the radar screen, our absolute positions are less certain than the relative movements. The movements referred to here are, of course, those of the tracking vessel. The fish itself may have been quite active, circling and changing direction, even at times when its position was changing slowly (see Figure 10).

Swordfish #3:

After following Swordfish #2 for 5 days we were convinced that it had a clear pattern of moving offshore at night and inshore during the day. We abandoned #2 to try another swordfish to see if it did the same. Swordfish #3 weighed about 150 lbs and was harpooned in about 50 fathoms of water early in the afternoon of 26 April. Two transmitters tied in tandem were placed on this fish, allowing us to record both depth and water temperature.

Swordfish #3 moved in the same pattern as #2, and its course covered the same area (Figures 7, 8). It moved offshore several hours before sunset and spent the night in deep water. At first light it immediately turned inshore and moved back to the bank. On the afternoon of that day, 27 April, it remained in one spot, apparently on the bottom from 1100 to 1800 hrs. We determined this by driving *SEA WORLD* directly over the fish and noting that the bottom depth indicated on the fathometer was the same as the telemetered fish depth. The weather was bad and it was

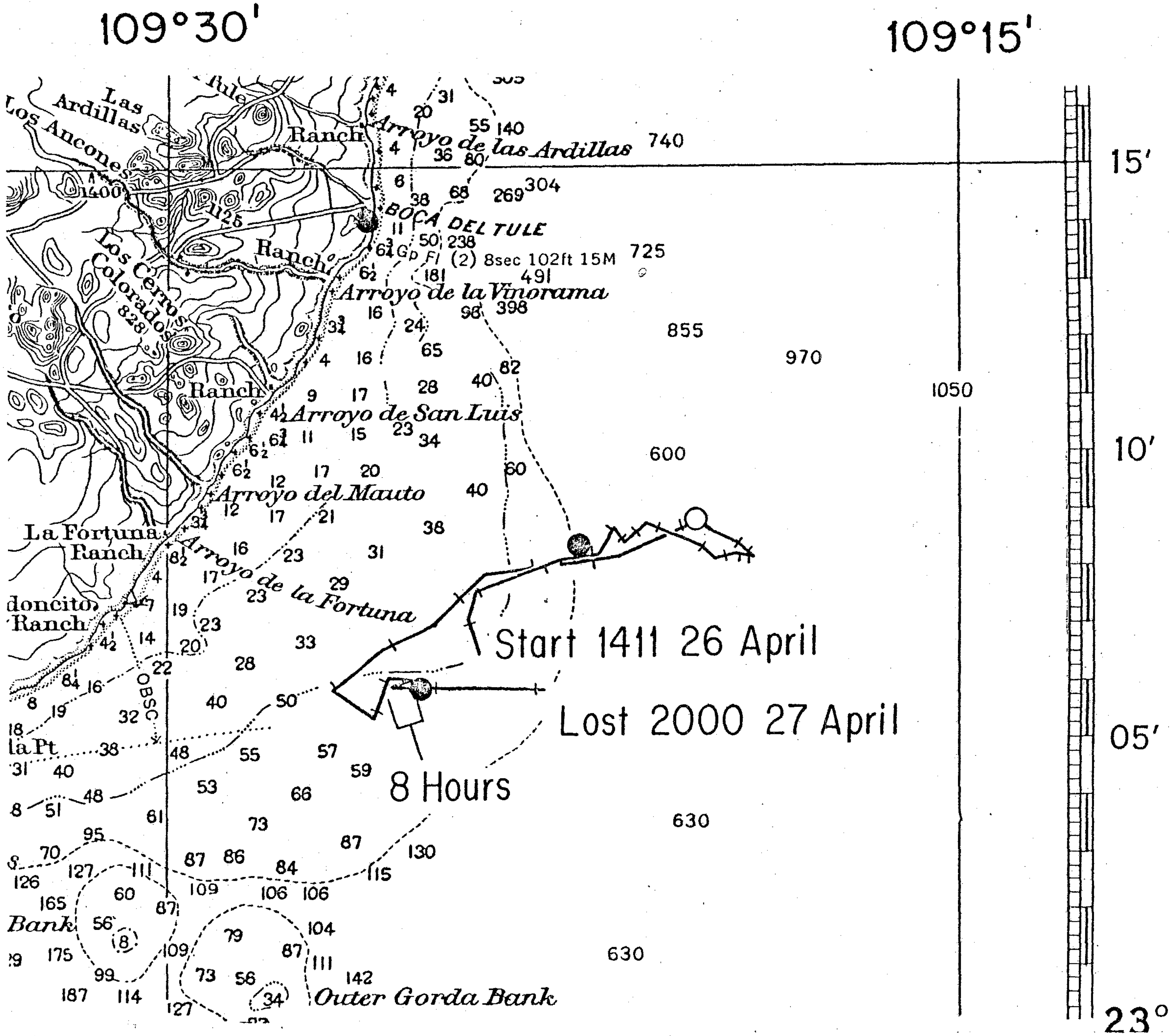

Figure 7. Swordfish #3. The movements of this fish were identical to those of #2. During the eight hour period indicated it was resting on the bottom. ● = sunset, O = sunrise, 1 hour tics.

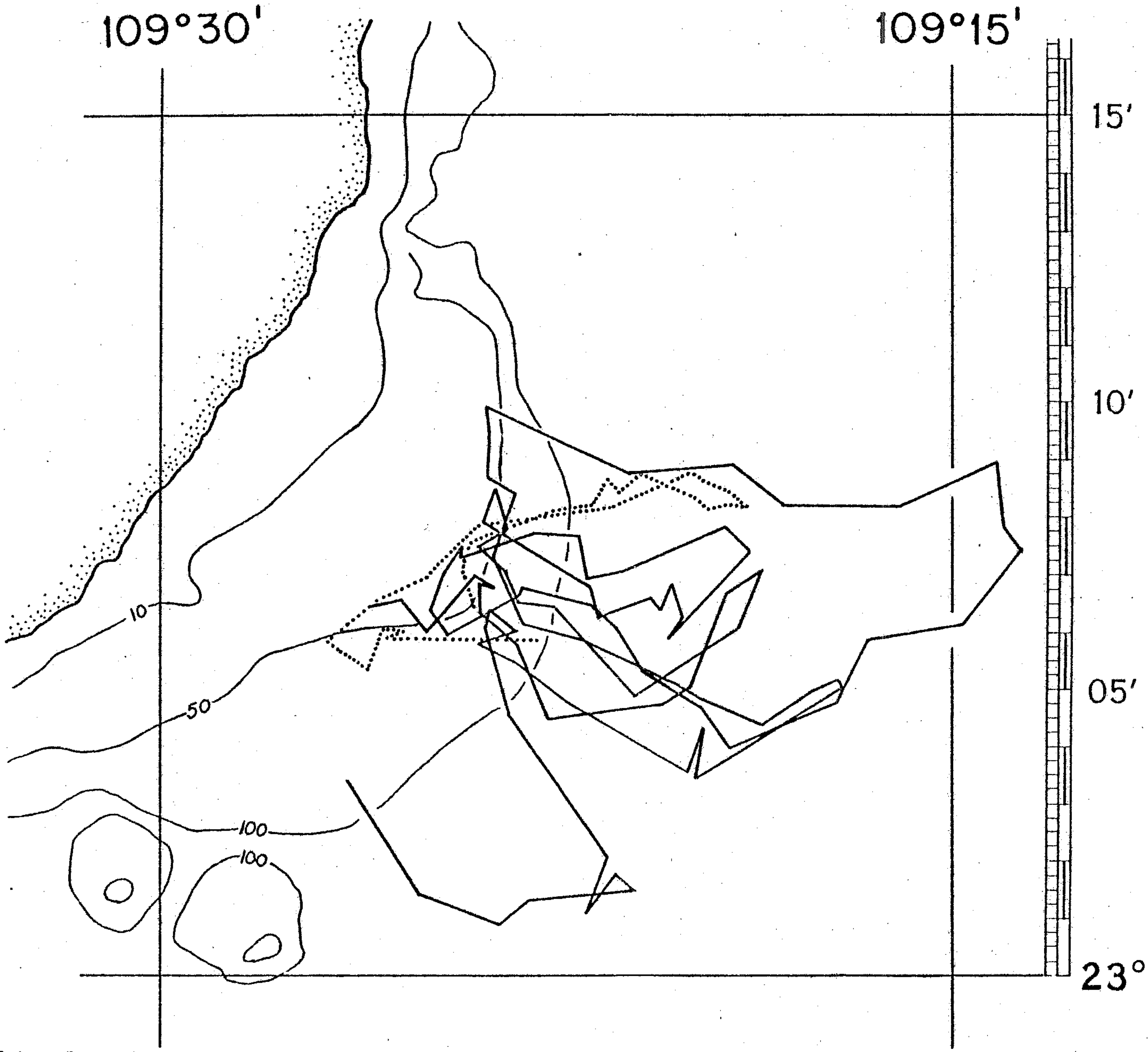

Figure 8. This plot shows how closely the track of #3 can be superimposed on that of #2. Solid line = #2; dotted line = #3.

difficult to hold position with the vessel, but as far as we could tell, it did not move from the bottom during this time. It remained on the bank after sunset, something which #2 had not done and we began to worry that the transmitters had pulled out and were sitting on the bottom. We were relieved when the swordfish rose from the bottom and headed off shore. Unfortunately, the weather grew worse and we were forced to abandon #3 when we dipped the harpoon stand into a sea and broke it. Despite very choppy seas, Captain Vile skillfully salvaged the harpoon stand without damaging the hull and we ran downwind 20 miles to shelter in a cove. The next day was spent lashing the harpooning stand back together and repairing our gear.

Swordfish #4:

Pleased with finding such impressive similarity in the activities of Swordfish #2 and #3 (Figure 8) we decided to work with some of the larger fish found offshore in deep water. On 30 April we harpooned a depth transmitter into a swordfish weighing about 175 lbs which we found on the surface in over 800 fathoms of water. After following it for about 2 hours, we decided that the signal from the transmitter was not powerful enough to enable us to track the fish if conditions got worse. We rigged a harpoon and coming up on the swordfish we harpooned it to recover the transmitter for examination. During the time that we were with #4 it stayed on the surface, frequently with its fins showing and did not seem to go below 10 m. The day was breezy with whitecaps. Our later experience suggests that our difficulties were not with the

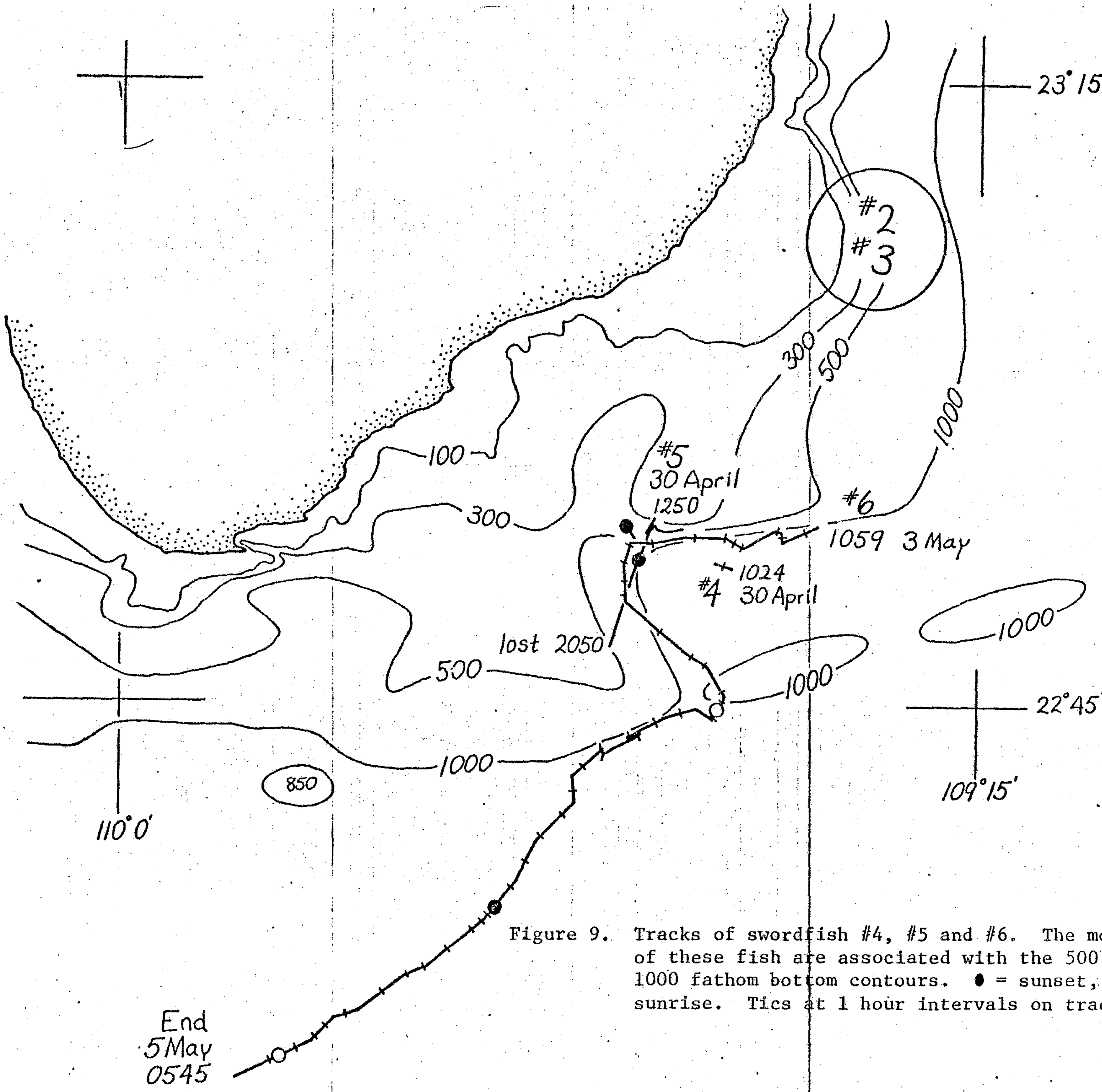

Figure 9. Tracks of swordfish #4, #5 and #6. The movements of these fish are associated with the 500 and 1000 fathom bottom contours. ● = sunset, 0 = sunrise. Tics at 1 hour intervals on track #6.

transmitter, but caused by absorbtion of sound in the bubble-laden surface waters.

Swordfish #5:

After harpooning swordfish #4, we spotted a swordfish finning and leaving #4 and our transmitter to be picked up by another boat, we placed a depth transmitter on #5. This swordfish was estimated to weigh about 225 lbs. It moved slowly, covering less than two miles in the first 5 hours and surfaced frequently. After sunset it began to swim south toward deeper water at a speed of about 2 knots. The weather grew worse and we lost this fish early in the evening.

Swordfish #6:

Swordfish #6 was large, 300 lbs, and was found about 15 miles offshore over the edge of a slope where the bottom drops sharply from 300 to 1000 fathoms (Figure 9). Swordfish #4 and #5 had also been found along this edge 3 and 6 miles to the west of #6. Both depth and temperature transmitters were attached to #6 at 1040 on 3 May. For the rest of the day the fish swam slowly to the west along the edge of the slope. At sunset it turned south and moved to the southeast during the night. At dawn it turned again and moved to the west southwest. These turns approximate the course of the 1000 fathom bottom contour. The swordfish followed this contour until noon on 4 May when it turned southwest and swam off into the Pacific, maintaining a southwest course for 24 miles during the next 17 hours. We abandoned #6 after dawn on 5 May, the weather being too rough to continue the experiment. While we

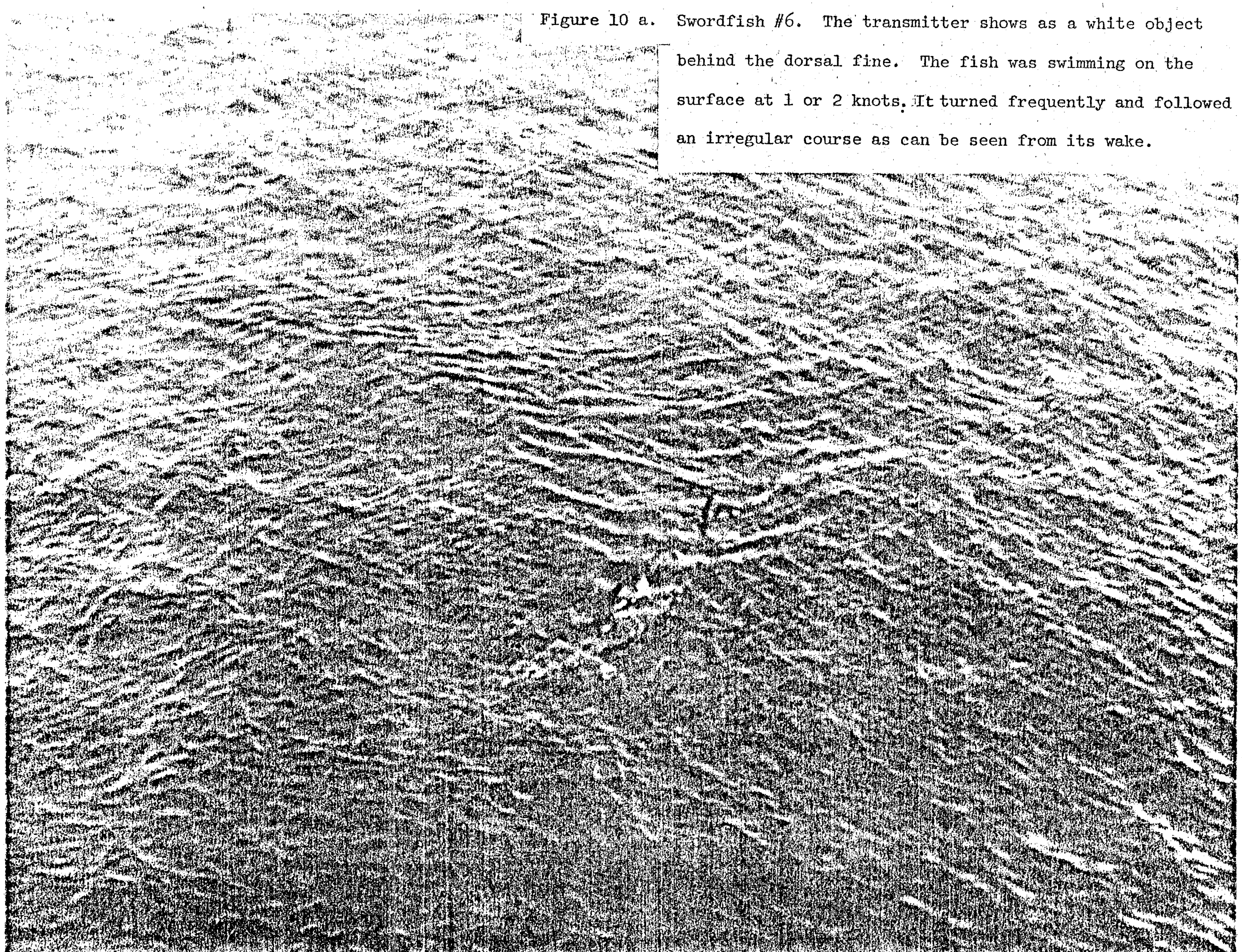

Figure 10 a. Swordfish #6. The transmitter shows as a white object behind the dorsal fine. The fish was swimming on the surface at 1 or 2 knots. It turned frequently and followed an irregular course as can be seen from its wake.

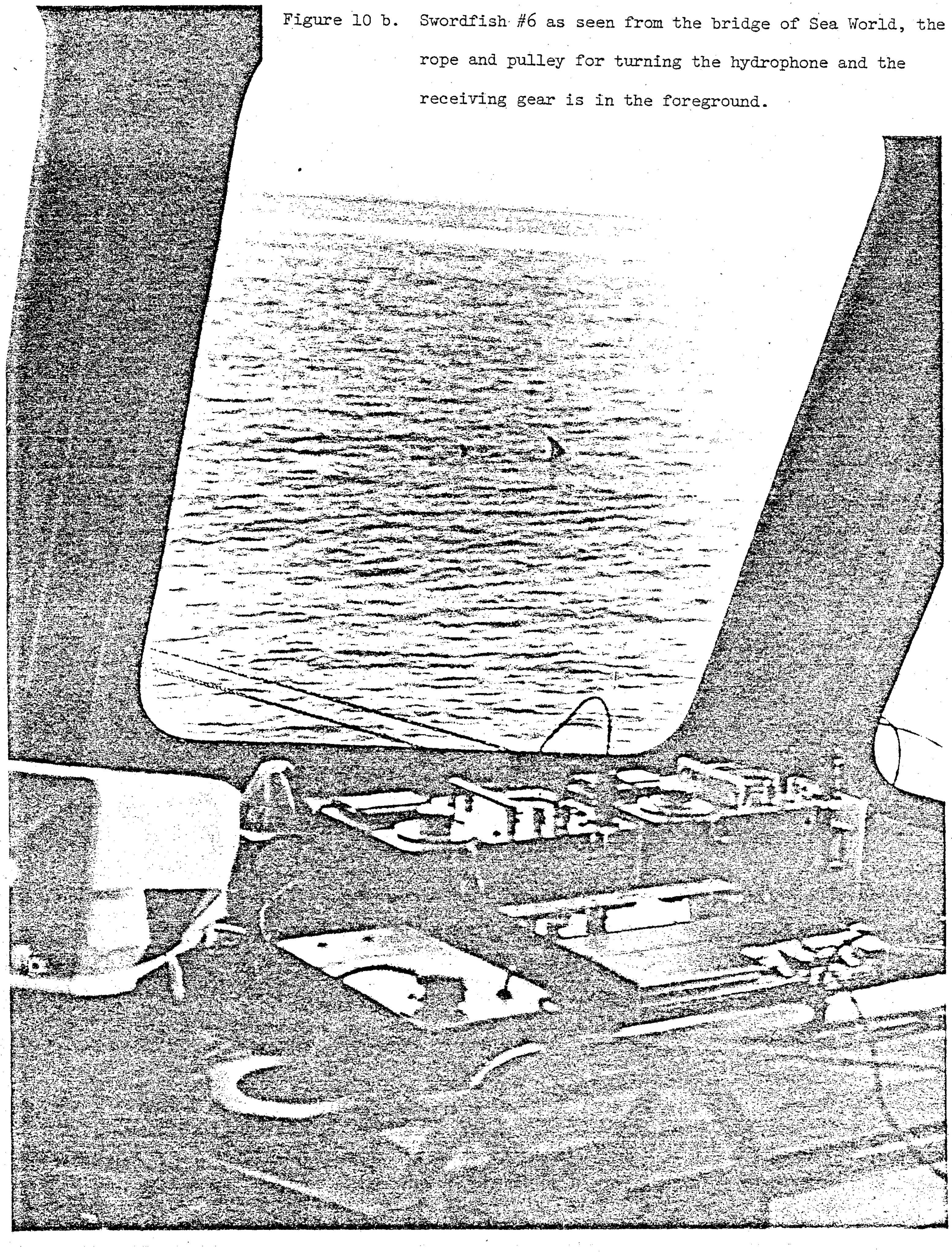

Figure 10 b. Swordfish #6 as seen from the bridge of Sea World, the rope and pulley for turning the hydrophone and the receiving gear is in the foreground.

were with it this fish traveled 48 miles in 44 hours.

There are parallels between the activities of the "offshore" swordfish, but they are not as clear as the almost duplicate records for fish #2 and #3. The three fish, #4, 5 and 6, were tagged on the surface within 6 miles of each other. They all moved west along the 1000 fathom curve during the day, and #5 and #6 both turned to the south after sunset, again following the trend of the 1000 fathom curve (Figure 9). While there are not enough soundings in this area to draw the bottom contours with any great confidence, the apparent relationship of the course followed by the fish to the bottom relief is an interesting one. If this relationship is real, what is the coupling factor between the fish at a depth of less than 200 meters and the bottom at 2000 meters? Perhaps some current which reaches the surface reflects the bottom topography in this area. In any case it appears as if Shedd was correct when he suspected that the larger fish offshore were in passage while the smaller ones inshore remained in the area. I am often impressed with the ability of some fishermen to correctly predict what fish are doing on the basis of very limited and tenuous observations.

These "offshore" fish came to the surface frequently to fin. On the surface they often moved about actively. Swordfish #6 was estimated to be swimming at 1 to 2 knots as we watched him (Figure 10), but in a random pattern with much turning so that he progressed slowly. This fish appeared to be responsive and moved after a live Pacific mackerel which was tossed to him. When on the surface the swordfish did not always go down readily, even when chased by the boat. On the second day we attempted to drive swordfish #6 down by over-running him. He would settle down a few meters and easily avoid us. When we pressed him, he finally went off in a series of long horizontal leaps, but did not go below a few meters depth until he had been on the surface for about an hour.

Swordfish #7:

We were pleased to have an opportunity to work on our own Northeast coast when Jack Casey, NMFS, Narragansett Marine Laboratory, offered us an opportunity to track swordfish during his November shark-tagging cruise. The fishing vessel *DIANE - MARIE* had been chartered for this purpose. She was a 75' steel hull, twin-screw vessel, fast, maneuverable, well equipped and well maintained (Figure 11). We welded a scaffolding on the bow to support the same hydrophone fin we had used on *SEA WORLD* in Baja California.

Captain Jimmy Ruhle and the crew of the *DIANE - MARIE* were skilled fishermen, as they demonstrated by setting 100 hooks of longline gear and picking it up within an hour with two live swordfish on it. We placed a depth transmitter on the second of these. The swordfish was hooked in the tip of the lower jaw and seemed to be in good condition. The transmitter was harpooned in place just ahead of the dorsal fin and the fish released and on its way seconds after it had come alongside the boat. I was very impressed with this smooth operation. As we located and tracked the fish with our hydrophone, the men continued to recover the longline gear. Much of it was back aboard when, the signal getting faint, we buoyed off what remained of the line and left it behind as we went after the fish. The *AUDREY-LYNN* recovered the remaining gear for us.

Swordfish #7 was released near the 100 fathom curve, northeast of Cape Hatteras. Figures 12, 13 and 14 show a satellite infrared picture of the area, a sea surface temperature chart for the time and the track of #7. Note that this region has a complex pattern of currents and eddies formed by interaction of the Slope Waters with the Gulf Stream which sweeps by just south of here. Swordfish #7 moved off to the east at about 1 knot. By morning of the second day it had reached the Gulf Stream, as can be seen in Figure 24, where the isotherms deepen at this time. In the stream it was carried to the northeast at a speed of about 2.5 knots. It must still have had an active southeasterly component to its swimming however, for by the end of the third day it had crossed the Gulf Stream and entered the Sargasso Sea. In Figure 24 on the afternoon of the last day, the deep isotherms can be seen leveling off as we entered the Sargasso Sea. Total distance moved was about 130 miles in 67 hours.

3. SWORDFISH DEPTH

All of the swordfish we followed showed a clear pattern of diurnal vertical movements, going deep during the daylight hours and coming to the surface at night. Swordfish #7, on 10 and 11 November (Figure 15), gives the best illustration of what we have come to consider to be a typical depth cycle in the absence of complicating factors. The fish is on or near the surface at night. It descended about an hour before

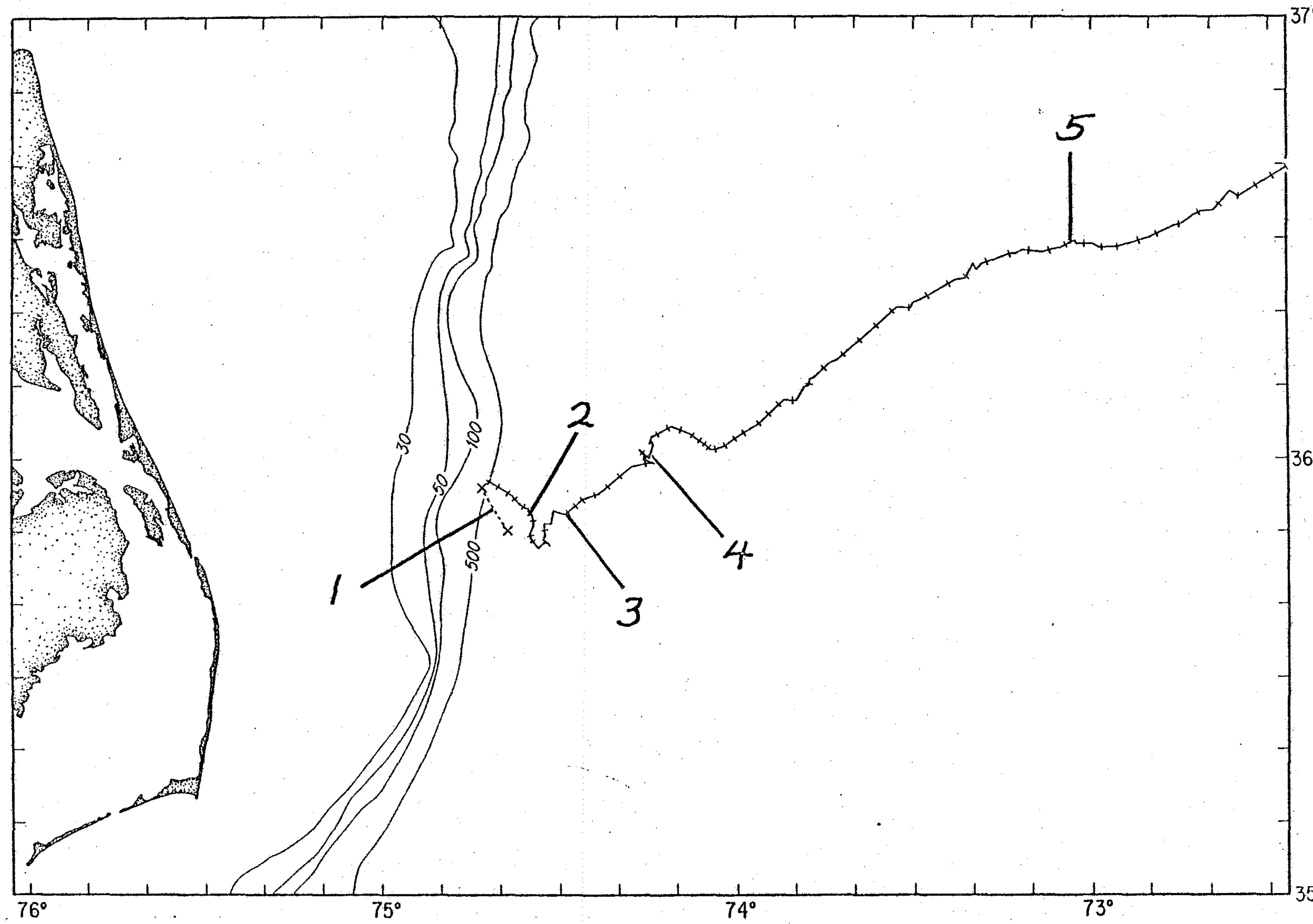

Figure 14. Track of #7. 1. Dotted line indicates position of longline set where #7 was caught. 2. The fish moved beneath a layer of cold surface water at 1000 on 9 November and made a sharp turn south. 3. The fish came out from beneath the cold surface water and back to the surface at 1800 on 9 November. 4. By this point, 0500, on 10 November, #7 was in the Gulf Stream. 5. At 1500 on 11 November, #7 had crossed the Gulf Stream and entered the Sargasso Sea. Tics at 1 hr intervals.

dawn, when we could just notice a brightening in the eastern sky. Moving down rapidly, it reached a depth of 200 to 400 meters by sunrise. During the rest of the morning it gradually moved to greater depths. At noon on 11 November it reached a depth of 617 meters. The greatest depth on record for swordfish is 630 meters (*DEEPSTAR* dive #217, 28 May 1967, 29°28'N, 86°53.7'W). We were disappointed not to break this record. After mid-day swordfish #7 began to come up and rose rapidly after sunset, returning to the surface at about the end of twilight. The other fish (see swordfish #2 and #3 in Figure 16 and swordfish #5 and #6 in Figure 17) while not going as deep as #7 followed the same pattern, particularly in the timing of the descent in the morning and ascent in the evening.

I suggest that the diurnal vertical movement of swordfish #7 on 10 and 11 November is typical of swordfish because the area in which it was swimming on those days was a relatively unlimited environment. The water had no sharp temperature or oxygen concentration gradients which might limit its depth range nor did the bottom at more than 1000 fathoms limit the depth of the fish. There are two factors which may have been important in causing the different appearance of the depth record on 9 November. These are the experience of being caught on the longline and the presence of numerous sharp thermal gradients and inversions in the water column during that day. The descent in the morning had been delayed until after dawn. This is the only time that any of the swordfish were late in going down in 11 dawn observations.

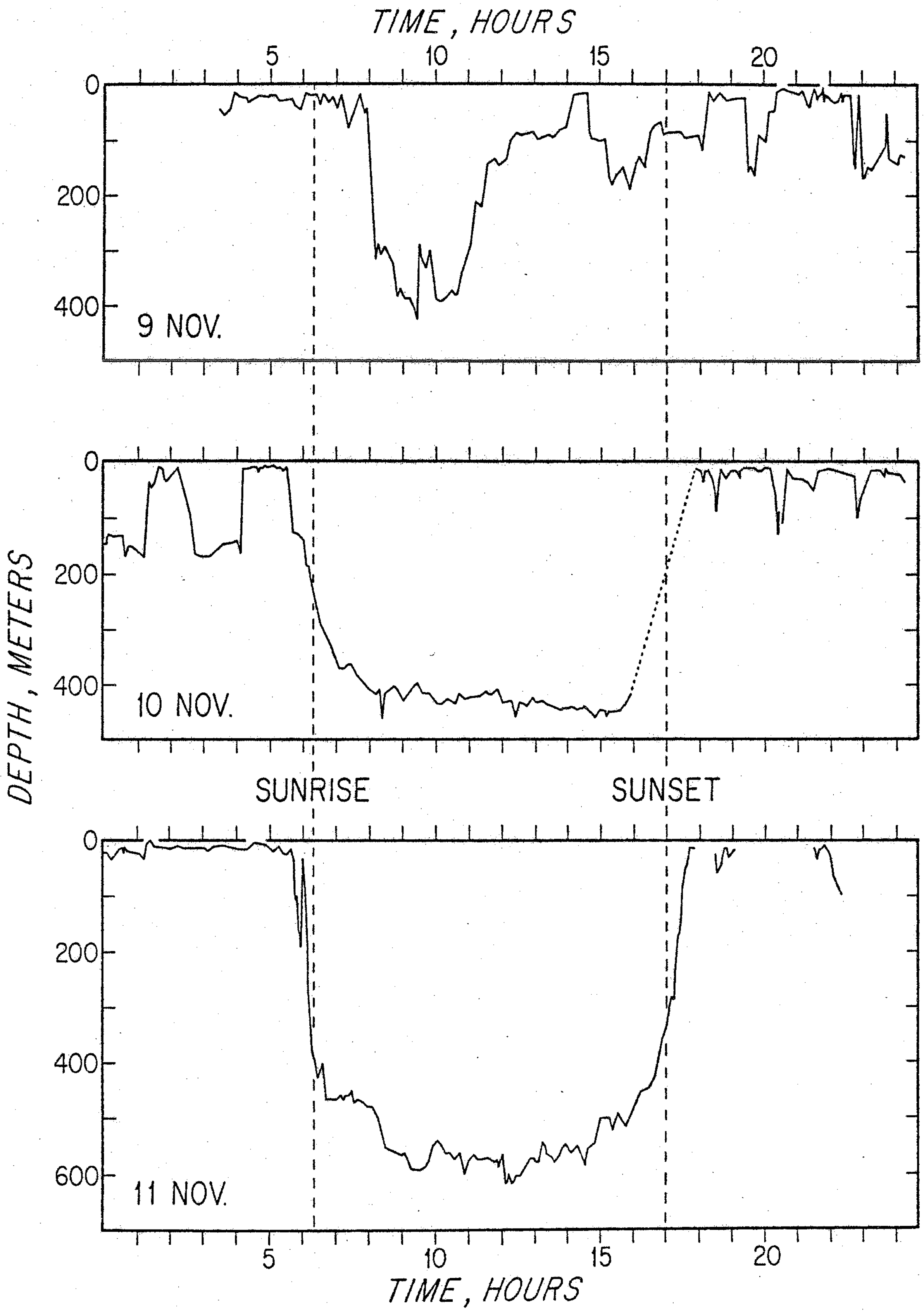

Figure 15. Depth record for swordfish #7 plotted from midnight to midnight. The dotted line at sunset on 10 November represents a period where we lost contact with the fish.

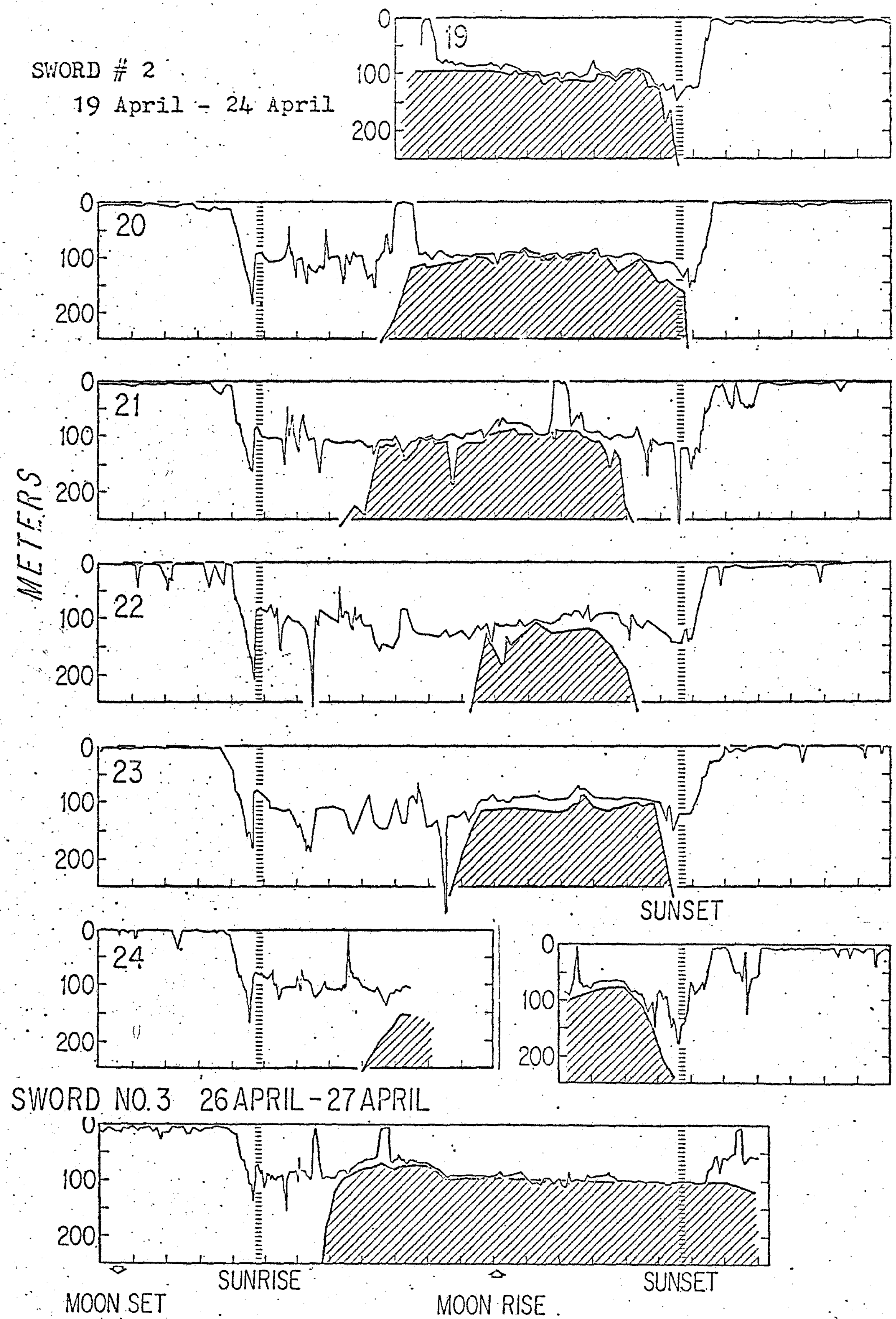

Figure 16. Depth record for swordfish #2 and #3 plotted from midnight to midnight. Depth to the bottom when on the bank is shown as cross-hatched area. Horizontal axis, time in hours. The daily patterns are remarkably similar.

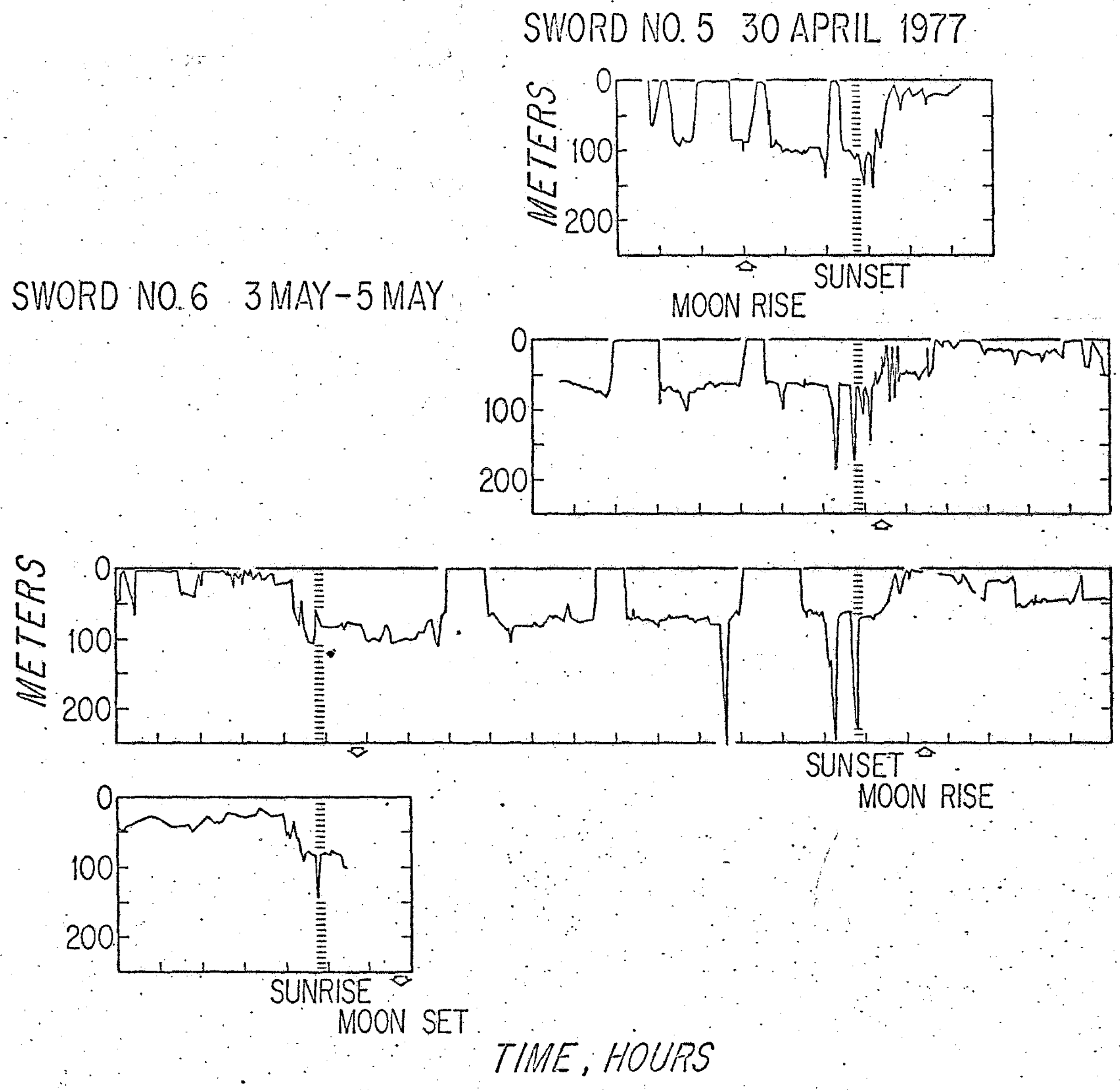

Figure 17. Depth record for swordfish #5 and #6. These fish show the same repetitive pattern as the others. The daytime depth was not as great and they came to the surface more frequently to fin. The greater night time depth compared with #2 and #3 is probably associated with the full moon at this time.

Possibly this was an effect of its recent capture on the longline. The time at depth on 9 November was shortened with swordfish #7 moving up to 100 meters at noon and spending the remainder of the day and that night between 160 meters and the surface.* At this point in our experience with swordfish, the several dives of one or two hours' duration made during the night of 9 - 10 November seem unusual. This behavior ceased when the fish moved out of the complex thermal structure of the Slope Water and into the Gulf Stream.

Figures 16 and 17 show the vertical movements of the Baja California fish. The repetitive pattern is clear. All of the fish descend from the surface approximately one hour before dawn. They seem to overshoot, going deeper than the depth that they will average during the next few hours, then coming back up to that level at sunrise.

Swordfish #2 and #3, which spent the night offshore, turned and swam inshore at first light (Figures 6 and 7). This turn toward land began at the same time as the fish left the surface. The inshore movement was made at a depth of about 100 meters with occasional forays to greater depths, going as deep as 300 meters on brief dives.

The appearance of these fish on the bank was not as punctual as the descent and turning inshore at dawn and the ascent to the surface after sunset, but they did return to the same 50 fathom area every day. Their time of arrival on the bank varied from 0600 (swordfish #3, 27 April) to 1030 (swordfish #2, 22 April). Some hours before sunset they would turn toward deeper water and, holding the same depth that they had been at during the day, swim out to sea with the bottom dropping away beneath

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*See note on page 28.

them. The depth records show diving around sunset. This was not as obvious as the morning dive, but occurred to some extent almost every day.

Swordfish #5 and #6 followed the same general depth pattern as swordfish #2 and #3 with the difference that they came to the surface frequently for periods of 15 to 90 minutes ten times during a three day period (Figure 17). The inshore fish, #2 and #3, surfaced only seven times in eight days and stayed on the surface for a shorter time, 10 to 40 minutes (Figure 16). As discussed below, this difference in the amount of time spent on the surface may be related to hydrography and to the different dissolved O_2 concentrations in the two areas.

4. BUOYANCY

Swordfish #3 apparently spent from 1100 to 1800 on the bottom on 27 April. Swordfish have been seen resting on the bottom on several occasions by observers in research submarines (Zarudski and Haedrich, 1974), and this may be a common habit. The fixed pectoral fins would give it a firm base to rest on. Its swimbladder, while large, has capillaries in the *rete mirabile* of the gas gland which are quite short and are comparable to those of a surface dweller such as the flying fish (N. B. Marshall, personal communication). Mesopelagic fish which secrete oxygen into their swimbladders against high pressure, have long capillaries in the *retia* (Marshall, 1960). It is unlikely that the gas gland of the swordfish with its short *rete* capillaries, would be suited to keeping the bladder inflated at depth. Even with a partially collapsed bladder however, the swordfish would probably not have any trouble

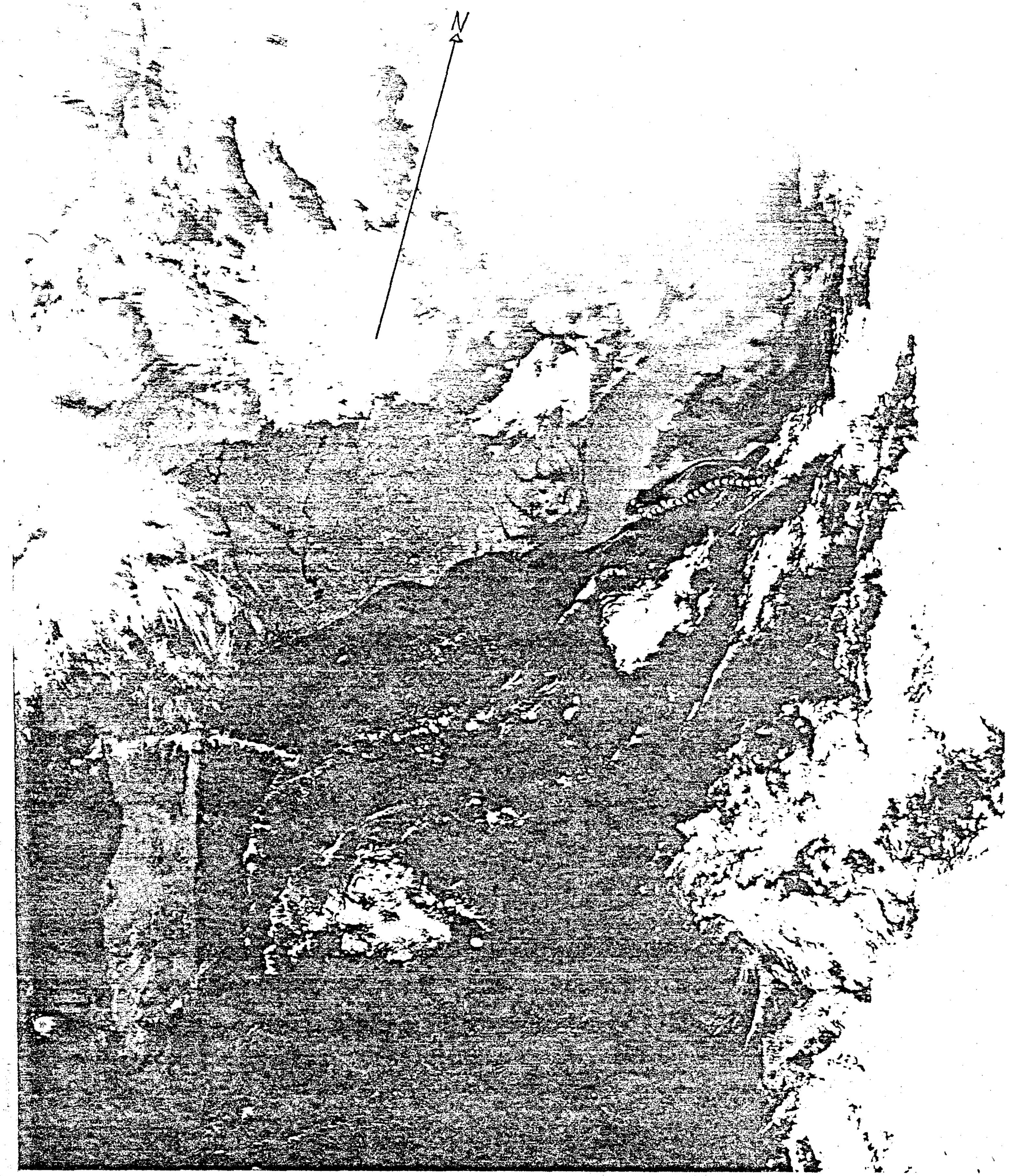


Figure 12. Image from a satellite infrared sensor for 8 November with the track of swordfish #7 as it appears in Fig. 13.

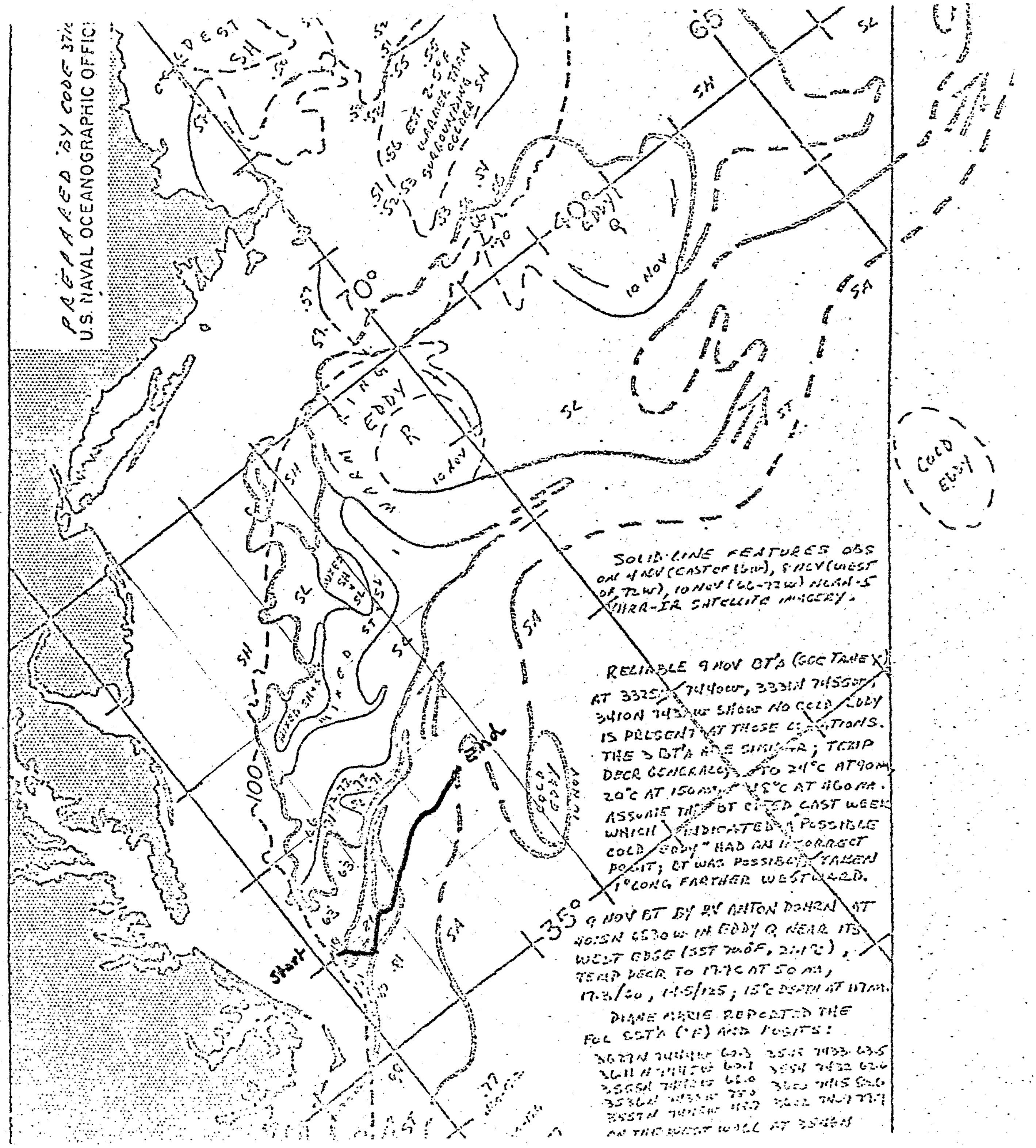


Figure 13. Frontal Analysis Chart for 9 November, 1977 prepared by the U S Navy Hydrographic Office using information from satellite infrared sensors and surface vessels. The track of #7 is superimposed on the surface temperature plot.

staying up in the water. The high lipid content of the meat and bone of this fish would lower its density and this, along with hydrodynamic lift from the flat bill and fixed pectoral fins, would hold the fish up when moving. When stopped, however, the excess density might prevent it from hovering easily and resting on the bottom might be a convenient position.

The reverse situation probably occurs at the surface. If the bladder is partially collapsed at depth, the swordfish can undergo a rapid rise without excessive expansion. Swordfish do come up raidly. On 11 November swordfish #7 rose from 300 meters to 40 meters in about 18 minutes, and our records show frequent instances of fish rising from 100 meters to the surface in less than 5 minutes. These changes in pressure would cause an 8 to 10-fold expansion in a free bubble. Such rapid expansion in the large swordfish bladder could probably not be controlled by the fish and this is further reason to suppose that at depth the bladder is collapsed relative to its volume at the surface.

At some depths the swordfish probably maintains neutral buoyancy. Fish taken in the longline fishery commonly float belly up with greatly expanded bladders when hauled to the surface. They are clearly not at surface equilibrium. A less extreme example of an overinflated bladder may explain swordfish "finning", the fish having enough excess buoyancy to lift the dorsal and caudal fins and sometimes part of the back into the air.

5. LIGHT

Light is clearly an important regulator of swordfish activities. The depth records show that when it is dark the fish are on the surface and when it is light they go deep. It is possible that the cause of this relationship is some other factor, such as pursuit of light sensitive prey. I think that the symmetry of the swordfish movements (they go down with the first appearance of light and are up on the surface again as soon as it is dark) is an indication that they were responding to light directly. If they were following after some other light sensitive organism, I would expect a noticeable lag and asymmetry in the descent and ascent with respect to sunrise and sunset.

There is such an asymmetry in the onshore-offshore movements of swordfish #2 and #3. Both these fish dived and swam inshore, at an appreciably increased speed, as soon as the sky began to lighten an hour before dawn. Their offshore movement, however, usually began an hour or two *before* sunset and they were well out in deep water by the time it was dark enough for them to come to the surface. Depth and the movement onshore were closely related to light but the movement offshore started well before darkness and the ascent to the surface.

Moonlight also affected the fish. There was no moon during the time we were tracking swordfish #2 (new moon on 21 April) and only a thin 1st quarter moon, setting about midnight for swordfish #3. The nights were clear, but dark, and the fish came right to the surface. For swordfish #5 and #6 there was a full moon shining brightly through scattered clouds.

These fish were considerably deeper at night than swordfish #2 and #3. Their depth varied from a few meters to about 50 meters. There are some notes in our records which indicate that the fish were on the surface when there were clouds and deeper when it cleared. The greater average depth on the moonlit nights suggests that they were responding to this illumination.

We regret that we did not keep better records of light conditions and plan to have some continuous recording of irradiance during future experiments.

During the second and third days that we followed swordfish #7, it was in a situation where light was probably an important clue. At this time it had moved offshore, out of the Slope Water and into the Gulf Stream and Sargasso Sea. In these areas the water is very clear and there are no sharp thermal boundaries. The depth record on 11 November is a symmetrical "U" shape (Figure 15). The greatest depth was reached at noon when the light was strongest and the most rapid change in depth came at sunrise and sunset when the relative light level was changing most rapidly. This is almost certainly a response to light and the fish appears to have been following an isolume.

We have calculated the light level at the fish using light attenuation factors for Gulf Stream water from the literature (Clarke and Backus, 1964). Having no means of measuring surface irradiance aboard, Dick Payne of W.H.O.I. supplied us with irradiance data which was corrected for this date, longitude and latitude. While the surface irradiance varied by 50 to 60-fold, the light level at the fish varied only by a factor of 2 and may well have been constant. The swordfish was staying in the dark; on the surface at night and at depth during the day, it probably maintained a light level around 10^{-3} to 10^{-4} $\mu W/cm^2$. This amount of light is still well above the threshold of vision for deep sea fishes which has been estimated to be 3×10^{-10} $\mu W/cm^2$ (Clarke and Denton, 1962). The grapefruit-sized eyes of the swordfish are probably well suited to vision in dim light.

Numerous oceanographic observations (e.g., Boden and Kampa, 1967; Clarke and Backus, 1956) show that some organisms of the sound scattering layers follow isolumes. Usually the depths of these layers are recorded for a few hours at sunrise or sunset and show changes similar to swordfish #7. Because of the difficulties of maintaining ship position and the confusion of intermingling layers it is impractical to follow a single scattering layer for an extended time. In addition, there is usually doubt about the identity of the organisms making up the scattering layer. We are pleased to think that our swordfish records are superior in several aspects to previous records of diurnal migration in the sea. We are sure of the species. We recorded the activities of one individual rather than an assemblage and we were able to follow it through several daily cycles.

Our thesis that swordfish #7 was following an isolume is based on the symmetrical "U"-shaped depth record from 11 November. On 10 November, while the fish went quite deep, the depth record was not a symmetrical "U"-shape. Depth increased gradually in the afternoon with the maximum being reached just before the fish began to swim up to the surface for the evening. This can be reconciled with maintaining a constant light level if we take into account the movement from Slope to Gulf Stream water which took place at this time and can be seen as a spreading and deepening of the isotherms in Figure 24. Light attenuation would progressively decrease during the day as the fish moved into clearer water. The depth at 1540 hrs when it was starting up to the surface for the night was 420 meters on 10 November and 460 meters on 11 November. This similarity was appropriate since by 1540 hrs on 10 November it had entered the same body of water which it would be in on 11 November. If the swordfish was maintaining a constant light level it should be at the same depth on the two successive evenings. The asymmetry in the depth record for 10 November can be attributed to the probable increase in water transparency during that day.

6. OXYGEN

An important hydrographic feature in the Pacific Ocean near the tip of Baja California is the presence of an oxygen minimum layer. Griffiths (1968) published an account of the oceanography of the area and some figures from that publication are included here. Figure 18 shows the distribution of dissolved oxygen in a section running from the mouth of the Gulf of California 300 miles SW into the Pacific. The section passes about 30 miles south of Cabo San Lucas. Temperature distribution in this section is shown in Figure 19 and oxygen and temperature profiles can be compared in Figure 20. The oxygen minimum layer is defined as the region

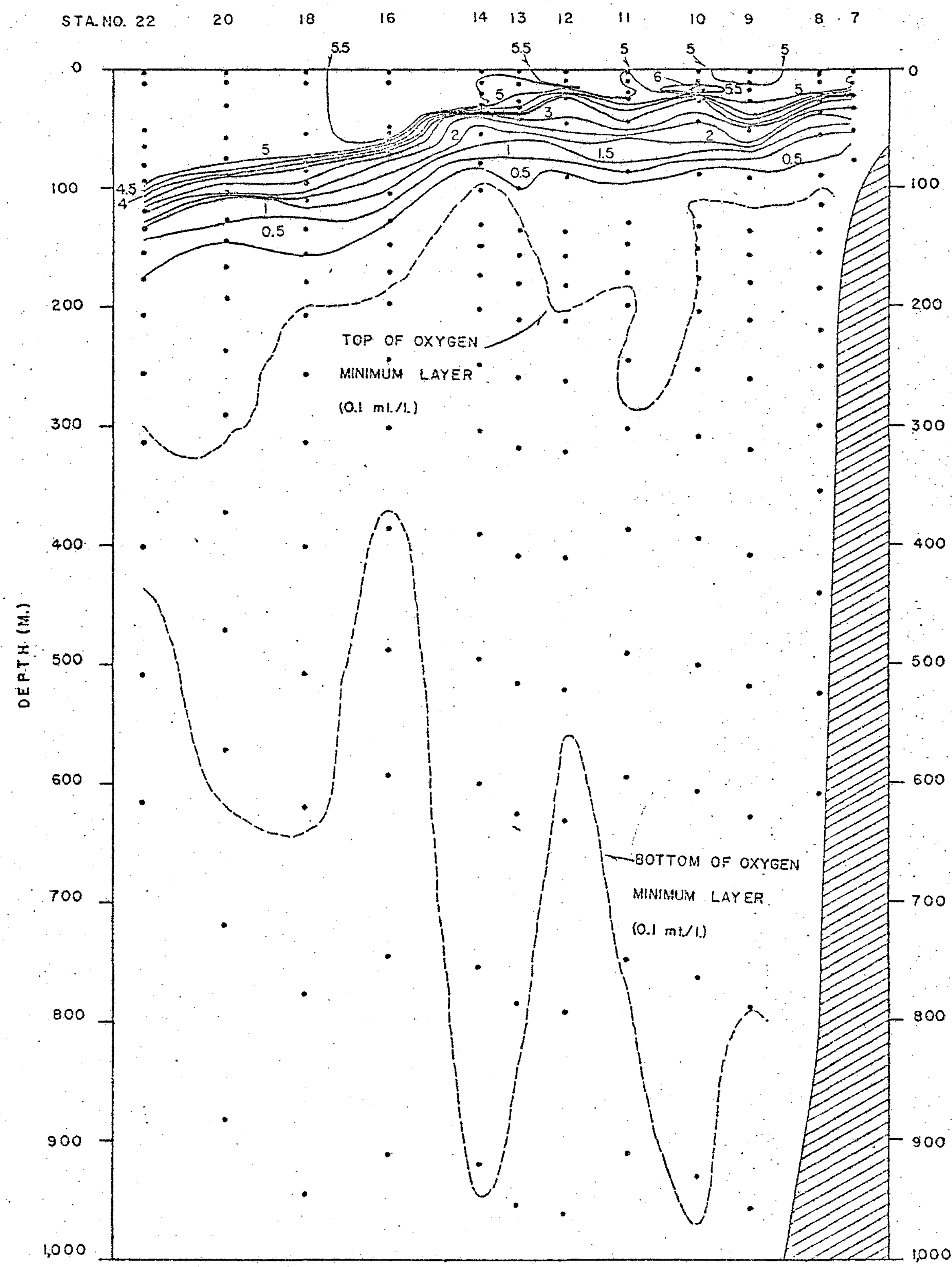


Figure 18. Vertical profile of dissolved oxygen near Baja California from Griffiths 1968. Below 100 meters the oxygen content is less than 10% that at the surface. The section runs for about 300 miles NE - SW. Stations 11-14 are about 30 miles south of Cabo San Lucas.

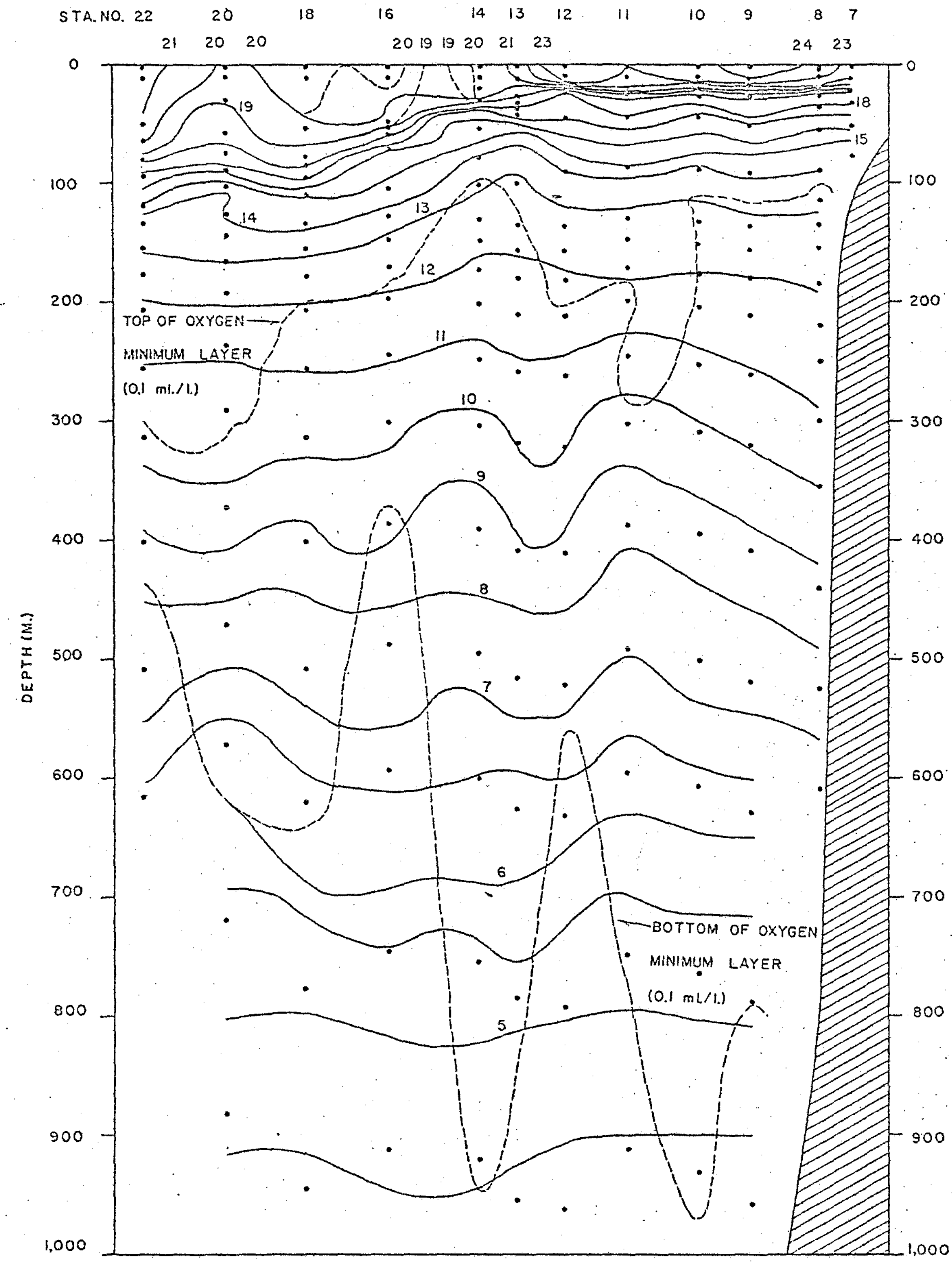


Figure 19. Temperature profile near tip of Baja California. The thermocline parallels and is slightly above the oxycline shown in figure 19. We used this correlation to infer the presence of poorly oxygenated water from our XBT data.

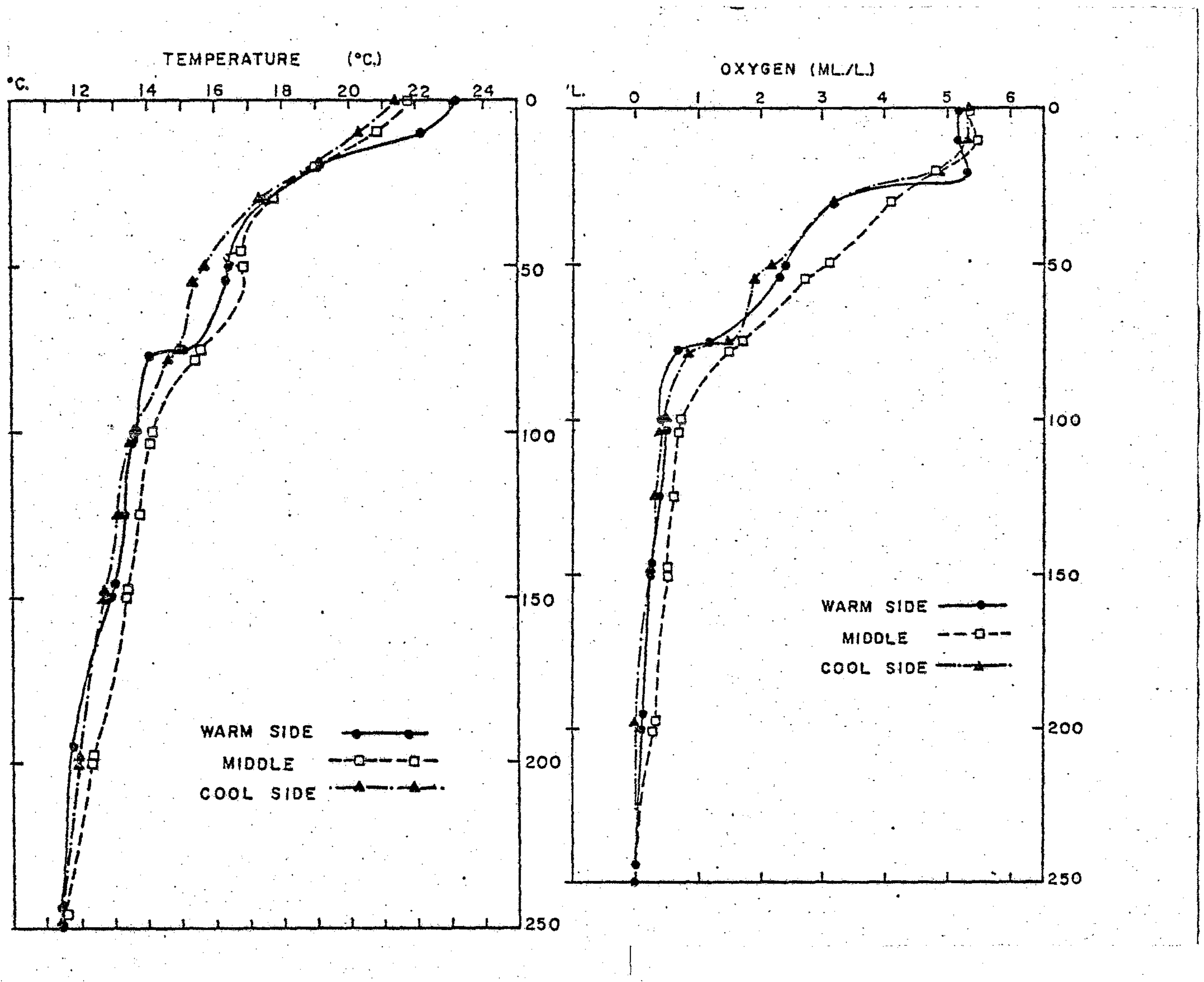


Figure 20. Oxygen and temperature data for the region where we followed swordfish #6. The oxygen concentration is closely related to the temperature structure of the water. From Griffiths, 1968.

containing less than 0.1 ml O_2/liter and lies at several hundred meters below the surface. From the thermocline down, however, the water is seriously depleted in oxygen and concentrations at 100 meters are less than 10% of those at the surface.

We were not prepared to measure oxygen on our Baja California expedition and thus have no direct information on oxygen concentration with depth. Studies such as the above have clearly demonstrated that the "oxycline" parallels and although slightly deeper, is closely related to the thermocline. From the depth and water temperature record of swordfish #6 presented in Figure 21, it is clear that the fish was in the low oxygen region below the thermocline much of the time. During the day it spent 60 to 80% of the time at about 75 meters where the water temperature was 56° to 58°F (13.3° to 14.5°C). From Griffith's data the oxygen concentration in this water would be 0.5 ml/liter.

This anoxic experience may be linked to the basking behavior which we observed in these fish (see Figure 10). It is possible that swordfish come to the surface and fin to recover from stressful conditions at depth. The stress may be low temperatures for fish on the harpoon grounds near New England, or low oxygen in Baja California. If our suggestions about buoyancy are correct, the surface makes a convenient position to rest and does not require precise regulation of the gas bladder as the fish come up to recover in the warm, well-aerated water. There seems to be a rough correlation between time spent beneath the thermocline and the succeeding period on the surface (Figure 22), as would be expected if the fish were on the surface to metabolize lactic acid accumulated while they were below the thermocline.

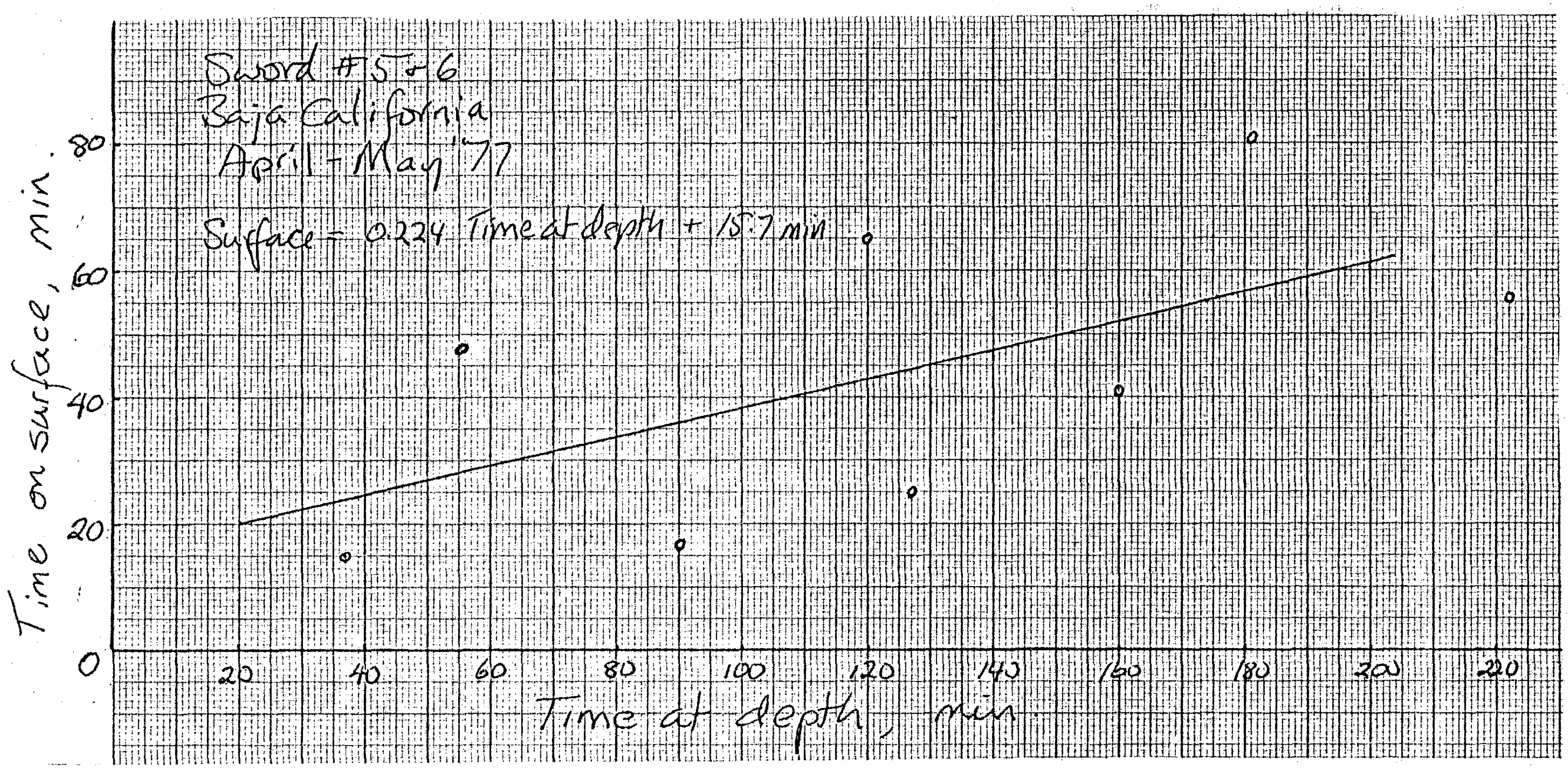


Figure 22. There is a rough correlation between the length of time #6 spent finning on the surface and the duration of the previous period in anoxic water. We take this as an indication that time on the surface was related to recovery from anoxia.

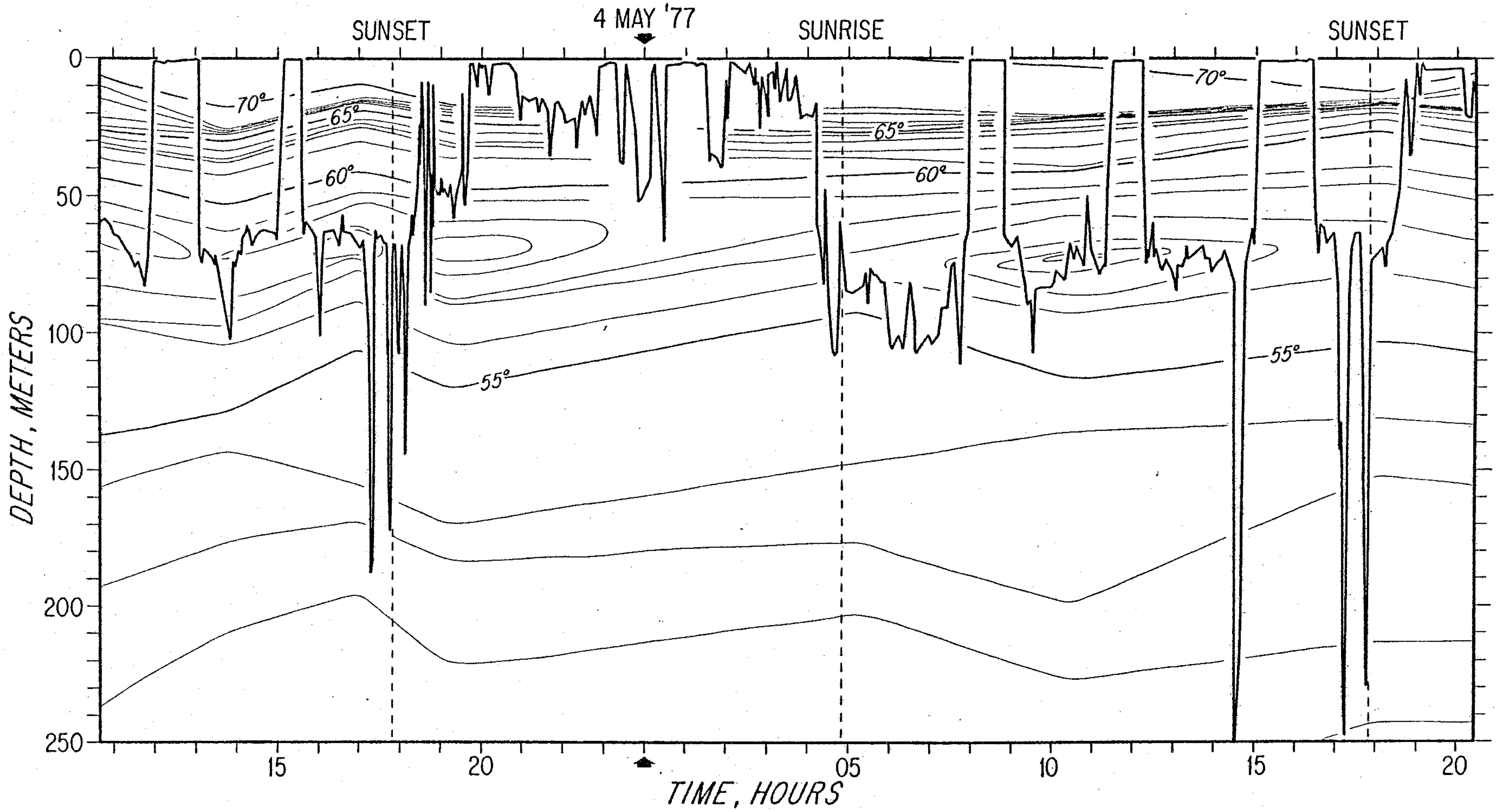
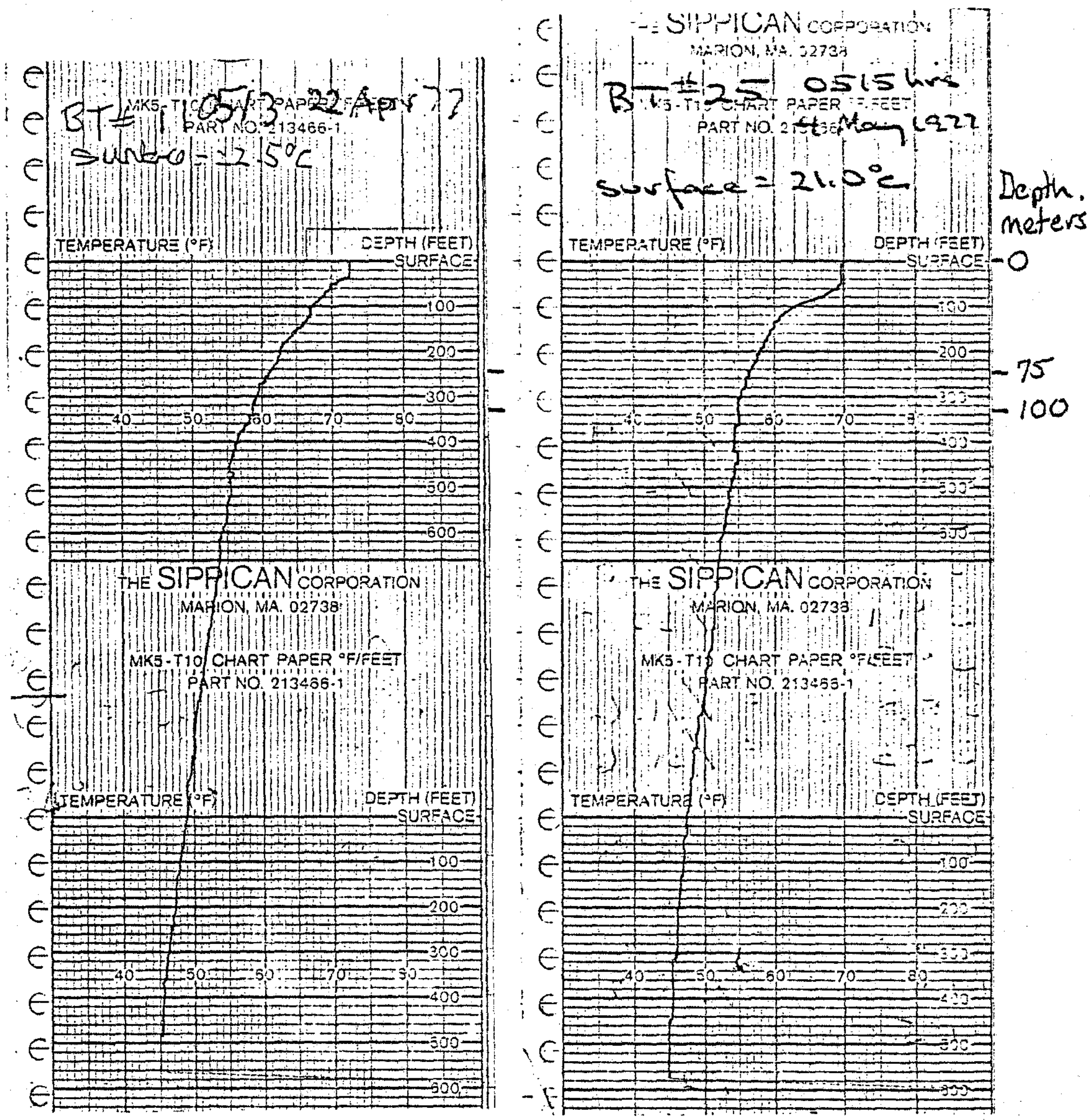


Figure 21. Depth record for swordfish #6 with isotherms drawn in from XBT casts. Time at depth was interspersed with time on the surface which would take the fish out of the anoxic layer and into the well aerated surface waters.

Swordfish #5 and #6 surfaced frequently, coming up to fin every few hours during the day. Swordfish #2 and 3 came up much less often, less than once a day. The difference may be related to the regions that the fish were in. The first two fish were inshore at the mouth of the Gulf, while swordfish #5 and #6 were further out in the Pacific. The temperature gradient in the first area was less sharp (Figure 23) and at the 100 m depth which the fish occupied on the bank, the water may have been more oxygenated than at 75 meters in the area where swordfish #5 and #6 were. Swordfish #2 and #3 may have been moving onshore and offshore along a boundary between Gulf of California and Pacific water, usually finding enough oxygen and only rarely having to come to the surface.

Water of low oxygen content has been reported to be a barrier to the vertical migration of euphausiids in a sound scattering layer (Barry *et al.*, 1962; Boden and Kampa, 1965). An oxycline was reported to be a barrier to skipjack in the southeast tropical Atlantic where the fish were confined to a surface layer with oxygen concentrations above 3.5 ml/liter (Ingham, Cook and Hausknecht, 1977). Although skipjack are much more active than swordfish and less tolerant of anoxic conditions, the several hour long periods spent at oxygen concentrations of 0.5 ml/liter imply that the swordfish may have gradually been accumulating lactic acid and building up an oxygen debt which required it to move up to well aerated waters to recover periodically.

On every morning in our records from Baja California the fish started down abruptly at first light, overshot the depth at which they would spend the next few hours, then come back up to that level. This is



Sword #2 Sword #6

Figure 23. The thermocline was much sharper in the region where we followed #6 than where we worked with #2. #2 spent the day at about 100 meters in water which may have been reasonably well oxygenated, while at 75 meters, #6 was well below the thermocline and probably in poorly oxygenated water. This may be the reason that #6 came to the surface more frequently to fin.

probably the result of the light response being modified by the presence of a barrier of low oxygen water. Maintaining a constant light level (which we believe swordfish tend to do) would take the fish far below the thermocline. Because it was going down rapidly with the quickly increasing light stimulation at dawn, it penetrated too far into the anoxic layer and was forced to come up again. This happened every morning (see Figures 16 and 17).

6. TEMPERATURE

Our primary goal at the start of this series of telemetry experiments with swordfish was to record the range of water temperatures which they experienced in their daily activities. The experiments were a great success and we have ample proof that swordfish will frequently undergo rapid changes in temperature of many degrees. Some of this evidence will be reviewed here.

The temperature regime encountered by swordfish near Baja California is illustrated in Figure 21. A 10°C gradient was presented to the fish between the surface and the depth of the deepest dive, 300 meters. The gradient between the surface and the usual daytime depth was 5° to 7°C. The fish made frequent excursions through the thermocline, passing through such a gradient in a few minutes time. While this is a considerable temperature change, the behavior of the swordfish in this area was probably more influenced by the presence of the anoxic water than by temperature.

The experiment with swordfish #7 in the North Atlantic coast shows the ability of this species to penetrate marked thermal boundaries (Figure 24). The first thing to notice on this record is the remarkable change in water temperature occurring as the fish moved to depth. At 0800 hrs on 9 November the swordfish dived from 25°C water at 20 meters to 8°C water at 400 meters. The following dawn it moved from 27°C at the surface to 8°C at 440 meters, a 19°C temperature excursion. These are large temperature changes for any organism to undergo and remain active. Our thesis was that a specialized organ which warms the brain of swordfish would allow it to experience a degree of chilling that would immobilize another fish. We feel that this is a most convincing demonstration that swordfish experience large temperature changes in the normal course of their activities. We have been outstandingly successful in recording such temperature changes and are pleased with our results.

The coldest water which swordfish #7 went into for any significant time was 8°C. This may represent a lower preferred limit for swordfish as it agrees with the 8°C temperatures reported for the deeper sightings of swordfish from research submarines (Zarudzki and Haedrich, 1974). The 8°C temperature may only reflect a light or depth limit, however, and we look forward to more data from swordfish in areas where water colder than 8°C is readily accessible.

The behavior of swordfish #7 on 9 November was different from what we feel is "typical" swordfish behavior and the differences may be related to temperature. We were in a region on the continental slope

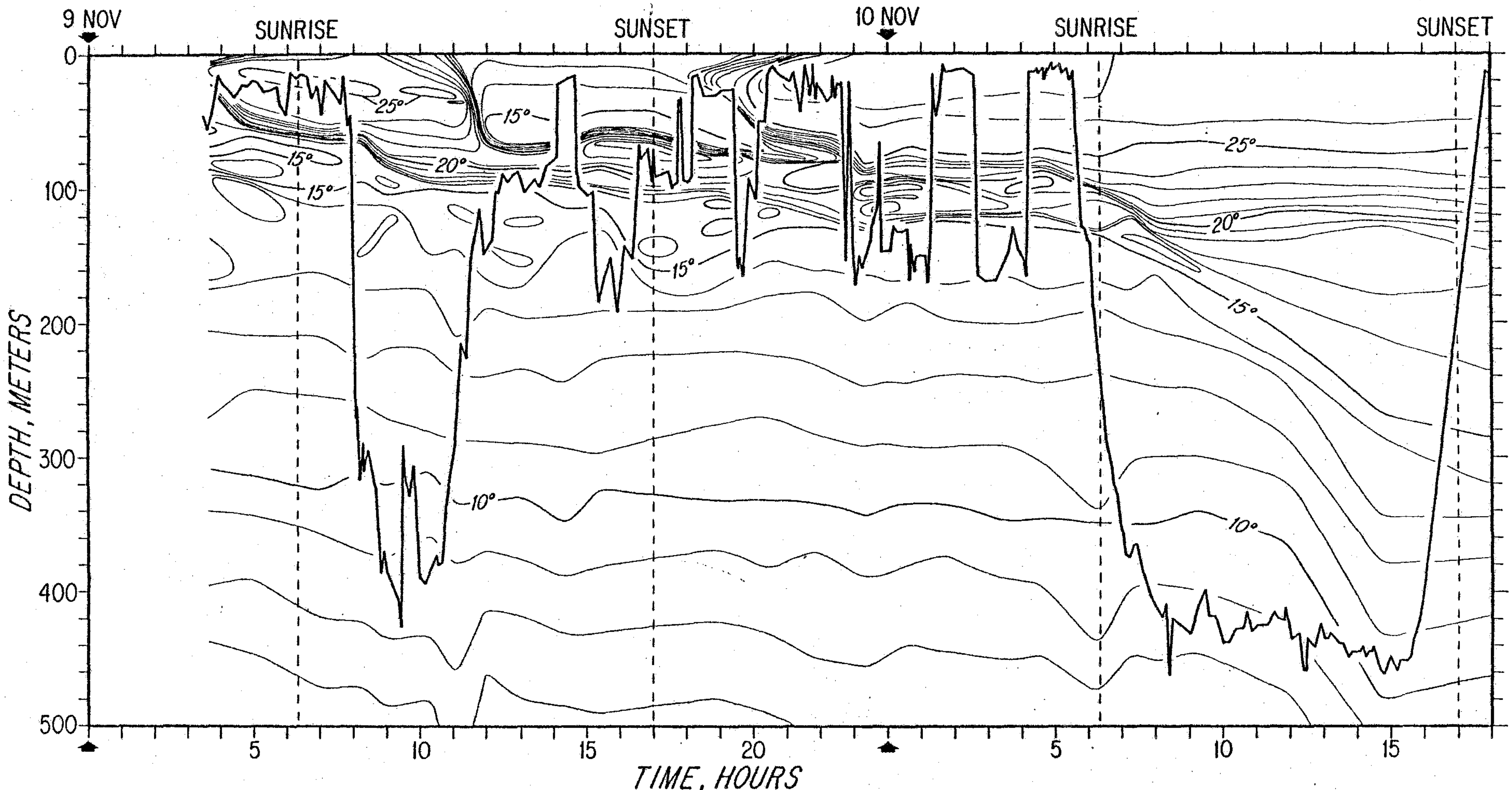


Figure 24a. Depth record for #7 on 9 and 10 November. The isotherms are drawn in form XBT casts. During 9 November the area we were in had a complex thermal structure with sharp thermoclines and inversion layers. On 10 November at dawn the deepening isotherms indicate that the fish was moving into the Gulf Stream.

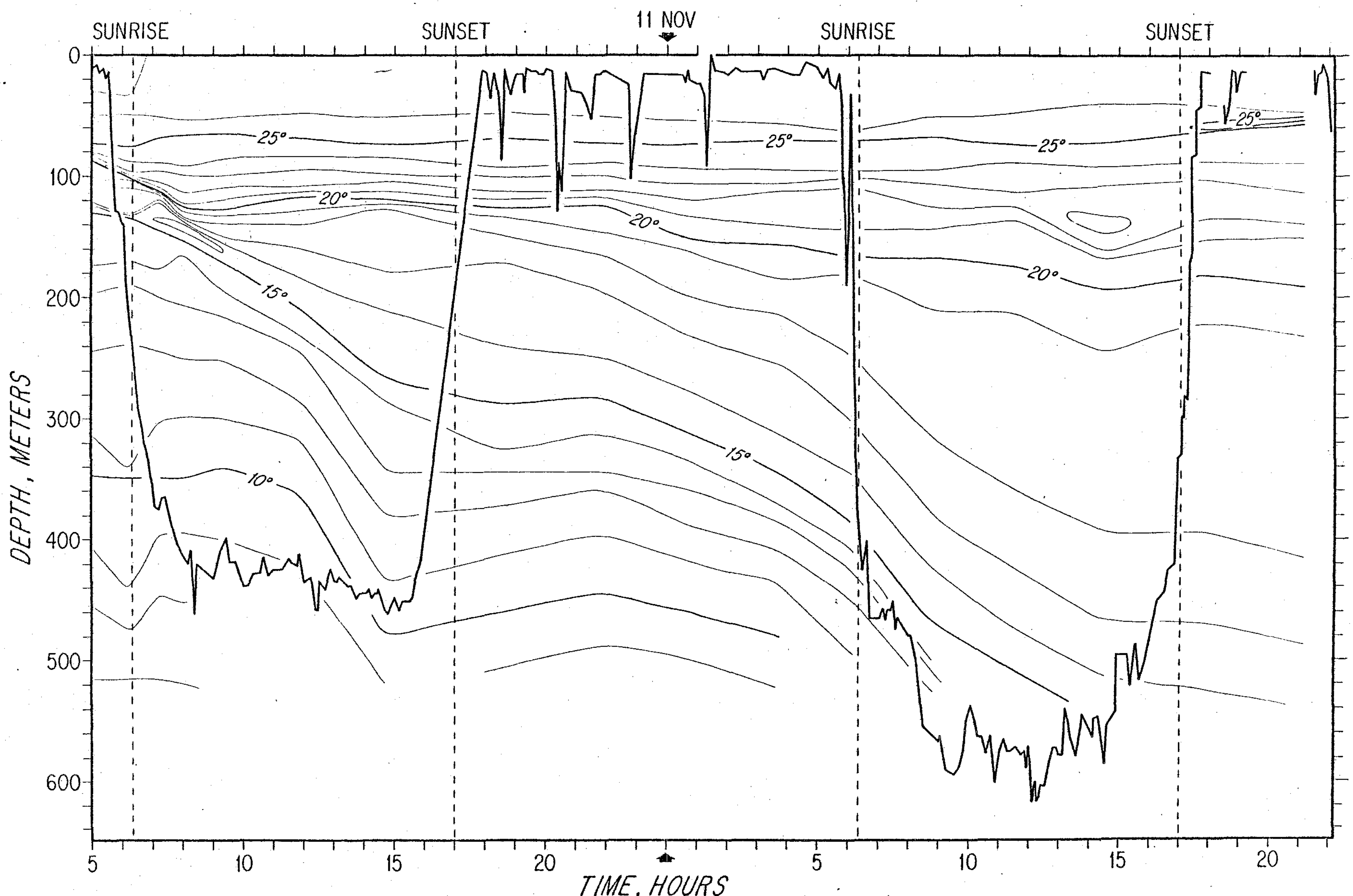


Figure 24b. Depth record for #7 on 10 and 11 November. From dawn of 10 November to the afternoon of 11 November the fish was moving across the Gulf Stream. On these two days the depth of the fish was probably regulated by light level.

where cold water was mixing with warm water thrown off from the Gulf Stream. The water temperature structure was very complex, with sharp thermoclines and pronounced inversions. For instance, at 1700 hrs on 9 November the fish located itself in the warmest part of an 8°C inversion (Figure 25). It seems likely that the presence of these complicated thermal structures at approximately 100 meters was responsible for other deviations in activity noted that day. While we had come to expect that swordfish would remain at depth during the daylight hours, this fish came up at mid-day* and moved about in the various thermal gradients for the rest of the day and night. Around sunrise on 10 November, we moved out of this region of eddies and mixed shelf and stream water into the Gulf Stream. From then on both the behavior of the fish and the water temperature structure became more regular. We argued earlier that light is an important cue to the activities of swordfish. On 9 November, however, it seems that the effect of light was overridden by some pronounced temperature features. Boden and Kampa (1958) reported a scattering layer which was coming up at twilight, maintaining a constant light level, but stopped when it encountered the bottom of the thermocline. Temperature is clearly not a barrier to swordfish, but this region might collect food organisms and attract the swordfish by the presence of its prey. In future experiments it would be of great value to have the use of a good echo sounder to indicate the position of scattering layers and potential food organisms.

In the original proposal for this work we speculated that by tracking a pelagic fish, we might be able to detect and interpret its responses

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*See note on Page 28.

to various eddies and current systems. The experiment with swordfish #7 provided a good opportunity to try this. Using the U.S. Navy Experimental Ocean Frontal Analysis Chart for 9 November (Figure 13) we superimposed the Loran positions for the track of swordfish #7 over the temperature information represented on the chart. Not surprisingly, agreement between our data and the surface temperatures on the chart was not all that good. Such a plot puts us in a long streamer of cold shelf water being swept along on the margin of the Gulf Stream. Our surface temperature data show that we had actually crossed this band of cold water and were moving in the Gulf Stream itself.

It is difficult to transfer precisely the position of a temperature feature seen on the satellite image of the earth's curved surface to the flat temperature chart. In addition, such features are volatile, and can be seen to change from day to day. The contours on the chart were drawn from a satellite photo taken on 8 November and the situation probably changed considerably by 9 November when we were there. Using our temperature data (Figure 24), we can reconstruct the path taken by the fish relative to the surface temperature features seen in the satellite image. It starts where the fish was caught and tagged, near the southwest corner of a tongue of warm water. It moved to the southeast and by 1000 hrs on 9 November it had reached a streamer of cold water being carried along the margin of the Gulf Stream. The fish crossed beneath this, swimming in an underlying warm inversion layer, and at 1800 was back in the warm surface water along the edge of the Gulf Stream. While under the cold surface layer the fish had made a

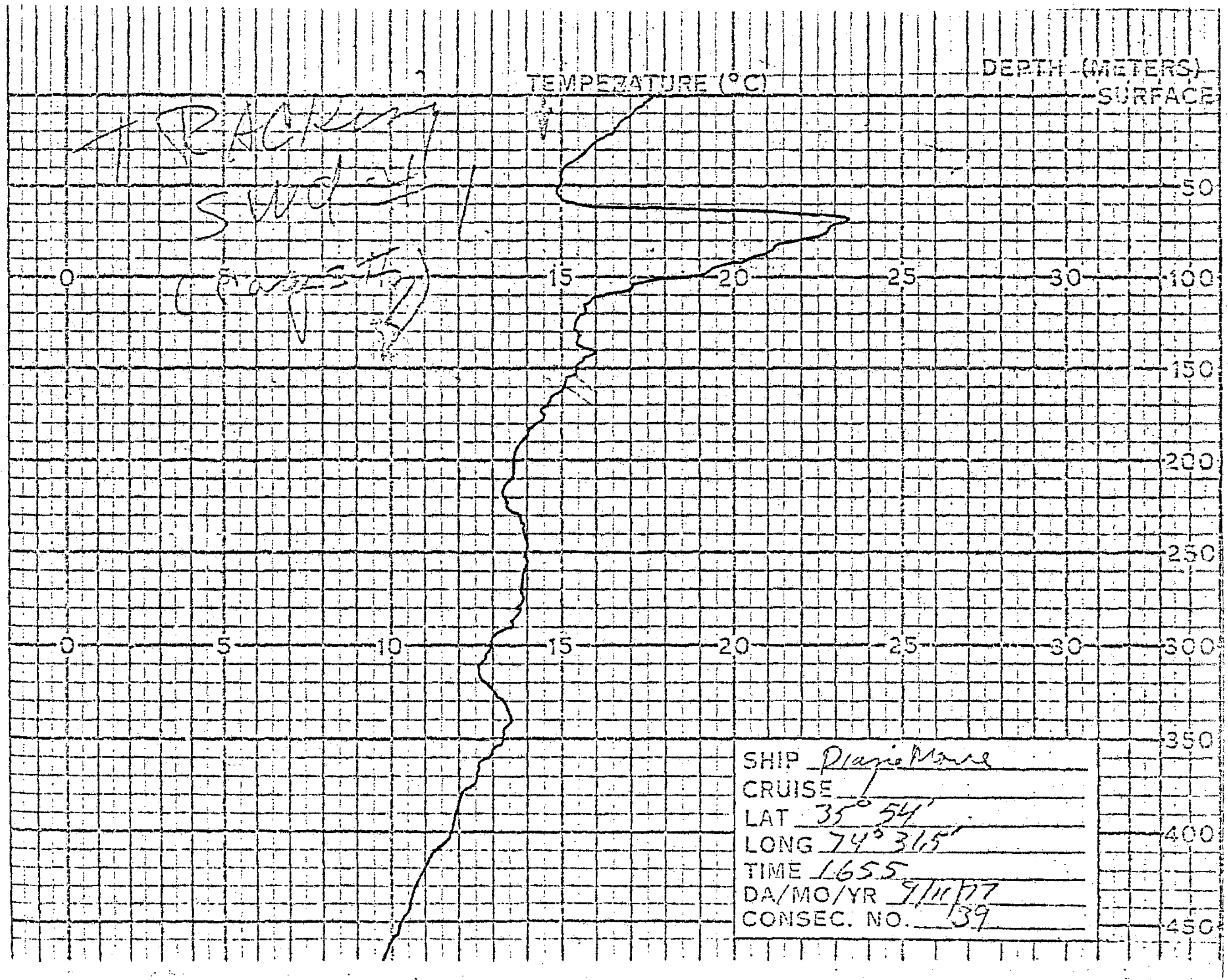

Figure 25. XBT record from 1700, 9 November during track of Swordfish #7. At this time the fish was in the prominent 8°C inversion layer under the cold surface water.

dog leg turn to the south, then came around to the north then to the east before reaching the edge of the Stream. For the next 11 hours it moved northeast, parallel to the temperature boundary between warm and cold water. When the boundary turned north, the swordfish continued to the northeast into the Gulf Stream and Sargasso Sea.

This fish responded to the major temperature feature appearing in the satellite image of this area by swimming beneath it. We hope to have an opportunity to repeat these experiments and see the response of swordfish to features which cannot be so easily avoided, such as the warm and cold core rings.

NOTE:

Swordfish #7 on 9 November did not follow the supposed pattern of swordfish swimming deep during daylight hours and at the surface at night. After this report was written, John Stegeman (W.H.O.I.) suggested to me that the late descent coincided with a kink in the thermocline at 50 m and that the early return from depth occurred just as the fish began to swim under the streamer of cold shelf water seen so clearly in Figures 12 and 13. This early return to shallow depths in the middle of the day can probably be explained as a response to light level. The streamer of cold shelf water had a rich growth of phytoplankton and was a dark green-blue color. Coastal waters absorb much more light than oceanic waters and to the fish it must have been as if swimming under a dark cloud. The cold water was so opaque with phytoplankton that the swordfish moved from 400 to 100 m to stay with the same isolume.

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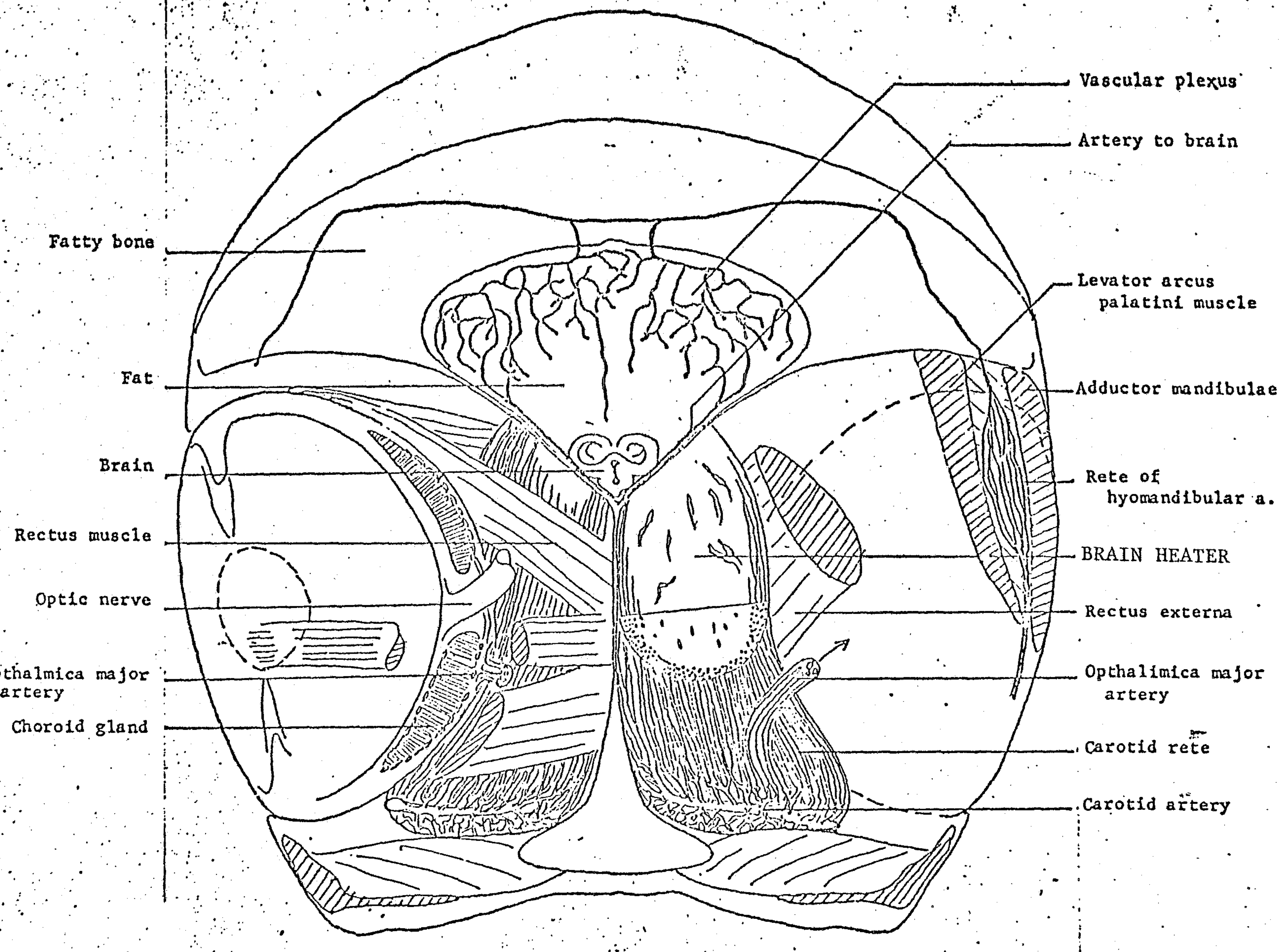

Figure 8. Cross-sectional diagram of a swordfish head showing the relationship of the small brain to some other organs.

Brain heater.

Some years ago we noticed that the brain of swordfish was warm, in some cases as much as 8.5°C warmer than the water. The swordfish we worked with were taken by longline and were in poor condition so that the brain of a healthy fish in nature may be even warmer than this. White marlin also have warm brains. The warmest of these was 4.6°C above water temperature.

Now other warm fish we have worked with, the tunas, mako, and porbeagle sharks also have warm brains, but this is less remarkable because the entire animal is warm. Billfish, however, have evolved warm brains in their otherwise cold bodies. The brain, the retina of the eye, and a large organ lying beneath the brain are warm. The relationships of these organs in the swordfish can be seen in Figure 8. The warm organ beneath the brain is composed of outgrowths of an eye muscle. The tissue is brown in color and has the consistency of liver. It has a massive blood supply in the form of a large bundle of small arteries and veins which conduct blood from the carotid artery to the brown tissues and acts as a heat exchanger. A small fraction of the blood flowing through this warm tissue may go on to the brain. The brown tissue itself serves to produce heat. Examination by electron microscope shows that it is full of mitochondria, the energy converters of the cell. It also has a very high concentration of cytochrome c, a key enzyme in mitochondrial oxidation. The large blood supply brings ample amounts of oxygen and food substances to this tissue where they are oxidized to produce metabolic heat. The heat exchanger in the blood supply prevents this heat from being carried away and lost in the venous bloodstream. Metabolic heat stays in the organ and raises the temperature. The blood to the brain and to the retina passes through this organ and is warmed in transit. In addition, the brain is warmed by conduction, being separated from the brown tissue by only a thin shelf of bone and being well insulated from the exterior by several inches of fat and fatty bone.

The brain itself is tiny. A brain from a 200 lb swordfish is smaller than the end of your thumb. Metabolic heat generated by the tiny brain would not be sufficient for it to warm itself if it were located in the otherwise cold head. The large accessory organ, the brain heater, is required to produce enough metabolic heat to warm the brain.

An organ thus specialized to produce heat is not unknown to biology. Infant mammals have a tissue known as "brown fat" which generates enough heat to keep the infant warm when the mother is away for short times. It functions mainly in the very young infant, before the muscles are developed sufficiently to shiver. When an animal, such as man, is old enough to shiver and produce heat by muscle contraction, the brown fat disappears. It remains in adults of those mammalian species which hibernate and aids in arousal from the low temperatures of hiberation. This is the first instance of such a tissue being found in an animal other than a mammal and in a fish at that!

Why should a swordfish evolve such a large, elaborate structure for warming its little brain? The answer probably lies in the effect of low temperatures on the nervous system. In general the more complicated the neural circuits are, the more susceptible they are to malfunction when cooled. A catfish can be trained to respond in a certain way, say by stopping its respiration movements, when a light is flashed on it. If the catfish which has been living and trained at room temperature, 70°F, is cooled to 60°F, it cannot give the proper response (Prossar and Farhi, 1967). It seems normal. Its nervous system functions well enough so that it can eat, swim, respire, balance, but the trick is gone. I have had a similar experience after diving in cold water and getting severely chilled, so cold that I could not get the mercury up into the stem of a fever thermometer. I could see, breathe, and walk home, but my perceptions were altered and I could not do mental arithmetic. What we call the higher mental functions are easily degraded by chilling.

Now the swordfish is known to be a deep living animal. They have been caught on deep set fishing trawls, frequently have deep water animals in their stomachs and have been seen at depth by research submarines. The water is cold at depth, but living in cold water is not of itself a problem. Fish are very well able to acclimate to cold. Freshwater fish do this when their ponds grow cold in winter, but acclimation takes place over a time span of weeks. It is likely, however, that the same swordfish seen on the surface are going down into cold water and doing it frequently and rapidly. Such rapid changes would case difficulties. An active predator chasing swift prey will need quick reflexes. The usual mental impairment that results from chilling would be a great disadvantage. If the swordfish goes into deep cold water for just a few moments, there will be no serious chilling and no problem. Again, if it remains in cold water for the ways or weeks needed to acclimate, there will be no difficulties. It is when the fish dives for periods of many minutes of hours that chilling will affect the central nervous system. It seems likely that the swordfish does this, and if it does, the presence of the brain heater makes sense. We can say "this is its function; to insure the swordfish's rapid reactions when it enters cold water". Acoustic tracking experiments with depth or temperature transmitters are the way to find out what depths and water temperatures the swordfish seeks. Such information on the behavior of the animal is essential to understanding what is going on.

This is going to be a complex and rewarding series of experiments. All of the billfish that I have examined (white marlin, Atlantic and Pacific blue marlin, striped marlin and sailfish) have this same organ that I called the brain heater in the swordfish. Now some of these are surface fish from the warm tropics. Why should animals which do not encounter cold water have such a structure? A puzzle, but it is important to remember that we really know very little about these fish. I would have been sure that the white marlin was a surface fish. The very appearance of its head with eyes angled down like a seagull's seems to confirm this, but we tracked one in the Tongue of the Ocean that dove to 100 meters three times. The water was still warm at that depth, but we were surprised at how deep it went. If a white marlin made such a dive anywhere along the mainland coast north of Florida, it would have entered cold water and thus may have had use for a warm brain.

The dives we observed in marlin open the possibility that all the billfish may, under some circumstances, enter cold water and thus have use for a warm brain. At present we know almost nothing about the behavior of these fish. The telemetry experiments give us a valuable insight into their activities and will be most useful in our arguments about the function of the brain heater.

The idea that the brain heater evolved to protect the nervous system from chilling is a useful one. It is probably correct in the case of the swordfish. There are other possibilities however, particularly with the surface-dwelling, warm-water species of billfish. The eye as well as the brain of billfishes is warm and there may be some advantage to a higher temperature for processing visual information in the retina and in the brain. While the warming that we would expect from the brain heater would probably not produce behaviorly important effects by increasing the velocity of nerve conduction or the speed of a simple reflex, circuits involving many synapses might be speeded up enough to have a significant effect on reaction time. The visual elements themselves may benefit. The turtle retina has a slow electrical response with a rise time of about 100 to 150 msec for cones and 300 to 500 msec for rods at 20°C (Baylor and Hodgkin, 1973). With a Q_{10} of about 2, temporal resolution might show considerable improvement on warming. A faster response time would provide a significant advantage to a visual predator such as the billfish. The "brain heater" might thus serve a useful purpose by warming the eye even in those fish which do not encounter warm water.